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

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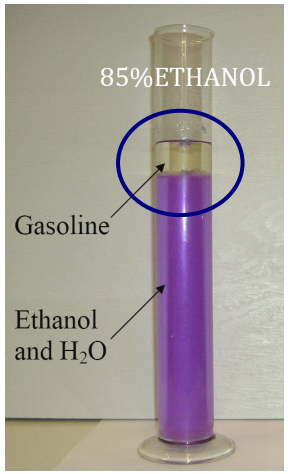
1. Why Ethanol?

- **Ethanol has been the primary fuel extender:**
  - Historically, yields of ethanol were high relative to other biologically derived alternative fuels
  - Ethanol was an available replacement for MTBE which was known to cause significant environmental related issues

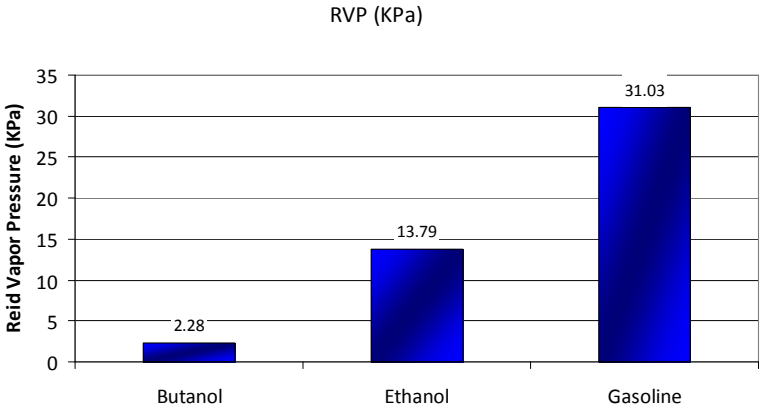
  - Government subsidies and low-interest loans for ethanol producers have lead to many ethanol production facilities across the U.S
  - The establishment of the U.S Renewable fuels standard mandated specific quantities of ethanol production
  - Ethanol reduces dependency on foreign sources of oil

2. Issues with ethanol

- **Issues with ethanol**
  - Ethanol is hygroscopic, meaning it has an affinity for water.
  - Terminal blending is required as ethanol can not be shipped in pipelines (due to its corrosive nature, water solubility, and strong solvency)
  - Ethanol at 15% by volume contains approximately 5% oxygen. Increasing ethanol content in gasoline increases the oxygen level causing open loop engines to experience increased combustion temp
  - Ethanol raises the Reid Vapor Pressure of gasoline which increases evaporative emissions.

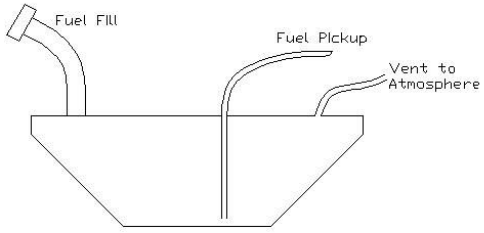


Phase Separation



2. Issues with ethanol

- **Specific to the marine environment**
  - The majority of boats use an open-vented fuel system in which water is more likely to enter the fuel system which results in phase-separation of the fuel.



Basic Marine Built-In Fuel Tank System

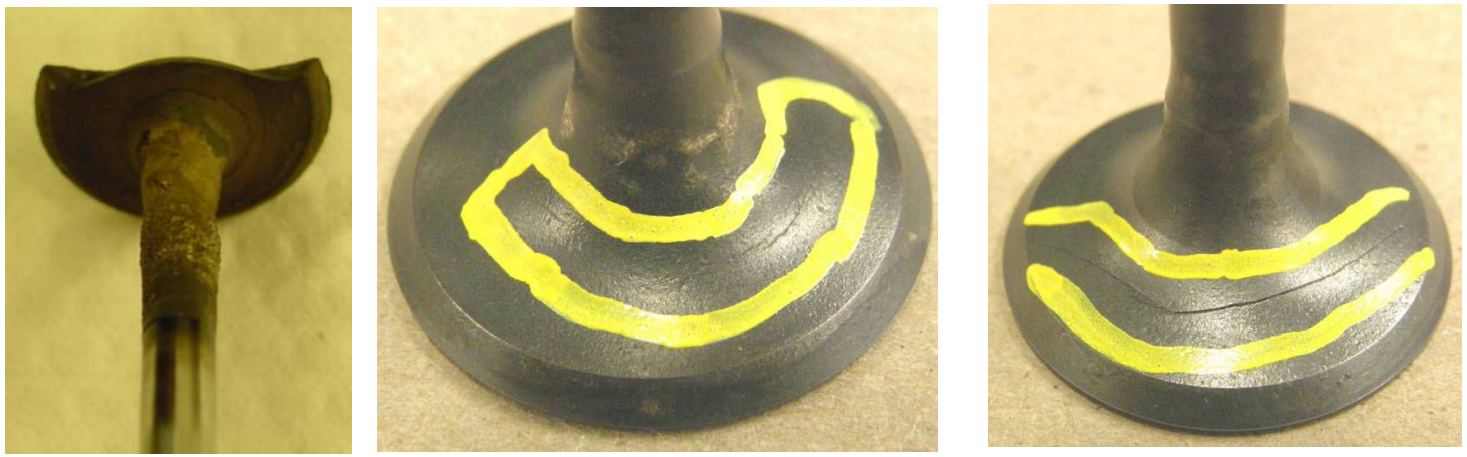
  - Ethanol causes deterioration in many fiberglass fuel tanks which are structurally part of the boat
  - The usage frequency of boats, especially in northern climates, results in a greater likelihood of fuel/fuel system related issues

2. Issues with ethanol

Higher quantities of ethanol beyond 10% by volume will only exacerbate these issues.

3. E15 NREL Report

- **Based on data and tests conducted by the National Renewable Fuels Laboratory, E15 has caused substantial damage to marine engines.**
- **E15 marine outboard engine failed exhaust valves. Metlab analysis showed excessive metal temperatures caused a reduction in fatigue strength.**



Failed Exhaust Valves from 300 HP Mercury Verado Outboard Engine

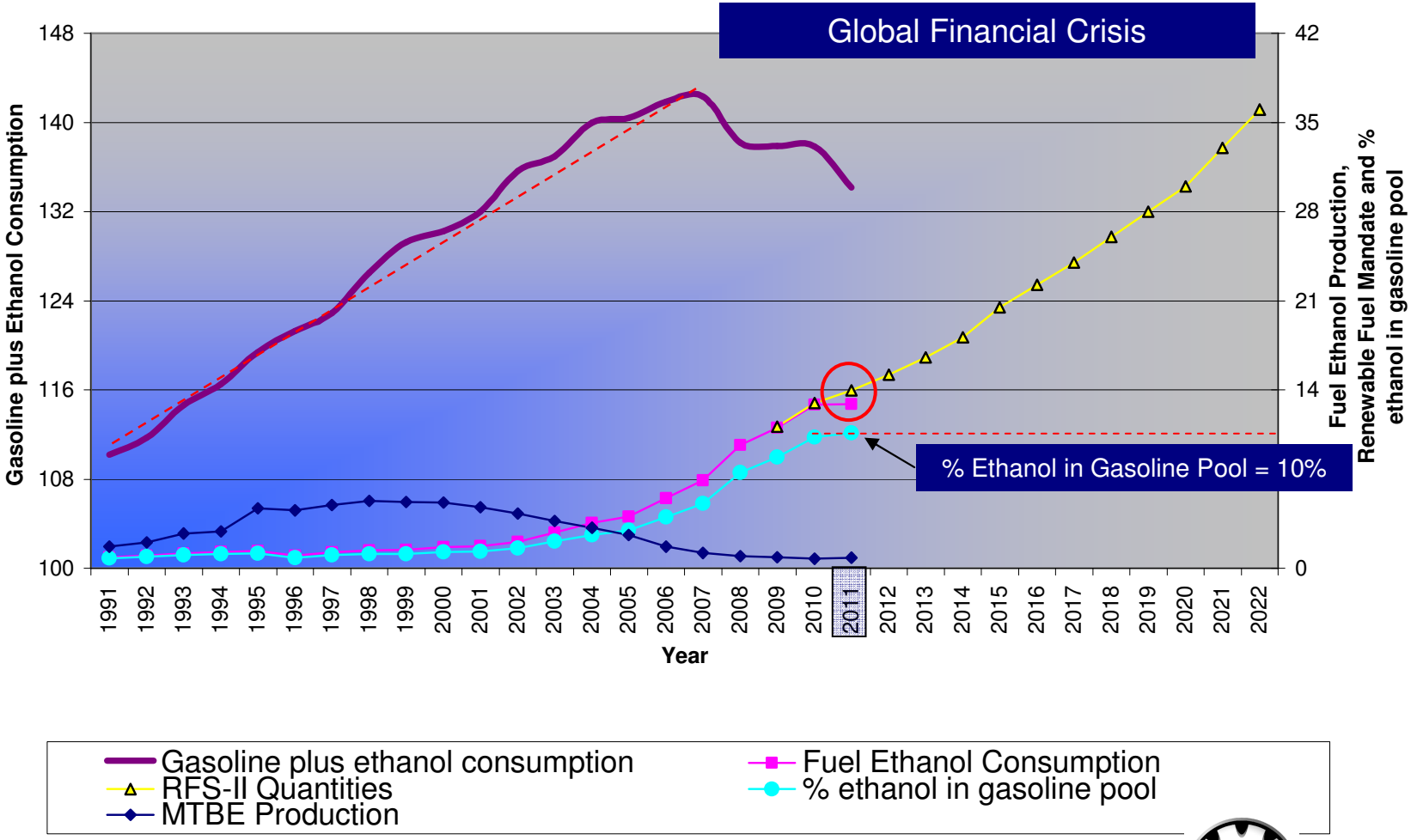
3. E15 NREL Report

- **Damaged rod bearing at 235 hours operated on E15.**
- **Gasoline (E15) and oil is mixed in two-stroke engine. Impact of E15 on solvency and lubricity of oil is unknown.**

So why the push to E15?

2007 - 2011

US Gasoline + Ethanol Consumption 1991 - 2011 and Renewable Fuels Standard (RFS-II) Total Renewable Fuel Requirements through 2022 [Billion gallons per year]



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5. Solutions

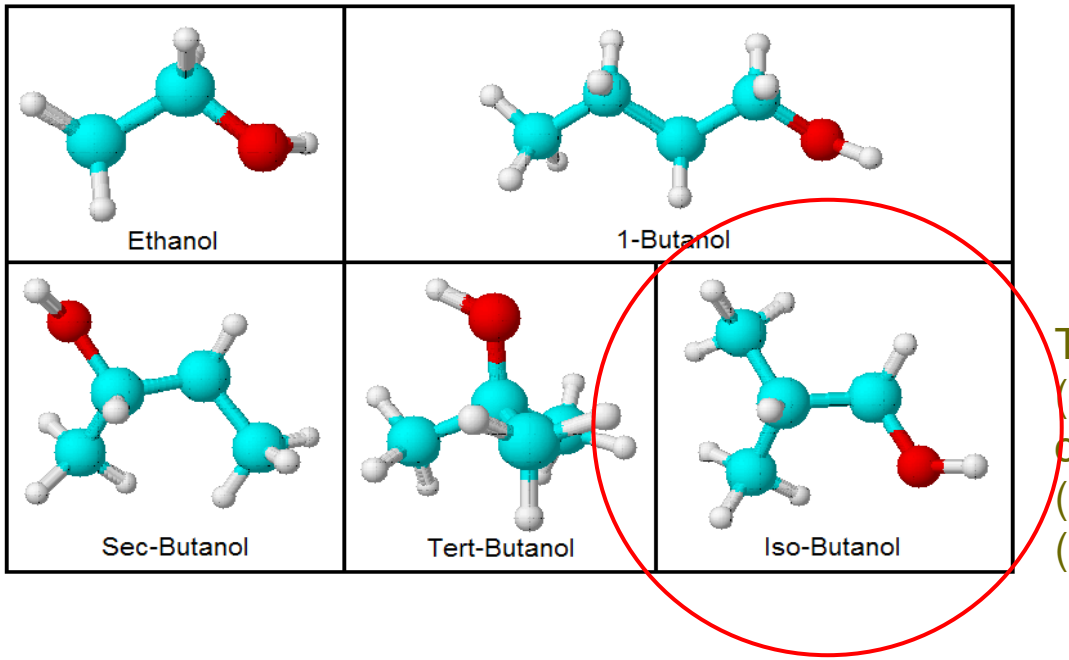
The US Market was saturated with ethanol in 2010. The industry cannot continue to grow beyond that of exports.

– **Solutions:**

- Quickly start consuming more gasoline (unlikely)
- Realign the RFS to match the new fuel demand reality (unlikely - does nothing to address the growth of the ethanol industry)
- Raise the amount of ethanol allowed in gasoline (E15 waiver request granted – source of much debate, will cause issues)
- Find another alternative fuel that can better satisfy the RFS volumes without affecting millions of existing engines

What is Butanol?

- A four carbon alcohol (C4H9OH), colorless, neutral liquid of medium volatility with a characteristic banana-like odor.
- Traditional petrochemical derived - Generally used to make other chemicals, or used as a solvent or an ingredient in formulated products such as cosmetics.
- Can be biologically derived in a fermentation process
- Butanol exists in four (4) different isomers:



The structure of the four (4) isomers of butanol in comparison to ethanol (a two carbon alcohol (C2H5OH))

Properties of Butanol - Overview

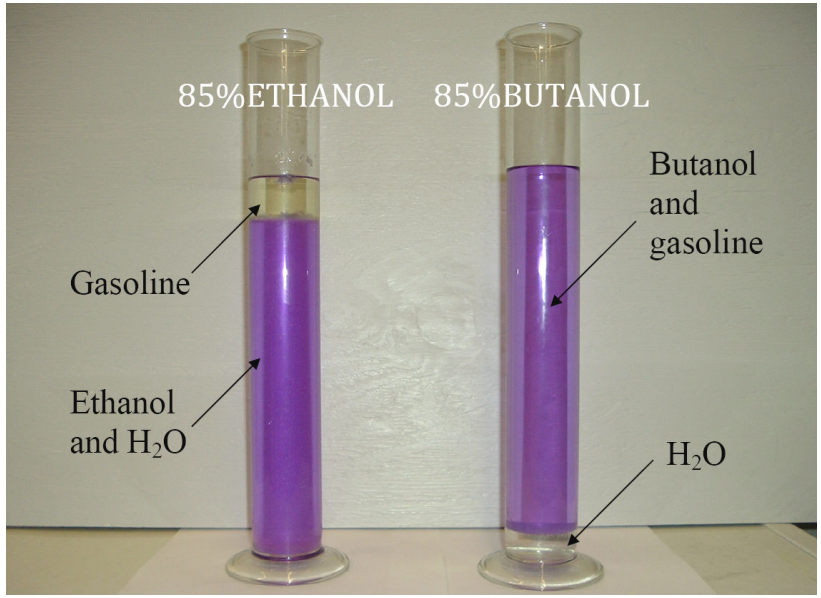
	Gasoline (EEE)	Ethanol	1-butanol	2-butanol	3-butanol	Iso-butanol
Composition (C,H,	86, 14,	52, 13, 35	65, 13.5, 21.5	65,	65,	65, 13.5, 21.5
RON	97	107.4	98.3	106	105	105.1
MON	88.3	88.2	84.4	92	89	89.3
Melting point (ºC)	-	-112	-79.9	-114.7	25.5	-108
Energy content (MJ/kg)	42.9	25.6	32.9	32.9	32.9	32.8
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

6. Butanol as a Fuel Extender

- **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 – can be blended into gasoline at higher percentages than ethanol**



Adding water to ethanol and butanol

7. Test Boats

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

Figure 1. 18' Mako boat with 175 HP Evinrude Direct Fuel Injection Outboard

Figure 2. 24' SeaDoo Challenger boat with 215 HP Rotax engine

Evaluate 16% isobutanol-extended fuel over summer boating season (50 hrs)

8. Test Method - MPSS

- **Marine Portable Bag Sampling System (MPSS)**
  - Developed for the U.S EPA Marine Green House Gas reporting requirement.
  - First portable emissions sampling system used to evaluate emissions from recreational boats operated on-water.
  - Integrated 5-gas emissions analyzer
  - Contains sample preparation unit / chiller
  - Filters, pumps, sample timer, condensation pumps, flow meters, mass flow

In-Use Emissions Evaluation of Butanol Fuel

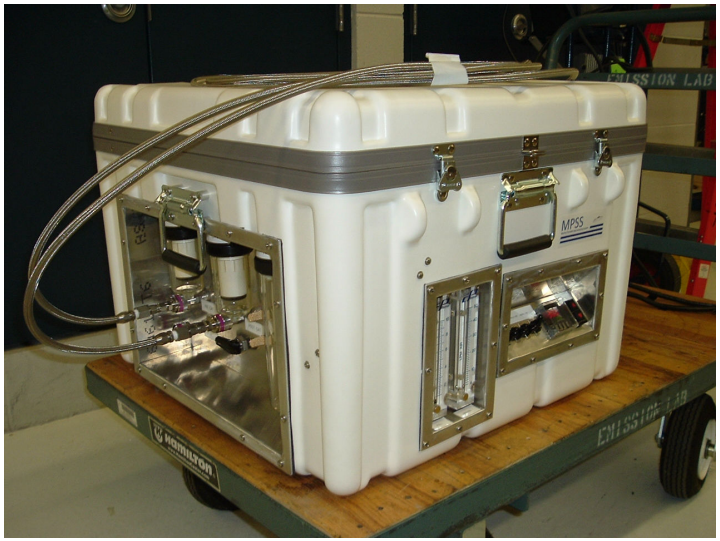
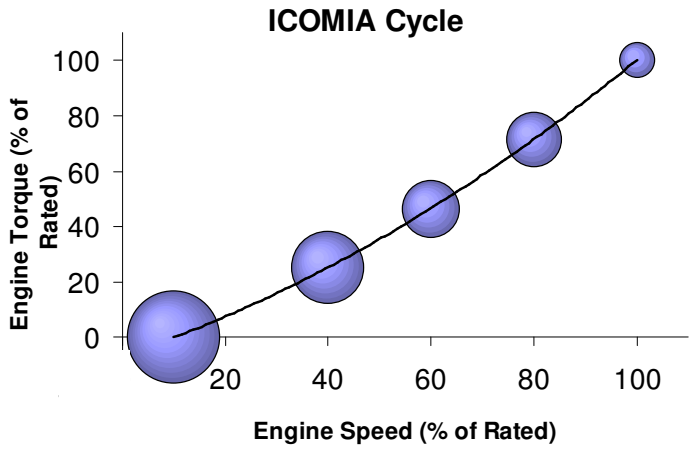


Figure 3: MPSS Bag Sampling System

- **Marine Test Cycle**
  - **Laboratory ISO 8178 discrete test modes**
  - **On-water sampling method according to NTE procedure**

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



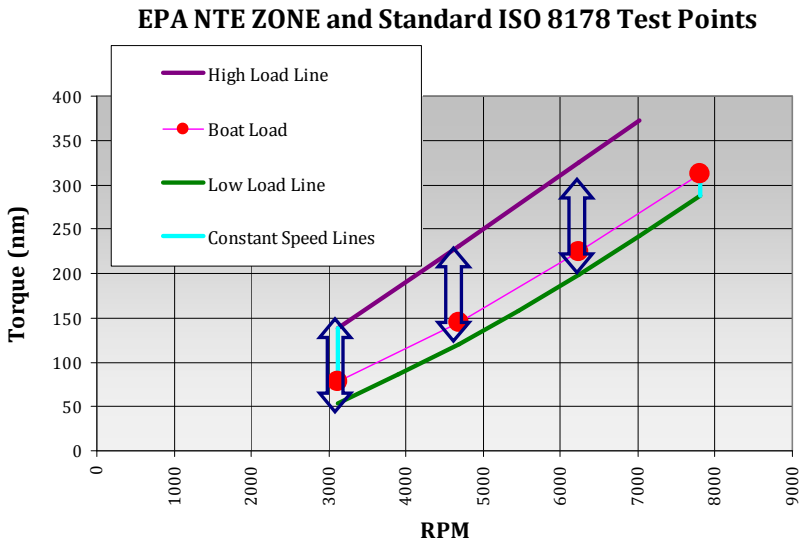


Figure 7. Example of EPA NTE test zone. Red points indicate the standard ISO 8178 test points

9. Results

- **Evinrude E-TEC Outboard**
  - **Bag 1 and Bag 2 results – Indolene vs. isobutanol**
  - **HC, NOx and CO**
  - **Good repeatability between test 1 and test 2**

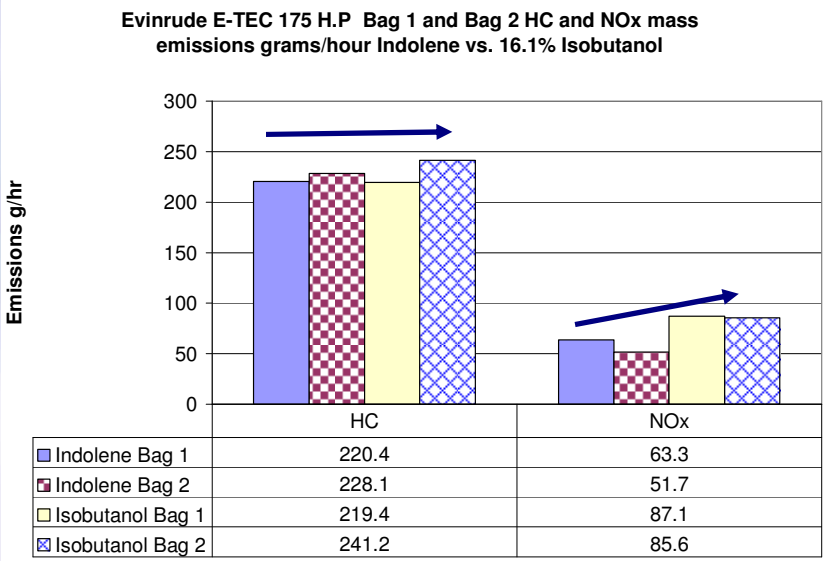
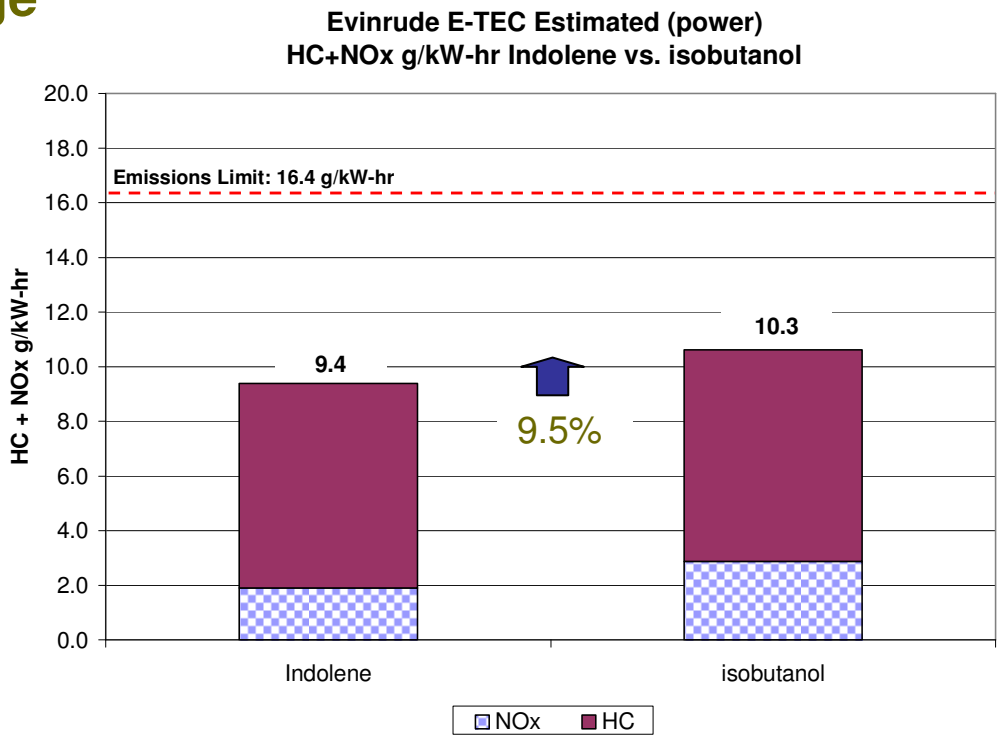


Figure 8. Evinrude E-TEC emission results sample bag 1 and 2 HC and NOx grams per ICOMIA hour

sample bag 1 and 2 CO grams per ICOMIA hour

9. Results

- **Evinrude E-TEC**
  - **Estimated weighted power kW using throttle position and RPM look-up**
  - **Tests comfortably under the limit and within expected range**



Evinrude E-TEC average HC+NOx g/kW-hr indolene vs. isobutanol calculated from estimated power

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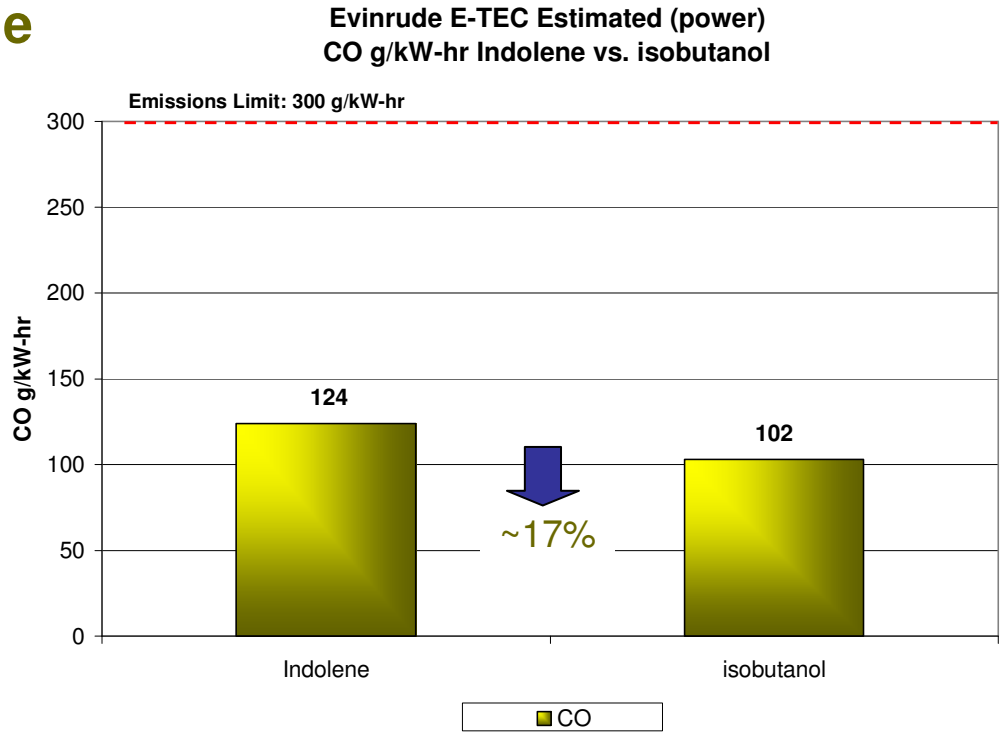
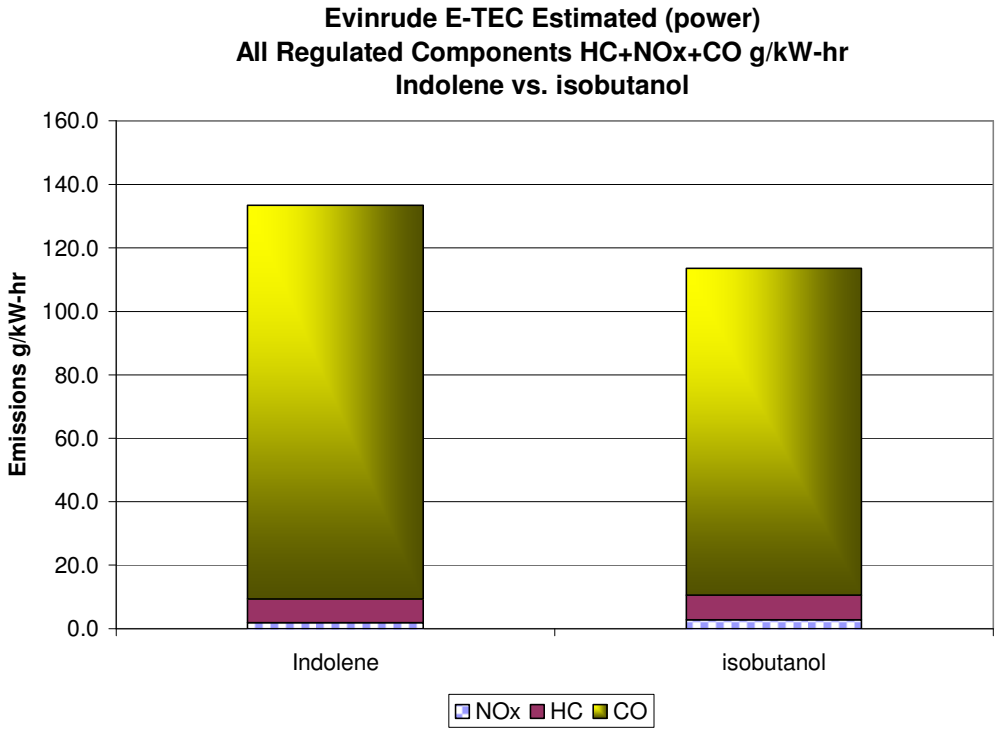


Evinrude E-TEC average CO g/kW-hr indolene vs. isobutanol calculated from estimated power

9. Results

- **Evinrude E-TEC**
  - **Estimated weighted power kW using throttle position and RPM look-up**
  - **All regulated components HC+NOx+CO**



Evinrude E-TEC all regulated components g/kW-hr indolene vs. isobutanol calculated from estimated power

9. Results

- **SeaDoo Challenger**
  - **Bag 1 and Bag 2 results – Indolene vs. isobutanol**
  - **HC, NOx and CO**
  - **Good repeatability between test 1 and test 2**

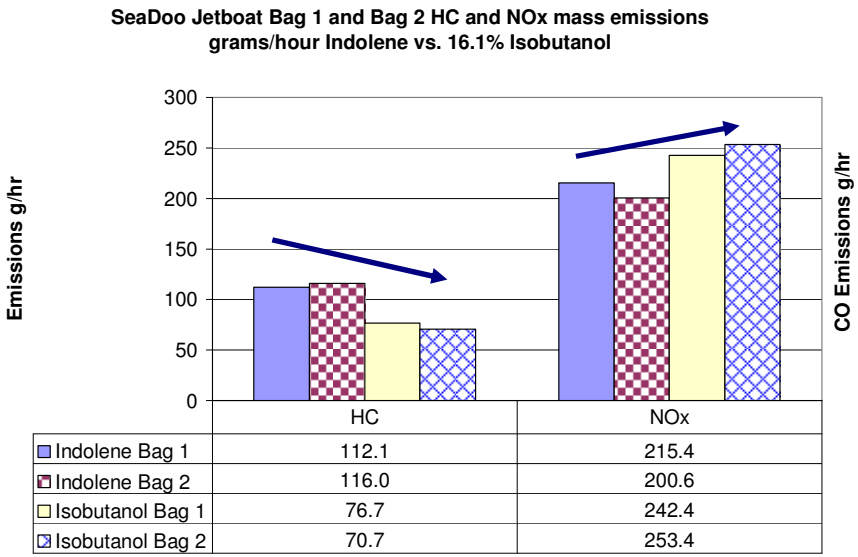
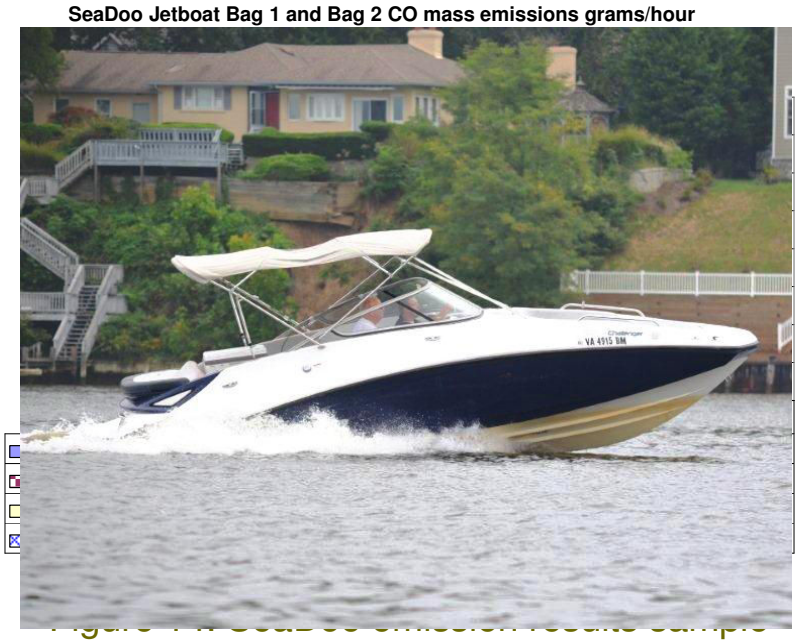


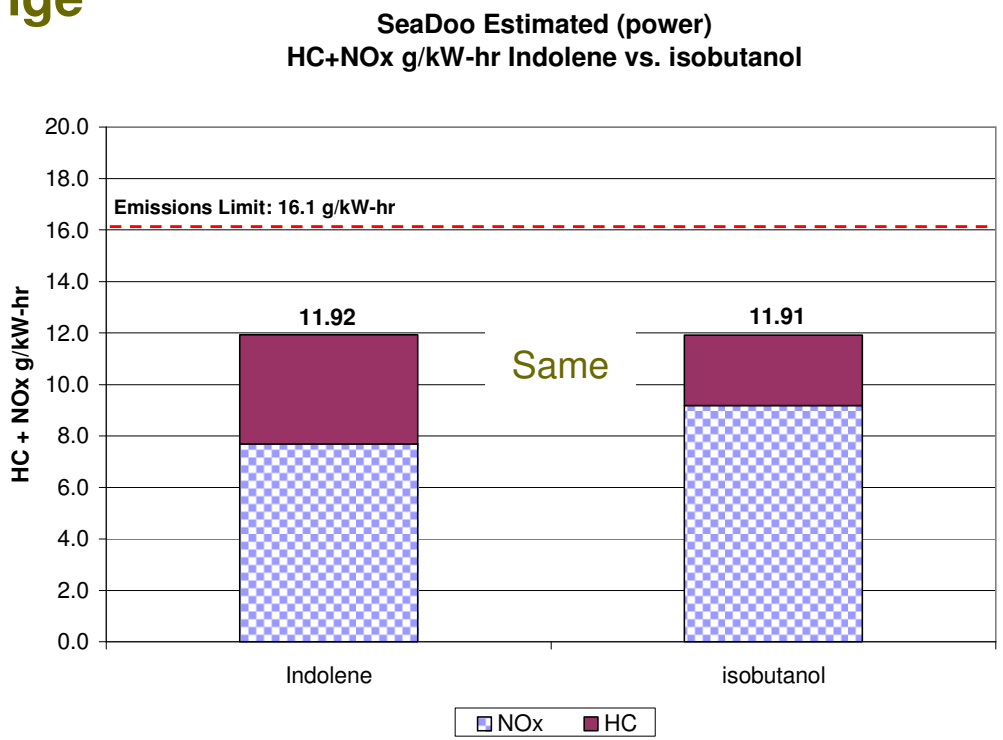
Figure 13. SeaDoo boat emission results sample bag 1 and 2 HC and NOx grams per ICOMIA hour



bag 1 and 2 CO grams per ICOMIA hour

6. Results

- **SeaDoo Challenger**
  - **Estimated weighted power kW using throttle position and RPM look-up**
  - **Tests comfortably under the limit and within expected range**



SeaDoo Challenger average HC+NOx g/kW-hr indolene vs. isobutanol calculated from estimated power

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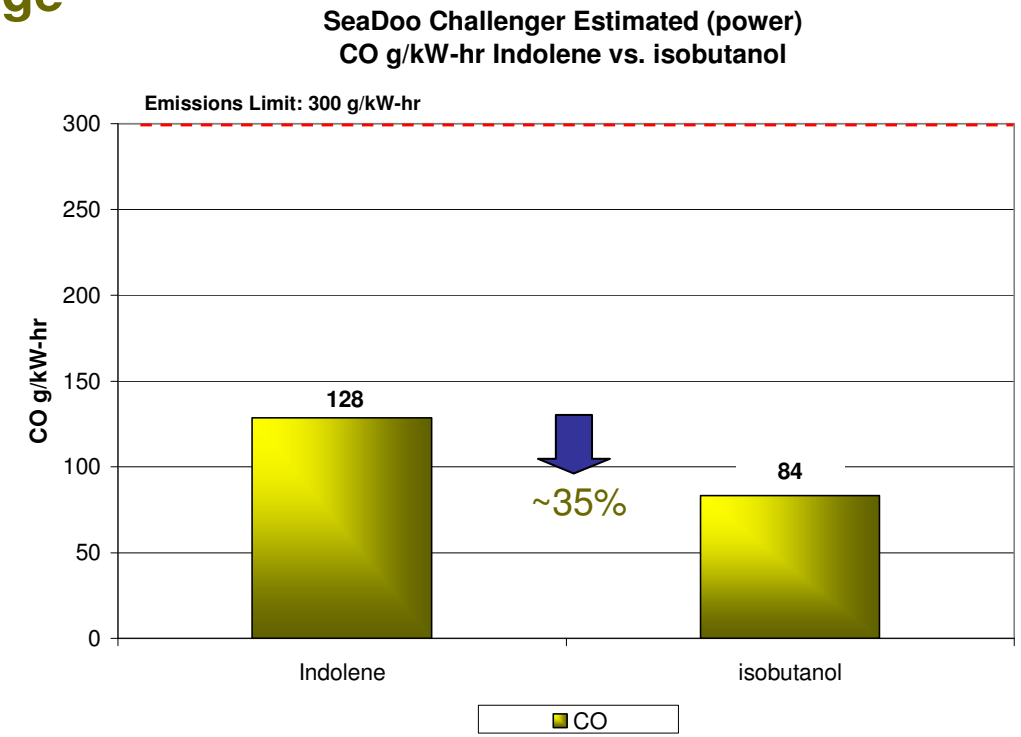
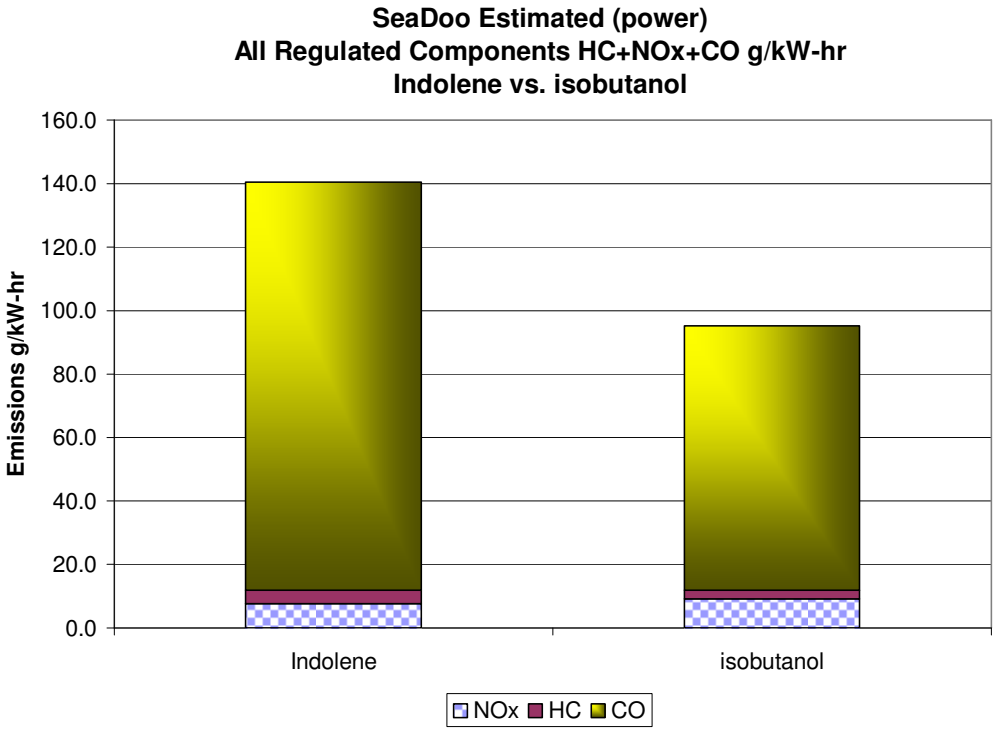


SeaDoo Challenger average CO g/kW-hr indolene vs. isobutanol calculated from estimated power

9. Results

- **SeaDoo Challenger**
  - **Estimated weighted power kW using throttle position and RPM look-up**
  - **All regulated components HC+NOx+CO**



SeaDoo Challenger all regulated components g/kW-hr indolene vs. isobutanol calculated from estimated power

9. Results

- **Expected Enleanment**
  - **The CO enleanment caused by 16.1% isobutanol (partially oxidized fuel) is within the typical range of E10**

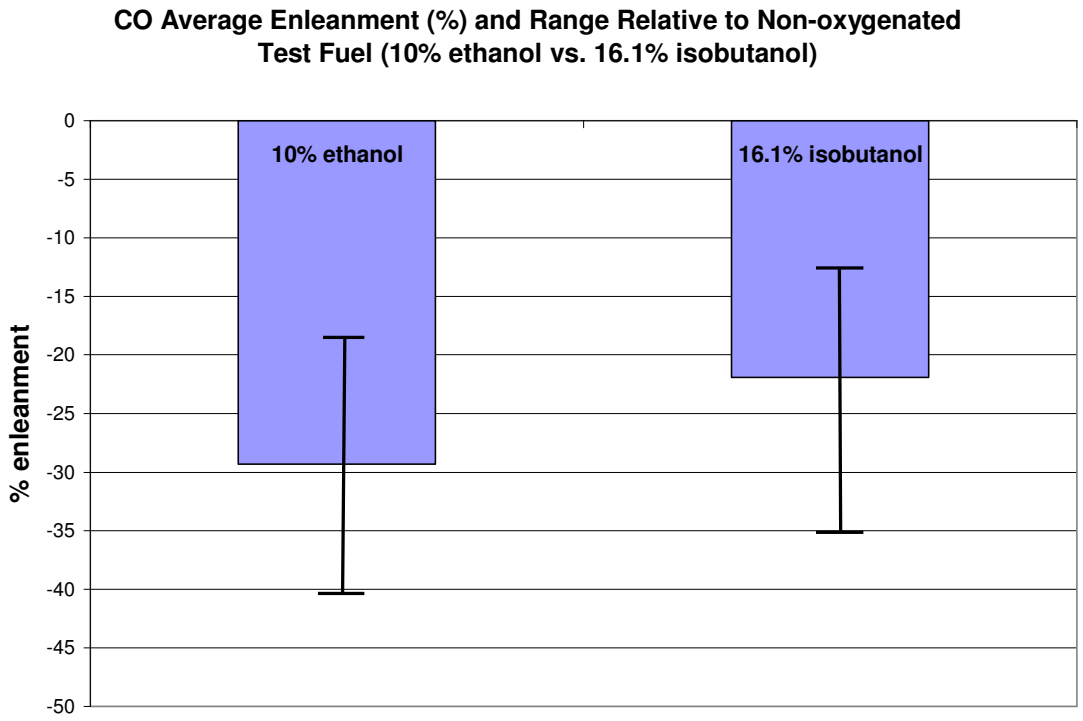


Figure 18. Percent Reduction in Open-loop Engines Mass CO relative to Non-oxygenated Indolene Certification Fuel. The enleanment for B16.1 fuel is similar to typical enleanment of E10

10. Conclusion

- **Conclusion:**
  - **The boats and engines operated on a 16% isobutanol-extended fuel performed well over the 50 hour field test program**
    - **No engine runability, startability or other issues were reported**
  - **Field emission testing results using a 16% isobutanol-extended fuel relative to a non-oxygenated indolene test fuel indicate:**
    - **No change in HC+NOx for the supercharged four-stroke engine**
    - **Slight increase in HC+NOx for the two-stroke direct fuel injection engine.**
  - **Carbon Monoxide emissions were reduced on both boats using a 16% isobutanol-extended fuel.**
  - **CO emissions on isobutanol are within normal expected ranges of E10**

10. Conclusion

Where do we go from here?

- DOE interest in butanol-extended fuels
- The marine industry is leading up one of the largest and most comprehensive recreational marine study using an advanced biofuel other than ethanol with Argonne National Laboratory and U.S Department of Energy oversight
- DOE interest in fuel comingling gasoline/ethanol/butanol to lower RVP
- Continued tests with the Department of Energy