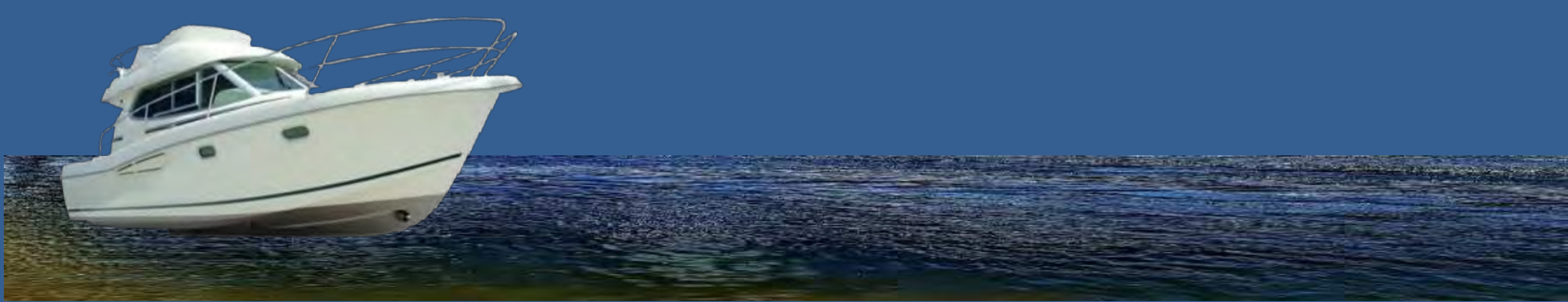
Emissions and Operability of Gasoline, Ethanol, and Butanol Blends in Recreational Marine Applications

PUBLISHED RESEARCH PAPERS DETAILING ENGINE AND VESSEL COMPATIBILITY WITH ISOBUTANOL-EXTENDED FUELS



Emissions and Operability of Gasoline, Ethanol, and Butanol Blends in Recreational Marine Applications

PUBLISHED RESEARCH PAPERS DETAILING ENGINE AND VESSEL COMPATIBILITY WITH BIOBUTANOL-EXTENDED FUELS

EXECUTIVE SUMMARY --
EMISSIONS AND OPERABILITY OF GASOLINE, ETHANOL, AND BUTANOL BLENDS IN RECREATIONAL MARINE APPLICATIONS

The National Marine Manufacturers Association (NMMA) and the American Boat and Yacht Council (ABYC) under the direction and guidance of the US Department of Energy and Argonne National Laboratory were engaged in a multi-year program to evaluate the performance of recreational marine engines and vessels operated on biologically produced isobutanol fuel[1]. With known issues associated with ethanol fuels and the ongoing push toward higher quantities of ethanol such as E15, the marine industry has come together to evaluate an advanced biofuel with properties better suited for the marine environment than ethanol.

Isobutanol contains nearly 90% of the energy content of gasoline compared to 67% for ethanol. A higher energy content means that 16 vol% isobutanol (iB16) is equivalent to the energy content of 10 vol% ethanol (E10). Both iB16 and E10 contain the same oxygen by weight, and both raise octane when blended into gasoline. ***Isobutanol is particularly interesting to the marine industry as it is significantly more resistant to phase separation than ethanol. It is also less corrosive to fuel system component materials such as fuel tanks, fuel hoses, primer bulbs, gaskets and orings compared to ethanol***[2]. Lack of phase separation and low solvency means that isobutanol could be transported in the existing pipeline distribution infrastructure, minimizing the need for truck and rail transportation, which is required for ethanol[3]. When added to gasoline, isobutanol lowers the Reid Vapor Pressure (RVP) of the finished gasoline blend which results in lower evaporative emissions and allows for a less costly gasoline blend stock.

Years-long engine and vessel testing performed through a collaborative industry effort conducted on many different engine technologies and boats have confirmed the compatibility of isobutanol fuel blends with marine engines and vessels. The major tests performed during this testing program and conclusions are highlighted below.

The entire marine industry has approved the use of isobutanol fuel blends up to 16.1 volume percent[4].

TESTS PERFORMED

- Gaseous and particulate engine exhaust emissions (regulated and non-regulated)
- Greenhouse gas emissions (GHG)
- Combustion analysis
- Cold start
- Power and performance
- Runability
- Winter storage
- Oil tribology and lubricity
- Exhaust gas temperature
- Stoichiometric air/fuel ratio (Lambda)
- Field engine and vessel performance
- Full useful life endurance/durability
- Engine tear down and component inspection

TYPES OF FUELS TESTED

- E10 (10 vol% ethanol – control fuel)
- iB16 (16 vol% isoButanol)
- Tri-fuel blend (8 vol% isobutanol, 5 vol% ethanol and 87 vol% gasoline)
- Indolene (non-oxygenated certification fuel)

ENGINE TECHNOLOGIES TESTED

- Electronic fuel injection four-stroke outboards
- Carbureted four-stroke outboards
- Open-loop (CARB 3-star) SD/I and PWC engine
- Closed-loop (CARB 4-star) SD/I engines
- Conventional carbureted two-stroke outboard
- Direct fuel injection two-stroke outboards

ENGINE BRANDS TESTED

- BRP – Evinrude and SeaDoo
- Mercury
- Volvo-Penta
- Yamaha
- Tohatsu
- Indmar
- OMC – Johnson

MAJOR CONCLUSIONS

Laboratory, endurance, and field testing results on boats and engines indicate no discernable difference in power, performance, runability, emissions or durability between E10 and butanol test fuels (iB16/Trifuel blends).

All test engines remained below EPA and CARB emissions standards for HC+NOx and CO. Exhaust emissions comparisons between E10 and butanol test fuels were virtually the same on all engines tested. No significant emissions differences between E10 and butanol test fuels were found regardless of engine technology.

Full useful life engine tear-down and inspection on pistons, cylinder heads, cylinder bores, intake/exhaust valves, intake/exhaust ports, connecting rods and rod bearings indicate similar wear between the E10 control engines and iB16 test engines. No unusual wear, carbon build-up or durability issues were observed with either fuel during the 350 hour (equivalent 10 year useful life) testing.

No engine runability, engine durability, or engine/boat performance issues were experienced during the test program. All engines and boats performed well throughout the test program.

Engine startability performed at two different temperatures indicates similar seconds to start and pulls to start at 75°F between E10 and iB16 test fuels. At 30°F, data indicates a slight advantage in startability for butanol fuels.

Friction, wear and scuffing tests performed on engine oils suggest that E10 and iB16 in the fuel result in a slight friction reduction but a noticeable reduction in scuffing load compared to a non-oxygenated test fuel. There were no major differences between the load carrying capacity of the oil with either E10 or iB16.

The comprehensive data collected during this multi-year test program suggests that butanol blends up to 16 vol% can be used in recreational marine engines and boats without deterioration of engine/boat performance, emissions characteristics, durability or runability. Moreover, butanol blends up to 16 vol% will mitigate many fuel related issues experienced with ethanol fuels, primarily related to phase-separation and corrosion.

TABLE 1. RECREATIONAL MARINE ENGINE TEST HOURS ACCUMULATED

TEST CATEGORY	*HOURS*
ENDURANCE/DURABILTY	**2,203**
FIELD ENGINE AND VESSEL EVALUATION	**742**
LABORATORY TESTING	**425**
TOTAL	**3,370**

[1] DOE Annual Progress Reports - Emissions and Operability of Gasoline, Ethanol, and Butanol Blends in Recreational Marine Applications – 220p Board book

[2] Kass, M., Theiss, T., Janke, C., Pawel, S., et al "Compatibility Study for Plastic, Elastomeric, and Metallic Fueling Infrastructure Materials Exposed to Aggressive Formulations of Isobutanol-blended Gasoline" Oak Ridge National Laboratory, 2014

[3] Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., "In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels," SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.

4 *Recreational Boating Industry Turning to Biobutanol as Alternative Biofuel* - Press Release June 2015 http://www.nmma.org/press/article/19947 retrieved April 4, 2018

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IV.11 Emissions and Operability of Gasoline, Ethanol, and Butanol Fuel Blends in Recreational Marine Applications

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Objectives

- Assess suitability of butanol as a drop-in fuel for blending with gasoline for recreational marine engine applications.
- Ensure engine operability on butanol blends for a wide range of recreational marine engine applications.
- Quantify emissions of recreational marine engines operated on butanol blends compared to gasoline and ethanol blends.
- Demonstrate durability of recreational marine engines when operated on butanol blends.

Fiscal Year (FY) 2012 Objectives

- Establish detailed performance and emissions baseline of commonly used recreational marine engines using ethanol and butanol blends employing laboratory engine testing.
- Collect in-use emissions data of commonly used recreational 2- and 4-stroke marine engines employing field vessel testing.
- Evaluate the impact of fuel dilution on the lubrication performance of marine engine oil.

Accomplishments

- Engine lab testing with 10% ethanol in gasoline (E10) and 16 vol% gasoline iso-butanol (iso-But16) showed a 20-40% decrease in CO emissions relative to Indolene for the 4-stroke and 2-stroke direct injection engines. Reduction in CO using E10 was slightly higher compared to the iso-B16 alcohol blend. Oxides of nitrogen (NOx) emissions increased for both engines by 10-30% using alcohol blends. Overall net emissions were similar between the E10 and iso-But16 alcohol blends for each engine technology.
- In-use vessel testing with Indolene, E10 and iso-But16 showed a 20, 70 and 10% reduction in CO, NO, and total hydrocarbon (THC) emissions for 2-stroke engines when using alcohol blends. 4-stroke engines showed a 5-20% reduction in CO emissions but a 10-40% increase in NO emissions. No significant emissions differences between E10 and iso-But16 were found regardless of engine technology.
- Friction, wear and scuffing tests suggest that the presence of bio-based components (E10, iso-But16) in the fuel results in a slight friction reduction but a noticeable reduction in scuffing load compared to the baseline case.

Future Directions

- Conduct end-of-life performance and emissions laboratory tests upon completion of run-time accumulation.
- Perform laboratory engine testing with focus on engine cold start performance and particulate matter emissions assessment.
- Extend test matrix to include tri-fuel blend (gasoline/ethanol/butanol) combustion analysis and emissions on laboratory engine as well as tri-fuel blend field evaluation.
- Assess the wear mechanisms in samples tested with clean engine oils and oils contaminated with different levels of fuel for E0, E10 and iso-But16 fuels. If possible, wear mechanisms in engine components after teardown will also be evaluated. Attempt to develop a correlation of wear mechanisms in laboratory tested samples and engine tested components.

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INTRODUCTION

The Renewable Fuel Standard under the Energy Independence and Security Act of 2007 mandates an increase in the volume of renewable fuel to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022 [1]. This mandate is estimated to result in a hypothetical ethanol blend ratio of 24-29 vol-% in 2022 [2]. In order to further increase the renewable fuel fraction in transportation fuels, the U.S. Environmental Protection Agency recently granted a waiver for use of 15 vol-% ethanol blends (E15) in model year 2001 and newer light-duty motor vehicles [3].

The impact of extended ethanol blends and other alcohol fuels on recreational marine engines and vessels is widely unknown. However, given the dominant engine control strategies employed and materials used in the legacy marine fleet, it is suspected that increased ethanol levels can have detrimental effects on engine and vessel operation, performance, durability and emissions. Therefore, this project investigates the potential of iso-butanol as an alternative to ethanol as a blend component for recreational marine applications.

APPROACH

The project is designed to provide a comprehensive assessment of the impact of iso-butanol as a blending agent for a range of recreational marine engine applications. The assessment includes laboratory and in-use vessel testing of engine performance and emissions at several stages during the useful life of typical recreational marine 2-stroke and 4-stroke engines. Several test engines as well as vessels are operated for extended periods of time to evaluate the effects of iso-butanol on engine durability compared to certification gasoline and typical ethanol blends. Upon completion of the durability runs, engines are inspected and torn down to evaluate the fuel impact on engine components. In parallel, tests are conducted to assess the impact of ethanol and butanol blends on oil dilution and the lubrication performance of marine engine oil.

RESULTS

The initial phase of this project focuses on a relative comparison of gasoline-ethanol blends and gasoline-butanol blends compared to neat gasoline reference fuel (Indolene) as a baseline. Currently alcohol content in transportation fuels is limited by oxygen content and E10 is widely used throughout the United States.

Butanol exists in four isomers that differ in structure resulting in a variation of fuel properties. Due to its higher knock resistance compared to the other isomers, iso-butanol is being promoted by several fuel producers (e.g. BP, Gevo) and was selected for this study. Butanol is a four-carbon alcohol and has an oxygen content of 21.6 wt% compared to 34.7 wt% of ethanol. Therefore the iso-But16 blend was selected since it has equal oxygen content (3.5 wt%) to E10.

Engine Lab Testing

Three engine models from three different marine engine manufacturers were selected for laboratory emissions testing and useful life endurance testing. The engines include (2) 10 H.P Tohatsu 4-stroke carbureted outboards, (2) 90 H.P Mercury 4-stroke fuel-injected outboards and (2) 200 H.P Evinrude 2-stroke direct fuel-injected outboards. All engines operate open-loop without the use of lambda feed-back sensors. The Mercury and Evinrude engines were each baseline tested in the emissions laboratory according to the International Council of Marine Industry Associations (ICOMIA) test cycle (ISO8178) using three fuels, Indolene, E10 and iso-But16. The ICOMIA test is a 5-mode test that includes full load (Mode 1), engine idle (Mode 5) as well as three additional points covering the entire engine load and speed range. The emissions values for the operating points are weighted at 40% for idle, 25, 15 and 14% for the mid-load points and 6% for full load to provide one result value per test. Baseline emissions were recorded for each test fuel using an AVL i60 five-gas emissions analyzer.

Figure 1 shows the changes in CO, NOx and THC emissions with E10 and iso-But16 operation relative to the Indolene baseline for the Mercury and Evinrude engine. The Mercury engine showed a reduction in CO emissions of 35% and 38 % with iso-But16 and E10 respectively as compared to the Indolene baseline. The Evinrude showed a reduction in CO emissions of 15% and 22% with iso-But16 and E10 respectively relative to the Indolene baseline test fuel. The NOx emissions increased by approximately 30% for the Mercury and by approximately 12% for the Evinrude relative to the baseline Indolene test fuel. THC emissions showed a slight reduction for both the Mercury and the Evinrude using both alcohol fuels.

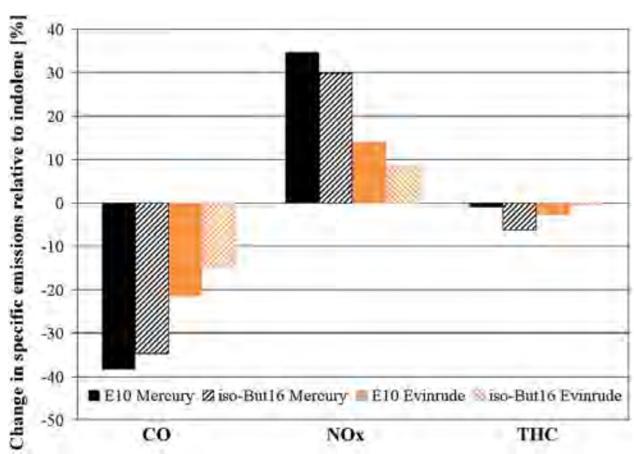

FIGURE 1. Average change in laboratory cycle-weighted emissions for E10 and iso-But16 operation compared to Indolene.

Engine endurance testing is ongoing with one engine from each set of engines operating on E10 and the other engine from each set operating on iso-But16. Upon completion of endurance testing, all engines will be emissions-tested and then torn-down to inspect and compare engine components.

In-Use Vessel Testing

Three vessel/engine combinations were selected for the in-use testing performed in May and September 2012 near Annapolis, MD. The tested engines include an INDMAR 6.0-l L96 V8 4-stroke engine in a Malibu Wakesetter Ski Boat, a Volvo Penta 5.7-l Gxi V8 4-stroke engine in an Alamar Aluminum Hull boat and an OMC Johnson Legacy 2.6-l, 6-cylinder 2-stroke outboard engine in a Promarine Fiberglass Inc "Intruder" boat. The vessels were tested according to the ICOMIA test cycle (ISO8178) and a Marine Portable Bag Sampling System [4] and Sensors, Inc. Semtech-DS Onboard Vehicle Emissions Analyzer were used to collect emissions data.

Figure 2 shows the changes in CO, NO and THC emissions with E10 and iso-But16 operation relative to the Indolene baseline for the INDMAR, Volvo Penta and OMC Johnson engines. The INDMAR engine showed a reduction in CO emissions of approximately 4% with E10 as well as iso-But16 compared to the Indolene baseline while the other two engines showed an approximately 20% reduction regardless of alcohol used for blending. The NO emissions increased for the two 4-stroke engines while a significant decrease was observed for the 2-stroke engine. THC emissions showed an inconclusive trend for the 4-stroke engines and a slight decrease for the 2-stroke engine. Overall emissions for the iso-butanol blend are equal or slightly lower compared to the ethanol blend.

The emissions trends are likely caused by variations in air/fuel ratio. Typical emissions trends for spark ignition engines include a reduction of THC and CO emissions with leaner operation and an NO peak at λ~1.05. The two 4-stroke engines employ closed-loop feedback control to maintain stoichiometric air/fuel ratios in order to maximize the efficiency of the aftertreatment system. At full-load conditions the engine controller deviates from stoichiometric operation and operates fuel-rich to reduce exhaust temperatures and prevent engine knock. The OMC Johnson 2-stroke engine uses a carburetor, has no closed-loop feedback control and no emissions aftertreatment system.

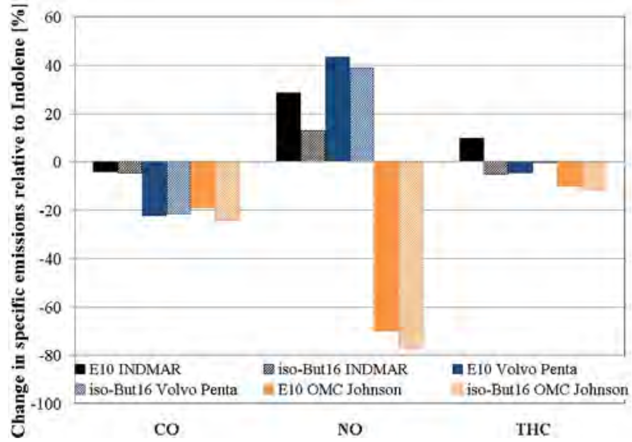

FIGURE 2. Change in cycle-weighted emissions for E10 and iso-But16 operation compared to Indolene.

Figure 3 shows the relative air/fuel ratio for all three engines at the different modes throughout the ICOMIA test. The INDMAR and Volvo Penta 4-stroke engines operate at close to stoichiometric air/fuel ratios regardless of fuel except for full load operation (Mode 1). Thus the changes in emissions shown in Figure 2 likely result from leaner operation at full load when using alcohol blends compared to Indolene. The OMC Johnson engine operates open-loop and air/fuel ratios using alcohol blends are generally leaner compared to Indolene operation except for engine idle (Mode 5). The increased air/fuel ratios are consistent with a decrease in CO and THC emissions as shown in Figure 2. The significant reduction in NO emissions is inconsistent with the

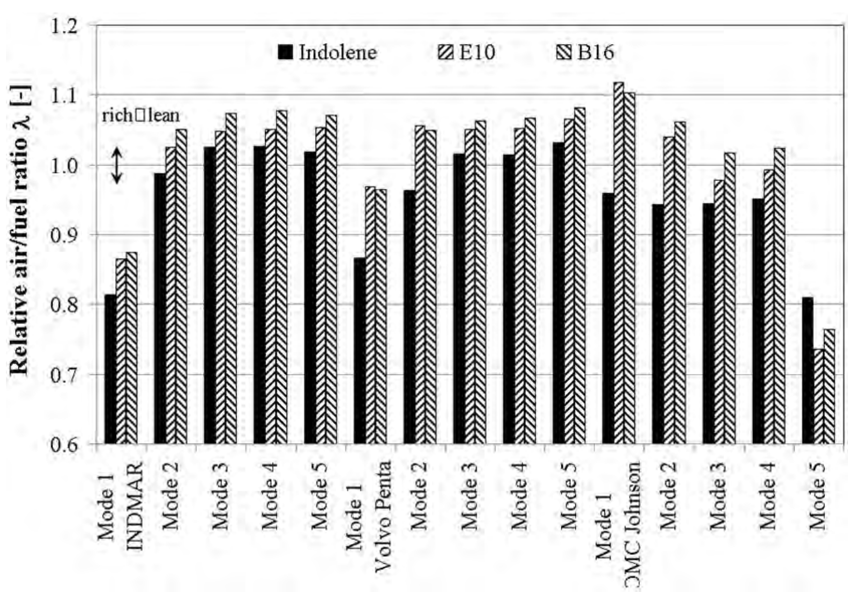

FIGURE 3. Relative air/fuel ratio for E10 and iso-But16 operation compared to Indolene.

general emissions trend and could be due to additional charge cooling from the alcohol fuel, uncertainties in the air/fuel ratio determination of the modal data as well as the richer operation at the heavily weighted idle point.

Lubricants Testing

Four different types of bench top friction and wear tests were conducted to assess the impact of fuel dilution on the lubrication performance of marine engine oil. The tests included unidirectional and reciprocating sliding and 4-ball test for friction and wear as well as block-on ring for scuffing. Three groups of engine oils were used for the tests including fresh engine oil (Yamalube 4M 10W30), surrogate model oils with 5, 10, 20, 30 and 50% of fuel (E0, E10 and iso-But16) added as well as used engine oil from a Yamaha test boat subjected to a sequence of 60 cold-start cycles with oil samples taken at 15-cycle intervals.

The tests on the surrogate oils suggest that average friction for all the oils is nearly identical and that fuel dilution resulted in a slight reduction of scuffing load and increased wear in proportion to fuel content regardless of fuel type compared to fresh oil.

The analysis of the oil generated from the cold-cycle tests showed a nearly linear reduction in viscosity as well as an increase in fuel dilution of the engine oil with increasing number of test cycles with no significant differences between E0, E10 and iso-But16.

Figure 4 shows the results of the 4-ball test and Figure 5 shows the scuffing test results for fresh oil as well as the oils from the Yamaha test boat cold start cycles. It appears that the presence of bio-based components (E10, iso-But16) in the fuel results in a slight friction reduction compared to the baseline case. However, oil dilution by bio-based containing fuels (E10

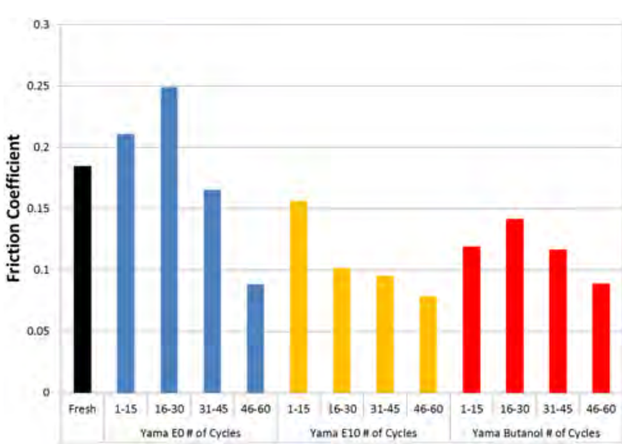

FIGURE 4. 4-ball test friction results for used oils from Yamaha engine tests.

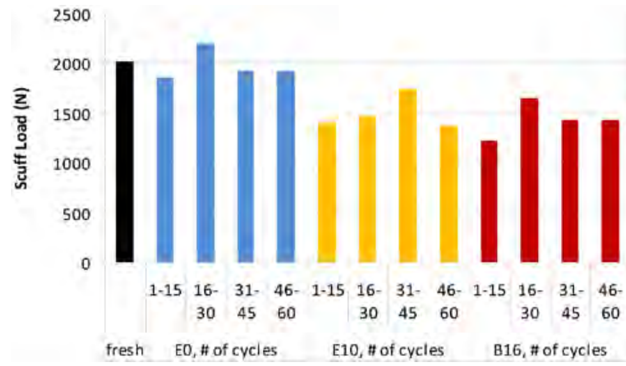

FIGURE 5. Scuffing test results for used oils from Yamaha engine tests.

and iso-But16) also resulted in a noticeable reduction in scuffing load. No significant differences between E10 and iso-But16 were discovered.

CONCLUSIONS

- Engine lab testing with E10 and iso-But16 showed a decrease in CO emissions relative to Indolene for the 4-stroke and 2-stroke direct injection engines. Reduction in CO using E10 was slightly higher compared to the iso-B16 alcohol blend. NOx emissions increased for both engines using alcohol blends. Overall net emissions were similar between the E10 and iso-B16 alcohol blends for each engine technology.
- In-use vessel testing with Indolene, E10 and iso-But16 showed a reduction in NO, THC and CO emissions for 2-stroke engines when using alcohol blends. 4-stroke engines showed reduced THC and CO emissions but increased NO emissions. No significant emissions differences between E10 and iso-But16 were found regardless of engine technology.
- Friction, wear and scuffing tests suggest that the presence of bio-based components (E10, iso-But16) in the fuel results in a slight friction reduction but a noticeable reduction in scuffing load compared to the baseline case.

REFERENCES

1. Section 201-202 Renewable Fuel Standard (RFS) Energy Independence and Security Act of 2007 (Pub.L. 110-140, originally named the CLEAN Energy Act of 2007).

2. Ickes, A. 'Improving Ethanol-Gasoline Blends by Addition of Higher Alcohols' 18th Directions in Engine-Efficiency and Emissions Research (DEER) Conference. Dearborn/MI. 2012.

3. Environmental Protection Agency (EPA) 'Partial Grant of Clean Air Act Waiver Application Submitted by Growth

Energy To Increase the Allowable Ethanol Content of Gasoline to 15 Percent'; Federal Register Vol. 76, No. 17. 2011.

4. Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., 'In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels,' SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.

FY 2012 PUBLICATIONS/PRESENTATIONS

1. Sevik, J. 'Exhaust emissions of low level blend alcohol fuels from two-stroke and four-stroke marine engines' Master Thesis. 2012.

2. Wasil, J. '1991 – 2011: A 20 Year History of Biofuels policy and the impact on the Recreational Marine Industry' Seminar 409: 'Boat Fuel and Fuel Systems: Designing Boats to Meet EPA Rules' The International BoatBuilders' Exhibition & Conference. Louisville, KY. 2012.

3. Wallner, T. 'Butanol Blends as Marine Fuels - An Overview' Seminar 409: 'Boat Fuel and Fuel Systems: Designing Boats to Meet EPA Rules' The International BoatBuilders' Exhibition & Conference. Louisville, KY. 2012.

4. Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., 'In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels,' SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. In-use testing work featured in an article and video on www.boats.com by Lenny Rudow http://blog.boats.com/2012/05/butanol-the-next-great-biofuel-for-boats/

2. Press release published on www.boatingindustry.com on May 9, 2012 http://www.boatingindustry.com/news/2012/05/09/brp-to-begin-testing-next-generation-biofuel/

3. 'Isobutanol Testing, Round Two' published in Boat U.S. Magazine's News From The World Of American Boating in August/September 2012 http://www.boatus.com/magazine/2012/august/BoatUS-Reports-Jurisdictions-Target-Boat-Gatherings.asp

IV.8 Emissions and Operability of Gasoline, Ethanol, and Butanol Fuel Blends in Recreational Marine Applications

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Overall Objectives

- Assess suitability of butanol as a drop-in fuel for blending with gasoline for recreational marine engine applications
- Ensure engine operability on butanol blends for a wide range of recreational marine engine applications
- Quantify emissions of recreational marine engines operated on butanol blends compared to gasoline and ethanol blends
- Demonstrate durability of recreational marine engines when operated on butanol blends

Fiscal Year (FY) 2013 Objectives

- Characterize particulate matter (PM) emissions of 10 vol% blend of ethanol in gasoline (E10) and 16 vol% blend of iso-butanol in gasoline (iB16) compared to indolene
- Quantify emissions performance over the full useful engine life for E10 and iB16 compared to indolene for a range of test engines
- Perform field testing of vessels operated on tri-fuel blends
- Assess the impact of extreme fuel dilution on engine oil performance

FY 2013 Accomplishments

- Operation on E10 and iB16 was found to result in a 15-30% reduction in total PM emissions due to a significant reduction in organic carbon emissions accompanied by a moderate increase in elemental carbon emissions
- A test over the full Environmental Protection Agency (EPA) useful life of six recreational marine engines ranging from 10 HP to 200 HP indicates that hydrocarbon plus oxides of nitrogen ($HC+NO_x$) emissions limits are met even after 350 hours of deterioration with E10 and iB16
- Over 100 hours of field testing of two vessels on 3.5 wt% oxygen (E10 equivalent) tri-fuel blends comprised of 5 vol% ethanol, 8 vol% iso-butanol, and 87 vol% gasoline were successfully completed
- Scuffing load showed a near-linear decrease with increased amount of bio-derived fuel blend content up to 20-25% at 50% oil dilution

Future Directions

- Perform end-of-season testing on recreational marine engines operated on 3.5 wt% oxygen (E10 equivalent) tri-fuel blends
- Expand laboratory and field tests to include operation on mid-level blends with 5 wt% oxygen including 15 vol% ethanol blends, 24 vol% blend of iso-butanol in gasoline, and a tri-fuel blend
- Conduct cold start, fuel system, and fuel stability/long-term storage tests

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INTRODUCTION

The Renewable Fuel Standard under the Energy Independence and Security Act of 2007 mandates an increase in the volume of renewable fuel to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022 [1]. Assuming that all alternatives were introduced as blends of ethanol and gasoline, this mandate is estimated to result in a theoretical ethanol blend level of 24-29 vol% in 2022 [2]. In order to further increase the renewable fuel fraction in transportation fuels, the U.S. EPA granted a waiver for use of 15 vol% ethanol blends in model year 2001 and newer light-duty motor vehicles [3].

The impact of extended ethanol blends and other alcohol fuels on recreational marine engines and vessels is widely unknown. However, given the dominant engine operating strategies without closed-loop feedback controls and materials used in the legacy marine fleet, it is suspected that increased ethanol levels can have detrimental effects on engine and vessel operation, performance, durability, and emissions [4]. This project is specifically designed to assess the suitability of butanol as a drop-in fuel for blending with gasoline for recreational marine engine applications. The main focus is the quantification of performance, efficiency and emissions on a range of widely used marine engines through laboratory and field testing with butanol blends compared to gasoline and ethanol blends.

APPROACH

The project is designed to provide a comprehensive assessment of the impact of iso-butanol as a blending agent for a range of recreational marine engine applications. The assessment includes laboratory and in-use vessel testing of engine performance and emissions at several stages during the useful life of typical recreational marine 2-stroke and 4-stroke engines. Several test engines as well as vessels are operated for extended periods of time to evaluate the effects of iso-butanol on engine durability compared to certification gasoline and typical ethanol blends. Upon completion of the durability runs, engines are tested for end of life emissions, inspected and torn down to evaluate the fuel impact on engine components. In parallel, tests are conducted to assess the impact of ethanol and butanol blends on oil dilution and the lubrication performance of marine engine oil.

RESULTS

To ensure a comprehensive assessment, experiments were conducted on a range of commonly used recreational marine engines covering a range of technologies, engine sizes, and power ratings. An overview of the engines and specifications as well as the respective focus area for the performed tests is given in Table 1.

The current phase of the project focuses on a comparison of ethanol and iso-butanol blends at constant fuel oxygen content of 3.5 wt% relative to the indolene baseline. Results reported here include an assessment of PM characteristics and useful life emissions assessment for E10 and iB16, field testing of a tri-fuel blend with 5 vol% ethanol and 8 vol% iso-butanol content as well as assessment of fuel dilution effects on engine oil performance.

PM Emissions Assessment

Two 90-HP engines with different cylinder configurations (I-3 and I-4) and combustion cycles (two-stroke and four-stroke) were selected for PM emissions testing. Fuel grade ethanol and neat bio iso-butanol were splash blended with base indolene certification fuel to create the E10 and iB16 test fuels for PM testing. Mass particulate emissions were determined gravimetrically using a partial flow sampling system which collected an emissions sample at the base of the engine power head prior to water injection in the mid section of the outboard engine. 90mm Pall Emfab™ Teflon® glass fiber filters were stabilized in a constant temperature/constant humidity glove box prior to initial weighing and stabilized for two hours prior to final weighing. A weighted composite particulate sample (five modes on one filter) was collected by varying the sample time of the partial flow sampling system to match the five-mode International Council of Marine Industry Associations weighted test cycle (ISO8178). Two back-to-back samples were collected for each of the three test fuels.

After total mass PM determinations, the extractable organics (referred to as the soluble organic fraction) were removed by Soxhlet extraction for 24 hours using dichloromethane. After extraction, each filter was stabilized overnight and re-weighed to determine the percentage of elemental carbon and organic carbon.

As indicated in Figure 1, both alcohols, on average, increased elemental carbon, reduced organic carbon, and

TABLE 1. Overview of the Test Engines and Respective Test Scope

Engine Manufacturer	BRP Evinrude	Mercury	BRP Evinrude	Tohatsu	BRP Evinrude	Yamaha
Engine Model Number	E90DPL	1F90413ED	E200DHX	F9.8A3	E135DPX	F90XA
Combustion Cycle	Two-Stroke	Four-Stroke	Two-Stroke	Four-Stroke	Two-Stroke	Four-Stroke
Cylinder Configuration	I-3	I-4	V-6	I-2	V-6	I-4
Fuel Induction	DFI	EFI	DFI	Carbureted	DFI	EFI
Displacement [L]	1.3	1.7	3.3	0.2	2.6	1.6
Power [HP]	90 @ 5000	90 @ 5500	200 @ 5500	9.8 @ 5500	135 @ 5500	90 @ 5500
Bore x Stroke [mm]	91 x 66	82 x 82	98 x 73	55 x 44	91 x 66	79 x 81
Test Scope	PM emissions	PM emissions Durability	Durability	Durability	Tri-fuel	Tri-fuel

I – inline; V – vee; DFI – direct fuel injection; EFI – electronic fuel injection reduced total PM compared to baseline indolene test fuel for both engines tested.

The aforementioned results for total PM are consistent with published data on closed-loop automotive engines operating on increasing amounts of ethanol [5,6]. However, the trends for increased organic carbon are somewhat contrary to published data. This may be due to the lack of closed-loop engine control, and changes in overall air/fuel ratio as a result of the enleanment effects of the fuel.

Full Useful Life Emissions

Six engines from three different engine manufacturers (Mercury, Evinrude, Tohatsu) in a power range from 10 HP to 200 HP were selected to run for their full 350-hour EPA useful life according to the International Council of Marine Industry Associations weighted duty cycle. One engine from each set of two test engines from each engine manufacturer accumulated hours operating on E10, and the other engine accumulated hours operating on iB16. Baseline emissions and final deteriorated emissions were recorded for each of the six engines. As indicated in Figure 2, final $HC+NO_x$ emissions after 350 hours of deterioration followed similar trends between the E10 control engine and the iB16 test engine. Regardless of the test fuel used during engine deterioration, all test engines passed the final $HC+NO_x$ EPA Part 1045 standards (dashed line). The Tohatsu engine operating on E10 experienced more deterioration because of the variability of carburetion rather than effects of the test fuel.

Tri-Fuel Blend Field Testing

There are several pathways for the introduction of iso-butanol to the market. From a refiner's perspective, the inherently low Reid Vapor Pressure (RVP) of neat iso-butanol may help to lower the overall finished gasoline RVP, particularly when blended at 16 vol%. Comingling ethanol and iso-butanol has some advantages such as the ability of butanol to trim the overall RVP [7], minimize depression in the distillation curve, and improve water tolerance of the finished gasoline. Moreover, if iso-butanol is introduced into the market, tri-fuel blends consisting of gasoline, ethanol, and butanol will inevitably occur. To account for this scenario, a 9-RVP tri-fuel blend comprised of 5 vol% ethanol, 8 vol% iso-butanol, and 87 vol% gasoline was evaluated over the summer boating season on two boats: a 26' Premier pontoon with twin 135 HP Evinrude DFI engines and a 16' Angler with a single 90 HP Yamaha EFI engine. Baseline laboratory emissions tests were conducted prior to placing the engines in the field for hour accumulation. The baseline emissions results relative to indolene certification fuel are presented in Figure 3. The increase in HC, NO_x, CO, and CO_2 emissions observed with the Evinrude DFI 2-stroke engine is less than 10% for all measured components suggesting only slight changes in

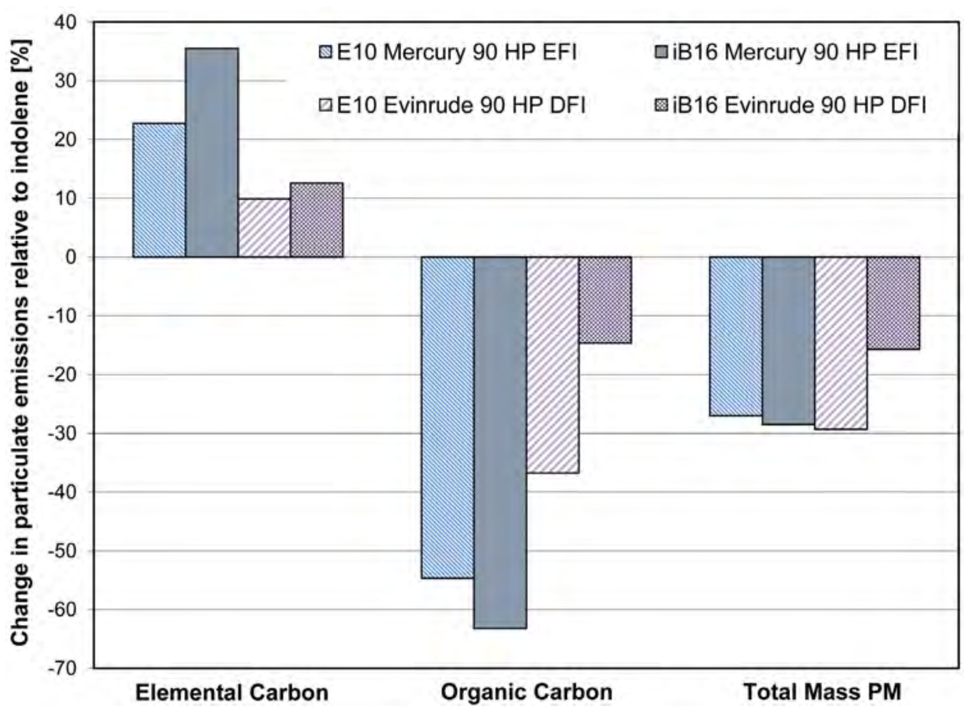

FIGURE 1. Average Change in Cycle-Weighted PM Relative to Baseline Indolene Test Fuel for 90-HP Mercury and 90-HP Evinrude

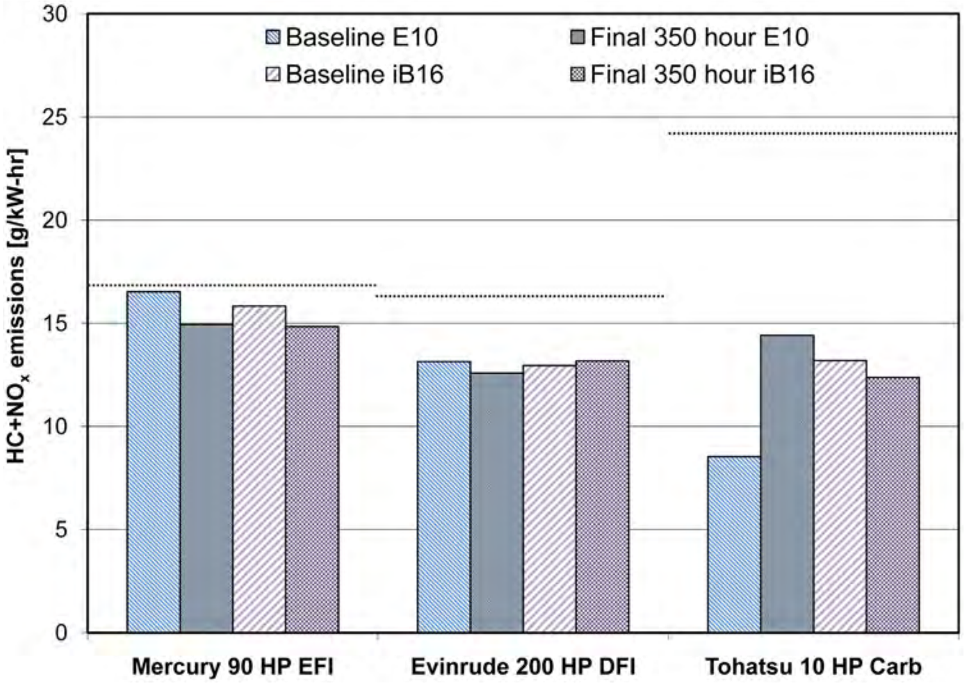

FIGURE 2. Baseline and Final 350-hour HC+NO_x Emissions for iB16 Engines and E10 Control Engines

operational characteristics due to changes in air/fuel ratio compared to indolene. On the other hand the Yamaha EFI 4-stroke engine showed a reduction in HC and CO emissions with a simultaneous increase in NO_x and CO_2 emissions consistent with enleanment due to the reduced energy content of the tri-fuel blend compared to indolene. After official baseline testing occurred, emissions results have been verified on a second Evinrude 135HP engine operating on tri-fuel and Indolene. The results of this additional test also indicate very similar emissions output on both fuels. The Evinrude carbon monoxide emissions from the tri-fuel are inconsistent with results from other outboard engines operated on E10. However, based on previous testing, DFI has typically resulted in less CO enleanment relative to multi-port fuel injection. Nonetheless, additional engine testing and combustion analysis on tri-fuel will be conducted in effort to better understand the effects. At the time of this report the engines had accumulated over 100 hours of field operation on the tri-fuel blend and were being prepared for final emissions testing.

Effect of Fuel Dilution on Engine Oil Performance

Although the measured fuel dilution in the crankcase is in the 4-7% range [8], it is well known that the level of fuel dilution in the engine ring pack is usually substantially higher. Those higher levels of dilution can make the ring-liner contact interface more susceptible to scuffing failure. In the scuffing test with used oil from a Yamaha engine boat test reported last year, gasoline fuel dilution resulted in less than 5% reduction in scuffing load while E10 and iB16 contamination of the oil resulted in as much as 25% reduction in scuffing load. Consequently, scuffing tests were conducted with surrogate fluids consisting of marine engine oil containing different levels (up to 50%) of three fuels—gasoline, E10 and iB16. Scuffing tests were conducted with a block-on-ring contact configuration using a step load increase protocol. Tests were conducted at a constant speed of 1,000 RPM with initial contact load of 50 N, followed by 25 N increase every minute until scuffing occurred as indicated by a sudden rapid rise in friction coefficient. The load at which scuffing occurred is judged to be an indication of scuffing life or scuffing resistance. The higher the load, the better the scuffing protection by the lubricant. Figure 4 shows the results of average scuffing loads for various surrogate fluids in comparison with fresh marine engine oil. Any level of fuel dilution resulted in a noticeable decrease in scuffing load. Scuffing load reduction ranges from 5% to as much as 25%. These results suggest that the presence of fuel in the engine oil will result in a decreased load carrying capacity of the engine oil, i.e., reduction in protection against scuffing. Furthermore, fuels containing bio derived components (E10 and iB16) showed a near-linear decrease in scuffing load with increasing amount of fuel in the oil.

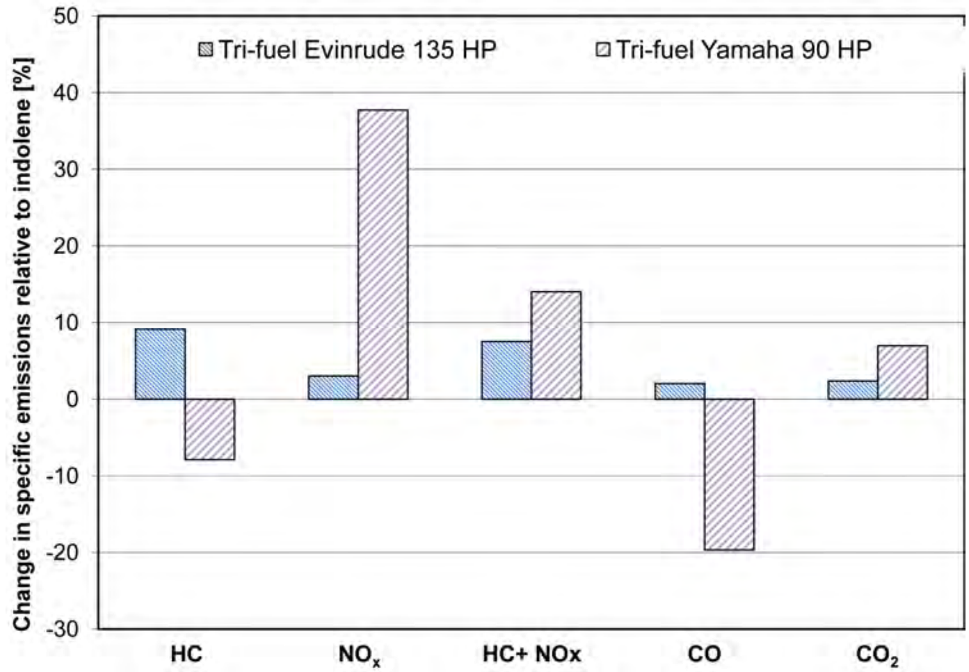

FIGURE 3. Average Change in Cycle-Weighted Gaseous Emissions Relative to Baseline Indolene Test Fuel

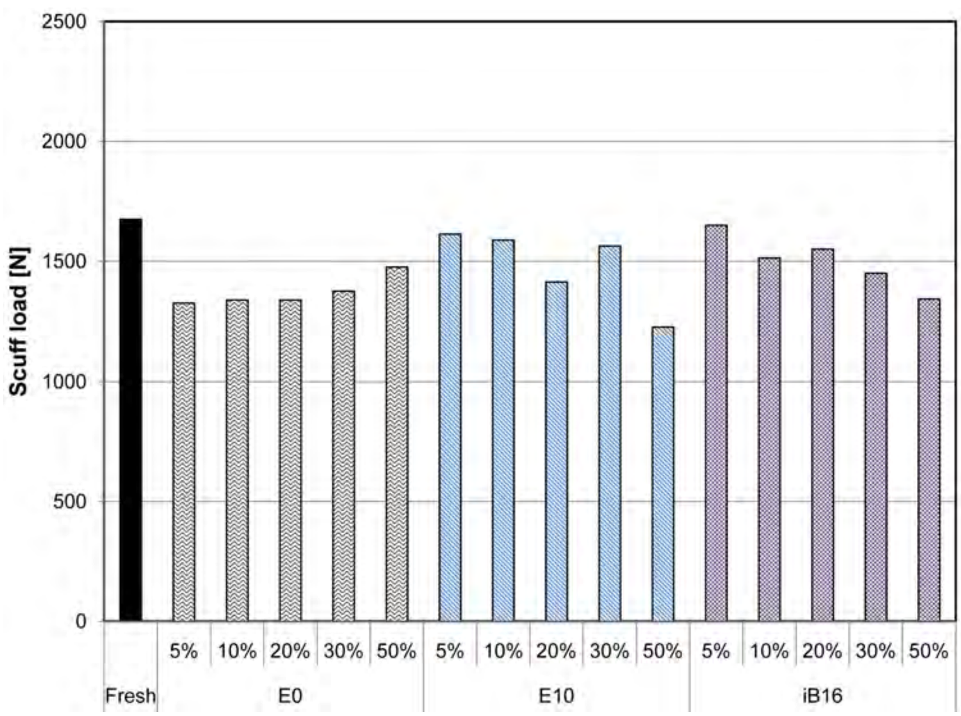

FIGURE 4. Average Scuffing Load for Surrogate Fluid Containing Different Levels of Gasoline, E10, and iB16 Fuels

CONCLUSIONS

Laboratory and field testing on a range of recreational marine engines from 10 HP to 200 HP was performed using gasoline-alcohol blends with a constant oxygen content of 3.5 wt%. The tested fuels included E10, iB16, and a 5 vol% ethanol, 8 vol% iso-butanol, 87 vol% gasoline tri-fuel blend. The results support the following conclusions:

- Addition of alcohol reduces total PM mass emissions by 15-30% due to a significant reduction in organic carbon emissions accompanied by a moderate increase in elemental carbon emissions.
- Six engines of different size and technology including two 10-HP carbureted four-stroke, two 90-HP EFI four-stroke, and two 200-HP DFI two-stroke engines all passed final $HC+NO_x$ EPA emissions standards upon completion of full EPA useful life 350 hour durability runs on E10 and iB16.
- Compared to fresh marine engine oil, noticeable reduction in scuffing load was observed for surrogate fluids containing large amounts of gasoline, E10, and iB16 fuels with a near-linear decrease for bio derived components at up to 20-25% at 50% oil dilution.

REFERENCES

1. Section 201-202 Renewable Fuel Standard (RFS) Energy Independence and Security Act of 2007 (Pub.L. 110-140, originally named the CLEAN Energy Act of 2007).

2. Ickes, A. 'Improving Ethanol-Gasoline Blends by Addition of Higher Alcohols' 18th Directions in Engine-Efficiency and Emissions Research (DEER) Conference. Dearborn/MI. 2012.

3. Environmental Protection Agency (EPA) 'Partial Grant of Clean Air Act Waiver Application Submitted by Growth Energy To Increase the Allowable Ethanol Content of Gasoline to 15 Percent'; Federal Register Vol. 76, No. 17. 2011.

4. Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., "In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels," SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.

5. Storey, J., Barone, T., Norman, K., Lewis, S., "Ethanol Blend Effects On Direct Injection Spark-Ignition Gasoline Vehicle Particulate Matter Emissions" SAE Technical Paper 2010-01-2129, 2010.

6. Dutcher, D., Stolzenburg, M., Thompson, S., Medrano, J., et al., "Emissions from Ethanol-Gasoline Blends: A Single Particle Perspective" Atmosphere 2011, 2, 182-200; doi:10.3390/atmos2020182.

7. BP "1-Butanol as a Gasoline Blending Bio-component" U.S. EPA Mobile Sources Technical Review Subcommittee March 28, 2007. Retrieved December 12, 2013 http://www.epa.gov/air/caaac/mstrs/March2007/Wolf.pdf.

8. Shayler, P., Winborn, L., and Scarisbrick, A., "Fuel Transport to the Crankcase, Oil Dilution and HC Return with Breather Flow During the Cold Operation of a SI Engine," SAE Technical Paper 2000-01-1235, 2000.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Wallner, T.; Ickes, A.; Wasil, J.; Sevik, J.; Miers, S.: 'Impact of blending gasoline with iso-butanol compared to ethanol on efficiency, performance and emissions of a recreational marine 4-stroke engine.' SAE Technical Paper 14PFL-0436. Scheduled for publication at the SAE 2014 World Congress.

2. Wasil, J. 'Biofuels and Potential Impacts on the Recreational Marine Industry.' The International Boat Builders Exhibition and Conference. Louisville, KY September 2013.

3. Ajayi, O.; Lorenzo-Martin, C.; Fenske, G.; Corlett, J.; Murphy, C.; and Przesmitzki, S.: "Bio-derived Fuel blend dilution of marine engine oil and impact on friction and wear behavior" To be submitted to ASME Journal of Tribology.

4. Ajayi, O.; Lorenzo-Martin, C.; Fenske, G.; and Przesmitzki, S.: "Scuffing performance of bio-derived fuel contaminated marine engine oil" To be submitted to STLE Tribology Transactions.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Oyelayo Ajayi received NMMA Environmental Achievement Award "for innovative research and outstanding contribution to the recreational boating industry"

IV.3 Emissions and Operability of Gasoline, Ethanol, and Butanol Fuel Blends in Recreational Marine Applications

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Overall Objectives

- Assess suitability of butanol as a drop-in fuel for blending with gasoline for recreational marine engine applications
- Ensure engine operability on butanol blends for a wide range of recreational marine engine applications
- Quantify emissions of recreational marine engines operated on butanol blends compared to gasoline and ethanol blends
- Demonstrate durability of recreational marine engines when operated on butanol blends

Fiscal Year (FY) 2014 Objectives

- Assess engine cold-start capability operating on 16 vol% blend of iso-butanol in gasoline (iB16) compared to 10 vol% ethanol in gasoline (E10)
- Complete engine tear-down inspections and compare iB16 and E10 engine components
- Perform end-of-season emissions and performance testing on engines operated on 3.5 wt% oxygen (E10 equivalent) tri-fuel blends comprised of 5 vol% ethanol, 8 vol% iso-butanol, and 87 vol% gasoline
- Perform additional field testing of vessels operated on tri-fuel blends

FY 2014 Accomplishments

- Engine cold-start performance was found to be nearly identical between iB16 and E10 fuel blends at 24°C. The data indicate a reduction in time to start at -1°C for the Mercury four-stroke outboard engine operating on iB16 compared to E10 fuel.
- Engine tear-down inspections performed after full useful life durability testing indicate similar wear characteristics between control engines operated on E10 and test engines operated on iB16.
- End of season testing performed on field test engines operated on tri-fuel blends indicate similar gaseous emissions and engine performance as E10 test fuels. All engines remained below the Environmental Protection Agency (EPA) emissions standards for hydrocarbons plus oxides of nitrogen and carbon monoxide, and no engine runability or durability issues were encountered during the testing program.
- An additional 100 hours of field testing of two vessels operating on 3.5 wt% oxygen (E10 equivalent) tri-fuel blends comprised of 5 vol% ethanol, 8 vol% iso-butanol, and 87 vol% gasoline were successfully completed.

Future Directions

- Determine critical blend level for iso-butanol in laboratory test engines
- Expand laboratory and field tests to include operation on mid-level blends with ~5 wt% oxygen including 15 vol% ethanol blends, 24 vol% blend of iso-butanol in gasoline, and a tri-fuel blend
- Perform end-of-season testing on recreational marine engines operated on 3.5 wt% oxygen (E10 equivalent) tri-fuel blends

✧ ✧ ✧ ✧ ✧

INTRODUCTION

The Renewable Fuel Standard under the Energy Independence and Security Act of 2007 mandates an increase in the volume of renewable fuel to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022 [1]. Assuming that all alternatives were introduced as blends of ethanol and gasoline, this mandate is estimated to result in a theoretical ethanol blend level of 24-29 vol% in 2022 [2]. In order to further increase the renewable fuel fraction in transportation fuels, the U.S. EPA granted a waiver for use of 15 vol% ethanol blends (E15) in model year 2001 and newer light-duty motor vehicles [3].

The impact of extended ethanol blends and other alcohol fuels on recreational marine engines and vessels is widely unknown. However, given the dominant engine operating strategies without closed-loop feedback controls and materials used in the legacy marine fleet, it is suspected that increased ethanol levels can have detrimental effects on engine and vessel operation, performance, durability and emissions [4]. This project is specifically designed to assess the suitability of butanol as a drop-in fuel for blending with gasoline for recreational marine engine applications. The main focus is the quantification of performance, efficiency and emissions on a range of widely used marine engines through laboratory and field testing with butanol blends compared to gasoline and ethanol blends.

APPROACH

The project is designed to provide a comprehensive assessment of the impact of iso-butanol as a blending agent for a range of recreational marine engine applications. The assessment includes laboratory and in-use vessel testing of engine performance and emissions at several stages during the useful life of typical recreational marine 2-stroke and 4-stroke engines. Several test engines as well as vessels are operated for extended periods of time to evaluate the effects of iso-butanol on engine durability compared to certification gasoline and typical ethanol blends. Upon completion of the durability runs, engines are tested for end of life emissions, inspected and torn down to evaluate the fuel impact on engine components.

RESULTS

Recreational marine engines produced by several different engine manufacturers covering a range of technologies, engines sizes and power ratings were included in the test program in order to ensure a comprehensive assessment. An overview of the engine specifications and area of focus for the tests is presented in Table 1.

Engine Cold-Start Assessment

Three outboard engines were selected for cold-start assessment which include a 200-HP Evinrude direct fuel injection two-stroke, a 90-HP Mercury electronic fuel injection four-stroke, and a 10-HP Tohatsu carbureted pull-start four-stroke. The engines were instrumented to record engine block temperature, air intake temperature, battery voltage and engine RPM. Each engine was preconditioned for 45 minutes across several operating points from idle to midrange loading on the respective test fuel to ensure the test fuel was fully flushed through the fuel system. After the conditioning was complete, the engine was shut off and remained at the test temperature for 24 hours.

Block temperature was verified prior to each start event. A battery maintainer was used to ensure consistent battery voltage and charge prior to the start event. For each start event for the electric start models, the starter solenoid was energized continuously until the engine started. If the engine did not start within 45 seconds of continuous cranking, the start event was considered a failure. The data was processed and the time to start was determined. For the pull-start engine, the choke was set on the carburetor and the starter rope was pulled until the engine started. The number of pulls to start was recorded. If the engine did not start within 10 pulls, the start event was considered a failure.

TABLE 1. Overview of the Test Engines and Respective Test Scope

Engine Manufacturer	Mercury	BRP Evinrude	Tohatsu	BRP Evinrude	Yamaha
Engine Model Number	1F90413ED	E200DHX	F9.8A3	E135DPX	F90XA
Combustion Cycle	Four-Stroke	Two-Stroke	Four-Stroke	Two-Stroke	Four-Stroke
Cylinder Configuration	I-4	V-6	I-2	V-6	I-4
Fuel Induction	EFI	DFI	Carbureted	DFI	EFI
Displacement (L)	1.7	3.3	0.2	2.6	1.6
Power (HP)	90 @ 5,500	200 @ 5,500	9.8 @ 5,500	135 @ 5,500	90 @ 5,500
Bore x Stroke (mm)	82 x 82	98 x 73	55 x 44	91 x 66	79 x 81
Test Scope	Cold-Start Teardown	Cold-Start Teardown	Cold-Start Teardown	Tri-Fuel	Tri-Fuel

EFI – electronic fuel injection; DFI – direct fuel injection

The engines were cold started at 24°C and at -1°C using E10 and iB16. Each alcohol was splash blended with Indolene certification fuel. The cold-start event was performed three times at each temperature set-point, and the average time to start in seconds or average pulls to start is presented. The engines were equilibrated for a minimum of 12 hours between each start event. The seconds to start for the Mercury and Evinrude outboard engine are indicated in Figure 1. As shown, the time to start (seconds) for the Mercury and Evinrude are nearly identical between E10 and iB16 test fuels at 24°C, and at -1°C for the Evinrude. The time to start for the Mercury at -1°C on iB16 was reduced by approximately 40% compared to the ethanol test fuel. It is unclear as to why the time to start was reduced using the iB16 fuel. Additional testing will need to be performed to further validate the results of the -1°C cold start on the four-stroke engine.

Pulls to start for the Tohatsu engine are indicated in Figure 2. As shown, the pulls to start at 24°C were similar for both test fuels. The engine failed to start within 10 pulls on either fuel at -1°C.

Engine Tear-Down Assessment

Six engines from three different engine manufacturers were tested for the full useful life of the engine. One engine from each set of two matching engines was run for the full useful life on E10 fuel as a control, and the other engine run for the full useful life on iB16. Gaseous emissions were recorded throughout the test program and the data reported in the FY 2013 annual report [5]. All engines remained below the U.S. EPA standards on both fuels. After hour accumulation was completed, the engines were torn down for side-by-side comparisons between the E10 control engine and iB16 test engine. Engine components such as pistons, cylinder heads, cylinder bores, intake/exhaust valves, intake/exhaust ports, connecting rods and rod bearings were inspected.

Tear-down inspection reports indicate similar wear characteristics between E10 and iB16 engines. Carbon buildup on the cylinder heads and pistons (Figure 3) generally appear to be very similar between the E10 and

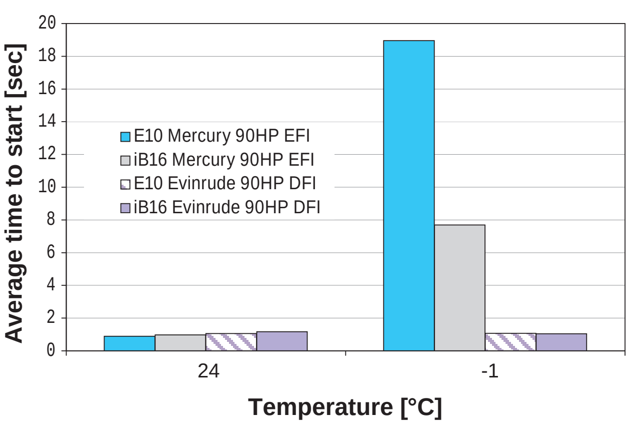

FIGURE 1. Average Time to Start for Evinrude and Mercury Engines at 24°C and -1°C on E10 and iB16 Test Fuels

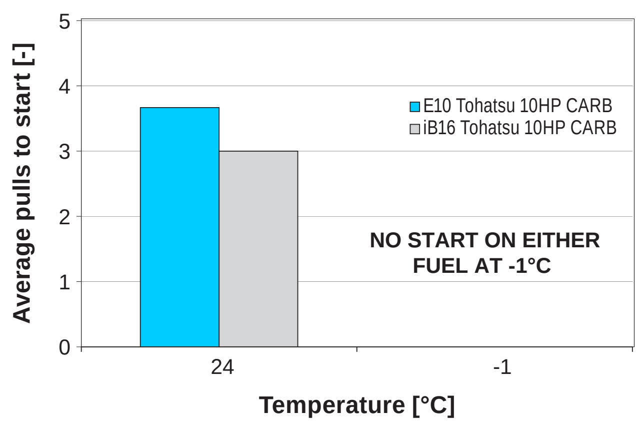

FIGURE 2. Average Pulls to Start for the Tohatsu Engine at 24°C and -1°C on E10 and iB16 Test Fuels

FIGURE 3. Comparison of Pistons (cylinder number 1) for the Evinrude and Mercury Engines Operated on E10 and iB16

iB16 engines. As indicated in Figure 4, the cylinder bore #1 cross hatch for the Evinrude engines are clearly visible and in good condition between the E10 and iB16 engines. The Tohatsu piston #1 and cylinder head #1 for the E10 and iB16 engine are shown in Figure 5. As indicated, deposits are nearly identical for both engines.

End-Of-Season Testing

Three engines successfully completed 100 hours of field operation on boats. Two Evinrude 135-HP engines were in service on a 27' Premier pontoon boat located in Washington, D.C., and one 90-HP Yamaha was in service on a 17' Angler boat located in Annapolis, MD. Each vessel operated during the boating season on a tri-fuel blend comprised of 5 vol% ethanol, 8 vol% iso-butanol and 87 vol% gasoline. No engine runability or performance issues were encountered during the 100-hour test program. It is important to note that based on the EPA useful life for recreational marine engines, 100 hours represents approximately three years of operation for a typical boater. All engines remained below the EPA emissions standards on the tri-fuel blend. Engine wide open throttle corrected brake horsepower for one Evinrude 135-HP and the 90-HP Yamaha operating on E10 and tri-fuel blend is shown in Figure 6. As indicated, engine power is nearly identical between the two test fuels.

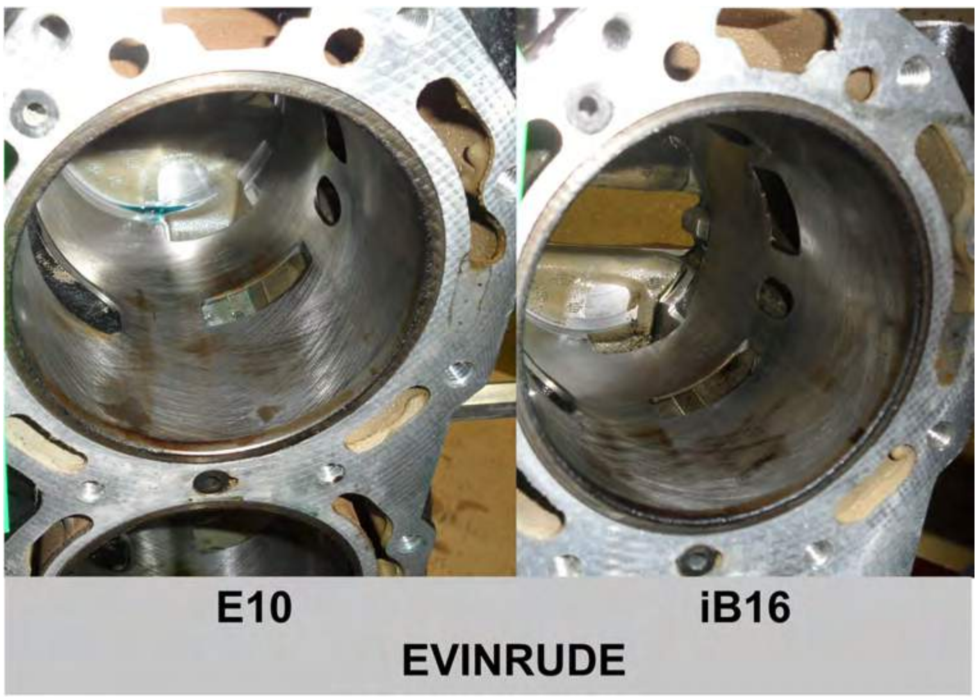

FIGURE 4. Comparison of Cylinder Bore (cylinder number 1) for the Evinrude Engines Operated on E10 and iB16

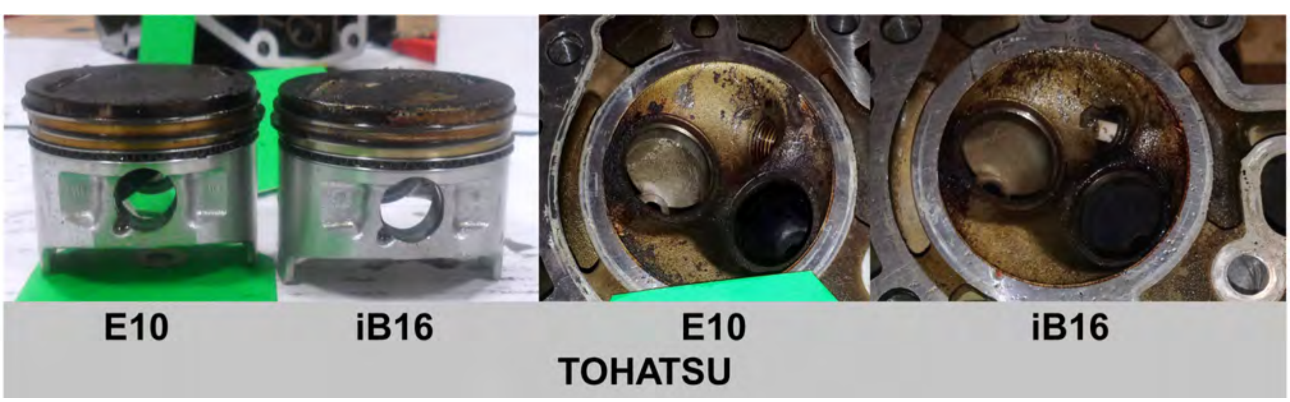

FIGURE 5. Comparison of Pistons and Cylinder Heads (cylinder number 1) for the Tohatsu Engines Operated on E10 and iB16

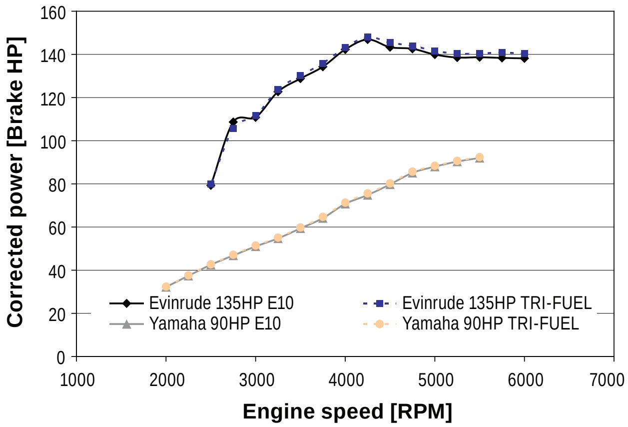

FIGURE 6. Corrected Wide Open Throttle Brake Horsepower (CBHP) for Field Test Engines Operated on E10 and Tri-Fuel Blends

CONCLUSIONS

- Engine cold-start data indicate similar seconds/pulls to start for E10 and iB16 fuel blends at 24ºC for all engines tested. Engine cold start at -1ºC showed little difference between E10 and iB16 fuels for the Evinrude, and a 40% reduction in seconds to start for the mercury on iB16 fuel compared to E10. Additional testing is required to understand the difference in start times between E10 and iB16 fuels at -1ºC for the Mercury engine.
- Full useful life engine tear down and inspection on pistons, cylinder heads, cylinder bores, intake/exhaust valves, intake/exhaust ports, connecting rods and rod bearings indicate similar wear between the E10 control engines and iB16 test engines. No unusual wear, carbon build-up or durability issues were observed with either fuel during the 350-hour (equivalent 10-year useful life) testing.
- Two field test engines were operated on a tri-fuel blend comprising of 5 vol% ethanol, 8 vol% iso-butanol and 87 vol% gasoline. End-of-season exhaust emissions and performance testing was performed at 100 engine hours which represents nearly three years of operation for a typical boater. All engines remained below the EPA exhaust emissions standards and no engine issues were encountered. Engine power and performance remained very similar between E10 and the tri-fuel blend.
- Three field test engines successfully completed an additional 100 hours of operation (for a total of 200 engine hours) on tri-fuel blends. No engine runability or durability issues were encountered. Exhaust emissions and engine performance testing will be completed in due course.

REFERENCES

1. Section 201-202 Renewable Fuel Standard (RFS) Energy Independence and Security Act of 2007 (Pub.L. 110-140, originally named the CLEAN Energy Act of 2007).

2. Lawyer, K., Ickes, A., Wallner, T., Ertl, D. et al., “Blend Ratio Optimization of Fuels Containing Gasoline Blendstock, Ethanol, and Higher Alcohols (C3-C6): Part I - Methodology and Scenario Definition,” SAE Technical Paper 2013-01-1144, 2013, doi:10.4271/2013-01-1144.

3. Environmental Protection Agency (EPA) ‘Partial Grant of Clean Air Act Waiver Application Submitted by Growth Energy To Increase the Allowable Ethanol Content of Gasoline to 15 Percent’; Federal Register Vol. 76, No. 17. 2011.

4. Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., “In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels,” SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.

5. FY 2013 PROGRESS REPORT FOR FUEL & LUBRICANT TECHNOLOGIES. DOE/EE-1042. 2014.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. McKnight, J., Wasil, J., ‘E15 and Isobutanol Test Programs’ Marine Oil Certification Committee Meeting. February, 2014.

2. Wallner, T., Ickes, A., Wasil, J., Sevik, J. et al., “Impact of Blending Gasoline with Isobutanol Compared to Ethanol on Efficiency, Performance and Emissions of a Recreational Marine 4-Stroke Engine,” SAE Technical Paper 2014-01-1230, 2014, doi:10.4271/2014-01-1230.

3. Wasil, J. ‘Marine Industry Alternative Fuel Isobutanol Testing Program’ U.S. EPA Marine Certification Meeting. Ann Arbor, MI April, 2014.

4. Wasil, J. ‘New Requirements for Boat Fuel and Fuel Systems – Isobutanol Testing Program’ International Boat Builders Exhibition and Conference. Tampa, FL September, 2014.

5. Wasil, J. McKnight, J., ‘Marine Isobutanol Testing Update’ International Council of Marine Industry Associations - International Marine Engine Committee. October, 2014.

6. Wasil, J. and Wallner, T., “Gaseous and Particulate Emissions Using Isobutanol-Extended Fuel in Recreational Marine Two-Stroke and Four-Stroke Engines,” SAE Int. J. Fuels Lubr. 7(3):1062-1068, 2014, doi:10.4271/2014-32-0087.

SPECIAL RECOGNITIONS & AWARDS/PATENTS ISSUED

1. Wisconsin Business Friend of the Environment Award in recognition of the unique emissions sampling equipment developed in support of the U.S. Department of Energy’s search for a more environmentally friendly gasoline alternative. Wisconsin Manufacturing and Commerce May, 2014

2. Press release announcing Gulf Racing Fuels supplying three new fuels for marine and all-terrain vehicle use containing 16.1 vol-% iso-butanol (iso-butanol sourced from Gevo) http://

www.biofuelsdigest.com/bdigest/2014/10/02/gevo-sells-isobutanol-to-gulf-racing-fuels-for-marine-and-off-road/

2010-32-0054 / 20109054

Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine

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ABSTRACT

In pursuit of reducing dependencies on foreign oil coupled with U.S. renewable fuel standards and an overall focus and interest in greenhouse gas emissions, investigations continue on feasibility of replacement biologically derived fuels such as ethanol and butanol. Majority of existing recreational products such as marine outboard engines, boats, personal watercraft, all terrain vehicles and snowmobiles are carbureted or operate open-loop, meaning the engine does not have the capability to sense air-fuel ratio. Ethanol has a specific energy content that is less than gasoline. Without means to compensate for air-fuel ratio requirements of specific fuels, open-loop engines may suffer from a condition known as enleanment, in which catastrophic engine failure may result.

On the contrary, butanol has specific energy content closer to that of gasoline, suggesting open-loop engines may be less prone to negative effects of increased biologically derived fuel concentrations in gasoline.

This is a preliminary investigation into the effects of butanol/gasoline mixtures on a two-stroke direct injection recreational marine outboard engine. Additionally, ethanol/gasoline mixtures are also tested as comparison. Engine performance, combustion characteristics and emission results including overall effects of various butanol/gasoline and ethanol/gasoline blends will be explored.

INTRODUCTION

Engines used in a marine environment to power recreational craft are subject to very different operating conditions, usage cycles and overall physical running conditions than automotive engines. Therefore, it is important to understand these variations on how fuel blends primarily intended for automotive use may affect recreational marine engines and fuel systems.

Engine and drive weight is very critical for recreational marine products. Engine power to weight ratio has a direct effect on vessel performance and fuel economy. Additionally, it is not uncommon for recreational marine engines to be operated at wide open throttle (WOT) at rated speed for extended periods of time. During WOT, components are stressed more, not only from a mechanical standpoint, but also thermally. Subtle differences in combustion as a result of fuel properties can have a significant affect on performance, engine durability and emissions [1, 2].

According to the National Marine Manufactures association (NMMA), as of 2007, 12,185,568 gasoline powered recreational boats are currently registered in the United States [3]. Of that, approximately 225,000 have been retired from the fleet, which is less than 2% of the total powerboat fleet. The recreational marine industry as a whole has one of the oldest fleets of the engine sector. This results in a particularly difficult challenge in development of alternative fuels that will minimize engine run-ability issues, fuel system component issues or potential engine failures considering the wide range and age of products currently still in use.

Several different materials are used for boat fuel tank construction including aluminum, polyethylene and fiberglass. Alternative fuel compatibility with different types of fuel tank materials needs to be considered and understood [4, 5].

Most boat fuel systems are vented directly to the atmosphere, which allows moisture to enter the fuel tank during daily diurnal temperature changes. This is further complicated by the marine environment itself - in which water or salt water is more likely to be inadvertently introduced into fuel systems. Moreover, typical usage of boats, especially in northern parts of the US, equates to longer periods of storage and subsequently potential for more fuel system related issues [6].

With respect to the aforementioned vented fuel system issue, as compared to ethanol, butanol is not hygroscopic and is much less susceptible to phase separation. Figure 1 shows the difference between ethanol and butanol fuels when 10% H_2O is added to each fuel. A colorant was added to highlight differences between the two samples. As shown, the cylinder containing ethanol on left has phase separated, meaning water and ethanol have formed an aqueous mixture forcing the gasoline to the top of the cylinder. In the cylinder, on the right containing butanol, water has settled to the bottom of the cylinder, leaving butanol and gasoline for the most part unaffected. Phase separation with ethanol causes additional engine enleanment due to both the fact that gasoline is displaced and water is present in the fuel causing the engine to ingest an ethanol water mix. Lack of phase separation in presence of H_2O is a desirable basic property of butanol, not only for the recreational marine industry, but also for the overall fuel distribution network, as butanol could be successfully delivered in existing pipelines [7].

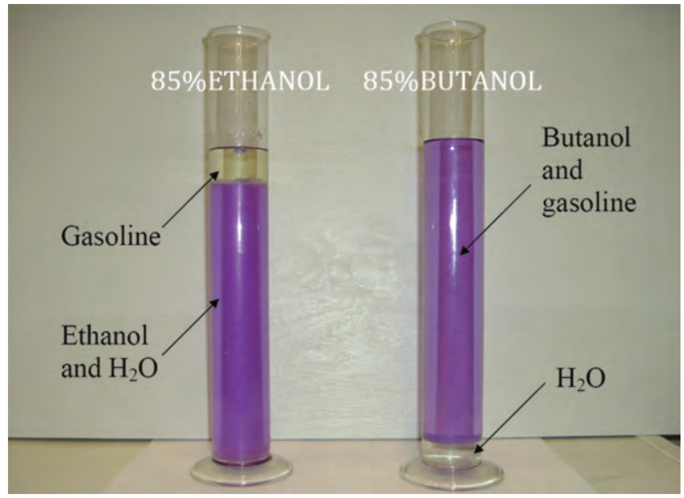


Figure 1. Effect of adding 10% water by volume to 85% ethanol and 10% water by volume to 85% butanol.

TEST SETUP

This section includes a description of the test engine, fuel flow system, test fuels, emissions analyzers, combustion analysis equipment, engine cooling water system, and overall test process. A schematic of engine test cell set-up is presented in Figure 2.

TEST ENGINE

A three cylinder 90 horsepower (67.1 kW) spray-guided stratified charge direct injection two-stroke production outboard engine was used for testing. The engine operates open-loop and does not have any type of combustion feed back sensor. This particular engine was chosen as it tends to be slightly more knock and fuel sensitive. Moreover, it is a scalable design, as this configuration forms 150, 175 and 200 horsepower V-6 outboard engine models. Engine specifications are shown in table 1.

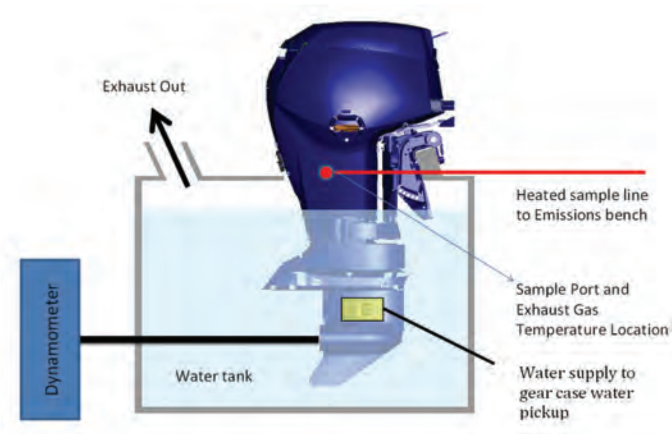


Figure 2. Engine test setup

Table 1. Test Engine Specifications

Model Year	2010
Fuel System	Gasoline Direct Fuel Injection (GDI)
Emissions Rating	California Three-Star Ultra-Low
Engine Cycles	2
Valves	Reed
Number of cylinders	3
Displacement	1296
Rated power HP (kW)	90 (67.1)
Full throttle operating range	4500 - 5500
Idle speed	650
Engine Hrs	175
Midsection length (inches)	20

FUEL AND FUEL FLOW INFORMATION

Fuel used for baseline emissions testing and as a base for blending is Indolene clear, which is a standardized gasoline test fuel that conforms to EPA CFR part 1065 requirements for certification testing [8]. Fuel flow is measured volumetrically using a Pierburg 60 lph fuel metering system along with a Calibron Densitrak DT625L density meter to arrive at fuel consumption in grams per hour. The fuel specifications are shown in Table 2. Calculated stochiometric air/fuel ratios for various alternative fuel blends are shown in Figure 3.

Various amounts of butanol or ethanol were blended with base indolene fuel to arrive at the desired concentrations of alternative fuel by volume:

- (B-10): 10% Butanol, 90% Indolene
- (B-15): 15% Butanol, 85% Indolene
- (B-20): 20% Butanol, 80% Indolene
- (E-10): 10% Ethanol, 90% Indolene
- (E-15): 15% Ethanol, 85% Indolene

Table 2. Test Fuel Specifications

Property	Gasoline	Ethanol (CH3OH)	n-Butanol (C4H9OH)	Indolene
Specific gravity @60F	0.72-0.75	0.79	0.8133	0.74
Net Lower Heating Value (BTU/lbm)	18700	11600	14280	19500
Octane Number Research	91-100	111	96	96
Motor	82-92	92	80	88
Stoichiometric AFR	14.6	9	11.1	14.3
Self-ignition Temperature (C)	450	420	343	450

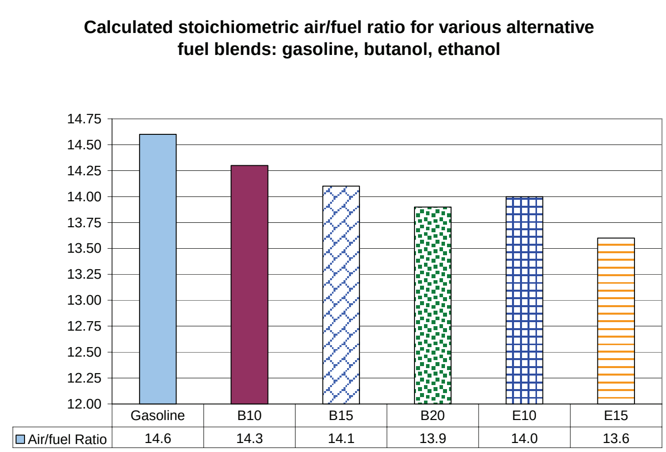


Figure 3. Calculated stoichiometric air/fuel ratio for various butanol and ethanol blends.

EMISSION ANALYZERS

A Pierburg AMA-2000 five-gas emissions bench was used for emissions analysis. A heated flame ionization detector (FID), heated chemoluminescence detector (CLD), non-dispersive infrared (NDIR) and paramagnetic analyzers were used for measurements of THC, NOx, CO, CO_2 and O2 respectively.

COMBUSTION ANALYSIS

An AVL Indicom 2 crank-based combustion analysis system was used to acquire 500 cycles of cylinder pressure on all three cylinders. Data was then processed to determine, burn rates, %COV of IMEP, misfire rate and to quantify knock characteristics.

WATER COOLING SYSTEM

Engine cooling water is supplied to the engine through the gear-case water pick up as shown in Figure 2. Water pressures are regulated with a Tescom ER-3000 electronic pressure controller to provide pressures typically seen at the gear case of a boat while underway.

TEST PROCESS

For each test fuel, the engine was run according to the International Council of Marine Industry Associations (ICOMIA) five-mode steady state test cycle as shown in Table 3 [9]. Two consecutive five mode emissions tests followed by two wide open throttle (WOT) power tests were conducted on each fuel blend. This was done in order to more accurately account for small deviations in test results. The average results from two tests on each fuel blend are reported. Five gas emissions HC, NOx, CO and CO_2, exhaust gas temperature, fuel flow, and combustion characteristics were recorded for each test mode and test fuel. EGT and emissions were sampled in the midsection megaphone, just below the base of the engine powerhead as indicated in Figure 2.

No changes or modifications to the base engine calibration, spark timing or injection timing were made at anytime during the testing process.

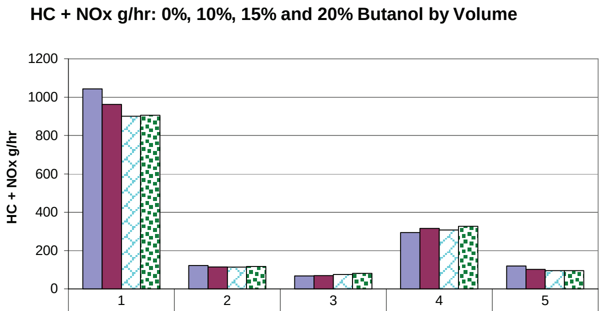
Table 3. ICOMIA five mode steady state marine test cycle [9].

Mode	% RPM	% Torque	% Weight Factor
1	100	100	6
2	80	71.6	14
3	60	46.5	15
4	40	25.0	25
5	Idle	0	40

RESULTS

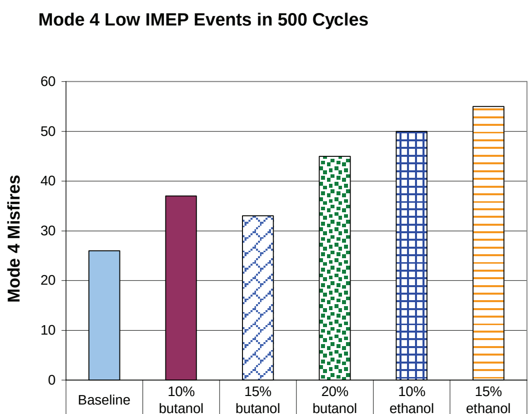
Figure 4 shows the result of increasing butanol percentages by volume on HC + NOx emissions at different test modes in g/hr. As shown, a noted decrease in HC + NOx was observed at wide open throttle (test mode 1). Increase in HC + NOx occurs at mode 4 with increasing amounts of butanol. This is due to a higher number of misfires which directly contribute to an increase in HC emissions. Combustion data shown in Figure 5 indicates that the number of misfires at mode 4 increases with increasing quantities of butanol. Mode 4 is operated in a spray guided, stratified mode of combustion where the fuel is injected late in the cycle (70-50 degrees BTDC) and ignited directly by the spark plug as the fuel cloud passes by. As a result, the running quality, or misfire rate of the engine is susceptible to the local AFR at the spark plug and to the vaporization & burn rates of the fuel [10].

ICOMIA five mode weighted HC + NOx in g/kW-hr for increasing amounts of butanol by volume is shown in Figure 6. As shown, gradual reductions in HC + NOx are achieved as the concentration of butanol in gasoline is increased with the greatest reduction occurring at 15% butanol by volume. Mode 4 emission increases are offset by reduction in emissions at Mode 1.



	1	2	3	4	5
0% Butanol	1043	122	67	294	120
10% Butanol	962	115	69	316	102
15% Butanol	900	114	76	308	95
20% Butanol	905	118	81	327	95

Figure 4. Total Hydrocarbons plus Nitrogen Oxides (HC + NOx) g/hr per test mode with increasing amounts of butanol by volume. (Average of two tests per test fuel)



	Baseline	10% butanol	15% butanol	20% butanol	10% ethanol	15% ethanol
Total Misfires 500 Cycles	26	37	33	45	50	55

Figure 5. Total engine misfire rate at Mode 4 with increasing volumes of butanol and ethanol. Misfire is calculated as an event <75% of average IMEP for the 500 cycle data sample. (Average of two tests per test fuel)

Carbon Monoxide emissions in g/hr per mode are shown in Figure 7 for increasing amounts of butanol by volume. As shown, reductions in CO emissions are due to the increased oxygen content of butanol. The overall ICOMIA five mode weighted CO emissions in g/kW-hr (Figure 8) was reduced by approximately 15% using B-20 as compared to the baseline fuel.

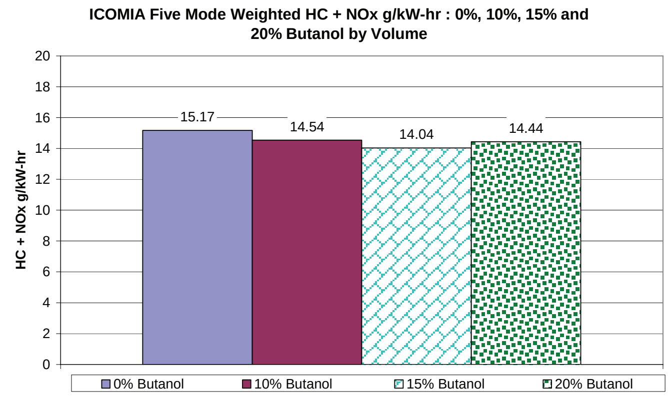
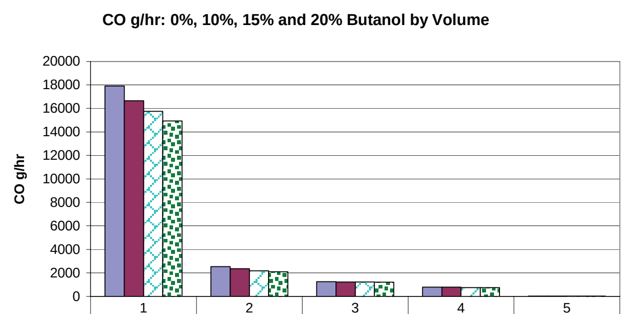


Figure 6. Total ICOMIA five mode weighted Hydrocarbons plus Nitrogen Oxides (HC + NOx) g/kW-hr with increasing amounts of butanol by volume. (Average of two tests per test fuel)



	1	2	3	4	5
0% Butanol	17905	2550	1253	782	20
10% Butanol	16649	2359	1231	783	16
15% Butanol	15748	2179	1226	746	16
20% Butanol	14943	2101	1208	752	20

Figure 7. Carbon Monoxide (CO) g/hr per test mode with increasing amounts of butanol by volume. (Average of two tests per test fuel)

Overall ICOMIA five mode weighted Carbon Dioxide (CO_2) emissions in g/kW-hr are presented in Figure 9. A minimal increase on CO_2 was observed with increasing amounts of butanol by volume.

Exhaust gas temperatures at 5 different modes are shown in Figure 10. A two percent increase in exhaust gas temperature was observed at mode 1 (WOT) with B-20 as compared to the baseline fuel. At Modes 2 and 3, on average, a six percent decrease in exhaust gas temperature was observed. At these test modes, the engine relies on post oxidation in which additional thermal reaction is occurring in the exhaust. This decrease in temperature is most likely due to the change in air/fuel ratio requirements of each specific test fuel. However, it appears this reduction in EGT at modes 2 and 3 do not significantly affect the HC + NOx emissions at these modes.

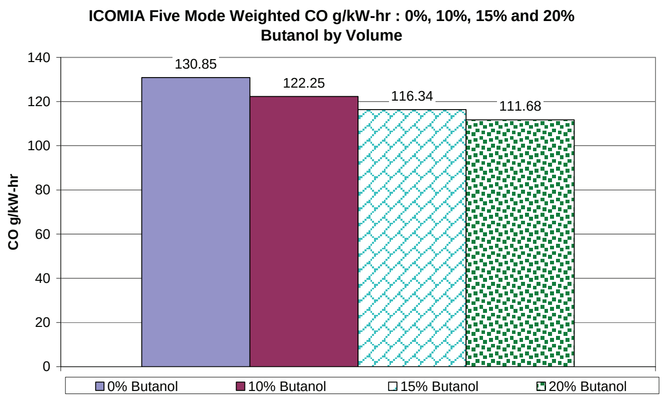


Figure 8. Total ICOMIA five mode weighted Carbon Monoxide (CO) g/kW-hr with increasing amounts of butanol by volume. (Average of two tests per test fuel)

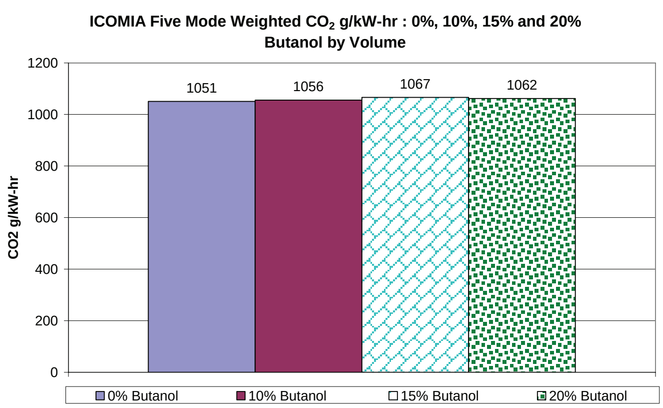
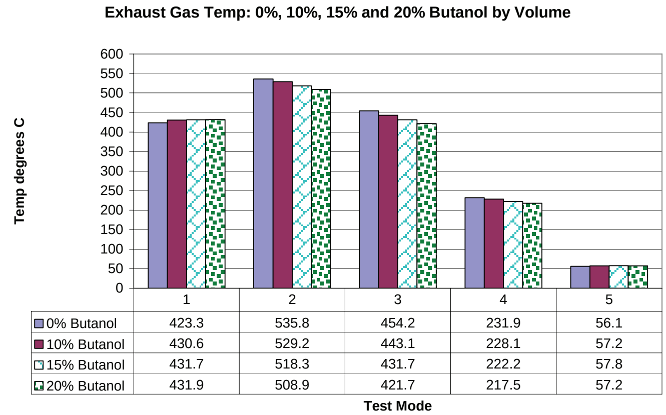


Figure 9. Total ICOMIA five mode weighted Carbon Dioxide (CO_2) g/kW-hr with increasing amounts of butanol by volume. (Average of two tests per test fuel)

Engine performance as indicated by wide open throttle corrected brake horsepower was maintained for increasing amounts of butanol by volume as shown in Figure 11.



	1	2	3	4	5
0% Butanol	423.3	535.8	454.2	231.9	56.1
10% Butanol	430.6	529.2	443.1	228.1	57.2
15% Butanol	431.7	518.3	431.7	222.2	57.8
20% Butanol	431.9	508.9	421.7	217.5	57.2

Figure 10. Exhaust gas temperature (EGT) per mode with increasing amounts of Butanol by volume. (Average two tests per test fuel)

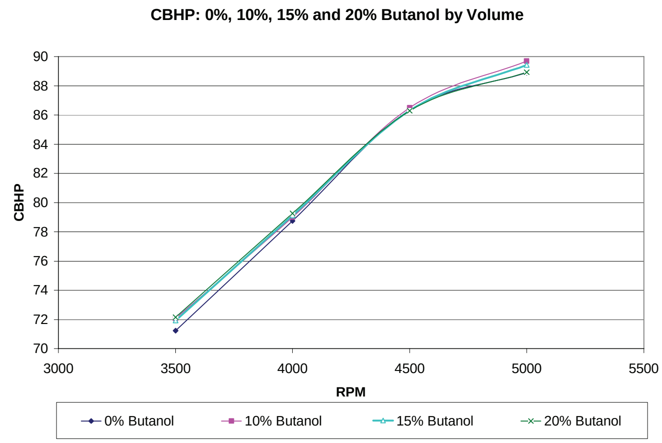
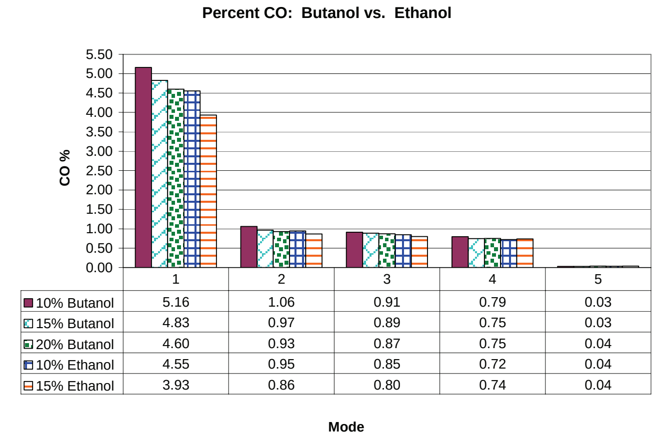


Figure 11. Wide open throttle corrected brake horsepower with increasing amounts of butanol by volume. (Average of two tests per test fuel)

COMPARISON BETWEEN BUTANOL AND ETHANOL

This section explores differences in emissions comparing B-10, B-15, B-20, E-10 and E-15. As shown in Figure 12, E10 and E-15 results in leaner running of the engine as indicated by raw CO percentage as compared to butanol. B-20 results in very similar raw CO in percent as E-10. A twenty percent reduction in raw CO using E-15 was observed at mode 1 (WOT) in comparison to a six percent reduction in raw CO using B-15. Figure 13 indicates the five mode weighted CO in g/kW-hr for the various fuel blends. Five mode weighted HC + NOx emissions were similar on both butanol and ethanol with a slight increase in emissions with ethanol as compared to butanol as shown in Figure 14. CO_2 emissions were generally lower with butanol blends as compared to ethanol blends as indicated in Figures 15 and 16.



	1	2	3	4	5
10% Butanol	5.16	1.06	0.91	0.79	0.03
15% Butanol	4.83	0.97	0.89	0.75	0.03
20% Butanol	4.60	0.93	0.87	0.75	0.04
10% Ethanol	4.55	0.95	0.85	0.72	0.04
15% Ethanol	3.93	0.86	0.80	0.74	0.04

Figure 12. Percent Carbon Monoxide (%CO raw gas sampling) per mode comparing 10% butanol, 15% butanol, 20% butanol, 10% ethanol, and 15% ethanol by volume. (Average two tests per test fuel)

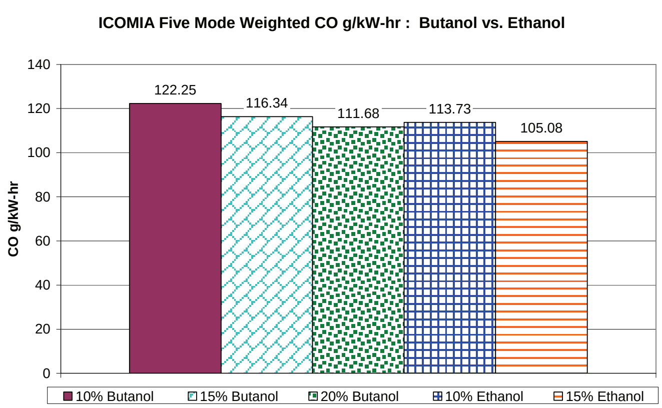


Figure 13. ICOMIA five mode weighted Carbon Monoxide (CO) g/kW-hr comparing 10% butanol, 15% butanol, 20% butanol, 10% ethanol, and 15% ethanol by volume. (Average two tests per test fuel)

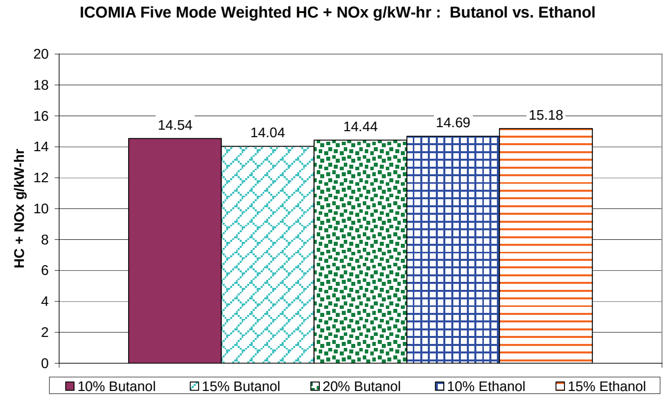
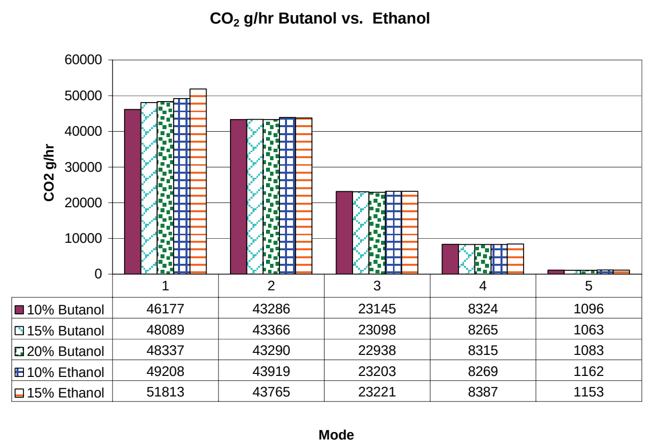


Figure 14. ICOMIA five mode weighted HC +NOx g/kW-hr comparing 10% butanol, 15% butanol, 20% butanol, 10% ethanol, and 15% ethanol by volume. (Average two tests per test fuel)



	1	2	3	4	5
10% Butanol	46177	43286	23145	8324	1096
15% Butanol	48089	43366	23098	8265	1063
20% Butanol	48337	43290	22938	8315	1083
10% Ethanol	49208	43919	23203	8269	1162
15% Ethanol	51813	43765	23221	8387	1153

Figure 15. CO_2 g/hr per mode comparing 10% butanol, 15% butanol, 20% butanol, 10% ethanol, and 15% ethanol by volume. (Average two tests per test fuel)

Lambda was measured using the modified Spindt method based on raw five-gas emissions for the various alternative fuel blends [11]. Figure 17 indicates the measured Lambda for increasing amounts of alternative fuel blends. Notice that 20% butanol by volume yields similar Lambda values as 10% ethanol by volume at modes one and two.

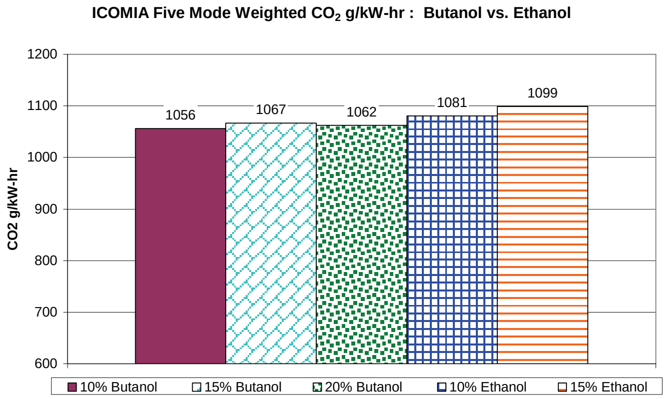
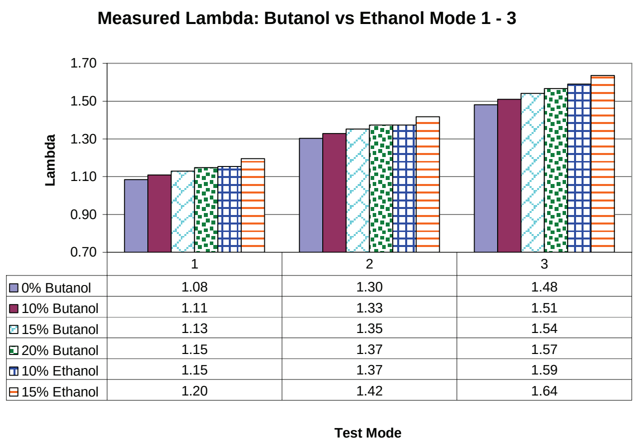


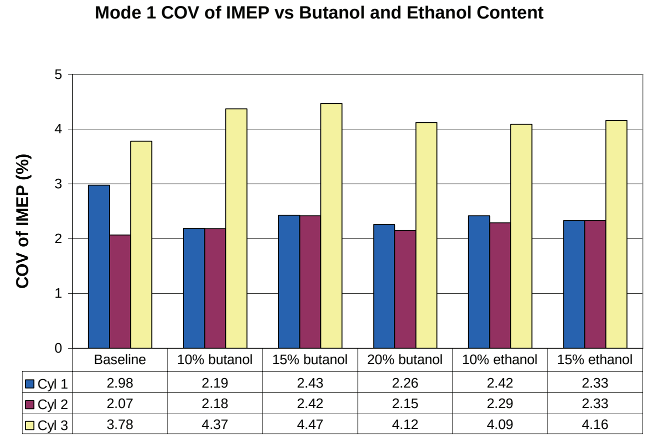
Figure 16. ICOMIA five mode weighted CO_2 g/kW-hr comparing 10% butanol, 15% butanol, 20% butanol, 10% ethanol, and 15% ethanol by volume. (Average two tests per test fuel)



	1	2	3
0% Butanol	1.08	1.30	1.48
10% Butanol	1.11	1.33	1.51
15% Butanol	1.13	1.35	1.54
20% Butanol	1.15	1.37	1.57
10% Ethanol	1.15	1.37	1.59
15% Ethanol	1.20	1.42	1.64

Figure 17. Measured Lambda comparing baseline fuel to 10% butanol, 15% butanol, 20% butanol, 10% ethanol, and 15% ethanol by volume. (Average two tests per test fuel)

In addition, cylinder pressure data was analyzed at Mode 1 to evaluate the impact of butanol and ethanol concentration on combustion quality. Figure 18 indicates that the % COV of IMEP does not radically change with increasing quantities of butanol or ethanol which is consistent with the findings of direct fuel injection closed-loop automotive engine research [12]. Cylinder three has a slightly higher COV due to knock reduction strategies in the engine calibration.



	Baseline	10% butanol	15% butanol	20% butanol	10% ethanol	15% ethanol
Cyl 1	2.98	2.19	2.43	2.26	2.42	2.33
Cyl 2	2.07	2.18	2.42	2.15	2.29	2.33
Cyl 3	3.78	4.37	4.47	4.12	4.09	4.16

Figure 18. Mode 1 (WOT) %COV of IMEP by cylinder for increasing quantities of butanol and ethanol.

The Mahle Knock Index is calculated to determine changes in knock activity due to higher butanol or ethanol concentrations and is calculated by assigning a weighting to the Knock Peak value for each cycle. The weightings for each knock peak are then summed and divided by the number of cycles, which gives the Knock Index. A higher Knock Index value indicates more knock activity. The absolute value of the Knock index will vary depending on filtering frequencies and weightings applied to the Knock Peak value. The knock peak value is determined by filtering and rectifying each cylinder pressure trace so that only the oscillations from the knock event remain. The peak oscillation from that event becomes the Knock Peak Value for that cycle. This calculation is done for each cycle on each individual cylinder. Figure 19 shows that the Mahle Knock Index remained mostly unchanged. This is due to the increased octane rating of the higher butanol and ethanol content fuels. The engine was calibrated on a fuel similar to the baseline fuel, allowing the knock characteristics of the lower octane fuel to be minimized. As a result, any increase in octane number will reduce the knock activity.

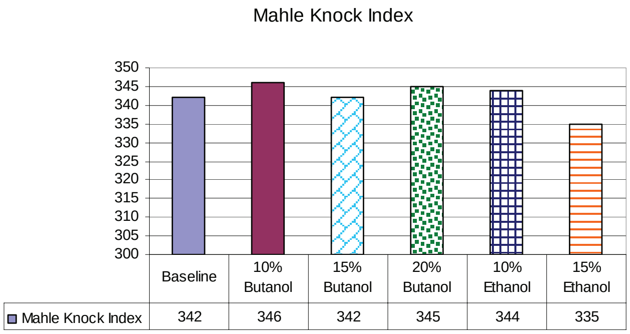


Figure 19. Mode 1 (WOT) Mahle Knock Index for all cylinders.

Mode 1 burn rates were also calculated for each concentration of butanol and ethanol. Figure 20 indicates the engine average burn rates for increasing quantities for butanol and ethanol. The peak burn rate for butanol was slightly reduced (0.5%/deg) and occurred 1-2 degrees earlier in the cycle. For increasing ethanol content, the peak burn rate is reduced the same amount, but phased 2-3 degrees earlier in the cycle.

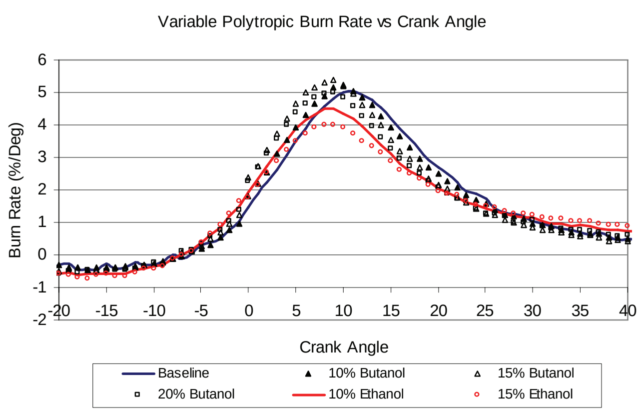


Figure 20. Mode 1 Engine average burn rate.

Figures 21, 22, and 23 show normalized cylinder pressures for each of the cylinders averaged over 500 cycles. In all instances, the higher concentrations of butanol and ethanol incrementally advance the combustion process, with peak cylinder pressure occurring 2 to 3 degrees earlier than the baseline fuel. This correlates with the advance in the burn rate for increasing butanol and ethanol content and is caused by a decrease in the ignition delay, or zero to 10% burn duration.

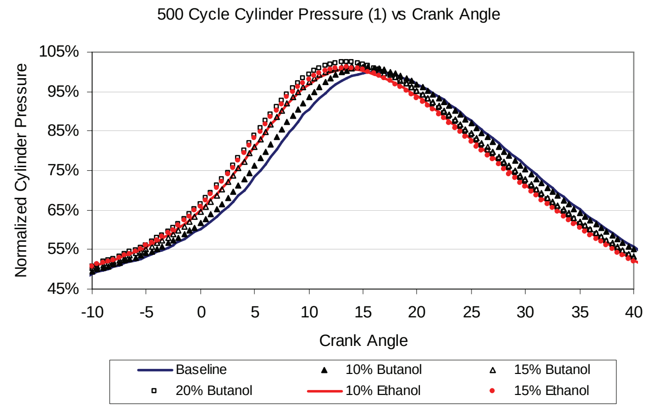


Figure 21. Mode 1 Cylinder 1 pressure averaged over 500 cycles.

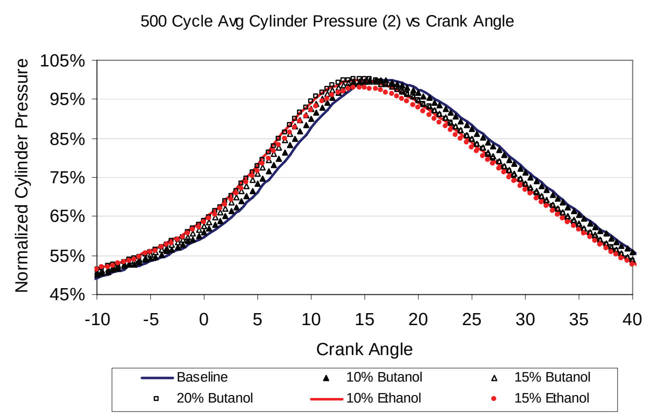


Figure 22. Mode 1 Cylinder 2 pressure averaged over 500 cycles.

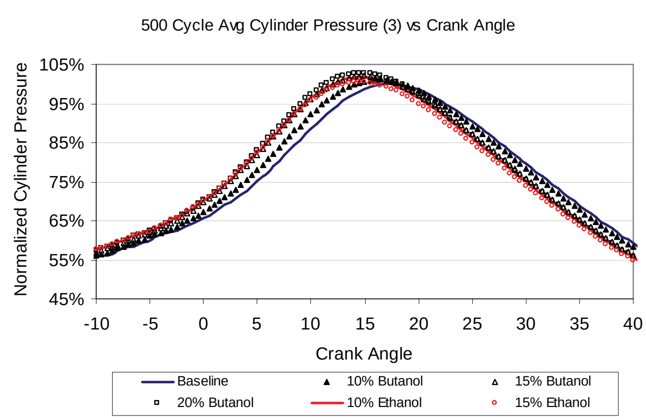


Figure 23. Mode 1 Cylinder 3 pressure averaged over 500 cycles

SUMMARY/CONCLUSIONS

This work was intended to be a first investigation assessing potential of butanol as a drop-in alternative fuel blend for direct injection two stroke recreational marine engines. A significant amount of work is needed to assess wide scale effects of butanol on gasoline recreational marine engine technologies and fuel systems prior to drawing any significant conclusions. However, based on this study, initial results look promising and are summarized below.

- Compared to the same percentage blend of ethanol, butanol blends result in less engine enleanment as indicated by CO and Lambda. This means butanol can be tolerated in higher blend percentages in open-loop engines as compared to ethanol.

- 20% butanol by volume resulted in similar emissions and engine power as 10% ethanol by volume.

- Misfire events at mode 4 (fully stratified) generally increased slightly with increasing amounts of butanol by volume but misfire events were more prevalent with ethanol than butanol.

- Compared to the same percentage blend of ethanol, butanol blends result in less Carbon Dioxide (CO_2), which is considered a form of green house gas emission. The reduction in CO_2 for butanol blends compared to ethanol blends is due in part to the stronger enleanment effects of ethanol, which cause HC emissions to decrease more substantially, NOx emissions to increase slightly and CO emissions to decrease. Because there is less HC, less CO and more NOx, this forces the carbon (as part of the carbon balance) to convert to CO_2.

- No discernable changes to the WOT COV of IMEP or knock characteristics were noticed, with higher concentrations of butanol or ethanol.

- Combustion phasing was slightly advanced with increased levels of butanol and ethanol.

REFERENCES

1. Orbital Engine Company, "Marine Outboard Driveability Assessment to Determine Impacts of a 10% and 20% Ethanol Gasoline Fuel Blend on a Small Batch of Engines" Market Barriers to the Uptake of Biofuels Study - Report to Environment Australia, February 2003

2. Knoll, Keith et al., "Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines" , Report 1 – Updated, February 2009 Oak Ridge National Laboratory

3. National Marine Manufactures Association (NMMA), Recreational Boating Statistical Abstract - U.S. Boat Registrations, 2008

4. Vatalaro, Michael, "A Serious Problem, a Corny Solution" Boat/US Magazine, July 2006

5. "Results of BoatU.S. Sponsored Fuel and Fiberglass Gas Tank Tests". Boat/US Seaworthy Magazine. 03/20/2010 http://www.boatus.com/seaworthy/fueltest.asp#results

6. "Recommendations on Storing Ethanol-Enhanced Gasoline" Boat/US Magazine – Seaworthy, 2010

7. "BP-Dupont Biofuels Fact Sheet". BP. 03/21/2010 http://www.bp.com/liveassets/bp_internet/globalbp/STAGING/global_assets/downloads/B/Bio_bp_dupont_fact_sheet_jun06.pdf

8. United States Code Of Federal Regulations CFR 40, Part 1065.710 - Test Fuel Specifications for Gasoline

9. ISO 8178-4:2007 Reciprocating internal combustion engines - Exhaust emission measurement Part 4: Steady-state test cycles for different engine applications

10. Smith, J., Sick, V., “The Prospects of Using Alcohol-Based Fuels in Stratified-Charge Spark-Ignition Engines” SAE 2007. 2007-01-4034

11. Roy Douglas, “AFR and Emissions Calculations for Two-Stroke Cycle Engines”, SAE paper 901599, 1990

12. Wallner, T., Miers, S., McConnell, S., "A Comparison of Ethanol and Butanol as Oxygenates Using a Direct-Injection, Spark-Ignition Engine" ASME: Journal of Engineering for Gas Turbines and Power, May 2009, Vol. 131 / 032802-1

13. Bata, R., Elrod, A., “Butanol as a Blending Agent with Gasoline for I.C Engines” SAE 1989. 890434

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Impact of Blending Gasoline with Isobutanol Compared to Ethanol on Efficiency, Performance and Emissions of a Recreational Marine 4-Stroke Engine

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Abstract

This study evaluates iso-butanol as a pathway to introduce higher levels of alternative fuels for recreational marine engine applications compared to ethanol. Butanol, a 4-carbon alcohol, has an energy density closer to gasoline than ethanol. Isobutanol at 16 vol% blend level in gasoline (iB16) exhibits energy content as well as oxygen content identical to E10. Tests with these two blends, as well as indolene as a reference fuel, were conducted on a Mercury 90 HP, 4-stroke outboard engine featuring computer controlled sequential multi-port Electronic Fuel Injection (EFI). The test matrix included full load curves as well as the 5-mode steady-state marine engine test cycle.

Analysis of the full load tests suggests that equal full load performance is achieved across the engine speed band regardless of fuel at a 15-20°C increase in exhaust gas temperatures for the alcohol blends compared to indolene. This increase as well as the observed 2.5-3% point improvement in brake thermal efficiency of both alcohol blends compared to the reference fuel are caused by changes in air/fuel ratio; an effect ultimately attributable to the open loop engine control strategy. This control strategy also explains the reduced CO as well as the increased HC+NO_x emissions of E10 and iB16 compared to indolene consistently observed across the 5 operating modes of the steady-state test cycle. The study also suggests that formaldehyde and acetaldehyde emissions increased with alcohol blend level.

With equivalent performance and emissions compared to E10 iB16 could be a viable option for increasing renewables utilization in recreational marine engines.

Introduction

In an effort to increase energy security, the United States has enacted legislation that mandates increased amounts of ethanol and advanced biofuels to be introduced in the market over the coming years. Since ethanol is currently mainly used in E10 blends, saturation of the E10 market creates a barrier commonly known as the ethanol blend wall. Relaxation of the blend limit for ethanol to be used in non-flexfuel vehicles is one option to temporarily mitigate this issue [1].

In 2010 the U.S. Environmental Protection Agency granted a first waiver for use of E15 in vehicles of MY2007 and newer, followed in 2011 by a second partial waiver for vehicles MY2001 - MY2006 [2]. Issues such as potential for misfueling, vehicle warranty and limited E15 station availability have so far hindered large-scale introduction of E15 in the marketplace [3].

Studies evaluating the effects of increased ethanol content have been focused on light duty-vehicles as the largest consumer group. However, although significantly smaller in total size compared to the 250 Million unit automotive market [4], the recreational marine sector in the United States still accounts for more than 10 Million powerboats (see Figure 1) [5]. The powerboat market also differs from the automotive market in retirement/scrappage rate; while the automotive scrappage rate is consistently around 5% [4], the powerboat retirement rate shows much stronger fluctuations but averaged just above 3% over the last 10 years [5]. As a consequence, the average powerboat is significantly older than the average light-duty vehicle.

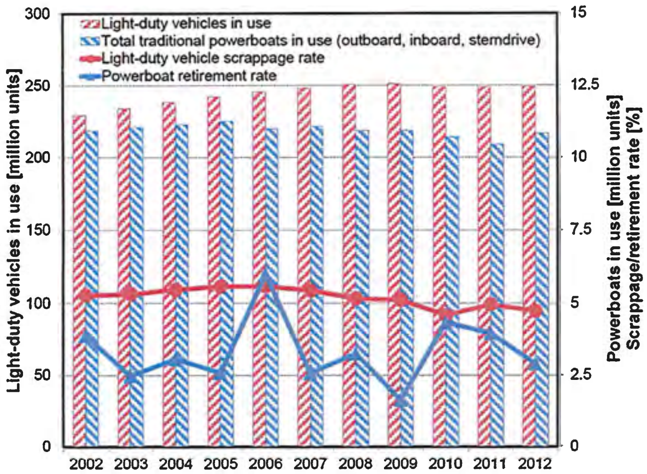

Figure 1. Comparison of light-duty vehicle and powerboat population and scrappage/retirement rate in the United States [4,5]

In addition to the higher average engine age, recreational marine engines and vessels also operate under different boundary conditions compared to automobiles. Major challenges for introduction of biofuels for recreational marine engines include open vented fuel systems, tank and fuel system material compatibility, and open loop engine control strategies [6].

While the significant differences in engine age, technology implementation and system design by themselves warrant an assessment of the effects of ethanol addition to gasoline on recreational marine engines, this study has a wider focus and also evaluates butanol blends as an alternative that could enable increased use of alternative fuels in boat engines.

A number of studies of butanol blends compared to gasoline and ethanol blends on automotive engines have been published focusing on emissions characteristics, combustion as well as efficiency [e.g. 7,8,9]. However, recreational marine engines typically do not employ closed loop air/fuel ratio feedback controls and therefore present a fundamentally different platform for the assessment of gasoline/alcohol blends. The absence of closed loop controls has been identified as a key challenge negatively affecting startability, engine run quality and durability in experiments performed on recreational marine engines operated on E15 blends [10,11]. Limited information on the effect of butanol blends in marine engine applications has so far focused on 2-stroke engines [12] as well as in-use testing in recreational vessels [6].

This study was specifically designed to assess the suitability of butanol as a drop-in fuel for blending with gasoline for recreational marine engine applications. The main focus is the quantification of performance, efficiency and emissions on a widely used marine engine operated on butanol blends compared to gasoline and ethanol blends. The data presented here defines the baseline for a durability study on this engine and is part of a larger program that includes performance, efficiency, emissions and durability testing on a range of recreational marine engines with complimentary research on the effects of alcohol addition on lubricant performance and wear [13].

Experimental Details

This study was designed to allow direct comparison between gasoline/ethanol blends and gasoline/butanol blends at equivalent oxygen content. The following sections provide details on fuel selection and specifications as well as engine setup, instrumentation and test protocols.

Fuel Specifications

The two blending agents of interest for this study are ethanol, a 2-carbon alcohol, and butanol, a 4-carbon alcohol. Butanol exists in four isomers that differ in structure and the location of the OH group. Due to its higher knock resistance and preferable properties compared to the other isomers, iso-butanol is widely considered the most promising butanol isomer [e.g. 14,15,16]. Table 1 summarizes the fuel properties of indolene (reference fuel) and the two alcohol blends. Ethanol and butanol were blended with blendstock for oxygenate blending (BOB) rather than indolene to achieve fuel properties that are similar to fuels currently used in the field. Iso-butanol was blended to achieve equivalent oxygen content to a 10 vol% gasoline/ethanol blend (E10). The resulting blend level is 16 vol% iso-butanol (iB16) at an oxygen content of 4 wt%. The oxygen content in the fuel also impacts the stoichiometric air demand, AFR_{ST}, which is approximately 13.8 for E10 and iB16 compared to 14.6 for indolene, as well as the energy content. The resulting lower heating value of the alcohol blends is around 29.5 MJ/L compared to 32 MJ/L for indolene. These changes in properties are particularly relevant since the test engine, like most recreational marine engines, does not employ a closed loop engine feedback control. Reid Vapor Pressure (RVP) of the E10 blend is almost as high as indolene compared to the lower RVP of iB16. These changes are attributable to the azeotropic behavior of ethanol blends which are not exhibited with butanol [17]. Both neat ethanol and iso-butanol have octane ratings significantly higher than gasoline [18]. Research Octane Number (RON) and Motor Octane Number (MON) of the blends are slightly lower than indolene due to the low RON and MON of the BOB used for blending compared to indolene.

Table 1. Fuel Specifications

			Indolene	E10	iB16
Density	ASTM D4052	kg/L	0.743	0.7397	0.7489
RVP	ASTM D5191	psi	9.1	8.81	7.97
Carbon	ASTM E191	wt%	86.31	82.916	83
Hydrogen	ASTM E191	wt%	13.34	13.094	12.998
Oxygen		wt%	0	3.99	4.002
H/C ratio	ASTM E191	mole/mole	1.841	1.895	1.879
O/C ratio		mole/mole	0	0.036	0.036
AFR_{ST}			14.571	13.856	13.832
RON	ASTM D2699		96.6	94.0	94.7
MON	ASTM D2699		88.7	85.4	83.8
LHV	ASTM D240	MJ/kg	43.01	39.75	39.54
LHV		MJ/L	31.96	29.40	29.61

Engine Setup

A 1.7L spark-ignition in-line 4-cylinder 4-stroke outboard engine was selected for these tests. The engine operates open-loop and does not use any combustion feedback sensors to adjust for changes in fuel properties. The engine was selected to expand the knowledge base since so far published laboratory results from recreational marine engine tests with butanol blends have been limited to 2-stroke engines [12]. The engine is also representative of a large family of naturally aspirated as well as supercharged outboard models of similar design. The specifications of the test engine are shown in Table 2.

No changes or modifications to the base engine calibration, spark timing or injection timing were made at any time during the testing process.

Table 2. Test Engine Specifications

Engine type	Mercury 90 Horsepower, 4 Stroke
Propeller power [HP/kW]	90/67
Maximum engine speed [RPM]	5000-6000
Cylinder/Configuration	In-line 4, 16-valve, direct acting dual, overhead cam (DOHC)
Displacement [CID, cc]	105.7/1732
Bore/Stroke [mm]	82/82
Cooling System	Water-cooled w/thermostat
Ignition System	Inductive Coil on Plug
Gear Ratio	2.33:1
Exhaust System	Through prop
Lubrication System	Integrated dry sump
Fuel Induction System	Computer controlled sequential multi-port Electronic Fuel Injection (EFI)
Recommended fuel	87 octane/up to 10 vol% ethanol
Dry Weight [kg]	181

A schematic of the engine setup on the dynamometer is shown in Figure 2. Engine cooling water is supplied to the engine through the gear-case water pick-up. Since the exhaust is routed through the propeller, exhaust emissions and exhaust gas temperatures are sampled upstream above the water line before the exhaust is routed through the water tank. An AVL i60 five-gas emissions bench was used to sample THC, NO_X, CO, CO_2 and O_2. Reported total hydrocarbon (THC) emissions using the Flame Ionization Detector are not corrected for changes in sensitivity of the analyzer due to oxygen content of the fuel blends since the blends do not exceed the 25 vol% threshold specified in the CFR [19]. An AVL SESAM FTIR was used for exhaust speciation of hydrocarbons as well as measurement of N_2O emissions. Specific emissions results are calculated based on 40 CFR Parts 89, 90, and 91 and 40 CFR Parts 1065 using raw emissions results as well as measured fuel flow rates and engine performance as inputs.

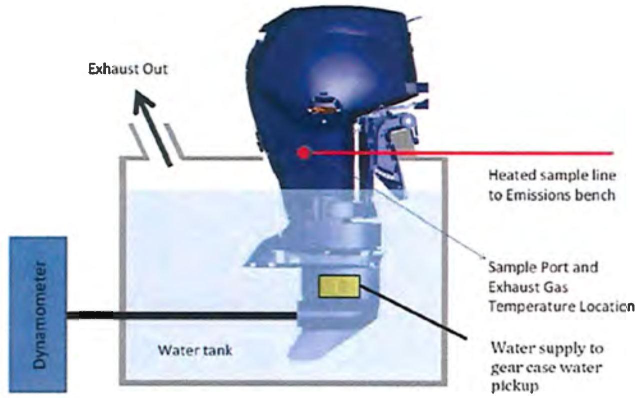

Figure 2. Schematic engine test setup [12]

Test Matrix

The test program included wide open throttle (WOT) power tests as well as steady-state operating points. The 5-mode steady-state points are defined in *CFR PART 1045-Control of emissions from spark-ignition propulsion marine engines and vessels* [20]. The torque and speed target values for the 5 steady-state points as well as the weighting factors for the individual modes are summarized in Table 3.

Table 3. 5-mode steady-state marine test cycle [20]

Mode	% RPM	% Torque	% Weight Factor
1	100	100	6
2	80	71.6	14
3	60	46.5	15
4	40	25	25
5	Idle	0	40

For the WOT power tests the engine was run for approx. 3 min at each load point. Data presented represents the arithmetic average of 30 data samples collected at a frequency of 1 Hz at the end of the stabilization phase. For clarity of the results no error bars are shown on the graphs.

For the 5-mode steady-state tests the engine was run for approx. 7 min at each load condition to ensure stability. Data presented here was averaged over a 2 min time window at a sample frequency of 1 Hz. Measurement errors were estimated using the uncertainties of the respective input variables. Error bars are shown for efficiency, fuel consumption data as well as emissions results based on data from the AVL i60 five-gas emissions bench. Due to the nature of the measurement and the employed method, uncertainties for FTIR data were not estimated.

Full Load Performance Results

Full load performance was evaluated at 15 speed points under wide open throttle operating conditions. Figure 3 shows the resulting engine power curve as well as the measured exhaust gas temperatures in the speed range from 2500 to 6000 RPM. Engine power is virtually identical regardless of fuel, however, engine exhaust temperatures are higher for the alcohol blends compared to indolene. The temperature increase is consistent across the speed range at approximately 15-20°C. The typical standard deviation of individual exhaust gas temperature measurements is less than 0.5°C.

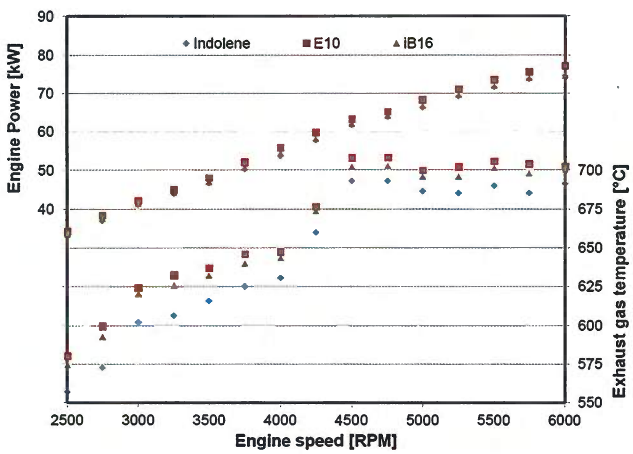

Figure 3. Engine power curves and exhaust gas temperatures for indolene, E10 and iB16 operation

Figure 4 compares brake thermal efficiencies (BTE) as well as volumetric fuel consumption in full load operation. E10 and iB16 both show a consistent 2.5 - 3% point improvement in BTE compared to indolene. This results in identical or slightly reduced volumetric fuel consumption of E10 and iB16 compared to the baseline fuel. This is particularly important to note since the energy content of the alcohols is approximately 8% lower than that of gasoline. Therefore, the 10% improvement in BTE offsets the 8% reduction in fuel energy content. As discussed in more detail in a later section, the cause for the significant improvement in engine efficiencies and increased exhaust gas temperatures is changes in air/fuel ratio. Since the engine does not have a combustion feedback loop, operation with oxygenated fuels results in less fuel energy being injected with the same commanded injection duration. Neither emissions nor air flow were measured during the WOT test runs, therefore the actual air/fuel ratio could not be determined.

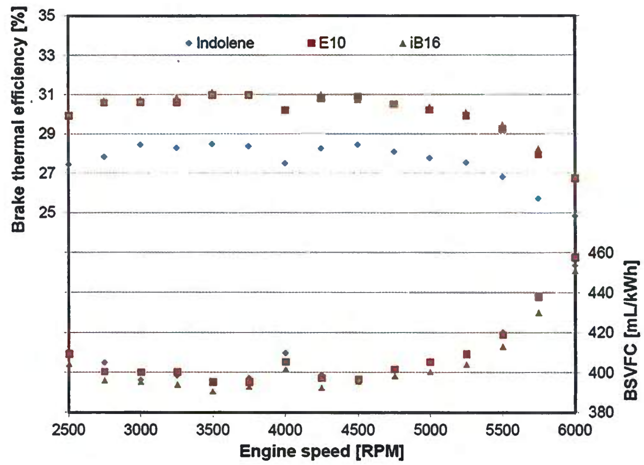

Figure 4. Comparison of brake thermal efficiencies and brake specific volumetric fuel consumption at full load

5-Mode Test Results

Following a general assessment of performance, exhaust temperatures and efficiencies of indolene, E10 and iB16 at the full load curve, efficiencies as well as greenhouse gas and regulated emissions are analyzed over the 5-mode test cycle.

Efficiency

Figure 5 shows brake thermal efficiency as well as relative air/fuel ratio λ values for the 5 operating modes. Since Mode 5 is idle with no positive power output, efficiency equals zero. Otherwise, the 2.5-3% point improvement in efficiency as outlined with the performance data is also seen in the modal results. Relative air/fuel ratio values for indolene are richer compared to the ethanol and butanol blends. As load decreases with increasing mode number, less fuel enrichment is used. Nonetheless, the relative difference between indolene and the alcohol blends remains at approximately 0.05 λ points. Although still fuel rich, this operation closer to stoichiometry with the oxygenated fuels is the main reason for the improved engine efficiency.

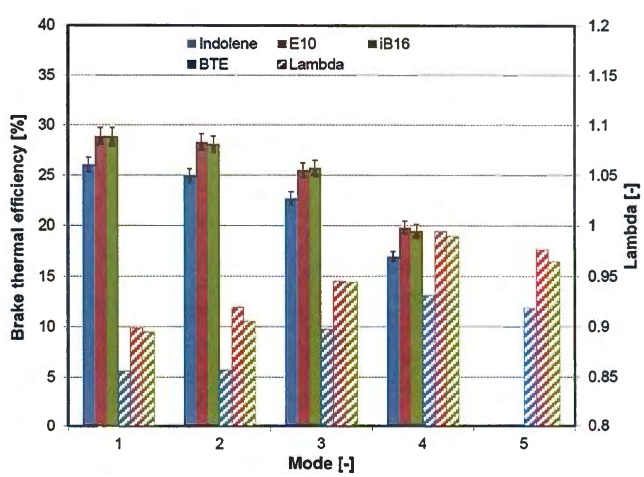

Figure 5. Comparison of brake thermal efficiencies and relative air/fuel ratio in 5-mode steady-state operation

The efficiency advantage of the blends compared to indolene is also reflected when comparing both gravimetric and volumetric specific fuel consumption shown in Figure 6. Since the efficiency advantage of the alcohol blends overcompensates for the reduced energy content, the brake specific (gravimetric) fuel consumption (BSFC) of E10 and iB16 is slightly lower than that of indolene. Due to the marginal differences in fuel density between the three fuels (< 1%), the brake specific volumetric fuel consumption (BSVFC) shows the same trends. In real world operation, the efficiency advantage of the alcohol blends would translate into reduced fuel consumption of the alcohol blends compared to indolene despite the lower energy content of the alcohols.

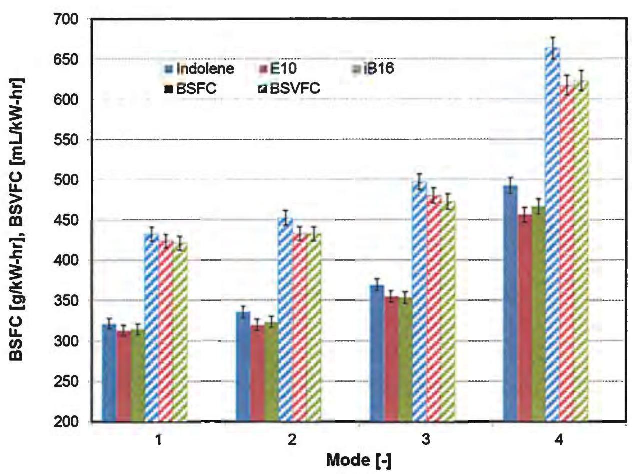

Figure 6. Comparison of gravimetric and volumetric specific fuel consumption in 5-mode steady-state operation

Greenhouse Gas Emissions

Following the assessment of fuel consumption and engine efficiency, resulting greenhouse gas emissions are analyzed. Figure 7 compares carbon dioxide (CO_2) and equivalent carbon dioxide (CO_{2e}) emissions for each of the 5 operating modes. Equivalent CO_2 emissions are calculated based on the Global Warming Potential (GWP) of greenhouse gases; GWP values of 21 and 310 are used for CH_4 and N_2O, respectively [21]. Carbon dioxide emissions appear to increase slightly for the alcohol blends in all operating modes expect engine idle (Mode 5); however, the increase is within the margin of error of the measurements. This may seem counterintuitive since the engine efficiency also improved for the alcohol fuels. However, the operation closer to stoichiometric conditions with E10 and iB16 results in more complete combustion as indicated by significantly reduced CO emissions (see Figure 11) causing increased CO_2 emissions.

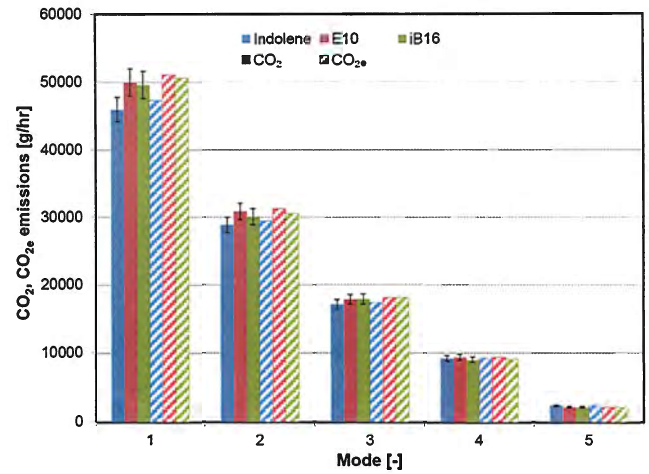

Figure 7. Comparison of carbon dioxide emissions in 5-mode steady-state operation

Figure 8 compares methane and nitrous oxide emissions for their contribution to equivalent CO_2 emissions. CH_4 emissions do not show a clear trend as a function of fuel composition, N_2O emissions show a significant reduction at higher engine loads (Mode 1 and 2) for the oxygenated fuels and a slight increase for the alcohol blends at light loads. The formation of N_2O is based on reaction of intermediates with NO [22]:

$$NH + NO \rightarrow N_2O + H \tag{1}$$

$$NCO + NO \rightarrow N_2O + CO \tag{2}$$

The formation mechanism is limited to the oxidation zone, an area with high hydrogen atom concentration causing destruction of nitrous oxides by the following reaction generally resulting in very little N_2O emissions [22]:

$$N_2O + H \rightarrow NH + NO \tag{3}$$

$$N_2O + H \rightarrow N_2 + OH \tag{4}$$

A vehicle level analysis comparing N_2O and CH_4 emissions of conventional and alternative fuel vehicles suggests that addition of ethanol does not result in significant changes in N_2O emissions compared to gasoline [23]. However, another study focusing on fundamental reactions of gasoline/ethanol blends hypothesizes that increased concentrations of OH due to the addition of ethanol reduces CO concentrations and thus limits the reaction [24]:

$$CO + NO \rightarrow N_2O + CO_2 \tag{5}$$

This is believed to increase NO_x emissions while in turn resulting in a reduction of N_2O emissions, trends consistent with the results observed in this study.

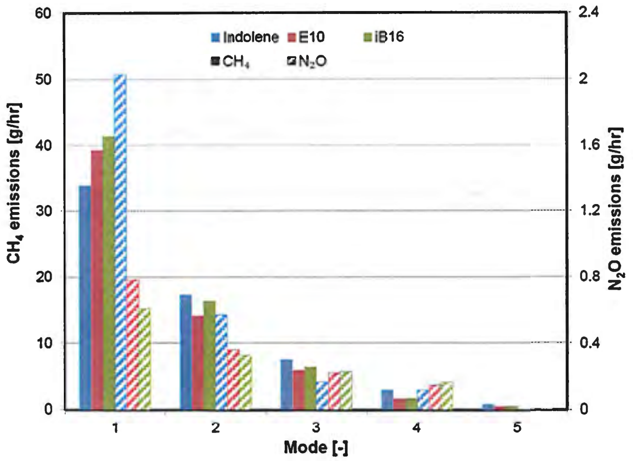

Figure 8. Comparison of methane and nitrous oxide emissions in 5-mode steady-state operation

The resulting 5-mode weighted greenhouse gas emissions are shown in Figure 9. As can be seen the differences in weighted specific emissions are marginal with no clear indication to the effect of fuel composition. Similar trends in CO_2 emissions were identified with a 2-stroke recreational marine engine of equivalent performance [12]. In both cases increasing CO_2 emissions with alcohol fuel blends were also accompanied by engine operation closer to stoichiometric conditions.

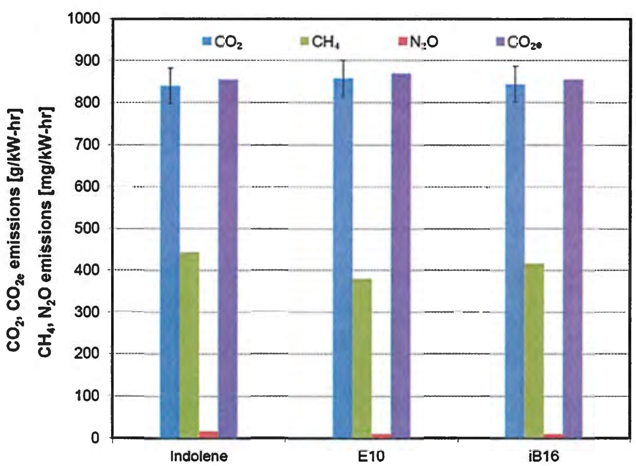

Figure 9. Comparison of 5-mode weighted greenhouse gas emissions

Regulated Emissions

The main regulated emissions components for recreational marine engines are carbon monoxide (CO) as well as hydrocarbon (HC) and oxides of nitrogen (NO_x) emissions. Emissions limits are defined separately for CO and combined for HC+NO_x. According to 40 CFR 1045 emissions standards are defined based on engine power with specific equations shown in Table 4.

Table 4. HC+NO_x and CO emissions standards for spark-ignition marine engines [20]

Pollutant	Power[1]	Emissions standard [g/kW-hr]
HC+NO_x	≤ 4.3 kW	30
	> 4.3 kW	$2.1 + 0.09 \times (151 + 557/P^{0.9})$
CO	≤ 40 kW	$500 - 5.0 \times P$
	> 40 kW	300

[1] Power (P) = maximum engine power for the engine family, in kilowatts [kW]

Steady-state HC and NO_x emissions for the 5 modes and three tested fuels are shown in Figure 10. Although regulated as a combined maximum, HC and NO_x emissions are shown separately in the graph to allow evaluation of the individual contributions. In all operating modes expect idle (Mode 5) NO_x emissions are the dominant contributor regardless of fuel. HC+NO_x emissions at the higher load points (Modes 1-3) increase with addition of alcohol compared to indolene operation. This increase is mainly caused by increased NO_x emissions with HC emissions slightly increasing in Mode 1 while remaining almost constant in the other modes. The increased NO_x emissions are likely attributable to increased combustion temperatures due to the operation closer to stoichiometry with the oxygenated fuels compared to the gasoline baseline.

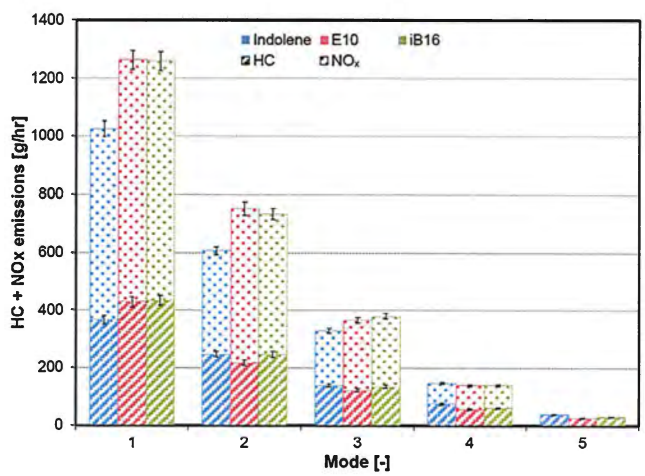

Figure 10. Steady-state HC and NO_x emissions for indolene, E10 and iB16 operation

Fuel rich operation, as employed with this test engine, shifts the balance of exhaust products from carbon dioxide to carbon monoxide. Figure 11 compares the CO emissions for the test fuels over the 5 operating modes. CO emissions for the oxygenated fuels are consistently approximately 35-50% lower than for indolene. The main cause is once again the change in relative air/fuel ratio due to the oxygen content in the alcohol fuels. The reduction in CO emissions in turn results in the increased CO_2 emissions shown in Figure 7.

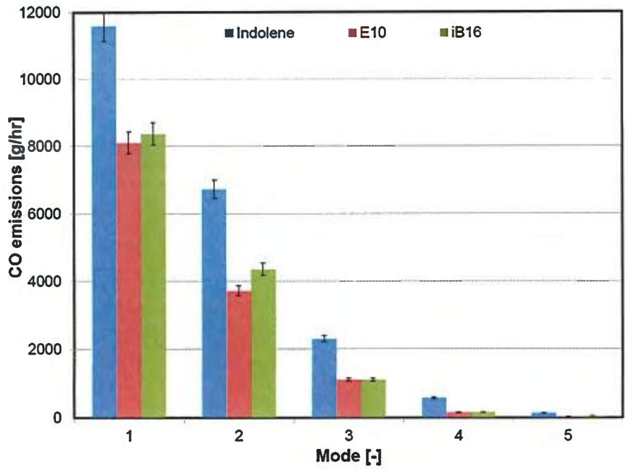

Figure 11. Comparison of carbon monoxide emission in 5-mode steady-state operation

The resulting 5-mode weighted regulated emissions for indolene, E10 and iB16 are shown in Figure 12. The weighted CO emissions for the alcohol fuels are approximately 40% lower than those of the indolene reference fuel. Even with indolene the CO emissions are approximately 50% below the applicable limit of 300 g/kW-hr. HC+NO_x emissions with indolene, the approved EPA and CARB marine certification fuel, amount to approximately 16.5 g/kW-hr compared to the actual limit of 16.8 g/kW-hr. The change in air/fuel ratio with operation on E10 and iB16 results in an approximately 10% increase in HC+NO_x emissions of the alcohols compared to gasoline. Since the engine was certified with indolene, not-to-exceed (NTE) field testing limits would apply for operation with alcohol fuels effectively increasing the emissions limits by a factor of 1.4 [20]. As shown and discussed in the modal emissions results in Figure 10, the increase in combined HC+NO_x emissions is mainly attributable to an increase in NO_x emissions. No significant differences between the ethanol and iso-butanol blends were observed.

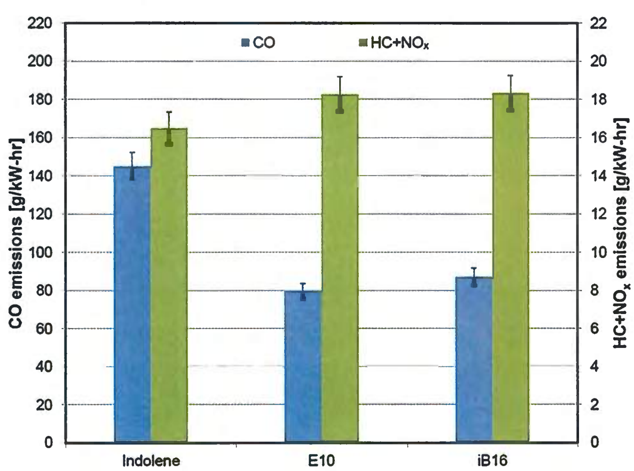

Figure 12. Comparison of 5-mode weighted regulated emissions

Speciated HC Emissions

In addition to reporting on total hydrocarbon emissions with indolene as well as the oxygenated fuels, select speciated hydrocarbon emissions were also analyzed. Certain emissions constituents, such as CO and CO_2, are directly comparable between traditional analyzers and Fourier Transformed Infrared (FTIR) measurements [25]. However, due to the fundamentally different measurement principle and the large range of individual constituents included, THC results from a Flame Ionization Detector (FID) are not directly comparable to data from a FTIR analyzer [26].

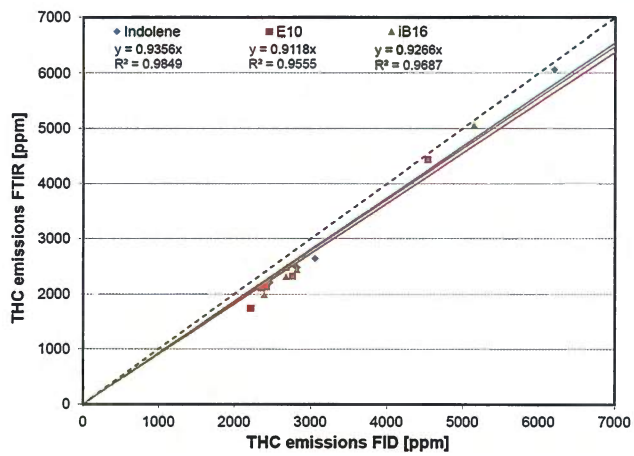

Figure 13. Comparison of total hydrocarbon measurement results from Flame Ionization Detector and FTIR

A THC estimate from the FTIR analyzer is calculated by adding select individual hydrocarbons. Figure 13 compares the resulting total hydrocarbon values from the FID and FTIR for the range of operating modes and tested fuels. In addition to the actual data points, linear regression curves with a forced zero intercept were also added. Nearly linear behavior can be observed with indolene as well as E10 and iB16 with R^2 values of 0.9849, 0.9555 and 0.9687, respectively. In general, the FTIR estimates are slightly below the FID measurements since not all hydrocarbon constituents are measured in the FTIR method. Nonetheless, the correlation supports the assumption that FTIR measurements allow for a reasonably accurate determination of speciated hydrocarbons.

Alcohol emissions, accounting for unburned ethanol for the E10 blend and unburned iso-butanol for the iB16 blend are reported in Figure 14 together with 1,3-Butadiene emissions. As expected, the respective alcohol emissions increase significantly with the oxygenated blends compared to indolene. The ratio of unburned iso-butanol to ethanol remains almost constant regardless of operating point. 1,3-Butadiene emissions increase significantly with oxygenate addition to the fuel regardless of engine load conditions with no apparent differences between ethanol and butanol. These results contradict other studies performed on automotive engines at stoichiometric conditions where no increase in 1,3-Butadiene emissions was observed with addition of ethanol or butanol [7,8,25]. Neither ethanol nor iso-butanol oxidation mechanisms offer a direct path for the formation of significant amounts of 1,3-Butadiene [27,28]. Therefore the increased formation of

1,3-Butadiene has to be attributable to changes in air/fuel ratio. This conclusion is also supported by findings of Russ et al. [29] reporting a significant increase in 1,3-Butadiene contribution to the total HC emissions with increasing air/fuel ratio.

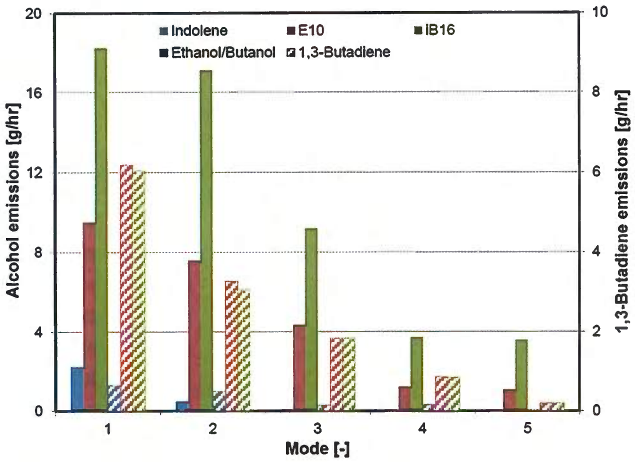

Figure 14. Alcohol and 1,3-Butadiene emissions in 5-mode steady-state operation

Figure 15 compares the aldehyde emissions for indolene, E10 and iB16 as a function of engine operating mode. The data suggests an increase in both, acetaldehyde as well as formaldehyde emissions, with addition of oxygenated fuel. The trends are similar regardless of alcohol type with a slightly higher increase of formaldehyde emissions with iB16 and acetaldehyde emissions with E10. While the increase in acetaldehyde is consistent, although not as pronounced as expected, compared to literature data for automotive engines in stoichiometric operation, the increase in formaldehyde with ethanol addition contradicts literature data [7,8]. However, as previously noted, the majority of the data available in the literature was collected at stoichiometric conditions. One study evaluating the influence of air/fuel ratio on spark ignition engine emissions concluded that formaldehyde emissions peak at stoichiometric conditions for gasoline as well as E20. Further, leaner air/fuel ratios were found to have little influence on acetaldehyde emissions in gasoline operation but resulted in significant reduction for E20 [30]. Thus the effects seen here represent a combination of competing trends. Formaldehyde emissions, expected to be independent of alcohol content, increase for E10 (and likely also for iB16) due to the operation closer to stoichiometric conditions. Acetaldehyde emissions are expected to increase significantly with increased oxygen content; however, the engine operation closer to stoichiometric conditions with the oxygenated fuels actually counteracts this effect.

The resulting 5-mode weighted specific alcohol, 1,3-Butadiene and aldehyde emissions are shown in Figure 16. The increase in unburned alcohol emissions is expected due to increased content in the fuel. Both, ethanol and iso-butanol addition also resulted in an increase in 1,3-Butadiene and aldehyde emissions.

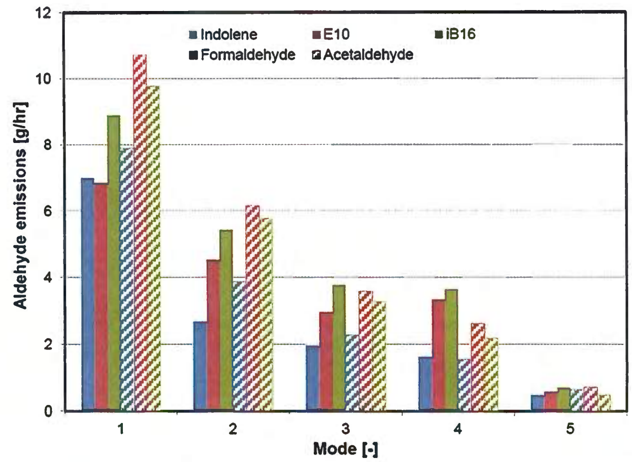

Figure 15. Comparison of aldehyde emissions in 5-mode steady-state operation

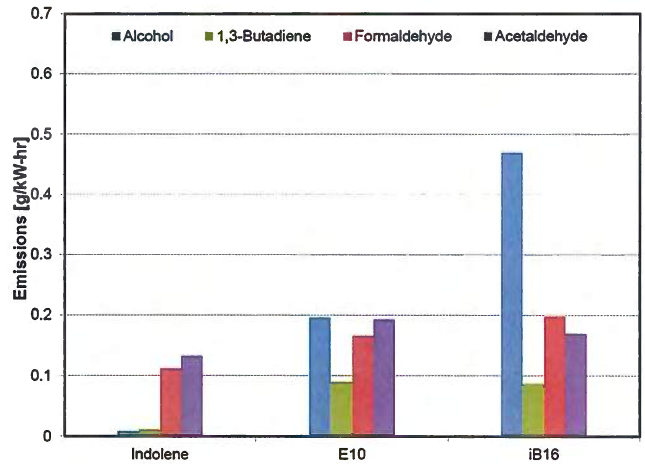

Figure 16. Comparison of 5-mode weighted speciated hydrocarbon emissions

Summary and Conclusions

Iso-Butanol at a blend level of 16 vol% (iB16), which is identical in oxygen content to a 10 vol% ethanol blend (E10), was evaluated for recreational marine engine applications. A test sequence using indolene, E10 and iB16 that included full load operation as well as the 5-mode steady-state marine test cycle was completed. The data generated during these steady-state tests supports the following conclusions:

- Operation with iB16 results in equivalent full load performance compared to E10 and indolene while both oxygenated blends exhibit approximately 15-20°C higher exhaust temperatures compared to the reference fuel
- Brake thermal efficiency increases by 2.5-3% points with the alcohol blends compared to gasoline
- While greenhouse gas emissions are generally comparable, a marginal increase in CO_2 emissions as well as a decrease in N_2O emissions at high loads is observed with the alcohol blends

- $HC+NO_x$ emissions tend to increase with oxygenated fuels while CO emissions show a significant reduction
- Unburned alcohol emissions as well as 1,3-Butadiene, formaldehyde and acetaldehyde emissions increased with E10 and iB16 compared to indolene

A majority of the observed trends is directly attributable to changes in air/fuel ratio with fuel oxygen content since the engine does not utilize a closed loop air/fuel ratio feedback control. Without compensation the reduced energy content of the oxygenated fuels results in engine operation closer to stoichiometric conditions compared to indolene. Given these observations as well as published results of studies on automotive engines it is likely that emissions characteristics of marine engines operating on E10 or iB16 would be closer to the indolene baseline if a closed loop air/fuel ratio feedback control was employed. While this would likely also result in exhaust temperatures with E10 and iB16 closer to those of indolene the presented efficiency advantages were likely to diminish if the engine was operated at similar air/fuel ratios regardless of fuel.

The presented data suggests that iso-butanol can be used at higher blend levels than ethanol without deterioration of engine performance or emissions characteristics. The presented results are the baseline for ongoing durability tests to be performed over the useful life of this recreational marine engine. Detailed efficiency and emissions analysis combined with a complete engine teardown will determine whether operation with oxygenate blends and the resulting increased exhaust gas temperatures have negative effects over the 350 hr durability runs. The presented results and ongoing efforts are part of a larger program that is comprised of efficiency, emissions and durability testing on a range of recreational marine engines with complimentary work on effects of alcohol addition on lubrication and wear [13].

References

1. Foster, H., Baron, R., Bernstein, P., Impact of the Blend Wall Constraint in Complying with the Renewable Fuel Standard, Report for the American Petroleum Institute, 2011
2. Environmental Protection Agency, "Final Rule of the Second Partial Waiver under the Clean Air Act," Jan. 2011.
3. U.S. GAO. Biofuels: Challenges to the Transportation, Sale, and Use of Intermediate Ethanol Blends; U.S. Government Accountability Office, Natural Resources and Environment: Washington, DC, 2011; pp 1-57.
4. National Automobile Dealers Association (NADA), NADA Data State of the Industry Report. 2013.
5. National Marine Manufacturers Association (NMMA), 2012 Recreational Boating Statistical Abstract. 2013.
6. Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., "In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels," SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.
7. Ratcliff M, Luecke J, Williams A, Christensen E, Yanowitz J, Reek A, McCormick R, Impact of Higher Alcohols Blended in Gasoline on Light-Duty Vehicle Exhaust Emissions, Environ. Sci. Technol., 2013, doi:10.1021/es402793p.
8. Zhang, F., Wang, J., Tian, D., Wang, J. et al., "Research on Unregulated Emissions from an Alcohols-Gasoline Blend Vehicle Using FTIR, HPLC and GC-MS Measuring Methods," *SAE Int. J. Engines* 6(2):1126-1137, 2013, doi:10.4271/2013-01-1345.
9. Wallner T, Miers SA, McConnell S. A Comparison of Ethanol and Butanol as Oxygenates Using a Direct-Injection, Spark-Ignition Engine. J. Eng. Gas Turbines Power. 2009;131(3):032802-032802-9. doi:10.1115/1.3043810.
10. Hilbert, D., "High Ethanol Fuel Endurance: A Study of the Effects of Running Gasoline with 15% Ethanol Concentration in Current Production Outboard Four-Stroke Engines and Conventional Two-Stroke Outboard Marine Engines." Report NREL/SR-5400-52909. 2011.
11. Zoubul, G., Cahoon, M., Kolb, R., "Volvo Penta 4.3 GL E15 Emissions and Durability Test." Report NREL/SR-5400-52577. 2011.
12. Wasil, J., Johnson, J., and Singh, R., "Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine," *SAE Int. J. Fuels Lubr.* 3(2):1071-1080, 2010, doi:10.4271/2010-32-0054.
13. Wallner, T. Ickes, A. Ajayi, O. Wasil, J. Emissions and Operability of Gasoline, Ethanol, and Butanol Fuel Blends in Recreational Marine Applications. US DOE Energy Efficiency and Renewable Energy Vehicle Technologies Office FY 2012 Progress Report for Fuel & Lubricant Technologies. Report DOE/EE-0911. 2013.
14. Wasil, J., Johnson, J., and Singh, R., "Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine," *SAE Int. J. Fuels Lubr.* 3(2):1071-1080, 2010, doi:10.4271/2010-32-0054.
15. Baustian, J. and Wolf, L., "Cold-Start/Warm-Up Vehicle Performance and Driveability Index for Gasolines Containing Isobutanol," *SAE Int. J. Fuels Lubr.* 5(3):1300-1309, 2012, doi:10.4271/2012-01-1741.
16. Stansfield, P., Bisordi, A., OudeNijeweme, D., Williams, J. et al., "The Performance of a Modern Vehicle on a Variety of Alcohol-Gasoline Fuel Blends," *SAE Int. J. Fuels Lubr.* 5(2):813-822, 2012, doi:10.4271/2012-01-1272.
17. Andersen, V. F.; Anderson, J. E.; Wallington, T. J.; Mueller, S. A.; Nielsen, O. J. Vapor Pressure of Alcohol-Gasoline Blends. Energy Fuels 2010, 24 (6), 3647-3654. doi:10.1021/ef100254w.
18. Lawyer, K., Ickes, A., Wallner, T., Ertl, D. et al., "Blend Ratio Optimization of Fuels Containing Gasoline Blendstock, Ethanol, and Higher Alcohols (C3-C6): Part I - Methodology and Scenario Definition," SAE Technical Paper 2013-01-1144, 2013, doi:10.4271/2013-01-1144.
19. 40 CFR PART 1065-ENGINE-TESTING PROCEDURES Subpart I-Testing With Oxygenated Fuels

20. 40 CFR PART 1045-CONTROL OF EMISSIONS FROM SPARK-IGNITION PROPULSION MARINE ENGINES AND VESSELS Appendix II to Part 1045-Duty Cycles for Propulsion Marine Engines
21. U.S. EPA "CLIMATE LEADERS GREENHOUSE GAS INVENTORY PROTOCOL. Design Principles."2005.
22. Degobert, P. Automobiles and Pollution. Editions Technip, Paris. 1992. ISBN 2-7108-0628-2.
23. Lipman, T.E., Delucchi M.A. Emissions of Nitrous Oxide and Methane from Conventional and Alternative Fuel Motor Vehicles. Climatic Change June 2002, Volume 53, Issue 4, pp 477-516.
24. Santos Antonio Carlos (2012). The Blend Ethanol/Gasoline and Emission of Gases, Greenhouse Gases -Emission, Measurement and Management, DrLiu Guoxiang (Ed.), ISBN: 978-953-51-0323-3.
25. Wallner, T. and Frazee, R., "Study of Regulated and Non-Regulated Emissions from Combustion of Gasoline, Alcohol Fuels and their Blends in a DI-SI Engine," SAE Technical Paper 2010-01-1571, 2010, doi:10.4271/2010-01-1571.
26. Wallner, T.: 'Correlation between Speciated Hydrocarbon Emissions and FID Response for Blends of Gasoline with Ethanol and Butanol.' Journal of Engineering for Gas Turbines and Power. Vol. 133, Issue 8. 2011. doi:10.1115/ICEF2010-35031.
27. Marinov, N. M. (1999), A detailed chemical kinetic model for high temperature ethanol oxidation. Int. J. Chem. Kinet., 31: 183-220. doi:10.1002/(SICI)1097-4601(1999)31:3<183::AID-KIN3>3.0.CO;2-X.
28. Sarathy, S. M. Vranckx, S. Yasunaga, K. Mehl, M. Oßwald P., Metcalfe W. K., Westbrook C. K., Pitz W. J., Kohse-Höinghaus K., Fernandes R. X. and Curran, H. J. "A comprehensive chemical kinetic combustion model for the four butanol isomers," Combust. Flame 159 (6) (2012) 2028-2055.
29. Russ, S., Kaiser, E., Siegl, W., Podsiadlik, D. et al., "The Effect of Air/Fuel Ratio on Wide Open Throttle HC Emissions from a Spark-Ignition Engine," SAE Technical Paper 941961, 1994, doi:10.4271/941961.
30. Zervas, E., Montagne, X., Lahaye, J., "Emission of alcohols and carbonyl compounds from a spark ignition engine: influence of fuel and air/ fuel equivalence ratio," Environ. Sci. Technol., 2002, 36(11): 2414-2421, doi:10.1021/es010265t.

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Definitions/Abbreviations

AFR_{ST} - Stoichiometric air/fuel ratio

BSFC - Brake specific fuel consumption

BSVFC - Brake specific volumetric fuel consumption

BTE - Brake thermal efficiency

CFR - Code of Federal Regulations

CH_4 - Methane

CO - Carbon monoxide

CO_2 - Carbon dioxide

CO_{2e} - Equivalent carbon dioxide

DOHC - Dual Overhead Cam

E10 - 10 vol% blend of ethanol in gasoline

E15 - 15 vol% blend of ethanol in gasoline

EFI - Electronic Fuel Injection

FID - Flame Ionization Detector

FTIR - Fourier Transformed Infrared

GWP - Global Warming Potential

iB16 - 16 vol% blend of iso-butanol in gasoline

LHV - Lower Heating Value

MON - Motor Octane Number

MY - Model year

N_2O - Nitrous oxide

NO_x - Oxides of nitrogen

NTE - Not-to-exceed

O_2 - Oxygen

OH - Hydroxyl group

P - Power

RON - Research Octane Number

RVP - Reid Vapor Pressure

THC - Total hydrocarbon

WOT - Wide Open Throttle

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Gaseous and Particulate Emissions Using Isobutanol-Extended Fuel in Recreational Marine Two-Stroke and Four-Stroke Engines

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ABSTRACT

Biologically derived isobutanol, a four carbon alcohol, has an energy density closer to that of gasoline and has potential to increase biofuel quantities beyond the current ethanol blend wall. When blended at 16 vol% (iB16), it has identical energy and oxygen content of 10 vol% ethanol (E10).

Engine dynamometer emissions tests were conducted on two open-loop electronic fuel-injected marine outboard engines of both two-stroke and four-stroke designs using indolene certification fuel (non-oxygenated), iB16 and E10 fuels. Total particulate emissions were quantified using Sohxlet extraction to determine the amount of elemental and organic carbon. Data indicates a reduction in overall total particulate matter relative to indolene certification fuel with similar trends between iB16 and E10. Gaseous and PM emissions suggest that iB16, relative to E10, could be promising for increasing the use of renewable fuels in recreational marine engines and fuel systems.

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INTRODUCTION

Ethanol, as an E10 blend, has been the primary alternative fuel in use in the United States due in part to cost effective fermentation and production processes, government subsidies, and congressionally mandated usage volumes. Additionally, local production of biologically derived feed-stocks for ethanol production may reduce reliance on fossil fuels [1].

The congressionally mandated Renewable Fuels Standard has established targets for the quantity of alternative fuel produced each year in the U.S, and requires 36 billion gallons by the year 2022 [2]. At the same time, consumption of finished gasoline has continued to decline since 2007, leading to a barrier known as the blend wall.

Recognizing the impending barrier, which would effectively limit the amount of ethanol production beyond E10, a waiver request for E15 was submitted to the U.S Environmental Protection Agency (EPA). In 2010, EPA approved the first of two partial waiver requests allowing for the use of E15 in model year 2007 and newer passenger vehicles, followed by a second partial waiver for model year 2001 - 2006 passenger vehicles [3]. However, E15 is not a direct replacement for gasoline, and several issues with respect to compatibility with engines, fuel system components and the potential for misfueling have limited the large scale introduction of E15 into the marketplace [4].

To that end, ethanol-extended fuels, particularly fuels with greater than 10 vol% ethanol, create a number of concerns for recreational marine engines and boat fuel systems. Outboard engines, on average, are used approximately 35 hours per year and are operated on a very aggressive duty cycle compared to automotive engines [5]. Most built-in boat fuel tanks are vented directly to the atmosphere which allows for moisture to enter the fuel system during daily diurnal temperature changes. The environment in which the engines are operated means it is more likely for water or salt water to enter the fuel system. Moreover, the long storage periods, particularly in northern climates, result in a greater chance for ethanol extended fuels to phase-separate.

The way in which recreational marine engines are operated and stored during the off season creates an ideal harsh testing environment for verifying the performance of alternative fuels.

With increased energy density, isobutanol has the potential of moving beyond the blend wall as it can be blended at 16 vol% while maintaining equivalent oxygen content of E10 fuels. A number of laboratory and field studies using iB16 in recreational marine engines indicate similar gaseous exhaust emissions and engine performance compared to E10 blends [6,7]. The purpose of this study, which is a continuation of ongoing research on isobutanol, is to quantify particulate emissions from open-loop recreational marine engines and differentiate between ethanol and isobutanol extended fuels.

TEST ENGINES

Two outboard engines were selected for particulate and gaseous emissions testing which include a direct fuel injection two-stroke and electronic fuel injection four-stroke. The test engines were selected because they represent two very different engine technologies that are commonly used to propel recreational boats. Both engines are certified to the California Air Resources Board (CARB) ultra-low emissions standards (three-star) and meet the applicable EPA standards for engine model year 2014. The engines operate open-loop, meaning there are no combustion feed-back sensors to compensate for the change in air/fuel ratio required by the test fuel. The specifications for both engines are indicated in Table 1.

No changes or modifications to the base engine calibration, spark timing or injection timing were made at any time during the testing process.

Table 1. Engine Specifications

Engine type	Mercury 90 Horsepower, 4 Stroke	Evinrude 90 Horsepower, 2 Stroke
Propeller power [HP/kW]	90/67	90/67
Maximum engine speed [RPM]	5000-6000	4500-5500
Cylinder/Configuration	In-line 4, 16-valve, direct acting dual, overhead cam (DOHC)	In-line 3 cylinder
Displacement [CID, cc]	105.7/1732	79 /1295 cc
Bore/Stroke [mm]	82/82	91/66
Cooling System	Water-cooled w/thermostat	Water-cooled w/thermostat
Ignition System	Inductive Coil on Plug	Inductive
Gear Ratio	2.33:1	2.00:1
Exhaust System	Through prop	Through prop
Lubrication System	Integrated dry sump	Integrated oil tank
Fuel Induction System	Computer controlled sequential multi-port Electronic Fuel	Spray-guided stratified direct fuel injection
Recommended fuel	87 octane/up to 10 vol% ethanol	87 octane/up to 10 vol% ethanol
Dry Weight [kg]	181	145

GENERAL TEST SET-UP

Measurement of particulate emissions from recreational marine outboard engines presents a number of challenges with respect to the handling of wet engine exhaust. As shown in Figure 1, a complete outboard engine is mounted in a test tank with a direct connection from the engine propeller shaft to the engine dynamometer. The tank is filled with water to a predetermined level to keep the gear-case cool and provide appropriate back-pressure on the engine exhaust system. An outboard engine uses surrounding lake water for engine cooling, and exhaust is routed through the center of the propeller hub for noise attenuation purposes. A certain percentage of engine cooling water is dumped into the midsection of the engine exhaust runner in an effort to lower exhaust temperature prior to exiting the engine through the propeller hub. Particulate samples must therefore be taken at the base of the power head, before water is mixed with the engine exhaust.

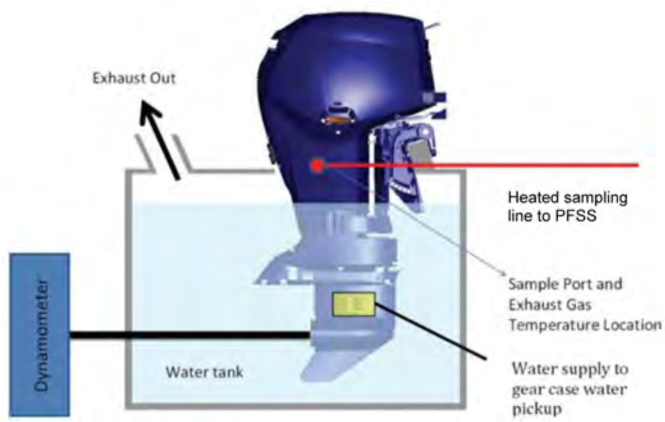


Figure 1. Typical outboard engine dynamometer test cell set-up schematic

Gaseous emissions (HC, NO_x, CO, CO_2, O_2) were measured at the base of the power head using an AVL i60 five-gas emissions bench. The bench utilizes a heated flame ionization detector (FID) for total hydrocarbons, heated chemiluminescence detector (CLD) for oxides of nitrogen, non dispersive infrared (NDIR) for CO and CO_2 and a paramagnetic detector for O_2. A heated sampling line connects the engine exhaust sampling probe to the emissions bench. The heated line is maintained at 185°C.

A Froude AG-150 eddy-current dynamometer is used to load the engine during the testing process. A Tescom water pressure controller is used to vary the engine cooling water pressure to what is typically expected at the gear case water pick-up location while the boat/engine is underway.

Engine fuel flow was measured with a Pierburg 60 LPH volumetric flow system using a density sensor to arrive at fuel consumption in grams per hour. An AVL Bobcat data acquisition system recorded test cell data at a frequency of 1 Hz. Test cell temperature and humidity are controlled to 23°C and 35% ±5%, respectively.

The engine is tested according to the International Council of Marine Industry Associations (ICOMIA) / EPA CFR 40 part 1045 steady state test cycle as shown in Table 2 [8]. All subsequent gaseous and particulate test results reflect a weighted total average based on specific output in grams per kiloWatt-hour (g/kW-hr).

The specifications for the fuels used throughout the testing program are indicated in Table 3. Ethanol and butanol were blended with blendstock for oxygenate blending (BOB) rather than indolene to achieve fuel properties that are similar to fuels currently used in the field. Isobutanol was blended to achieve equivalent oxygen content to a 10 vol% gasoline/ethanol blend (E10). The resulting blend level is 16 vol% isobutanol (iB16) at an oxygen content of 4 wt%. The oxygen content in the fuel also impacts the stoichiometric air demand, AFRST, which is approximately 13.8 for E10 and iB16 compared to 14.6 for indolene, as well as the energy content. The resulting lower heating value of the alcohol blends is approximately 29.5 MJ/L compared to 32 MJ/L for indolene. These changes in properties are particularly relevant since the test engines, like most recreational marine engines, do not employ a closed loop engine feedback control. Reid Vapor Pressure (RVP) of the E10 blend is almost as high as indolene compared to the lower RVP of iB16. These changes are attributable to the azeotropic behavior of ethanol blends, which are not exhibited with butanol [9]. Both neat ethanol and iso-butanol have octane ratings significantly higher than gasoline [10]. Research Octane Number (RON) and Motor Octane Number (MON) of the blends are slightly lower than indolene due to the low RON and MON of the BOB used for blending compared to indolene.

Table 2. 5-mode steady-state marine test cycle [8]

Mode	% RPM	% Torque	% Weight Factor
1	100	100	6
2	80	71.6	14
3	60	46.5	15
4	40	25	25
5	Idle	0	40

Table 3. Fuel Specifications

			indolene EEE	E10	iB16
Density	ASTM D4052	kg/L	0.743	0.7397	0.7489
RVP	ASTM D5191	psi	9.1	8.81	7.97
Carbon	ASTM E191	wt%	86.31	82.916	83
Hydrogen	ASTM E191	wt%	13.34	13.094	12.998
Oxygen		wt%	0	3.99	4.002
H/C ratio	ASTM E191	mole/mole	1.841	1.895	1.879
O/C ratio		mole/mole	0	0.036	0.036
AFR_{ST}			14.571	13.856	13.832
RON	ASTM D2699		96.6	94.0	94.7
MON	ASTM D2699		88.7	85.4	83.8
LHV	ASTM D240	MJ/kg	43.01	39.75	39.54
LHV		MJ/L	31.96	29.40	29.61

PARTICULATE MEASUREMENT

Total mass particulate matter was determined gravimetrically using a partial flow sampling system (PFSS) to collect an exhaust emissions sample from the base of the engine power head. The system consists of a 90mm dilution tunnel, heated and conditioned dilution air, vacuum pump, bellows meter, sample valves and sample timer. Based on previous test experiments, NO_x is used to determine dilution ratios of the sample system. A schematic of the dilution tunnel is shown in Figure 2, and the full system is further explained in detail in previous publications [11,12].

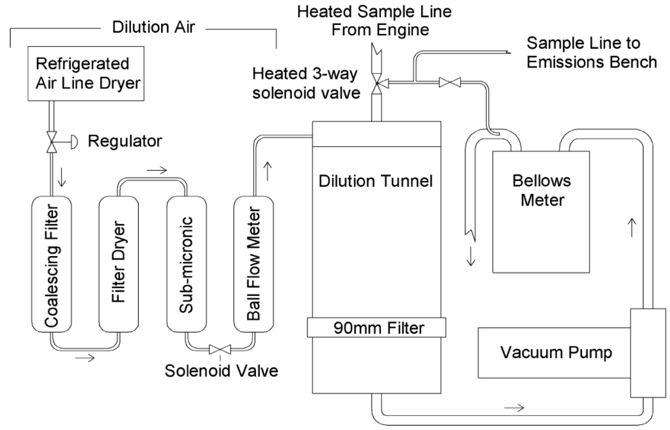


Figure 2. Partial flow dilution tunnel flow diagram

Figure 3. Constant temperature/constant humidity glove box - the scale sits atop a granite seismic mass table.

90mm Pall Emfab™ Teflon® glass fiber filters were stabilized in a constant temperature/ constant humidity glove box as shown in Figure 3 prior to initial weighing, and stabilized for two hours prior to final weighing. An Ainsworth M-220D scale with measurement resolution of 0.00001 gram was used to determine particulate filter mass. A weighted composite particulate sample (five modes on one filter) was collected by varying the sample time of the partial flow sampling system to match the five-mode ICOMIA weighted test cycle (EPA CFR 40 part 1045). Two filters were collected for each test fuel, and the average of the two filters used to determine overall total mass PM. Individual PM filters were also collected for each test mode so that total PM mass could be determined per mode.

Repeatability of the composite particulate filter measurement method is shown in Figure 4. As indicated, the repeatability is generally within about 10% between composite filter 1 and composite filter 2. The average of filter sample 1 and 2 is reported throughout the test program. Tests were conducted back-to-back on the same day to minimize changes in engine operating parameters due to barometric pressure and test cell conditions.

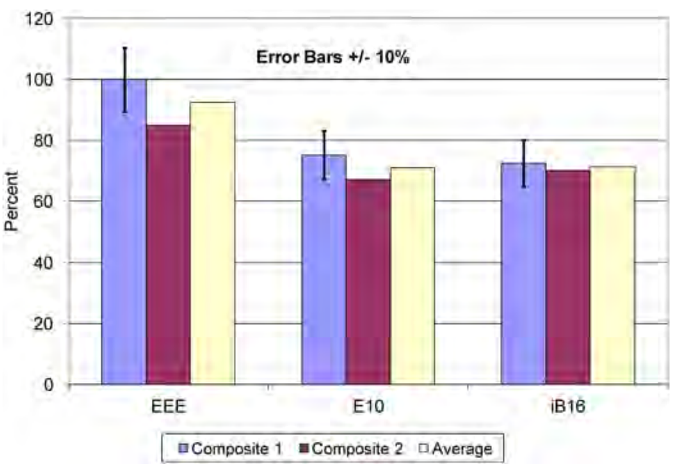


Figure 4. Total particulate matter composite filter method repeatability

After final weighing, each individual filter was carefully folded into a cone and inserted in a thimble filter for Sohxlet extraction using methylene chloride as shown in Figure 5. Each filter was extracted for 24 hours. After extraction, the filter was carefully removed from the thimble, placed into a glass Petri dish and then placed into the constant temperature/ constant humidity glove box. After 6 hours, the filter was reweighed to determine the amount of organic and elemental carbon. Several experiments were conducted using blank filters to determine the change in filter weight due to handling and extraction. In addition, the extraction process followed the recommendations from a previous study [13]. The average filter weight change from handling was then accounted for in the final particulate weight by using a correction factor.

RESULTS

The results for engine exhaust particulate matter including elemental carbon, organic carbon and total mass particulate matter relative to baseline indolene EEE test fuel are shown in Figure 6. Both engines exhibited similar results in terms of increased elemental carbon, decreased organic carbon and decreased total mass particulate matter using the alcohol-extended fuels.

The aforementioned results for weighted total PM are consistent with published data on closed-loop automotive engines operating on increasing amounts of ethanol [14,15]. However, the trends for increased elemental carbon are somewhat contrary to published data. This may be due to the lack of closed-loop engine control and changes in overall air/fuel ratio as a result of the enleanment effects of the fuel.

Figure 5. Sohxlet extraction using methylene chloride

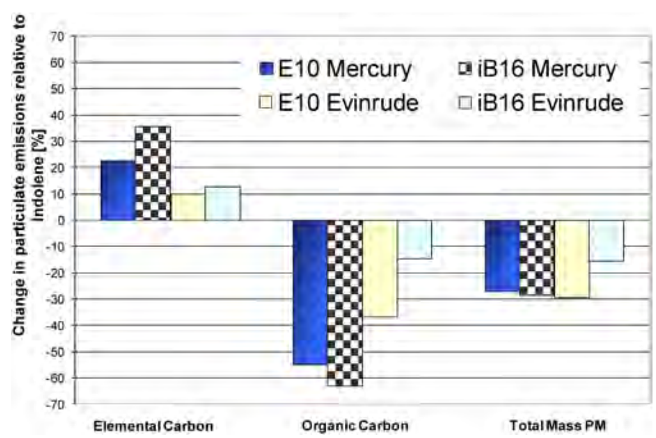


Figure 6. Five-mode weighted elemental carbon, organic carbon and total mass PM emissions relative to indolene (% change)

The average percent change in mass total particulate relative to indolene per test mode is shown in Figure 7. As indicated, the two-stroke DI Evinrude engine resulted in over a 50% reduction in mass PM at modes 2 and 3 on the alcohol fuels which is approximately two times the reduction seen with the four stroke Mercury engine at these modes. The emissions control strategy used for the Evinrude engine reduces gaseous emissions at modes 2 and 3 by retarding the ignition timing and injection timing in order to increase post-oxidation. Therefore the post-oxidation effects lead to improved reduction in mass PM on the alcohol blended fuels. Moreover, previous studies on DI two-stroke engines have shown a sharp reduction in mass PM with retarded fuel injection [16]. It is important to note that total particulate matter increased at idle in both engines and does not follow general trends of reduced particulate mass with alcohol fuels. However, one study did identify increased particle number (PN) at idle using E10 compared to the baseline indolene test fuel, although the high variation in test data leads to some uncertainty in the results [17]. Nonetheless, more research would be required to fully understand and quantify the increase in idle PM rates.

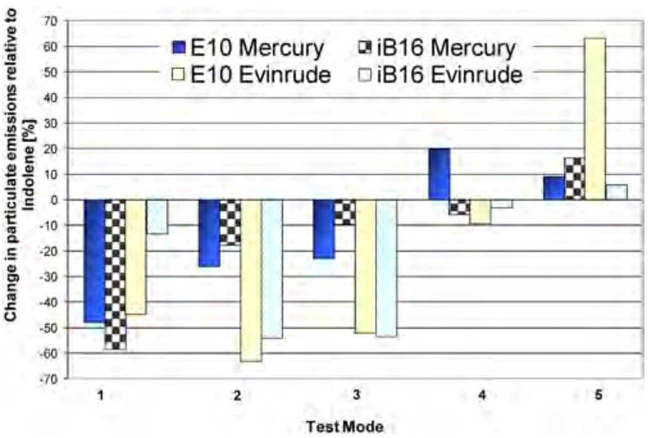


Figure 7. Total particulate matter per test mode relative to indolene EEE (% change)

Gaseous emissions results for both engines relative to baseline indolene EEE test fuel are shown in Figure 8. Both engines resulted in an average increase in HC+NOx emissions of approximately 14% compared to the baseline indolene EEE certification fuel. The average percent reduction in CO for E10 and iB16 is 27% and 20% respectively. For marine engines, the EPA specifies a non-oxygenated certification fuel. Therefore both engines are certified on indolene EEE fuel and the emissions results (increase in HC+NOx) from alcohol-extended fuels would be accounted for in EPA Not-To-Exceed zones (NTE) and would not exceed the EPA emissions standards. Both engines remained comfortably under the EPA emissions standards on E10 and iB16 fuels.

Average brake thermal efficiency (BTE) per mode is shown in Figure 9. E10 and iB16 fuels show a 2.5% point improvement over the baseline indolene EEE certification fuel. The alcohol-extended fuels contain approximately 8% less energy compared to the indolene EEE certification fuel. However, the 10% increase in BTE of the engine offsets the reduction in energy content of the fuel. Again, the engines do not utilize any form of combustion feed-back sensors. Therefore, less fuel energy is being injected for the same commanded injected quantity. The increase in CO_2 emissions also indicates an inherent improvement in engine efficiency using the E10 and iB16 test fuels.

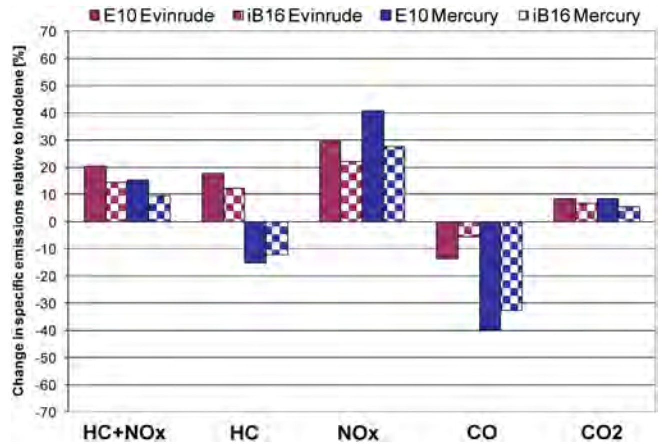


Figure 8. Five-mode weighted gaseous emissions relative to indolene (% change)

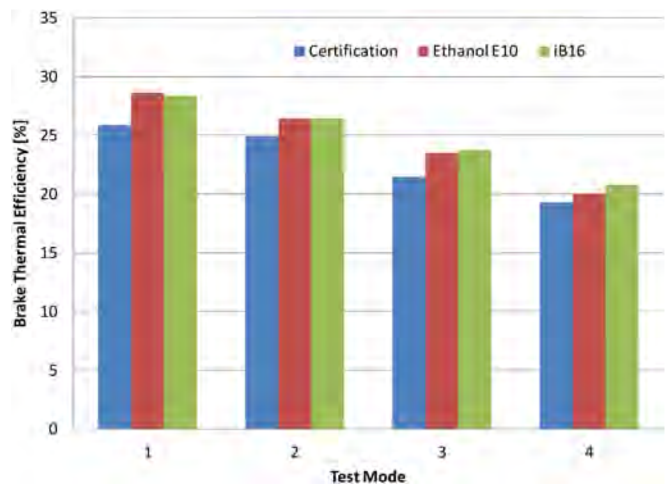


Figure 9. Average Brake Thermal Efficiency (BTE) at propeller shaft per test mode

Lambda air/fuel ratio for the Mercury and Evinrude engine is shown in Figure 10 and 11 respectively. As indicated, the alcohol-extended fuels resulted in similar enleanment. The Evinrude operates in a fully stratified mode at idle which explains the global lambda air/fuel ratio of approximately 7.5.

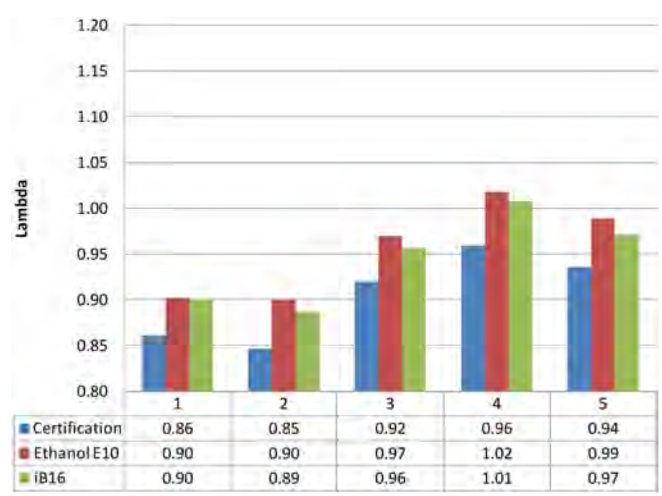
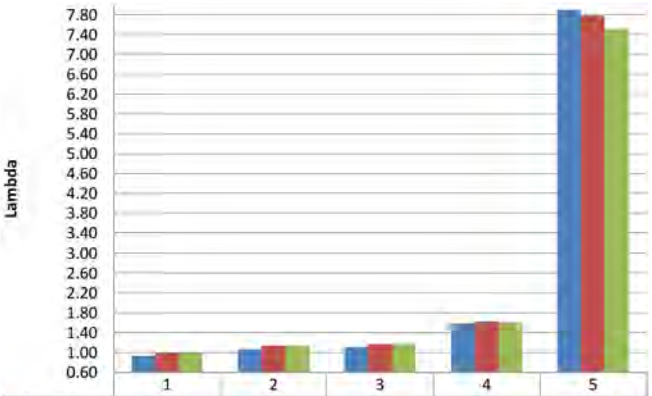


Figure 10. Mercury lambda air/fuel ratio per mode



	1	2	3	4	5
Certification	0.93	1.06	1.11	1.59	7.90
Ethanol E10	0.99	1.14	1.18	1.63	7.78
iB16	0.99	1.14	1.17	1.62	7.51

Figure 11. Evinrude lambda air/fuel ratio per mode

CONCLUSION

Engine exhaust particulate matter and gaseous emissions were quantified using isobutanol at 16 vol% (iB16) and ethanol at 10 vol% (E10). The results were then compared to a non-oxygenated indolene EEE certification test fuel. A partial flow sampling system and gravimetric method were used to determine total mass particulate matter. PM filters were then extracted using methylene chloride so that elemental carbon and organic carbon could be quantified.

Two 90 HP (67 kW) recreational marine outboard engines representing both two-stroke direct fuel injection and four-stroke electronic fuel injection were used in the test program. Both engines operate open-loop and do not utilize any form of combustion feed-back sensor. The results support the following:

- Addition of alcohol reduces weighted total PM mass emissions by 15 to 30% due to a significant reduction in organic carbon emissions accompanied by a moderate increase in elemental carbon emissions
- Mass particulate matter at modes 2 and 3 for the two-stroke DFI engine resulted in approximately two times the reduction in mass PM with both E10 and iB16 compared to the four-stroke EFI engine due to post-oxidation strategies at these test modes
- Both engines' mass PM increased slightly at Idle on E10 and iB16 fuels relative to the baseline indolene EEE certification fuel
- HC+NOx emissions tend to increase with oxygenated fuels while CO emissions show a significant reduction for the four-stroke EFI engine and a moderate reduction for the two-stroke DFI engine.
- Brake thermal efficiency increases by an average of 2.5% points with the alcohol blends compared to indolene EEE certification fuel
- The addition of alcohol to the fuels moved lambda air/fuel ratios closer to stoichiometry which is the main reason for improved engine efficiency
- No significant change in emissions between E10 and iB16 fuel was observed during the testing

The observed trends are most likely attributed to changes in air-fuel ratio (AFR) as both engines cannot compensate for the specific AFR required for oxygenated and non-oxygenated fuels.

The data suggests that isobutanol blended at 16 vol% can be used in recreational marine engines without significantly affecting particulate matter or gaseous exhaust emissions output in comparison to available E10 fuels. The higher quantity of biologically derived isobutanol in the fuel will help to move beyond the current ethanol blend wall without affecting gaseous or particulate emissions from marine engines.

REFERENCES

1. Hammerschlag, R., Ethanol's Energy Return on Investment: A Survey of the Literature 1990 Present Eniron. Sci. Technology 2006, vol 40,1744-1750
2. Energy Independence and Security Act of 2007 (EISA) EPA 40 CFR Part 80 Regulation of Fuels and Fuel Additives - Renewable Fuels Standard (RFS-II) Published March 26, 2010
3. Environmental Protection Agency, “Final Rule of the Second Partial Waiver under the Clean Air Act,” Jan. 2011.
4. Foster, H.; Baron, R.; Bernstein, P., Impact of the Blend Wall Constraint in Complying with the Renewable Fuel Standard, Report for the American Petroleum Institute, 2011
5. Wasil, J.; McKnight, J.; Kolb, R.; Munz, D. et al., “In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels,” SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.
6. Wasil, J.; Johnson, J.; and Singh, R., “Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine,” SAE Int. J. Fuels Lubr. 3(2):1071-1080, 2010, doi:10.4271/2010-32-0054.
7. Wallner, T. Ickes, A. Ajayi, O. Wasil, J. Emissions and Operability of Gasoline, Ethanol, and Butanol Fuel Blends in Recreational Marine Applications. US DOE Energy Efficiency and Renewable Energy Vehicle Technologies Office FY 2012 Progress Report for Fuel & Lubricant Technologies. Report DOE/EE-0911. 2013.
8. 40 CFR PART 1045-CONTROL OF EMISSIONS FROM SPARK-IGNITION PROPULSION MARINE ENGINES AND VESSELS Appendix II to Part 1045-Duty Cycles for Propulsion Marine Engines
9. Andersen, V. F.; Anderson, J. E.; Wallington, T. J.; Mueller, S. A.; Nielsen, O. J. Vapor Pressure of Alcohol-Gasoline Blends. Energy Fuels 2010, 24 (6), 3647-3654. doi:10.1021/ef100254w.
10. Lawyer, K.; Ickes, A.; Wallner, T.; Ertl, D. et al., “Blend Ratio Optimization of Fuels Containing Gasoline Blendstock, Ethanol, and Higher Alcohols (C3-C6): Part I - Methodology and Scenario Definition,” SAE Technical Paper 2013-01-1144, 2013, doi:10.4271/2013-01-1144.
11. Wasil, J. and Montgomery, D., “A Method to Determine Total PM Emissions from Marine Outboard Engines,” SAE Technical Paper 2003-32-0049, 2003, doi:10.4271/2003-32-0049.
12. Wasil, J.; Montgomery, D.; Strauss, S.; and Bagley, S., “Life Assessment of PM, Gaseous Emissions, and Oil Usage in Modern Marine Outboard Engines,” SAE Technical Paper 2004-32-0092, 2004, doi:10.4271/2004-32-0092.
13. Shimpi, S. and Yu, M., “Determination of a Reliable and Efficient Diesel Particulate Hydrocarbon Extraction Process,” SAE Technical Paper 811183, 1981, doi:10.4271/811183.
14. Storey, J.; Barone, T.; Norman, K.; Lewis, S., “Ethanol Blend Effects On Direct Injection Spark-Ignition Gasoline Vehicle Particulate Matter Emissions” SAE Technical Paper 2010-01-2129, 2010.
15. Dutcher, D.; Stolzenburg, M.; Thompson, S.; Medrano, J., et al., “Emissions from Ethanol-Gasoline Blends: A Single Particle Perspective” Atmosphere 2011, 2, 182-200; doi:10.3390/atmos2020182.

16. Cromas, J., "Particulate Matter Formation Mechanisms in a Direct-Injection Gasoline Engine" Master's Thesis University of Wisconsin - Madison, 2003.
17. He, X.; Ireland, J.; Ziglen, B.; Ratcliff, M, et al "Impacts of mid-level biofuel content in gasoline on SIDI engine-out and tailpipe particulate matter emissions" National Renewable Energy Laboratory Report NREL/CP-5400-49311 February 2011

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DEFINITIONS/ABBREVIATIONS

AFR_{ST} - Stoichiometric air/fuel ratio

BTE - Brake thermal efficiency

CARB - California air resources board

CFR - Code of Federal Regulations

CO - Carbon monoxide

CO_2 - Carbon dioxide

DOHC - Dual Overhead Cam

DFI - Direct fuel injection

E10 - 10 vol% blend of ethanol in gasoline

E15 - 15 vol% blend of ethanol in gasoline

EFI - Electronic Fuel Injection

FID - Flame Ionization Detector

iB16 - 16 vol% blend of iso-butanol in gasoline

Indolene EEE - Indolene certification fuel clear

LHV - Lower Heating Value

MON - Motor Octane Number

MY - Model year

NO_x - Oxides of nitrogen

NTE - Not-to-exceed zone

O_2 - Oxygen

PFSS - Partial flow sampling system

RON - Research Octane Number

RVP - Reid Vapor Pressure

THC - Total hydrocarbon

 BY RYCK LYDECKER

ALCOHOL & BOAT ENGINES, IS THERE ANOTHER WAY?

Federal law says the nation must increase its "biofuel" capacity dramatically in the next decade, but does it have to be ethanol?

A veteran Mako 19 powered by a conventional two-stroke outboard, one of three boats used for isobutanol fuel testing.

PHOTO: EMILY MCKNIGHT

AT ZERO-DARK-HUNDRED in an undisclosed marina somewhere on the western shore of the Chesapeake Bay, two men noiselessly transfer gear from the covered bed of a pickup truck to the cockpit of the non-descript center-console outboard at dockside. Quickly they stow hoses, canisters, and meters, plus vinyl pouches that sprout tubing with stainless-steel fittings. Two others silently remove unmarked barrels from a storage shed, wheeling them toward the boat.

Finally the men whisk a secret weapon known only as "MPSS" aboard, a white metal cabinet the size of a large ice chest. Laid flat on the cockpit sole, it's below sight from curious eyes that may pass in another boat, or attempt to spy from shore.

Once loaded, two of the team begin rigging the MPSS to its attendant vinyl bag, the hoses tracing umbilicals to the exhaust system of the 175-hp Evinrude E-Tec engine on the transom. It takes more time to rig a battery of sensors — from water temperature and barometric pressure, to fuel flow and boat speed — but eventually and with little fanfare, the boat heads for a quiet creek that shall remain nameless. Once on the unmarked, one-mile-course track, the boat begins a repetitious navigation routine — up and back, up and back — as team members monitor the MPSS, now sucking samples of engine exhaust into the pouch.

This being midweek, such boring, back-and-forth operation at various speeds apparently goes unnoticed from shore. Two minutes at 5,000 rpm, five more at 4,000, and so on, through a five-stage protocol from wide-open throttle to idle speed in neutral. After several laps, one crewmember switches out the portable fuel tank while another screws tubes from a fresh pouch into the MPSS. The routine repeats, lap after measured lap, until the technical appetites of both pouches are satiated and the boat heads back to the dock.

There, while two men unload equipment and reconfigure the boat to its inconspicuous, everyday appearance, the other two whisk the pouches into the truck. They head south where a late-night rendezvous with a gas-mass spectrometer awaits at an undisclosed lab three hours away. Anticipation in the truck is electric. The secrets the two pouches hold could do no less than revolutionize recreational boating.

TEAM BIOBUTANOL

All melodrama, intrigue, and clandestine-op allusions aside, the description above is a slightly embellished version of how three marine-industry engineers put together their equipment and expertise last June in an effort to solve one piece of the conundrum that a potential ethanol increase in gasoline poses for boat-engine manufacturers and the boat owners who use their products. After a series of on-the-water evaluations and laboratory tests conducted over the summer with, not ethanol, but another alcohol derivative called isobutanol, it turns out they may be on to something.

"We know that increasing ethanol content in gasoline to 15 percent wouldn't be good for modern marine engines, which today are designed to run on 10-percent ethanol," reported John McKnight, environmental and safety compliance director for the National Marine Manufacturers Association, who helped organize the on-the-water evaluations. "Ethanol adds oxygen, making engines run hotter, so if they increase the amount to 15 percent in the

Evinrude engineer Jeff Wasil loads a fresh emissions-trapping pouch into the Marine Portable Sampling System (MPSS) that he designed.

gasoline, that could lead to mechanical failures." McKnight is referring to the ethanol industry pressing to raise the content to 15 percent, and the partial approval for that given last year by the U.S. Environmental Protection Agency.

"The National Renewable Energy lab sanctioned a series of performance and durability tests on both two- and four-stroke outboards (see sidebar) and we know that E15 can seriously damage those engines," McKnight added. "Right now in the U.S. we use 14 billion gallons of corn-based ethanol in gasoline, but the nation is under a federal mandate to increase biofuel consumption to 36 billion gallons by 2022. So we thought it was time to look for an alternative to ethanol, and after analyzing our tests of last summer, we may have found just that in isobutanol."

Although discovery of isobutanol as a byproduct of plant fermentation goes back to 1861, it's only due to innovations in biology over the past 20 years that it's become a viable and potentially cost-effective fuel source, according to chemical engineer Dave Munz. As a member of the team that conducted the June boat trials, Munz and his company, Gevo, a Colorado-based isobutanol producer, supplied the fuel. Isobutanol, Munz said, is everything ethanol isn't; it's non-hygroscopic, meaning it absorbs little water, and its use would avoid the phase-separation problems in boat engines that aren't run regularly. In addition, isobutanol is not as potent a solvent as ethanol, so it might be the panacea for older boats with fiberglass fuel tanks.

From a distribution-cost perspective, Munz explains that because isobutanol is less corrosive than ethanol, it can be shipped by pipeline as opposed to the more expensive truck and rail transportation that ethanol demands. "We think it can solve a lot of problems for the fuel industry, as well as for the consumer," he adds.

The EPA has ruled that isobutanol, even at a higher percentage, is a "substantially similar" fuel, meaning that small retailers like rural convenience stores and marinas should not have to retrofit or replace their gas pumps, which can help keep prices down. That "higher percentage" is one of isobutanol's chief advantages: It's got 30 percent more energy than ethanol.

FUEL OF THE FUTURE?

Gevo, in fact, supplied isobutanol fuel for an entire summer of testing, according to John Adey, technical director for the American Boat and Yacht Council and a member of our *BoatU.S. Magazine* tech team writing "Ask The Experts." Adey handled logistics for the four-month project and designed test protocols that put three boats through their paces on isobutanol.

"By the time we were done in September, we'd gone through about 800 gallons of isobutanol-enhanced fuel," Adey reported. "We wanted to conduct the scientific emissions tests, but also just to operate the boats on this fuel the same way regular boaters would during a summer." Adey's work actually started in March, prepping the boats: a Mako 19 with a 175-hp Evinrude E-Tec, two-stroke outboard; an 18-foot Sea Ray with 135-hp Mercruiser inboard/outboard power; and a 23-foot Sea Doo with twin 215-hp Rotax engines driving its jet pump. In addition to the calibrated and controlled emissions testing in June, Adey, McKnight, and others (including a few BoatU.S. staff who were asked to help) logged 40 hours, what EPA determines the average "seasonal life" for recreational boat engines, on each boat.

The June emissions testing with the Mako provided a baseline for the entire summer suite of evaluations. According to Jeff Wasil, engineering technical expert for Evinrude Marine Engines, and inventor of the MPSS, which stands for Marine Portable Sampling System, the first "bag run" captured exhaust with the engine burning a pure, EPA-approved test gasoline called Indolene.

"Two years ago we investigated how isobutanol would work in one of our outboards and its properties seemed much better suited for marine engines," Wasil said. "We found no appreciable changes in emissions and because you get more energy without more pollution, and with a fuel that appears to be more compatible with marine engines, isobutanol looks more promising than ever as a replacement for ethanol."

HOW BAD CAN MORE ETHANOL BE?

GASOLINE-ENGINE MANUFACTURERS and the millions of Americans who use their products have lived almost exclusively with 10-percent ethanol in their automobiles, trucks, boats, generators, and lawn mowers for at least the last decade. Manufacturers and the marketplace have adjusted to the requirement, the public is using it, and air quality is better for it.

Two years ago, ethanol manufacturers began to push for half-again as much ethanol in our gas tanks, which is 15 percent, or what would be called E15. So what could be wrong with 50 percent more ethanol in the gasoline that powers our boats? Plenty, according to a new study conducted by Brunswick Marine and Volvo Penta, which was financed by a $400,000 grant from the U.S. Department of Energy and monitored by the National Renewable Energy Laboratory. For example, a total of 300 hours of E15 running time on three popular models of both 4-stroke and 2-stroke outboard engines, as compared with running on pure gasoline, showed metal fatigue, misfiring, emissions, and deterioration of some fuel-system components.

The peer-reviewed tests also ran a carbureted 4.3-liter, 4-stroke inboard engine on E15 and it exhibited cold-start problems and increased emissions. For test details, go to www.nrel.gov/docs/fy12osti/52909.pdf

Volvo Penta engineer Rich Kolb (standing) operated the Mako during June exercises to capture engine emissions for later testing at the firm's laboratory in Virginia.

COMING TO A PUMP NEAR YOU?

Wasil notes that the U.S. Department of Energy has designated isobutanol a "drop-in fuel," meaning that it can be used to displace petroleum under the Energy Independence and Security Act of 2007, and increasing its use could help reduce greenhouse-gas emissions faster as well. It can be produced from agricultural waste products like corn stalks, or from switch grass and wood chips. At last count at least 10 companies worldwide, including a BP-Dupont joint venture called Butamax were working toward commercializing isobutanol in the next few years, according to chemical-industry reports.

"There is no need to rush E15 into the marketplace," Wasil told the House Subcommittee on Energy and Environment in testimony for NMMA last July 7. He appeared before the panel to address the risks of the EPA's "partial waiver" allowing 15-percent ethanol fuel, or E15, to be used in some engines and not others. He told lawmakers, "Let's have a strategic pause while more testing is done to determine the effects of E15 on various kinds of engines and to see whether there might be alternatives to ethanol, such as isobutanol."

With the baseline emissions tests literally in the bag and a full summer of routine operation logged on all three boats, at press time Team Isobutanol had just conducted the emissions test sequence over again, looking for anomalies. "We wanted to find out if, after 40 hours of running time, the engines still complied, or if there were any ill-effects," Adey explained. "The engines were running better than ever by summer's end. Power was still excellent and fuel economy actually seemed improved. I'm amazed at how great this fuel appears to be."

According to emissions guru Wasil, the post-season tests showed "the same data and trends as the spring tests. We haven't finished crunching the numbers yet but I think it's safe to say we were seeing virtually identical results and that's very encouraging. It's important for the marine industry to secure a biofuel that we know is going to work in our products and that the boating consumer can depend upon."

McKnight said a full report on the project would be ready in time for the Miami International Boat Show in February.

In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels

Jeff R. Wasil
BRP U.S. Inc.
John McKnight
National Marine Manufacturers Association
Rich Kolb
Volvo-Penta of the Americas
Dave Munz
Gevo Inc.
John Adey and Brian Goodwin
American Boat and Yacht Council

ABSTRACT

Isobutanol-extended fuel was tested in two recreational marine vessels placed in Annapolis, MD and operated for fifty hours on the Chesapeake Bay and surrounding tributaries. Field emissions testing was conducted using a unique portable marine bag sampling system (MPSS) which collected a weighted five mode composite emissions sample consisting of total hydrocarbons (THC), oxides of nitrogen (NOx) and carbon monoxide (CO) while operating recreational boats on both a non-oxygenated baseline indolene certification fuel and a 16.1% isobutanol-extended gasoline. Engine and boat runability was also observed throughout the six month operational period. In addition, back-to-back sampling yielded excellent repeatability from the portable bag sampling equipment. Based on the results of this preliminary study, isobutanol-extended fuels look to be very promising for marine engine applications. An introduction to biofuels policy in the U.S. and characteristics and highlights of butanol-extended fuels will be explored.

INTRODUCTION

In 1973, the Organization of the Petroleum Exporting Countries (OPEC) announced an oil embargo against the United States that created massive shortages and sky rocketing prices of gasoline[1]. A need for renewable fuels was quickly recognized - not from the standpoint of environmental sustainability- but rather from the overwhelming need to reduce dependence on foreign sources of oil. Later, in 1974, U.S President Richard Nixon initiated “Project Independence” which sought to reach total energy independence by 1980[2]. As an extension of this initiative, government subsidies were put into place which effectively encouraged development of biofuels. Limited mainly by available technology at the time, production of corn-based ethanol resulted in the highest production yields compared to other biofuels[3].

In 1980 - far from reaching energy independence and initiatives of Project Independence, Congress passed the Energy Securities Act which provided secured government loans to ethanol producers and covered costs associated with building new ethanol plants[4]. Shortly thereafter, government subsidies were further increased in attempt to spark increased ethanol production[5]. In addition, two major pieces of Federal legislation directly and indirectly led to the astronomical growth of the U.S. biofuels industry. The first of which was the passage of the Clean Air Act Amendments of 1990 (CAA) in which methyl tert-butyl ether (MTBE) was first used in gasoline throughout the United States to meet the new fuel requirements to reduce carbon monoxide and ozone levels caused by auto emissions[6]. MTBE was first introduced in 1979 to replace lead as an octane enhancer. The CAA then redirected its application of MTBE as an oxygenate. Soon after its introduction, MTBE began leaking into ground and surface water from underground storage tanks and pipelines, through spills, from emissions from marine engines into lakes and reservoirs, and to some extent, from air deposition. Ethanol was therefore heavily promoted as the logical alternative due to the availability of an agricultural feedstock and lack of any perceived negative health effects.

The Energy Independence and Security Act of 2007 (EISA) took ethanol production and use to the next level by setting requirements to increase the U.S. consumption of renewable fuels to approximately 20% of the nation's fuel supply in 10 years. The stated purpose of the act is "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes"[7].

Due to environmental concerns, MTBE was phased out and a significant DC based ethanol lobby was formed in order to promote growth opportunities for U.S. agribusiness and ethanol producers[8]. As the production of renewable fuels skyrocketed, ethanol at first appeared to be the perfect solution to meeting the requirements of the EISA. In summary, ethanol offers a number of benefits to automobiles, the environment, the economy and national security:

- Ethanol adds oxygen to gasoline, which can reduce carbon monoxide emissions
- Ethanol usage reduces the dependence on imported oil

On the other hand, ethanol at concentrations greater than 10% by volume has serious process and distribution challenges[9] and may seriously damage millions of existing engines[10,11]. As ethanol was the prime renewable oxygenate available, it has become the leading alcohol produced; however, increasing the usage of ethanol in gasoline has created several challenges:

- Ethanol raises the Reid Vapor Pressure of gasoline which at higher levels increases evaporative emissions[12]. Meeting U.S. EPA and California Air Resources Board (CARB) standards require refineries to perform additional processing.
- Terminal blending is required as ethanol can not be shipped in pipelines (due to its corrosive nature, water solubility, and strong solvency)[13]
- Ethanol is hygroscopic, meaning it has an affinity for water
- Ethanol at 10% by volume contains approximately 3.5% oxygen. Increasing ethanol content in gasoline increases the oxygen level (referred to as enleanment) causing open loop engines (engines without feed-back sensors) to experience increased combustion temperatures

These issues are further highlighted as the Energy Independence and Security Act of 2007 was enacted obligating refiners/blenders to use increasing amounts of renewable biofuels based on their greenhouse gas (GHG) emissions profile. This created two problems: it exacerbated the issue of how to increase the amount of ethanol in the gasoline pool; it also implied that cellulosic and/or Brazilian ethanol and/or fatty acid methyl esters (FAME) were the only advanced products available because ethanol (from corn starch) could not be used to meet the EISA advanced biofuel target.

The project described within was driven by necessity to find an alternative renewable fuel to achieve the requirements of the Energy Independence and Security Act of 2007[14] while also ensuring fuel compatibility with recreational boats and engines. Most boat fuel systems are vented directly to the atmosphere, which allows moisture to enter the fuel tank during daily diurnal temperature changes. This is further complicated by the marine environment itself - in which water or salt water is more likely to be inadvertently introduced into fuel systems. Moreover, typical usage of boats, especially in northern parts of the U.S, equates to longer periods of storage and subsequently potential for more fuel system related issues.

As shown in Table 1, there are specific quantities of renewable fuel that have been mandated by the Energy Independence Act to be introduced each year. Reaching these requirements will be challenging because there are currently only small quantities of cellulosic derived biofuels available and, more importantly, the mandated quantities of ethanol cannot be met by E10 alone. Several automobile manufacturers have produced flex fuel vehicles that can operate on E85, but with fuel efficiency losses due to the lower energy content of ethanol[15] and general lack of availability[16] it is unlikely that E85 alone will satisfy the requirements for the forthcoming quantities of ethanol mandated in the Renewable Fuels Standard. The U.S. ethanol lobby has been an advocate in increasing the quantity of ethanol in gasoline from 10% to 15% by volume and beyond as a means to meet the specified quantities. As previously mentioned, this approach may have catastrophic impact to millions of legacy engines currently in use today.

Table 1: U.S. Renewable Fuel Standard (RFS) Mandates[17]

Renewable Fuel Volume Requirements for RFS2 (billion gallons)				
Year	Cellulosic biofuel requirement	Biomass-based diesel requirement	Advanced biofuel requirement	Total renewable fuel requirement
2008	n/a	n/a	n/a	9.0
2009	n/a	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	0.25	0.80	1.35	13.95
2012	0.5	1.0	2.0	15.2
2013	1.0	a	2.75	16.55
2014	1.75	a	3.75	18.15
2015	3.0	a	5.5	20.5
2016	4.25	a	7.25	22.25
2017	5.5	a	9.0	24.0
2018	7.0	a	11.0	26.0
2019	8.5	a	13.0	28.0
2020	10.5	a	15.0	30.0
2021	13.5	a	18.0	33.0
2022	16.0	a	21.0	36.0

BACKGROUND ON ISOBUTANOL

First generation renewable products such as ethanol have provided a start to improving air quality and energy independence, but may not provide an optimal economic solution across the value chain. Isobutanol, as a next generation biofuel, builds on the foundation established by the ethanol industry, provides additional product solutions beyond gasoline motor fuel extenders, and may mitigate the various usability and compatibility challenges not met by first generation products[18].

One of the first large-scale industrial fermentation processes to be developed was known as ABE (Acetone, Butanol, Ethanol). During the first part of the 20th century, ABE ranked second in importance only to ethanol fermentation. Two key impediments to its large scale use were:

- The butanol killed the yeast microorganism, as the amount of butanol produced in the fermentation broth increased beyond 2%, and
- It took significant energy to separate the three products.

The use of butanols in gasoline dates back to the 1970s/1980s and has been approved under Section 211(f) of the U.S. Clean Air Act via the "Arconol", "DuPont" and "Octamix" waivers. At the time, tert butyl alcohol (TBA) was the prime butanol used, although research suggests that isobutanol was also being evaluated[19]. Although n-butanol and isobutanol are naturally occurring materials and can be produced via fermentation, their actual production came from petroleum via the Hydroformylation or OXO process, and TBA was a by-product. However, due to cost and availability, the key oxygenates being used were MTBE (typically produced in the refinery) and ethanol (typically produced from the Midwest U.S. based corn starch plants), although TBA and other ethers were used in smaller amounts.

By 2005, two different issues arose which warranted a re-evaluation of butanols for transportation fuels. First, MTBE was effectively banned for use as an oxygenate. Secondly, per the U.S. Energy Act of 2005, the Renewable Fuel Standard (RFS) was established mandating that a given volume of renewable products fuels be used in fuels.

Advances in science were occurring at this time that allowed for the development of renewable isobutanol. In essence, scientists developed a way to turn "off" the ethanol production in yeast and turn "up" the isobutanol production.

Highlights of Isobutanol as a motor fuel extender

Isobutanol, as a "drop in" gasoline blend stock, has many benefits for the industry.

- Isobutanol may be considered a "bridge" between the existing downstream petroleum and the growing renewable fuels industry. Finding renewable materials that can be integrated and used in the existing infrastructure previously developed by the petroleum industry would be one approach that would optimally integrate the petroleum and renewable fuels industry[20,21]
- Isobutanol can be made from a variety of feed stocks – although in the near term it will most likely be produced by converting existing corn starch ethanol plants to isobutanol. However, the technology can use cellulosic sugars as and when they become available in a cost-effective manner
- Isobutanol production can be readily scaled up through a capital light, fast retrofit upgrade to the existing 200+ ethanol plants constructed in the U.S.[22]
- The key to using the existing pipeline distribution system is to have a renewable material that meets the integrity, quality, and operational needs of the network. Isobutanol does not cause stress corrosion cracking[23], does not appear to have any elastomeric compatibility issues, can be blended into gasoline at EPA defined "substantially similar" levels (these products have shipped in pipelines before), and may offer opportunities to use both the NGL pipeline systems (could bring isobutanol from the Midwest to refining centers) or finished product pipeline systems (take finished products to markets)[24,25,26].
- Isobutanol can be readily converted to isobutylene, a precursor to a variety of petrochemical and/or transportation fuels products.
- Isobutanol gasoline blending properties provide opportunities; for example:

    a. Its low RVP blend value of 5 psi (+- 1PSI for aromaticity) allows butane, pentane, and other low cost blend stocks to be used[27,28,29]
    b. Its 30% higher energy content, relative to ethanol, allows an EISA equivalence value of 1.3, thereby generating a greater Renewable Identification Number (RIN) generation rate (relative to the EISA renewable volume obligation) and potentially, improving consumer benefits[30,31]
    c. Its low water solubility keeps it in the gasoline phase in the presence of water[32]. This is of particular interest to the marine engine environment as the majority of boats use open-vented fuel systems in which water can more easily enter the fuel system.
    d. Its lower oxygen content allows larger volumes to be used; (relative to ethanol) hence the EISA targets can more readily be attained with a fuel that can be used in all gasoline engines[33,34,35]

- Isobutanol may qualify as an EISA "advanced" other biofuel; this might provide refiners/blenders an American made product with a high RIN generation rate[36,37,38].

- Isobutanol may provide many of the end user groups (automobile industry, small engine manufacturers, marine engine manufacturers, retail equipment providers) with solutions that do not require major capital expense and/or re-engineering[39,40].
- Isobutanol is a known, naturally occurring molecule that may be a very good environmental material[41,42].

As the demand for renewable products intensifies, it is imperative that consumers and the fuels industry have the necessary alternative fuel choices which adequately fit their needs[43].

EXPERIMENTAL METHODOLOGY

Tests conducted included two recreational marine vessels limited to on-water emissions collection along with analyses performed at Volvo-Penta emissions laboratory in Chesapeake, Virginia. The recreational vessels included a 18 foot (5.5m) Mako center console fishing boat with a 175 hp BRP Evinrude E-TEC™ two-stroke stratified charged, spray guided direct fuel injection outboard as shown in Figure 1, and a 24 foot (7.3m) BRP SeaDoo™ Challenger Jet Boat with twin 215 hp four-stroke supercharged Rotax™ engines as shown in Figure 2. The engine specifications are shown in Table 2. Both engines are designed to run on 0 - 10% ethanol-extended fuels and operate open-loop, meaning the engine does not compensate for air/fuel ratio requirements of the specific test fuel. Emissions were collected using both an Indolene non-oxygenated certification test fuel and a 16.1% isobutanol-extended fuel. 16.1% isobutanol by volume was chosen because it matches the energy and oxygen content of 10% ethanol-extended fuel. The fuel specifications are shown in Table 3. To better match the performance specifications of the baseline indolene test fuel, isobutanol was blended with a conventional clear base gasoline yielding a finished octane value of 93 (R+M)/2.

Figure 1. 18 foot Mako boat with 175 HP Evinrude Direct Fuel Injection Outboard undergoing on-water field emissions testing

Figure 2. 24 foot SeaDoo Challenger boat undergoing on-water field emissions testing

Table 2: Engine Specifications

	Evinrude E-TEC™	SeaDoo Rotax™
Engine Type	Spray-Guided Direct Fuel Injection Stratified Charged Two-Stroke	Four-Stroke Single Overhead Camshaft. Liquid Cooled. Supercharged
Horsepower	175	215
Displacement (cc)	2592	1503
Cylinders	6	3
Bore and Stroke (mm)	91 x 66	100 x 63.4
Max HP RPM	5500	8000

Table 3: Test Fuel Specifications

Property	Gasoline	Indolene	Ethanol	IsoButanol	10% ethanol-extended fuel	16.1% Isobutanol-extended fuel
Specific graity [g/cc] at 60°F	0.72-0.75	0.74	0.79	0.81	0.748	0.749
Net Lower Heating Value [BTU/lb]	18,700	18,500	11,600	14,280	18,000	18,000
Stoichiometric Air Fuel Ratio	14.6	14.3	9	11.1	14.1	14.1
Octane (R+M)/2	87-93	92	112	102	94*	93*
O2 (% by wt)	0	0	35	22	3.5	3.5

*Actual octane is a function of aromoticity of base gasoline

Marine Portable Bag Sampling System Overview

Emissions were collected using a Marine Portable Bag Sampling System (MPSS) developed by BRP for the U.S. EPA/National Marine Manufacturers Association (NMMA) green house gas determination study and is shown in Figures 3 and 4. This unique equipment and test method represent a new method for determining exhaust gas emissions from on-water recreational craft. The test equipment measures and proportionally captures exhaust gas collected through emission probes located at the base of the engine power head of the outboard and in the exhaust manifold of the supercharged Rotax engine. The exhaust flow rate into the MPSS is maintained at a constant flow rate and the sample time adjusted at each specific mode so that a composite weighted five mode sample is contained in the Tedlar® sample bag at the end of the five test mode cycle. The sample is first passed through a particulate filter and mechanical chiller in which the water is removed via a peristaltic pump. The sample time for each mode is determined based on the overall mass exhaust flow rate per mode. Each mode fuel consumption and emissions must be sampled using the built in five gas emissions analyzer in the MPSS prior to determining the proper sample time for subsequent weighted modal emissions collection. The overall engine exhaust flow rate is calculated using the Spint air/fuel ratio calculation. The MPSS basic flow diagram is shown in Figure 5. Additional sample preparation such as filters, flow meters, pressure sensors and solenoid valves are contained within the MPSS.

The MPSS performance was validated against a standard laboratory test engine and test method to evaluate system performance and overall accuracy. The standard laboratory test method for marine engines consists of raw gas emissions sampling using a five-gas emissions bench and measurement of engine fuel consumption. The carbon balance method is used to determine mass emissions at each specific test mode. Each constituent is then multiplied by the associated weighting factor for each mode. The sum is then totaled and divided by the weighted power to arrive at total ICOMIA five-mode mass emissions. As shown in Figure 6, the MPSS correlation to the standard test method is within 3% for HC and NOx, and within 8% for CO. Although the MPSS is a very different test method for determining mass emissions, test results solidify the accuracy and performance of the MPSS relative to the standard test method.

Figure 3. MPSS Bag Sampling System

Figure 4. MPSS Bag Sampling System in use in the 18' Mako boat

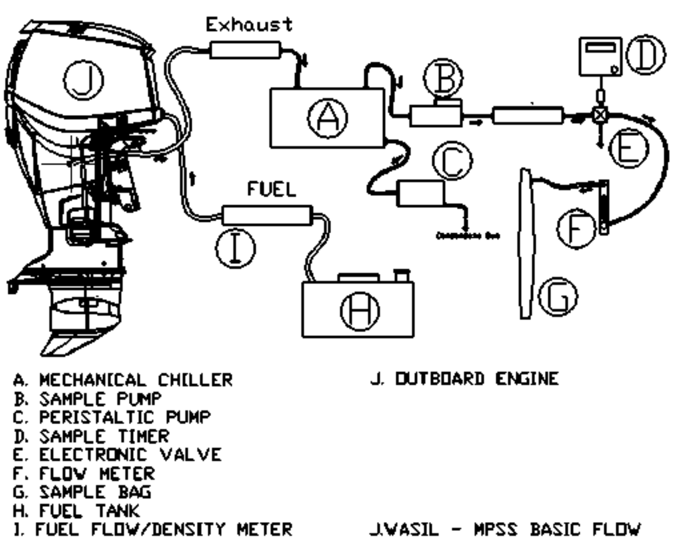


Figure 5. Basic MPSS Flow Diagram

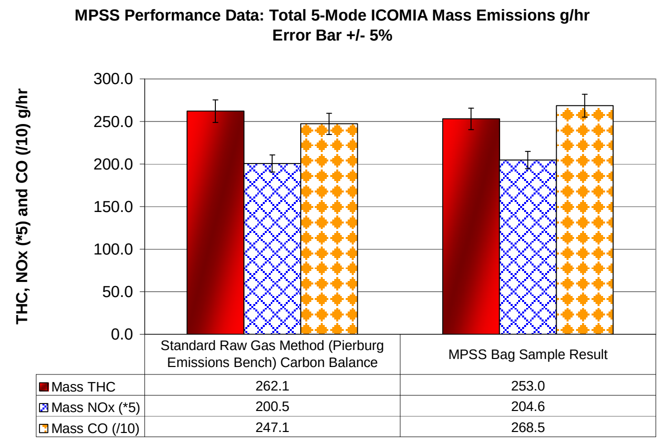


Figure 6. Standard Raw-gas method vs. MPSS bag sampling Conducted on Laboratory Test Engine

Emissions are reported in grams per ICOMIA[45] hour for total hydrocarbons (THC), nitrogen oxides (NOx), and carbon monoxide (CO). Fuel flow was measured using an AVL PLU 120 liter/hour volumetric flow meter along with density to arrive at fuel consumption in grams/hour. During testing in Annapolis, MD, boat speed, engine RPM, barometric pressure, humidity and temperature were recorded using a SoMat™ portable data acquisition system. Two bag samples per test fuel were collected in order to better account for test variability. A flame ionization detector (FID), chemiluminescence detector (CLD), and a non dispersive infrared detector (NDIR) were used to determine THC, NOx, and CO and respectively. The ICOMIA test cycle (ISO 8178) is the standard U.S EPA and California Air Resources Board (CARB) approved marine test cycle and is shown in Table 4. In this particular case, as emissions are sampled from recreational craft operated on-water, speed set-points according to the ISO 8178 marine test cycle are followed and the torque is allowed to float. The U.S. EPA marine regulations contain a defined Not-To-Exceed (NTE) zone[46] which accounts for various operational points typical of recreational craft as shown in Figure 7. The lines bordering the four test points define the test zone where marine engines are expected to operate under normal recreational boating activities. During emissions certification and subsequent production line testing, recreational marine engine emissions are reported to the U.S EPA and CARB as total HC+NOx. In this study, however, the individual HC, NOx and CO are shown to better understand the effects of the two test fuels on emissions.

Table 4. ISO 8178 Marine Test Cycle

Mode	% RPM	% Torque	% Weight Factor
1	100	100.0	6
2	80	71.6	14
3	60	46.5	15
4	40	25.0	25
5	Idle	0.0	40

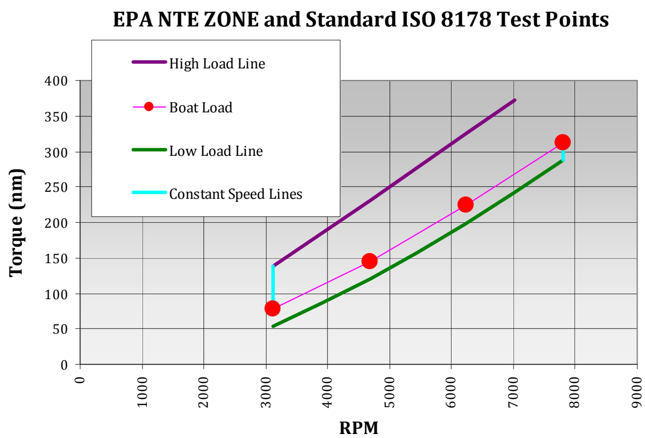


Figure 7. Example of EPA NTE zone. The red points indicate the standard ISO 8178 marine test points

TEST RESULTS

Evinrude E-TEC™

As shown in Figure 8, total ICOMIA weighted five mode hydrocarbon emissions between both tests (bag 1 and bag 2) and test fuels were very similar. NOx emissions did increase by approximately 50% with the use of 16.1% isobutanol and was a direct result of engine enleanment because isobutanol is a partially oxidized fuel. For comparison, increased NOx emissions in open-loop engines are often observed using 10% ethanol-extended fuels relative to non-oxygenated fuels[47]. ICOMIA weighted mass CO emissions are indicated in Figure 9. As shown, the mass CO was reduced by approximately 17% relative to the non-oxygenated fuel. Figure 10 indicates air-fuel ratio (AFR) for both test fuels. The overall lean operation of the Evinrude is due to the fact that the engine runs homogeneous at test mode #1 and transitions to completely stratified operation. Figure 11 indicates measured raw CO% per test mode. The engine RPM during data collection is indicated in Figure 12. The slight variation in RPM at test mode 3 is caused by sensitivity of the boat hull at this specific test condition. All measurements were made while operating the boat on water. As boat speed decreases, variations in speed due to waves and wind conditions become more prevalent as this particular boat was close to minimum planning speed at 3000 RPM. However, any slight variations in emissions at this test speed were accounted for in the fuel flow measurement and the composite bag emission sampling analysis. Moreover, variations test-to-test were actually quite good considering that all measurements were collected on a recreational boat operating on the water. For reference, the standard test-to-test variability in the laboratory for these engine types is typically within 5%.

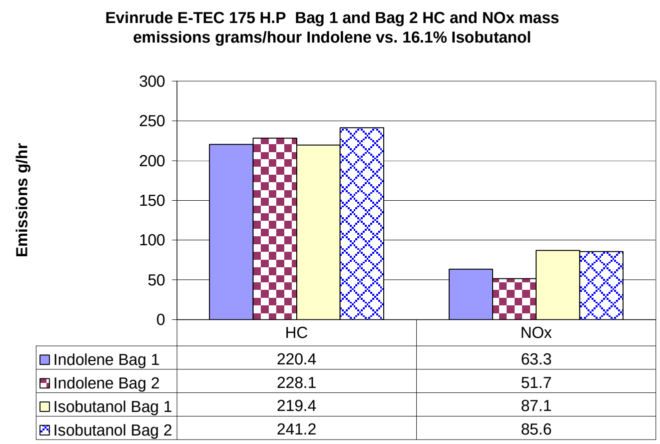


Figure 8. Evinrude E-TEC emission results sample bag 1 and 2 HC and NOx grams per ICOMIA hour (weighted over the test cycle) Indolene Certification Fuel vs. 16.1% Isobutanol-extended Fuel

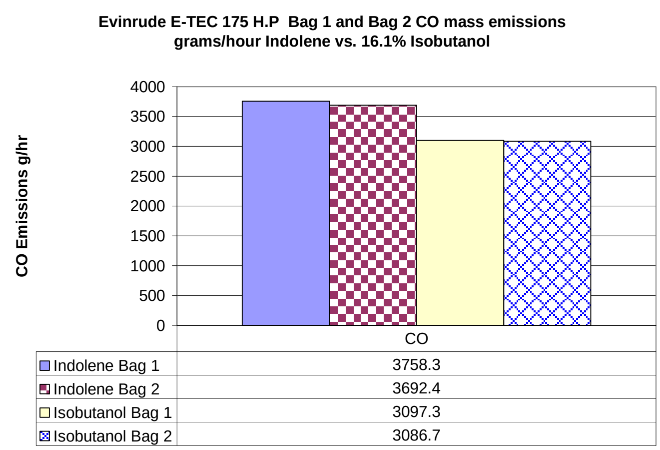


Figure 9. Evinrude E-TEC™ CO weighted emission results sample bag 1 and 2 Indolene Certification Fuel vs. 16.1% Isobutanol-extended Fuel

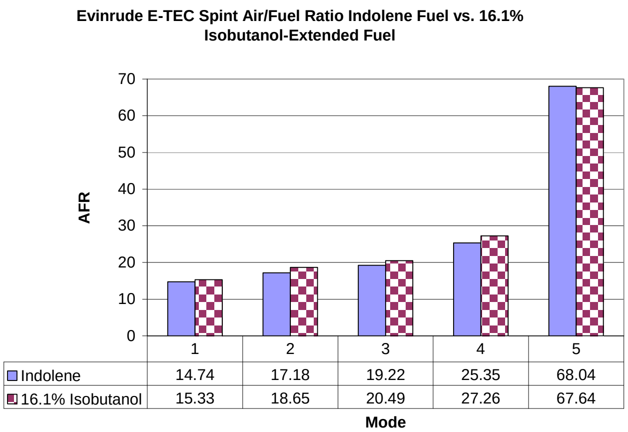


Figure 10. Evinrude E-TEC™ Average Air-Fuel Ratio per Test Mode

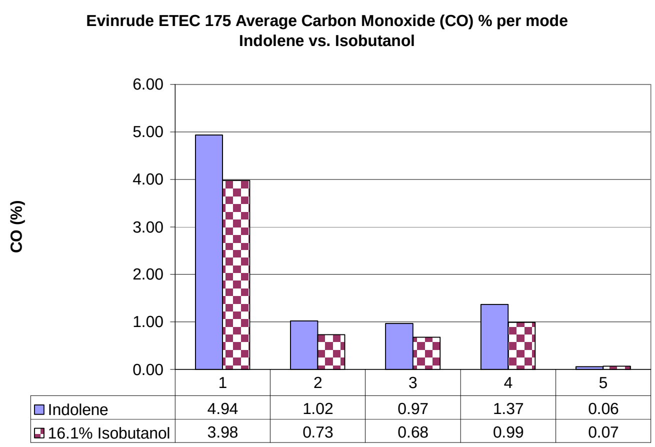


Figure 11. Evinrude E-TEC™ Average raw CO% per mode – Indolene Certification Fuel vs. 16.1% Isobutanol-extended Fuel

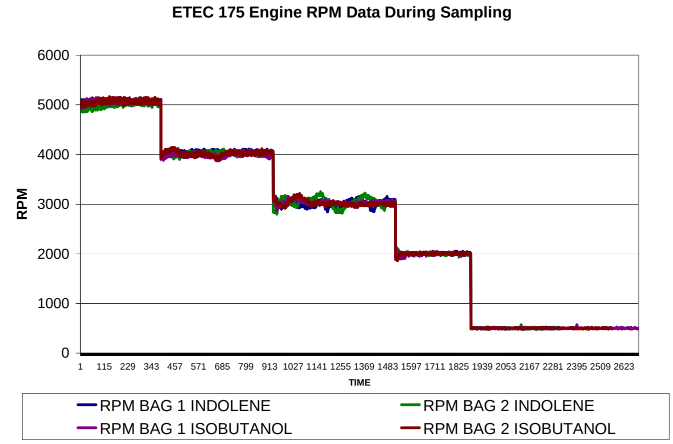


Figure 12. Evinrude E-TEC™ Engine RPM During sampling bag 1 and 2 Indolene Certification Fuel and 16.1% Isobutanol-extended Fuel

SeaDoo Jetboat

As shown in Figure 13, ICOMIA five-mode weighted total hydrocarbon emissions decreased by approximately 35% using a 16.1% isobutanol-extended fuel. NOx emissions increased by approximately 20%. CO emissions were reduced by approximately 35% as shown in Figure 14. Average air-fuel ratio per test mode is shown in Figure 15. Figure 16 indicates measured raw CO% per test mode. Approximately 40% decrease in raw CO% was observed. As shown in Figure 17, engine RPM was very consistent throughout the data collection. This is because jet pumps inherently tend to load more consistently without regard for overall boat speed.

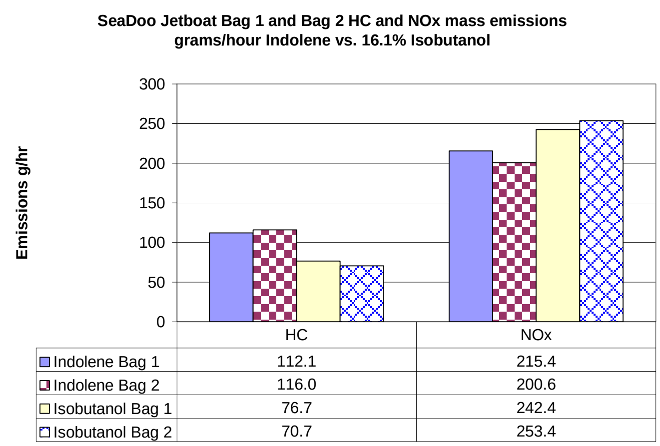
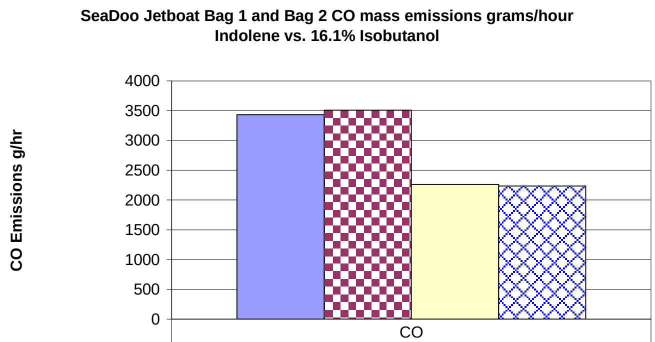
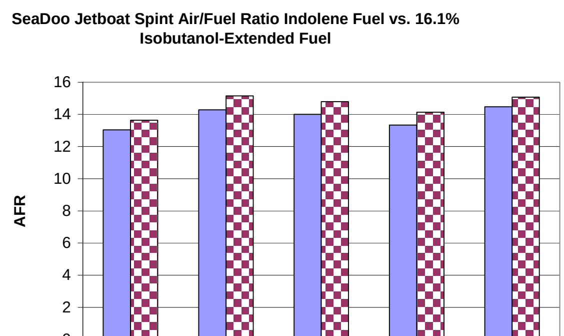


Figure 13. SeaDoo Jetboat emission results sample bag 1 and 2 HC and NOx grams per ICOMIA hour (weighted over the test cycle) Indolene Certification Fuel vs. 16.1% Isobutanol-extended Fuel



	CO
Indolene Bag 1	3432.4
Indolene Bag 2	3508.8
Isobutanol Bag 1	2261.2
Isobutanol Bag 2	2235.9

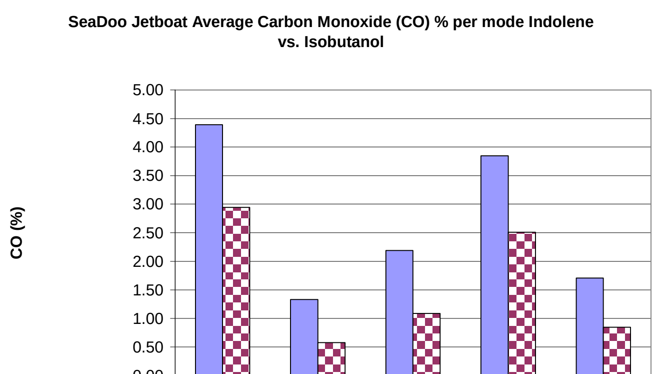
Figure 14. SeaDoo Jetboat CO weighted emission results sample bag 1 and 2 Indolene Certification Fuel vs. 16.1% Isobutanol-extended Fuel



	1	2	3	4	5
Indolene	13.04	14.28	14.00	13.34	14.47
16.1% Isobutanol	13.63	15.16	14.79	14.14	15.07

Mode

Figure 15. SeaDoo Jetboat Average Air-Fuel Ratio per Test Mode



	1	2	3	4	5
Indolene	4.39	1.33	2.19	3.85	1.71
16.1% Isobutanol	2.94	0.58	1.09	2.51	0.85

Figure 16. SeaDoo Jetboat Average CO% per Mode - Certification Fuel vs. 16.1% Isobutanol-extended Fuel

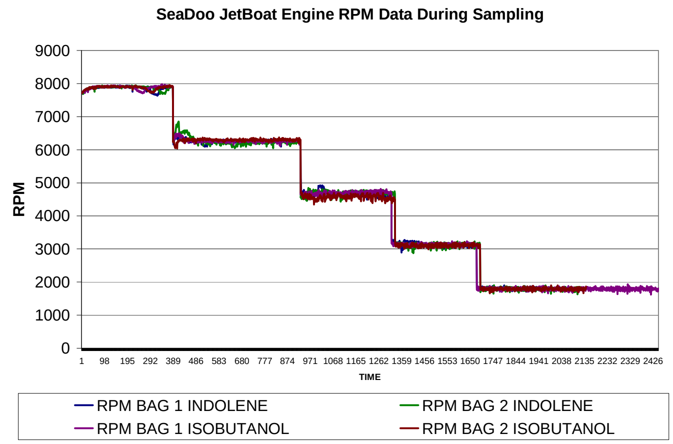


Figure 17. SeaDoo Jetboat Engine RPM During sampling bag 1 and 2 Indolene Certification Fuel and 16.1% Isobutanol-extended Fuel

The reduction in mass CO for both the Evinrude and the SeaDoo jet boat are within typical enleanment expected for 10% ethanol-extended fuels relative to non-oxygenated EPA certification fuels[49]. As shown in Figure 18, 10% ethanol-extended fuels result in an average reduction in mass CO of approximately 29% with a range of 18 to 41%. Based on this study and other butanol data collected from marine engines, the overall average reduction in mass CO is approximately 26% with a range of 12% to 35%[50].

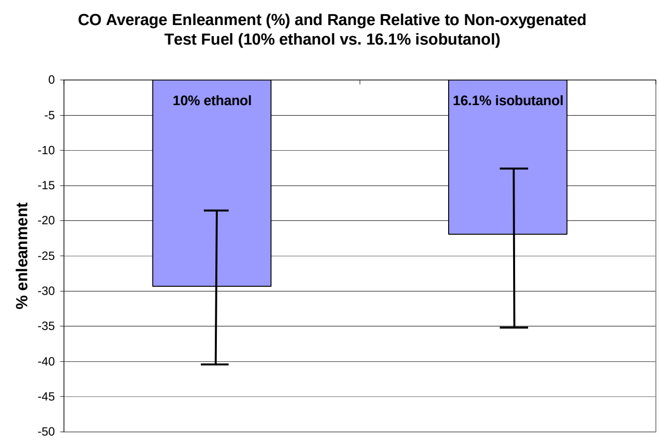


Figure 18. Percent Reduction in Open-loop Engines Mass CO relative to Non-oxygenated Indolene Certification Fuel. The enleanment for B16.1 fuel is similar to typical enleanment of E10[51,52]

EMISSIONS SUMMARY

- ICOMIA five-mode weighted THC emissions for the two-stroke direct fuel injection engine were similar between non-oxygenated fuel and 16.1% isobutanol-extended fuel.
- ICOMIA five-mode weighted NOx emissions for the two-stroke direct fuel injection engine increased from an average of 58 g/hr on non-oxygenated fuel to 86 g/hr on 16.1% isobutanol-extended fuel. It is anticipated that E10 would also cause a similar increase in NOx emissions relative to non-oxygenated fuel. For reference, NOx typically accounts for about 15 to 25% of the total HC+NOx emissions on these types of engines. Therefore the overall HC+NOx emissions increased by approximately 10%. Previously published data on an Evinrude E-TEC engine running on butanol-extended fuels in a laboratory setting also indicate an increase in NOx emissions relative to non-oxygenated fuel. But the total HC+NOx emissions were less because hydrocarbon emissions were reduced offsetting the increase in NOx. The engine is calibrated to meet the emission standard using E10 during engine development and then certified for emissions on non-oxygenated fuel. For that reason the increase in NOx emissions is already accounted for in the Family Emissions Limit (FEL) and is therefore not expected to cause the engine to exceed the standard.
- ICOMIA five-mode weighted carbon monoxide emissions for the two-stroke direct fuel injection engine decreased 17% relative to non-oxygenated fuel (3,725 g/hr to 3,086 g/hr)
- ICOMIA five-mode weighted THC emissions for the supercharged four-stroke engine decreased approximately 35% relative to non-oxygenated fuel (114.1 g/hr to 73.7 g/hr)
- ICOMIA five-mode weighted NOx for the supercharged four-stroke engine increased 19% relative to non-oxygenated fuel (208 g/hr to 247 g/hr)
- The reduction in CO for the two-stroke direct fuel injection engine and the supercharged four-stroke engine was within the expected enleanment range for 10% ethanol-extended fuels.

The Evinrude E-TEC and the SeaDoo jet boat are both engines that were produced prior to introduction of EPA NTE zone requirements and are therefore not NTE compliant. The introduction of NTE zones have resulted in emission calibrations that are more robust throughout the normal operating ranges. For these particular engines, changes in emissions reported may or may not have occurred to the same extent when operated according to the standard laboratory test method. It would be incorrect to assume a given percent change in emissions for field testing would equate to an exact percent change in emissions for laboratory certification testing.

CONCLUSION

Based on results of this study, boats and engines operated on a 16.1% isobutanol-extended fuel performed well over the 50 hour field test program and no engine runability, startability or other issues were reported. Biologically derived isobutanol at 16.1% by volume has potential to displace more petroleum based fuels while satisfying the congressionally mandated fuel quantities specified in the renewable fuel standard.

Field emission testing results using a 16.1% isobutanol-extended fuel relative to a non-oxygenated indolene test fuel indicate no change in HC+NOx for the supercharged four-stroke engine, and a slight increase in HC+NOx (due to increased NOx) for the two-stroke direct fuel injection engine. Increase in NOx is often observed using 10% ethanol-extended fuels relative to non-oxygenated fuels. CO emissions were reduced on both the supercharged four-stroke and the two-stroke direct fuel injection engine.

With accuracy within 3% for HC+NOx and within 8% for CO relative to the standard laboratory discrete raw-gas test method, the MPSS represents a new method to accurately collect and analyze emissions from recreational marine engines in the field. Repeatability between test sample bag 1 and 2 for each fuel and boat was quite good relative to laboratory repeatability when considering the variables with respect to collecting data from recreational boats operating on-water. Test-to-test repeatability in a laboratory setting for these engine types are typically within 5%. Therefore the MPSS on-water test repeatability is exceptional.

Further Testing

Field emission testing on recreational boats and vessels is a new method and there is much to learn about the relationship between laboratory tests and field emissions performance. This preliminary boat test program was an important first step in evaluating isobutanol as a potential drop-in fuel. This test was run without third party oversight and no outside sources of funding. A formal project investigating the effects of isobutanol-extended fuels on several recreational marine engines and boats has currently been initiated with Argonne National Laboratory with U.S. Department of Energy oversight. The test project has been expanded to not only investigate emissions, but also the effect that ethanol and isobutanol have on engine lubricants and oils. The results of this study will be published in due course.

TERMS

OPEC – Organization of the Petroleum Exporting Countries
THC – Total hydrocarbons
NOx – Oxides of nitrogen
CO – carbon monoxide
CAA – Clean Air Act Amendments of 1990

MTBE- Methyl tert-butyl ether
EISA – Energy Independence and Security Act of 2007
CARB – California Air Resources Board
GHG – greenhouse gas
FAME – fatty acid methyl esters
E85 – 85% ethanol by volume
E10 – 10% ethanol by volume
RFS – Renewable Fuel Standard
ABE – acetone, butanol, ethanol
TBA – tert butyl alcohol
n-butanol – normal butanol
EPA – Environmental Protection Agency
FEL – Family Emissions Limit
RVP – Reid Vapor Pressure
RIN – Renewable Identification Number
BRP – Bombardier Recreational Products
MPSS – Marine Portable Bag Sampling System
NMMA – National Marine Manufacturers Association
FID – flame ionization detector
CLD – chemiluminescence detector
NDIR – non dispersive infrared detector
O2 – Oxygen
ICOMIA – International Council of Marine Industry Associations
ISO 8178 – International Standards Organization
NTE zone – Not-To-Exceed zone
RPM – revolutions per minute

REFERENCES

[1] Toyin Falola, Ann Genova *The politics of the global oil industry: an introduction*. Westport: Praeger Publishing, 2009. 76-79. Print

[2] November 7th, 1973 - President Richard Nixon: Speech on energy conservation and energy independence.

[3] Jones, D., Woods, D., 'Acetone-Butanol Fermentation Revisited' *American Society for Microbiology*, Vol. 50, No. 4 Dec. 1986, p. 487-488

[4] 96th Congress (1979 - 1980)S.932: Energies Security Act

[5] Tax Reform Act of 1983 increases the ethanol subsidy from 50 cents a gallon to 60 cents a gallon.

[6] Methyl Tertiary Butyl Ether (MTBE) U.S EPA Fact Sheet http://www.epa.gov/mtbe/gas.htm

[7] H.R. 6 (110th): Energy Independence and Security Act of 2007 110th Congress, 2007–2009

[8] Growth Energies http://www.growthenergy.org/

[9] Voegele E., 'It's not just a Pipe Dream' Ethanol Producers Magazine Retrieved 11/20/2010 http://www.ethanolproducer.com/article.jsp?article_id=5270&q=&page=1

[10] Hilbert, D., High Ethanol Fuel Endurance: *A Study of the Effects of Running Gasoline with 15% Ethanol Concentration in Current Production Outboard Four-Stroke Engines and Conventional Two-Stroke Outboard Marine Engines* National Renewable Energy Laboratory (2011)

[11] Zoubul, G., Cahoon, M., Kolb, R., *Volvo Penta 4.3 GL E15 Emissions and Durability Test* National Renewable Energy Laboratory (2011)

[12] Martini, G. Joint EUCAR/JRC/CONCAWE Study on: *Effects of Gasoline Vapour Pressure and Ethanol Content on Evaporative Emissions from Modern Cars* Institute for Environment and Sustainability – European Commission 2007

[13] op. cit. Voegele

[14] op. cit Energy Independence and Security Act of 2007

[15] Roberts, M., *E85 and Fuel Efficiency: An Empirical Analysis of 2007 EPA Test Data* Energy Policy The International Journal of the Political, Economic, Planning, Environmental and Social Aspects of Energy (2008)

[16] "The great ethanol debate." Consumer Reports, January 2011. http://www.consumerreports.org/cro/cars/new-cars/news/ethanol/overview/index.htm

[17] U.S. EPA-420-F-09-023, May 2009

[18] Ryan, C., Munz, D., Bevers, G., 'Isobutanol – A Renewable Solution for the Transpiration Fuels Value Chain' Pipeline stress corrosion cracking (SCC) and elastomeric compatibility. http://www.biofuelstp.eu/downloads/wp-isob-gevo.pdf

[19] Guibet, J.C, Chauvel, A., 'Utilisation de produits organiques oxygenes comme carburants et combustibles dans les moteurs' Editions Technip Vol 36 No. 5 Septembre-Octobre 1981

[20] 2011 NPRA Annual Meeting Presentation: Top Ten Reasons to Use Isobutanol, San Antonio, TX, Dave Munz, Gevo

[21] 2012 OPEI Annual Meeting, Presentation: Commercializing Isobutanol: The Next Generation of Biofuels, Colorado Springs, Chris Ryan, Gevo …Gautam, M., Martin, D., EMISSIONS CHARACTERISTICS OF HIGHER ALCOHOL/GASOLINE BLENDS, Chapter 20 - Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV

[22] 2011 International Biorefining Conference, Presentation: Gasoline Blendstocks and Drop-In Replacement Fuels, Houston, TX, Dave Munz, Gevo

[23] op. cit Ryan, C.

[24] op. cit, Munz, D, 2011.

[25] Gui, N. Sridhar, M. Peters, Compatibility of Carbon Steel with Isobutanol, 2011 NACE Corrosion International - Paper Number 11139 F. DNV Dublin, OH

[26] op. cit, Munz, D, 2011.

[27] Bata, R., Elrod, A., "Butanol as a Blending Agent with Gasoline for I. C. Engines", Clemson University, Clemson, SC SAE 890434

[28] An alternative fuel for spark ignition engines, A Hull - Institute for Surface Chemistry, Stockholm, Sweden, I Golubkov - Swedish Biofuels AB, Stockholm, Sweden, B Kronberg, T Marandzheva - Tuchkov Most, Sankt-Peterburg, Russia and J van Stam - Department of Physical Chemistry, Karlstads University, Karlstad, Sweden

[29] Serras-Pereira, J., Wallace, S., Aleiferis, P.G., Characteristics of Ethanol, Butanol, Iso-Octane, and Gasoline

Sprays and Combustion from a Multi-Hole Injector in a DISI Engine SAE paper 2008-01-1591
[30] ibid.
[31] op. cit Energy Independence and Security Act of 2007
[32] op. cit, Serras-Periera, J.
[33] op. cit, Bata, R.
[34] op. cit, Kronberg, T.
[35] op. cit. Serras-Periera, J.
[36] op. cit Energy Independence and Security Act of 2007
[37] U.S EPA, Guidance on New Fuel Pathway Approval Process http://www.epa.gov/otaq/fuels/renewablefuels/compliancehelp/rfs2-lca-pathways.htm
[38] 2011 OPIS RINS and RFS Forum, Presentation: Advanced Biofuels, Chicago, IL, Dave Munz, Gevo
[39] op. cit, Bata, R.
[40] op. cit, Kronberg, T.
[41] Organization for Economic Cooperation and Development (OECD) SIDS CAS No: SIDS Initial Assessment Report 78-83-1
[42] Defining maximum levels of higher alcohols in alcoholic beverages and surrogate alcohol products, Dirk W. Lachenmeier and Simone Haupt - Chemisches und Veterinaruntersuchungsamt (CVUA) Karlsruhe, Weißenburger Strasse 3, D-76187 Karlsruhe, Germany, and Katja Schulz - Institut fur Rechtsmedizin, Technische Universitat Dresden, Fetscherstrasse 74, D-01307 Dresden, Germany
[43] op. cit, U.S EPA, Guidance on New Fuel Pathway Approval Process.
[45] International Council of Marine Industry Associations
[46] U.S. EPA 40 CFR Part 1045.515 Control of Emissions From Nonroad Spark-Ignition Engines and Equipment
[47] Knoll, K et al., ‘Effects of Intermediate Ethanol Blends on Legacy Vehicles and Small Non-Road Engines’ National Renewable Energy Laboratory Report 1 – Updated, February 2009 Oak Ridge National Laboratory
[49] ibid.
[50] Wasil, J., Johnson, J., Singh, R., ‘Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine’ SAE Paper 2010-32-0054
[51] op. cit, Knoll, K.
[52] op. cit. Wasil, J.

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ISOBUTANOL Marine Test Program Report

Draft

J.Wasil

07/15/2011

Tests conducted on 06/14/2011 in Annapolis, MD using the Portable Marine Bag Sampler (MPSS) developed by BRP
Samples analyzed at Volvo-Penta

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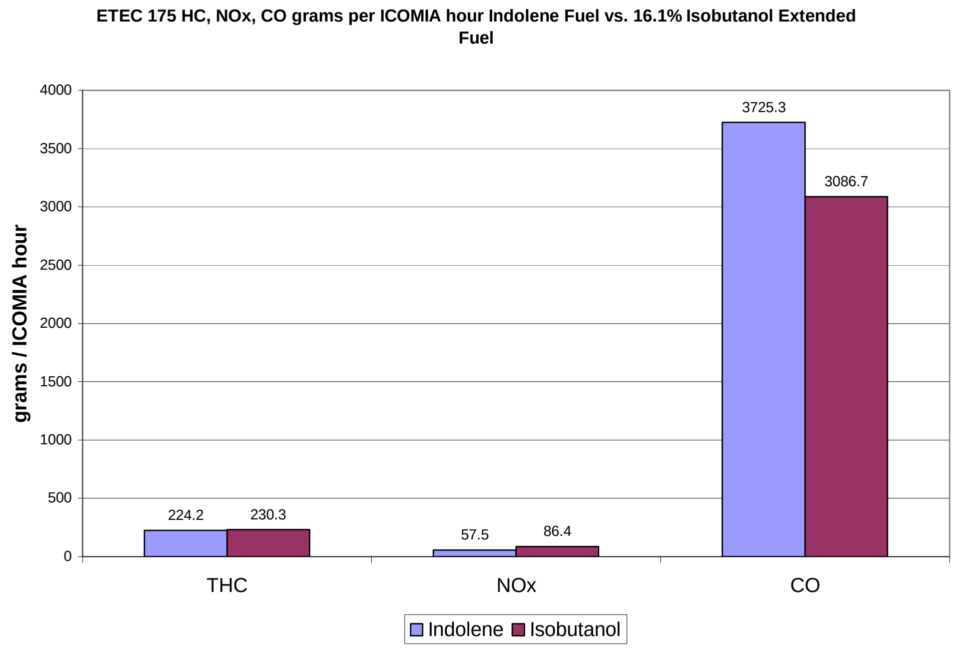
Rich Kolb – Volvo-Penta

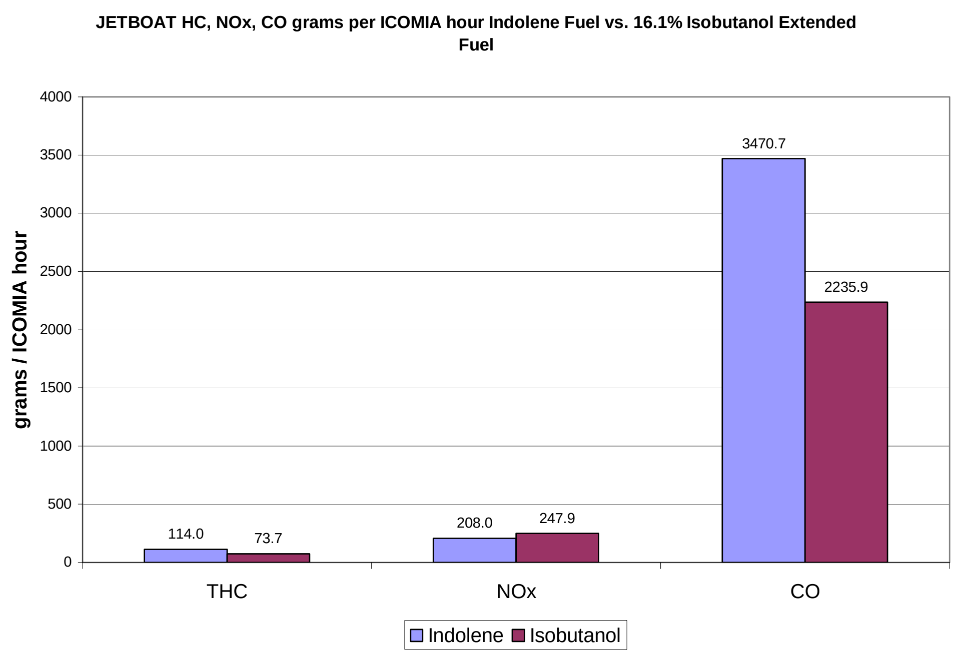
Test Oversight:
John McKnight – NMMA
John Adey – ABYC
Margaret Podlich – BoatUS
Dick Rowe – Indmar
Dave Munz – Gevo
Glen Johnston - Gevo

Evinrude E-TEC 175 Stratified Charged Direct Fuel Injection Two-Stroke on water emissions evaluation – 21' Mako Boat Test Set-up

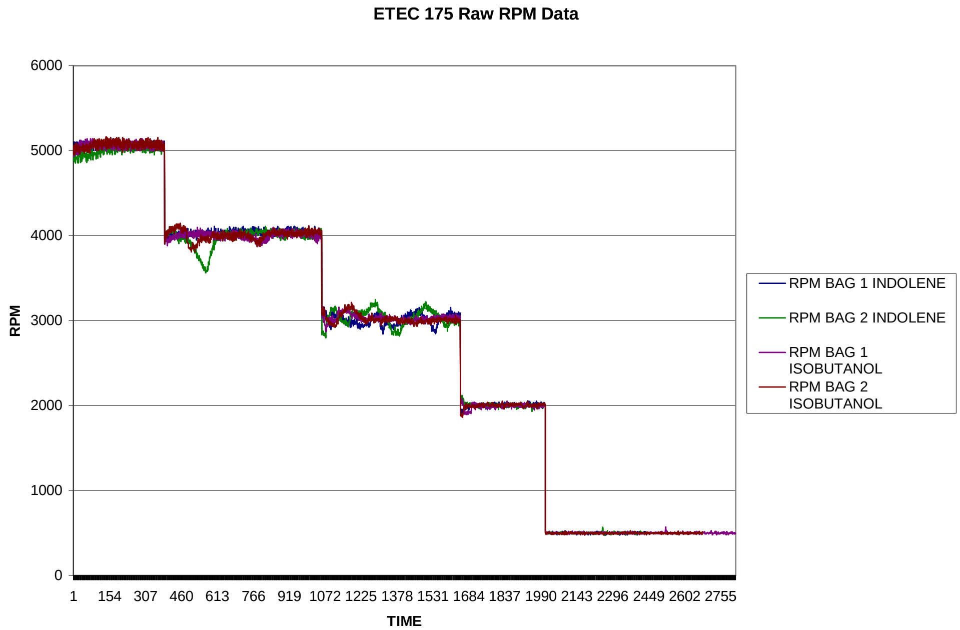
SeaDoo Challanger Jet-boat on water emissions evaluation Rotax 1503 Supercharged Four-stroke engine test set-up



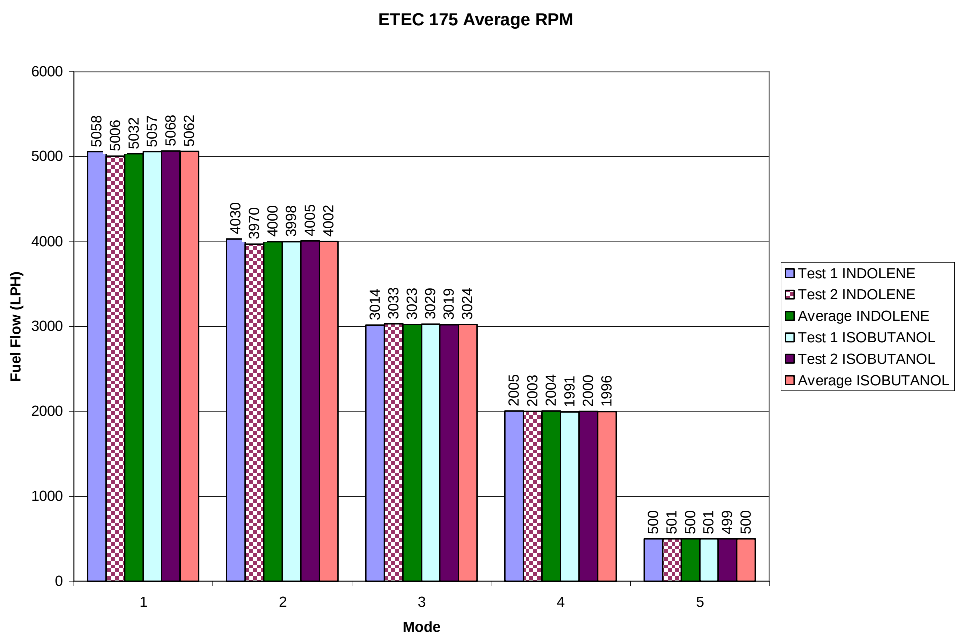
Evinrude E-TEC 175 Stratified Charged Direct Fuel Injection Two-Stroke on water emissions evaluation [HC, NOx, CO] – 21' Mako Boat. Comparison between Indolene fuel and 16.1% isobutanol extended fuel. Values in grams per ICOMIA hour average of two tests per fuel type



SeaDoo Challanger Jet-boat on water emissions evaluation [HC, NOx, CO] – Rotax 1503 Supercharged Four-stroke engine. Comparison between Indolene fuel and 16.1% isobutanol extended fuel. Values in grams per ICOMIA hour average of two tests per test fuel.

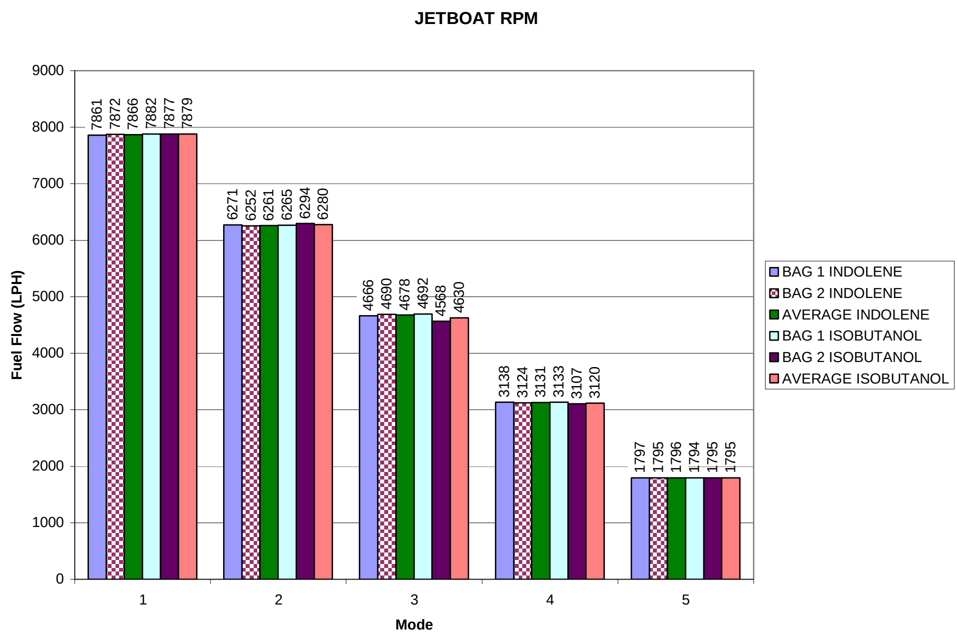


Evinrude E-TEC 175 Stratified Charged Direct Fuel Injection Two-Stroke on water emissions evaluation – 21' Mako Boat. Plot of Raw Engine RPM

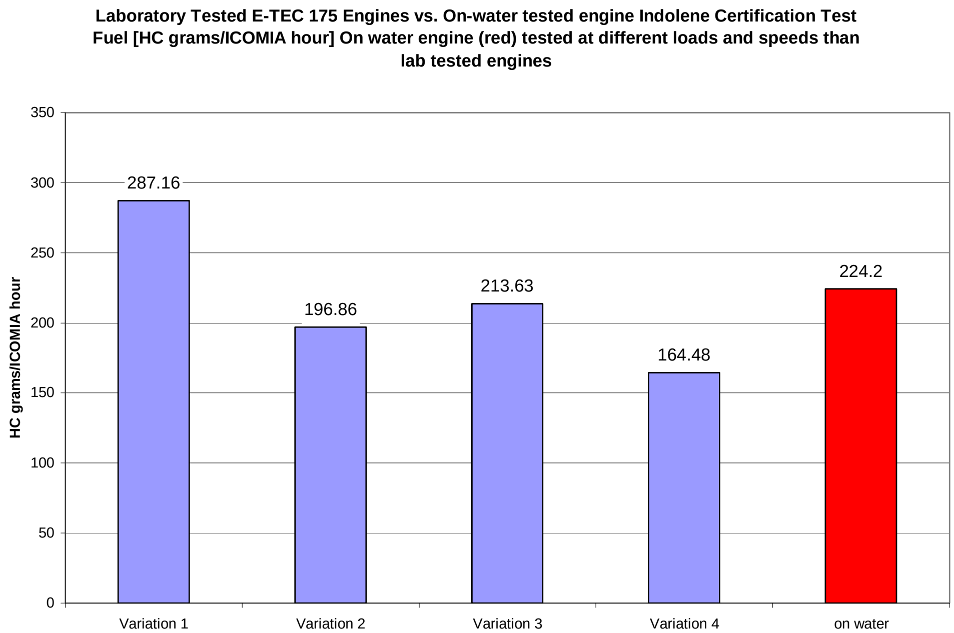


Evinrude E-TEC 175 Stratified Charged Direct Fuel Injection Two-Stroke on water emissions evaluation – 21' Mako Boat. Average engine RPM Indolene and Isobutanol

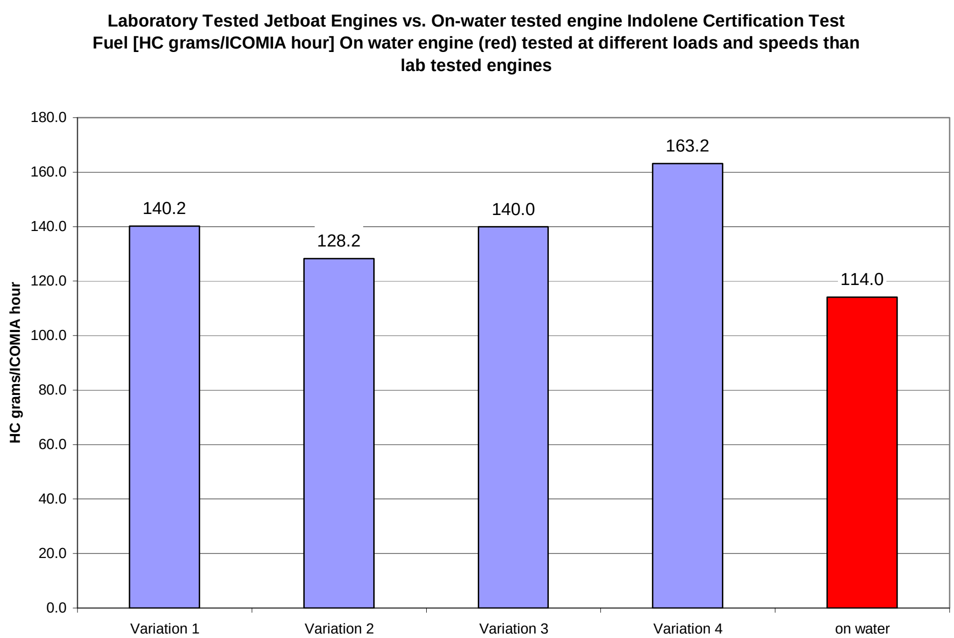
SeaDoo Challanger Jet-boat on water emissions evaluation– Rotax 1503 Supercharged Four-stroke engine. Comparison between Indolene fuel and 16.1% isobutanol extended fuel. Plot of raw engine RPM



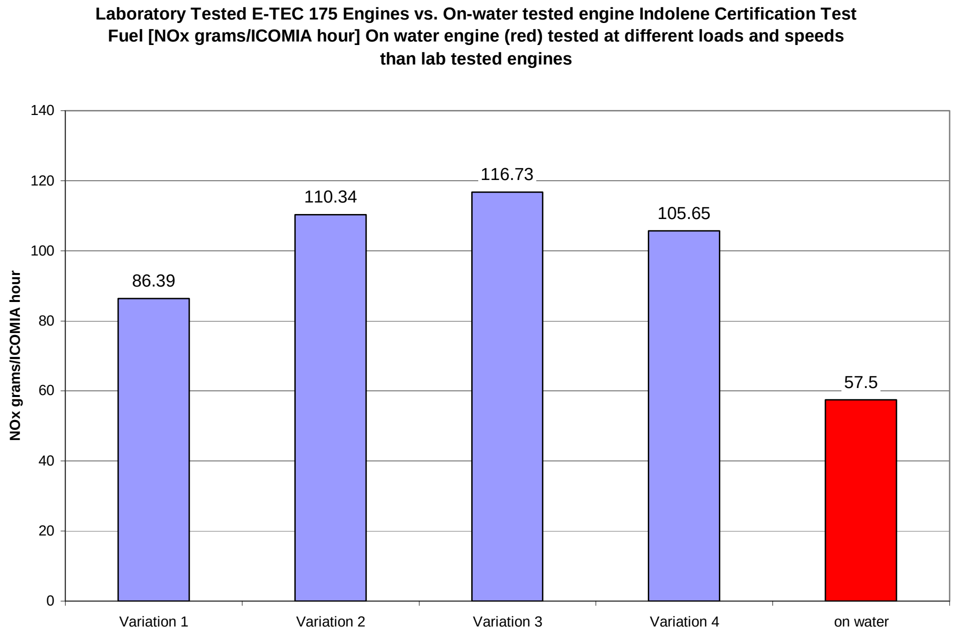
SeaDoo Challanger Jet-boat on water emissions evaluation– Rotax 1503 Supercharged Four-stroke engine. Average engine RPM Indolene and Isobutanol



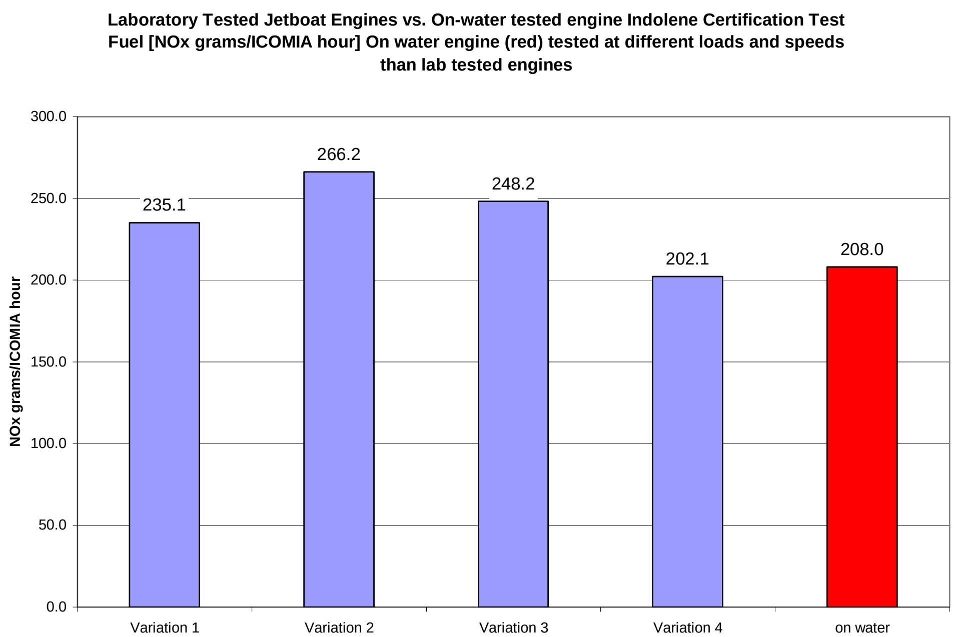
HC Variation – Comparison of laboratory tested E-TEC 175's vs. on-water E-TEC 175. On water evaluation is tested at different speeds and loads than laboratory tested engines.



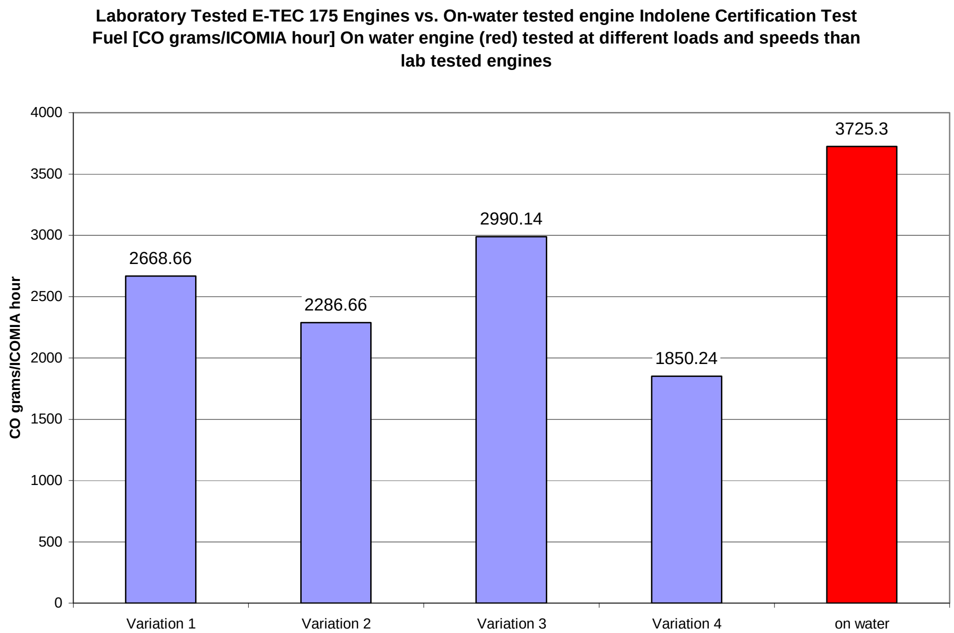
HC Variation – Comparison of laboratory tested Jetboat engines vs. on-water Jetboat. On water evaluation is tested at different speeds and loads than laboratory tested engines.



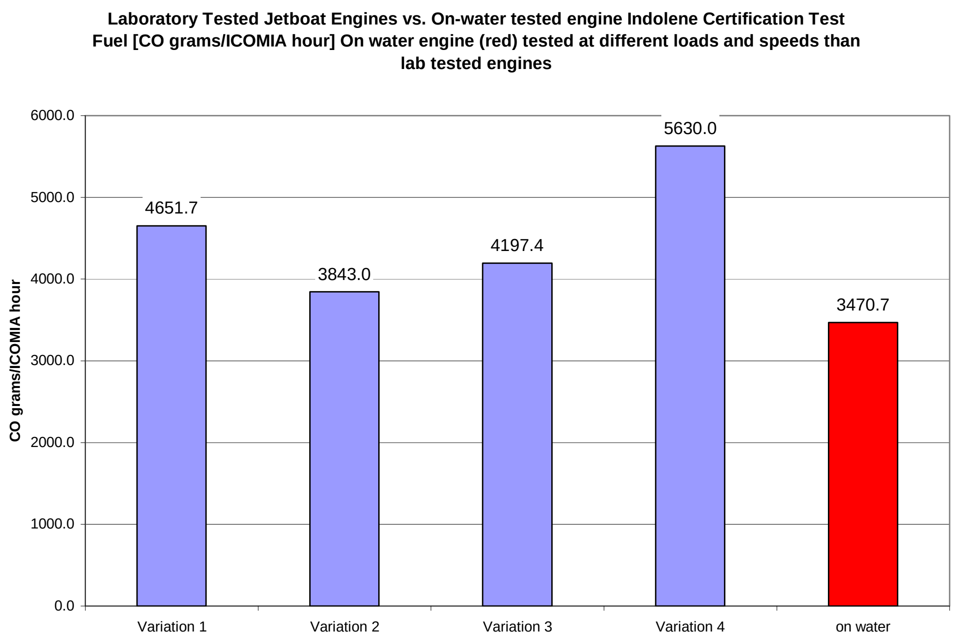
NOx Variation – Comparison of laboratory tested E-TEC 175's vs. on-water E-TEC 175. On water evaluation is tested at different speeds and loads than laboratory tested engines.



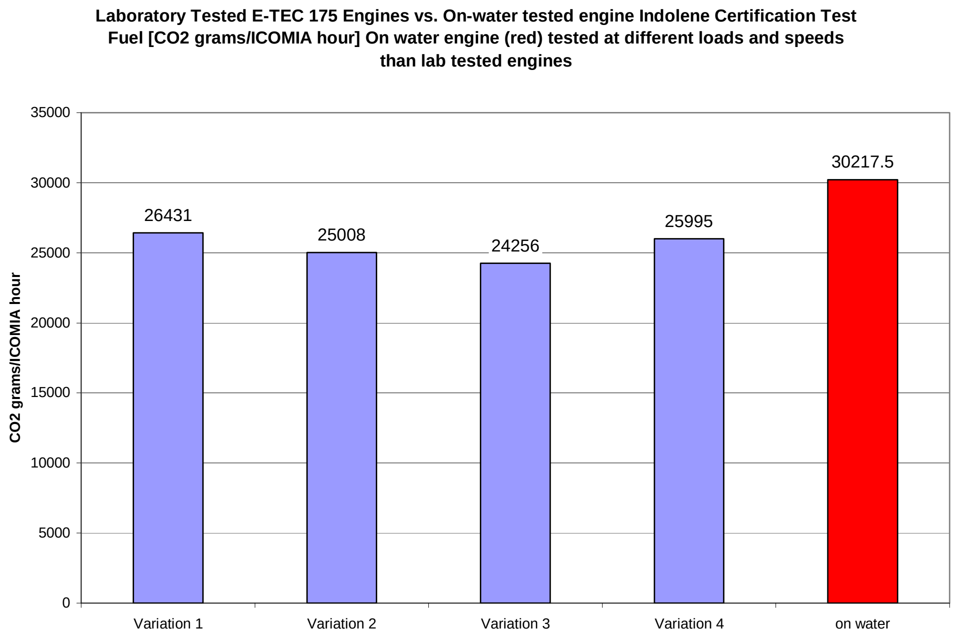
NOx Variation – Comparison of laboratory tested Jetboat engines vs. on-water Jetboat. On water evaluation is tested at different speeds and loads than laboratory tested engines.



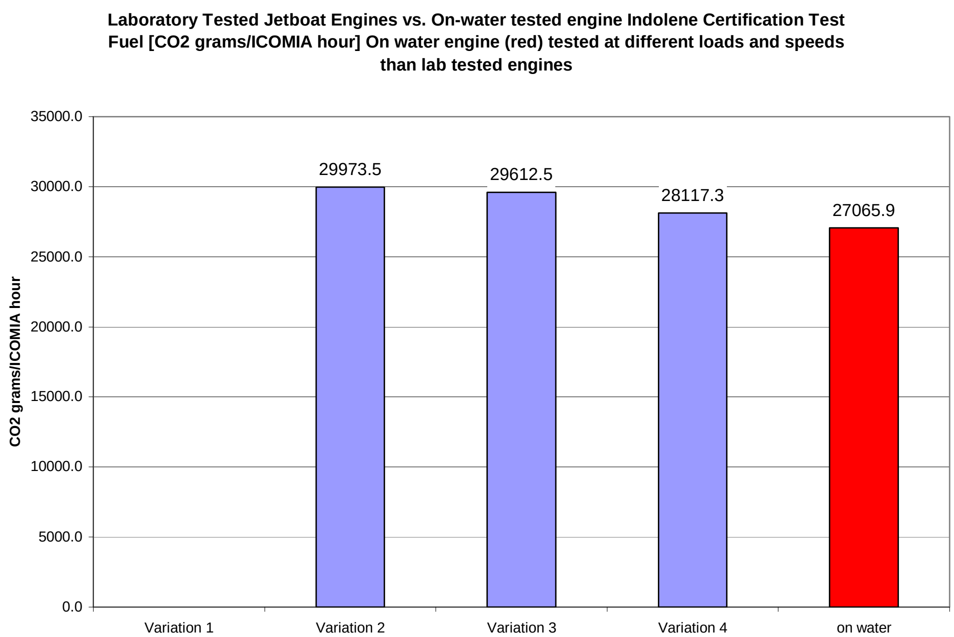
CO Variation – Comparison of laboratory tested E-TEC 175's vs. on-water E-TEC 175. On water evaluation is tested at different speeds and loads than laboratory tested engines.



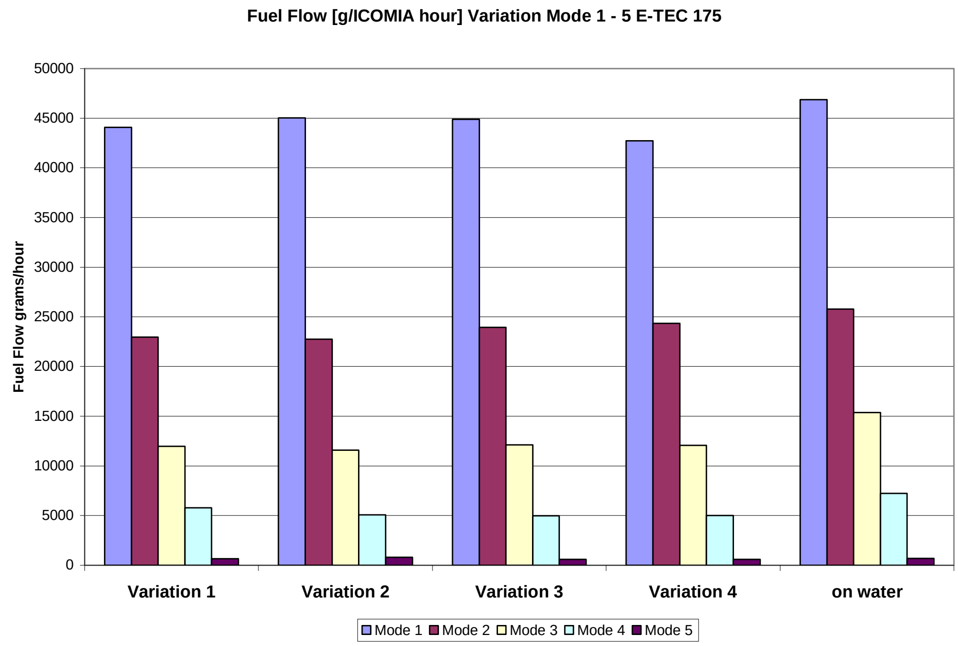
CO Variation – Comparison of laboratory tested Jetboat engines vs. on-water Jetboat. On water evaluation is tested at different speeds and loads than laboratory tested engines.



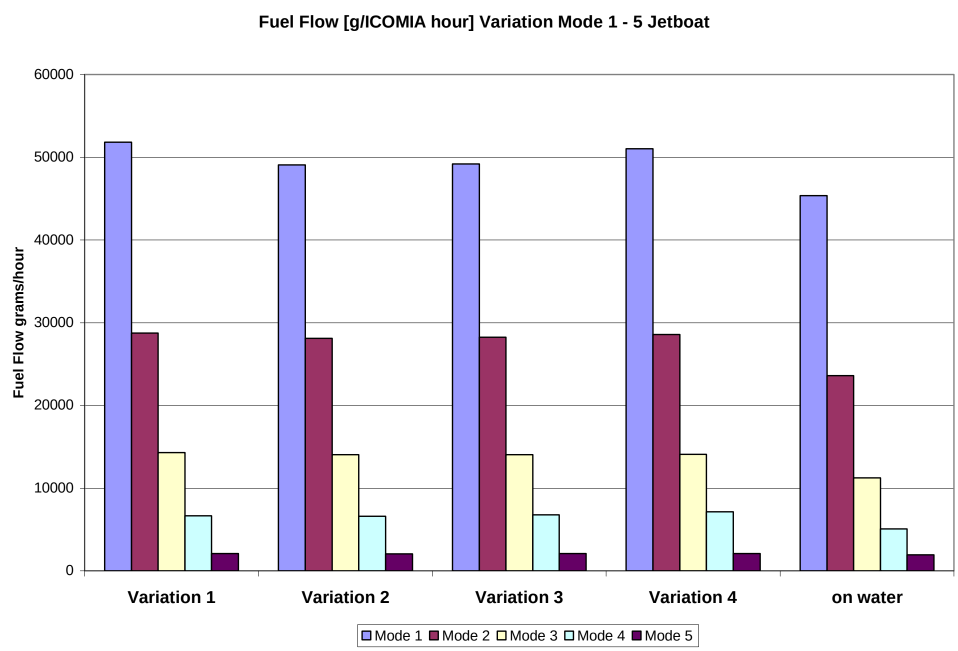
CO2 Variation – Comparison of laboratory tested E-TEC 175's vs. on-water E-TEC 175. On water evaluation is tested at different speeds and loads than laboratory tested engines.



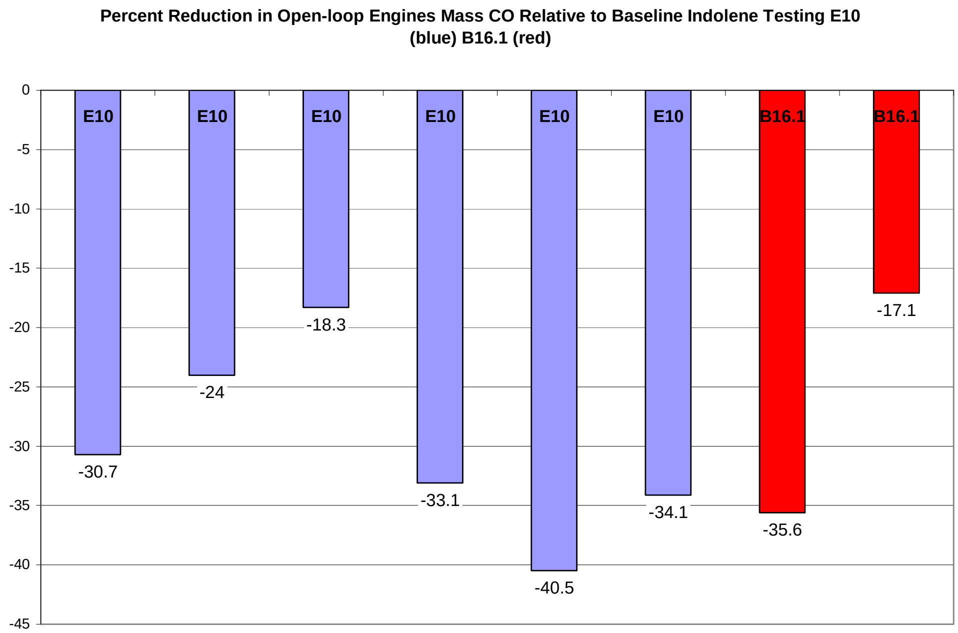
CO2 Variation – Comparison of laboratory tested jetboat engines vs. on-water jetboat. On water evaluation is tested at different speeds and loads than laboratory tested engines.



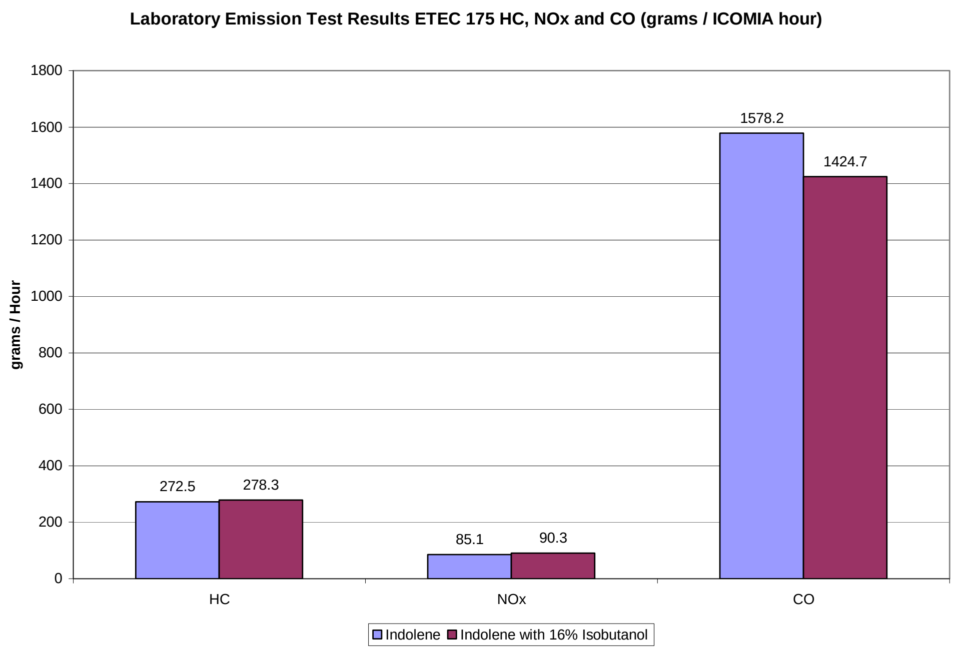
Fuel Flow [grams/ICOMIA hour] Variation – Comparison of laboratory tested E-TEC 175's vs. on-water E-TEC 175. On water evaluation is tested at different speeds and loads than laboratory tested engines.



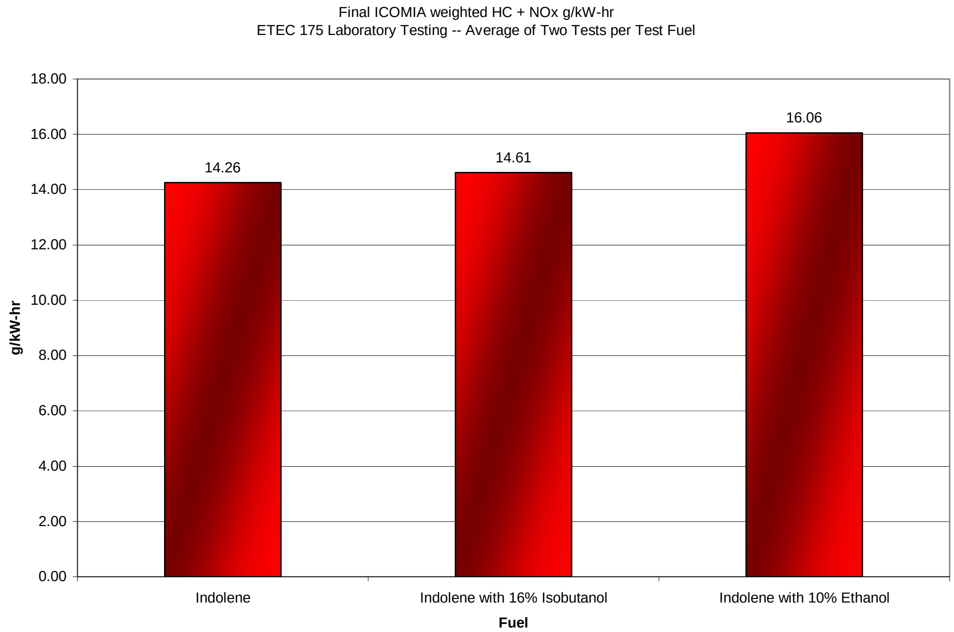
Fuel Flow [grams/ICOMIA hour] Variation – Comparison of laboratory tested jetboat engines vs. on-water jetboat. On water evaluation is tested at different speeds and loads than laboratory tested engines.



Typical Engine Enleanment Relative to Indolene E-10 vs. B16. E10 engine CO data as reported by DOE (Knoll et al.)



ETEC 175 Laboratory Testing Indolene vs. Isobutanol 16%. Average of two tests per test fuel HC, NOx, CO grams / ICOMIA hour



ETEC 175 Laboratory Testing Indolene vs. Isobutanol 16% vs Ethanol 10% . Average of two tests per test fuel HC, NOx, CO grams / kW-hr

Effect of Fuel Contamination of Lubrication with Marine Engine Oil

Layo Ajayi, Cinta Lorenzo-Martin, and George Fenske
Tribology Group, Energy Systems Division
Argonne National Laboratory

Project Update
October 25, 20102

Background

- DOE has program to evaluate the use of bio-derived fuels (ethanol and butanol) addition for fuel extension in a variety of marine engines.
- Engine tests to evaluate the impact of the fuel on various performance characteristics are on-going.
- One aspect under investigation is the impact of fuel on engine lubrication
  - Fuel dilution of engine oil is expected
- Bench-top laboratory friction and wear tests are ongoing to evaluate the impact of various fuel contamination/dilution.
  - This is a status update report on the lubrication bench top testing.

Test Plan

- Four different types of tests to evaluate friction, wear and scuffing attributes of the fuel diluted engine oils
  - Unidirectional sliding (friction and wear)
  - Reciprocating sliding (friction and wear)
  - Four ball (wear)
  - Block on ring (scuffing)

- Three groups of engine oils for testing
  - Fresh engine oil (Yamalube 4M 10W-30)
  - Surrogate model oils with 5, 10, 20, 30, 50% of fuel added
    - Three fuels were tested – E0, E10, B16
  - Used engine oil from Yamaha test subjected to many cold start cycles
    - Details of Yamaha tests for generating used engine oil in the next few slides

Yamaha Isobutanol Test

Purpose

- To evaluate the effects of dilution and friction/wear on E-0, E-10 and B-16 comparatively
- To seek alternatives for E-15 such as Isobutanol

Test Details

- 3 sets of 60 cycles each were performed on E-0, E-10 and B-16
- 1 cycle = 2 minutes idle / 2 minutes WOT
- Each 60 cycle pattern consisted of 3 sets of 15 cycles with E/G off for 10 min @ 5 cycle intervals
- 100 ml samples were taken @ 15 cycle intervals
- Engine oil was flushed completely, twice at start of test and between each fuel change
- E-0 fuel supplied by Yamaha Test Facility
- E-10 and B-16 fuel supplied by Gevo
- Measured data included E/G RPM, E/G water temp, E/G oil sump temp and sea water temp

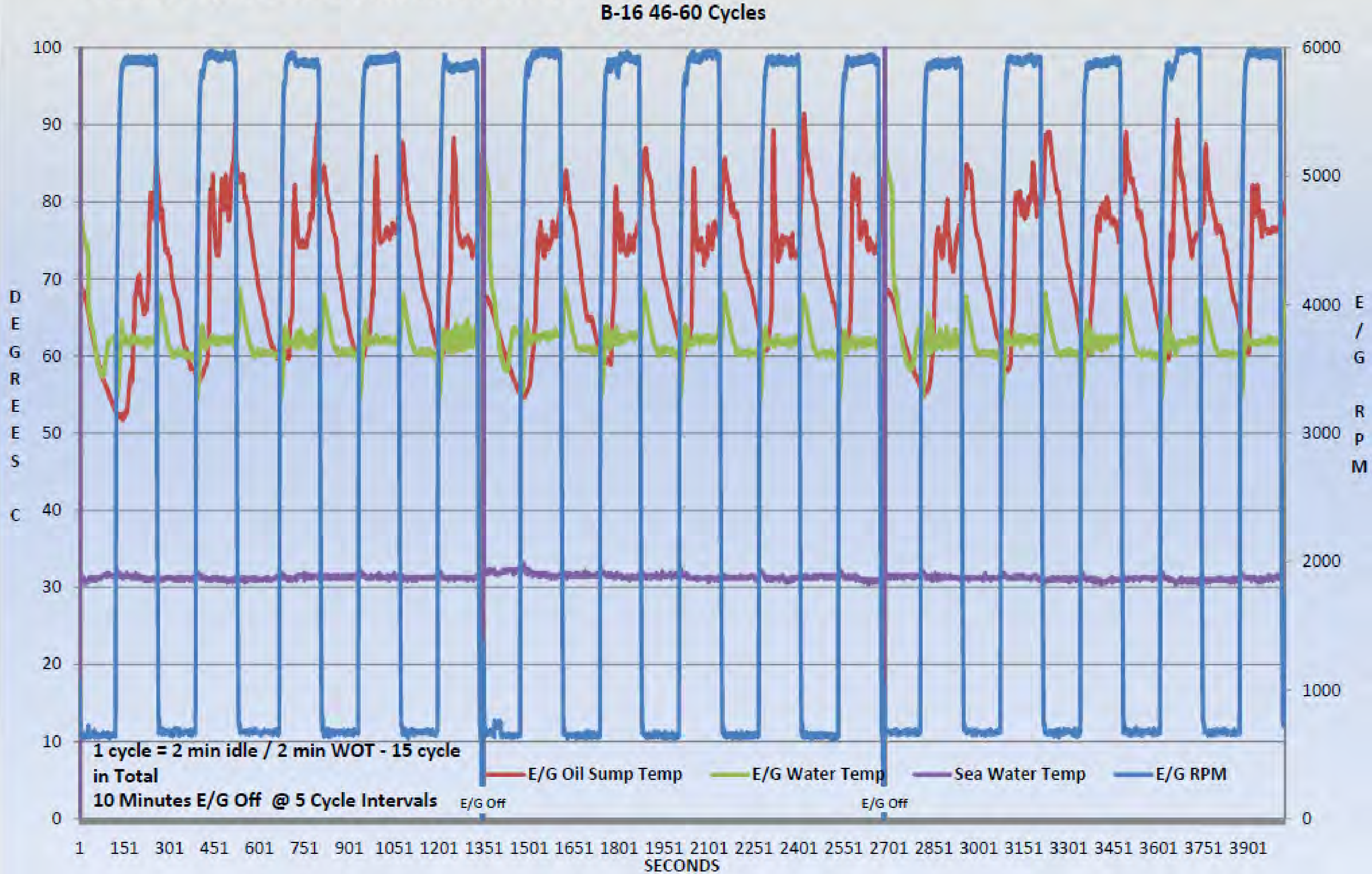
Equipment Used

- Century 1900 Bay
- Yamaha F150
- Portable 12 gallon deck mounted fuel tanks
- 1 man operating boat with 2 men supporting

Provided by John Corlett of Yamaha

Yamaha Isobutanol Test 7/9/2012-7/13/2012

- Test Cycle Sample of B-16, Cycles 46-60 Shown
- All Test Cycle Data is Attached in Additional File

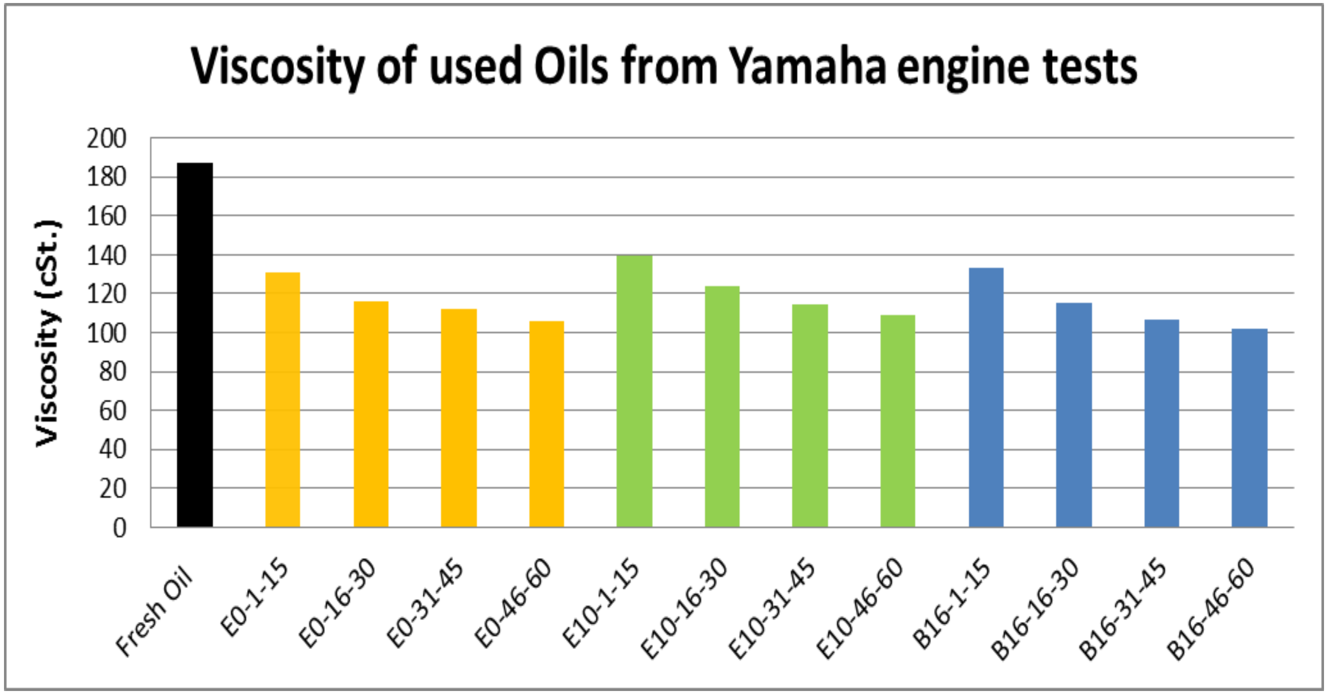


Provided by John Corlett of Yamaha

Viscosity Results from Used Oil samples from Yamaha Engine test

- Significant reduction in viscosity for the used oil compared to the fresh oil.
  - The decrease is nearly linear with increasing number of cycles.

Fluid	Viscosity RT (cSt.)
Yamalube Fresh Oil	187.4
E0-1-15	131.0
E0-16-30	115.8
E0-31-45	112.0
E0-46-60	105.9
E10-1-15	139.9
E10-16-30	123.5
E10-31-45	114.8
E10-46-60	108.8
B16-1-15	133.6
B16-16-30	115.6
B16-31-45	106.8
B16-46-60	101.6



Fuel Content of used oil from Yamaha engine test

# of cycles	Fuel		
	E0	E10	B16
15 (1-15)	3.7	2.9	3.6
30 (16-30)	4.8	4.3	5.3
45 (31-45)	5.1	4.9	5.9
60 (46-60)	5.6	5.4	6.2

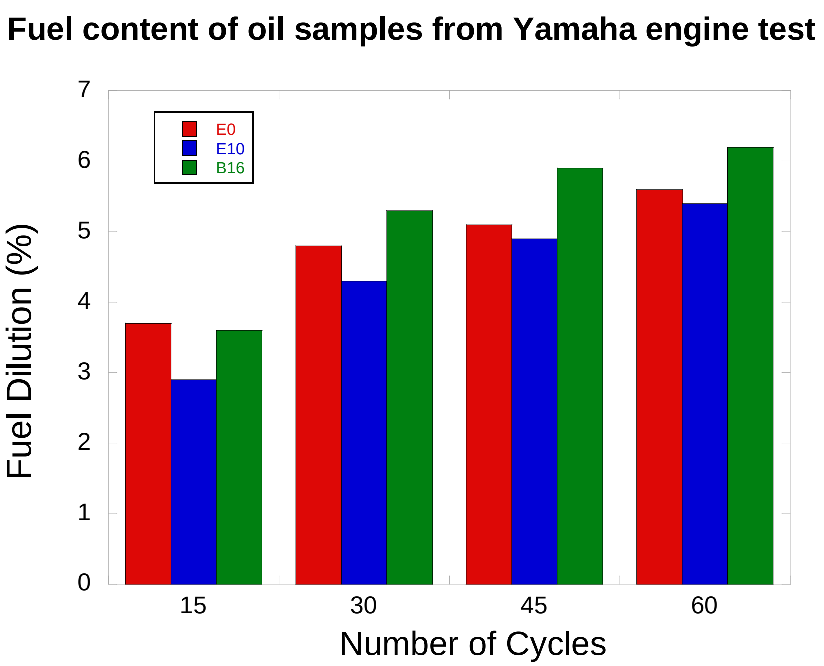
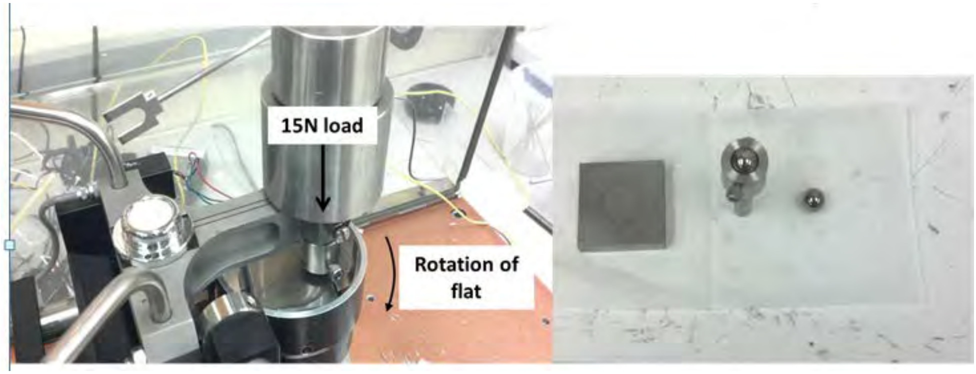


Table and plot of fuel content as a function of number of cycles in the used oil from the Yamaha engine tests

Unidirectional sliding test

- Ball- on-flat contact configuration
  - Ball : ½'' 52100 ball
  - Flat: Gray cast iron

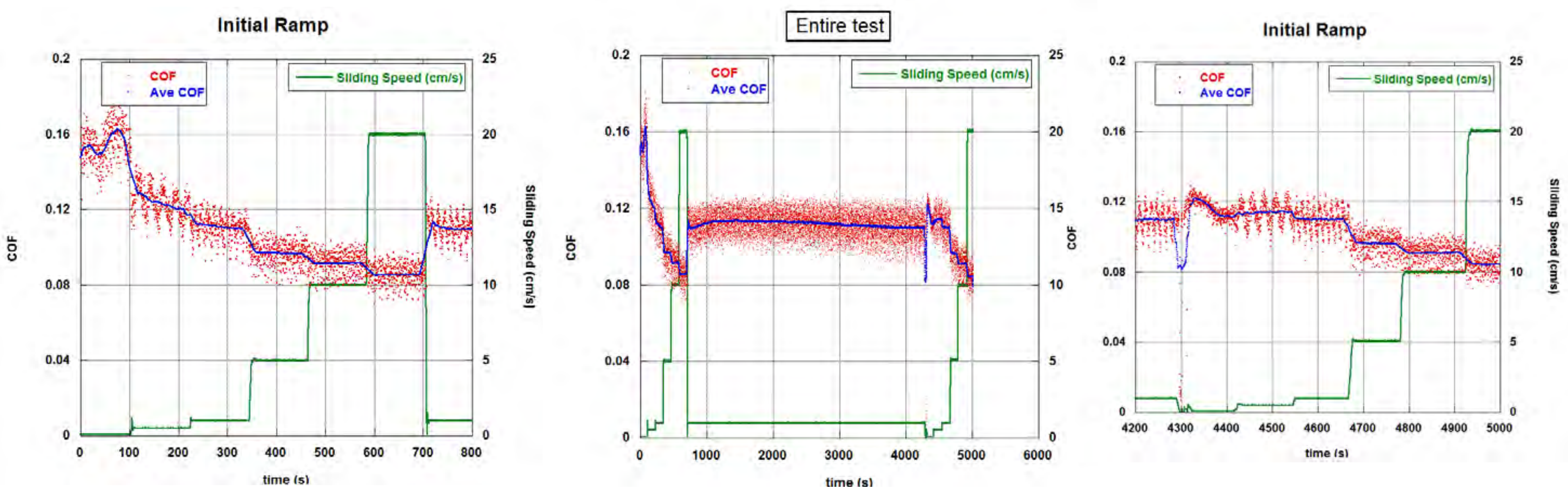


- Test parameters and procedure
  - Normal Load - 15 N
  - Temperature – RT
  - Sliding velocity -Variable
    - Sliding speed ramp cycle at beginning and end of test: 0.1 cm/s; 0.5 cm/s; 1.0 cm/s; 5.0 cm/s; 10.0 cm/s; 20.0 cm/s for 2 min. at each speed
    - Continuous monitoring for 1 hour at 1.0 cm/s

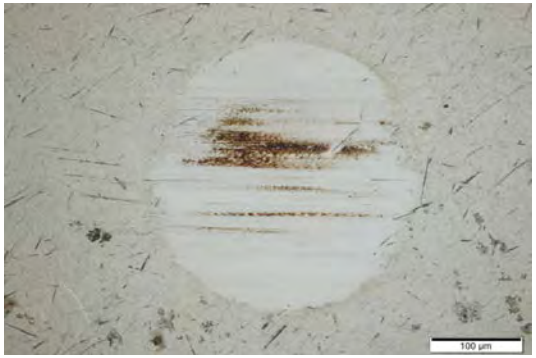
The speed ramp at the beginning and the end of test allows the assessment of transitions in the lubrication regimes and the friction behavior of different oil.

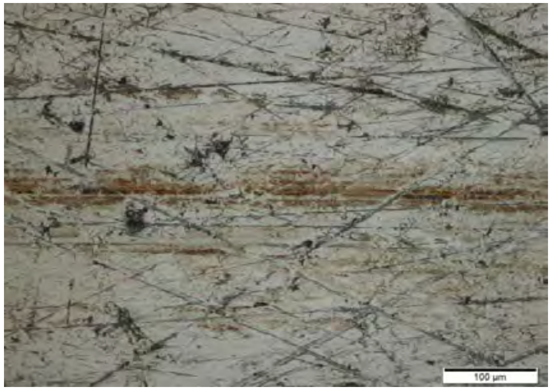
Typical Friction behavior

- During the slow speed of the initial ramp, boundary lubrication occurs. At high speed, there is transition to hydrodynamic or mixed lubrication regime.
- Average friction is determined from the 1 hr duration at 1 cm/sec.
- Effect of run-in is assessed by the friction behavior of the ramp at the end.

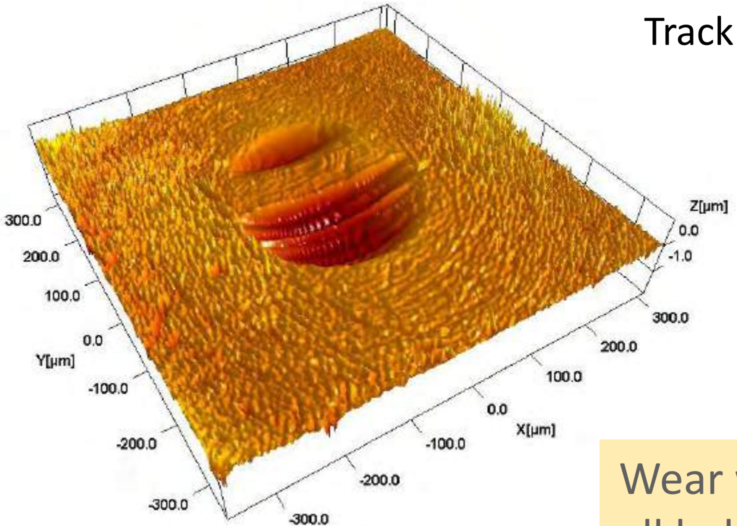


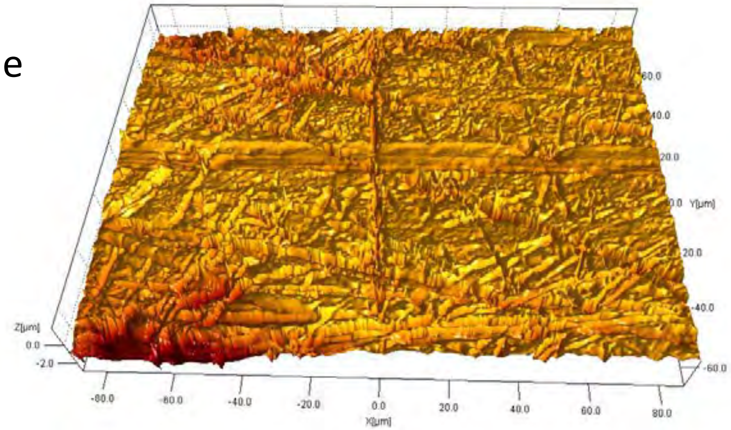
Wear measurements





<u>Wear volume (µm^3)</u>
Ball: 2.47E+04
Track: Not measurable

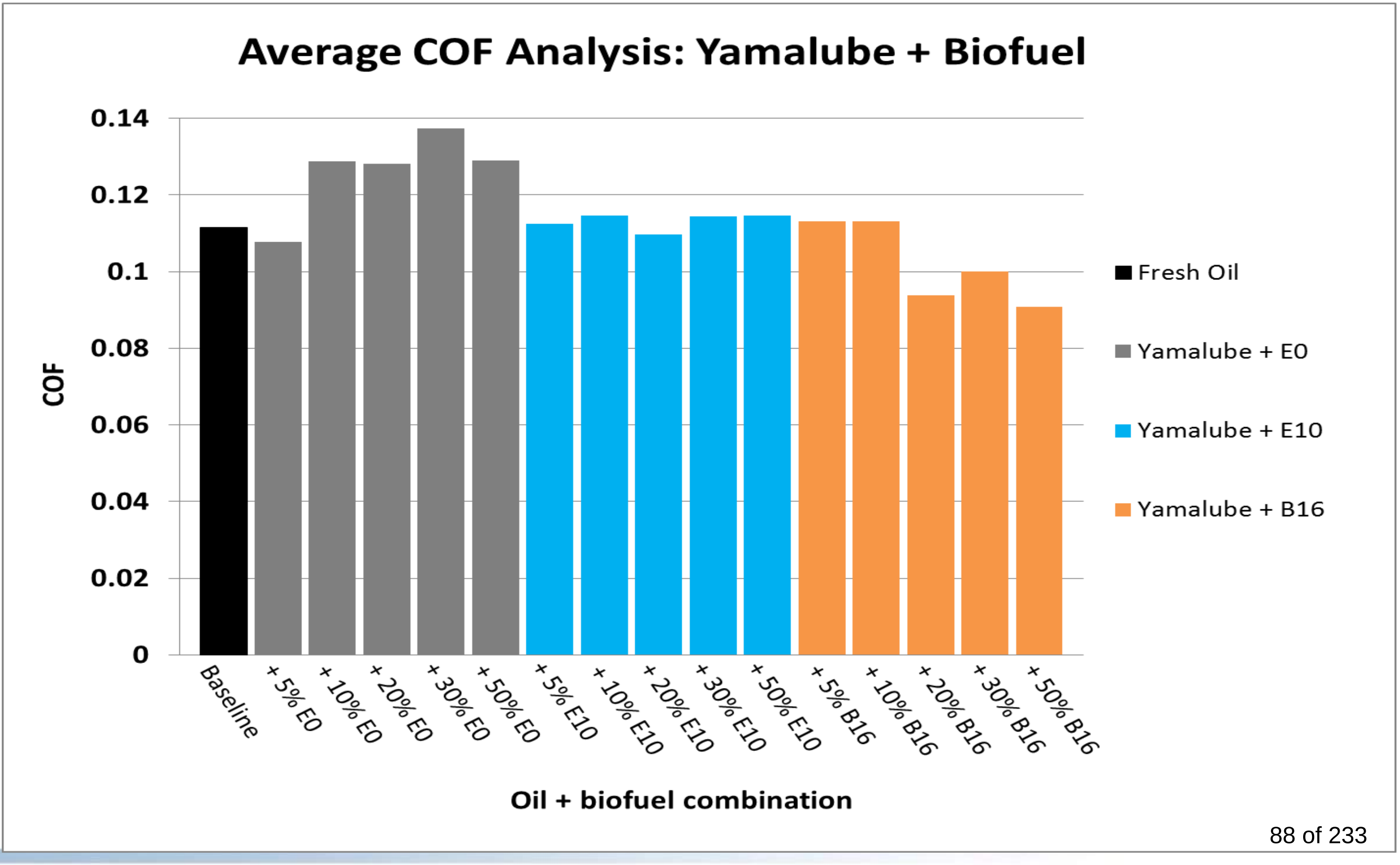




Wear was calculated for all ball scars. For most of the flats wear track was non-measurable.

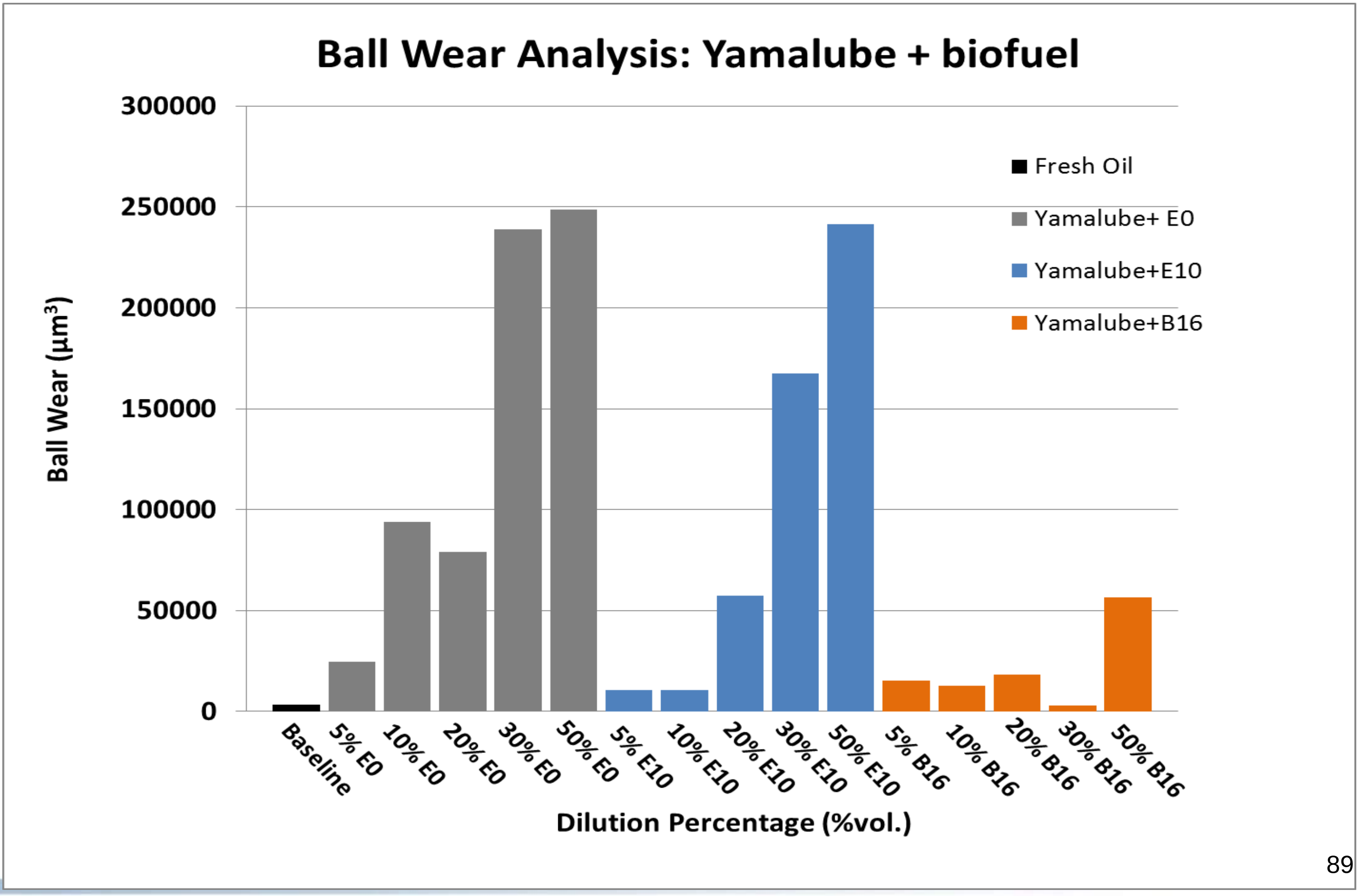
Friction Results for fresh and model surrogate oils

- The average friction is noticeable higher for oils with E0 dilution
- Average friction for oils with E10 and B16 dilution about same as fresh oil.

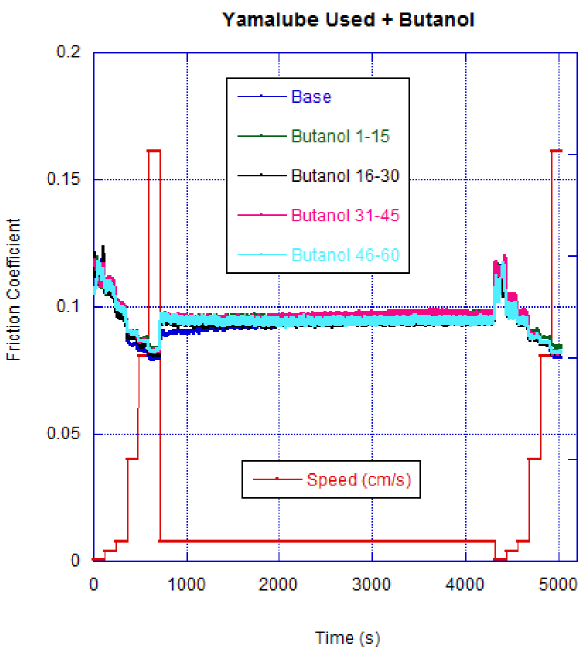


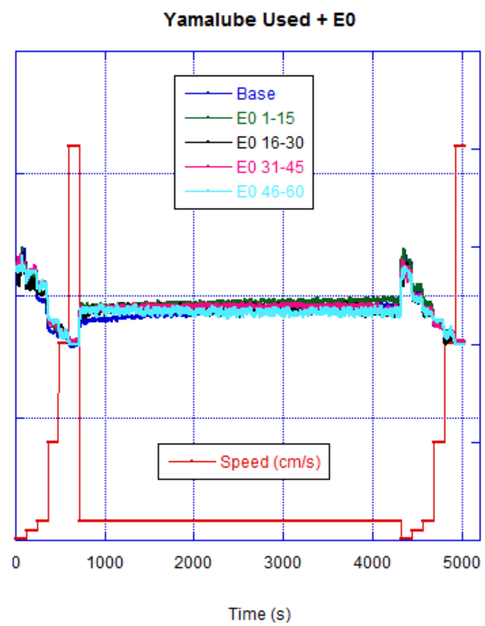
Wear Results for fresh and model surrogate oils

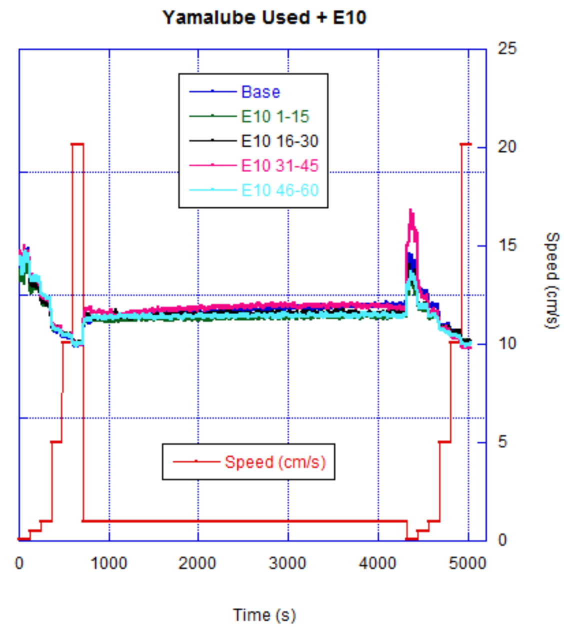
- Significant increase in wear with oil dilution with the three fuels.
  - E0 causes most increase in wear while B16 caused the least increase in wear
  - In general, the higher the level of fuel dilution, the more the wear.

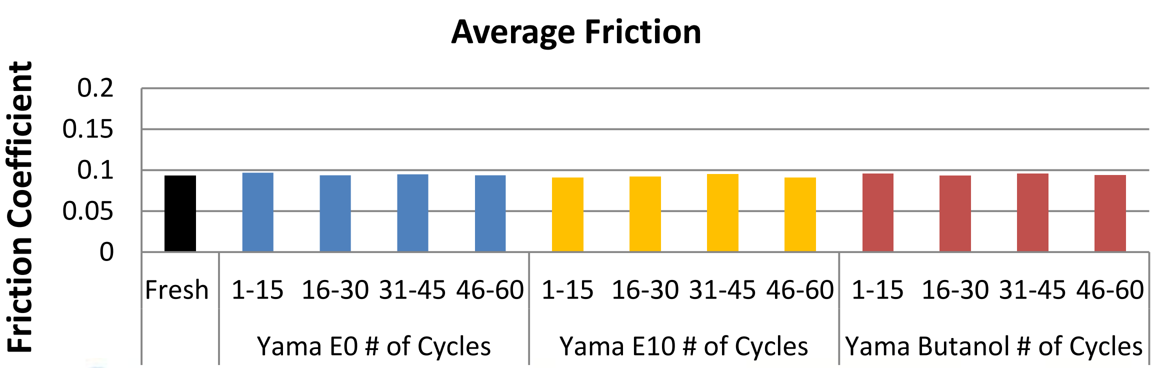


Friction results from test with used oils from Yamaha engine test



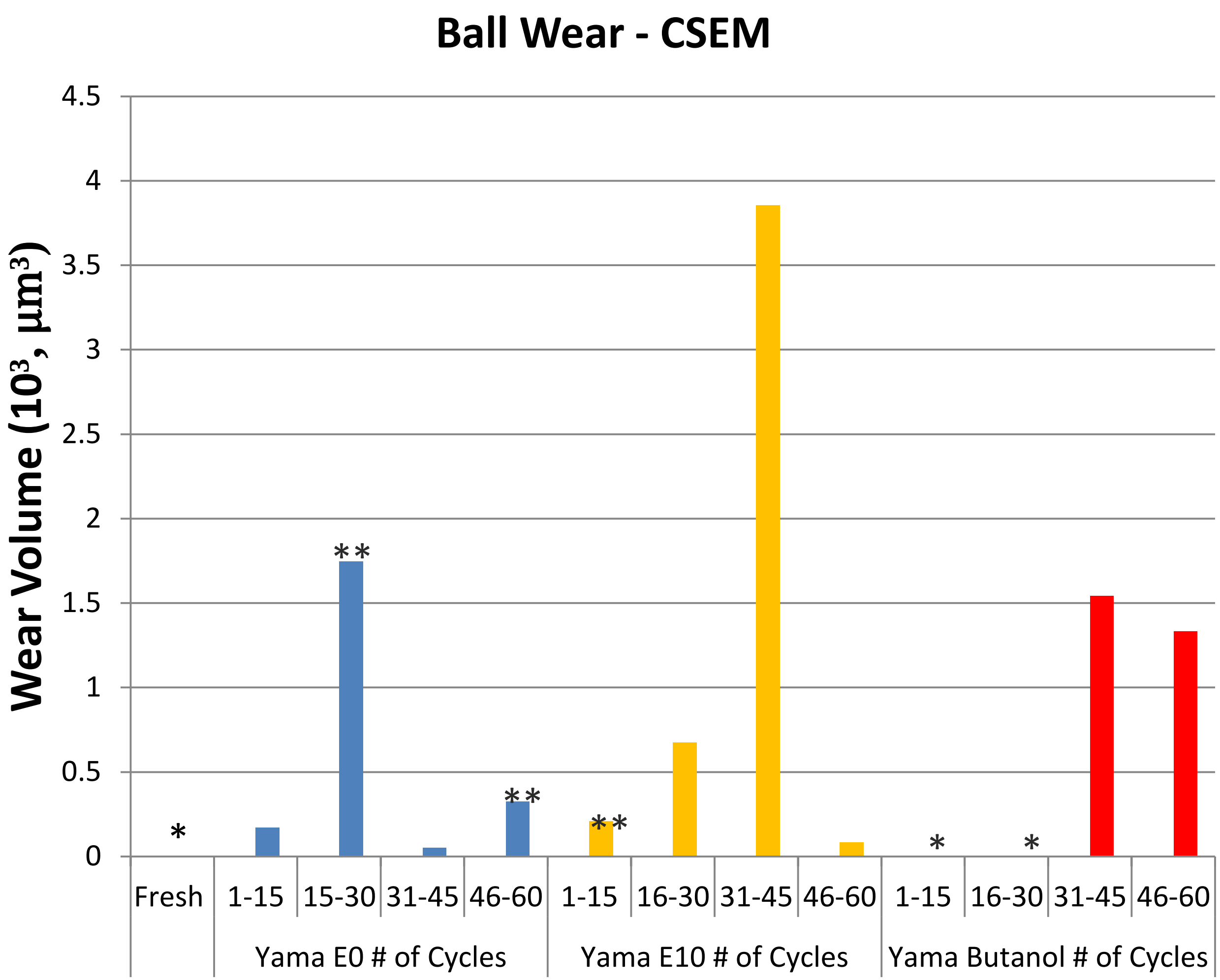






Preliminary results from unidirectional sliding tests showed that friction for used oil from the three fuels are nearly identical.

Friction results from test with used oils from Yamaha engine test



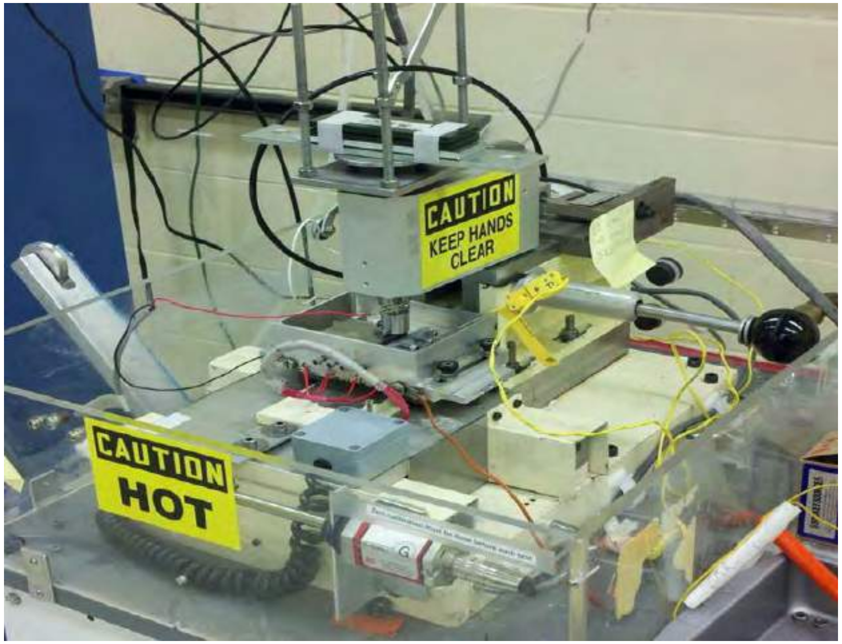
Preliminary results from unidirectional sliding tests showed that wear fuel dilution of engine oil sometimes results on more wear, sometimes no effect and in some cases resulted in the formation of deposits on the sliding surfaces

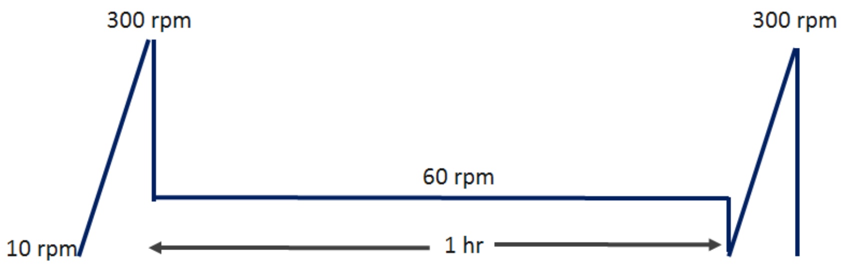
* No Measurable Wear   ** Deposit formation(No Wear)

Reciprocating sliding test

- Ball- on-flat contact configuration
  - Ball : ½'' 52100 ball
  - Flat: Gray cast iron

- Test parameters and procedure
  - Normal Load - 15 N
  - Temperature – RT
  - Stroke length – 20 mm
  - Sliding velocity -Variable





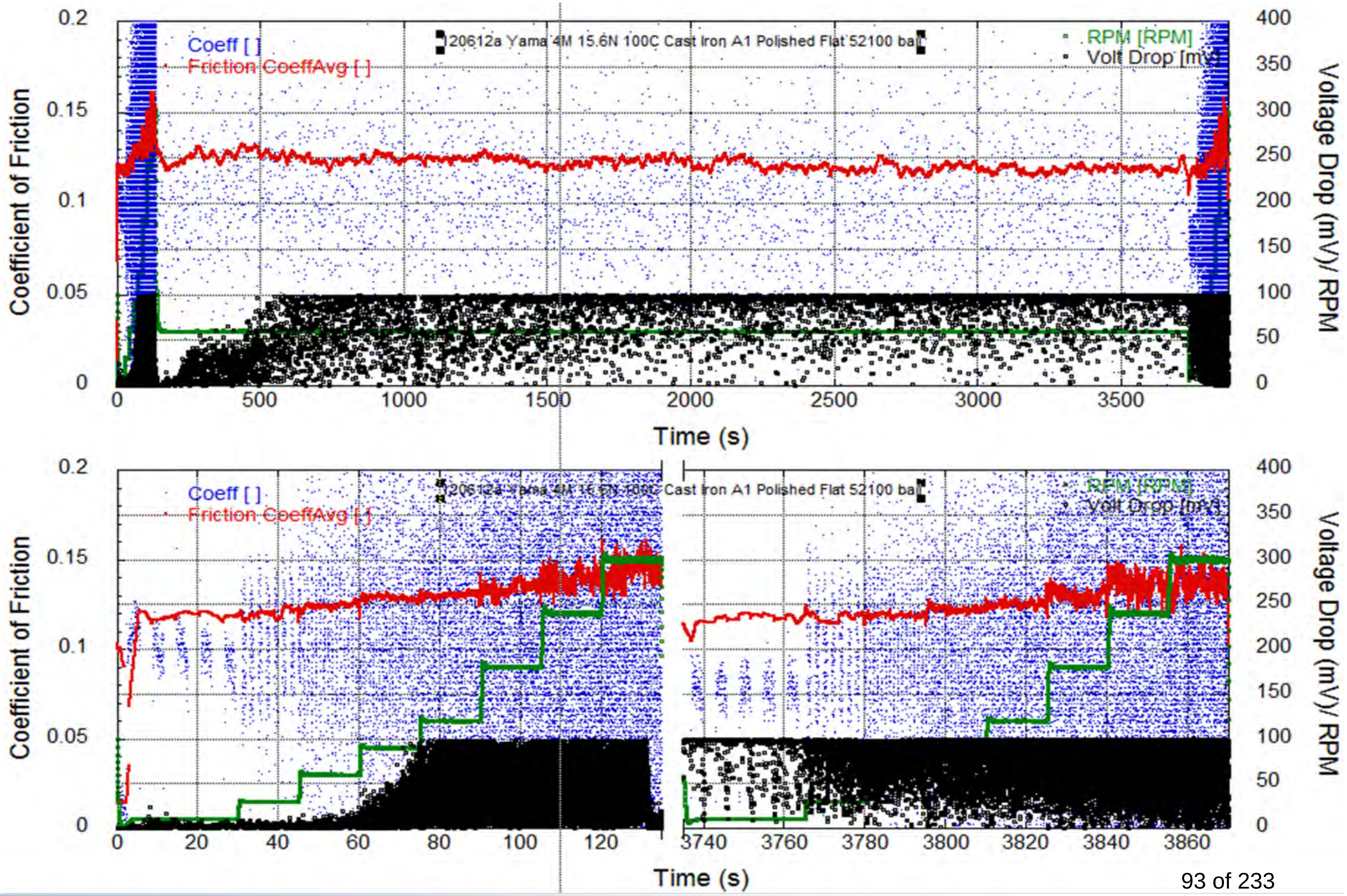
Speed profile

Cast Iron polished flat

52100 ball

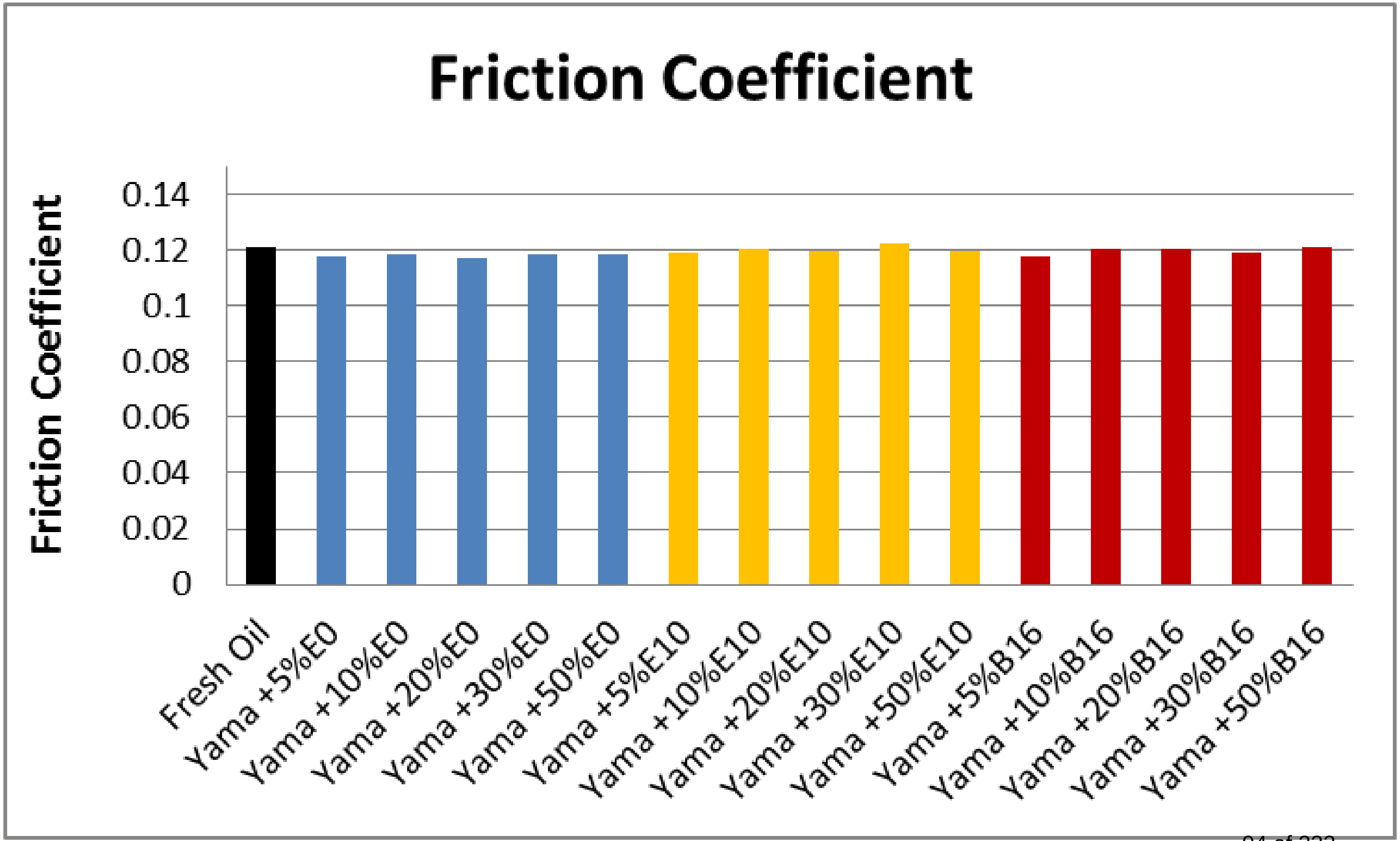
The speed ramp at the beginning and the end of test allows the assessment of transitions in the lubrication regimes and the friction behavior of different oil.

Typical Friction result from reciprocating sliding test



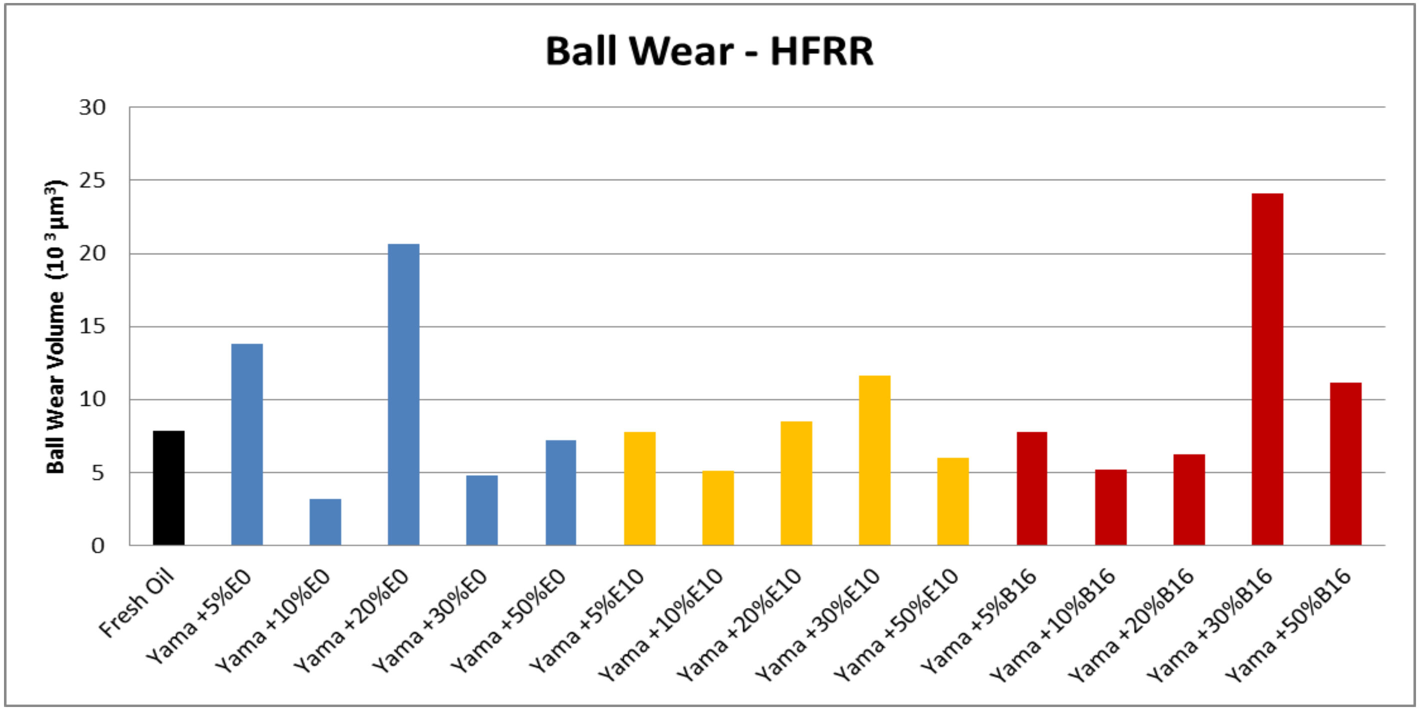
Results for reciprocating sliding friction for fresh and model surrogate oils

- Average friction for all the oils are nearly identical

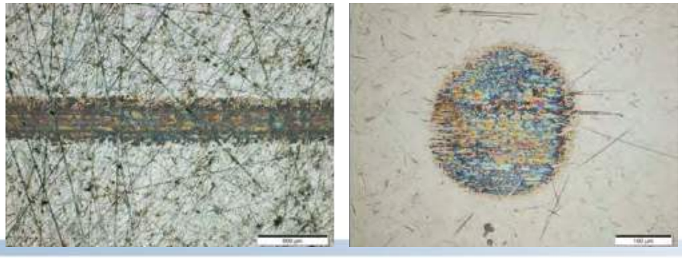


Results for reciprocating sliding Wear for fresh and model surrogate oils

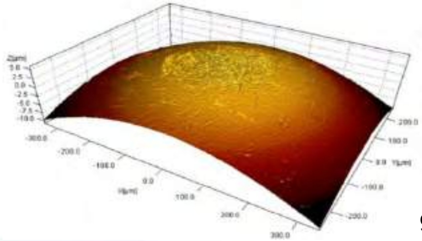
- No clear trend in wear behavior with fuel dilution during reciprocating sliding test



Typical wear scars

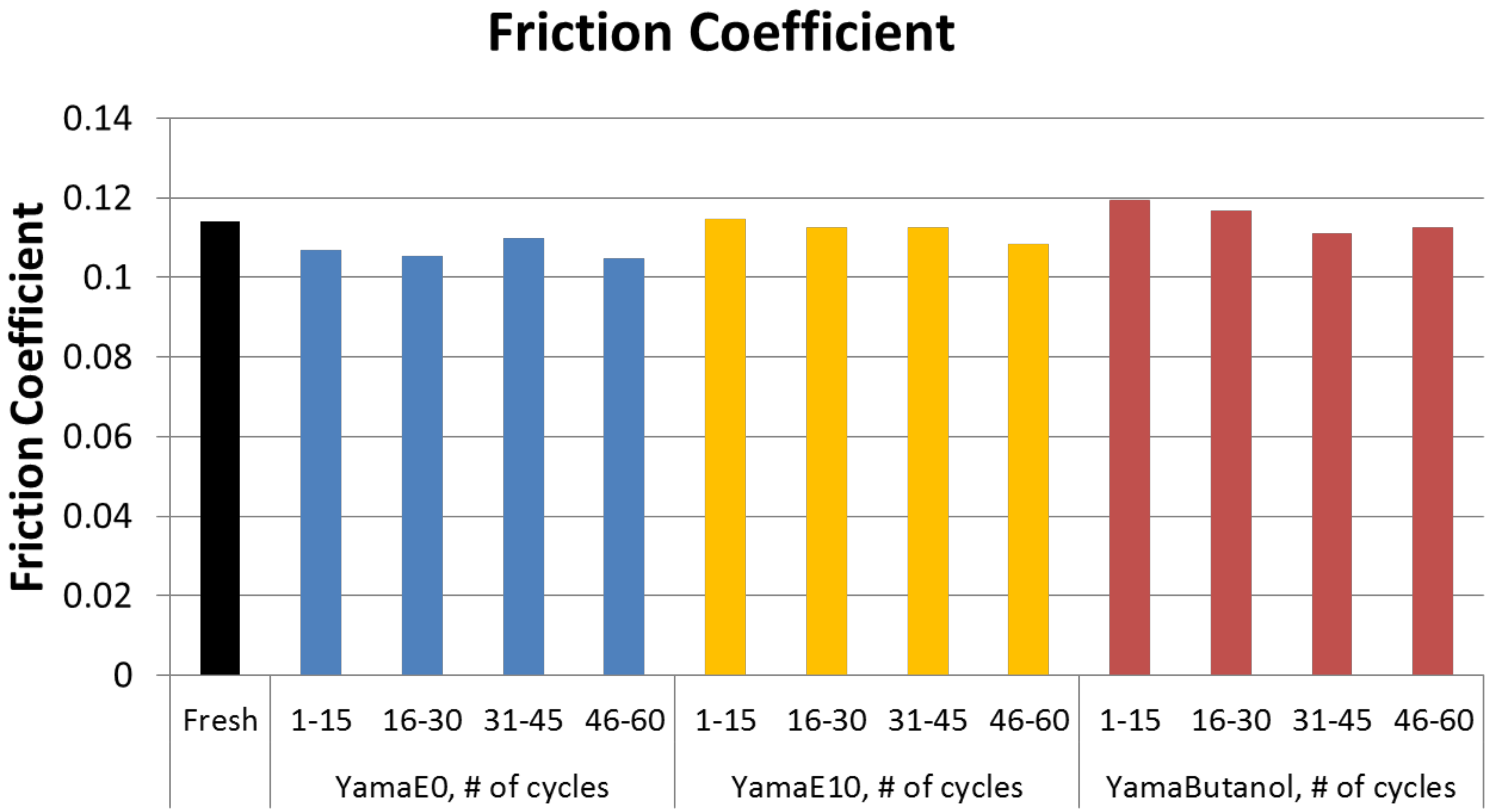


Wear was measure by profilometry



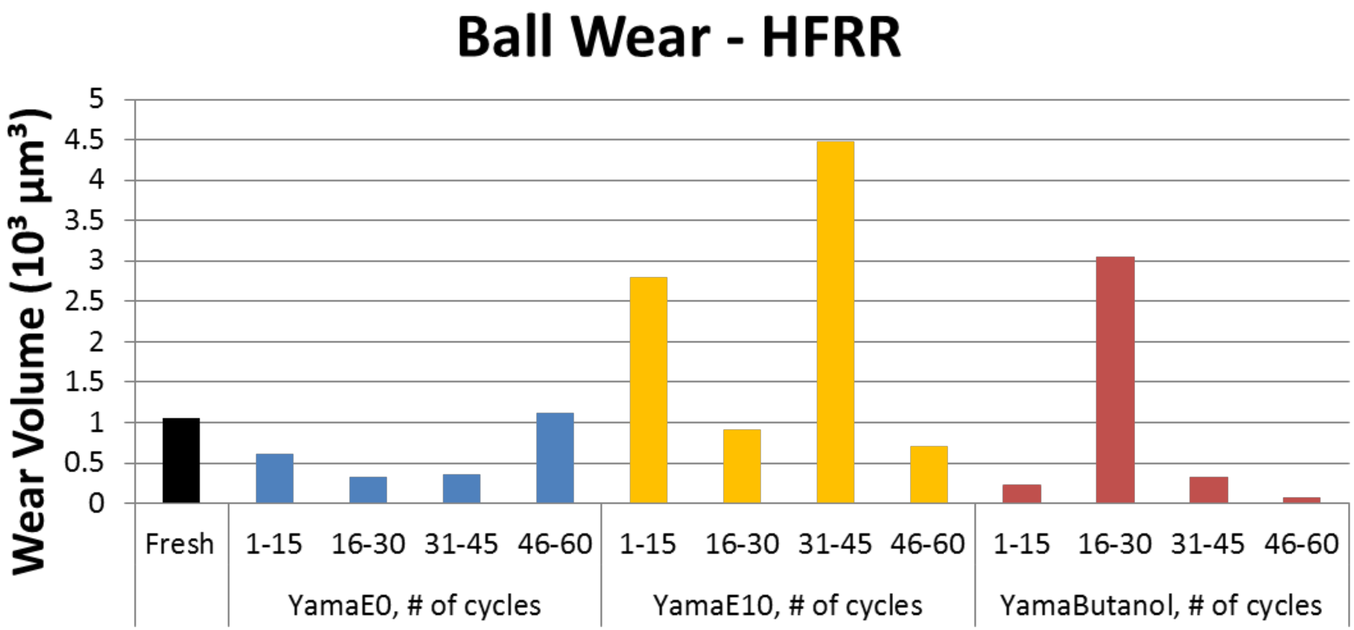
Results for reciprocating sliding friction for used oils from Yamaha engine

- Average friction for all the oils are very similar

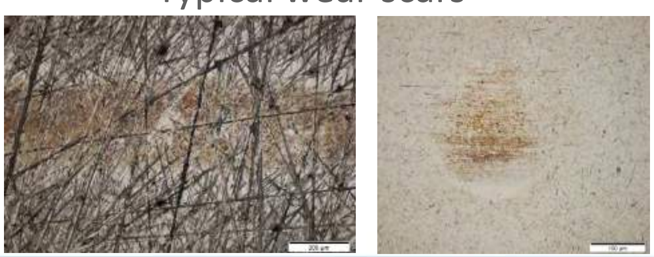


Results for reciprocating sliding wear for used oils from Yamaha engine

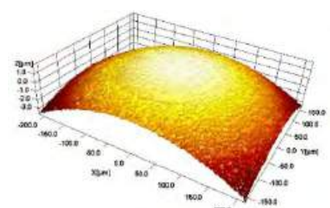
- No clear trend in wear behavior during reciprocating sliding test
  - It appears contamination with E10 produced more wear on the average



Typical wear scars



Wear was measure by profilometry



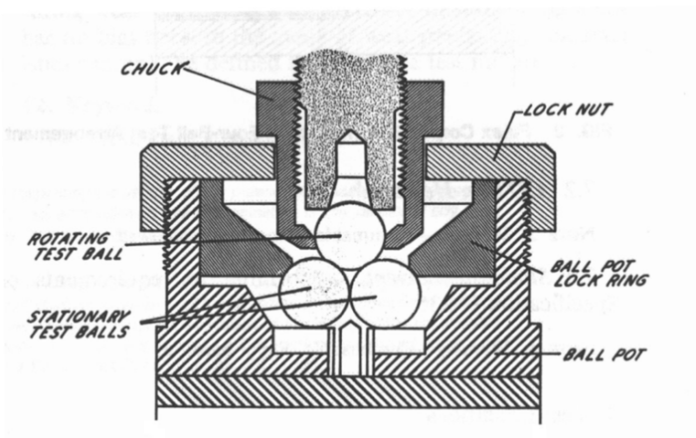
4 Ball Wear test

Ball specimen: 52100 Steel

TEST PARAMETERS

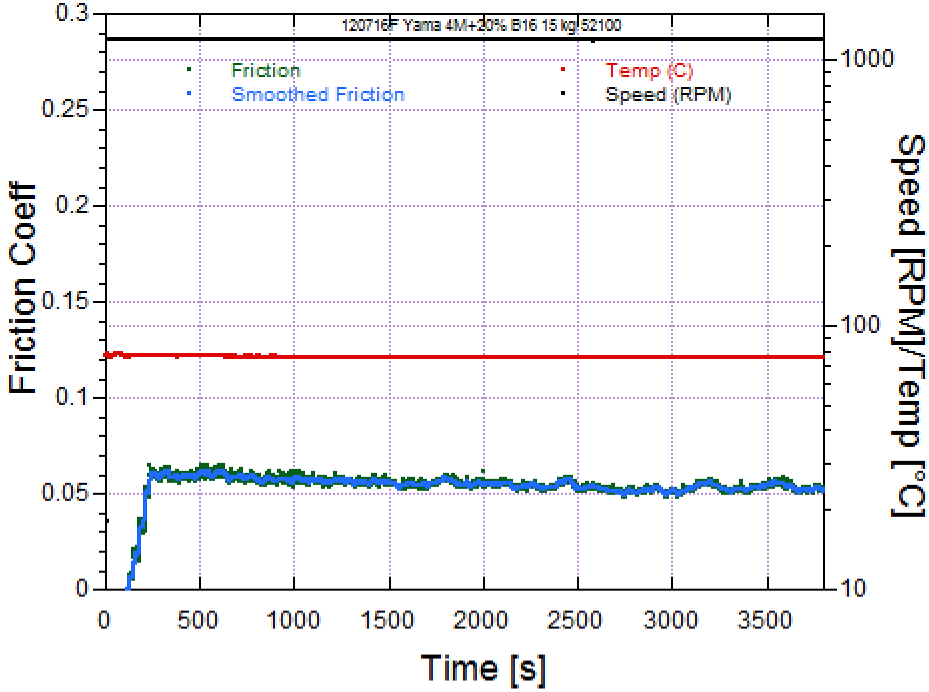
- Load: 15 kg
- Speed : 1200 rpm
- Temperature: RT
- Duration: 1 hr

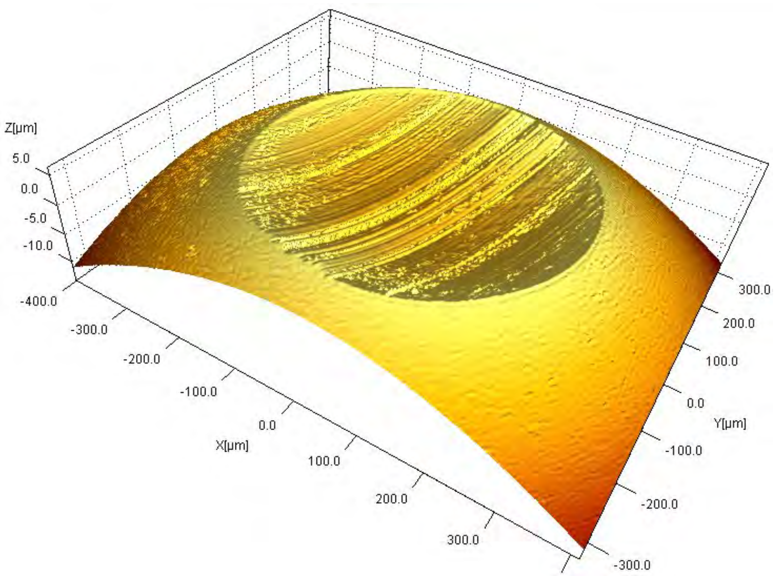
4 Ball Falex Tribometer



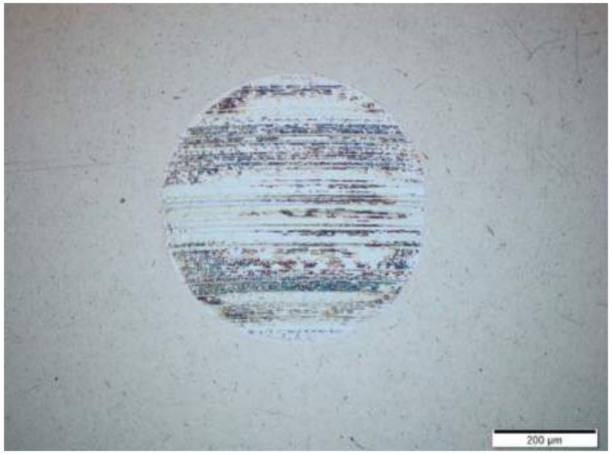
Schematic of contact configuration

4 Ball Wear test typical results



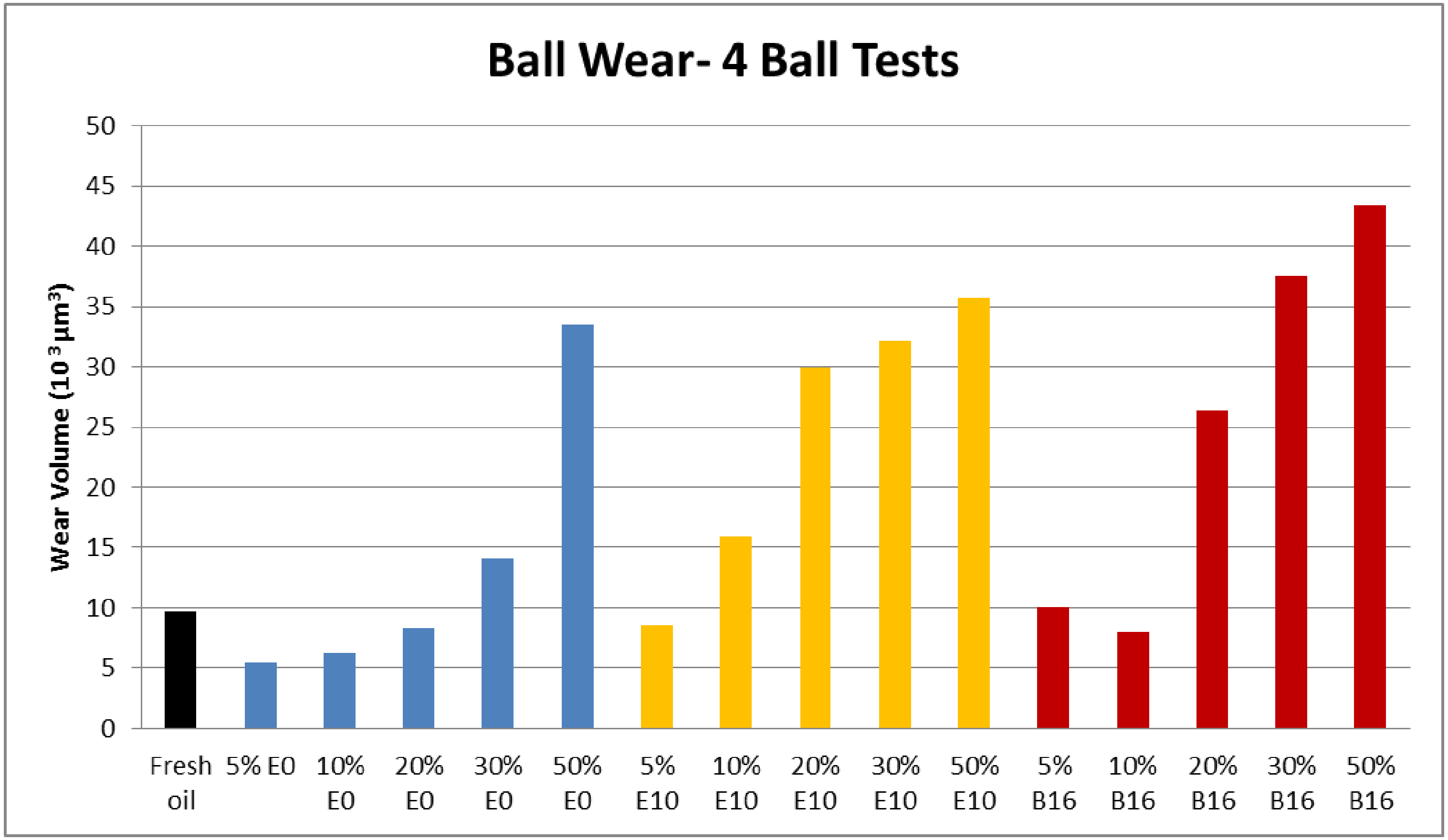


Wear Volume: 1,317,000 µm3



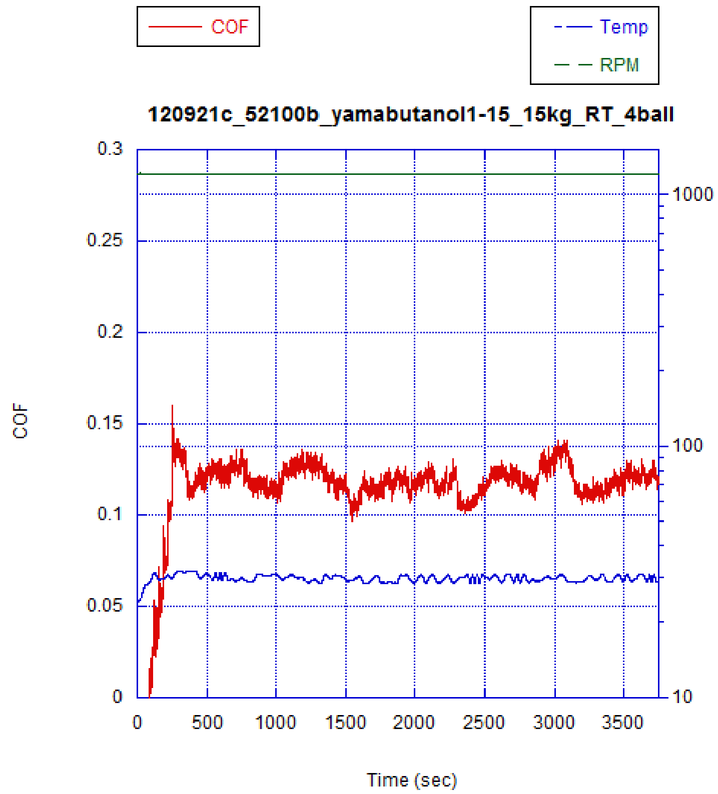
Wear measured on the three stationary balls

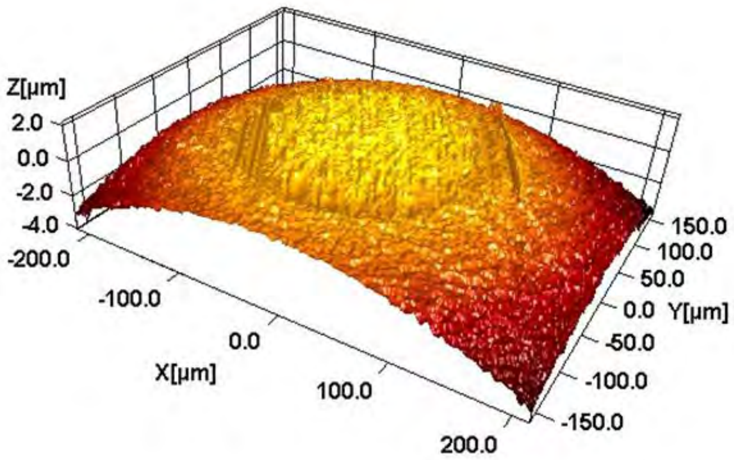
4 Ball test wear results for fresh and surrogate model oils



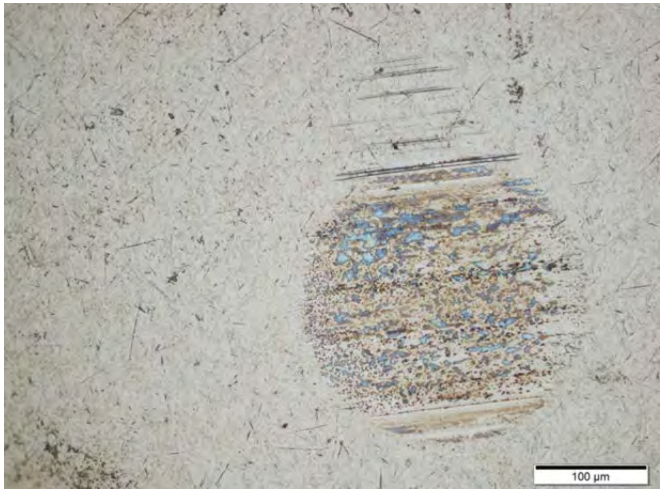
Fuel dilution increase wear in proportion to fuel content for the three fuels. At low levels of dilution (5%), there is only marginal effect on wear.

4 Ball Wear test typical results for used oils from Yamaha engine tests



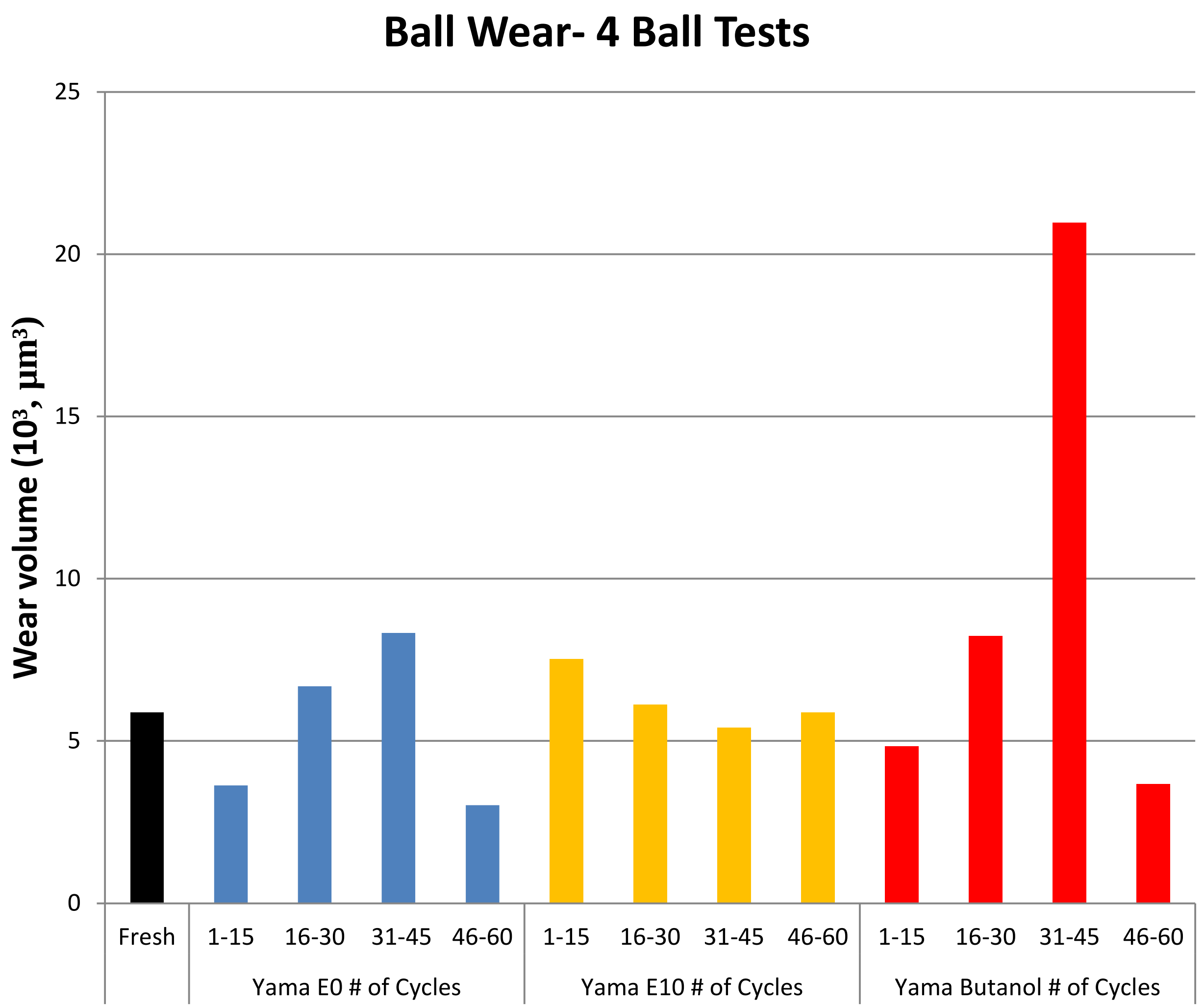


Average Wear Volume: 8,246



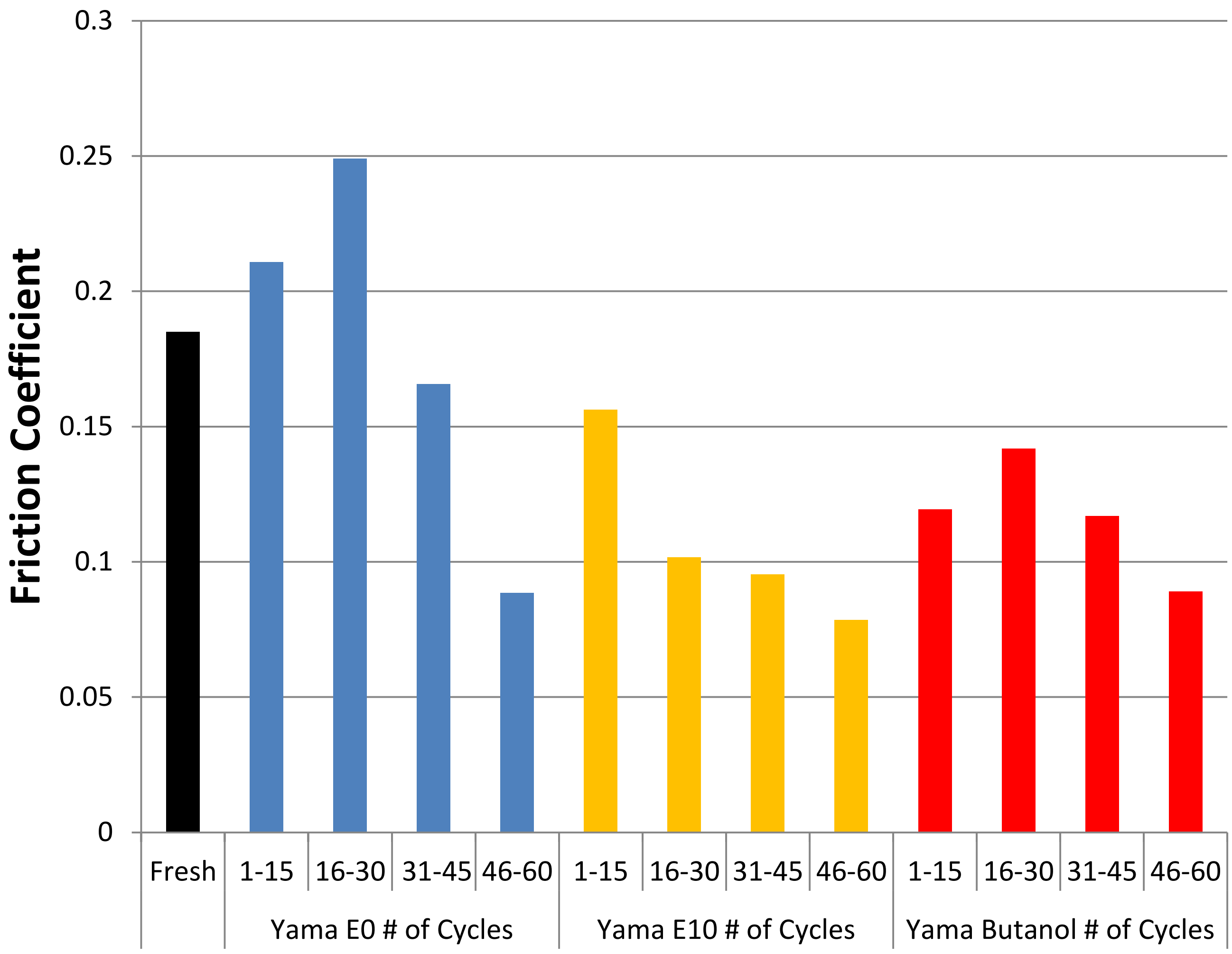
Wear measured on the three stationary balls

4 Ball test wear results for used oils from Yamaha engine tests



Except for one case (Butanol 31-45), impact of fuel dilution from engine test on wear is not very clear.

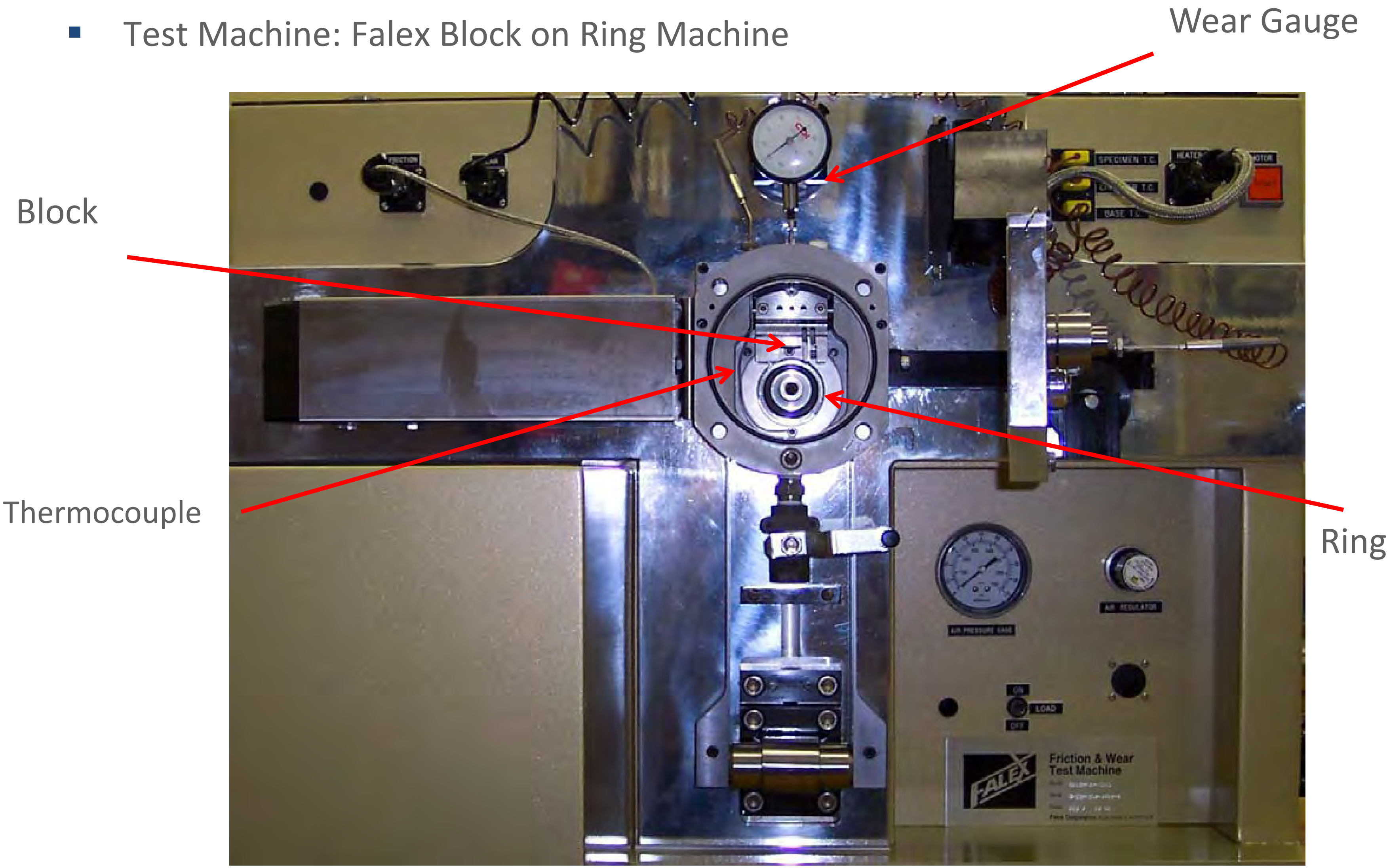
4 Ball test friction results for used oils from Yamaha engine tests



It appears presence of bio-based components (E10, B16) in the fuel results in slight friction reduction

Block-on-Ring Scuffing Tests

- Test Machine: Falex Block on Ring Machine

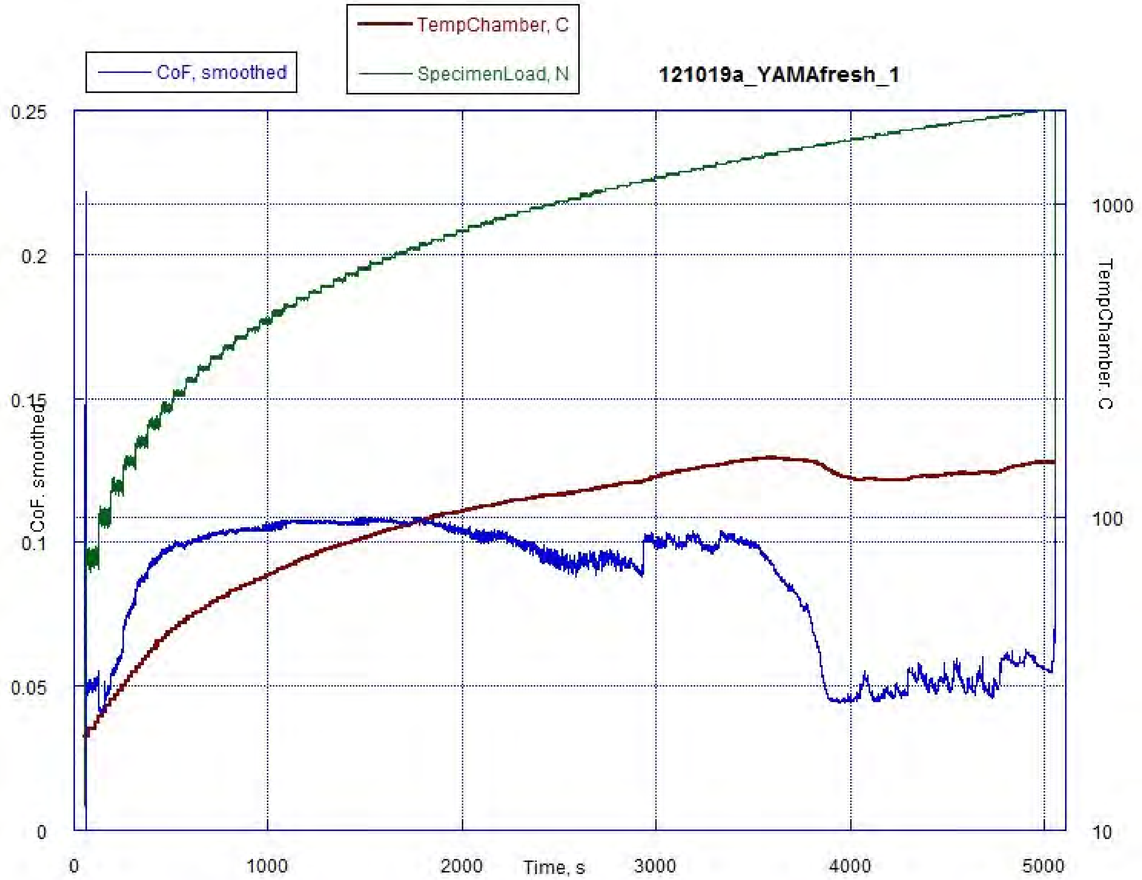


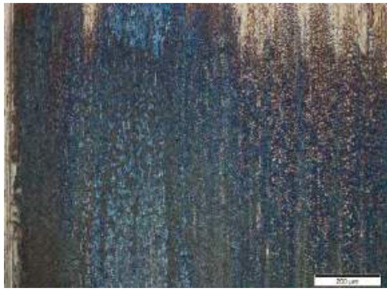
Scuffing Test Procedure

- 100 mL lubricant loaded into test chamber prior to test
- 1000 rpm
- 75N starting load
- 25N/min step
- Temperature not controlled
- Tests stopped once scuffing occurs

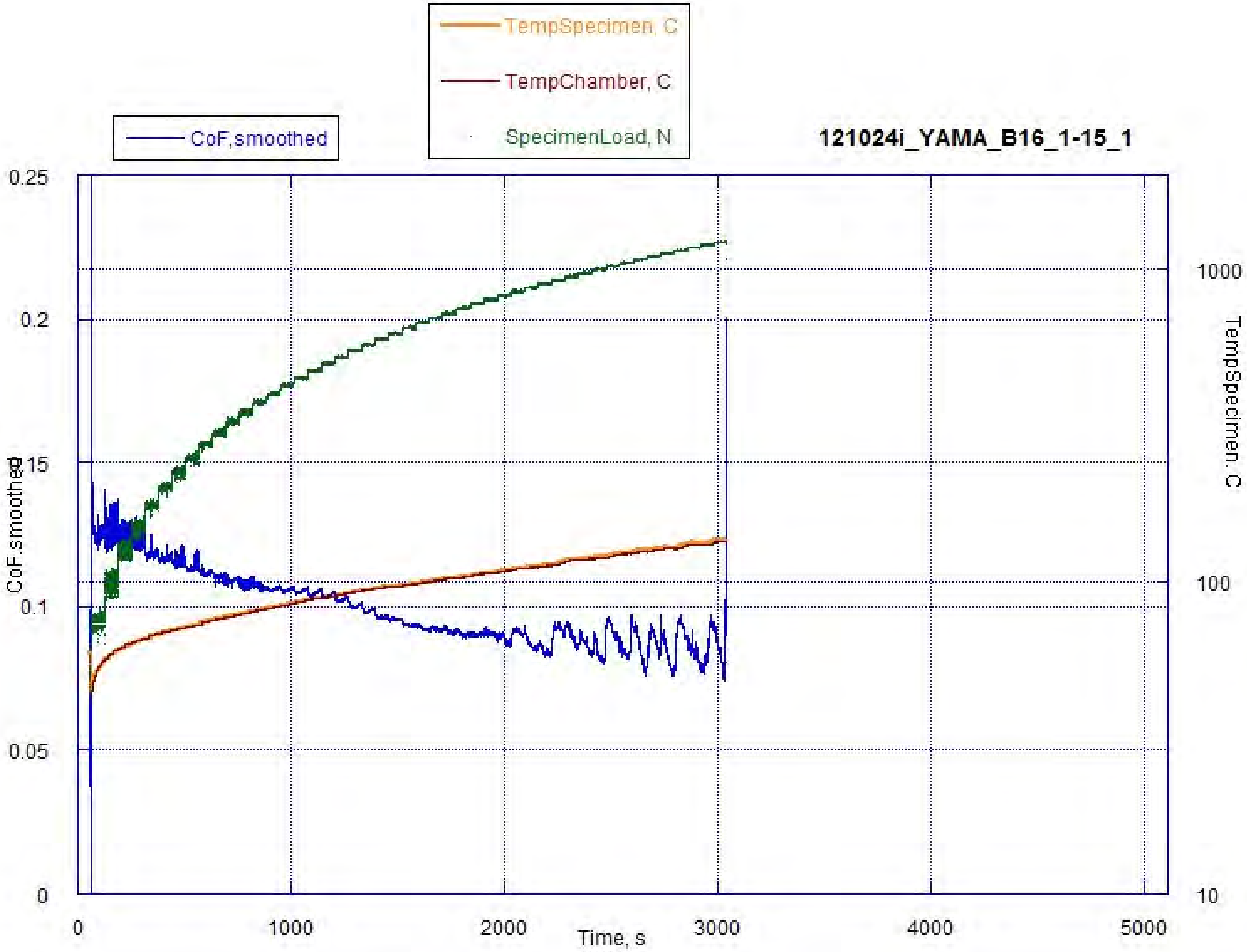
Scuffing typical friction plot for fresh YAMALUBE

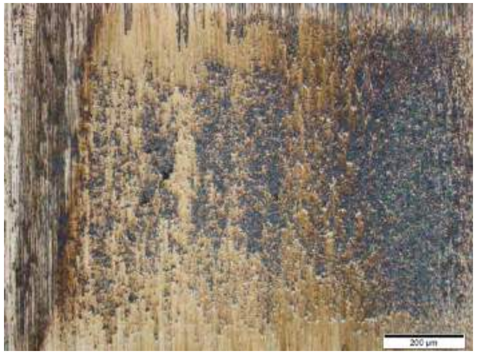
PARAMETERS FOR ALL SCUFFING TESTS:
100cc oil, 1000rpm, 75N starting load, 25N/minute loading



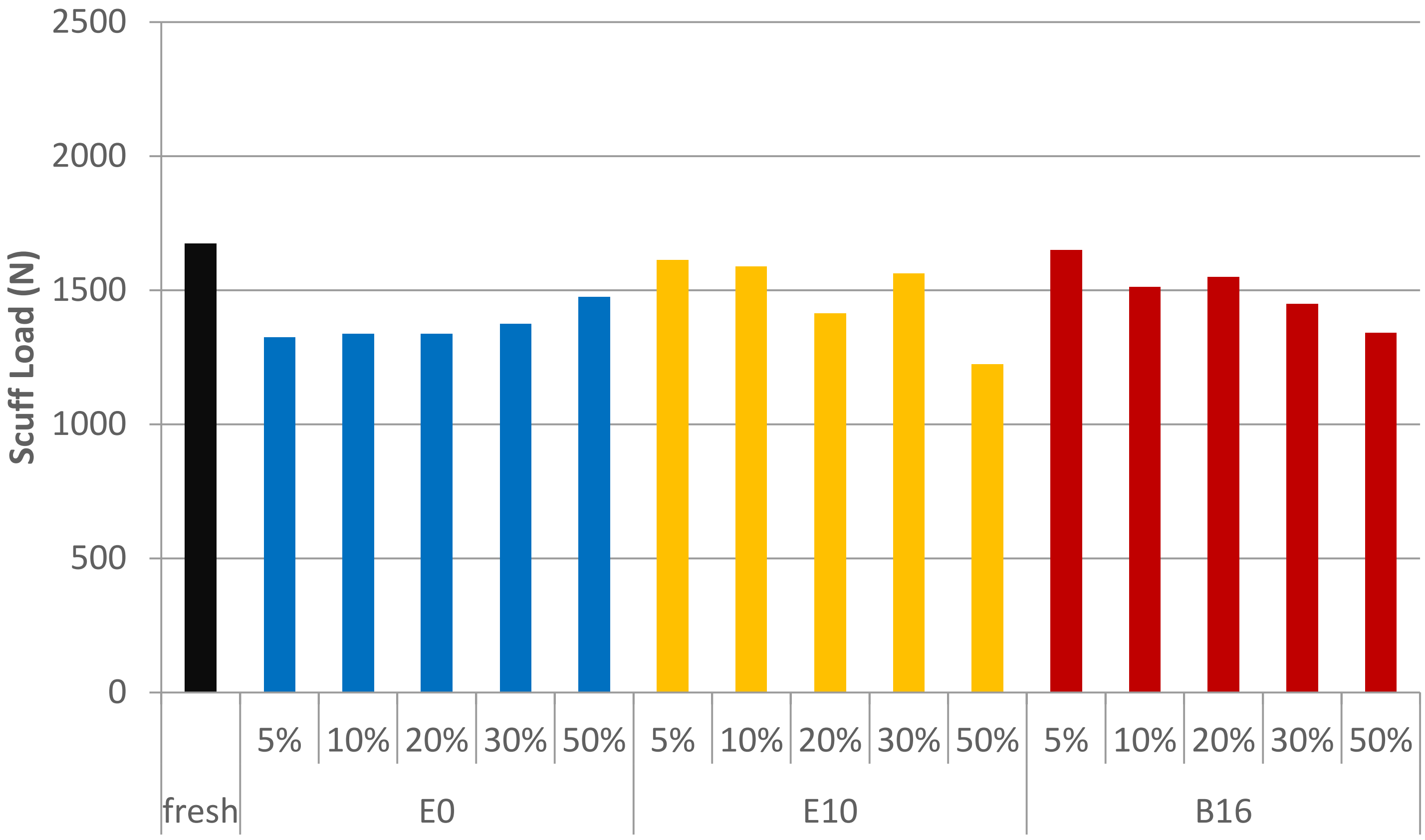


Scuffing typical friction plot for surrogate contaminated YAMALUBE



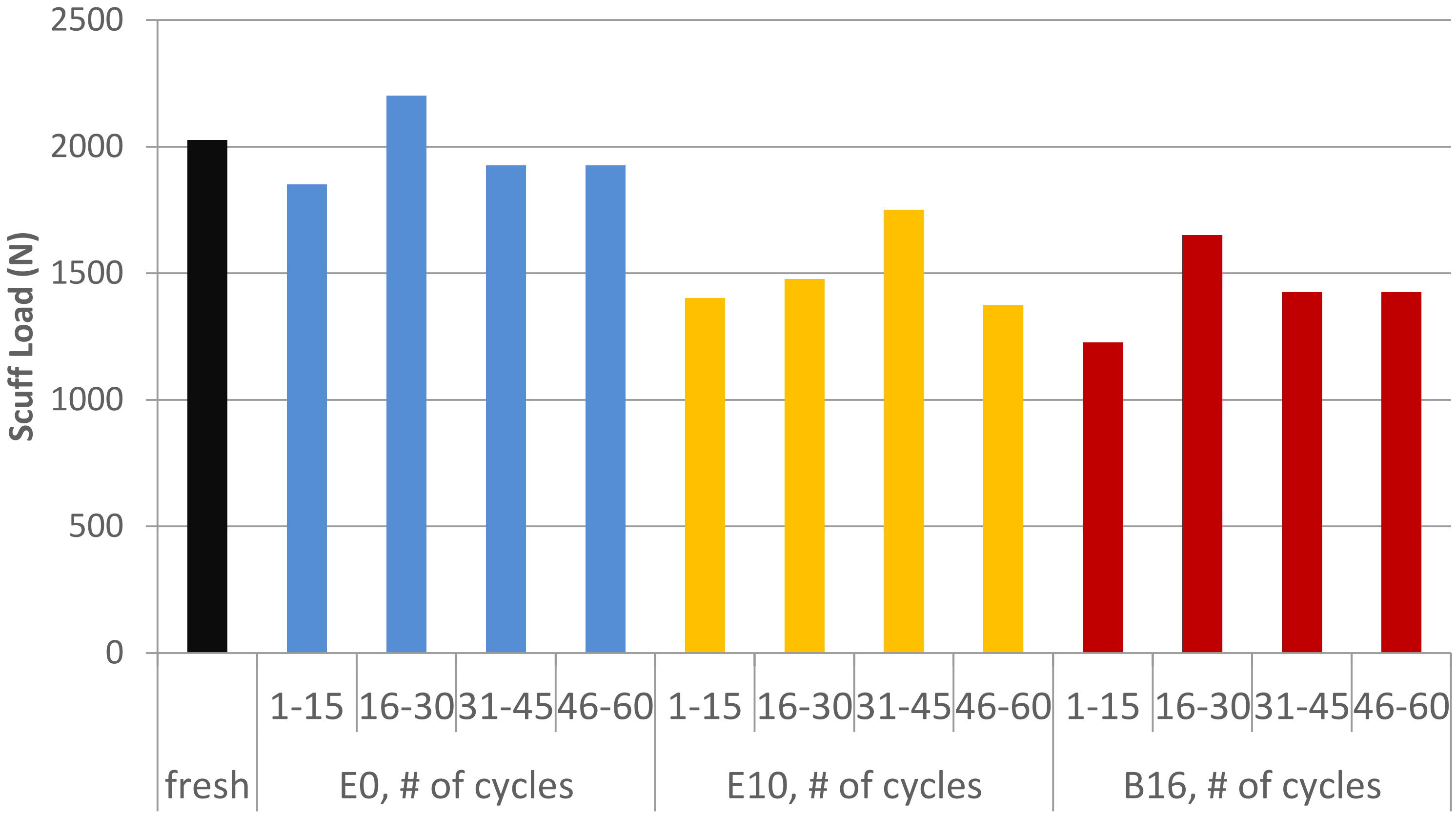


Scuffing Test results for fresh and surrogate model oils



Fuel dilution resulted in slight reduction of scuffing load compared to fresh oil

Scuffing Test results for used oils from Yamaha engine tests



Based on the current preliminary result, it appears that oil dilution by bio-based containing fuels (E10 and B16) resulted in noticeable reduction in scuffing load.

Summary

- Four different types of bench top friction and wear tests were conducted to assess the impact of fuel dilution on the lubrication performance of marine engine oil.
  - Unidirectional; reciprocating ; 4-ball; and block-on-ring scuffing
- Test were conducted with three fuels – E0, E10 and B16
  - Used oil from engine tests by Yamaha and surrogate model oil
- Results showed that fuel dilution during engine test resulted in reduction of oil viscosity.
- Fuel contamination had minimal effect on friction performance of the oil.
- Fuel contamination resulted in noticeable reduction in scuffing load for E10 and B16.
- The impact of fuel dilution on wear is not clear based on these preliminary results.
  - More work needed to adequately assess wear behavior of fuel contaminated engine oil.
- The long terms impact of fuel dilution of engine lubrication cannot be determined from these preliminary testing.

ISOBUTANOL

Isobutanol Testing Update

International Boat Builders Exhibition

IBEX 2014 Tampa

10/01/2014

J.Wasil

IBEX
THE INTERNATIONAL BOATBUILDERS' EXHIBITION & CONFERENCE

BACKGROUND

- History of issues in marine products with ethanol
- Congressionally mandated Renewable Fuel Standard (RFS) and the push to E15+
- Proactive leadership in demonstrating a possible replacement for ethanol that may be more compatible with marine products
- Opportunity to influence public policy

KEY MEMBERS

U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

NMMA

ABYC
Setting Standards for Safer Boating

Industry-wide participation and collaboration

PROPERTIES

Properties of Butanol - Overview

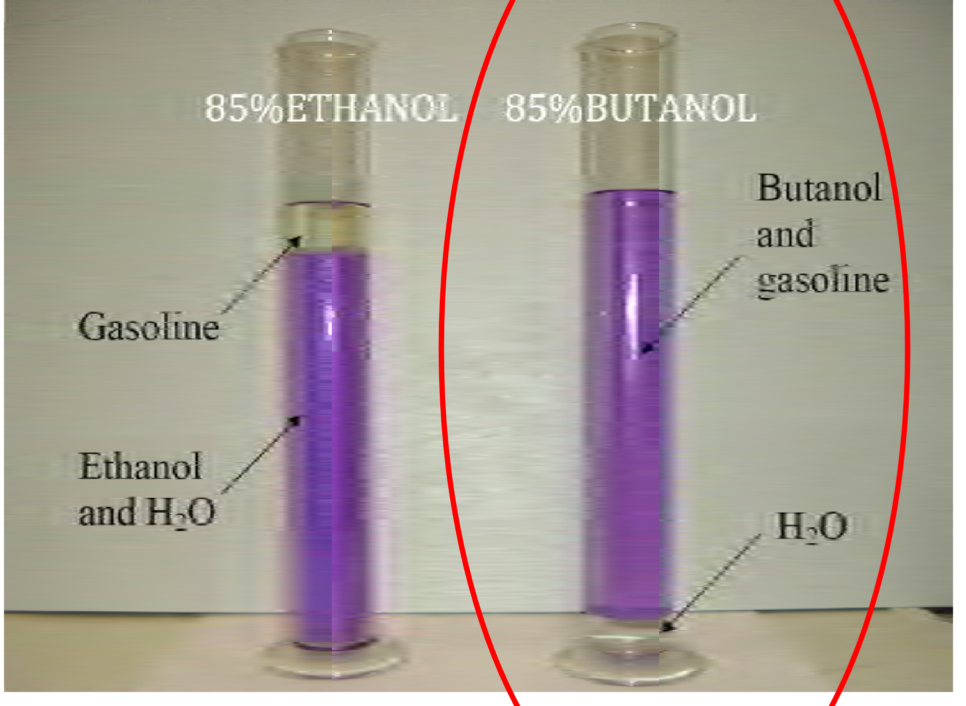
	Gasoline (EEE)	Ethanol	1-butanol	2-butanol	3-butanol	Iso-butanol
Composition (C,H,	86, 14	52, 13, 35	65, 13.5, 21.5	65, 21.5	65, 21.5	65, 13.5, 21.5
RON	97	107.4	98.3	106	105	105.1
MON	88.3	88.2	84.4	92	89	89.3
Melting point (ºC)	-	-112	-79.9	-114.7	25.5	-108
Energy content (MJ/kg)	42.9	25.6	32.9	32.9	32.9	32.8
Density (kg/L)	0.742	0.789	0.81	0.81	0.79	0.81
Energy content relative to gasoline (%)	-	64	84	84	82	83
Solubility in water	<0.1	Fully miscible	7.7			7.6

(R+M)/2 = 97.8

(R+M)/2 = 97.2

PROPERTIES

- **Properties of butanol**
  - **Less susceptible to phase separation means butanol could be successfully delivered in existing pipelines**
  - **Eliminates need for splash-blending**
  - **Least corrosive of alcohols**
  - **Higher energy content**



Adding water to ethanol and butanol

PROPERTIES

- **Can be produced from multiple feed stocks**
- **Fermentation process similar to ethanol**

REVIEW OF TESTS

Review of Tests Completed on Isobutanol

REVIEW OF TESTS

• 2011/2012:


18’ Mako boat with 175 HP Evinrude GDI Outboard


24’ SeaDoo Challenger boat with 215 HP Rotax engine


Volvo-Penta 5.7 Closed-loop catalyst – Almar Boat


1999 OMC Johnson Conventional Carbureted 2-stroke Intruder Boat


Indmar 6.0L Closed-loop catalyst – Malibu Ski Boat


150 HP Yamaha on Century Boat

- Power
- Performance
- Field In-Use Emissions Testing

iB16 – 16% Isobutanol

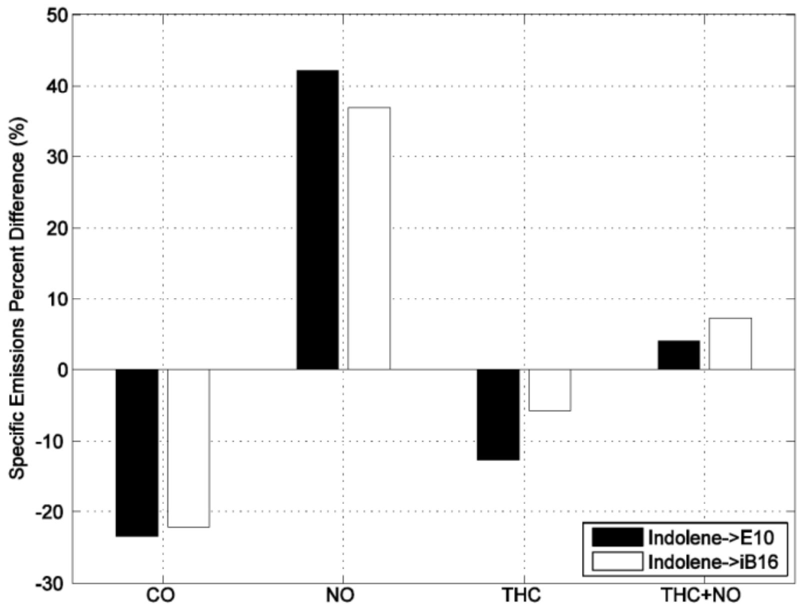
REVIEW OF TESTS

MPSS
Marine Portable Bag Sampling System

REVIEW OF TESTS

High level results of field testing iB16:

- E10 and iB16 result in similar emissions (No emission related failures)
- No reported engine runability or fuel system issues during summer test program
- Similar performance and running characteristics



Portable Emissions Sampling Equipment in Boat

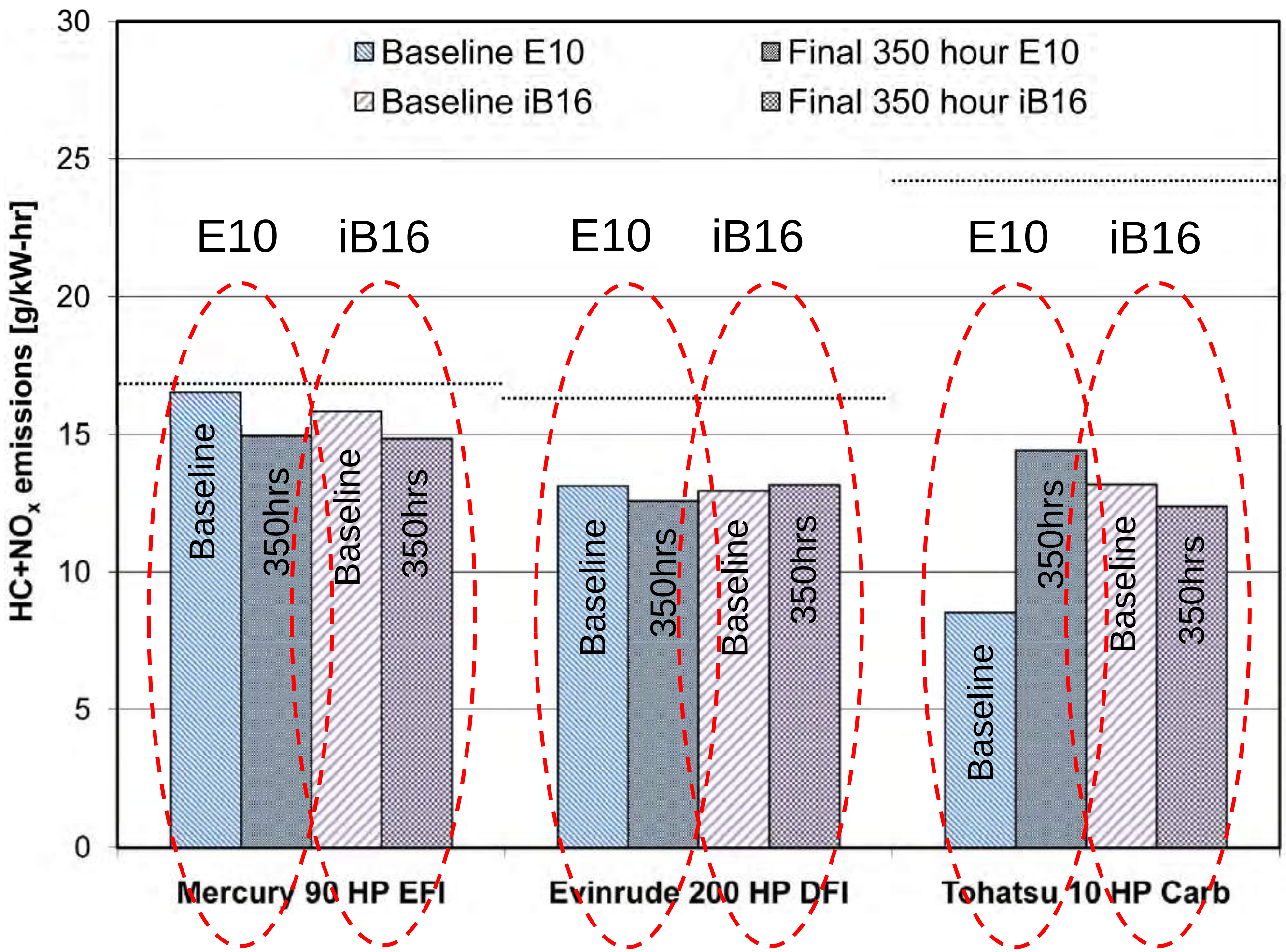
REVIEW OF TESTS

- 2012/2013 – Engine Durability Testing 16% isobutanol

- Emissions Testing
- Full Useful Life Engine Durability
- Engine Efficiency
- Performance

REVIEW OF TESTS

- Durability Results:



REVIEW OF TESTS

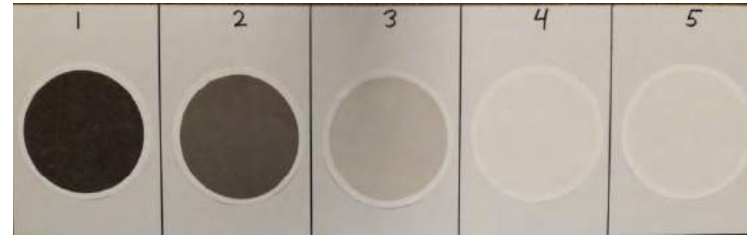
- 2013/2014
  - Tri-Fuel
    - 5% Ethanol
    - 8% Isobutanol
    - 87% Gasoline
  - The addition of isobutanol helps to lower the RVP of the fuel, keeping the finished fuel at 9 RVP – No waiver required

Tri-fuel end of season testing completed

- Engines accumulated over 100 hours of field operation last summer
- No engine runability issues reported
- All engines passed end of season emissions testing
- Additional 100 hrs this year

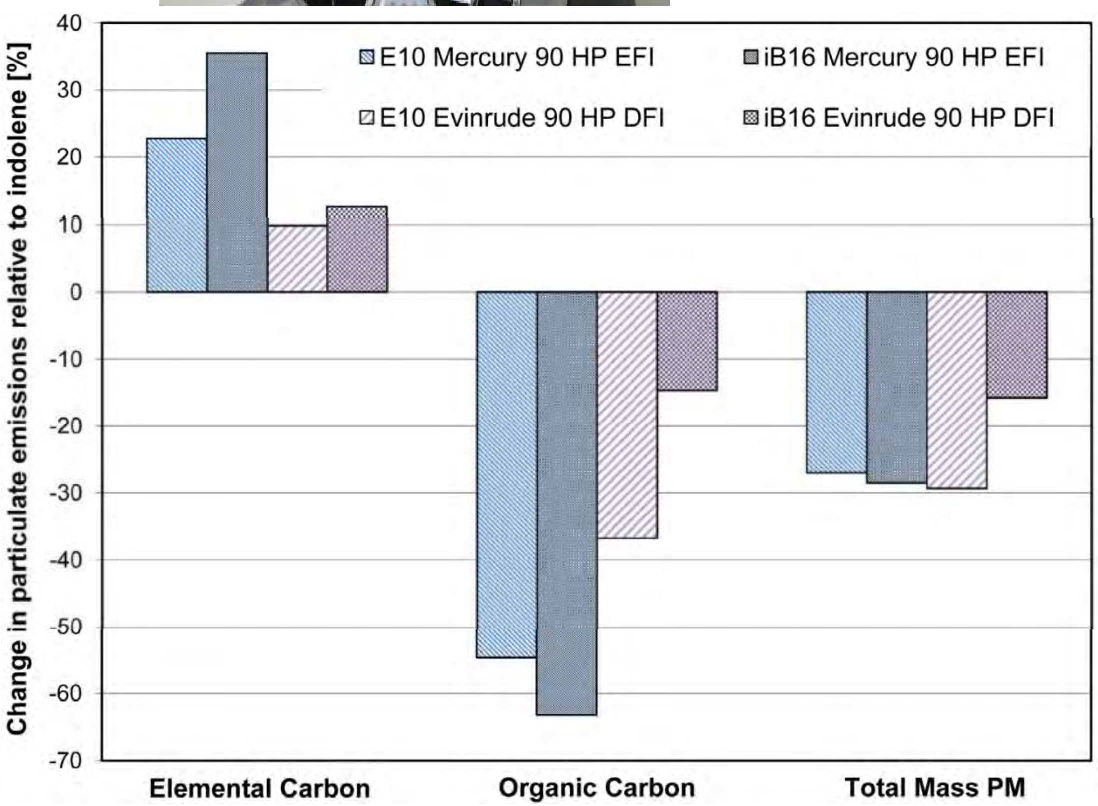
REVIEW OF TESTS

- 2013/2014
  - Particulate Matter Testing



90mm Sample Filters Modes 1-5

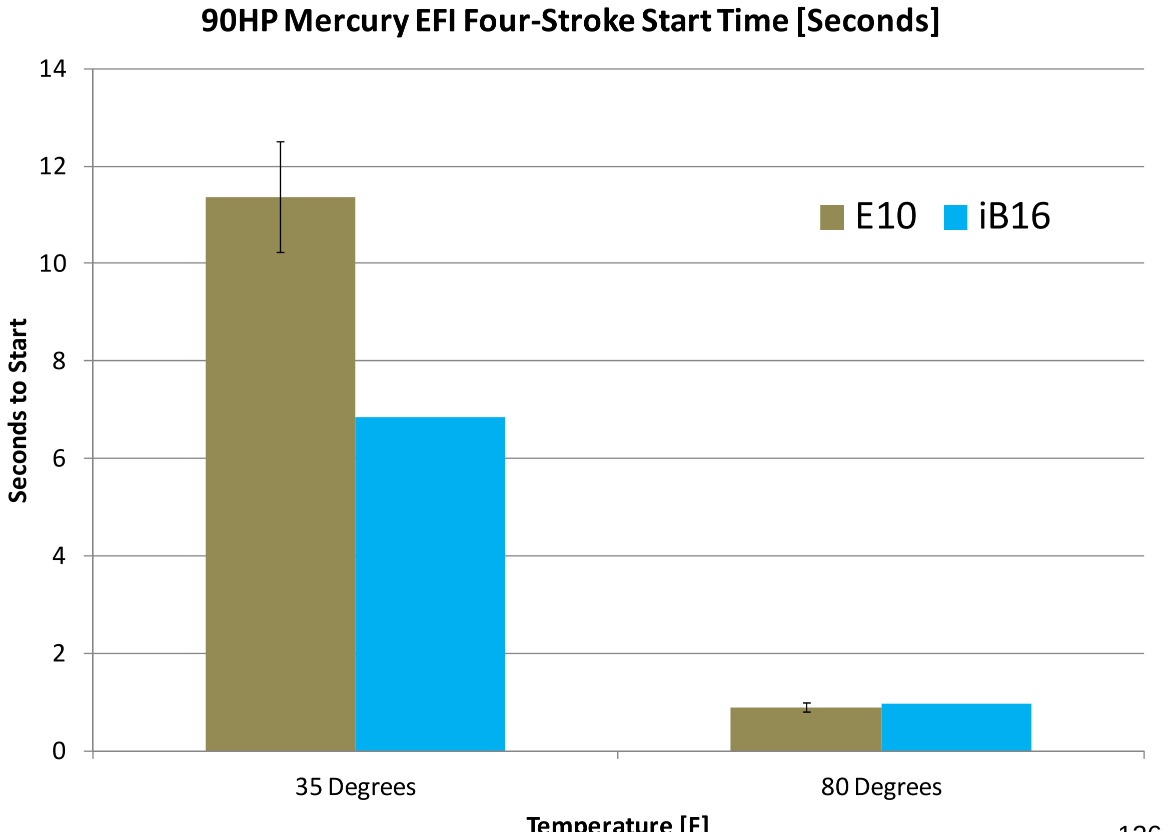
Soxhlet extraction



REVIEW OF TESTS

Engine Cold-Start:

- E10 and iB16
- Tests conducted at 74ºF (Baseline) & 31ºF
- Engines instrumented and time to start recorded

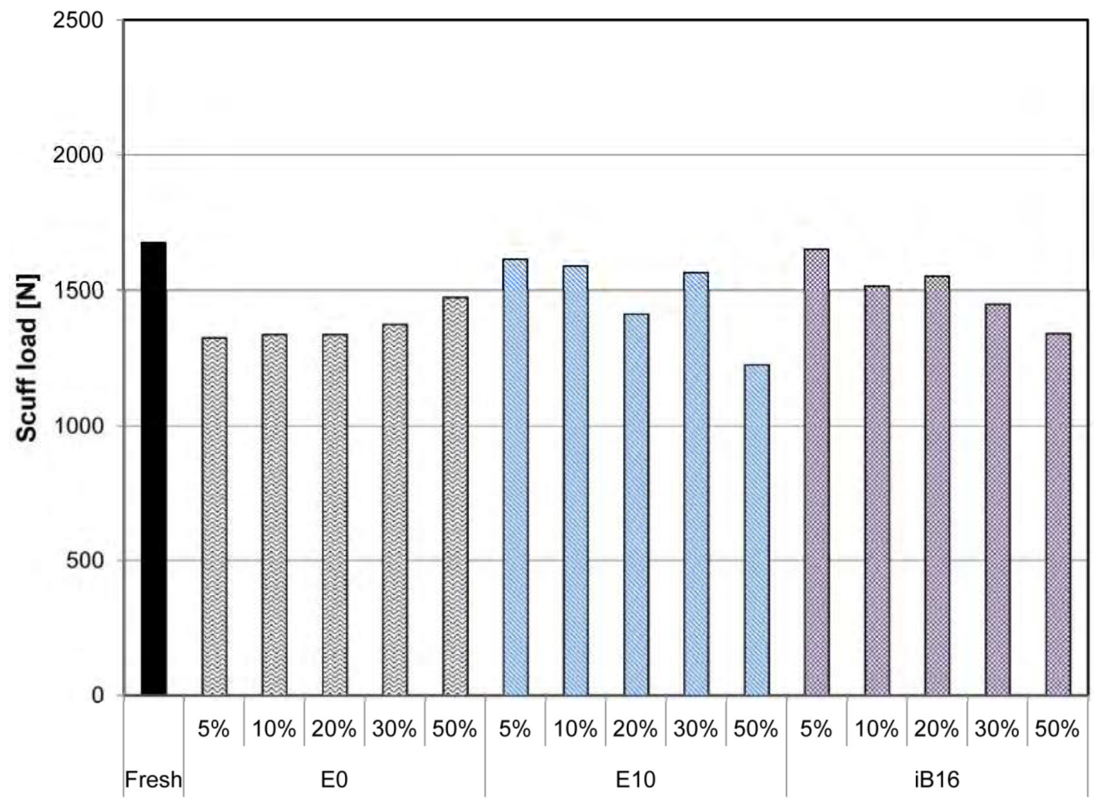


Average of several cold start events

REVIEW OF TESTS

Scuffing Load:

– block-on-ring contact configuration
– 1,000 RPM with initial contact load of 50 N, followed by 25 N increase every minute



REVIEW OF TESTS

Recap:

- 2,800+ hrs testing completed operating on isobutanol
- No major issues encountered during testing
- All engines passed emissions evaluations throughout the program
- Reduced PM operating on alcohols with similar results between E10 and iB16
- Engine cold starting looks favorable on iB16
- Oil dilution testing looks comparable between E10 and iB16

REVIEW OF TESTS

Next Steps:

- Completion of tri-fuel testing (200 hours)
  - Yamaha 90 and Evinrude 135 (Target additional 100 hours of operation)
- Laboratory testing on 5% O2 and beyond to understand critical blend level
  - Fuels E10, iB16, E15, iB24, E20 and iB32 (3.5, 5 and 7% O2)
  - (2) 10HP Yamaha, (2) 30HP Evinrude, and (2) 150HP Mercury
- Summer 2015 engine durability / field test program operating on higher quantities of isobutanol (outboards and SD/I engines)

Published reports:

- SAE Small Engine Technology Conference:
  - In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels
  - Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine
- DOE Annual Report 2013/2014:
  - Emissions and operability of Gasoline, Ethanol, and Butanol Fuel Blends in recreational Marine Applications
- SAE World Congress 2014:
  - Impact of Blending Gasoline with Iso-Butanol Compared To Ethanol on Efficiency, Performance and Emissions of a Recreational Marine 4-Stroke Engine

Wallner, T., Ickes, A., Wasil, J., Sevik, J. et al., "Impact of Blending Gasoline with Isobutanol Compared to Ethanol on Efficiency, Performance and Emissions of a Recreational Marine 4-Stroke Engine," SAE Technical Paper 2014-01-1230, 2014, doi:10.4271/2014-01-1230.

Wasil, J., McKnight, J., Kolb, R., Munz, D. et al., "In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels," SAE Technical Paper 2012-32-0011, 2012, doi:10.4271/2012-32-0011.

Wasil, J., Johnson, J., and Singh, R., "Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine," SAE Int. J. Fuels Lubr. 3(2):1071-1080, 2010, doi:10.4271/2010-32-0054.

EXHAUST EMISSIONS OF LOW LEVEL BLEND ALCOHOL FUELS FROM TWO-STROKE AND FOUR-STROKE MARINE ENGINES

By

James M. Sevik Jr

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2012

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

Department of Mechanical Engineering-Engineering Mechanics

Thesis Advisor: *Dr. Scott A Miers*

Committee Member: *Dr. Thomas Wallner*

Committee Member: *Dr. Susan Bagley*

Department Chair: *Dr. William W. Predebon*

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Preface

The work performed in this study was performed as a subcontractor for Argonne National Laboratory, providing third-party oversight and peer review to any data collected by representatives from the marine industry.

Acknowledgements

I would like to acknowledge the unconditional support of my advisors, Dr. Scott A. Miers, and Dr. Thomas Wallner. I have been involved with research of Dr. Miers' and Dr. Wallner since the sophomore year of my undergraduate degree. They have provided innumerable support as I have progressed in my academic career.

Jeff Wasil and Jerry Oliver of BRP provided great support with questions pertaining to the marine industry while in the field.

I would also like to thank John McKnight of the National Marine Manufacture Association (NMMA) and Bryan Goodwind of the American Boat and Yacht Council (ABYC) for their generous hospitality during both rounds of field testing.

Figures 7 of [1] and Figure 9 of [2] are reprinted with permission of SAE International. Full permission can be seen in A.3.

Nomenclature

ABYC – American Boat and Yacht Council

BRP – Bombardier Recreational Products

CLD - chemiluminescence detector

CO_2 – carbon dioxide

CO – carbon monoxide

ECM – engine control module

ECU – engine control unit

FID – flame ionization detector

ICOMIA – International Council of Marine Industry Associations

NDIR – non dispersive infra-red

NDUV – non dispersive ultra-violet

NMMA – National Marine Manufacturers Association

NO_2 – nitrogen dioxide

NO – nitrogen monoxide

NO_x – oxides of nitrogen

RVP – Reid vapor pressure

THC – total hydrocarbon

WOT – wide open throttle

Abstract

The U.S. Renewable Fuel Standard mandates that by 2022, 36 billion gallons of renewable fuels must be produced on a yearly basis. Ethanol production is capped at 15 billion gallons, meaning 21 billion gallons must come from different alternative fuel sources [3]. A viable alternative to reach the remainder of this mandate is iso-butanol. Unlike ethanol, iso-butanol does not phase separate when mixed with water, meaning it can be transported using traditional pipeline methods. Iso-butanol also has a lower oxygen content by mass, meaning it can displace more petroleum while maintaining the same oxygen concentration in the fuel blend [3].

This research focused on studying the effects of low level alcohol fuels on marine engine emissions to assess the possibility of using iso-butanol as a replacement for ethanol. Three marine engines were used in this study, representing a wide range of what is currently in service in the United States. Two four-stroke engine and one two-stroke engine powered boats were tested in the tributaries of the Chesapeake Bay, near Annapolis, Maryland over the course of two rounds of weeklong testing in May and September. The engines were tested using a standard test cycle and emissions were sampled using constant volume sampling techniques.

Specific emissions for two-stroke and four-stroke engines were compared to the baseline indolene tests. Because of the nature of the field testing, limited engine parameters were recorded. Therefore, the engine parameters analyzed aside from emissions were the operating relative air-to-fuel ratio and engine speed.

Emissions trends from the baseline test to each alcohol fuel for the four-stroke engines were consistent, when analyzing a single round of testing. The same trends were not consistent when comparing separate rounds because of uncontrolled weather conditions and because the four-stroke engines operate without fuel control feedback during full load conditions. Emissions trends from the baseline test to each alcohol fuel for the two-stroke engine were consistent for all rounds of testing. This is due to the fact

the engine operates open-loop, and does not provide fueling compensation when fuel composition changes. Changes in emissions with respect to the baseline for iso-butanol were consistent with changes for ethanol. It was determined iso-butanol would make a viable replacement for ethanol.

1. Introduction

There is a need to understand the effect of increasing alcohol fuel concentrations on the marine recreational industry. As the percentage of ethanol content in fuel available at the gas pump increases, adverse effects on marine engines not capable of compensating for an increase oxygen concentration, can occur. For example, enleanment of the engine can take place, causing catastrophic damage.

1.1 Renewable Fuel Standard

In 2005, the Renewable Fuel Standard (RFS) was created under the Energy Policy Act. The RFS was the first renewable fuel mandate, specifically stating the quantity of a renewable fuel needed to be produced each year [4]. In 2007, the Energy Independence and Security Act (EISA) expanded the RFS in multiple ways. The EISA expanded a section to include diesel, increasing the amount of renewable fuel required to be blended into transportation fuels to 36 billion gallons by 2022, and renewable fuels were placed into distinctive categories. Under the RFS, corn-based ethanol is capped at 15 billion gallons by 2015, requiring the remaining 21 billion gallons to come from other biofuels [5].

1.2 Well to Wheels

Ethanol and iso-butanol are both alcohol fuels, derived from renewable resources such as corn, grass, and waste biomass [6]. Both ethanol and iso-butanol create difficulties when going from the original source, to the wheels of motorists. Ethanol is 100% miscible in water, and will phase separate from gasoline if introduced to water. Iso-butanol is only 8.5% miscible in water, and therefore will not phase separate as easily as ethanol. However, iso-butanol is corrosive, similar to ethanol.

Ethanol and iso-butanol blended fuels have their own characteristic route when analyzed in a well to wheel perspective; that is, the process taken from the initial steps where the oil is drawn from the ground to filling the consumer's tank. Figure 1.1 shows a flow chart of the process used to produce ethanol blended fuels.

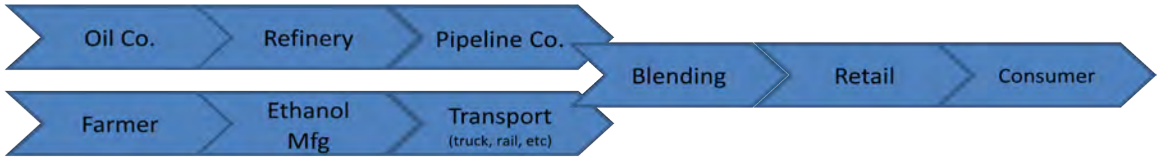

Figure 1.1: Well-to-wheel analysis of ethanol blended fuels

Accordingly, Figure 1.2 shows the well to wheel analysis of iso-butanol blended fuels. As seen, there are inherently more steps involved to produce ethanol blended gasoline than iso-butanol blended gasoline.

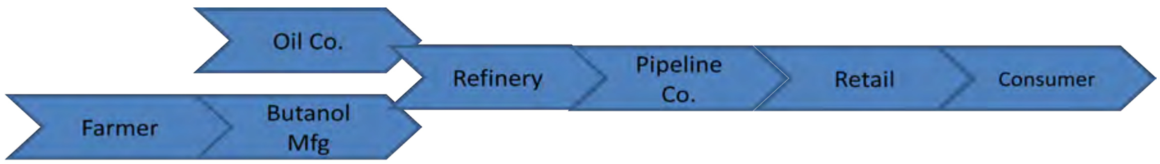

Figure 1.2: Wheel-to-wheel analysis of iso-butanol blended fuels

The main difference between the two fuels is seen at the blending step. Because of ethanol's miscibility, it cannot be blended at the refinery. Blending fuel at the refinery has intrinsic advantages as opposed to blending at the pump. The overall cost of the fuel decreases because there are less intermediary steps with getting the fuel to the consumer. Blending at the refinery allows for a higher quality fuel to be produced because there is tighter control of the blending process, as opposed to blending the fuel at the pump. Eliminating the need to transport the fuel, using means such as truck or rail, reduces the overall greenhouse gas emissions over the lifecycle of the fuel. In total, this allows for a higher quality fuel for the consumer, potentially improving fuel economy and reducing the risk of low quality fuel for the auto, marine, and small engine industry.

1.3 Oxygen Concentrations

With the removal of lead as a fuel oxygenate in the 1970's, fuel refiners were forced to find different materials to boost the octane rating of gasoline. Methyl tertiary butyl ether (MTBE) and ethanol were used in the late 1970's and early 1980's as an oxygenate replacement to lead [7]. In 1998 the US's yearly production of MTBE was up to 2.8 billion gallons, and concerns about environmental and health risks of MTBE increased. The California Air and Resources Board (CARB) produced the Reformulated Gasoline (RFG) guidelines, to be implemented in three phases [8]. Effective in 2003, the third phase of the CARB RFG set a cap on oxygenate in gasoline to 3.5wt%. With the prohibition of MTBE following in 2004, ethanol was found to be the only viable source to reach the 3.5wt% limit, required by some states [7].

For comparison purposes, pure ethanol has 35% oxygen by mass, while iso-butanol has 21.5% oxygen by mass. Accordingly, the lower heating value of ethanol and iso-butanol are 20.0 and 32.96 MJ/kg, respectively. As seen in Figure 1.3, iso-butanol provides the same oxygen concentration at 16Vol% as 10Vol% ethanol, while displacing 6% more petroleum based fuels [3]. For comparison purposes, an 83Vol% blend of iso-butanol will yield the same oxygen concentration by mass as a 50Vol% blend of ethanol. Iso-butanol provides the opportunity to meet the same oxygen concentrations as ethanol blends, while further displacing petroleum based fuels, consequently decreasing foreign oil dependence. Also seen in Figure 1.3, iso-butanol maintains a higher lower heating value as blend ratio with neat gasoline is increased.

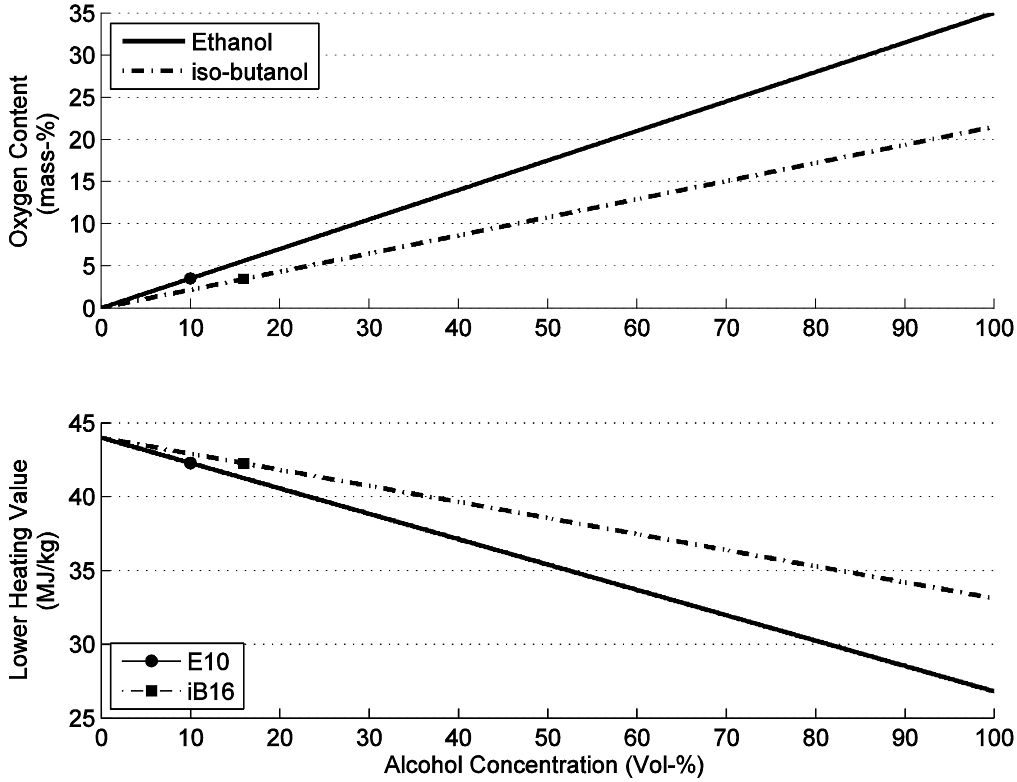

Figure 1.3: Oxygen content and lower heating value of alcohol blended fuels

To further reinforce data presented in Figure 1.3, Table 1.1 shows specific blends of ethanol and iso-butanol, with their respective oxygen concentrations. Based off of 2011 estimates, the United States consumes 18.84 million barrels of oil per day [9]. Replacing 10Vol% ethanol with 16.1Vol% iso-butanol would displace 3.03 million barrels of oil consumed daily.

Table 1.1: Oxygen content of varying blends of ethanol and iso-butanol

	10% Ethanol	16.1% Iso-butanol	15% Ethanol	24.2% Iso-butanol
Oxygen Content (Wt%)	3.5	3.5	5.2	5.2

1.4 Research Goals and Objectives

The goal of this research was to study the effects of low level blend alcohol fuels on two-stroke and four-stroke marine engine emissions. There were four main objectives in this study:

- Develop baseline emissions using indolene fuel
- Perform tests with 10% ethanol and compare with baseline data
- Perform tests with 16% iso-butanol and compare emissions trends with the baseline and 10% ethanol data
- Based off of emissions results, determine if iso-butanol will be a viable substitute for ethanol, as well as being an amiable fuel to fill the gap in the RFS

Three marine engines were tested in this research, which provide a representative sample of the engines currently in service in the marine recreational industry. Field testing was performed in the tributaries of the Chesapeake Bay near Annapolis, Maryland. Each boat was tested over an adapted ICOMIA test cycle, with emissions being sampled using constant volume sampling techniques. A Sensors Inc. Semtech-DS five gas emissions analyzer was used to analyze emissions from the constant volume samples.

Testing was performed in May and September of 2012, providing a comparison for emissions results. Two constant volume emissions samples were taken per fuel, for each boat. Two tests were performed to evaluate repeatability on a test-to-test basis. Engine and boat speed data sets were also recorded to reveal any variability incurred during field testing.

2. Background/Literature Review

In the recreational marine industry, there is a growing concern over the increasing alcohol content in fuels available from the pump. Many engines in the marine industry, regardless of fuel delivery strategy, operate in an open-loop manner. An engine operating in an open-loop manner does not offer any compensation when there is a change in the oxygen content of the fuel, whereas an engine operating closed-loop provides feedback and changes fueling when oxygen concentrations change via a wideband sensor. As the percentage of alcohols increases in the fuel, open-loop engines run the risk of enleanment, which can cause catastrophic engine failure. In addition, increasing alcohol concentration has a direct impact on emissions.

2.1 Effects of Alcohol Fuels on Emissions

The following literature review aims to show the effects of alcohol fuels on both two-stroke and four-stroke engines, which operate in closed-loop and open-loop operation. Because numerous literature sources for marine engines are not readily available, literature utilizing engines with similar technologies are referenced.

Alcohol fuels such as pure ethanol (E100) and pure iso-butanol (iB100) have clear distinct advantages over neat gasoline. E100 and iB100 have a higher octane rating than neat gasoline, making them more resistant to engine knock [3]. E100 and iB100 also have a higher flame speed, decreasing burn duration. Conversely, alcohol fuels are corrosive, which can be detrimental to an engine and fuel system. These differences from the neat gasoline baseline will affect engine-out emissions

2.1.1 Impact of Ethanol Fuels on Regulated Tailpipe Emissions – Four-Stroke Engines [10]

For this study, researchers used a 2006 Chrysler Town & Country minivan featuring a 3.3 liter closed-loop, port fuel injected, liquid cooled, spark ignited engine. A series of EPA FTP 75 test cycles were performed on a chassis dynamometer, a test cycle which is used to perform emissions certification for light duty vehicles. Constant volume emissions sampling techniques were performed using an AVL GEM 110 analyzer with Rosemount analyzers for total hydrocarbon (THC), oxides of nitrogen (NO_x), carbon dioxide (CO_2), and carbon monoxide (CO). This flex-fuel vehicle was tested running 0%, 10%, 20%, and 85% ethanol by volume.

The emissions of interest recoded in this study were THC, CO, CO_2, and NO_x, seen in Table 2.1. A decrease in THC, CO, CO_2, and NO_x emissions were seen for increasing ethanol content in the test fuel. Decreases in THC and CO were due to higher flame speeds of alcohol fuels. NO_x decreased due to the charge cooling effect of alcohol fuels. NO_x and THC trends will be insightful for the four-stroke engines, which operated closed-loop except for wide open throttle conditions.

Table 2.1: Emissions change with respect to E0, for increasing alcohol concentration

	THC (%)	CO (%)	CO_2 (%)	NO_X (%)
(E10-E0)/E0	-45.17	-83.24	-3.50	-57.48
(E20-E0)/E0	-58.49	-83.40	-3.25	-60.16
(E85-E0)/E0	-60.51	-82.07	-8.93	-74.08
(E20-E10)/E10	-24.30	-0.92	0.26	-6.29

2.1.2 In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels [1]

Field testing was performed for this study, and two different engines were tested. A 15ft Mako Center Console fishing boat was equipped with a BRP Evinrude E-Tec™ two-stroke outboard engine, featuring spray-guided direct fuel injection, stratified charged fuel delivery. A 24 foot SeaDoo Challenger boat was also tested, utilizing twin four-stroke liquid cooled supercharged 215HP SeaDoo Rotax™ engines, and featuring a single overhead cam. Testing took place in Chesapeake, Virginia using the five-mode weighted ICOMIA test cycle. A Marine Portable Bag Sampling System (MPSS) was used to measure emissions of THC, NO_x, and CO. As standard with the marine industry, emission values were reported on a THC+NO_x basis for certification gasoline and 16% iso-butanol.

For the Evinrude E-TEC™ engine, seen in Figure 2.1, there was an increase in NO_x for the iB16 case. Engines running open-loop operation typically see an increase in NO_x emissions because oxygen is being introduced with the fuel, and the engine cannot compensate for the increased oxygen concentration. This pushes combustion closer to higher temperature stoichiometric levels. The changes in THC emissions were not appreciable with a change in fuel.

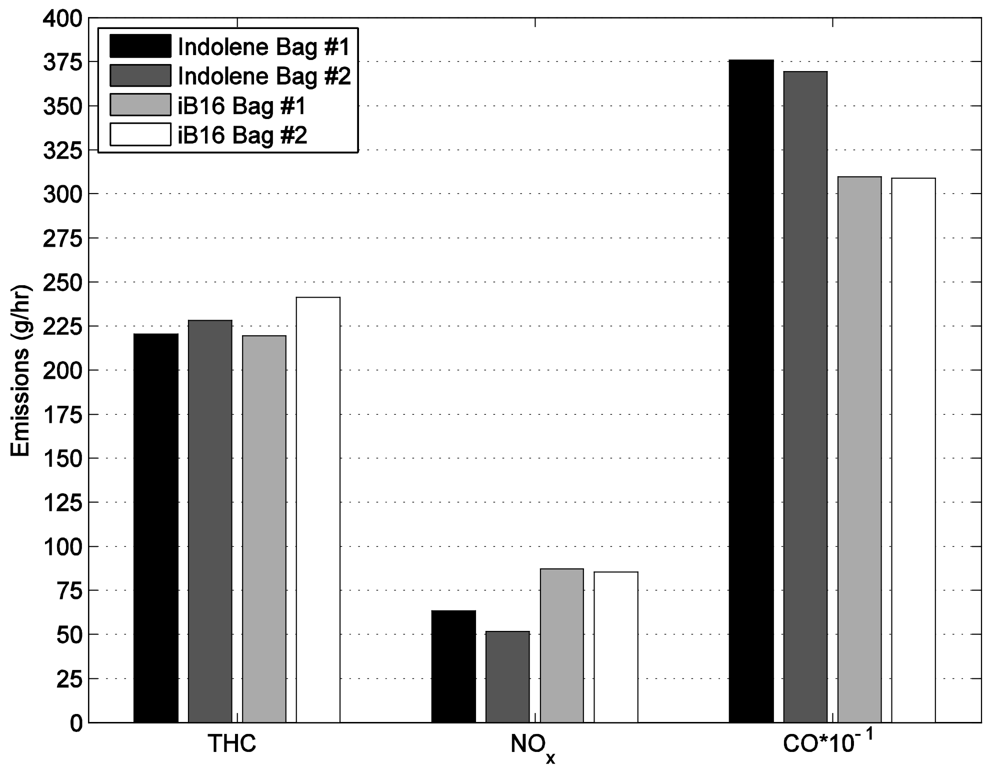

Figure 2.1: Evinrude E-TEC™ THC, NO_x, and CO emissions for indolene and iB16

Seen in Figure 2.2, THC emissions for the four-stroke SeaDoo Rotax™ engine decreased for iB16, with respect to the indolene baseline. THC decreased because the SeaDoo Rotax engine operates open-loop for all five modes of the ICOMIA test cycle, and with an increased oxygen concentration in the fuel, the engine operates closer to stoichiometric conditions. The increase in NO_x emissions can also be explained by the engine operating closer to stoichiometric conditions, increasing combustion temperatures allowing for more diatomic N_2 to dissociate and form NO_x.

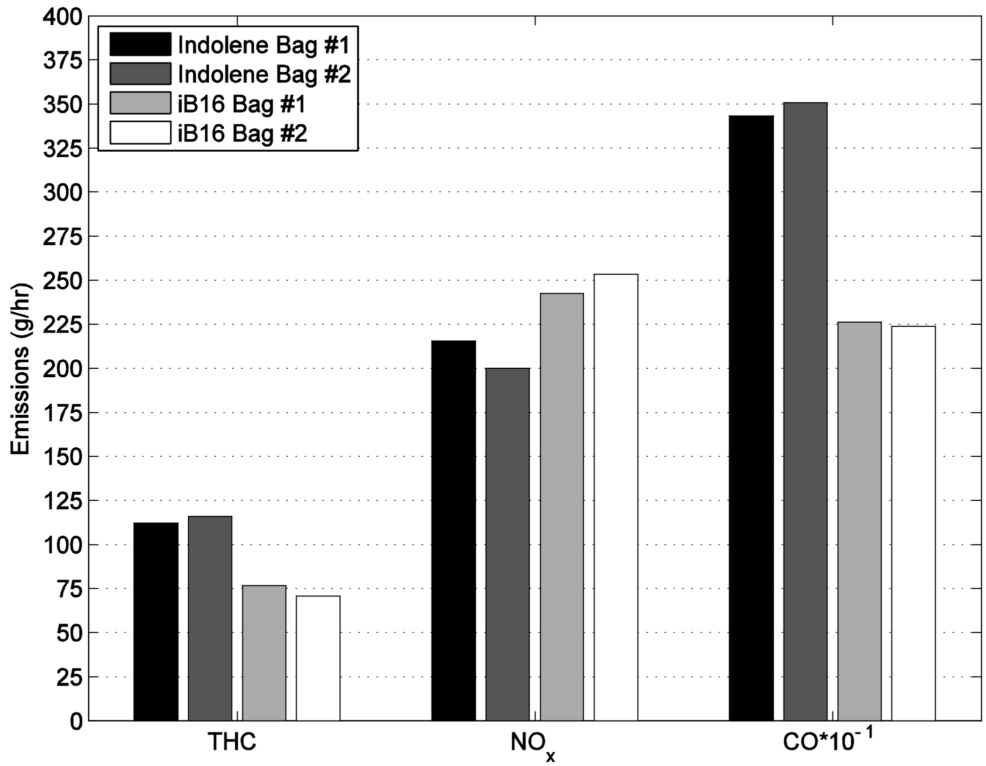

Figure 2.2: SeaDoo Rotax™ THC, NO_x, and CO emissions for indolene and iB16

Trends discussed for both the two-stroke and four-stroke engines will help to reinforce findings performed in this research. Results from the four-stroke SeaDoo Rotax will be important, because the four-stroke engines tested operate in an open-loop manner during wide open throttle (WOT) conditions.

2.1.3 Impact of E22 on Two-Stroke and Four-Stroke Snowmobiles [11]

Testing was performed using three snowmobiles, each with varying engine technologies. A 2009 Arctic Cat Z1 Turbo Touring featured a two-cylinder, four-stroke liquid cooled, turbo-charged, intercooled engine utilizing closed-loop, throttle body fuel injection. A 2009 Yamaha Apex featured a liquid cooled four-cylinder, four-stroke engine, running open-loop with port fuel injection. A 2010 Polaris Rush featured a two-cylinder, two-stroke liquid cooled engine, running open-loop and semi-direction injection. A four mode test cycle was performed, using a water brake dynamometer to set all speed and load points. A Horiba MEXA 1600D emissions analyzer was used to sample raw exhaust emissions while running 0% and 22% ethanol.

Testing performed on the Yamaha Apex, seen in Figure 2.3, showed a decrease in THC and CO emissions and an increase in CO_2 emissions, with respect to baseline tests. Because the engine operates open-loop, lambda on a per mode basis will approach stoichometric conditions, leaning out the air-fuel ratio. THC and CO emissions are both decreased in leaner operation. The increase in oxygen content delivered with the fuel to the combustion event also contributed to an increase in CO_2 emissions.

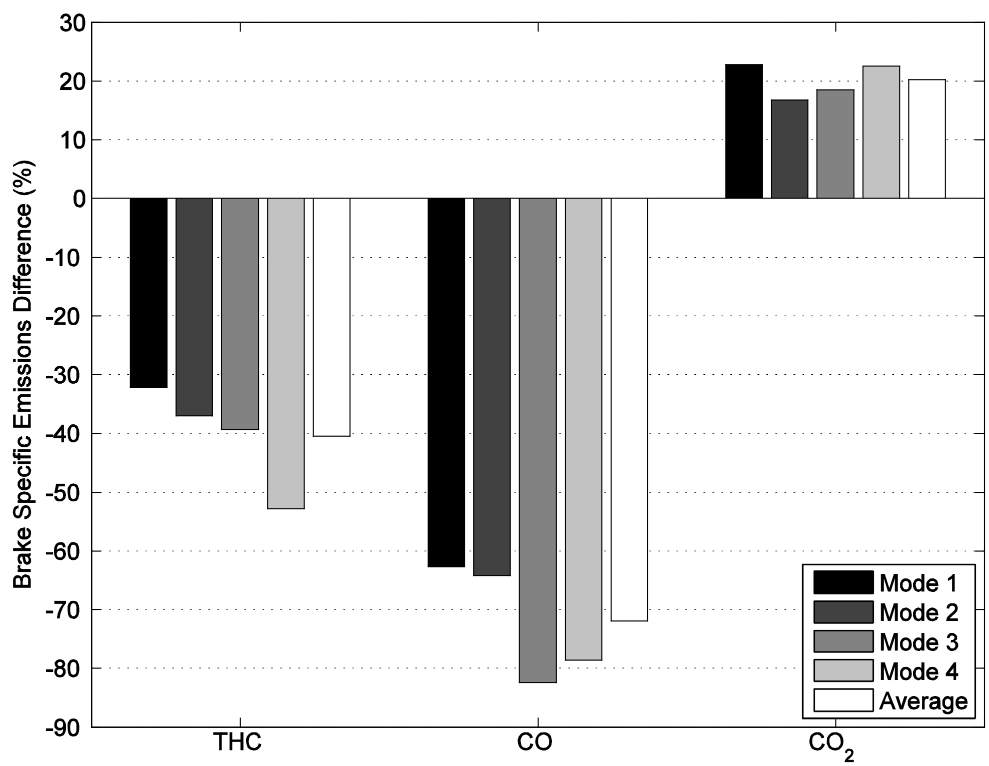

Figure 2.3: Brake specific change in emissions on the Yamaha Apex

Testing performed on the Polaris Rush, seen in Figure 2.4, showed a decrease in THC and CO emissions and an increase in CO_2 emissions, with respect to baseline tests. The Polaris Rush saw similar trends in changes of exhaust emissions, because both engines operate open loop, offering no compensation for changing oxygen content of the fuel. Changes at Mode 1 for the Polaris Rush are smaller with respect to other snowmobiles in this study because of the fuel calibration, controlled by a resistor. Polaris includes resistors for E0 and E10 operation, which change fueling management; the E10 resistor was used for E22 operation, not accounting for the higher ethanol content of E22.

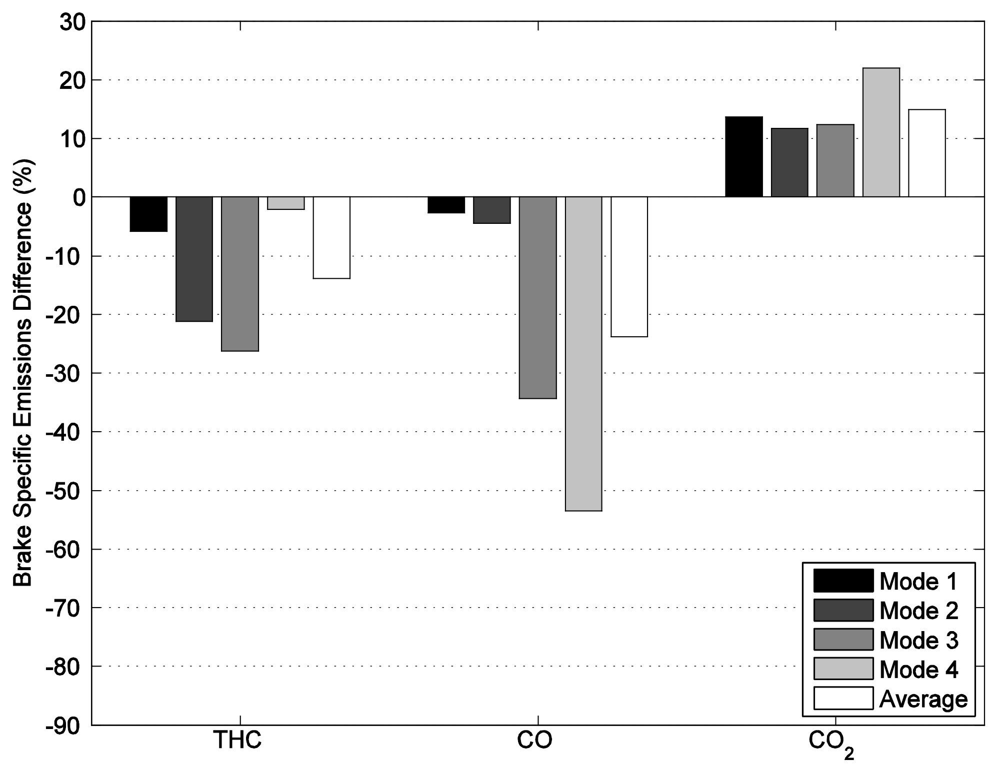

Figure 2.4: Brake specific change in emissions on the Polaris Rush

Testing performed on the Arctic Cat Z1 Turbo Touring, seen in Figure 2.5, shows a decrease in THC and CO emissions, while an increase in CO_2 emissions. Emissions trends for this engine follow the two aforementioned snowmobiles, but with a smaller change with respect to the baseline tests. This is due to the closed-loop operation of the engine, keeping an air-to-fuel ratio closer to that of the stock factory calibration.

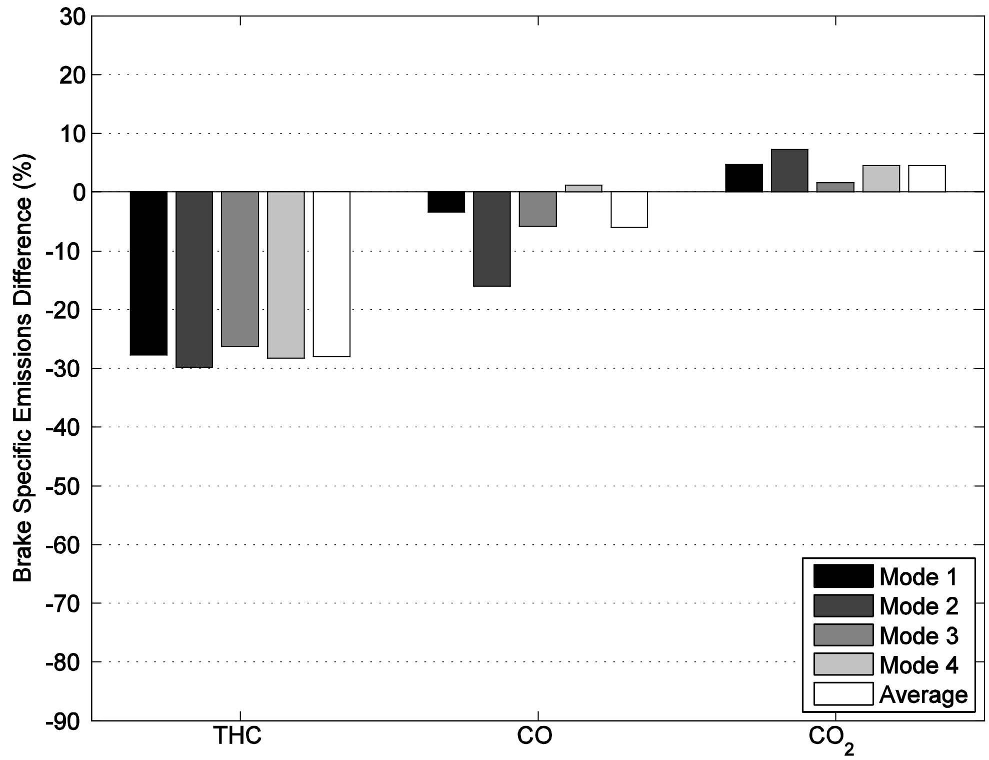

Figure 2.5: Brake specific change in emission on the Arctic Cat Z1 Turbo Touring

2.1.4 Effect of Alcohol Blended Fuels on the Emissions and Field Performance of Two-Stroke and Four-Stroke Engine Powered Two Wheelers [12]

For this study, four two-stroke, single cylinder, 145cc scooters were tested over the same fuels on a Mileage Accumulation Chassis Dynamometer (MACD), accumulating mileage all the way up to 20,000 km. THC, CO, CO_2, and NO_x emissions were analyzed using a Horiba MEXA 9400D emissions analyzer. Each scooter was tested with operation on 0%, 5%, 10% ethanol.

Research performed on two-stroke scooters focused on the impact of increasing alcohol concentrations, as engine age increased. Seen in Figure 2.6, there was an increase in THC emissions as engine age increased, regardless of fuel. This can be explained by clearances of the engine becoming larger, increasing crevice volumes which aid in the THC formation process.

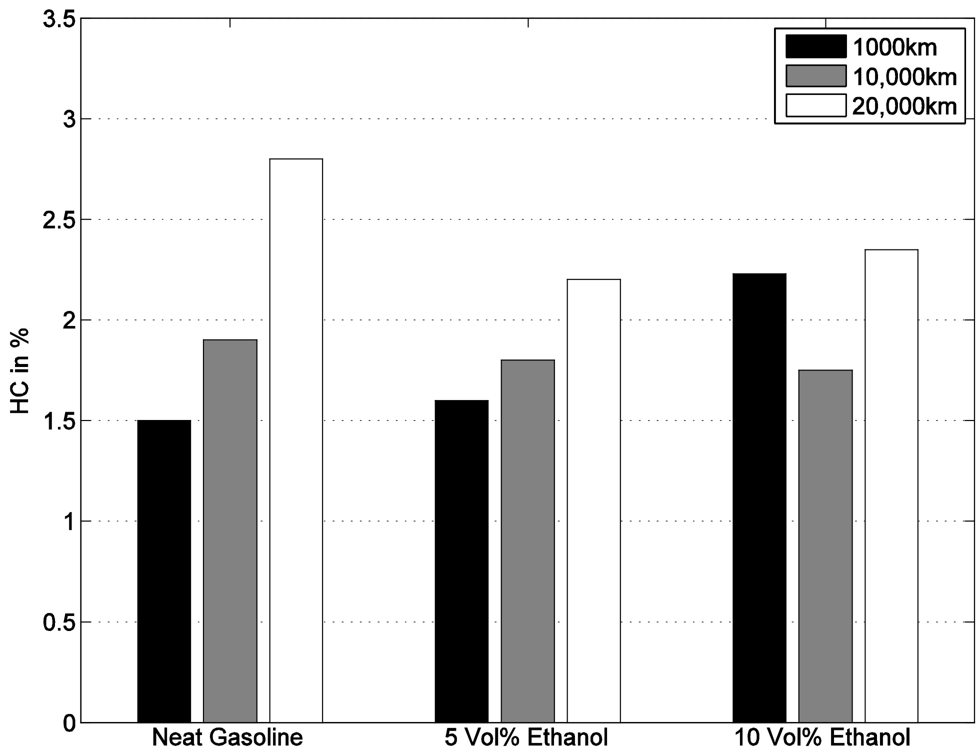

Figure 2.6: HC emissions of two-stroke scooters with varying alcohol blends

Seen in Figure 2.7, there was a decrease in CO emissions for the E5 and E10 case, as engine age increased past the 1000km mark. As oxygen was introduced with the fuel, more oxygen was available for the combustion process, reducing CO. The author attributes the increase in CO emissions with age for indolene operation to hydrocarbon buildup on the exhaust port. The author does not provide explanation why there is an increase in CO with increasing alcohol content, for the 1000km test.

Trends seen in this study for CO and THC will be important in understanding the two-stroke emissions data, because both engines deliver fuel in a similar manner, while also operating open-loop.

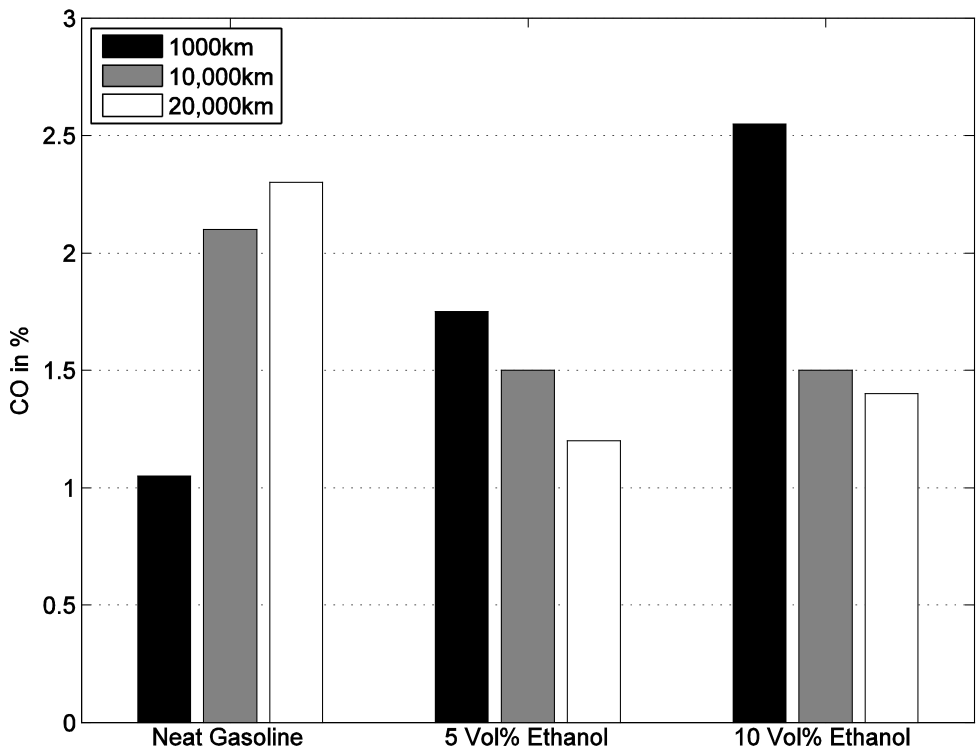

Figure 2.7: CO emissions of two-stroke scooters with varying alcohol blends

2.1.5 Influence of the Alcohol Type and Concentration in Alcohol-Blended Fuels on the Combustion and Emission of Small Two-Stroke SI Engines [2]

The exhaust emissions of hand-held maintenance equipment are of importance, because of the users close interaction with the exhaust. For this study, a 45.6 cc two-stroke, crankcase scavenged, external mixture formation power tool was used. Crank resolved cylinder pressure data sets were recorded, as well as exhaust back pressure. Constant volume emissions sampling techniques were used, utilizing an AVL SORE AMAi60-COMBI and AVL SESAM i60 FR 5Hz Fourier Transform Infrared Spectroscope (FTIR) for emissions analysis. Varying blends of ethanol, 1-butanol, and 2-

butanol were tested, separated into two categories of research octane number (RON) 95 and Alkylate fuel, which differ in their hydrocarbon fractions. The Alkylate fuel was developed specifically for use in hand-held power tools, by reducing the percentage of aromatic compounds to nearly zero to reduce the amount of aromatic hydrocarbons produced, such as benzene. Accordingly, the Alkylate fuel contained twice the amount of iso-Paraffin compounds as the RON 95 fuel. The RON 95 fuel is an example of what is available commercially.

With testing performed running a 45.6 cc handheld powertool, there was a definitive decrease in THC and NO emissions with increasing alcohol concentration regardless of base fuel, as seen in Figure 2.8. Because fuel delivery is controlled with a carburetor, the engine cannot compensate for an increased oxygen concentration of the fuel. A decrease in THC emissions for ethanol, 1-butanol, and 2-butanol were seen, caused by the engine operating in a more efficient combustion zone, near stoichiometric. A clear decrease in NO emissions was also seen for ethanol, 1-butanol, and 2-butanol. Cylinder pressure data recorded for this study shows that there was a decrease in burn duration, with increasing alcohol concentrations. The author states that the shorter burn duration allowed for the fuel to be oxidized quicker, but does not provide an analysis past that.

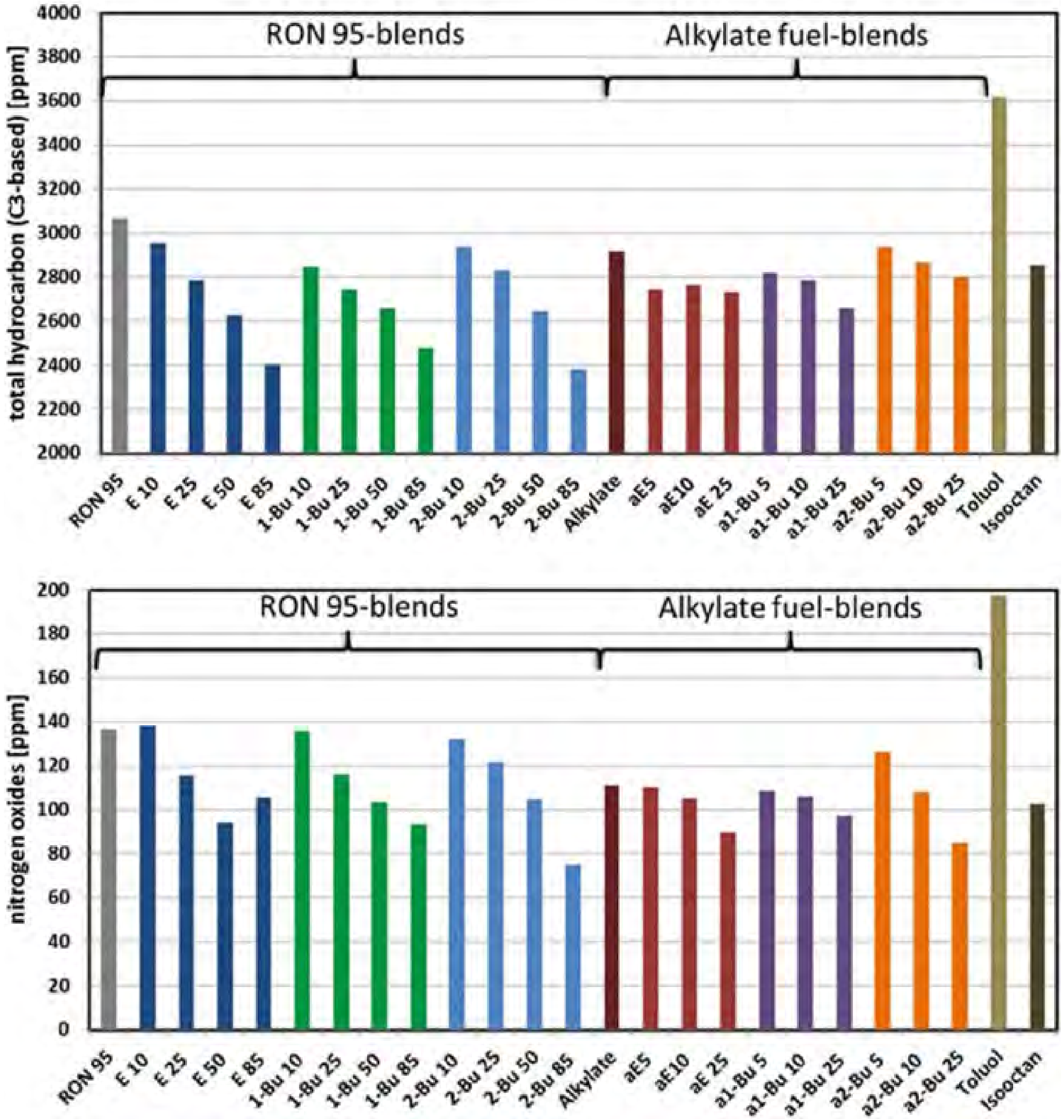

Figure 2.8: THC and NO emissions for 45.6cc handheld power tool [2]

The NO trends shown in Figure 2.8 will provide insight to emission trends recorded for the two-stroke outboard engine. The NO trend seen in Figure 2.8 with increasing alcohol concentration is contradictory to that of Figure 2.1. Although both engines are two-stroke, differing engine technologies such as fuel injection and carburetion, may be the root cause of the difference.

2.2 Literature Review Summary

Four of the five studies show a clear decrease in THC emissions as alcohol concentration increased, with respect to the baseline gasoline. For engines operating open-loop, an increase in oxygen concentration in the fuel causes the global lambda values to approach stoichiometric conditions. There were more oxygen atoms present to oxidize the fuel during these conditions, allowing for more efficient combustion. Engines operating closed-loop were able to compensate for changes in oxygen concentration. A strong decrease in THC emissions for the Chrysler Town & Country vehicle was seen due to higher flame speeds, allowing for a more complete combustion event. It is also theorized that oxygenated THC's deteriorate in the exhaust stream, but this is not a well understood or documented phenomenon.

NO emissions varied from study to study, appearing to be predominantly controlled by engine technology. Four-stroke engines operating closed-loop showed a consistent decrease in NO emissions with increasing oxygen concentration. The engine is able to compensate for an increase in oxygen concentration introduced by the fuel, and holds lambda at a constant stoichiometric condition. Engines that operate open-loop cannot compensate for changes in oxygen concentration. As the mixture is leaned out towards stoichiometric conditions, the NO formation mechanism is triggered by the increase in combustion temperatures.

There is a different trend between the two-stroke emissions, as seen by Wasil et al. [1] and Bertsch et al. [2]. The first engine is a spray guided direct injection two-stroke, which finely controls the fuel delivery process. The second engine is a two-stroke carbureted engine, with fuel delivery being controlled by the pressure difference across the carburetor. The E-Tec engine, although not truly closed-loop, has provisions built into the engine allowing for fuel flow to be changed based off operating conditions. Conversely, the 45.6cc handtool does not provide any compensation for differing fuels. In order to make the same power level with an alcohol fuel, more fuel needs to be delivered. Increasing the amount of alcohol fuel delivered decreases combustion temperatures because of the charge cooling effect introduced when inducting an alcohol fuel through the crank case.

3. Experimental Setup

The goal of this research was to investigate the effects of alcohol fuels on marine engines. Three different engines from different manufactures were tested, providing a representative sample of the engines available in the marine industry today. Tests were performed on a baseline certification test fuel and subsequent runs were performed running E10 (10% ethanol 90% gasoline by volume) and iB16 (16% iso-butanol 84% gasoline by volume). The two oxygenated fuels have the same oxygen concentration by mass, as specified by the EPA. Each boat was tested on the water using an adapted five-mode ICOMIA test cycle.

Each engine was tested on all three fuels, with two cycles being performed per fuel. Performing two test cycles per fuel enables test-to-test repeatability to be studied for each given fuel. Post catalyst emissions were sampled using Bombardier Recreational Products (BRP) MPSS [1], which places raw exhaust gas into special emissions bags. From there, a Sensors-Inc. Semtech five-gas raw emissions analyzer sampled the weighted emissions from Tedlar© emissions bags.

3.1 ICOMIA Test Cycle

The International Council of Marine Industry Associations (ICOMIA) developed a five mode weighted test cycle used to certify marine engines, known as the ICOMIA test cycle [13].

Table 3.1 outlines the different engine speed, torque, and emissions weightings for each mode.

An example calculation of a weighted emission constituent is seen in Equation 3.1; CO is used for this case, but the weightings apply to any emissions constituent.

$$CO_{weighted} = CO_{Mode1} * 0.06 + CO_{Mode2} * 0.14 + CO_{Mode3} * 0.15 + CO_{Mode4} * 0.25 + CO_{Mode5} * 0.40 \quad \text{……} \textit{Eqn 3.1}$$

Table 3.1: Weighting factors for ICOMIA Test Cycle (ISO #8178)

Mode	% RPM	% Torque	% Weighting Factor for Emissions
1	100	100	6
2	80	71.6	14
3	60	46.5	15
4	40	25	25
5	Idle	0	40

For the testing in Annapolis, MD, a maximum engine speed was found for each engine. From there, the maximum engine speed was given the respective weighting for each respective mode. Since engine torque was not able to be controlled during the field testing, torque was allowed to vary based off of water and throttle conditions. The EPA sets a Not-To-Exceed (NTE) zone, seen in Figure 3.1, for typical operation of recreational craft, based off of various operating conditions [1]. Given these guidelines, it was assumed the engine torque never deviated outside of the NTE zones. Therefore, an adaptation of the five-mode ICOMIA test cycle was performed in the field, subsequently referred to as the adapted ICOMIA test cycle.

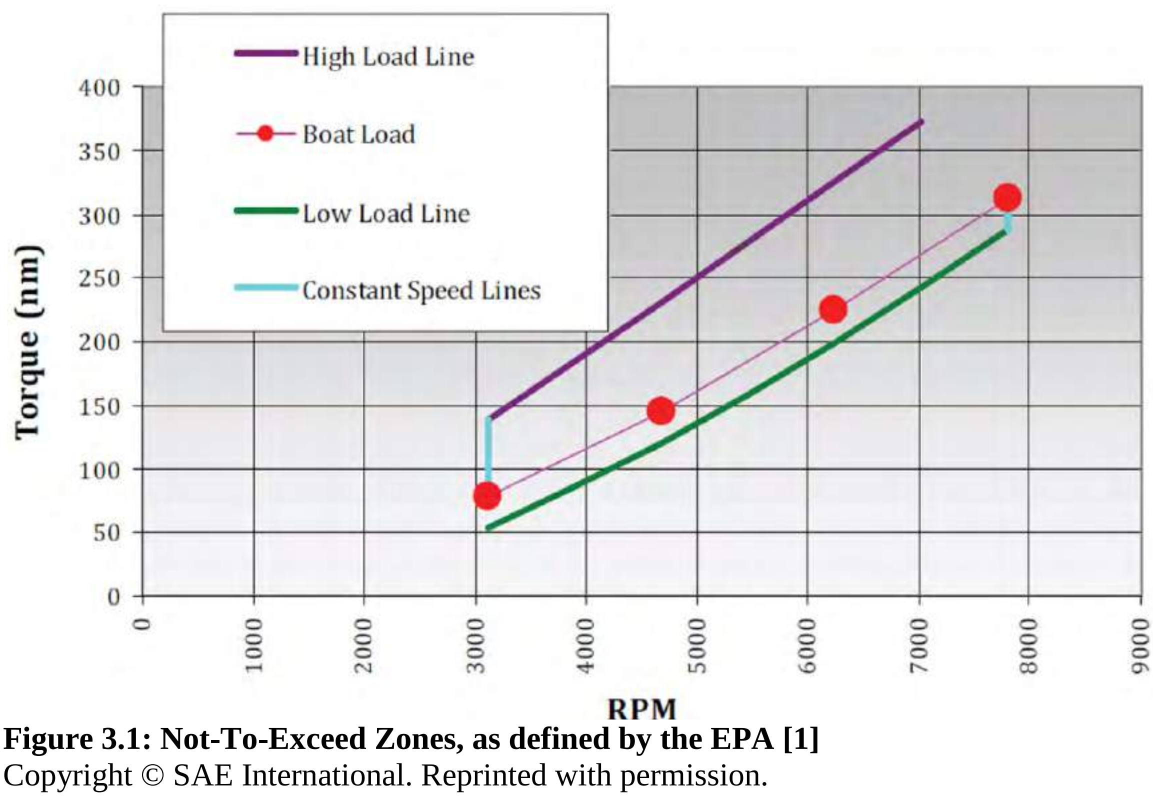

Figure 3.1: Not-To-Exceed Zones, as defined by the EPA [1]

3.2 Test Vessel Description

The engines tested during this research represent a broad range of technologies in the industry. Two-stroke carbureted and four-stroke fuel injected engines were tested, running different types of feedback strategies. The two-stroke engine ran open-loop operation at all times, providing no feedback to the engine when the oxygen concentration of the fuel changed. The four-stroke engines ran closed-loop operation, except at Mode 1. The closed-loop operation allowed for the engine to change fueling rates to the fuel injectors through the use of a wideband oxygen sensor. Table 3.2 displays parameters for each engine tested.

Table 3.2: Boat and engine specifications

Boat Manufacturer	Malibu	Alamar	Promarine
Engine Manufacturer	INDMAR	Volvo Penta	OMC
Displacement (l)	6.0	5.7	2.6
Rated Power (Hp)	362	320	150
Operation	Four-Stroke	Four-Stroke	Two-Stroke
Feedback	Closed-loop except at Mode 1	Closed-loop except at Mode 1	Open-loop
Number of Cylinders	8	8	6
Fuel Delivery	Port Fuel Injected	Port Fuel Injected	Carbureted
BoreXStroke (mm)	101.6 X 92	101.6 X 88.4	91.44 X 65.74

3.2.1 INDMAR

Pictured in Figure 3.2 is the Malibu Wake Setter ski boat which featured an INDMAR 6.0l L96 engine. The INDMAR shares the same design as the GM Generation IV small block engine. This engine features variable exhaust valve timing, allowing for the exhaust valve timing to be varied based off of operating conditions. Exhaust valve timing is retarded at launch for increased low end torque, and advanced during full speed operation to increase power. The engine operates in a closed-loop fashion, except for Mode 1, when the engine goes to open-loop. During open-loop operation, the fuel delivery goes to a pre-determined value in the engine control unit (ECU), which helps to cool the catalytic converters. Three-way catalysts are used to aid in meeting emissions regulations.

Figure 3.2: Malibu Wakesetter ski boat featuring an INDMAR engine

3.2.2 Volvo Penta

Pictured in Figure 3.3 is the Alamar Aluminum Hull boat which featured a Volvo Penta 5.7l Gxi engine. The Volvo Penta shares the same design as a GM Generation IV small block engine, featuring steel cylinder heads and block, to aid in corrosion resistance. Engine diagnostics are controlled using an ECU, which controls fuel delivery, spark timing, and performs various other diagnostics. Three-way catalysts are used to aid in meeting emissions regulations. This engine also operates closed-loop, except for full load conditions, when the engine goes open-loop. During open-loop operation, the fuel delivery goes to a pre-determined value in the ECU, which helps to cool the catalytic converters.

Figure 3.3: Alamar Aluminum Hull boat featuring a Volvo Penta engine

3.2.3 OMC

Pictured in Figure 3.4 is the Promarine Fiberglass Inc Intruder boat. This hull is equipped with an OMC Johnson Legacy outboard engine. This 2.6l, 6 cylinder, loop charged engine features two, triple throat carburetors, with float feed for fuel delivery. This engine is not equipped with an after-treatment system and thus emissions compliance relies on the set tune of the engine. This engine also does not come equipped with an ECU.

Figure 3.4: Promarine "Intruder" boat featuring an OMC outboard engine

3.3 Fuel Flow and Power

In order to convert raw emissions concentrations to a specific mass basis, fuel flow and power values were needed. For the INDMAR and Volvo Penta engines, fuel flow and power values were recorded from the ECU. A serial cable attached to the ECU allowed representatives from INDMAR and Volvo Penta to display ECU values on a laptop. Subsequent emissions values for the INDMAR and Volvo Penta are displayed on a g/kW-hr basis. An AVL PLU 120 fuel flow meter was used to measure fuel flow to calculate fuel consumption in g/hr for the OMC. Power values were not available for the OMC, because this engine is not equipped with an ECU. Therefore, all emissions values for the OMC are displayed on a g/hr basis.

3.4 Field Test Setup

The research discussed was performed in Annapolis, Maryland in the tributaries of the Chesapeake Bay. The location near the Chesapeake contained a long tributary that did not have many boaters, allowing for continuous testing without interruption of other boating traffic.

Testing was performed in various weather conditions, ranging from clear blue skies to cloudy blustery days. Ambient temperatures were near 60°F and 80°F for testing performed in May and September, respectively.

Annapolis, Maryland was chosen for this testing, as a historical meeting place. Numerous marine manufacturers come to Annapolis to perform research, because of the long boating season.

3.5 Sensors-Inc. Semtech-DS Onboard Vehicle Emissions Analyzer

A Sensors-Inc. Semtech-DS five-gas raw emissions analyzer was used to sample all gaseous emissions from Tedlar© emissions bags [14]. The Semtech-DS unit features a flame ionization detector (FID) for total hydrocarbon (THC) measurements, a Non-Dispersive Ultraviolet (NDUV) analyzer for nitrogen oxide (NO) and nitrogen dioxide (NO_2) measurements, a Non-Dispersive Infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO_2) measurements, and an Electrochemical sensor for oxygen (O_2) measurements. Table 3.3 outlines the range of measurement, accuracy, resolution, and data sampling rate for each associated emission constituent. Properties for NO_2 measurement are not listed, because a span gas for NO_2 was not available.

Table 3.3: Properties of Semtech-DS analyzers

Constituent	Range of measurement	Accuracy	Resolution	Data Rate
THC	0-100 $ppmC_1$ 0-1,000 $ppmC_1$ 0-10,000 $ppmC_1$ 0-40,000 $ppmC_1$ (User Defined)	±2.0% ±2.0% ±2.0% ±2.0%	0.1 $ppmC_1$ 1.0 $ppmC_1$ 1.0 $ppmC_1$ 10.0 $ppmC_1$	Up to 4Hz
NO	0-3000, 0-900, 0-300 ppm	±2.0%	0.1ppm	1Hz
CO	0-8%	±3.0%	10ppm	0.833Hz
CO_2	0-20%	±3.0%	0.01%	0.833Hz
O_2	0-25%	±1.0%	0.1%	N/A

An optional external charcoal filter was installed downstream of the FID analyzer, onto the back of the Semtech-DS unit. The purpose of this filter was to reduce the level of hydrocarbon emissions which could contaminate the NDUV and NDIR analyzers. The charcoal filter does not affect the measurement of CO, CO_2, or NO.

3.6 Marine Portable Bag Sampling System

The Marine Portable Bag Sampling System (MPSS) was originally developed by Bombardier Recreational Products (BRP) for use in previous studies with the National Marine Manufacturers Association (NMMA) [1]. The MPSS samples gaseous emissions from the exhaust manifold of the particular engine, at a constant flow rate. The exhaust sample first enters a particulate filter, and is then sent to a mechanical chiller, which uses a peristaltic pump to remove any condensate. THC emissions are measured using a FID, NO/NO_2 emissions are measured using a chemiluminescence detector (CLD), and CO emissions are measured using a NDIR. After the analyzers, the emissions sample is routed to a Tedlar® emissions sampled bag. An internal timer is used to properly weight the amount of emissions introduced to the Tedlar® bag, based off of exhaust mass flow rate for each mode, measured using an adjustable flow rotometer. Two five-mode weighted bag samples are recorded for each fuel, in order to better assess test-to-test variability.

3.7 SoMat™ Portable Data Acquisition System

A SoMat™ Portable Data Acquisition System was used to measure engine speed, boat speed, relative humidity, ambient temperature, and barometric pressure. Data sets recorded from the SoMat™ were used to validate the test-to-test consistency for each boat.

3.8 Test Procedure

3.8.1 Test Fuels

For testing performed in May and September, three fuels were tested: indolene, E10, and iB16. Table 3.4 shows all of the fuels tested for both rounds of testing.

Table 3.4: Properties of fuels tested in Annapolis, MD

	Indolene	**E10**	**E10 (Field Blended)**	**iB16**
Specific Gravity	0.7365	0.7397	0.7474	0.7489
Composition (C,H,O) Wt%	86.2, 13.8, 0	82.9, 13.1, 4.0	80.0, 13.8, 3.9	83.0, 13.0, 4.0
Octane Number (R+M)/2	92.4	89.7	91.0	88.7
RVP (psi)	9.0	8.8	6.7	8.5
Lower Heating Value (MJ/kg)	42.51	39.75	39.25	38.89

For testing performed in May, the shipment of E10 from the fuel manufacturer did not arrive in time for testing. Due to constraints with getting the research completed on schedule, a splash blend of E10 was created with fuel from local ExxonMobil and Shell gas stations. Because it was known ethanol will phase separate in the presence of water, a graduated bottle was used to measure the volume of ethanol that phase separated. Figure 3.5 shows the phase separation between water and ethanol. Using a graduated bottle, a solution of 10ml water and 90ml ExxonMobil 87 octane gasoline was created. The water was added to the fuel to force the ethanol to phase separate from the gasoline, allowing for the amount of ethanol in the fuel to be determined. After shaking the bottle vigorously and allowing for separation, there was indication the ExxonMobil gasoline had 7-8%

ethanol. In order to reach the 10% ethanol concentration, E85 from a local Shell Gas Station was added to achieve a field blended E10. Once the correct volumes for the 87 octane and E85 fuels were determined, batches of fuel were purchased from the same ExxonMobil and Shell gas stations. Enough fuel was purchased to create a 55 gallon batch, mixed in a clean 55 gallon drum.

After testing was performed, a sample of this fuel was shipped for analysis. Following the ASTM D5599 test standard, it was determined the field blended E10 contained 10.69% ethanol, by volume, validating the in-field blending technique. The field blended E10 was only used for May testing; testing performed in September used E10 from the fuel manufacturer.

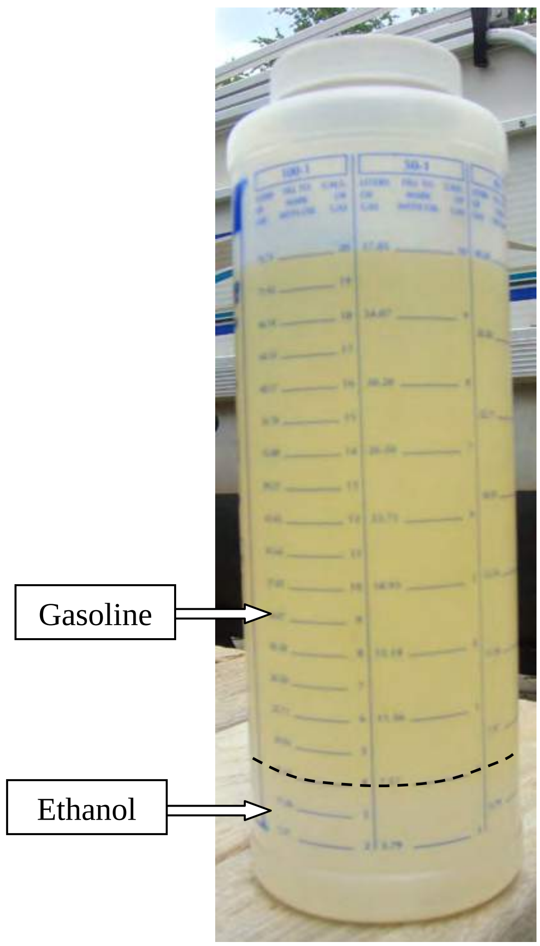

Figure 3.5: Graduated bottle showing phase separation between ethanol and water

3.8.2 Engine Warm-Up Procedure

Before emissions were sampled for each fuel, each engine was warmed up to full operating temperature. The location where each mode of the adapted ICOMIA test cycle was performed was 15 minutes away from the marina, giving the engine ample time to reach and maintain full operating temperature. WOT speed runs were performed for each fuel to locate the maximum engine speed of each boat. For all three fuels, maximum engine speed remained constant for each boat. During this warm-up period, the trim of the boat was set based off of varying weather conditions including: wind speed, ambient temperature, and water conditions. This ensured the engine was able to achieve the same speed for each mode.

3.8.3 Setting Constant Engine Speed

In order to ensure consistency from test-to-test, engine speed on a per mode basis was held constant. The INDMAR featured a factory installed Precision Speed Control, allowing the user to define engine speed. The Volvo Penta engine featured a standalone Zero Off Speed Controller, allowing the user to define engine speed [15]. The engine speed for the OMC was controlled by adjusting the throttle position to achieve the desired engine speed. Because this engine was not equipped with an ECU, the engine speed control methods described above were not able to be employed. The OMC engine speed fluctuated less than 5% for each fuel and mode of testing.

3.8.4 Emissions Sampling: MPSS

Gaseous emissions were sampled using the MPSS in pre and post catalyst locations, when applicable. Figure 3.6 and Figure 3.7 show pre and post catalyst emissions sampling locations for the INDMAR and Volvo Penta engines, respectively. Figure 3.8 shows the emissions sampling location for the OMC engine. Because this engine runs without after-treatment, only one sample probe was used.

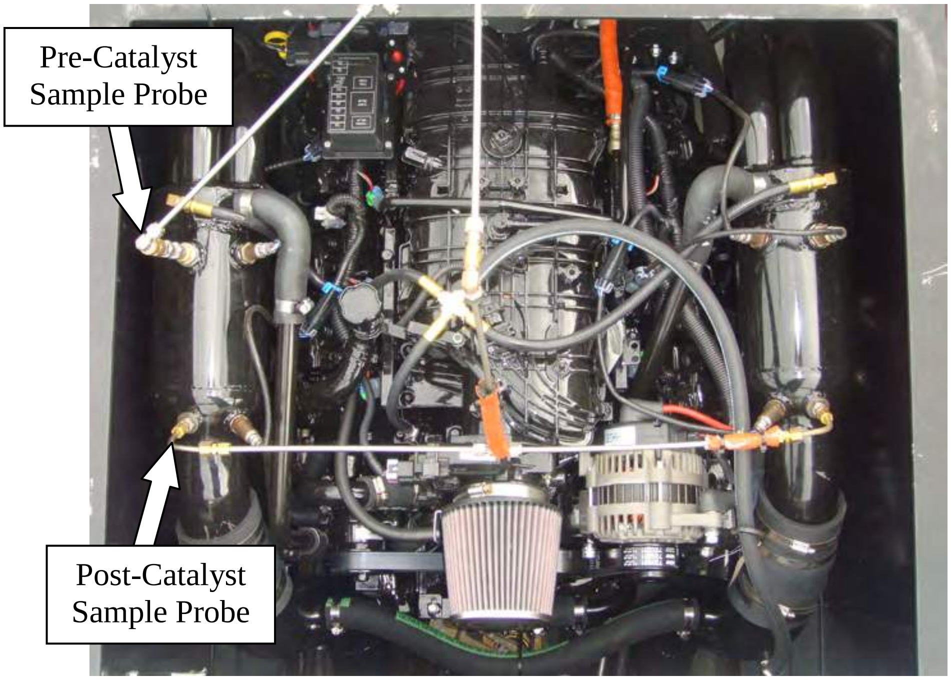

Figure 3.6: Pre and post-catalyst emission probes for the INDMAR

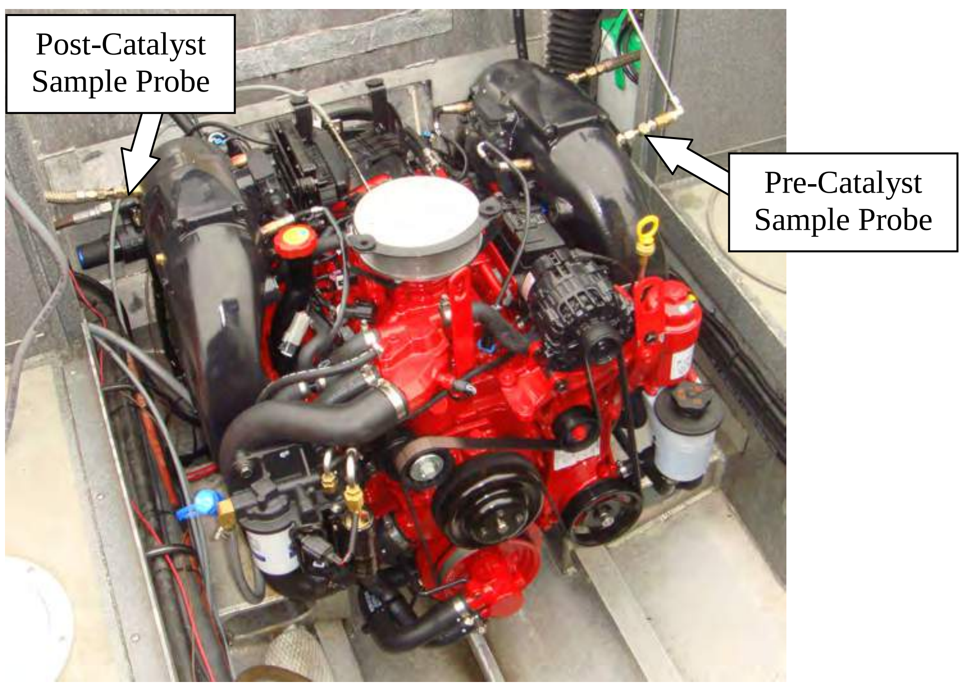

Figure 3.7: Pre and post-catalyst emission probes for the Volvo Penta

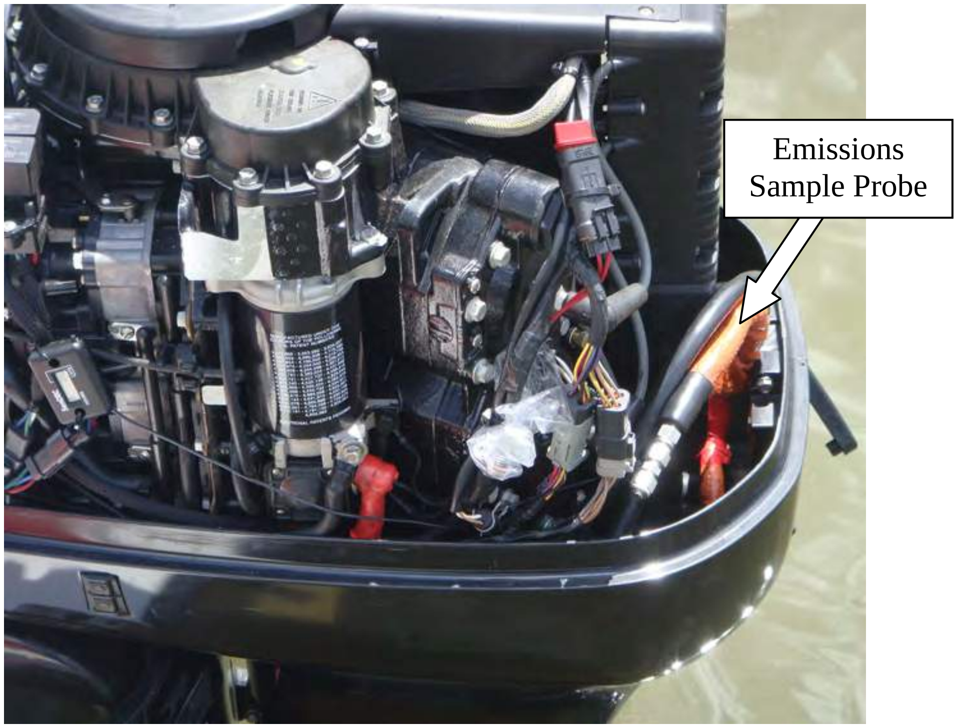

Figure 3.8: Gaseous emissions sample probe for the OMC

The MPSS uses the pre-catalyst sample locations to determine engine exhaust flow rate using an adjustable flow rotometer, on a per mode basis. Calculations are performed to determine the amount of time to sample emissions for each mode. An internal timer is set on the MPSS controlling sample volume, ensuring the Tedlar© emissions bag accurately represents the weighted five mode adapted ICOMIA test cycle. Post-catalyst emissions, when applicable, are sampled and run through the five-gas analyzer built into the MPSS. For the case of the OMC, one sample location serves the same purpose as pre and post catalyst sampling. These values are then recorded to a data file for post-processing. For each mode, the boat was run at the specific mode conditions and once a steady state speed was achieved, emissions were sampled.

3.8.5 Emissions Sampling Procedure

The Semtech-DS was used to sample emissions from the Tedlar© emissions bags, which were filled by the MPSS. All bags were sampled within three hours of filling with emissions. A quad blend gas was used to calibrate the Semtech-DS before and after each measurement. A gas of known concentrations was run through each analyzer, and the measured difference was taken into account for in the software and applied to each measurement.

Table 3.5 shows the concentrations for each gas constituent in the quad blend, used to span the Semtech-DS unit for testing performed in May and September. This blend was not used for testing in September when sampling OMC emissions.

Table 3.5: Quad blend span gas used in May and September

Gas Constituent	Concentration
CO	8.00%
CO_2	12.00%
NO	794.9ppm
THC	2023ppmC_1

Table 3.6 shows the concentrations for each gas constituent in the quad blend, used to span the Semtech-DS unit for testing performed in September, used with the OMC only. This bottle of span gas was not available during May testing due to complications with shipping from the supplier. The higher concentrations of the THC allowed for a better response of the FID analyzer when measuring THC in the exhaust. Because the response of a FID analyzer is linear, the lower THC span concentration used in May was not believed to significantly impact the exhaust THC measurement.

Oxides of nitrogen values are defined NO, and not NO_x. For this testing, the Semtech-DS was only spanned for NO, and therefore is the only calibrated oxide of nitrogen constituent.

Table 3.6: Quad blend gas used in September testing for the OMC

Gas Constituent	Concentration
CO	8.15%
CO_2	12.20%
NO	1481.0 ppm
THC	7780 ppmC_1

Below is the procedure used to sample emissions from the Tedlar© bags:

- Allow one hour for the analyzer to reach full operating temperature, and perform pre-test span and zero
- Connect Swagelock connecter on the end of the heated sample line to Swagelock connected on the Tedlar© emissions bag
- Before recording sample, allow Semtech-DS to sample emissions for 30 seconds. Wait for the emissions constituent values to reach a steady state value
- Record emissions for 90 seconds for the INDMAR and Volvo Penta. Record emissions for 60 seconds for the OMC
- Perform post-test zero and span after sampling emissions for one fuel
- Perform pre-test zero and span before changing fuels

Emissions on the two-stroke engine were sampled for a shorter period of time, because of the smaller engine displacement. The OMC engine had a lower exhaust flow rate than the two four-stroke engines, resulting in a smaller sample volume.

When an emissions bag was finished with sampling, a vacuum pump was used to remove any remaining sample. The bag was then filled with nitrogen and a vacuum pump was used to remove the nitrogen. This purge method was performed twice for each bag and then the bag was reused.

3.8.6 Complications with Bag Sampling

There were inherent issues introduced with bag sampling emissions. The amount of sample volume in each bag varied from test-to-test, because each boat would create different exhaust flow rates. Because of the different bag volumes, it became difficult to sample each bag for the same period of time for each engine. If a measurement error was made, extra precautions needed to be put into place to ensure the bag sample was still useable. For instance, during September testing a high THC concentration span gas was used for one sample, resulting in large variability in the THC measurement. The

Semtech-DS was recalibrated for a lower THC concentration span gas, and the Tedlar® bag was sampled, closely monitoring the overall sample volume left in the bag.

THC hangup also became an issue when sampling gaseous emissions. THC hangup occurs when THC particles from the exhaust sample stick to the sample container, such as the constant volume Tedlar® bag.

The OMC engine produced THC values over an order of magnitude higher than either of the four-stroke engines. As a result, one of the Tedlar® bags used for one test with the Volvo Penta had higher THC's, because of THC hangup from the OMC engine. Correction factors were applied to this isolated incident, as discussed in 4.5.2.

4. Results and Discussion

4.1 Emissions Measurement Repeatability and Stability

To show emissions measurement repeatability and stability, a series of plots and tables are included below.

4.1.1 INDMAR

Figure 4.1 shows the INDMAR engine speed on a per mode basis, for each fuel. As seen in Figure 4.1, there is minimal deviation in engine speed for each mode. Table 4.1 shows the time averaged emissions constituent values, with one standard deviation over the 60 second averaging period. Subsequent plots of each emission constituent and boat speed for the second round of testing can be seen in the appendix in Figure A.4 and Figure A.9.

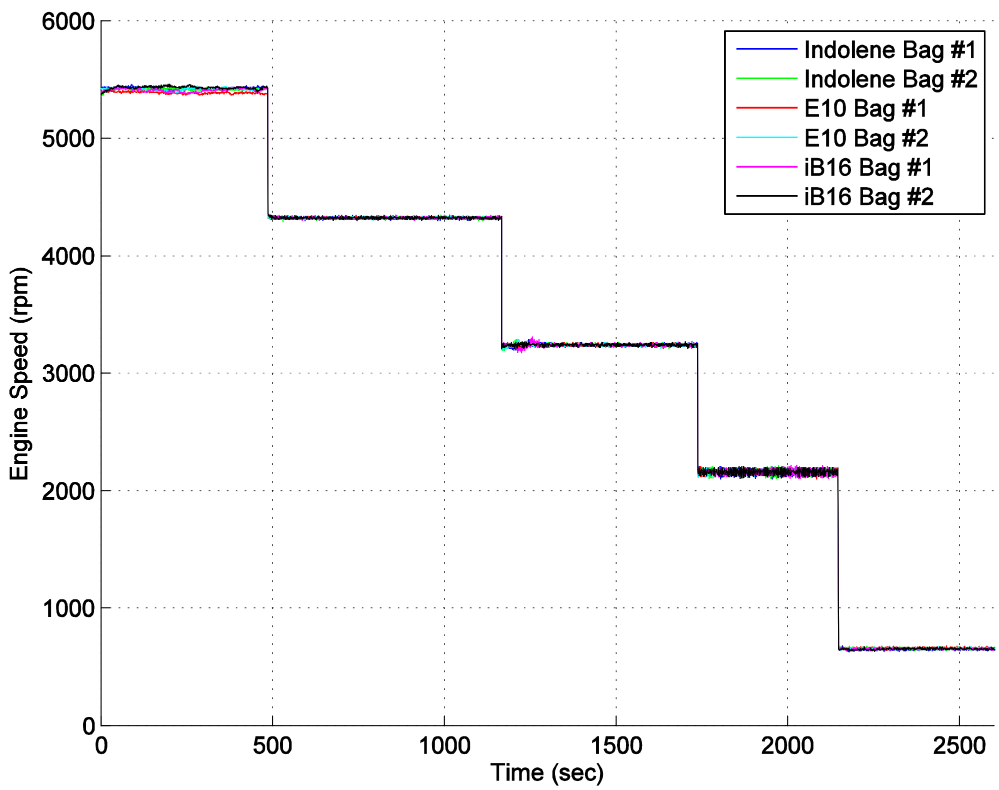

Figure 4.1: INDMAR engine speed – round 1

Table 4.1: INDMAR averaged emissions with one standard deviation – round 1

	CO (%)	NO (ppm)	THC (ppmC$_1$)
Indolene Bag #1	1.776±0.002	68.5±0.3	759.0±4.0
Indolene Bag #2	1.667±0.002	80.6±0.6	729.0±4.0
E10 Bag #1	1.840±0.001	115.0±1.0	895.0±4.0
E10 Bag #2	1.698±0.002	122.2±1.2	822.0±4.0
iB16 Bag #1	1.627±0.002	83.9±0.3	660.0±4.0
iB16 Bag #2	1.680±0.001	85.8±0.4	630.0±4.0

Figure 4.2 shows the boat speed for the INDMAR from May testing.

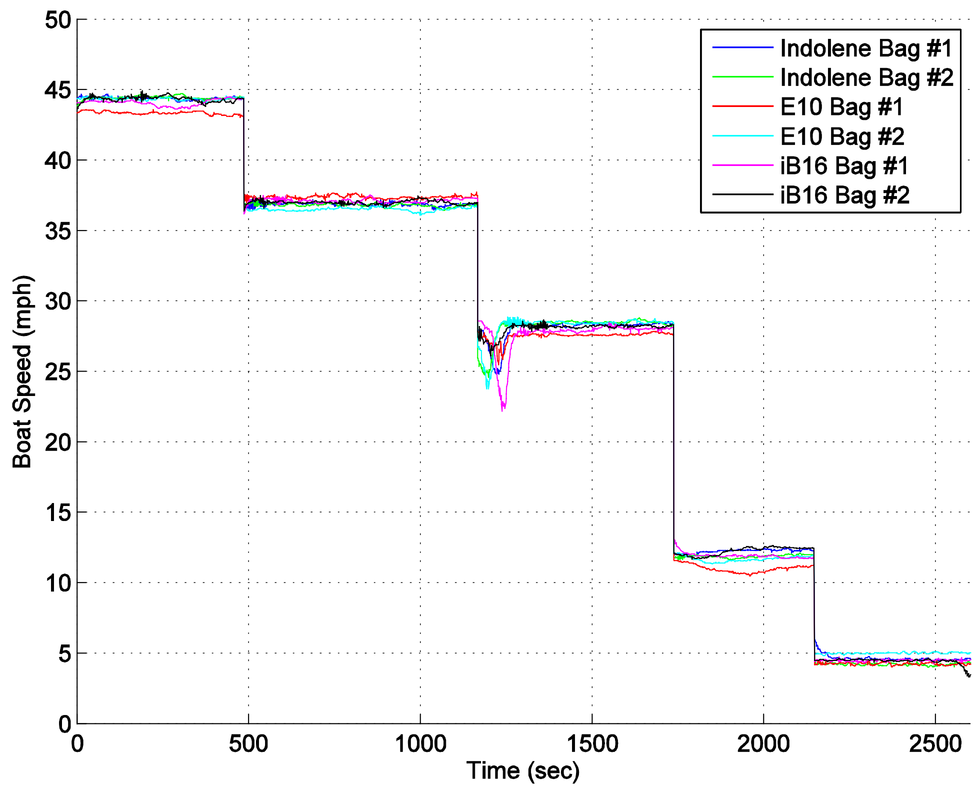

Figure 4.2: INDMAR boat speed – round 1

4.1.2 Volvo Penta

Figure 4.3 shows the Volvo Penta engine speed on a per mode basis, for each fuel. When data sets were taken for the second round of testing, there was a noisy tachometer signal; therefore the data sets were filtered to achieve the best result possible. An average was taken of the peaks for the engine speed signal, for each mode. Engine and boat speed plots are not available for the first round of testing due to corrupt data files. Table 4.2 shows the time averaged emissions constituent value, with one standard deviation over the 60 second averaging period. A subsequent data table of round 2 emissions standard deviation is available in the appendix, seen in Table A.2.

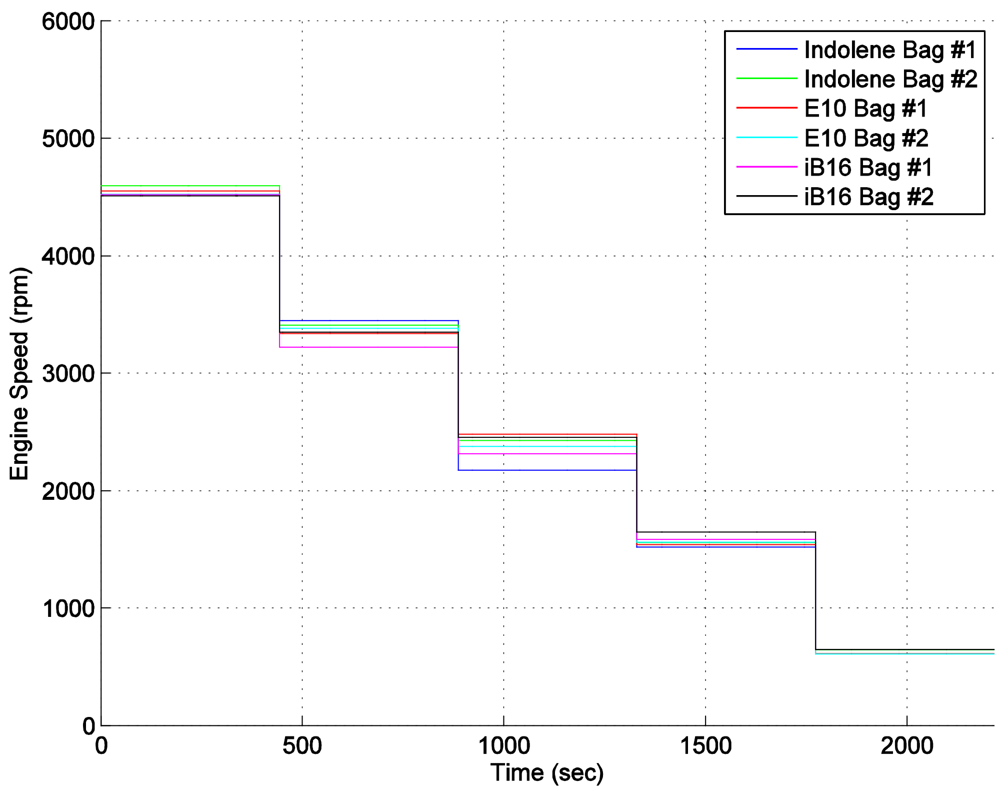

Figure 4.3 Volvo Penta engine speed – round 2

Table 4.2: Volvo Penta averaged emissions with one standard deviation – round 1

	CO (%)	NO (ppm)	THC (ppmC_1)
Indolene Bag #1	1.660±0.001	60.21±0.4	511±4
Indolene Bag #2	1.547±0.001	70.01±0.6	500±4
E10 Bag #1	0.951±0.001	102.1±1.0	365±4
E10 Bag #2	0.735±0.001	108.9±1.3	299±4
iB16 Bag #1	0.852±0.001	70.6±0.3	318 ±4
iB16 Bag #2	1.028±0.001	73.1±0.4	374±5

Figure 4.4 shows the boat speed for the Volvo Penta from September testing.

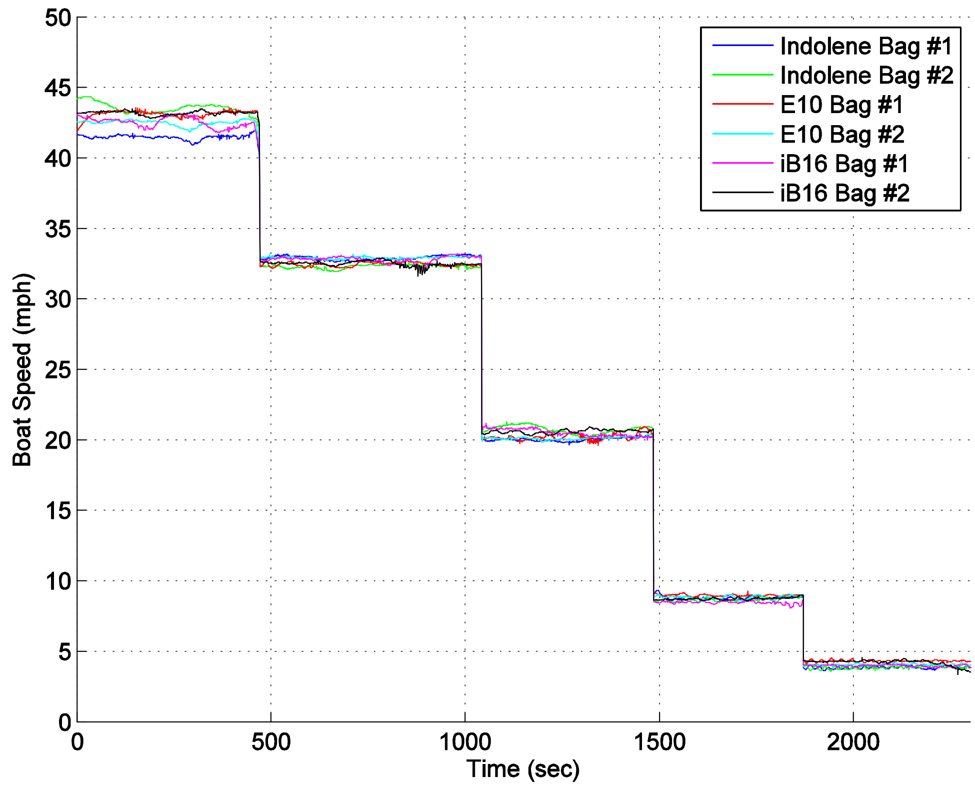

Figure 4.4: Volvo Penta boat speed – round 2

4.1.3 OMC

Figure 4.5 shows the OMC engine speed on a per mode basis, for each fuel. Table 4.3 shows the time averaged emissions constituent values, with one standard deviation over the 60 second averaging period. Subsequent plots of each emission constituent and boat speed for both rounds can be seen in the appendix in Figure A.6 and Figure A.10. Although a standard deviation of up to 50ppmC_1 THC seems large by comparison to the four-stroke engines, the raw concentration of THC for the OMC is three orders of magnitude larger. The standard deviation reflects the ±10 ppmC_1 resolution of the FID at high concentrations.

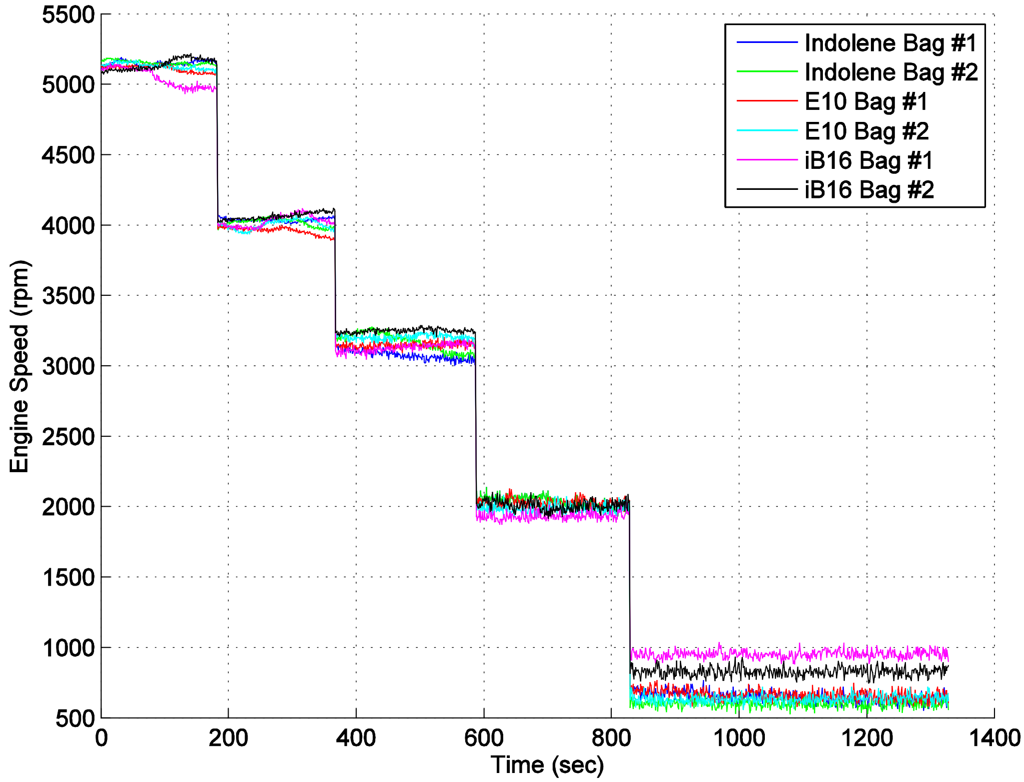

Figure 4.5: OMC engine speed – round 1

Table 4.3: OMC averaged emissions with one standard deviation – round 1

	CO (%)	NO (ppm)	THC ($ppmC_1$)
Indolene Bag #1	3.954±0.003	54.4±0.3	28610±40
Indolene Bag #2	3.838±0.002	71.4±0.2	28310±30
E10 Bag #1	3.210±0.003	15.0±0.2	24810±40
E10 Bag #2	3.247±0.002	13.5±0.1	26690±40
iB16 Bag #1	2.898±0.002	16.4±0.4	26160±50
iB16 Bag #2	2.804±0.002	15.7±0.1	24800±20

Figure 4.6 shows the boat speed for the OMC from May testing.

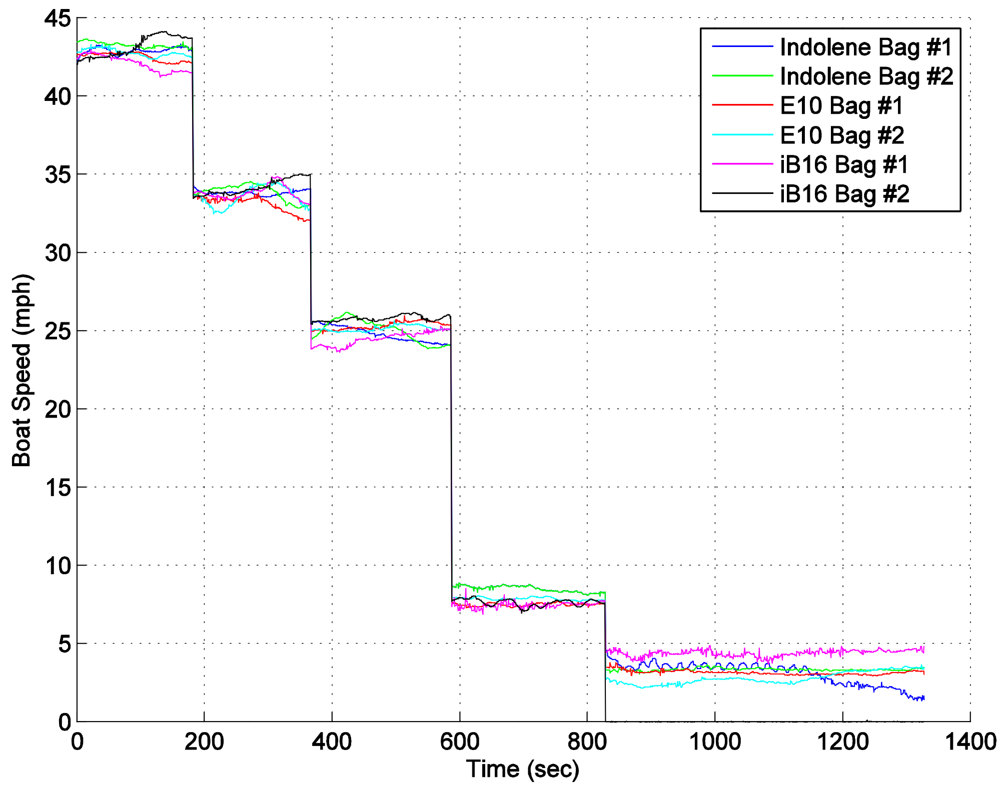

Figure 4.6: OMC boat speed – round 1

4.2 Hours of Operation

The marine industry sets specific guidelines for the useful life of engines, based on the class of engine. All three engines were aged in the summer months between the May and September testing, running the same iB16 fuel used for this study. Table 4.4 shows the useful life of each engine, and the amount of hours put onto each engine for the duration of this study.

Table 4.4: Hours of operation for all three engines

	Useful Life (hrs)	Beginning of study (hrs)	End of study (hrs)	Hours added (hrs)	Percent of Useful Life (%)
INDMAR	480	3	48	45	9
Volvo Penta	480	9	61	52	11
OMC	350	2	43	41	12

As seen in Table 4.4, none of the engines in this study were near the end of their useful life. To make a beginning-of-life to end-of-life comparison of emissions from May to September based off of engine hours would not be representative. Therefore, any difference seen in engine-out emissions between May and September testing reflects the variability between rounds of testing due to environmental impact, such as water conditions, wind speed, ambient temperature, boat speed, and boat trim. Some minor differences due to engine break-in may also be present.

4.3 May and September Ambient Conditions

Table 4.5 shows the ambient test conditions for testing performed in Annapolis, MD in the months of May and September. While the ambient temperature and pressure remained relatively constant during each round, relative humidity varied due to different weather fronts. The large change in weather conditions directly affected test results, affecting the variability between rounds of testing,

Table 4.5: Average ambient test conditions for May and September

	Ambient Temperature (°F)	Relative Humidity (%)	Ambient Pressure (mbar)
May	61	33-70	1018
September	80	33-57	1025

4.4 Baseline Indolene Emissions

4.4.1 INDMAR

Table 4.6 shows the raw emissions for the INDMAR engine running indolene for both rounds of testing. Emissions values shown below for each round are averaged over two emissions bag samples.

Table 4.6: Raw emissions for INDMAR – indolene

Emission Constituent	CO (%)	NO (ppm)	THC ($ppmC_1$)	THC+NO (ppm)
Round 1	1.722	65.6	746	811
Round 2	2.123	116.9	722	839
Average	1.923	91.3	734	825

Table 4.7 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.7: Specific emissions for INDMAR – indolene

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
Round 1	63.41	0.46	1.60	2.06
Round 2	85.37	0.89	1.66	2.56
Average	74.39	0.68	1.63	2.32

4.4.2 Volvo Penta

Table 4.8 shows the raw emissions for the Volvo Penta running indolene for both rounds of testing. Emissions values shown below for each round are averaged over two emissions bag samples.

Table 4.8: Raw emissions for Volvo Penta – indolene

Emission Constituent	CO (%)	NO (ppm)	THC ($ppmC_1$)	THC+NO (ppm)
Round 1	1.603	59.68	507	567
Round 2	1.371	55.49	377	433
Average	1.487	57.59	442	500

Table 4.9 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.9: Specific emissions for Volvo Penta – indolene

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
Round 1	53.63	0.38	0.98	1.37
Round 2	47.85	0.37	0.76	1.13
Average	50.74	0.38	0.87	1.25

4.4.3 OMC

Table 4.10 shows the raw emissions for the OMC running indolene. Emissions values shown below are averaged over two emissions bag samples.

Table 4.10: Raw emissions for OMC – indolene

Emission Constituent	CO (%)	NO (ppm)	THC ($ppmC_1$)	THC+NO (ppm)
Round 1	3.896	44.6	28470	28520
Round 2	4.047	39.7	29270	29310
Average	3.972	42.2	28870	28910

Table 4.11 shows specific emissions values for CO, NO, THC, and THC+NO on a g/hr basis.

Table 4.11: Specific emissions for OMC – indolene

Emission Constituent	CO (g/hr)	NO (g/hr)	THC (g/hr)	THC+NO (g/hr)
Round 1	6148	13.96	2666	2680
Round 2	6220	11.89	2648	2660
Average	6184	12.93	2656	2670

4.5 E10 and iB16 Emissions and Comparison to Indolene

For this section, all lambda values are calculated using the ISO #16183 standard [16]; this calculation method is used as the de-facto standard.

Figure 4.7 shows qualitatively how THC, NO, and CO emissions vary with changes in relative air-to-fuel ratio [17]. This qualitative plot will be used to explain general emissions trends.

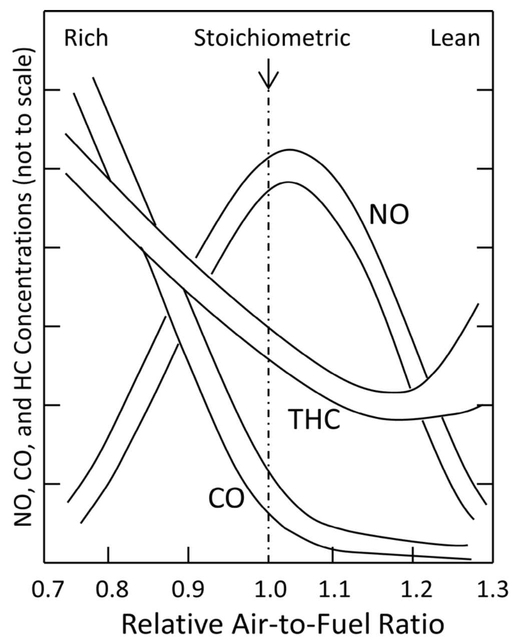

Figure 4.7: General emissions trends as a function of relative air-to-fuel ratio
Based off of Figure 11.2 in Heywood [17]

4.5.1 INDMAR

Table 4.12 shows the raw emissions for the INDMAR engine running E10 and iB16. Emissions values shown below are averaged over two emissions bag samples.

Table 4.12: Raw emissions for INDMAR – alcohol fuels

Emission Constituent	CO (%)	NO (ppm)	THC ($ppmC_1$)	THC+NO (ppm)
E10 Round 1	1.769	105.5	858	964
E10 Round 2	1.873	109.7	659	769
E10 Average	1.821	107.6	759	866
iB16 Round 1	1.654	71.9	646	717
iB16 Round 2	1.820	123.3	630	753
iB16 Average	1.737	97.6	638	735

Table 4.13 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.13: Specific emissions for INDMAR – alcohol fuels

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
E10 Round 1	64.80	0.75	1.96	2.71
E10 Round 2	76.80	0.85	1.61	2.46
E10 Average	70.80	0.80	1.78	2.59
iB16 Round 1	61.46	0.51	1.44	1.95
iB16 Round 2	80.20	1.03	1.66	2.69
iB16 Average	70.82	0.77	1.55	2.32

Figure 4.8 shows the percent change in specific emissions from indolene to each respective alcohol fuel. Values from Figure 4.8 and Figure 4.9 can be seen in Table A.4 and Table A.7, respectively.

CO emissions decreased as alcohol fuels were introduced. Because the engine operates open-loop at Mode 1, the overall air-to-fuel ratio was enleaned, as seen in Figure 4.9, decreasing CO emissions. This is exemplified in Figure 4.7, where leaning the global air-to-fuel ratio decreases CO emissions [17].

There was a general increase in NO emissions, explained by engine operation at Mode 1. While operating open-loop, the engine cannot compensate for an increase in oxygen concentration being introduced with the fuel. Therefore, the engine approached stoichiometric air-to-fuel ratios, seen in Figure 4.9, increasing combustion temperatures and promoting NO formation, as previously noted by Heywood [17]. This is cinsitent with research performed by Wasil [1].

There was a conflicting trend between E10 and iB16 for THC emissions. Literature by Yassine et al. [10] previously discussed clearly shows a decrease in THC emissions for closed-loop four-stroke engines. THC and CO emissions values for E10 from the Semtech-DS and MPSS were compared for testing performed in May, as seen in Table 4.14. There is a consistent trend between the two bag samples from both analyzers. Therefore, it is believed that the Semtech measurement is correct. The only way to reach a THC trend conclusion would be to perform the test again.

Table 4.14: Semtech-DS and MPSS emissions comparison – E10 May testing

	Semtech-DS		MPSS	
	THC (ppmC_1)	CO (%)	THC (ppm C_1)	CO (%)
Bag #1	895	1.840	744	0.555
Bag #2	821	1.699	612	0.481

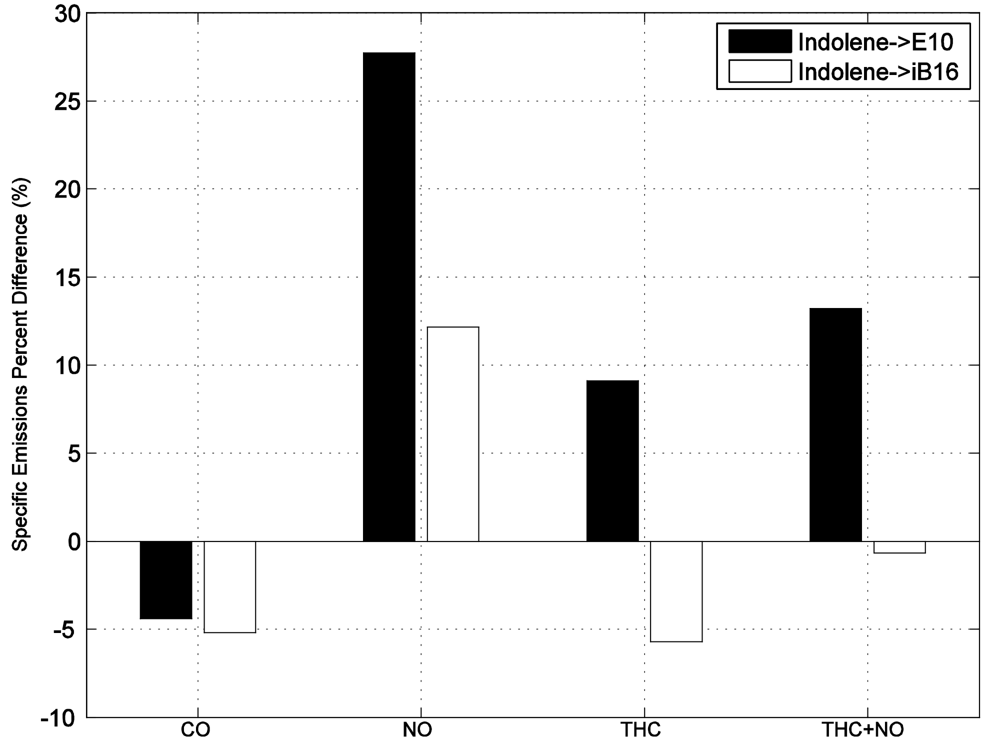

Figure 4.8: Specific emissions percent difference from indolene – INDMAR

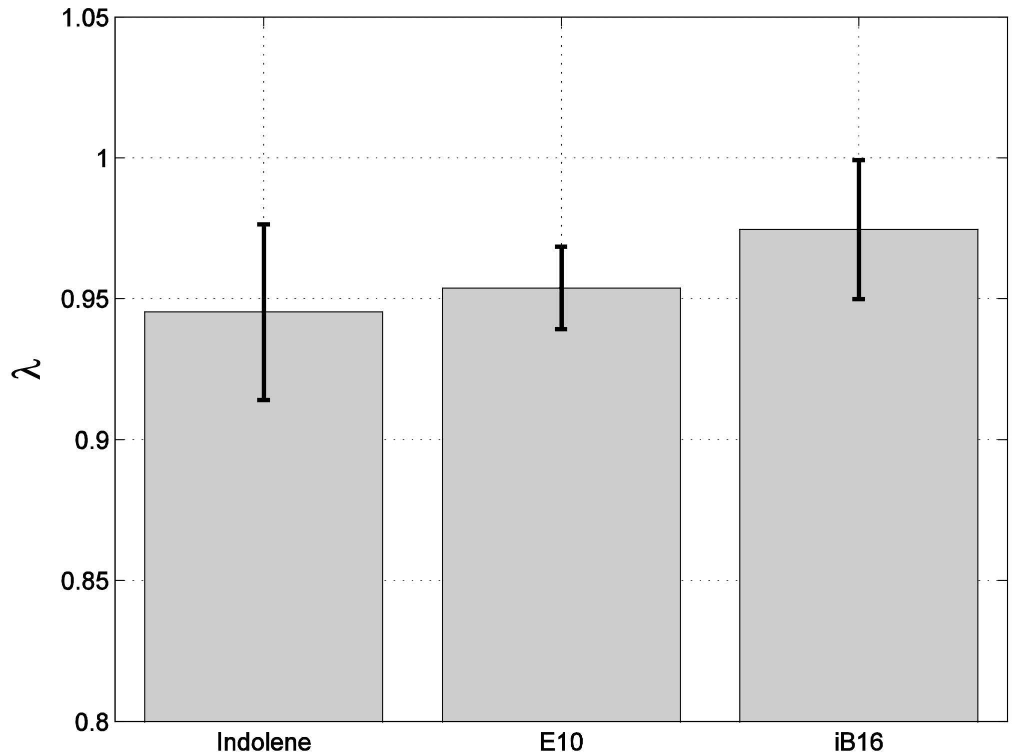

Figure 4.9: INDMAR averaged lambda values – ISO #16183

As seen in Figure 4.9, there is a difference between the lambda values for E10 and iB16, even though the oxygen concentrations by mass for E10 and iB16 are the same, as seen in Table 3.4. The difference seen between E10 and iB16 are within one standard deviation of each other. Note that one possible explanation for the difference is that the blended lower heating value of iB16 is lower than E10 by approximately 1%. Therefore in order to maintain the same power levels, the throttle position needs to be increased, increasing intake air flow rates. Additionally, changes in fuel fluid properties, such as viscosity, may impact the relative air-to-fuel ratio values as well.

Overall changes seen in THC+NO emissions are not necessarily a function of fuel composition, but of test conditions, as seen in Table 4.5. Because testing was performed in-field during two different seasons, it is difficult to show repeatability with respect to test conditions. With the exception of THC, iB16 emissions were consistent for each emission constituent, with respect to E10 operation. Overall, iB16 emissions followed the same trends as E10.

4.5.2 Volvo Penta

Table 4.15 shows the THC correction factors applied to three Tedlar© bags for the second round of testing. The values were subtracted from the raw THC values reported by the Semtech-DS, due to bag contamination from the OMC engine.

Table 4.15: Volvo Penta THC correction factors

iB16 Bag #1	15ppmC_1
iB16 Bag #2	30ppm C_1
E10 Bag #2	65ppm C_1

Table 4.16 shows the raw emissions for the Volvo Penta running E10 and iB16. Emissions values shown below are averaged over two emissions bag samples.

Table 4.16: Raw emissions for Volvo Penta – alcohol fuels

Emission Constituent	CO (%)	NO (ppm)	THC (ppmC_1)	THC+NO (ppm)
E10 Round 1	0.843	60.5	332	393
E10 Round 2	1.279	93.2	398	492
E10 Average	1.061	76.9	365	442
iB16 Round 1	0.940	60.2	347	407
iB16 Round 2	1.187	87.3	416	503
iB16 Average	1.064	73.8	381	455

Table 4.17 shows specific emissions values for CO, NO, THC, and THC+NO on a g/kW-hr basis.

Table 4.17: Specific emissions for Volvo Penta – alcohol fuels

Emission Constituent	CO (g/kW-hr)	NO (g/kW-hr)	THC (g/kW-hr)	THC+NO (g/kW-hr)
E10 Round 1	31.08	0.43	0.75	1.18
E10 Round 2	46.58	0.65	0.76	1.51
E10 Average	38.82	0.54	0.76	1.35
iB16 Round 1	35.02	0.42	0.77	1.19
iB16 Round 2	44.02	0.62	0.87	1.54
iB16 Average	39.52	0.52	0.82	1.36

Figure 4.10 shows the percent change in specific emissions from indolene to each respective alcohol fuel. Values for Figure 4.10 and Figure 4.11 can be seen in Table A.5 and Table A.7, respectively.

The overall decrease in CO emissions, as seen in Figure 4.10, can be attributed to leaner Mode 1 operation, as seen in Figure 4.11. CO formation is dependent upon excess fuel [17]; during Mode 1 the amount of excess fuel due to open-loop operation was decreased.

The increase in NO emissions is due to Mode 1 operation, where the engine runs rich open-loop. As oxygen is introduced with the fuel, lambda approaches stoichiometric conditions, seen in Figure 4.11, increasing combustion temperatures and NO formation. Seen in Table 4.17, there was a larger increase in NO formation for alcohol fuels for the second round of testing, with respect to the first round of testing. The increase in ambient temperature from May to September testing can be seen in Table 4.5. A higher intake charge-air temperature increased combustion temperatures, which increased NO formation. Previously discussed literature by Wasil et al. [1] has shown that open-loop four-stroke engines have an increase in NO concentrations with alcohol fuels.

Mode 1 operation caused the global air-to-fuel ratio to approach stoichiometric conditions, which decreases THC formation, as shown in Figure 4.7. There was less excess fuel during the combustion event, decreasing THC emissions.

iB16 emissions were consistent for each emission constituent, with respect to E10 operation. Overall, iB16 emissions followed the same trends as E10.

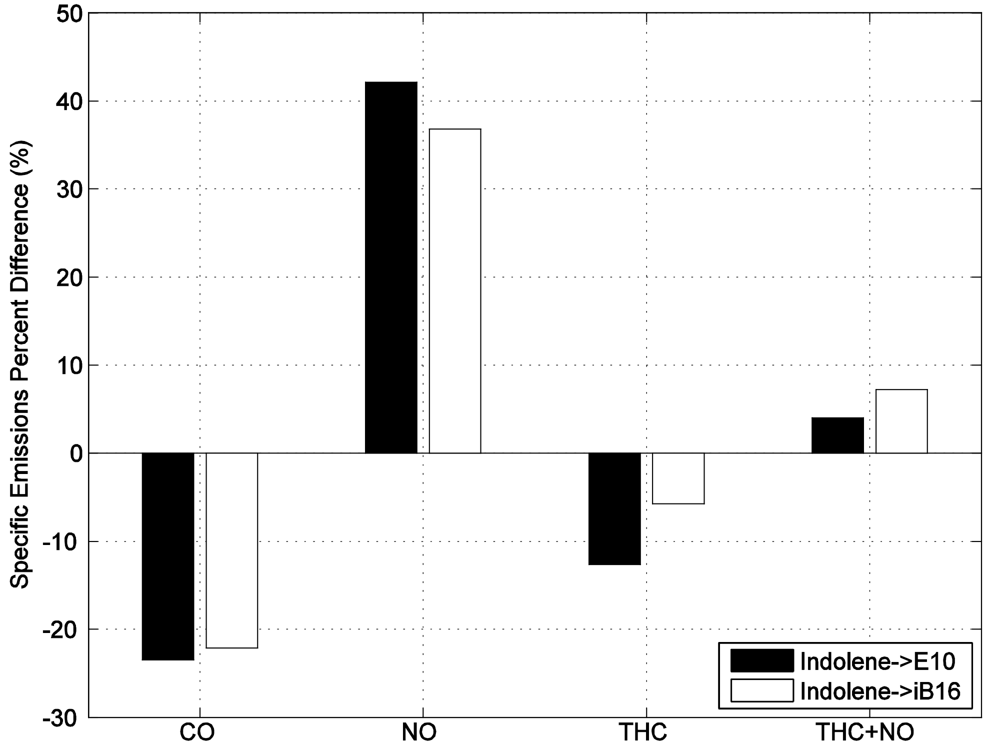

Figure 4.10: Specific emission percent difference from indolene – Volvo Penta

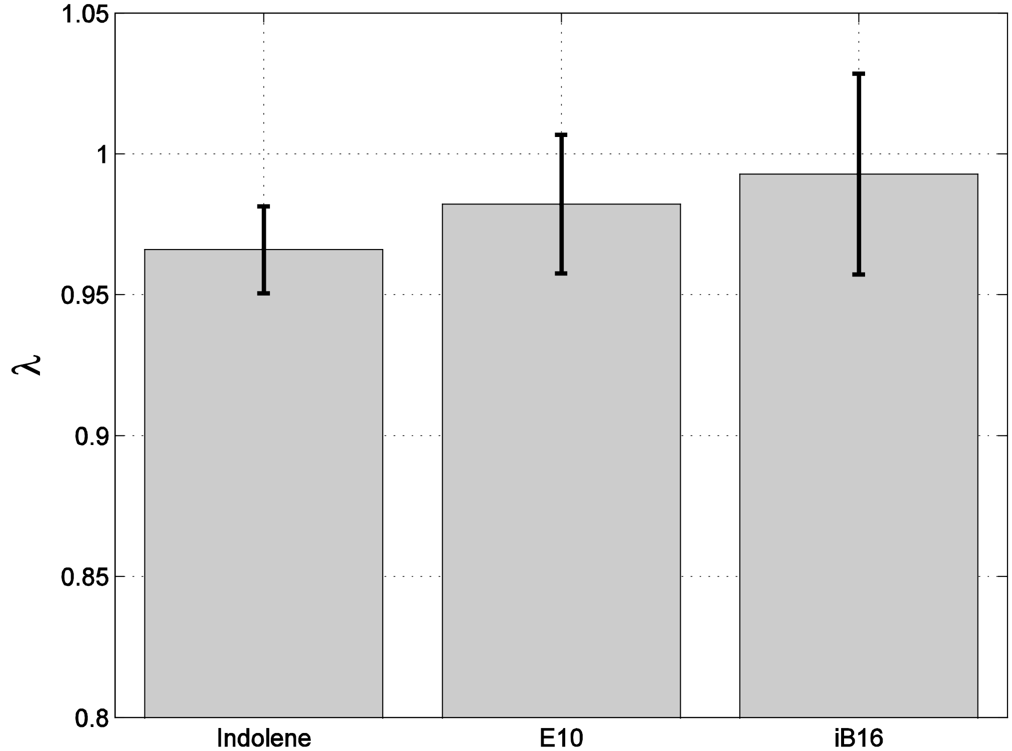

Figure 4.11: Volvo Penta averaged lambda values – ISO #16183

As seen in Figure 4.11, there is a difference between the lambda values for E10 and iB16, even though the oxygen concentrations by mass for E10 and iB16 are the same, as seen in Table 3.4. The difference seen between E10 and iB16 are within one standard deviation of each other. Note that one possible explanation for the difference is that the blended lower heating value of iB16 is lower than E10 by approximately 1%. Therefore in order to maintain the same power levels, the throttle position needs to be increased, increasing intake air flow rates. Additionally, changes in fuel fluid properties, such as viscosity, may impact the relative air-to-fuel ratio values as well.

4.5.3 OMC

Table 4.18 shows the raw emissions for the OMC engine running E10 and iB16. Emissions values shown below are averaged over two emissions bag samples.

Table 4.18: Raw emissions for OMC – alcohol fuels

Emission Constituent	CO (%)	NO (ppm)	THC ($ppmC_1$)	THC+NO (ppm)
E10 Round 1	3.229	9.9	25750	25760
E10 Round 2	3.359	15.6	25330	25340
E10 Average	3.294	12.8	25540	25550
iB16 Round 1	2.851	11.5	25480	25500
iB16 Round 2	3.315	8.9	25830	25840
iB16 Average	3.083	10.2	25660	25670

Table 4.19 shows specific emissions values for CO, NO, THC, and THC+NO on a g/hr basis.

Table 4.19: Specific emissions for OMC – alcohol fuels

Emission Constituent	CO (g/hr)	NO (g/hr)	THC (g/hr)	THC+NO (g/hr)
E10 Round 1	4724	2.86	2376	2380
E10 Round 2	5266	4.71	2396	2400
E10 Average	4996	3.78	2386	2390
iB16 Round 1	4246	3.30	2298	2300
iB16 Round 2	5134	2.63	2404	2406
iB16 Average	4690	2.97	2350	2354

Figure 4.12 shows the percent change in specific emissions from indolene to each respective alcohol fuel. Values for Figure 4.12 and Figure 4.13 can be seen in Table A.6 and Table A.7, respectively.

An overall decrease in CO emissions is caused by the relative air-to-fuel ratio approaching stoichiometric conditions. As shown in Figure 4.7, CO emissions are directly related to rich operation, and as oxygen is introduced with the fuel, the relative air-to-fuel ratio is pushed closer to stoichiometric, seen in Figure 4.13. Previous literature by Subramanian et al. [12] has shown that alcohol fuels can decrease CO emissions.

A reduction in specific THC emissions is again due to lambda approaching stoichiometric conditions, seen in Figure 4.13, while running alcohol fuels. During indolene operation, the OMC engine is oxygen deficient. Therefore, there is an inadequate amount of oxygen to fully oxidize hydrogen and carbon molecules [17].

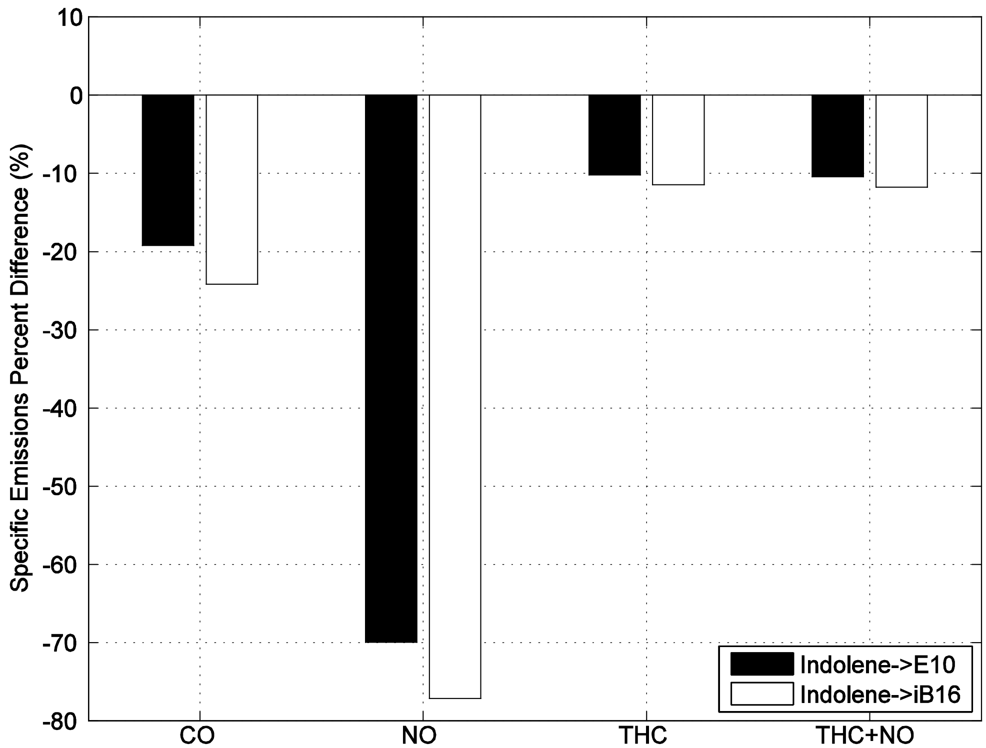

Figure 4.12: Specific emissions percent difference from indolene – OMC

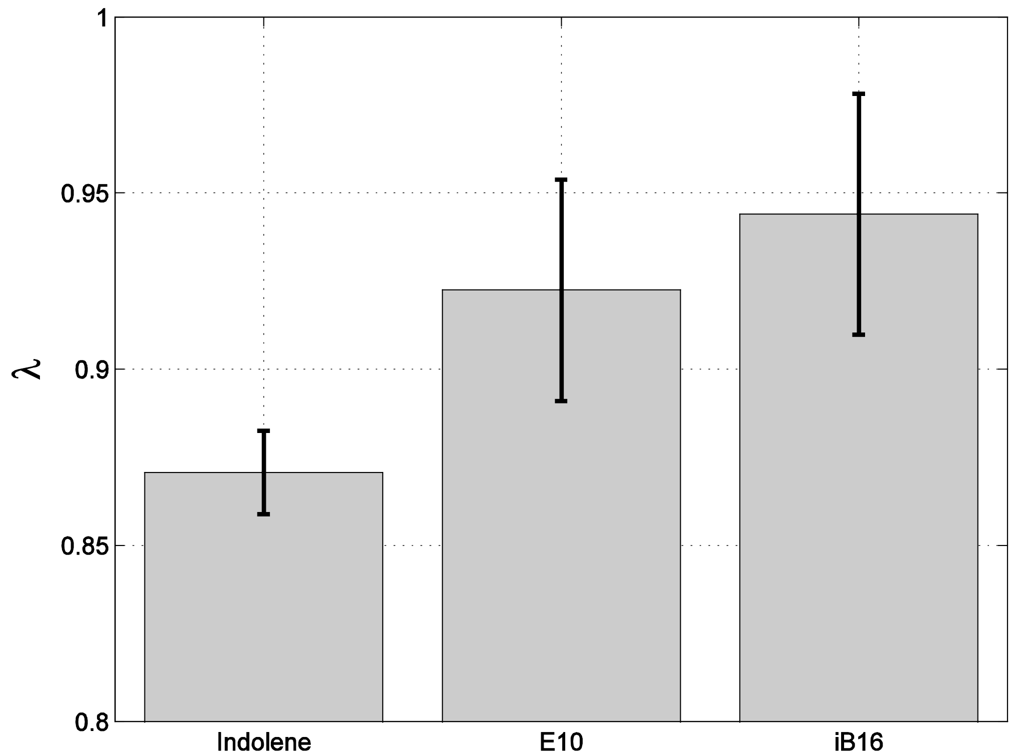

Figure 4.13: OMC averaged lambda values – ISO #16183

As shown in Figure 4.12, there was an overall decrease in NO emissions with respect to baseline indolene under alcohol operation. This trend it contradictory to that of typical two-stroke operation noted by Wasil et al. [1], where alcohol fuels increased NO formation due to higher combustion temperatures. Conversely, other studies performed by Bertsch et al. [2] and Subramanian et al. [12] show a decrease in NO emission with alcohol operation, running similar two-stroke engine technology.

In order to understand the decrease in NO emissions, the amount of energy delivered by the fuel during the combustion process needs to be investigated. Table 4.20 shows the total energy delivered by the fuel during testing.

Table 4.20: Total fuel energy delivered (kW) – OMC

Indolene	15.1
E10	13.7
iB16	13.2

As shown in Table 4.20, the amount of energy delivered is decreased because of alcohol fuels. As less energy is delivered, combustion temperatures are decreased, lowering NO formation.

As seen in Figure 4.13, there is a difference between the lambda values for E10 and iB16, even though the oxygen concentrations by mass for E10 and iB16 are the same, as seen in Table 3.4. The difference seen between E10 and iB16 are within two standard deviations of each other. Note that one possible explanation for the difference is that the blended lower heating value of iB16 is lower than E10 by approximately 1%. Therefore in order to maintain the same power levels, the throttle position needs to be increased, increasing intake air flow rates. Additionally, changes in fuel fluid properties, such as viscosity, may impact the relative air-to-fuel ratio values as well.

4.5.4 Emissions Results Summary

For the four-stroke engines, there was not a distinct trend when switching from the baseline fuel to alcohol fuel for both rounds of testing. This is due to a multitude of factors inherent to field testing, most importantly environmental test conditions, seen in Table 4.5. Although engine speed was the controlled variable in this experiment, ambient temperature ultimately influenced engine-out emissions. Emissions trends may have been more conclusive for the four-stroke engines if they operated closed-loop during Mode 1.

For the two-stroke OMC engine, there was a distinct trend when switching from the baseline test fuel to the alcohol fuels. This trend is due to the engine operating open-loop for every mode, and not providing compensation when the fuel composition changed.

Table 4.21 shows the change in mass specific THC+NO emissions from E10 to iB16 for the four-stroke engines, on a *g/kW-hr* basis.

Table 4.21: Specific THC+NO difference from E10 to iB16, on a g/kW-hr basis

	INDMAR	Volvo Penta
Round #1	-0.76	0.01
Round #2	0.05	0.03

Table 4.22 shows the change in mass specific THC+NO emissions from E10 to iB16 for the OMC, on a *g/hr* basis.

Table 4.22: Specific THC+NO difference from E10 to iB16, on a g/hr basis

	OMC
Round #1	-80
Round #2	6

As seen in Table 4.21, there is not a significant change between THC+NO emissions when going from E10 to iB16. The change seen in Table 4.21 is mainly due to test-to-test variation and also from different fueling strategies employed by INDMAR and Volvo Penta; the INDMAR ran richer during Mode 1 operation. The most significant difference in THC+NO emissions are seen in Table 4.22 for the OMC. This large difference is seen because of the inherent variability within this two-stroke carbureted engine.

In total, results have shown that there is not an appreciable difference between engine-out emissions for two-stroke or four-stroke engines while running E10 or iB16. Due to aforementioned benefits, iso-butanol would make a comparable replacement for ethanol as a blend fuel.

4.6 Comparison of Lambda Calculations – Equations

Four different methods were used to calculate lambda values from emission constituents. Calculations and a comparison of the different methods are outlined below.

4.6.1 ISO #16183: Air-to-fuel Ratio Measurement Method [16]

Since real time air and fuel flow measurements were not available, estimations for lambda using sampled emissions were used. Equation 4.1 is the determination of the stoichiometric air-to-fuel ratio, based off of fuel properties. The ISO #16183 standard [16] and specifically Equation 4.2, calculates lambda based off of dry emissions concentrations.

$$A/F_{st} = \frac{138.0\cdot(\beta+\frac{\alpha}{4}-\frac{\varepsilon}{2}+\gamma)}{12.011\cdot\beta+1.00794\cdot\alpha+15.9994\cdot\varepsilon+14.0067\cdot\delta+32.065\cdot\gamma} \quad \text{.........} Eqn4.1$$

$$\lambda_i = \frac{\beta\cdot\left(100-\frac{c_{co}\cdot 10^{-4}}{2}-c_{HC}\cdot 10^{-4}\right)+\left(\frac{\alpha}{4}\cdot\frac{1-\frac{2\cdot c_{co}\cdot 10^{-4}}{3.5\cdot c_{co_2}}}{1+\frac{c_{co}\cdot 10^{-4}}{3.5\cdot c_{co_2}}}-\frac{\varepsilon}{2}-\frac{\delta}{2}\right)\cdot(c_{co_2}+c_{co}\cdot 10^{-4})}{4.764\cdot\left(\beta+\frac{\alpha}{4}-\frac{\varepsilon}{2}+\gamma\right)\cdot(c_{co_2}+c_{co}\cdot 10^{-4}+c_{HC}\cdot 10^{-4})} \quad \text{.........} Eqn4.2$$

Where:

A/F_{st} is the stoichiometric air-to-fuel ratio

λ is the excess air ratio

C_{CO2} is the dry CO_2 concentration, in percent by volume

C_{CO} is the dry CO concentration, in parts per million

C_{HC} is the HC concentration, in parts per million

β, α, ε, and γ are the *C/C, H/C, O/C, S/C* ratios of the fuel, respectively

4.6.2 Modified Spindt Method [18]

In 1965, R. S. Spindt published the *Air-Fuel Ratios from Exhaust Gas Analysis*, calculating lambda for a pure hydrocarbon fuel based off of emission constituents [18]. The Spindt method was modified in 1998 to take into account the extra hydroxyl group as a result of oxygenated fuels [19]. Equation 4.3 shows modifications to the original Spindt method.

$$\left(\frac{A}{F}\right)_{actual}^{Spindt\ \#2} = F_b\left[11.492F_C\left(\frac{1+\frac{R}{2}+Q}{1+R}\right)+\left(\frac{120F_h}{3.5+R}\right)\right]-4.313F_O \text{ .... } Eqn\ 4.3$$

Where:

$$\boldsymbol{F_c = \frac{12.01 \cdot X}{12.01 \cdot X + 2.016 \cdot Y + 32.0 \cdot Z}}$$

$$\boldsymbol{F_h = \frac{2.016 \cdot Y}{12.01 \cdot X + 2.016 \cdot Y + 32.0 \cdot Z}}$$

$$\boldsymbol{F_o = \frac{32.0 \cdot Z}{12.01 \cdot X + 2.016 \cdot Y + 32.0 \cdot Z}}$$

$$\boldsymbol{F_b = \frac{P_{CO} + P_{CO_2}}{P_{CO} + P_{CO_2} + P_{HC}}}$$

$$\boldsymbol{R = \frac{P_{CO}}{P_{CO_2}}}$$

$$\boldsymbol{Q = \frac{P_{O_2}}{P_{CO_2}}}$$

P_i is the molar percentage of the i^{th} specie of the exhaust

X, *Y*, and *Z* are the *C/C*, *H/C*, *O/C* ratios of the fuel, respectively

4.6.3 Brettschneider Method [20]

In 1979, Johannes Brettschneider developed an adaptation to Spindt's equation, incorporating water in the ambient air, NO_x formed in the exhaust, and modification for oxygenated fuels [20]. Equation 4.4 shows the Brettschneider method for determining lambda [21]. Equation 4.4 assumes dry intake air simplifying the original Brettschneider equation and also maintains consistent with the other methods.

$$\lambda = \frac{[CO_2]+\left[\frac{CO}{2}\right]+[O_2]+\left[\frac{NO}{2}\right]+\left(\left(\frac{H_{CV}}{4}*\frac{3.5}{3.5+\frac{[CO]}{[CO_2]}}\right)-\frac{O_{CV}}{2}\right)*([CO_2]+[CO])}{\left(1+\frac{H_{CV}}{4}-\frac{O_{CV}}{2}\right)*([CO_2]+[CO]+[HC])} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn4.4$$

Where:

[XX] is the gas concentration in % Volume

H_{CV} is the atomic ratio of hydrogen to carbon in the fuel

O_{CV} is the atomic ratio of oxygen to carbon in the fuel

4.6.4 Modified Roy Douglas Method

In 1990, Roy Douglas published *AFR and Emissions Calculations for Two-Stroke Cycle Engine,* calculating the air-to-fuel ratio for a pure hydrocarbon fuel based off of emission constituents from a two-stroke engine [22]. Since the Roy Douglas method was developed for a pure hydrocarbon fuel, modifications were needed to account for the extra hydroxyl group added with an alcohol fuel.

With an alcohol fuel, the stoichiometric combustion equation is as follows, in Equation 4.5. The only difference with respect to the original equation is the oxygenated hydrocarbon in the exhaust and the oxygen on the fuel.

$$CH_xO_y + A(O_2 + 3.727N_2 + 0.044Ar) + BH_2O = aCO + bCO_2 + cO_2 + dH_2O + eCH_xO_y + fH_2 + gN_2 + hNO + jAr \quad \text{……} Eqn4.5$$

The Roy Douglas Method separates the stoichiometric combustion equation into three balances: carbon, hydrogen, and oxygen. With the addition of an oxygenated hydrocarbon, only the oxygen balance changes, seen in Equation 4.6. Therefore, the determination of the water concentration in the exhaust remains the same.

$$2A + y + B = a + 2b + 2c + d + e \cdot y + h \quad \text{……} Eqn4.6$$

The original solution provided a relationship stating hydrogen emissions are equal to half the CO emissions. With this substitution, the oxygen balance can be rearranged to solve for the variable *A*, seen in Equation 4.7.

$$A = \frac{1}{2}(a + 2b + 2c + d + e \cdot y + h - y - B) \quad \text{……} Eqn4.7$$

In order to substitute emissions concentrations in for each variable in Equation 4.7, a relationship is needed to relate each constituent to the total moles of exhaust. Equation 4.8 shows the relationship between an emission constituents concentration in the exhaust, to the total moles of exhaust, using NO as an example.

$$[NO] = \frac{100 \cdot h}{M_t} \quad \text{……} Eqn4.8$$

Knowing the relationship between the total moles of exhaust to each individual emissions concentration, Equation 4.7 reduces down to Equation 4.9.

$$A = \frac{\frac{1}{4}[CO]+[CO_2]+\frac{x}{4}([CO]+[CO_2])-\frac{y}{2}([CO]+[CO_2])+\frac{1}{2}[NO]+[O_2]}{[CO]+[CO_2]+[CH_XO_y]} \quad \text{.......................................} Eqn4.9$$

Using the original air-to-fuel ratio determination from [19], the modified air-to-fuel ratio equation can be seen in Equation 4.10.

$$AFR_{modified} = \frac{\frac{1}{4}[CO]+[CO_2]+\frac{x}{4}([CO]+[CO_2])-\frac{y}{2}([CO]+[CO_2])+\frac{1}{2}[NO]+[O_2]}{[CO]+[CO_2]+[CH_XO_y]} \cdot K_f \quad \text{...................} Eqn4.10$$

Where Equation 4.11 is the new relation for K_f, with an oxygenated fuel.

$$K_f = \frac{138.18}{12.011+1.008\cdot x+16.00\cdot y} \quad \text{...} Eqn4.11$$

4.6.5 Lambda Calculations – Results

There are inherent differences for each method of determining air-to-fuel ratio. The ISO #16183 standard is used as the de-facto standard, comparing all calculations against it. The modified Spindt method, derived for four-stroke operation, is not well suited for two-stroke engines. Brettschneider’s equation was considered an evolutionary improvement with respect to Spindt’s method, because of the incorporation of water in the ambient air, as well as NO_x in the exhaust [20]. While the Roy Douglas method was originally derived for two-stroke operation, results have shown it is applicable for four-stroke engines as well [22].

4.7 Comparison of Lambda Calculations – Results

4.7.1 INDMAR Lambda Comparison

Figure 4.14 shows four calculations for lambda, utilizing the ISO #16183 standard, Brettschneider method, modified Spindt method, and modified Roy Douglas method. The modified Spindt method provides a 10% over-estimate of the ISO result. Figure 4.14 also shows that the modified Roy Douglas method, though derived for two-stroke engines, is in agreement with the ISO #16183 standard.

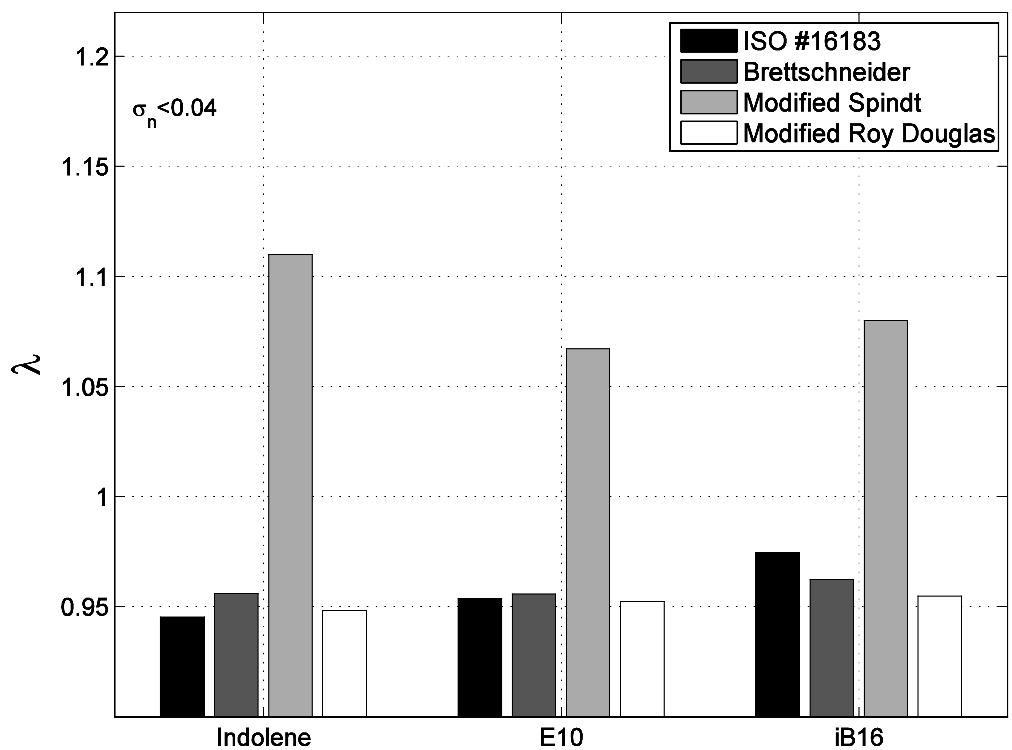

Figure 4.14: Lambda calculations comparison – INDMAR

4.7.2 Volvo Penta Lambda Comparison

Figure 4.15 shows four calculations for lambda, utilizing the ISO #16183 standard, Brettschneider method, modified Spindt method, and modified Roy Douglas method. Consistent with the INDMAR, the Spindt method provides a 10% over-estimate of the ISO method and, lambda values for the modified Roy Douglas method are in agreement with the ISO #16183 standard, seen in Figure 4.15.

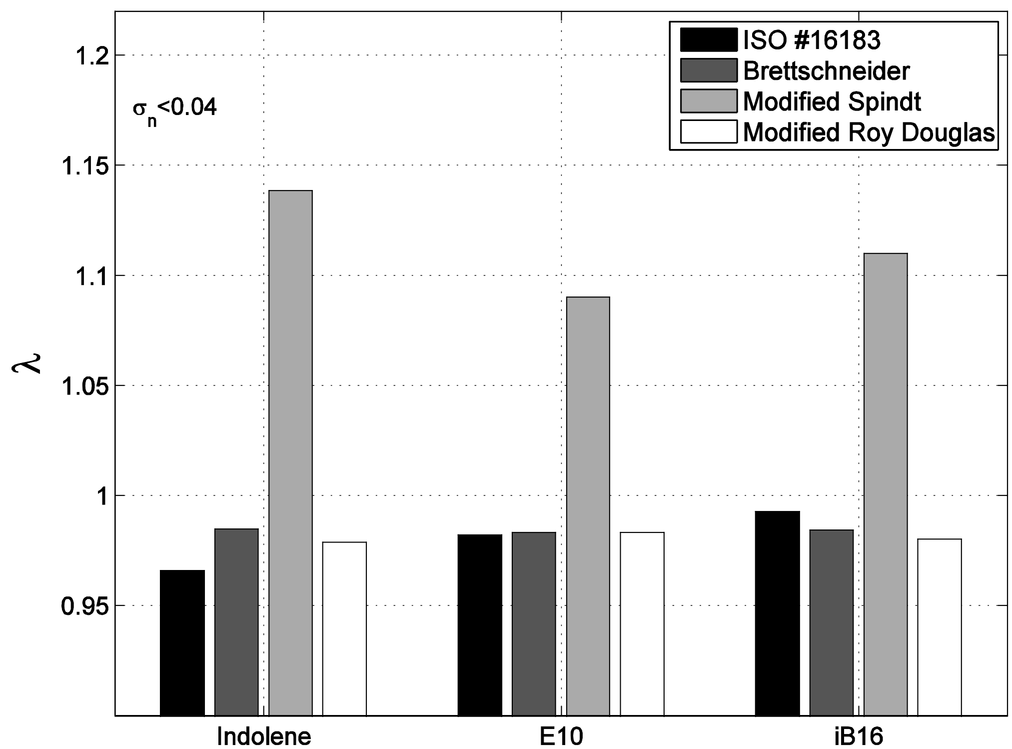

Figure 4.15: Lambda calculations comparison – Volvo Penta

4.7.3 OMC Lambda Comparison

Figure 4.16 shows four calculations for lambda, utilizing the ISO #16183 standard, Brettschneider method, modified Spindt method, and modified Roy Douglas method. The Spindt method, derived for four-stroke operation, provides an over-estimate of the global air-to-fuel ratio. As seen in Figure 4.16, the modified Roy Douglas method closely relates to the ISO standard, while the Brettschnieder equation yields a larger result.

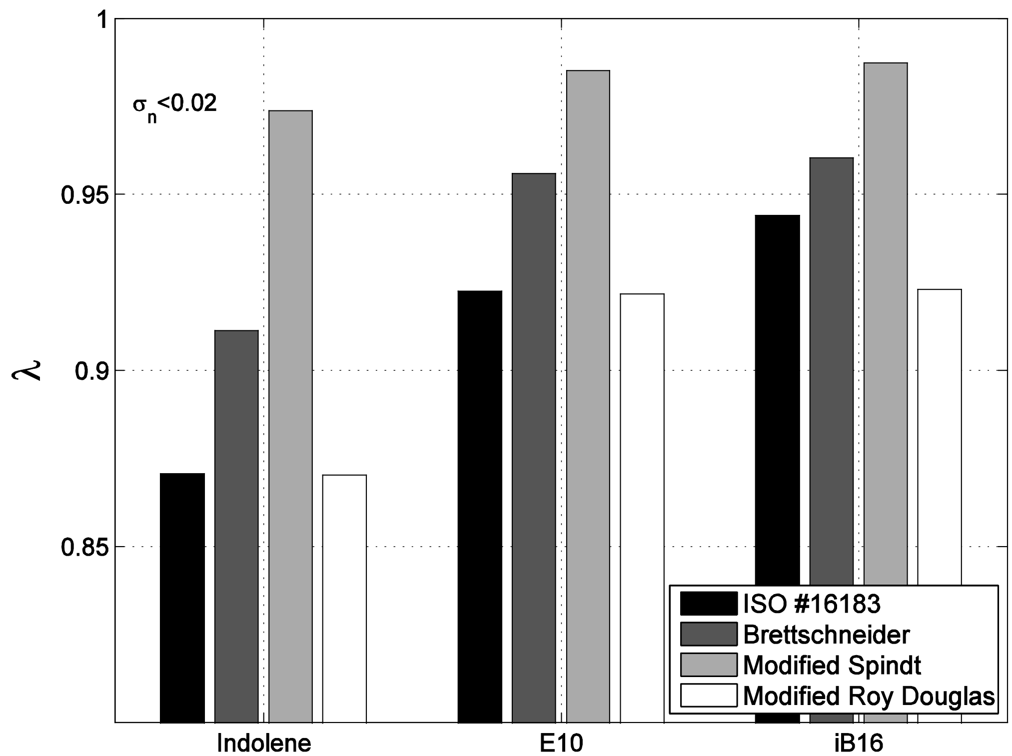

Figure 4.16: Lambda calculations comparison – OMC

As a result of two-stroke engines operating on a short-circuited, or scavenged, combustion process, analyzing the global air-to-fuel ratio of a two-stroke engine is not the best representation of the actual combustion process. Analyzing the mixture that took place in the combustion process, the burn zone air-to-fuel ratio, is the appropriate metric to measure [22].

From emissions measurement, the trapped efficiency of the air and fuel in the combustion process can be seen in Equation 4.12 and 4.13 [22], respectively. Direct substitution of air-to-fuel ratio values calculated using Equation 4.10 can be made into Equation 4.12.

$$TE_{air} = 1 - \frac{(1+AFR)\cdot[O_2]}{AFR\cdot[21\%]} \quad \text{Eqn 4.12}$$

$$TE_{fuel} = \frac{[CO]+[CO_2]}{[CO]+[CO_2]+[THC]} \quad \text{Eqn 4.13}$$

Knowing the trapped efficiencies of the air and fuel, the trapped air-to-fuel ratio can be calculated, seen in Equation 4.14.

$$AFR_{Burning\ Zone} = AFR_{Global} * \frac{TE_{air}}{TE_{fuel}} \quad \text{Eqn 4.14}$$

Figure 4.17 shows three methods of calculating lambda for the OMC engine: the ISO #16183 standard, the modified Roy Douglas method, and the trapped lambda using the modified Roy Douglas method.

The differences of the trapped lambda are not as pronounced for indolene operation, as they are with E10 and iB16. The effects of analyzing the trapped lambda would be more pronounced if emissions on a per-mode basis were available. For instance, the effect would be most pronounced at idle, where the short-circuited scavenging effect of a carbureted two-stroke is apparent. While the global lambda will be beyond the flammability of the fuel, the trapped lambda will be rich of stoichiometric.

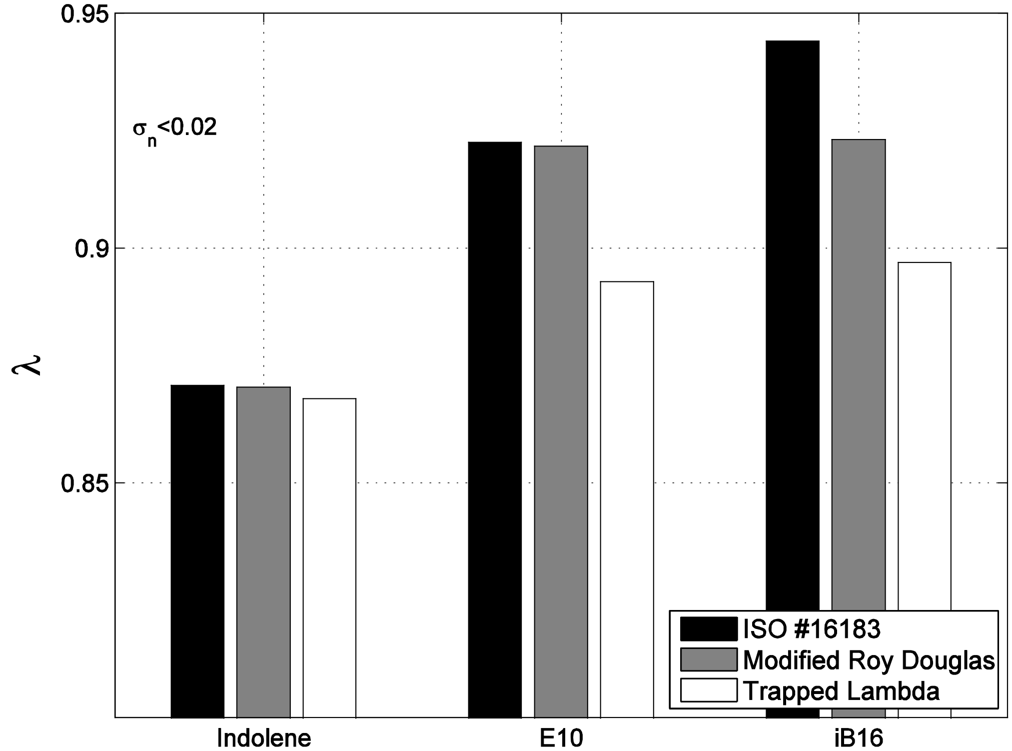

Figure 4.17: Trapped lambda comparison – OMC

5. Conclusions and Future Work

5.1 Conclusions

Constant volume emissions sampling techniques were used to assess the impact of low level blend alcohol fuels on two-stroke and four-stroke marine engine emissions. The impact of the low level blend alcohol fuels was compared to baseline tests performed using certification gasoline. The five-mode adapted ICOMIA test cycle was performed in the field on the Chesapeake Bay in Annapolis, MD. Three different marine engines were tested, which provided a representation of commercially available marine engines. Baseline emissions were developed for indolene operation, on all three engines. From there, E10 emissions were able to be compared relative to the baseline, and iB16 emissions were compared relative to the baseline and E10 emissions. The original objectives have been achieved, as outlined below:

- Due to environmental impacts, emissions trends for the four-stroke engines running low level blend alcohol fuels were not consistent with respect to the baseline between May and September testing
- Emissions trends for the two-stroke engines running low level blend alcohol fuels were consistent with respect to the baseline between May and September testing due to the open-loop operation of the engine, as well as weather conditions
- Regardless of the round of testing, the difference from the baseline indolene tests to ethanol and iso-butanol blended fuels followed the same trend

Iso-butanol provides many benefits over ethanol, such as the ability to be transported by pipeline, having a higher energy density, and the ability to be used in higher concentrations as a blend fuel while maintaining the same oxygen concentration by mass. The aforementioned emission trends discussed show that iso-butanol can be a viable substitute for ethanol as the ethanol blend cap is reached for the RFS.

5.2 Future Work

A concern when running low level blend alcohol fuels is the degradation of engine components with time. Although the engines used in this study were aged with iB16 between the months of May and September, the engines did not reach the end of their useful life, as determined by the marine industry. It would be advisable to complete a comprehensive laboratory study, isolating the degradation of engine components as durability testing is performed on marine engines.

As emissions standards become more stringent, engineers begin to research every venue possible to reduce engine-out emissions. Restrictions will soon be put into place to reduce the Reid vapor pressure (RVP) in fuels, especially for the marine industry. One way to achieve this would be to combine a tri-blend of indolene, ethanol, and iso-butanol. By blending iso-butanol at a higher ratio than ethanol, the overall RVP of a fuel can be decreased, while still maintaining the correct oxygen concentration.

To fully understand the effects of low level blend fuels on the engines tested for this thesis, laboratory testing using the five-mode ICOMIA Test Cycle would be advised, because of conflicting trends seen between the two rounds of testing. Performing this testing in a lab setting would allow for tighter control of variables that effect engine-out emissions.

Bibliography

[1] J. Wasil, J. McKnight, R. Kolb, D. Munz, J. Adey and B. Goodwin, "In-Use Performance Testing of Butanol-Extended Fuel in Recreational Marine Engines and Vessels," in *SAE International*, Warrendale, 2012-32-0011, 2012.

[2] M. Bertsch, K. Beck and U. Spicher, "Influence of the Alcohol Type and Concentration in Acohol-Blended Feuls on the COmbustion adn Emissions of Small Two-Stroke SE Engines," in *SAE International*, Warrendale, 2012-32-0038, 2012.

[3] T. Wallner and R. Frazee, "Study of negulated and non-regulated emissions from combustion of gasoline, alcohol fuels and their blends in a DI-SI engine," in *SAE International*, Warrendale, 2010-01-1571, 2010..

[4] United States Environmental Protection Agency, "Fuels and Fuel Addititves," [Online]. Available: http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

[5] United States Congress, "Energy Independence Security Act," [Online]. Available: http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf.

[6] Gevo, "Isobutanol-A Renewable Solution For The Transportation Fuels Value Chain," May 2011. [Online]. Available: http://www.gevo.com/wp-content/uploads/2011/05/GEVO-wp-iso-ftf.pdf. [Accessed 09 November 2012].

[7] J. Gomez, T. Brasil and N. Chan, "An Oveview of the Use of Oxygenates in Gasoline," California Environmental Protection Agency, 1998.

[8] J. Weaver, L. Exium and L. Prieto, "Gasoline Composition Regulations Affecting LUST Sites," U.S. Environmental Protection Agency, Washington DC, 2010.

[9] Central Intelligence Agency, "The World Factbook: US," November 2012. [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/geos/us.html. [Accessed 6 November 2012].

[10] M. Yassine and M. La Pan, "Impact of Ethanol Fuels on Regulated Tailpipe Emissions," in *SAE International*, Warrendale, 2012-01-0872, 2012.

[11] J. Weber, "Impact of E22 on Two-Stroke and Four-Stroke Snowmobiles," Michigan Technological University, Houghton, 2012.

[12] M. Subramanian, A. Setia, P. Kanal, N. Pal, S. Nandi and R. Malhotra, "Effect of Alcohol Blended Fuels on the Emissions and Field Performance of Two-Stroke and

Four-Stroke Engine Powered Two Wheelers," in *SAE International*, Warrendale, 2005-26-034, 2005.

[13] "Emissions Test Cycles ISO 8178," [Online]. Available: http://www.dieselnet.com/standards/cycles/iso8178.php. [Accessed 2012].

[14] "SEMTECH-DS: Gaseous Portable Emissions Measurement System," Sensors Inc., [Online]. Available: http://www.sensors-inc.com/ds.html.

[15] "Products: 5" Standard Wakeboard Zero Off," Zero Off, [Online]. Available: https://www.zerogps.com/product/5-standard-wakeboard-zero.

[16] ISO, [Online]. Available: http://www.iso.org/iso/catalogue_detail.htm?csnumber=32152.

[17] J. B. Heywood, "Internal Combustion Engine Fundamentals," McGraw-Hill Inc, 1988.

[18] D. Bresenham, J. Reisel and K. Neusen, "Spindt Air-Fuel Ratio Method Generalization for Oxygenated Fuels," in *SAE International*, Warrendale, 982054, 1998.

[19] R. S. Spindt, "Air-Fuel Ratio from Exhaust Gas Analysis," in *Society of Automotive Engineers*, 650507, 1965.

[20] W. M. Silvis, "An Algorithm for Calculating the Air/Fuel Ratio from Exhaust Emissions," in *SAE International*, Warrendale, 970514, 1997.

[21] BRIDGE analyzers, inc., "White Paper No. 1 Rev. 030227," [Online]. Available: http://www.bridgeanalyzers.com/EGA/Automotive/mediaRepos/productDocs/White%20Paper%201.pdf. [Accessed 1 12 2012].

[22] R. Douglas, "AFR and Emisisons Calculations for Two-Stroke Cycle Engines," in *SAE Internations*, Warrendale, 901599, 1990.

[23] "Semtech-DS," Sensors Inc., [Online]. Available: http://www.sensors-inc.com/ds.html. [Accessed 13 11 2012].

Appendix A

A.1 Additional Plots for Reference

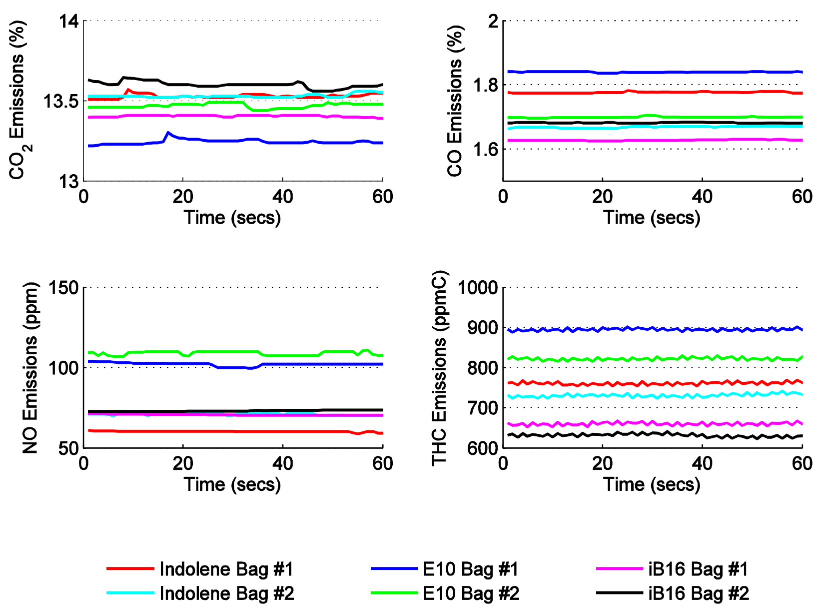

Figure A.1: Emissions stability for INDMAR – round 1

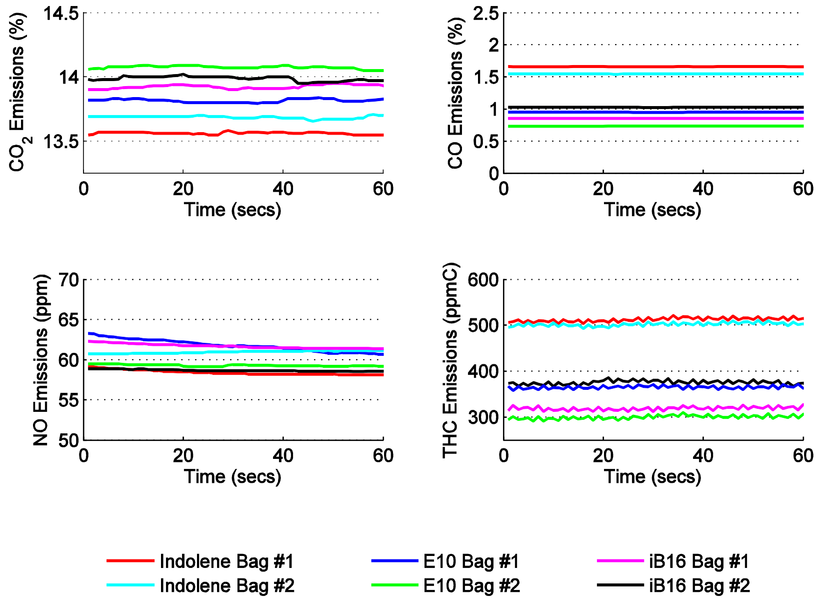

Figure A.2: Emissions stability for Volvo Penta – round 1

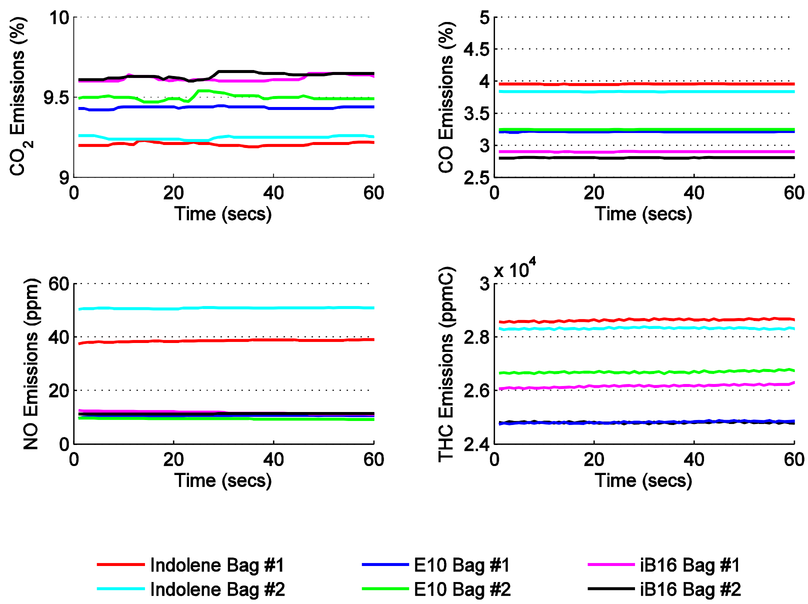

Figure A.3: Emissions stability for OMC – round 1

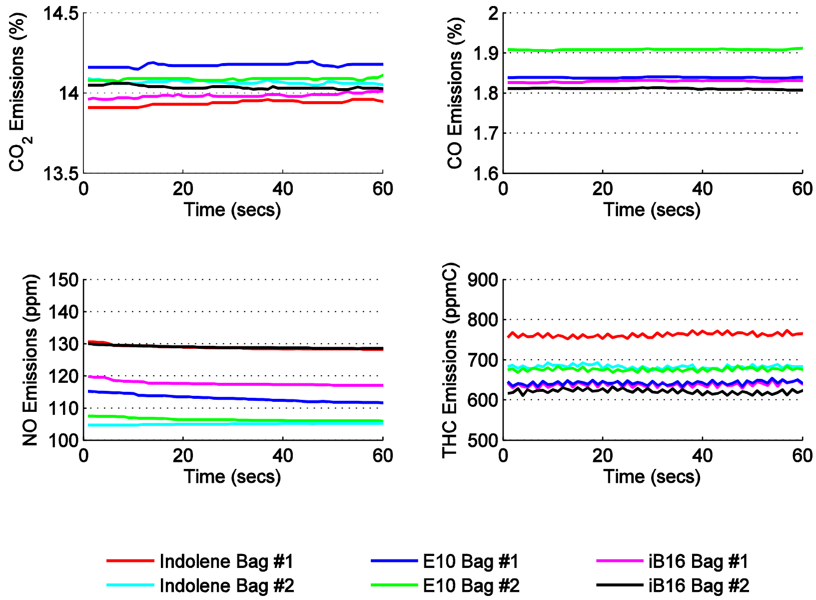

Figure A.4: Emission stability INDMAR – round 2

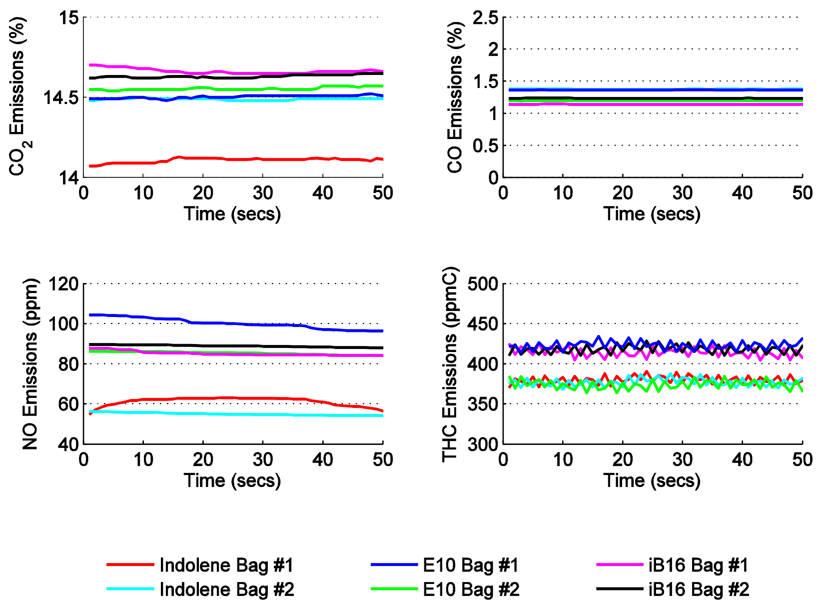

Figure A.5: Emissions stability Volvo Penta – round 2

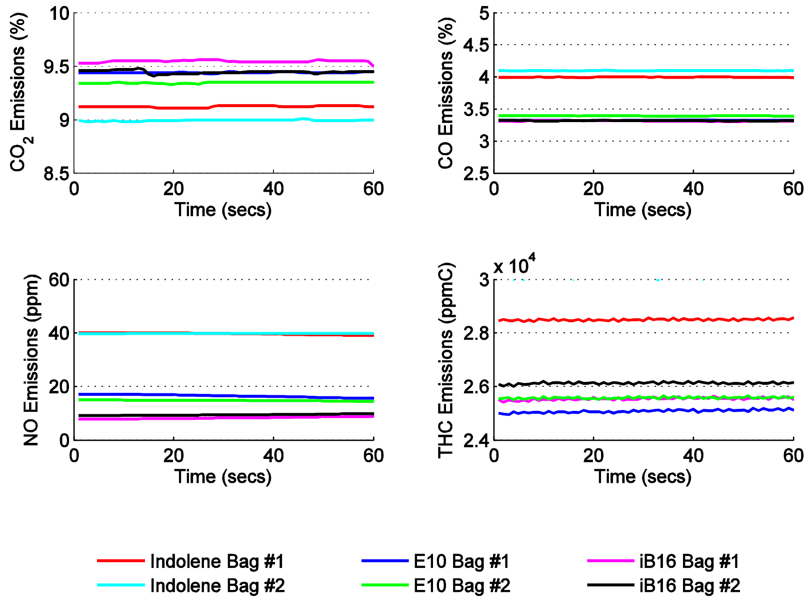

Figure A.6: Emissions stability OMC – round 2

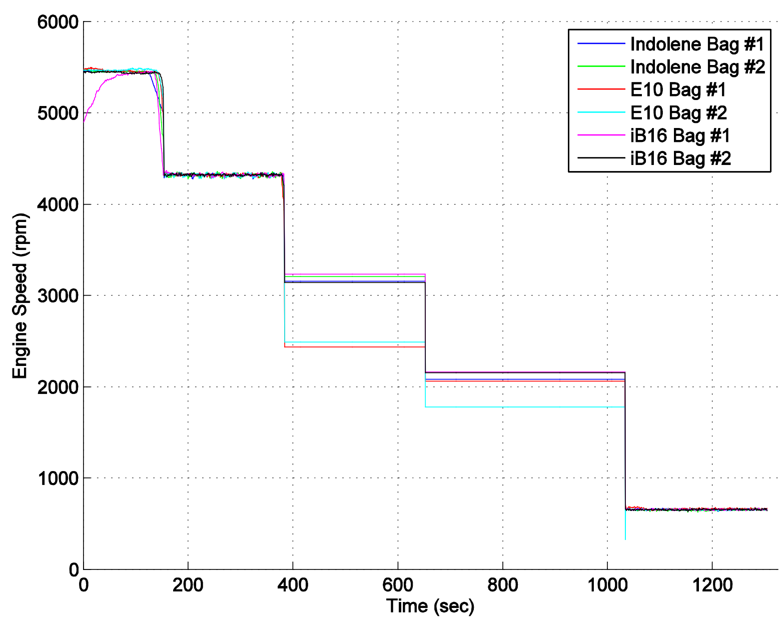

Figure A.7: INDMAR engine speed – round 2

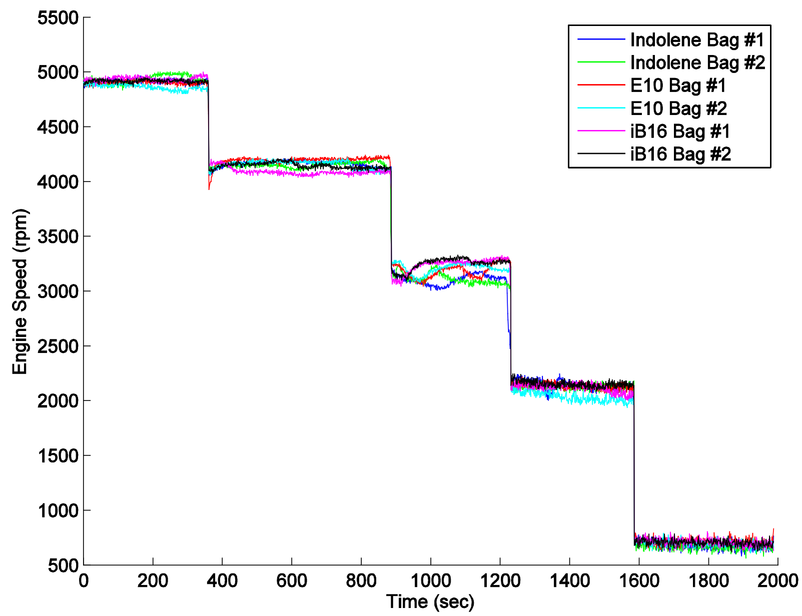

Figure A.8: OMC engine speed – round 2

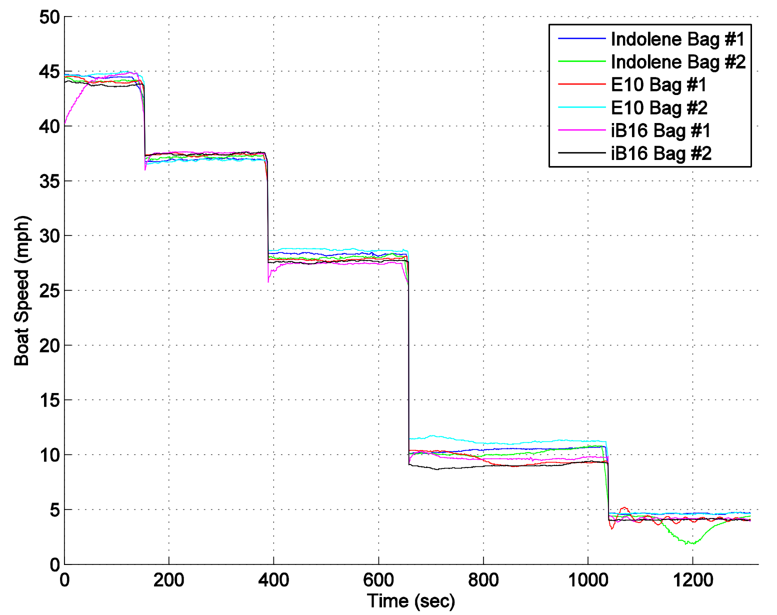

Figure A.9: INDMAR boat speed – round 2

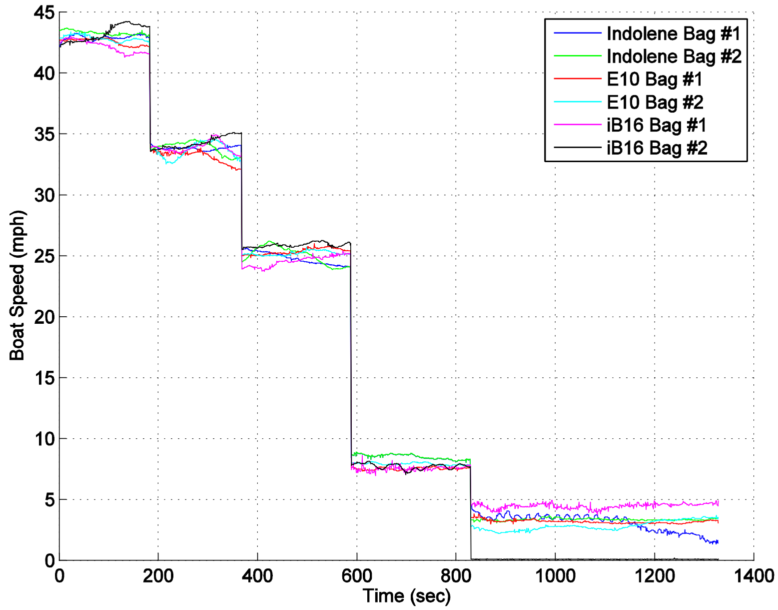

Figure A.10: OMC boat speed – round 2

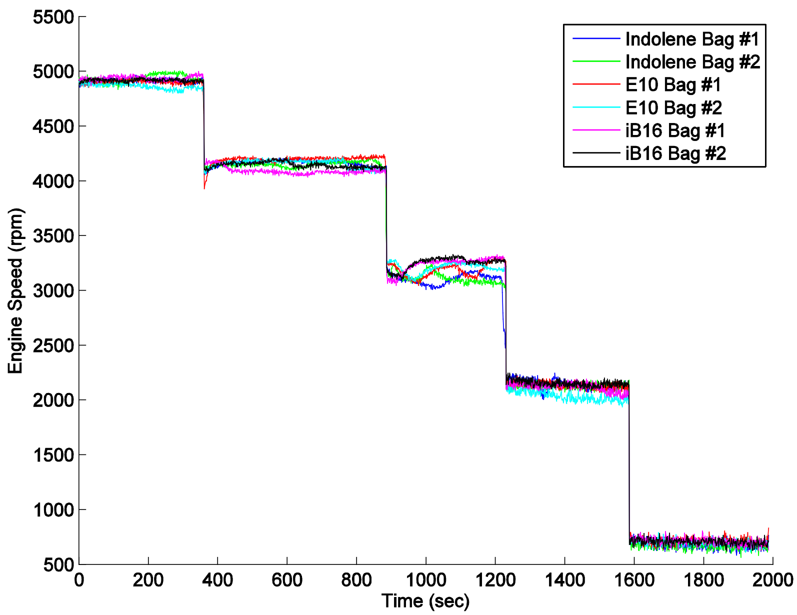

Figure A.11: OMC engine speed – round 2

A.2 Additional Data Tables for Reference

Table A.1: INDMAR averaged emissions with one standard deviation – round 2

	CO (%)	NO (ppm)	THC ($ppmC_1$)
Indolene Bag #1	2.244±0.002	128.8±0.6	762±5
Indolene Bag #2	2.003±0.002	105.0±0.2	682±5
E10 Bag #1	1.838±0.001	113.0±1.1	642±5
E10 Bag #2	1.908±0.001	106.4±0.5	676±4
iB16 Bag #1	1.829±0.002	117.6±0.7	639±7
iB16 Bag #2	1.811±0.002	128.9±0.4	621±6

Table A.2: Volvo Penta averaged emissions with one standard deviation – round 2

	CO (%)	NO (ppm)	THC ($ppmC_1$)
Indolene Bag #1	1.367±0.008	55.8±14.3	379±8
Indolene Bag #2	1.375±0.001	55.2±0.8	377±5
E10 Bag #1	1.362±0.001	100.9±3.2	423±6
E10 Bag #2	1.196±0.001	85.4±0.8	308±6
iB16 Bag #1	1.14±0.001	85.8±1.9	399±6
iB16 Bag #2	1.235±0.001	88.9±0.6	388±5

Table A.3: OMC averaged emissions with one standard deviation – round 2

	CO (%)	NO (ppm)	THC ($ppmC_1$)
Indolene Bag #1	3.997±0.003	39.7±0.3	28488±37
Indolene Bag #2	4.098±0.002	39.8±0.1	30047±34
E10 Bag #1	3.325±0.003	16.5±0.5	25077±57
E10 Bag #2	3.392±0.002	14.8±0.2	25575±36
iB16 Bag #1	3.313±0.006	8.3±0.3	25538±50
iB16 Bag #2	3.318±0.003	9.4±0.2	26122±41

Table A.4: Specific emissions percent difference from indolene – INDMAR

Emission Constituent	CO (%)	NO (%)	THC (%)	THC+NO (%)
E10 Average	-3.91	28.60	9.68	13.87
iB16 Average	-4.58	12.93	-5.14	-0.06

Table A.5: Specific emission percent difference from indolene – Volvo Penta

Emission Constituent	CO (%)	NO (%)	THC (%)	THC+NO (%)
E10 Average	-22.36	43.32	-12.64	4.00
iB16 Average	-21.36	38.89	-5.75	7.20

Table A.6: Specific emissions percent difference from indolene – OMC

Emission Constituent	CO (%)	NO (%)	THC (%)	THC+NO (%)
E10 Average	-19.26	-69.95	-10.19	-10.48
iB16 Average	-24.21	-77.12	-11.52	-11.84

Table A.7: ISO #16183 lambda values all engines

	Indolene	E10	iB16
INDMAR	0.95	0.95	0.97
Volvo Penta	0.97	0.98	0.99
OMC	0.87	0.92	0.94

A.3 Permissions

Dear James,

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Best regards,
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Testimony of Jeff Wasil

Evinrude Marine Engines

Sturtevant, Wisconsin

before the

Subcommittee on Energy and Environment

Committee on Science, Space, and Technology

United States House of Representatives

July 7, 2011

Good afternoon, Chairman Harris, Ranking Member Miller, other members of the subcommittee.

It is a pleasure to be here this afternoon. My name is Jeff Wasil and I am the Emissions Certification Engineer for BRP Evinrude Marine Engine division located in Sturtevant, Wisconsin . I am here today to testify on behalf of the National Marine Manufacturers Association, which represents over 1500 boat builders, marine engine, and marine accessory manufacturers. I ask that my full written testimony, with the attached exhibits, be made a part of the record of this hearing.

I am responsible for marine engine emissions certification testing: ensuring that all of our marine engines are compliant with US EPA, California, and other global marine emission regulations. Additionally, I ensure that the engines we sell will remain durable and perform to customers' expectations. Over the past 12 years, I have published several peer-reviewed technical papers on marine engine emissions, including particulate matter, gaseous emissions, green house gas emissions and alternative fuels. This experience and other marine testing I have done makes me uniquely qualified to tell you why I think it is a bad idea for the US Environmental Protection Agency to allow an increase in the volume of ethanol in gasoline and why I believe EPA has not followed proper procedures in either its decision to propose an ethanol increase in our gasoline supply or in their proposed warnings to consumers about the problems that they know would be caused by E15 gasoline.

As all of you most certainly know, EPA responded to a petition from "Growth Energy," which represents ethanol producers and supporters, by proposing to raise the percentage of ethanol in gasoline from 10 percent to 15 percent by volume. I am here today representing NMMA and my company, but in a larger sense, I am representing many different kinds of engine manufacturers -- marine, lawnmower, chain saw, snow blower, snow mobile. These types of engines that EPA refers to as "non-road engines" typically do not have combustion feedback sensors capable of adjusting the air/fuel ratio of the engine to match the specific requirements of the fuel. Ethanol is not gasoline, and the problem is that ethanol contains additional oxygen. As higher quantities of ethanol are blended into base gasoline, oxygen contained in the fuel increases, which leads to engine enleanment. Since many non-road engines do not have the capability of detecting the air/fuel ratio requirements of the fuel, the engine could face catastrophic failure. As a member of the team responsible for engine calibration, and the person responsible for emissions certifications, EPA requires me to design, certify, and lock-in with tamper-proof controls, the optimal fuel/air ratio needed to meet emission requirements. When the fuel changes in the marketplace and additional oxygenates added—such as by going from E10 gasoline to E15—engines run hotter, causing serious durability issues and increased emissions either in the form of increased Nitrogen Oxides (due to enleanment) or increased hydrocarbons (due to misfire). Additionally, ethanol is hygroscopic—meaning that it has an affinity for water. Obviously there is significant opportunity for fuel-related issues in the marine environment due to the presence of water near open-vented fuel systems and due to the inherent long-term storage and usage cycles unique to recreational boats. Ethanol only exacerbates these issues.

My concern is heightened by the EPA's statutory mandate to increase the biofuel content in the nation's gasoline supply to 36 billion gallons per year by 2022 and by the EPA's efforts to achieve this mandate. As I mentioned, EPA has responded to the petition from Growth Energy by proposing a "partial waiver," allowing E15 to be used in certain vehicles and not in others. As a result of this partial waiver, EPA has begun working on a rule that will change the certification fuel for our engines from a 0% ethanol-extended fuel to a 15% ethanol-extended fuel. In addition, last week, EPA finalized a label that would be required on fuel pumps at gas stations warning consumers that using E15 in certain types of engines may damage them. NMMA believes that the language in the label is severely inadequate and will do little to properly inform and educate consumers as to the serious consequences of using the wrong fuel. I have attached a copy of the label with our specific concerns as part of my full written testimony.

The reality is that if E15 becomes the standard gasoline in the marketplace, millions of consumers will run the risk of having their vehicles, boats, lawnmowers, and other gasoline-powered devices damaged, because they will not have the option of fueling them properly. Although NMMA and others petitioned EPA to require gas stations that offer E15 to also offer E10, EPA has denied this petition and has no plans to mandate the continued availability of E10. This will certainly lead to the very misfueling that EPA wants to avoid.

Growth Energy and other ethanol proponents will say that if there is a demand for E10, the marketplace will ensure that some stations will carry it, and this may be true to an extent. However, it is unlikely that every gas station would carry E10, and there might not be one anywhere near where you live or work. So that would inconvenience the consumer and increase the likelihood of misfueling.

Why have I been so insistent that increasing ethanol is almost certain to damage marine and other types of engines? As the person who works on calibrating these engines, I know first-hand how to damage them. I have seen some of the preliminary results of testing that has been conducted on such engines by the Department of Energy's National Renewable Energy Laboratory. These results have not yet been made public, and we have been asked by DOE not to say anything specific until the report is final, but I can say that in these tests, the majority of the marine engines that were run on E15 suffered significant damage or exhibited poor engine runability, performance and difficult starting—none of which is acceptable when on a boat out at sea. Why did this happen? As I mentioned in my opening, from a technical standpoint the failures are due to changes to the calibrated stoichometric air/fuel ratio requirements of E15—which is different from the fuel on which the engine was intended and designed to run. The full results of the DOE tests are scheduled to be released in the fall, but from what we have already learned, E15 will cause many engines to fail well before they should. We know that, and the EPA knows that, and it's the reason we should slow down this abrupt move to introduce E15 into the marketplace.

So that I do not end my testimony today on a completely negative point, I'd like to mention an alternative fuel that is currently being evaluated. Last year, I published a technical paper on the effects of butanol-extended fuels in marine outboard engines. Butanol has an energy content closer to that of gasoline and is not hygroscopic—meaning that it is unlikely to absorb water and phase-separate like ethanol. Based on this preliminary study, the data are promising in terms of better compatibility with existing engines and fuel systems. Additionally, the National Marine Manufacturers Association and others are also currently evaluating the use of butanol-extended fuels in marine products. Butanol, considered an advanced biofuel in the Renewable Fuels Standard (RFS), can be produced from many different types of biomass feedstocks, including corn. Recent advances in microbial fermentation processes have increased the yields of butanol, which make this product more cost-effective. We don't know for sure whether butanol is going to be a long-term viable alternative to ethanol, but it certainly does have potential. Testing is being done this summer by the NMMA and the American Boat and Yacht Council. We have also learned that other groups that make small engines are planning to test this new type of fuel. Butanol may allow for continued use of biofuel without the disadvantages of ethanol. We would like to talk with you about this when we complete our evaluation of butanol and when the DOE report on marine engines is final and we are allowed to talk more specifically about the DOE testing.

I was specifically asked by the subcommittee to comment on the draft legislation that you will be considering. This legislation calls for the National Academy of Sciences to conduct a survey of all available scientific information relating to the effects on engines of ethanol blends greater than 10 percent. This seems to me to be a terrific proposal, as it would bring together in one place all that is known about E15 and higher ethanol blends.

To summarize what I have told you today,

First, an increase in the ethanol content of gasoline from E10 to E15 has been proposed by the EPA.

Second, EPA acknowledges that E15 gasoline is suitable only for a limited set of gasoline-powered vehicles and engines, specifically not including marine engines, snowmobile engines, engines on outdoor power equipment, and cars older than the 2001 model year.

Third, the warning label EPA has proposed for placement on gasoline pumps is completely inadequate. The label they propose will not properly warn and inform consumers about problems associated with E15, and it is almost certain result in massive misfueling and subsequent engine damage.

Fourth, unless continued availability of E10 gasoline is mandated by the EPA—which the EPA has declined to do—E15 will almost certainly become the common fuel in the marketplace, with E10 having very limited availability.

Fifth, there is no need to rush E15 into the marketplace. Let's have a strategic pause while more testing is done to determine the effects of E15 on various kinds of engines and to see whether there might be alternatives to ethanol, such as butanol.

Thank you for allowing me to testify today.

Effects of Fuel Weathering on RVP, Distillation and Oxygen Content of Ethanol and iso-Butanol Blends

Thomas Wallner
Argonne National Laboratory

Jeff Wasil
Bombardier Recreational Products

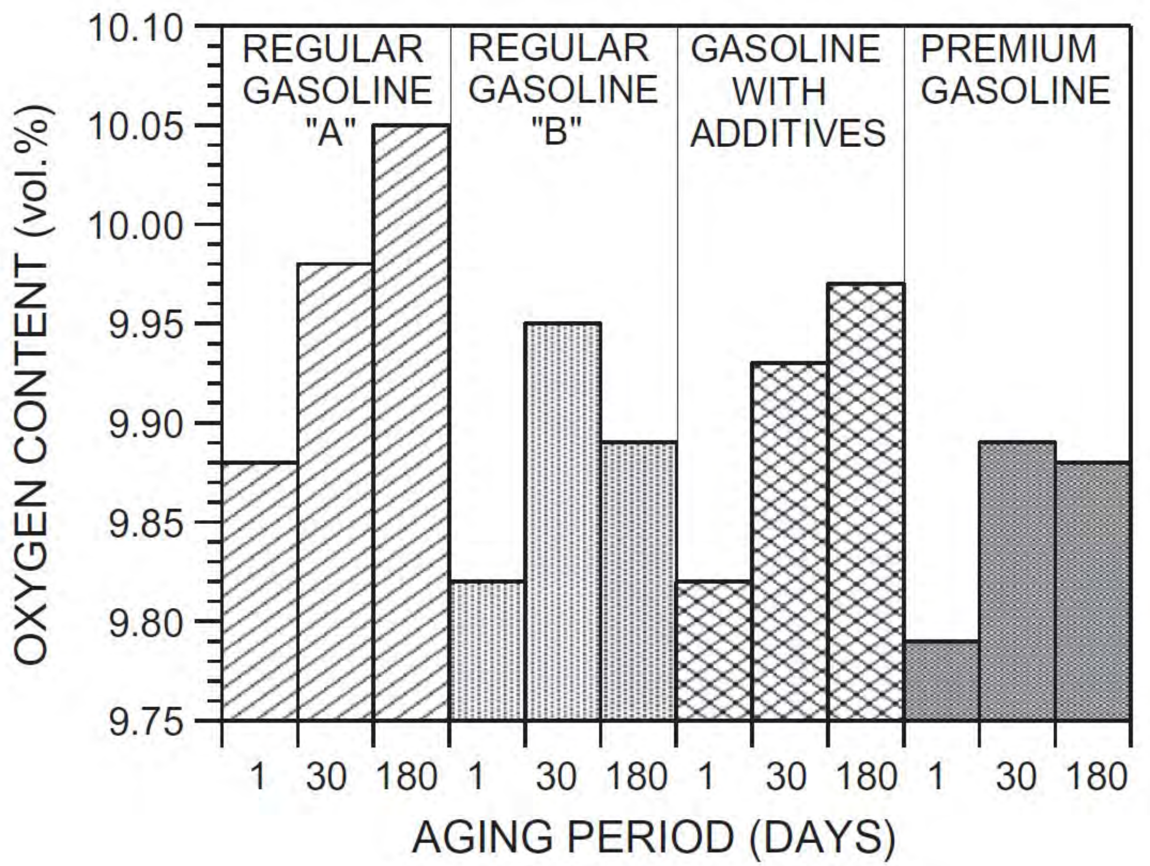
Engine Manufacturers Division Board of Directors
And General Membership Meeting

Miami/FL

February 11, 2015

Literature review

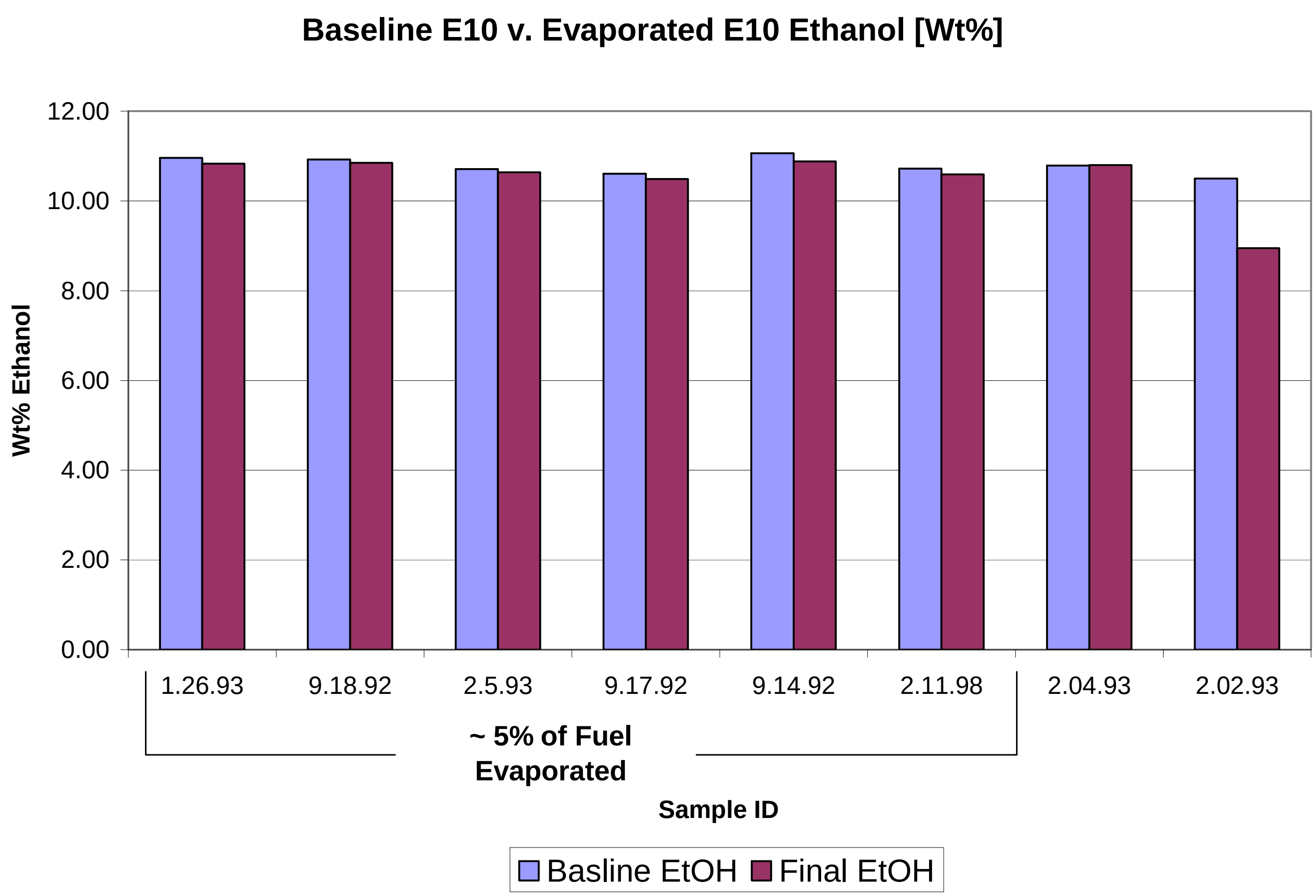
Average increase in oxygen content [wt%] of four 25 vol% (E25) ethanol blends over a 180 day aging period in automotive fuel tanks



Source: Streva, E., et al, "Aging effects on gasoline-ethanol blend properties and composition" Fuel 90 (2011) pp. 215-219

Literature review

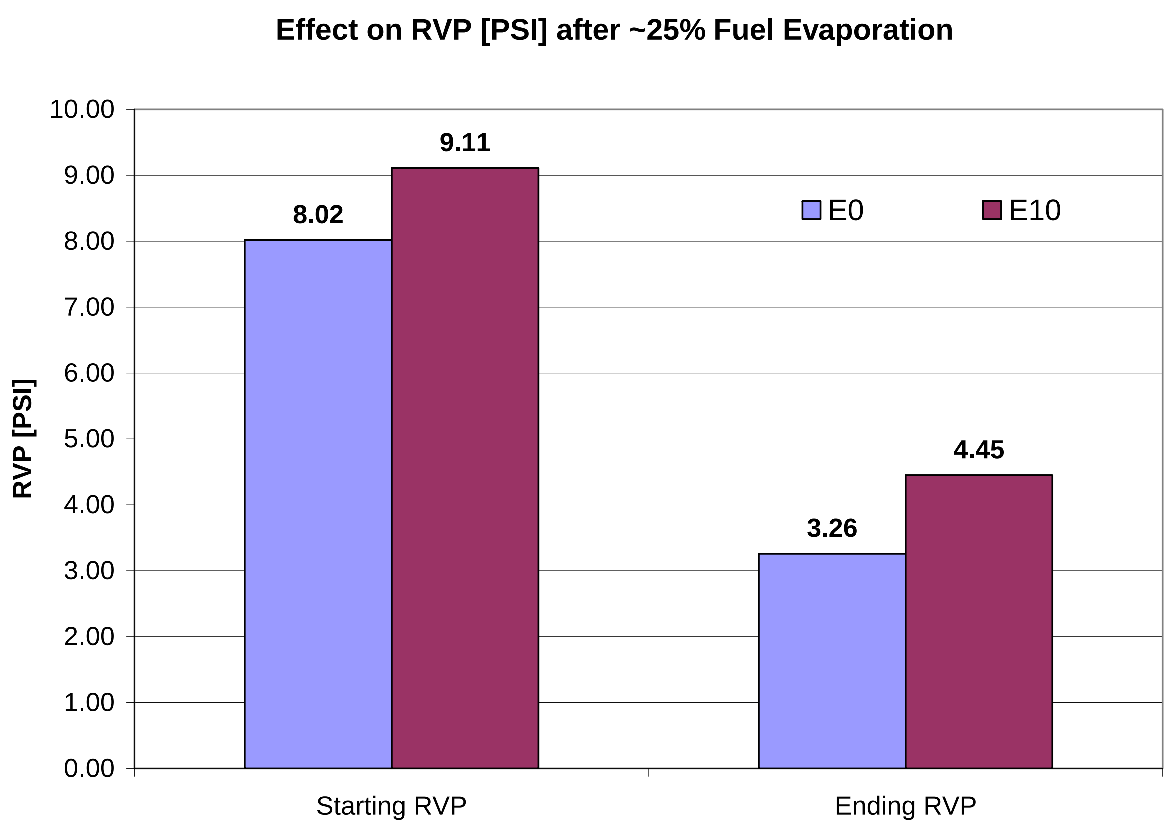
Loss in vol% ethanol in E10 fuels with approx. 5% total fuel evaporation



Source: Aulich, T., He, X., et al , "Gasoline Evaporation – Ethanol and Nonethanol Blends" Air and Waste Management Vol. 44 pp. 1004-1009

Literature review

Greater change in RVP with E0 (non-oxygenated) fuel compared to E10 fuel after approximately 25% fuel evaporation



Source: Aulich, T., He, X., et al , "Gasoline Evaporation – Ethanol and Nonethanol Blends" Air and Waste Management Vol. 44 pp. 1004-1009

Literature review
Summary

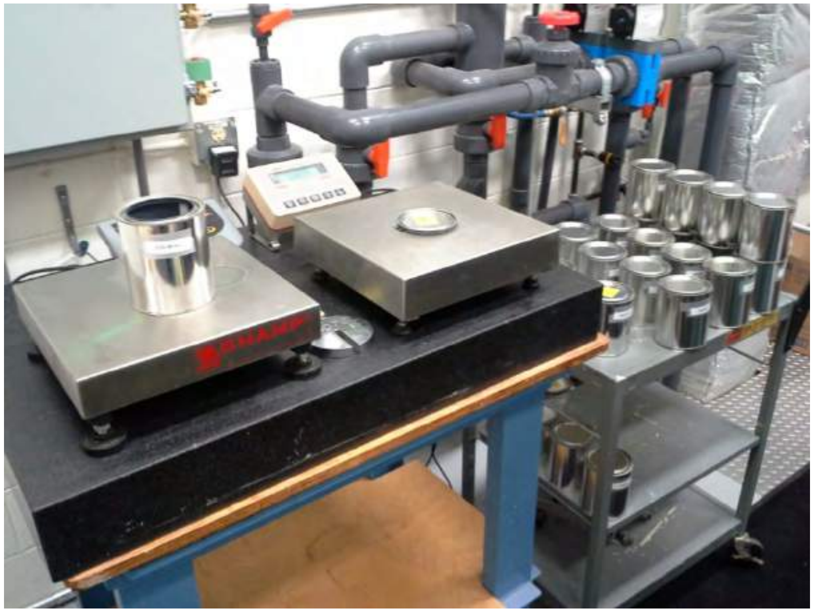
- Limited data and mixed results were found on O2 content of weathered ethanol blends
- No data available on O2 content of weathered iso-butanol fuel blends
- No direct comparison under the same conditions between E10 and iB16 weathered fuels

Severe Fuel Weathering Experiment Overview

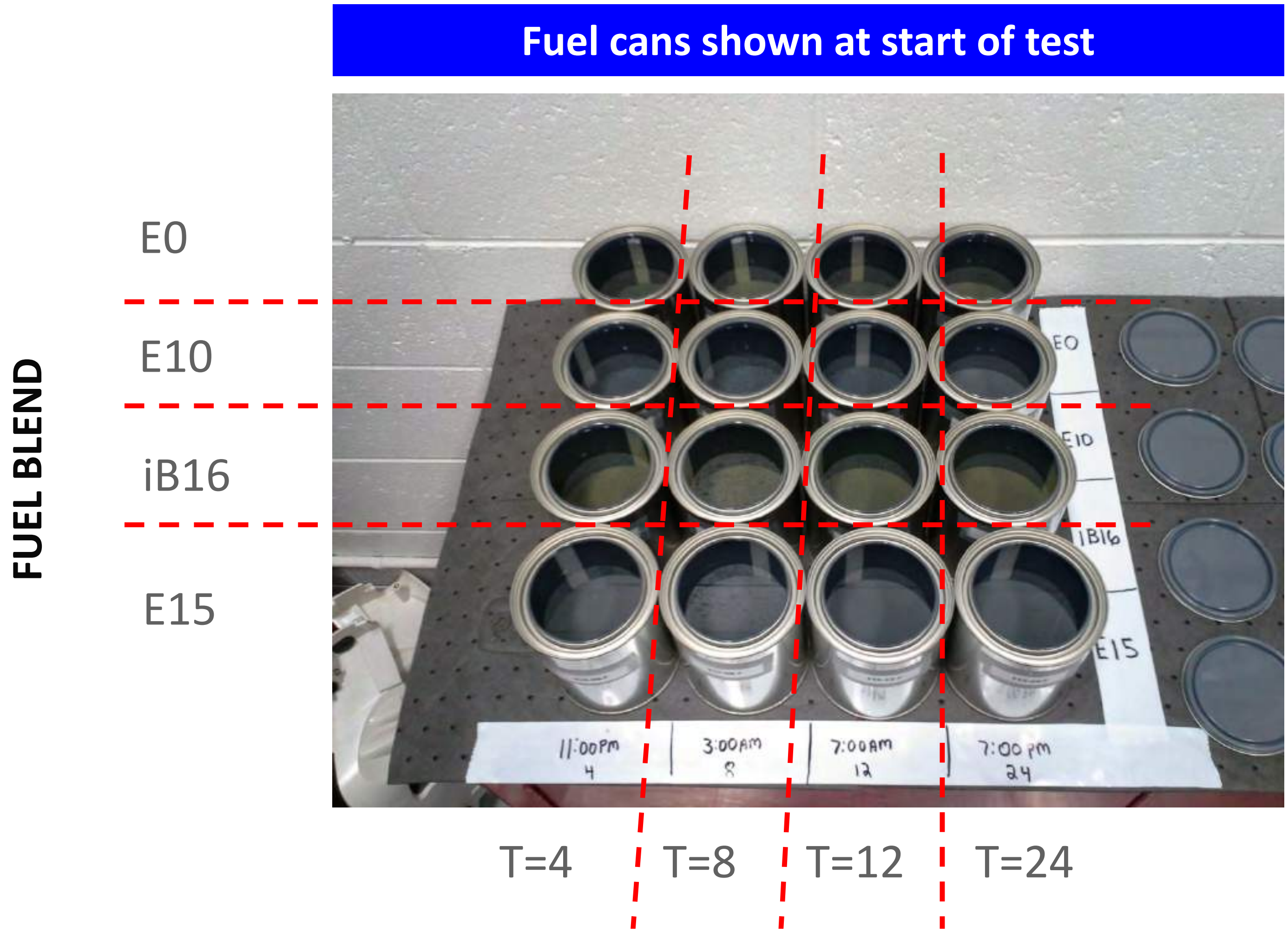
- **Input from BP/Butamax on fuel blending and experiment design**
- **Fuel analysis performed at Intertek Laboratory in Romeoville, IL**
- **Fuel blends tested:**
    - E0 (non-oxygenated)
    - E10 (3.5 wt% O2)
    - E15 (5.3 wt% O2)
    - iB16 (3.5 wt% O2)
- **Fuel blend stocks:**
    - Neat bio-isobutanol
    - Fuel grade ethanol
    - Indolene certification fuel 8.5 RVP (non-oxygenated)
    - Winter fuel 13 RVP (non-oxygenated)
- **BP/Butamax recipes were followed to blend 5-gallons of four unique finished test fuels:**
    - E0, E10, E15, iB16

Severe Fuel Weathering Experiment
Setup and Process

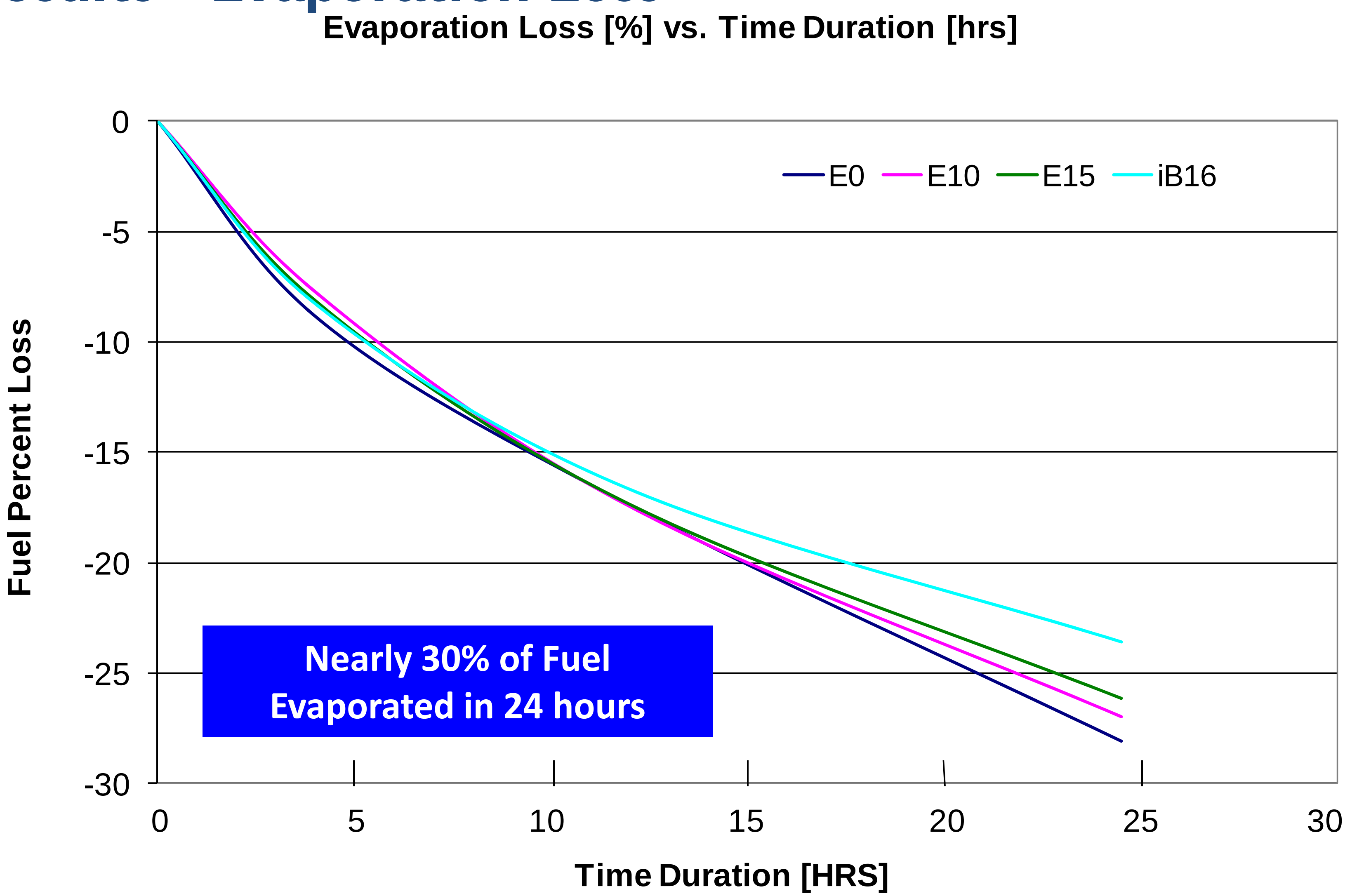
- Finished fuel blends were dispensed into 24 quart sized wide-mouth metal cans
- Each can was carefully weighed and the starting weight recorded for each fuel can
- After initial weighing, each fuel sample was covered to prevent evaporation until all cans were ready for start of test
- At the start of the test, all covers were removed from the fuel cans.
- Each fuel weathered for a specific period of time
- Cans were weighed then sealed after 4, 8, 12 and 24 hours of evaporation
- Cans were stored on ice until fuel analysis completed



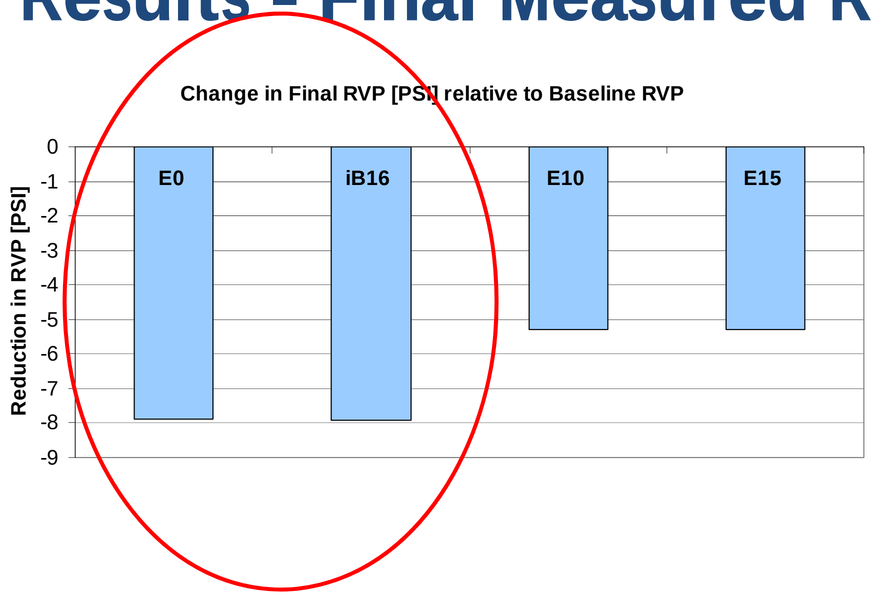
Severe Fuel Weathering Experiment Setup



Severe Fuel Weathering Experiment Results - Evaporation Loss

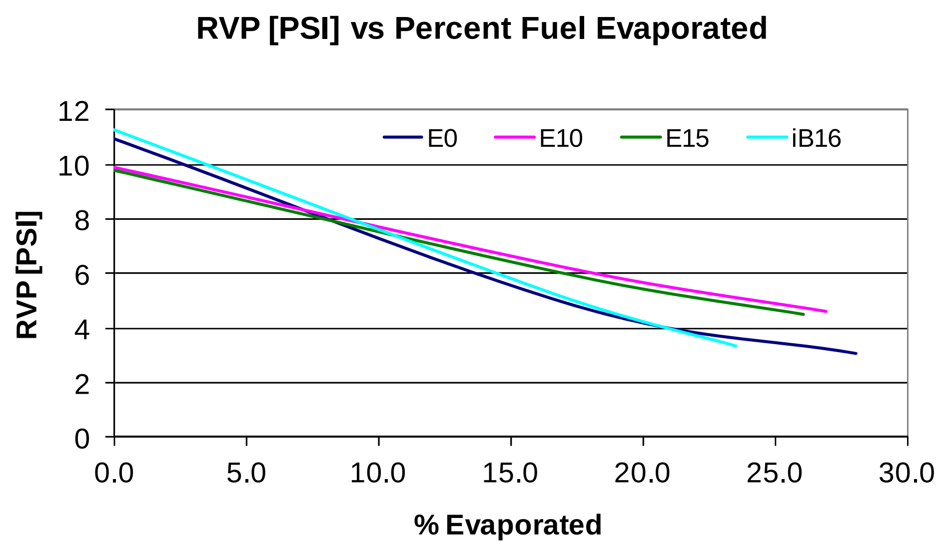


Severe Fuel Weathering Experiment Results - Final Measured RVP [PSI]



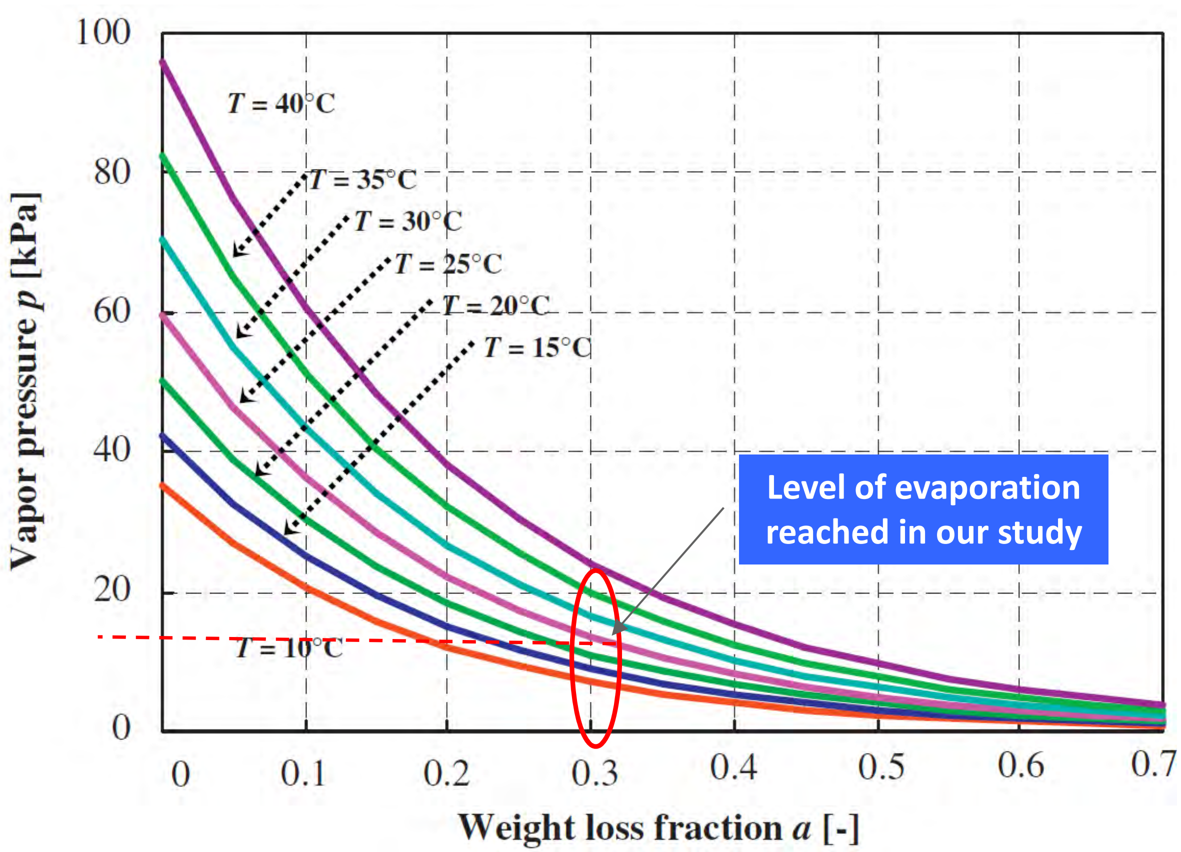
iB16 has nearly identical reduction in RVP as E0

~3.4RVP



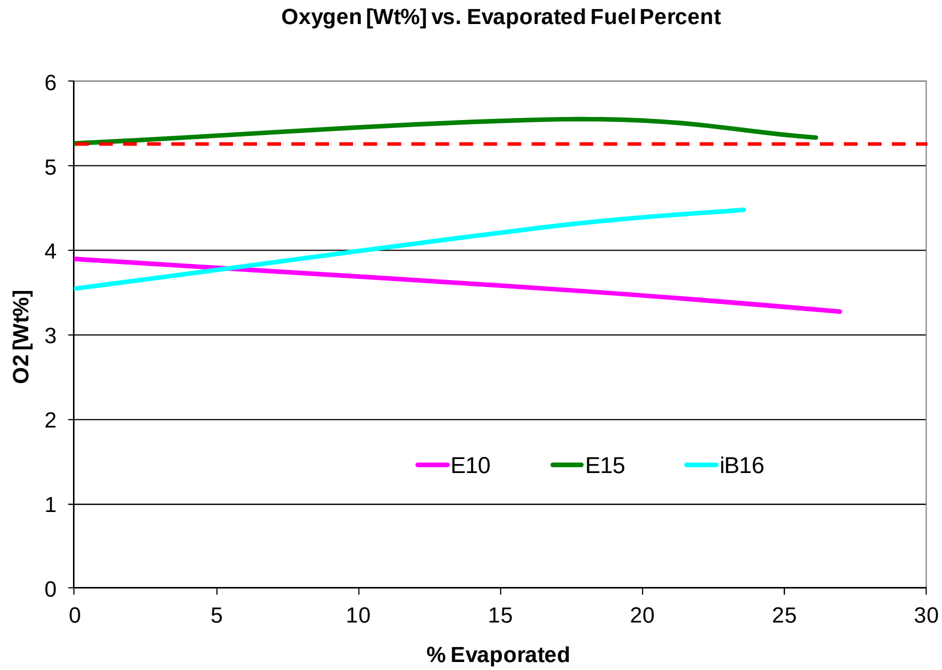
- **iB16 fuel closely followed the RVP of E0**

Severe Fuel Weathering Experiment Results – RVP versus Weight Loss Fraction



Source: Okamoto, K., Watanabe, N., et al, "Changes in evaporation rate and vapor pressure of gasoline with progress of evaporation" Fire Safety Journal 44 (2009) 756-763

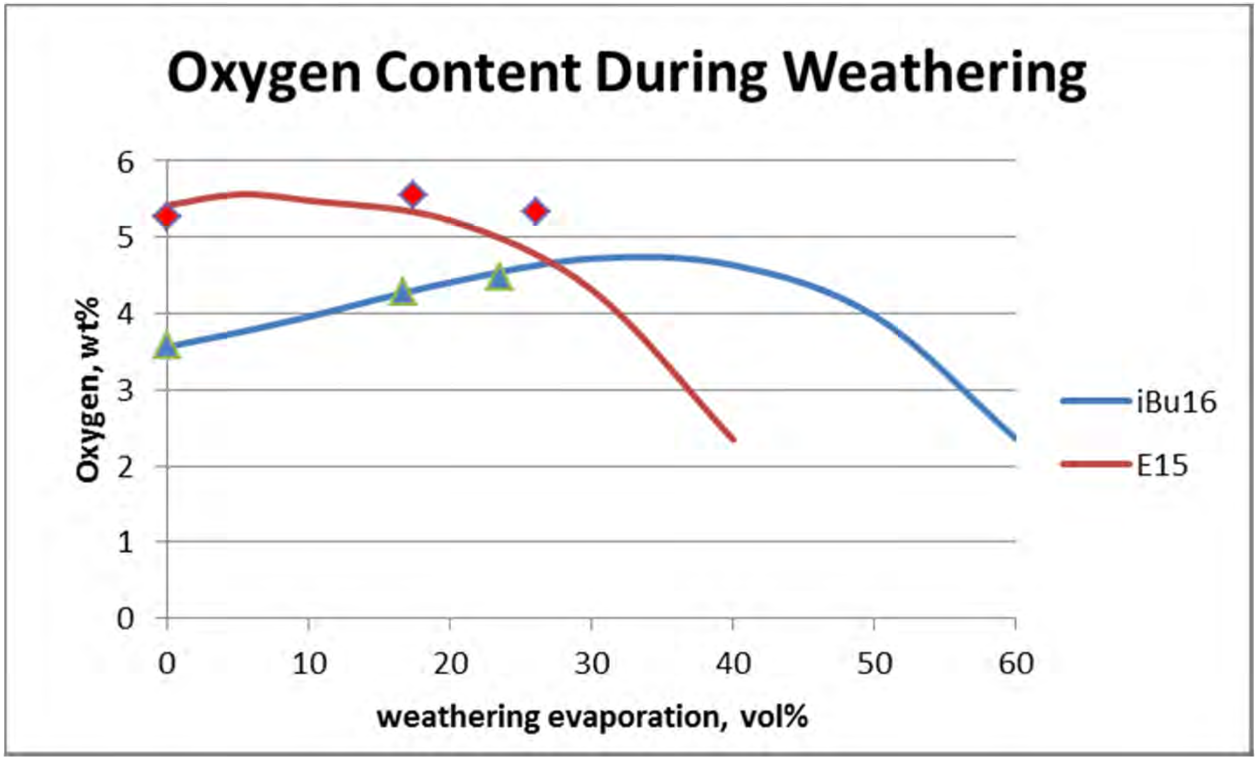
Severe Fuel Weathering Experiment Results - Oxygen Content



Final weathered iB16 oxygen content was equivalent to E12

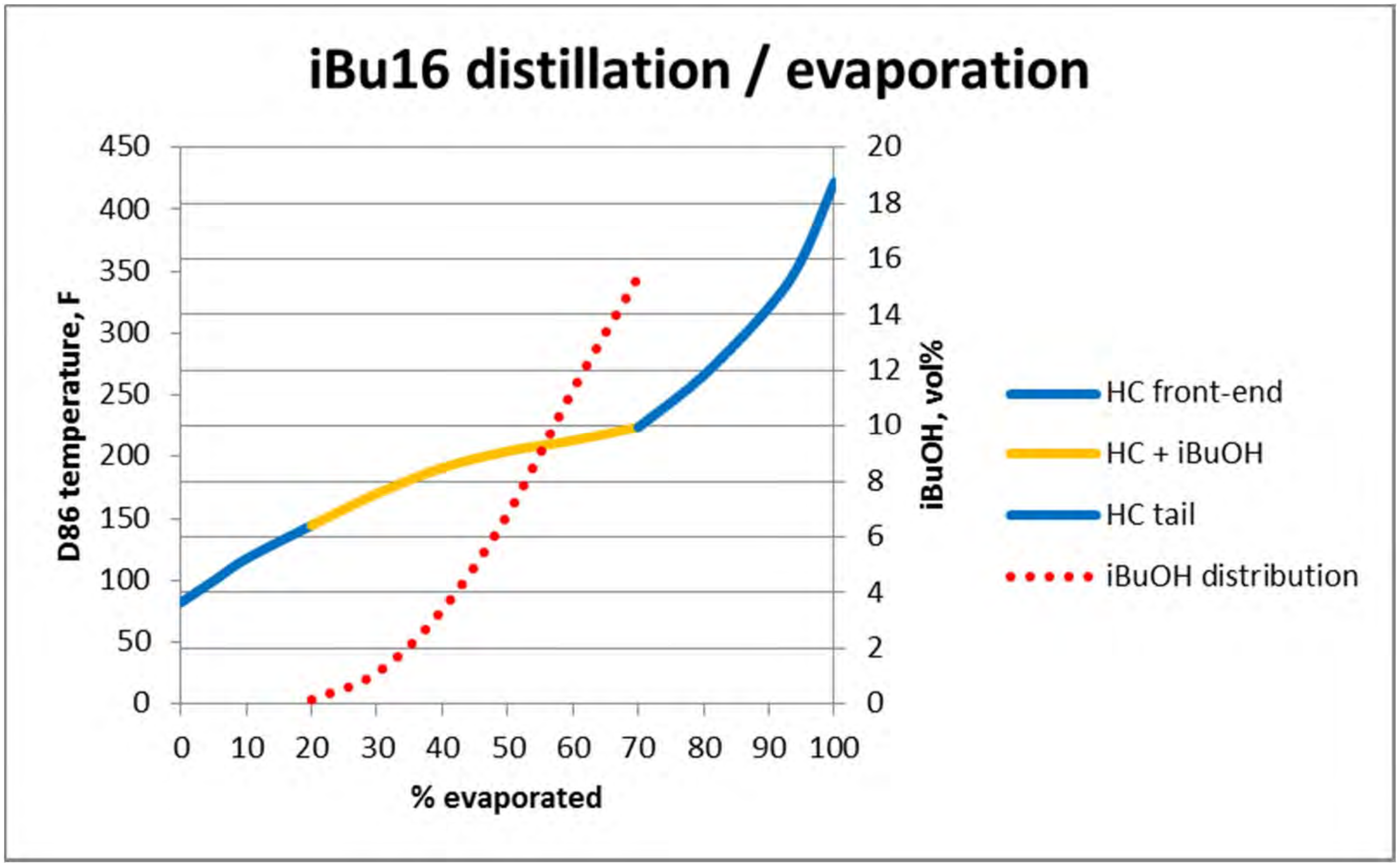
- E10 Oxygen content Wt% decreased with increasing evaporation
- E15 Oxygen content Wt% increased/maintained with increasing evaporation
- iB16 Oxygen content Wt% increased with increasing evaporation, but never reached the E15 equivalent Wt%

Severe Fuel Weathering - Oxygen Content



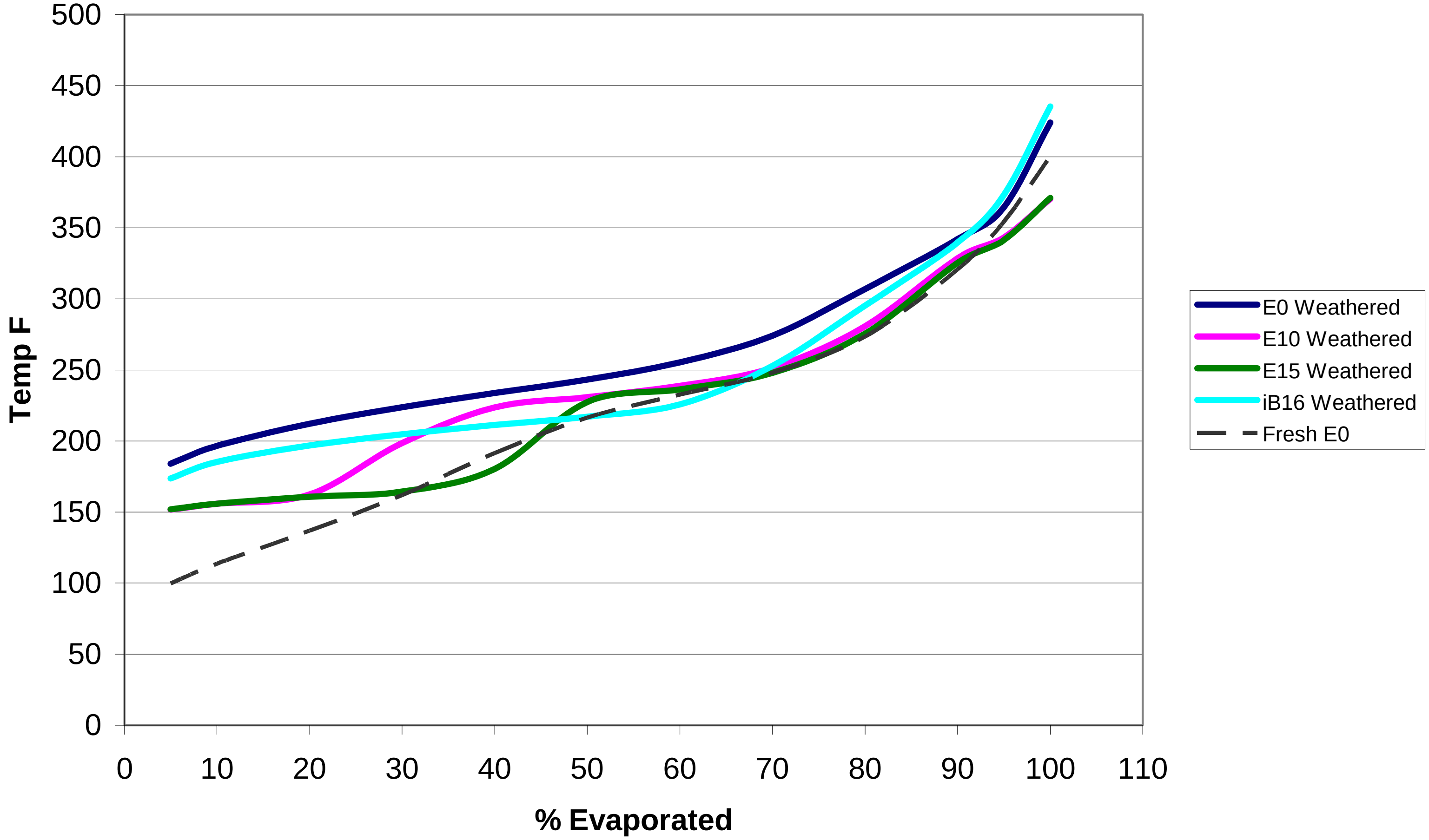
- BP/Butamax vapor-liquid equilibrium model for E15 & iBu16
- Calculates fuel composition during simulation of evap experiment
- E15 and iBu16 oxygen increase on initial weathering, then decrease as weathering continues
- Maximum iBu16 oxygen is lower than initial E15 concentration

Severe Fuel Weathering – Oxygen Content



- iBuOH and its HC azeotropes evaporate in the fuel's mid-range
- Initial weathering evaporates only HC, concentrating the alcohol
- Continued weathering begins to evaporate iBuOH as well, until by 70% evaporated only HC remains

Severe Fuel Weathering Experiment Results - Distillation of Weathered Fuels



- **iB16 maintains a better drivability index compared to E0**

Conclusions

- No comprehensive data available in the literature on fuel weathering behavior of ethanol compared to isobutanol
- Study was designed to evaluate worst case scenario fuel property changes due to weathering for E0, E10, E15 and iB16
- Evaporation loss and evaporation rate reduced with iB16 compared to E10
- RVP reduction due to weathering is lower for E10/E15, iB16 equivalent to E0
- Distillation curves shift significantly for all weathered fuels, changes for ethanol and butanol blends less critical than E0
- **Overall all alcohol blends show improvements in weathering behavior compared to neat gasoline**
- **Oxygen content Wt% of iB16 never reaches E15 O2 content**

Biobutanol FAQ

Q: What is biobutanol and how is it made?
Biobutanol is a four-carbon alcohol produced from renewable, plant-derived energy sources in a fermentation process similar to beer and wine production. Biobutanol can be produced using existing ethanol feedstocks, such as corn and sugar beets, or advanced feedstocks (cellulosic biomass) such as crop residues, wood residues, dedicated energy crops, and industrial and other wastes. Biobutanol delivers more renewable energy content than ethanol while remaining compatible with current vehicles, boats, and infrastructure.

Q: Why interest in biobutanol for recreational marine engines?
The congressionally-mandated US Renewable Fuels Standard (RFS) requires 36 billion gallons of renewable fuel to be blended into the gasoline supply by 2022. Methods to increase renewable fuels in the gasoline supply have primarily focused on ethanol and higher ethanol blends such as E15. Recreational marine industry reports show significant damage to marine engines using ethanol E15 fuels. Recognizing the issues associated with higher ethanol blends such as E15, the recreational marine industry has explored biobutanol fuel blends with very promising results. The approval of biobutanol fuel blends up to 16.1 vol percent (Bu16) for marine engines and boats positions the industry as a proactive leader in identifying renewable fuels that are more compatible with recreational marine engines and boats.

Q: How is biobutanol different from bioethanol?
Biobutanol has several characteristics which distinguish it from ethanol, making biobutanol an attractive gasoline bio component. For example:

- Biobutanol is compatible with existing recreational boats and refueling infrastructure at levels significantly higher than ethanol, overcoming the impending ethanol blendwall.
- Biobutanol is substantially less susceptible to phase separation in the presence of water than ethanol which means biobutanol behaves similarly to conventional non-ethanol gasoline when water is introduced to the boat fuel tank.
- Biobutanol has an energy content that is closer to gasoline, so consumers face less of a compromise on fuel economy at higher blend ratios. At 16.1 vol% in gasoline (Bu16), biobutanol has the exact same energy content of 10 vol% ethanol fuels (E10).
- Biobutanol is well-suited for current boat and engine technologies. It does not require boat builders or engine manufacturers to compromise on performance to meet environmental regulations.

Q: Has biobutanol caused any damage to recreational boats or engines?
No. Based on thousands of engine and boat test hours, extensive industry testing and published research reports, biobutanol fuel blends up to 16.1 vol percent (Bu16) resulted in no engine failures, no engine runability issues and no boat performance issues.

Q: Does an engine have to be altered to use biobutanol?
No. Biobutanol fuel blends up to 16.1 vol percent (Bu16) were rigorously tested in standard marine engines and boats with no alterations to the engine or fuel system.

Q: Can biobutanol be used in an old engine?
Yes. Biobutanol fuel blends up to 16.1 vol percent (Bu16) have been tested in a variety of recreational boats powered by many different engine technologies including fuel injected four-stroke outboards, two-stroke direct fuel injection outboards, catalyst based stern-drive and inboards, non-catalyzed inboards, carbureted four-strokes, and conventional carbureted two-stroke engines.

Q: Will my boat perform differently with biobutanol?
Based on thousands of hours of testing both in the laboratory and on water, boat and engine performance is transparent between fuels such as E10 and biobutanol fuel blends up to 16.1 vol percent (Bu16). Biobutanol fuel blends behave more similarly to conventional non-ethanol gasoline, particularly when water is introduced into the boat fuel tank.

Q: Is there any significant difference in fuel economy or other operating factors that I should expect when running my boat with biobutanol fuel blends?
Thousands of hours of testing on marine engines operated both in the laboratory and operated in boats on the water indicate no negative impact on fuel economy as compared to E10. More importantly, Biobutanol does not phase separate in the presence of water which is a very desirable property, particularly when used as a biofuel blend for recreational boats. Fuel phase separation with ethanol fuel blends such as E10 is a very common source of boat and engine related issues. Phase separated fuels can quickly deteriorate fuel system components and can lead to catastrophic engine failure. Biobutanol fuel blends up to 16.1 vol percent (Bu16) behave similarly to conventional non-ethanol gasoline, in its resistance to phase separation, making biobutanol an excellent biofuel for recreational boats when compared to E10.

Q: Are there any different maintenance requirements in a boat using biobutanol fuel blends?
No. Comprehensive material compatibility studies indicate that biobutanol fuel blends up to 16.1 vol% (Bu16) are compatible with a variety of fuel system components typical of recreational boats. In fact, research has shown biobutanol fuel blends to be more compatible with fuel system components than ethanol. Coupled together with desirable properties including resistance to phase-separation in the presence of water and thousands of hours of successful marine industry testing means that biobutanol (Bu16) is a biofuel better suited for recreational marine engines and boats.

Q: What is the difference between biobutanol, isobutanol and n-butanol?
Biobutanol is a description for biologically produced butanol which can include Isobutanol and n-butanol. Isobutanol and n-butanol are similar (same energy content and resistant to phase separation) but isobutanol has a higher octane rating than n-butanol making it more attractive for blending with gasoline. Both n-butanol and isobutanol have been evaluated in internal combustion engines.

Q: Who is involved in the recreational marine biobutanol testing program?
Biobutanol research is supported by the US Department of Energy, Office of Energy Efficiency and Renewable Energy coordinated through Argonne National Laboratory. There is participation across the industry from engine manufacturers as well as the National Marine Manufacturers Association (NMMA), the American Boat and Yacht Council (ABYC) and the United States Coast Guard (USCG).

Q: How many companies are working on commercializing biobutanol?
There are many companies currently working on commercializing and developing biobutanol as a building block for renewable chemicals and/or for use as a biofuel in internal combustion engines. The marine industry does not endorse any specific biofuel company, but rather is focused on biofuels that indicate compatibility with recreational marine engines.

Q: Where can I purchase this fuel?
Large scale availability of biobutanol fuel blends will take some time. However, marine industry approval of biobutanol fuel blends up to 16.1 vol percent (Bu16) for marine engines and boats as an alternative to ethanol will encourage its market expansion by providing marine fuel distributors, retailers and consumers with the confidence that this is not only a suitable, but a more compatible fuel for boats. Approval for the use of Bu16 blends is an important first step in securing a biofuel that is compatible with recreational boats and engines, particularly when the damaging effects of higher ethanol blends such as E15 are widely known.

Q: Will biobutanol fuel blends up to 16.1 vol percent (Bu16) be available in different octane ratings?
Yes, the existing fuel grade structure will remain applicable to biobutanol fuel blends.

Q: What is (or what will be) the relative price of biobutanol fuel blends vs. conventional gasoline?
Biobutanol production technology is being developed to compete against current market gasoline fuel costs

Q: With today's lower gas prices, why are we interested in biofuel alternatives like biobutanol?
Gasoline blended with oxygenated compounds like biobutanol is required in many parts of the US by EPA regulations in the Clean Air Act for reducing air pollution. In addition, a biofuel that is more compatible with recreational boats and engines such as biobutanol is key to realizing important goals of the Renewable Fuels Standard such as US energy security, rural and agricultural job growth, and greenhouse gas reduction.

Q: How can I learn more?
More information can be found on the following websites -- US Department of Energy Alternative Fuels Data Center and the Marine Biobutanol Research webpage:

http://www.afdc.energy.gov/fuels/emerging_biobutanol.html
http://marinebiobutanol.net