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# The Effects of Low-Level Ethanol Blends in 4-Stroke Small Non-Road Engines

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# **The Effects of Low-Level Ethanol Blends in 4-Stroke Small Non-Road Engines**

**By**

**Chris Reek**

**A Thesis Submitted in**

**Partial Fulfillment of the Requirements for the**

**Master of Science Degree in**

**Manufacturing Engineering Technology**

**Minnesota State University, Mankato**

**Mankato, Minnesota**

**May 2014**

**The Effects of Low-Level Ethanol Blends in 4-Stroke  
Small Non-Road Engines**

**Chris Reek**

**This thesis has been examined and approved by the  
following members of the student's committee.**

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Dr. Gary Mead - Advisor

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Dr. Kuldeep Agarwal - Committee Member

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Dr. Bruce Jones - Committee Member

## **Abstract**

**Title:** The Effects of Low-Level Ethanol Blends in 4-Stroke Small Non-Road Engines

**Author:** Chris Reek

**Degree:** Masters of Manufacturing Engineering Technology

**University:** Minnesota State University, Mankato 2014

Small Non-Road Engines (SNRE's) abound in numbers and are used daily by consumers and businesses alike.

Considering the atmosphere of change looming in the air regarding alternative fuels, this particular engine classification will also be affected by any change in standardization of fuels. This body of research attempts to address possible ways SNRE's can change their operational characteristics after being fueled by specific yet differing fuels. These characteristics will be contrasted against blends of ethanol with gasoline, from 0% ethanol to 20% ethanol, run on test engines to determine patterns, if any, of these characteristics. Topics include: materials compatibility, engine longevity/durability, engine performance, emissions characteristics, operational temperatures, engine oil characteristics, and inspection of engines. These parameters

will be used to compare the effects of low-level blends of ethanol with gasoline has on these particular SNRE's.

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## **Introduction**

This research is a small piece of a SNRE (Small Non-Road Engine) study on the effects of ethanol/gasoline blends being used. The overall research project carried out at Minnesota State University, Mankato consisted of many more engines, and engine types, using various blends of ethanol and gasoline ranging from E0 to E20.

The economic and environmental impact of offsetting fossil fuels with corn/cellulosic-based ethanol is a topic of great debate. While this is an important topic to regard before implementing any changes in fuel policy, this research will not cover those issues.

This body of work examines trends in post combustion emissions, durability, longevity, and performance of a specific engine type being operated on intermediate ethanol blends (E0, E10, E15, E20).

Small Non Road Engines, or SNRE's, are used on a massive scale. Millions of SNRE's are sold each year and are used for applications such as lawn mowers, leaf blowers, ice augers, electrical generation, and pumping.

Due to the price point and general use of SNRE's, engine development in this category has been limited. Production numbers must be high to feed consumer demand, while the price must be kept low to satisfy typical users. SNRE's must also be held to a high reliability standard like most products. SNRE's are typically

subjected to extremely hard use; they are stored for long periods, usually with lack of maintenance, and are expected to start every time and achieve full load. Keep in mind that they must also be emissions compliant throughout their lifetime. Other parts of the overall project address these issue.

## Literature Review

A sizable amount of research has been done in this sector. The National Renewable Energy Laboratory, or NREL, has summed up the situation nicely.

“The Energy Independence and Security Act of 2007 calls on the nation to significantly increase its use of renewable fuels to meet its transportation energy needs. The law establishes a new renewable fuel standard (RFS) that requires the nation to use 36 billion gallons of renewable fuel in its vehicles by 2022.

Given that ethanol is the most widely used renewable fuel in the United States and production is expected to grow steadily over the next several years, ethanol—both from corn and from cellulosic feedstocks—will likely make up a significant portion of the new renewable fuel requirements. The vast majority of ethanol used in the United States is blended with gasoline to create E10—that is, gasoline with up to 10% ethanol by volume. The remaining ethanol is sold in the form of E85—a gasoline blend with as much as 83% ethanol that can be used only in flexible-fuel vehicles (FFVs). Consumption of E85 is currently limited by both the size of the flex-fuel vehicle fleet and the number of E85 fueling stations. While U.S. automakers have committed to significantly ramping up production of FFVs, only about 7% of the existing U.S. fleet is replaced each year. That means a significant number of the non-FFVs in use today will remain in the vehicle stock for many years to come.” (National Renewable Energy Laboratory, 2009)

In lieu of changing regulations pertaining to renewable fuel regulations, ethanol will become a major factor in the general discussion regarding the United States' fueling needs. The use of 10% ethanol, 85% ethanol, and blender pumps around the nation may lead to more use in vehicles and equipment. The effects of the additional fuel use shall need to be determined before widespread use should take place.

Lawmakers in Minnesota have even taken the point of utilizing more renewable fuel sources to the extent of proposing increased ethanol content in fuel.

"Minnesota Statute 239.791 Subd.1a requires that on August 30, 2013, gasoline sold in the State of Minnesota shall contain at least 20% denatured ethanol by volume. If on December 31, 2010, however, it is determined that 20% of the State's gasoline volume is ethanol, then this provision expires. If 20% volume replacement is not achieved by 2010, then the 2013 requirement becomes effective provided the United States Environmental Protection Agency (US EPA) certifies E20 by December 31, 2010. In order to use E20 in non-Flex-Fuel vehicles, it will be necessary that the US EPA certify E20 as a motor fuel through a waiver under section 211(f) (4) of the Clean Air Act." (Univeristy of Minnesota Center for Diesel Research, 2008)

The EPA has granted a waiver for E15 to be used in vehicles from model year 2001 – 2006. The EPA declined to extend the E15 waiver for use in motorcycles, heavy-duty vehicles, or non-road engines.

The fact that Minnesota is set on increasing the amount of ethanol contained at the pumps warrants more research on the subject.

Minnesota lawmakers aren't the only ones looking to increase ethanol content in fuels. Growth Energy requested additional ethanol content be included at the pump.

“In March 2009 corn ethanol producers asked for help from the federal government to expand their industry. Growth Energy, a consortium of ethanol producers, petitioned the Environmental Protection Agency (EPA) to allow 50% more ethanol in gasoline than is currently permitted, requesting approval for E15 fuel (a mixture of gasoline with 15% ethanol).” (Growth Energy 2009)

Considering the petition to increase the ethanol/gasoline ratio, research should be conducted to evaluate the effects of additional low-level blends of ethanol on the products they would be used on.

The sheer amount of SNRE's in use and producing post combustion emissions is staggering. Changing the fuel they are burning to accomplish their desired tasks may have dire effects on the quantity and make-up of those emissions.

“Hundreds of millions of non-road engines are used across the country, including leaf blowers, line trimmers, chainsaws, lawn mowers, motor boats, generator sets, and small tractors. For many small engines, ethanol fuels could also be associated with increased emissions of hazardous air pollutants and ozone precursors such as hydrocarbons and nitrogen oxides (American Lung

Association 2009; Sahu 2009). The DOE study reported that NO<sub>x</sub> emissions increased by 50-75% for small engines operated on E10 and E15 ethanol blends (DOE 2009) compared to E0... Air pollution with nitrogen oxides leads to aggravation of respiratory disease and increased susceptibility to respiratory infections. NO<sub>x</sub> also contributes to formation of ozone and particulate pollution, which are associated with severe adverse respiratory effects (U.S. EPA 2008).” (Naidenko, 2009)

It's no doubt that altering the fuel that is used for combustion will inherently change the exhaust emissions, both in amount and type. While many things will affect this change, such as: lambda, compression ratio, combustion chamber geometry, a vague pattern should arise pertaining to the engines general emissions. Considering the volume of small engines in use today and their fueling controls, they may be the items most effected by the change in fueling.

Part of NREL's study included emissions sampling of some engines, here are their results.

“Open-loop engines tested in this study exhibited the following trends in emissions and temperatures with varying levels of ethanol.

- As ethanol levels increased, leaner engine operation was observed in all of the tested engines, as indicated by decreased CO emissions.
- Temperatures of both the exhaust and engine components increased

as ethanol levels increased.

- HC emissions generally decreased with increasing ethanol, although increases in HC emissions occurred in some engines.
- NOx emissions increased with higher levels of ethanol in all engines; however, combined NOx +HC emissions (which are regulated as such) were tempered by decreasing HC emissions in most cases. Net changes of HC + NOx with increasing ethanol ranged from –36% to +41% and were engine-specific.
- CO emissions decreased with higher levels of ethanol.
- In the case of the 2-cylinder engine tested, temperatures and emissions varied from cylinder to cylinder due to differences in the fuel:air distribution between cylinders. Given this observation, multicylinder open-loop engines may prove to be more sensitive to ethanol blends than single-cylinder engines.
- With greater ethanol content, three handheld trimmers demonstrated higher idle speed and experienced unintentional clutch engagement. The increased speed was again caused by the fuel:air mixture enleanment, which can be adjusted and mitigated in some engines.
- Residential and Commercial Class I and Class IV engines were aged to full life.”

(National Renewable Energy Laboratory, 2009)

The National Renewable Energy Laboratory (NREL), conducted a very thorough study on the effects of ethanol blends in small engines. They were able to

deduce trends based on emissions, temperatures, and operational variance.

Such research is an important building block in the effects of ethanol on SNRE's.

Regarding an important trend deduced from the NREL study is that NO<sub>x</sub> (Nitrogen Oxides) levels increase with ethanol content. More research goes on to explain why.

“The creation of Nitrogen Oxides correlates with the maximum temperature during the combustion, the duration of the combustion and the availability of oxygen. The influence of the oxygen availability could be excluded by a constant fuel-air ratio in the investigations. A tendency for NO<sub>x</sub> to decrease with increasing percentage of alcohol is obvious... (Bertsh, et al., 2012)

This research suggests that if the fuel-air ratio is held constant, the NO<sub>x</sub> levels actually decrease with higher ethanol content; making the claim that the fuel air ratio is a significant variable in the formation of NO<sub>x</sub>.

While emissions are clearly effected by changes in ethanol content, the overall performance of the machine may be just as important. Not only output power and reliability, but temperatures should be considered as well.

“Small engines such as those in lawn mowers and lawn tractors, generators, line trimmers, chainsaws, and other similar equipment are open-loop engines, in that exhaust-sensing feedback is not used to control the fueling rate. Open-loop engines are commonly air-cooled and customarily operate in the fuel- rich regime to achieve cooler combustion temperatures. With a fixed fueling calibration,



[increased ethanol content leads] to a higher combustion temperature and hence higher component temperatures (DOE 2009).” (Naidenko, 2009)

Considering that small engines usually employ open-loop fueling systems, they are very susceptible to fuel type changes. While modern vehicles have the ability to adjust fueling based on oxygen sensor feedback, small engines typically lack that ability.

Performance may be affected so substantially that OEM’s may void their usual warranties.

“Stale gas and ethanol-blended fuels are key contributors to engine issues and lawn mower problems that include the engine not starting, rough running, rust and corrosion and in many cases, failure. This damage to your lawn mower, snow blower or other outdoor power product ultimately adds up to costly small engine repair and voided engine warranties.” (Briggs and Stratton)

Small engine manufacturers have generally denounced ethanol use in engines and some will claim to void warranties based on its use in their products. If the EPA approves intermediate ethanol blends for commercial use, these manufactures may still void warranties based on its use. To the consumer, this may be a confusing issue to work around.

## **Experimental Design**

### **Engine Selection**

The engines used in this study were non-handheld Briggs and Stratton 525 series.

Engine specifications:

- 148cc displacement
- 4-stroke operation
- Flat or “L’ head design
- 5.25 ft-lb of torque (per SAE J1940)

Since this type of engine has been around for decades, and represents a wide cross-section of engines in use, this engine type was deemed to be important to include in the test.

An entire test outline can be found in the “Test Plan” portion of the appendix.

### **Engine Outfitting**

Engine RPM and Runtime were monitored during aging and performance testing with TTO brand hour meter/tachometer units.

The engines were outfitted with thermocouples to monitor temperatures in the following locations:

- Intake Air
- Oil
- Cylinder Head
- Exhaust Gas

The engines were also outfitted with a more convenient oil drain tube to make oil changes easier and faster while on the aging apparatus.

### **Sample Size**

The sample size for the study was determined to be 12 engines, based on time and budget constraints. A previous study with the same engine selection used 4 engines and did not produce enough data to form a conclusion.

During the entire testing lifecycle of the engines, the manufacturer's operators' manual was followed. The scheduled maintenance was followed to within 0.1 hours of the specified maintenance points.

### **Fuel assignment**

Fuels for this research were E0, E10, E15 and E20. Fuels for emissions testing were a combination of Ethanol and Tier 2 EEE certified test fuel, which were splash blended, while the aging fuels were created by using ethanol and non-oxygenated pump fuel.

All engines were broken in for 5hrs using E0. After initial break in, the engines were then performance tested, emissions tested and compression tested on E0. Immediately after initial E0 baseline testing, each engine was assigned a specific blended fuel. The fuel assignments used for the aging process were E0, E10, E15, or E20. Fuel assignment was based on initial E0 emissions testing to determine AFR (air fuel ratio). After AFR was determined, the assigned fuel was issued to a particular engine to replicate worst-case scenario. For example, the leanest engine was issued E20 to increase the enleanment consequence of running on more ethanol. Then engines were then tested immediately after fuel assignment (7hrs), tested at their Midlife (62.5hrs), and tested at End of Life (125hrs), then were returned to E0 to facilitate comparison at End of Life.

Fuel Assignment Schedule				
Engine	Fuel		Engine	Fuel
1	E20		7	E15
2	E15		8	E10
3	E10		9	E0
4	E10		10	E20
5	E0		11	E0
6	E15		12	E20

**Table 1**

Table 1 shows the respective fuel assignments for each engine.

A full test schedule can be found in the appendix.

## Aging

The test engines were aged to their emissions determination period (EDP), in this case 125 hours. The aging cycle was as follows:

- 2 minutes running at high idle/ minimum load
- 2 minutes running at full engine load (2.25hp)
- 6 minutes at approximately half engine load (1hp)

During the aging cycle, the engines were attached to Winco brand generator heads. The heads were then attached to electrical heaters with a timed-switching interface to control the loading of the engine/generator unit. Figure 1 shows the aging layout.

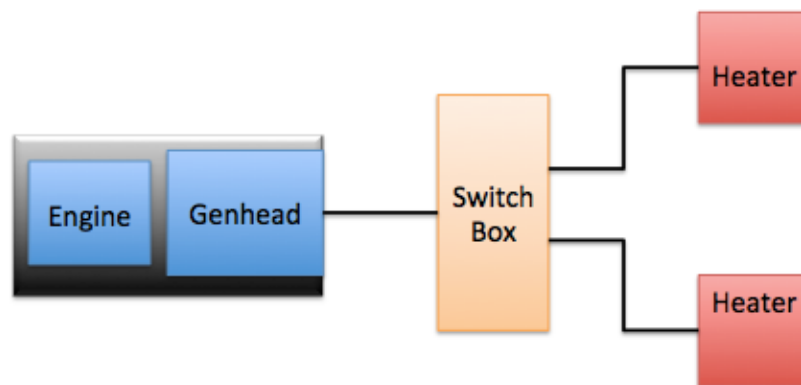


Figure 1

## **Crankcase Oil Analysis**

The engine oil analysis consisted of weighing the oil to determine oil consumption trends. At each oil change interval, a sample was sent in for chemical analysis. The chemical analysis included:

- Wear Metals (Iron, Aluminum, Copper, Lead)
- Contaminant Metals (Silicon, Sodium, Potassium)
- Multi-Source Metals (Titanium, Molybdenum, Manganese, Boron)
- Additive Metals (Magnesium, Calcium, Phosphorus, Zinc)
- Contaminants (fuel, soot, water)
- Fluid Properties (viscosity, acid)

## **Performance**

Performance of the engines was measured during the “Load Pickup” tests where the engine was attached to a Winco generator head, which was electrically attached to an adjustable load bank. The test was a modified version of SAE J1444 (SAE International, 2009). Parameters recorded for comparison were Hz, Volts, and Amps. Time was also recorded to indicate stabilization reactivity. Performance was also determined with the dynamometer during emissions testing by directly measuring horsepower and torque.

## Emissions

The emissions were tested using a CVS diluted sample stream. The engines were connected to a water-cooled, eddy current dynamometer during testing. All calibrations of equipment and testing followed CFR Title 40. (Environmental Protection Agency, 2014)

Mode Speed	1	2	3	4	5	6	7	8	9	10	11
	Rated Speed					Intermediate Speed					Idle
Mode Points—A Cycle						1	2	3	4	5	6
Load Percent—A Cycle						100	75	50	25	10	0
Weighting						9%	20%	29%	30%	7%	5%
Mode Points—B Cycle	1	2	3	4	5						6
Load Percent—B Cycle	100	75	50	25	10						0
Weighting	9%	20%	29%	30%	7%						5%
Mode Points—C Cycle	1										2
Load Percent—C Cycle	100										0
Weighting for Phase 1 Engines	90%										10%
Weighting for Phase 2 Engines	85%										15%

[60 FR 34598, July 3, 1995, as amended at 65 FR 24313, Apr. 25, 2000]

**Table 2 (Environmental Protection Agency, 2014)**

A complete procedure for Emissions testing can be found in the “Emissions Test Procedure” appendix. Table 2 represents the emissions testing procedure used. The testing included the “B” cycle modes and associated weighting factors.

## Post-Testing Inspection

After all testing of engines during their specified lifetime had been completed, the units were disassembled and inspected. This task was done to determine the correlation, if any, of ethanol content of fuel to physical wear characteristics of

engine internals. This inspection process consisted of physical measurements of critical components and also a visual inspection to spot differences in engine deposits on components most likely affected by altering fuel characteristics.



## Discussion of Results

### Aging

All engines successfully completed the specified aging process for the 125 hour EDP. While operating characteristics such as temperatures or engine power were altered, no apparent differences of engine reliability, durability, or longevity were noticed. Slight modifications or repairs were made to some engines in order to complete the entire aging process. Details of all major repair activities during the aging process can be found in the “Aging Notes” portion of the Appendix.

Presentation of findings will be primarily graphical, below is a general guideline for graphical labels throughout this paper.

#### Graphing Schedules:

- Baseline E0: Baseline Testing all engines running E0 (5hrs)
- Initial Blend: Initial Blended fuel testing engines running assigned fuel (7hrs)
- Midlife Blend: Midlife Blended fuel testing, engines running assigned fuel (62.5hrs)
- EOL Blend: End of Life Blended fuel testing, engines running assigned fuel (125hrs)
- EOL E0: End of Life E0 testing, all engines running E0 (127hrs)

## Oil Analysis

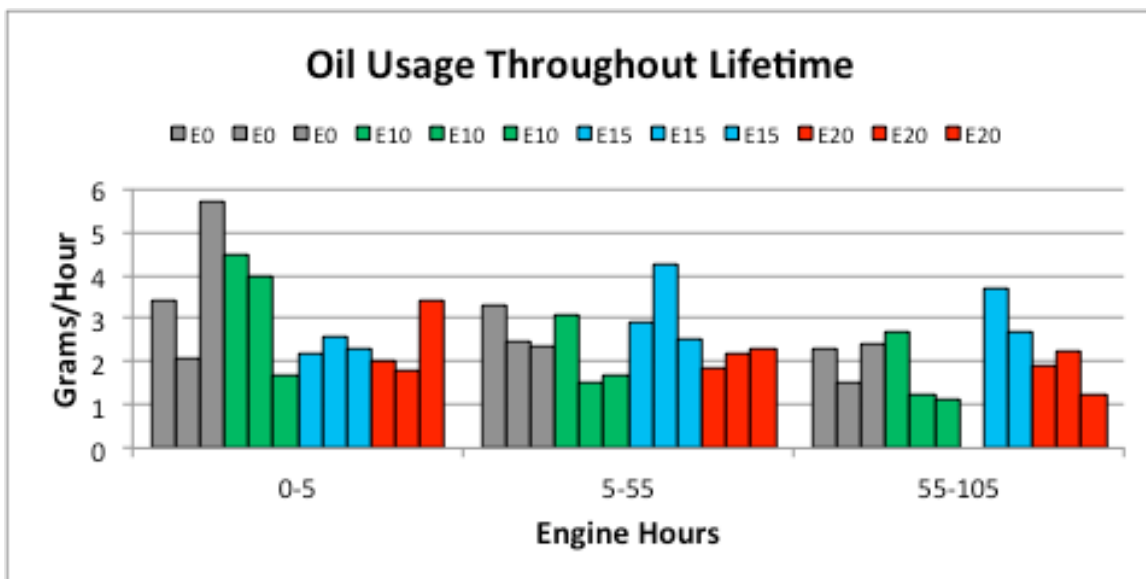


Figure 2

Figure 2 shows each engine's oil usage throughout its lifetime. The units of measure were normalized to oil usage per hour, due to varying oil change interval timelines. Oil usage was higher overall during the break in period, and then continued to drop as time went on. The E15 engines showed slightly higher oil usage than others throughout their lifetime.

No trending data or significant differences were apparent in most oil analysis results. If the specific data showed no trending information, they were omitted

from graphical comparison. The oil samples sent in for analysis showed no substantial trending information regarding the Following:

- Viscosity
- Fuel Contamination
- Soot Contamination
- Additive Metals
- Water Content
- Most Wear Metals
- Multi Source Metals
- Contaminant Metals

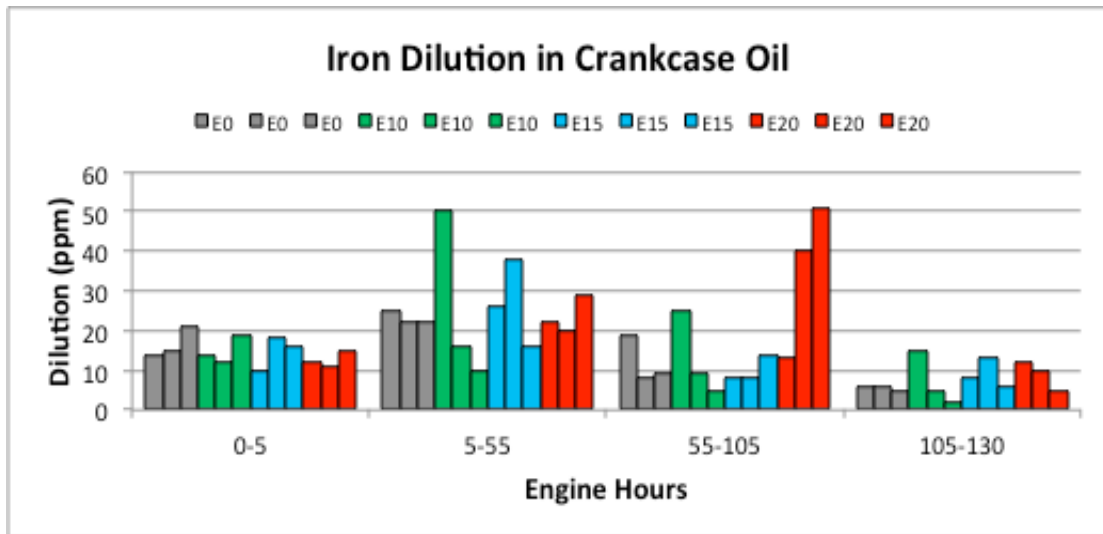


Figure 3

Although most of the oil samples showed no difference in properties between fuel assignments, a few showed contamination differences. Figure 3 shows Iron dilution in crankcase oil in ppm. As the engines aged, the E20 engines exhibited higher amounts of Iron suspended in oil this could be attributed to sources such as crankshaft journals and rings wearing.

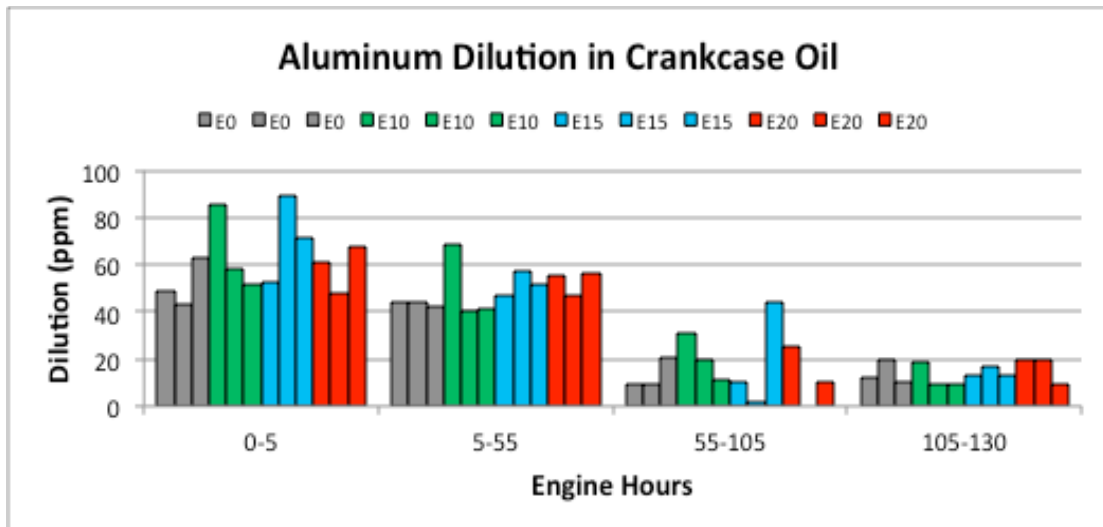
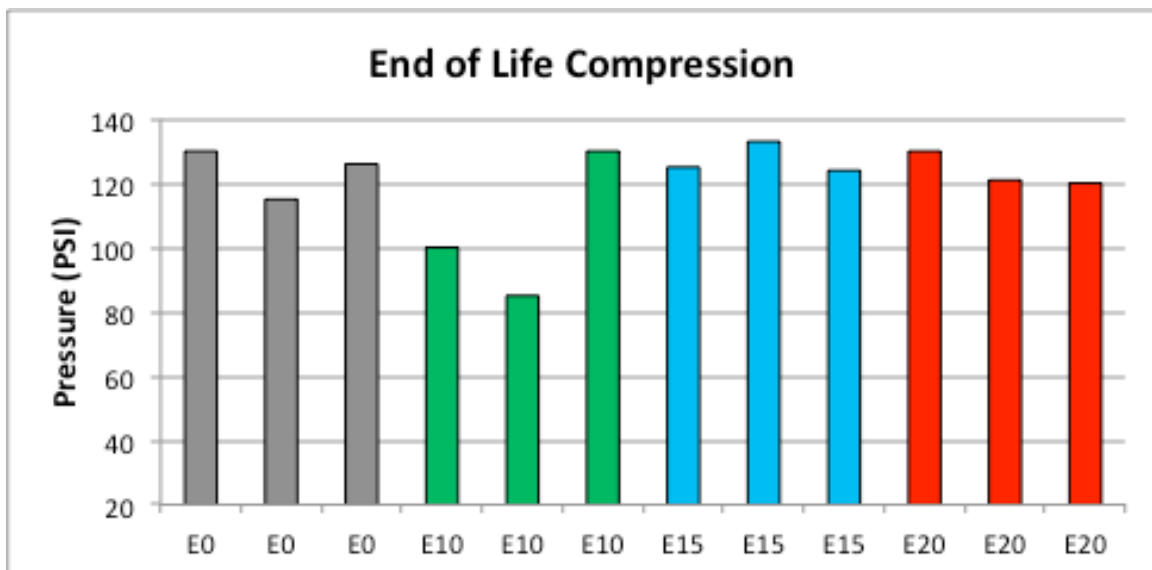


Figure 4

Figure 4 shows Aluminum contamination amount in the crankcase oil. During the break in period the engines exhibited higher aluminum content within the oil. This can be attributed to the break in process of the engine internals such as piston-skirt wear, cylinder wall wear, or bearing wear. The overall contamination continues to drop as the engines age and show no substantial differences based on fuel assignment.

## Performance



**Figure 5**

Figure 5 shows the compression discrepancy at the End of Life test. The overall range of compression results shows little variance (considering the consistency of compression testing in general) although it is apparent that a particular E10 engine (BS-4) exhibited a loss of compression at midlife testing. This compression drop will also be obvious on other results throughout the report. Results of this engine will be included for statistical relevance.

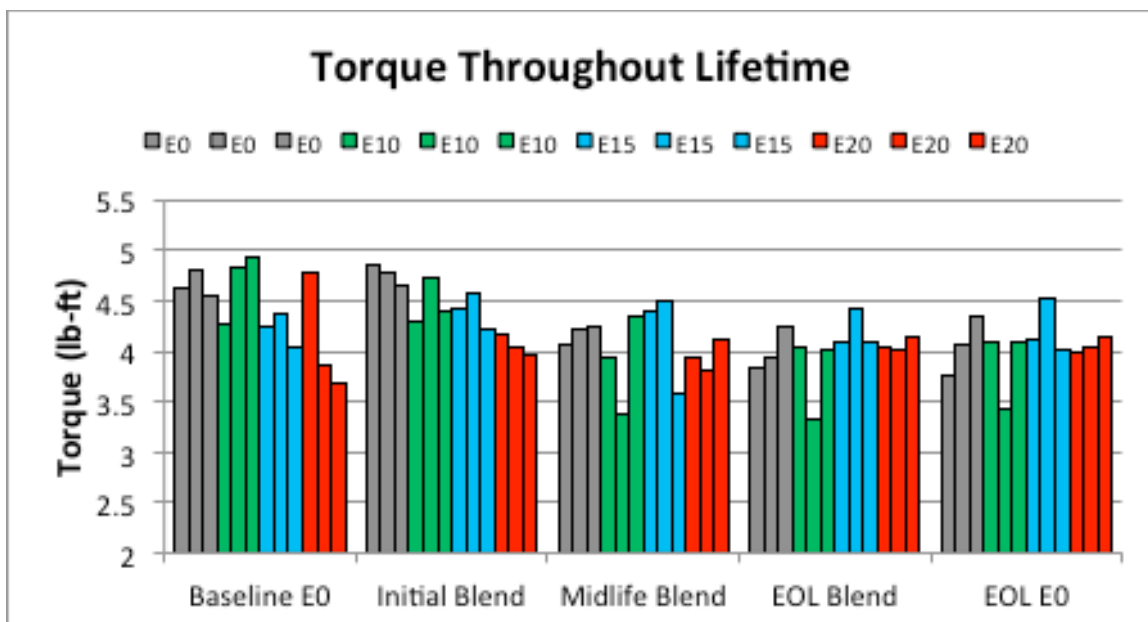


Figure 6

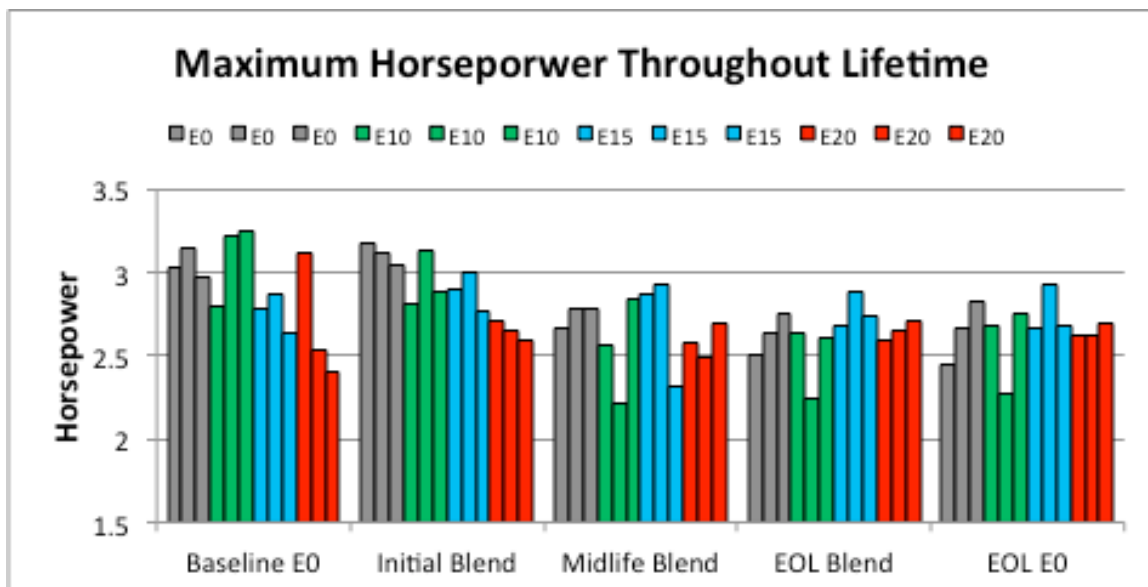


Figure 7

Figures 6 and 7 show the maximum horsepower and torque, respectively, tracked throughout each engine's lifetime. The Horsepower of the E0 and E10 blends seems to drop on average though EOL, while the E15 and E20 show no apparent change in power levels. Horsepower testing was done while coupled to the dynamometer during emissions testing.

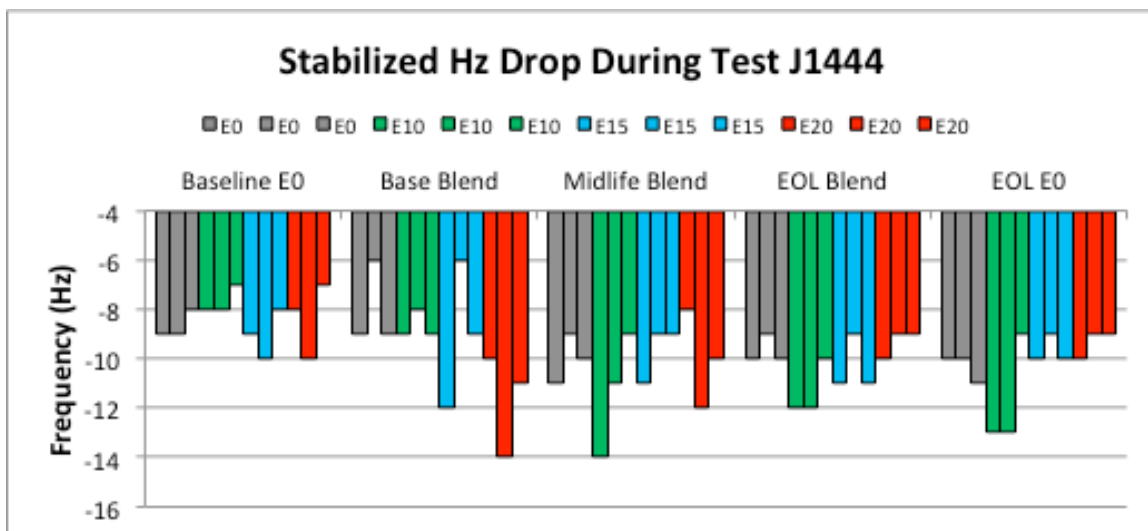


Figure 8

Figure 8 shows the test results from performance testing using SAE J1444.

Results show the stabilized frequency (Hz) drop during the test.



## Temperatures

Temperatures were measured during the emissions testing procedure during “Mode 1” when maximum engine output was being measured. Data was gathered once thermal stability of less than .5 degree F per minute was reached.

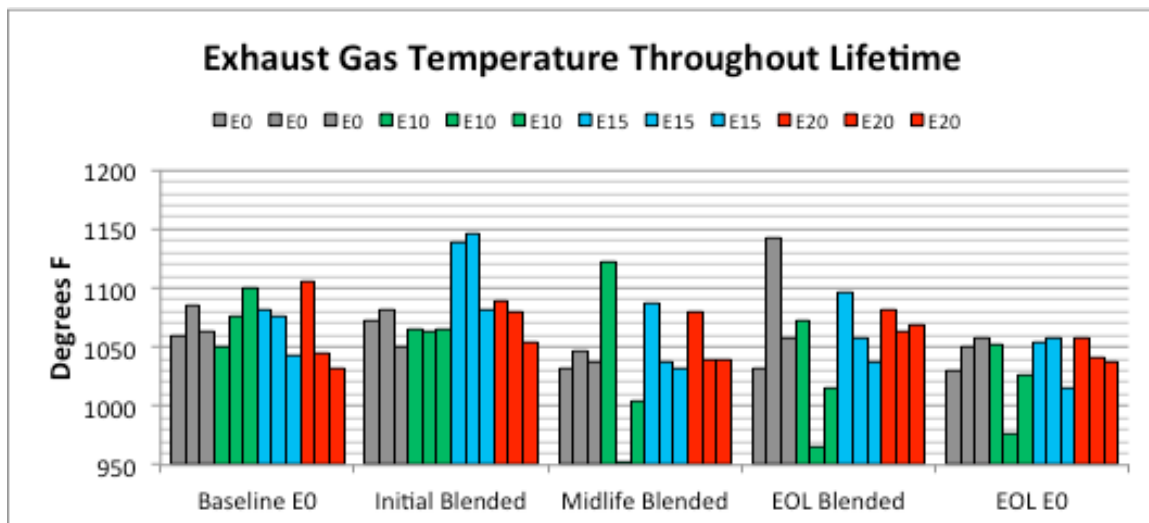


Figure 9

Figure 9 displays the EGT measurements during the engines’ lifetime. Since exhaust gas temperature readings can fluctuate during engine operation, even at the same loading point in this application, the EGT measurements show little trending information. The E0 and E10 blends show a general downward trend throughout their lifetime, while E15 and E20 blends show an increase initially and retain their original exhaust gas temperatures during aging.

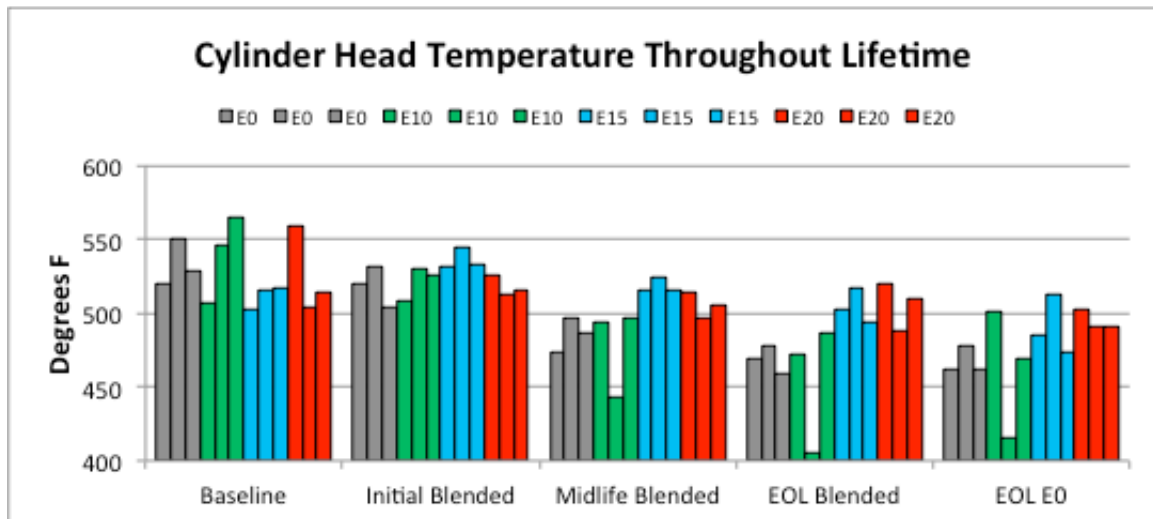


Figure 10

Figure 10 describes the Cylinder Head temperatures as the engines were aged. The measurement was taken at the cylinder head just under the sparkplug. The “Initial Blended” portion of the graph represents the general trend seen during testing. The temperatures generally increased with ethanol content, although the E20 engines exhibited lower temps than the E15 Engines. This condition could be attributed to an “over-enleanment” condition; or running a higher lambda. The loss of compression on engine number 4 is also apparent in Figure 10, as temperatures dropped substantially.

Additionally, the data shows E0 and E10 blends losing temperature as they are aged, while the E15 and E20 blends show a lesser affect by engine hour accumulation.

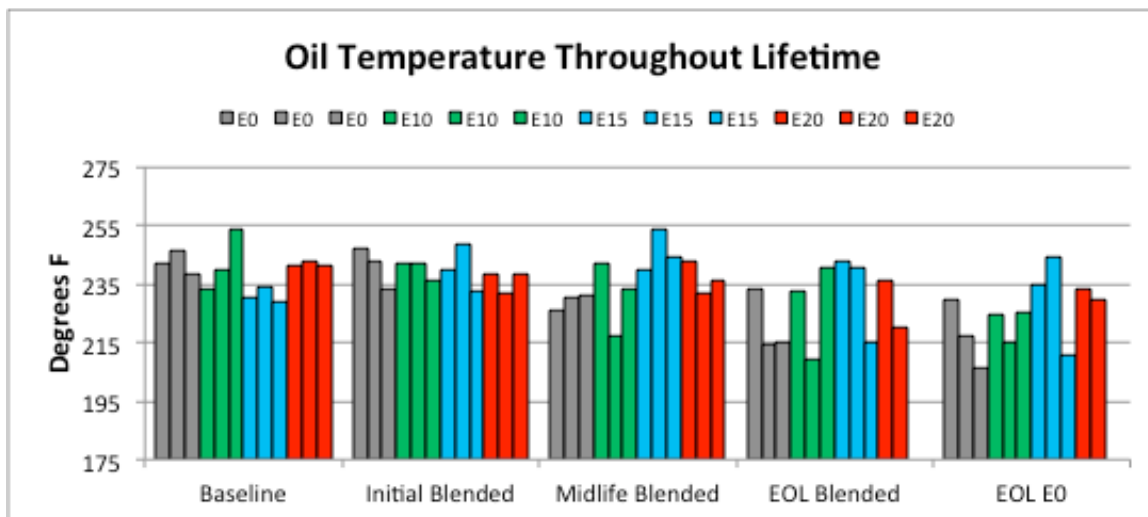


Figure 11

Figure 11 displays the Oil Temperature during the lifetime of the engines. The data contained within this graph shows E0 and E10 blends losing temperature as they are aged, while the E15 and E20 blends show a lesser affect by engine hour accumulation.

## Emissions

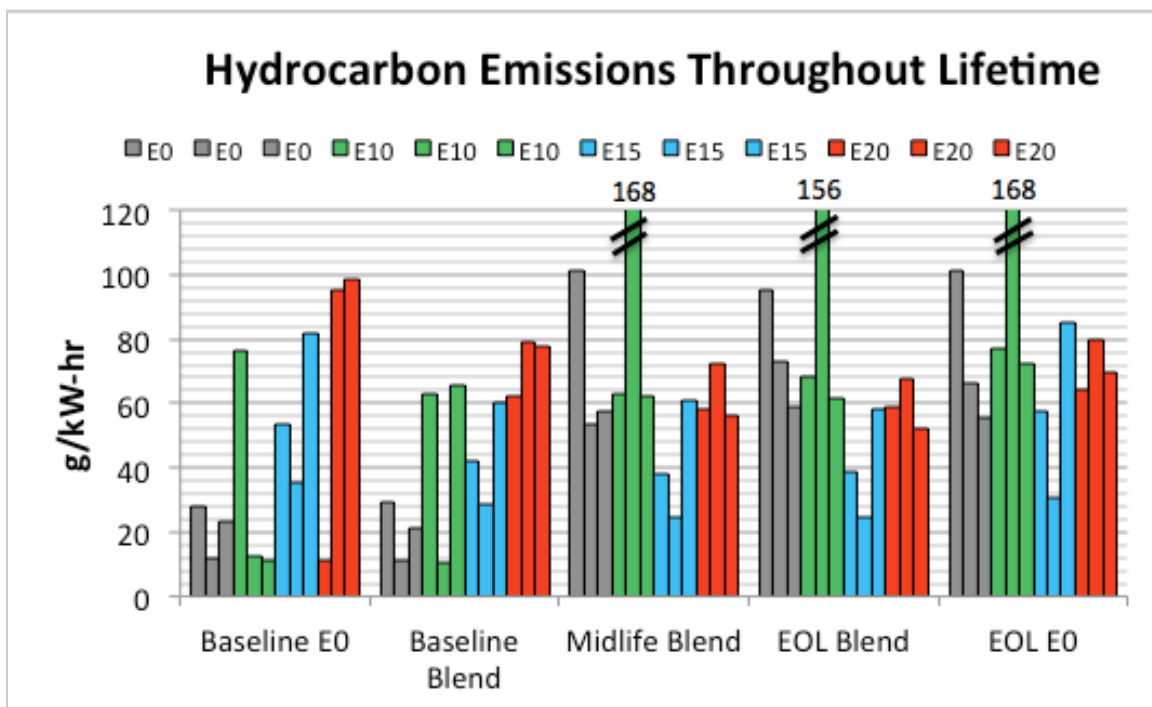


Figure 12

Figure 12 shows the HC emissions during the engines' lifetime. The E0 and E10 engines show a general increase of HC emissions as engine hours are accumulated. In the opposite regard, the E15 and E20 engines display in initial reduction in HC emissions and exhibit that reduction throughout their lifetime. Again, the loss of compression on engine 4 contributes to the massive increase in HC emissions starting at "Midlife Blend" testing.

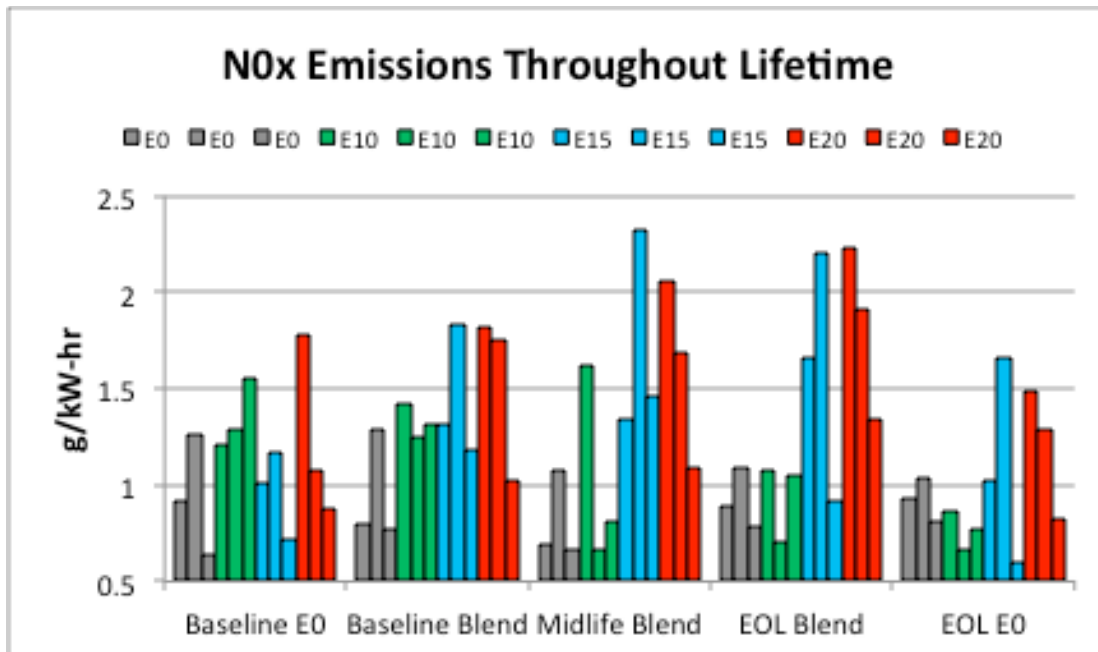


Figure 13

Figure 13 displays the NO<sub>x</sub> emissions during the engines' lifecycle. Over the lifetime of the engines, there is an apparent difference based on fuel assignment and emissions. The E0 and E10 blends slowly reduce their NO<sub>x</sub> emissions, while the E15 and E20 blends exhibit greater NO<sub>x</sub> emissions.

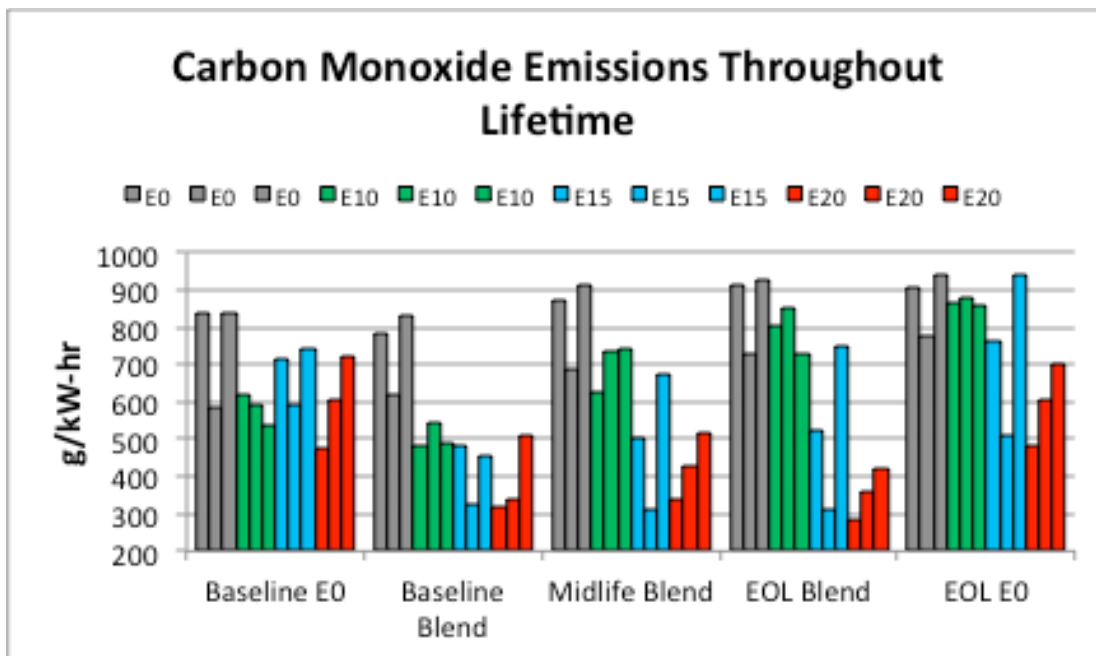


Figure 14

Figure 14 presents the Carbon Monoxide emissions measurements during the lifetime of the engines. The graph shows a correlation of higher ethanol content to a reduction in carbon monoxide emissions that is retained throughout the engines life while running on the specific ethanol blend.

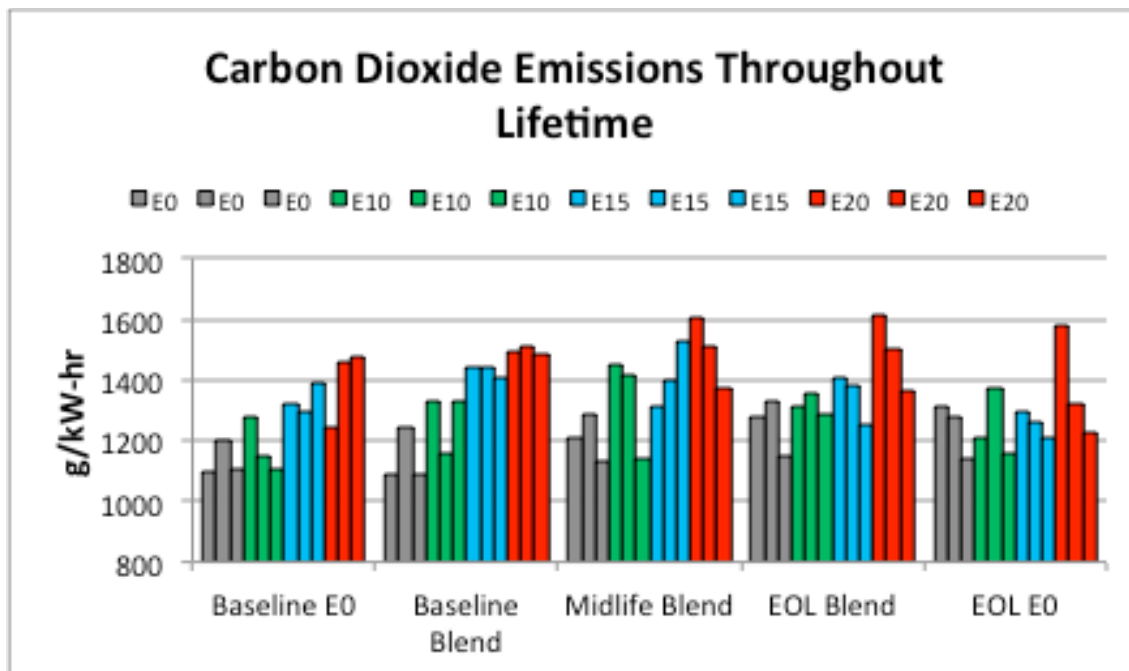


Figure 15

Figure 15 illustrates the Carbon Dioxide emissions through the lifetime of the engines. The data collected shows no substantial trending information.

Average Change in Emissions Over Lifetime				
	HC	Nox	CO	CO2
E0 Change	17%	-4%	-1%	1%
E10 Change	19%	4%	-8%	8%
E15 Change	-26%	57%	-33%	8%
E20 Change	5%	37%	-35%	8%

Table 3

Table 3 shows the overall change in HC, NO<sub>x</sub>, CO, and CO<sub>2</sub> emissions throughout the engines' lifetime. The values displayed represent the overall differences in specific emissions where all of the Baseline E0 Tests were averaged and compared to all of the Fuel Blend Tests. The E15 engines displayed the largest change of HC emissions at an overall reduction of 26%. The E15 engines also showed the greatest difference in NO<sub>x</sub>, exhibiting an average increase of 57%. The E15 and E20 engines both showed a 33% and 35% reduction in CO emissions respectively. Throughout the lifetime of the units, the CO<sub>2</sub> emissions showed no significant change based on ethanol content.

### **Disassembly**

Physical measurements of the dimensions of engine components were carried out after all other testing had been completed. No apparent pattern developed in wear amounts in relation to ethanol content of the engine's assigned fuel.

Physical measurements can be found in the Disassembly Measurements portion of the Appendix.

Visual inspection of the units also occurred during the tear down procedure. The visual inspection revealed no apparent trends in discoloration, deposit type, or amount. Photos of the visual inspection can be found in the "Disassembly Pictures" portion of the Appendix.



## Conclusion

Tests were carried out to illustrate the effects of low-level ethanol blends on 4-Stroke, Small Non-Road Engines. The characteristics affected by an increase in ethanol content included:

- NOx emissions were altered, on average, from baseline EO testing by:
  - E0: -4%
  - E10: 4%
  - E15: 57%
  - E20: 37%
- HC emissions were altered, on average, from baseline EO testing by:
  - E0: 17%
  - E10: 19%
  - E15: -26%
  - E20: 5%
- CO emissions were altered, on average, from baseline EO testing by:
  - E0: -1%
  - E10: -8%
  - E15: -33%
  - E20: -35%
- Cylinder Head temperatures increased as ethanol content climbed to 15%, but fell at the E20 blend, due to over-enleanment.

- Oil temperatures increased as ethanol content climbed to 15%, but fell at the E20 blend, due to over-enleanment.
- Torque of the E15 and E20 units held at baseline values throughout the units' lifetime, while E0 and E10 steadily lost original torque.
- The E20 engines exhibited an increase of Iron dilution in engine crankcase oil.

Many characteristics were unchanged based on ethanol content such as, reliability, longevity, engine wear, engine deposits, and most crankcase oil properties. While these results are documented on this specific platform, other engines may respond to changes in ethanol content in a different manner.

Ethanol clearly had an effect on specific operational parameters of the engines tested for this research. While the effects are limited to specific characteristics, it is clear that in regards to the open-loop fueled engines in study, the engines are not optimized for a broad mix of ethanol. They however, did display a tolerance for low-level ethanol blends when longevity and durability are in question.

## **Future Research**

Since this research only focused on a very specific application, more testing should be carried out on different types of SNRE's to gain a broad perspective on the effects low-level ethanol blends have. Research should also be performed in the arena of particulate matter, since changing the fuel structure may have consequences in that regard.

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## **Appendix**

### **List of Test Equipment**

- Briggs 525 series engines
- Fluke Model 289 multimeter
- Fluke Model 365 multimeter
- National Instruments SCXI-1001
- National Instruments LabVIEW
- Winco ULTB4000C/E
- California Analytical Instruments 600 Series Emissions Bench
- Magtrol 2WB65 Eddy Current Dynamometer
- Omega Model HH-23A Thermocouple Reader
- Simplex Swift-e Load Bank

## Test Plan

### Preparation:

1. Unpack and inspect engine for damage/issues
2. Record engine serial number and label engine appropriately
  - a. (NOTE: fuel is assigned after break-in)
3. Add oil to engine
  - a. Add 18-20 ounces of oil
    - i. Weight Oil and record in "Briggs Oil Spreadsheet"
4. Check/set spark plug gap to 0.030 in
  - a. Torque spark plug to 180 lb-in
5. Install thermocouples to read:
  - a. Cylinder head temperature
  - b. Exhaust gas temperature
  - c. Oil temperature
  - d. Intake air temperature
6. Install hour meter/tachometer
7. Perform Compression Test

### Break-in:

8. Fill up all engines with PE0 (pump E 0 fuel)
  - a. (NOTE: all engines will be broke-in using PE0)
9. Connect each engine with a Winco Generator Head
10. Connect Winco Generators to the switch box
  - a. Plug in the switch board
11. Connect Space heaters to switch Box

12. Set timers to correct positions
  - a. (NOTE: timers should be set so that there is 0% load for 2 minutes, 50% load for 6 minutes and 100% for 2 minutes. This cycle will repeat until break-in is completed)
13. Follow manufacturer's starting/warm up procedure
  - a. Verify idle and WOT rpm and temps
14. Break in for 5 hours following the correct cycle
  - a. Cycle= 0% load for 2 minutes, 50% load for 6 minutes, 100% load for 2 minutes
15. Record Engine RPM, Volts, Amps and temperatures every 30 minutes

Inspection:

16. Perform visual inspection
17. Check spark plug and note condition
18. Perform Compression Test
19. Perform Oil Change at 5 hours and for each engine:
  - a. Collect sample for Oil analysis
  - b. Record oil weight out and oil weight in, in "Briggs Oil Spreadsheet"

Initial Performance Test on PE0:

20. Perform "Briggs Performance Procedure"
21. Perform "Briggs Hot Restart Procedure"

Initial Emissions Test on TE0:

22. Drain PE0
23. Fill with TE0 (Test E 0 fuel)
24. Run engine at wide open throttle for 20 minutes or until thermally stable
  - a. NOTE: Thermal stability is reached when cylinder temperature does not change more than \_\_\_Degrees F for \_\_\_ minutes.
25. Record HP, Torque, RPM, and Temp data during warm-up
26. Perform "Briggs 6 Mode Emissions Procedure"
27. Drain TE0

Order Engines for Ethanol Blends:

28. Assign each engine its specific blend of ethanol
  - a. Determine 3 leanest engines and designate them for E20
  - b. Determine next 3 leanest engines and designate them for E15
  - c. Determine next 3 leanest engines and designate them for E10
  - d. Designate last 3 engines for E0
29. Label engine its assigned blend

Initial Emissions Test on Specific Ethanol Blend:

30. Drain TE0
31. Fill with correct blend of TE fuel
32. Run engine at wide open throttle for 20 minutes or until thermally stable
  - a. NOTE: Thermal stability is reached when cylinder temperature does not change more than \_\_\_Degrees F for \_\_\_ minutes.
33. Record HP, Torque, RPM, and Temp data during warm-up
34. Perform "Briggs 6 Mode Emissions Procedure"
35. Drain TE fuel from engine

Initial Performance Test on Specific Ethanol Blend:

36. Fill up correct engine with correct blend of PE
37. Perform "Briggs Performance Procedure"
38. Perform "Briggs Hot Restart Procedure"

Aging on Specific Blend:

39. Fill with correct blend of PE fuel
40. Couple engine with Winco generator head
41. Connect Winco Generators to the switch box
42. Set timers on switch box so the engines run at 0% load for 2 minutes, 50% load for 6 minutes and 100% load for 2 minutes.
  - a. Repeat the cycle
43. Follow manufacturer's starting/warm up procedure



44. Check and Record engine data every hour

- a. Temperatures at Max Load
  - i. Intake Air
  - ii. Oil Temp
  - iii. Cylinder Head
  - iv. Exhaust Gas
- b. RPM at Max Load/ Mid Load/ No Load
- c. Volts at Max Load/ Mid Load/ No Load
- d. Amps at Max Load/ Mid Load/ No Load

45. Stop engine and check oil every 8 hours

\*NOTE \* If oil is needed make sure to weigh oil before adding any and make note of how much was added

46. Perform Oil Change at 55 hours and for each engine:

- a. Collect sample for Oil analysis
- b. Record oil weight out and oil weight in, in "Briggs Oil Spreadsheet"

47. Age units to 62.5 hours

Midlife Inspection of Units:

48. Visually inspect Engine, exhaust and fuel system

- a. Leaks
- b. discoloration
- c. Broken/missing parts

49. Check oil and make note of condition/usage

50. Perform Compression Test

51. Inspect spark plug and note condition and gap of spark plug

Midlife Blended Performance Test:

52. Same as Initial Performance Test on Specific Ethanol Blend

Midlife Blended Emissions Test:

53. Same as Initial Emissions Test on Specific Ethanol Blend

#### Aging on Specific Blend:

54. Continue aging using process to 125 hours

- a. NOTE: Perform Oil Change at 105 hours and for each engine:
  - i. Collect sample for Oil analysis
  - ii. Record oil weight out and oil weight in, in "Briggs Oil Spreadsheet"

#### End of life Inspection:

55. Visually inspect Engine, exhaust and fuel system

- a. Leaks
- b. Discoloration
- c. Broken/missing parts

56. Check oil and make note of condition/usage

57. Perform Compression Test

58. Inspect spark plug and note condition and gap of spark plug

#### End of life Blended Performance Test:

59. Same as Initial Performance Test on Specific Ethanol Blend

- d. NOTE: Name the file "BS?? End life blended performance Hz

#### End of life Blended Emissions Test:

60. Same as Initial Emissions Test on Specific Ethanol Blend

#### End of life E0 Emissions Test:

61. Same as Initial Emissions Test on TE0

#### End of life E0 Performance Test:

62. Same as Initial Performance Test on PE0

#### Visual Inspection of Engines

63. Visually inspect Engine, exhaust and fuel system

- a. Leaks
- b. Discoloration

c. Broken/missing parts

64. Check oil and make note of condition/usage

a. Collect Sample for Oil analysis

b. Record oil weight out in "Briggs Oil Spreadsheet"

65. Perform Compression Test

66. Inspect spark plug and note condition and gap of spark plug

#### Disassembly

67. Disassemble engine

68. Visually inspect

69. Take measurements

70. Take detailed pictures of each component

71. Fill out proper engine check sheet

72. Items to inspect include:

d. Head conditions

i. Inspect for cracks and/ or deposits

e. Cylinder wear

i. Inspect for cylinder scoring

f. Valves

i. Inspect for improper valve seating, burning, deposits, and stem wear/ galling

g. Pistons

i. Inspect for heat conditions, scoring, and deposits

h. Piston rings

i. Inspect for ring cracking use feeler gauge to measure ring groove, and any ring sticking in the piston grooves

i. Crank and crank bearings

i. Inspect for improper crankshaft run-out and abnormal wear on the bearings

j. Carburetor and internal components

- i. Visually inspect the components for material properties and residue
- k. Overall gasket and seal inspection of all components present on engine

## Aging Procedure

### Prior to Starting

1. Make sure all thermo couples are plugged in
2. Power up Silver NI thermocouple box
  - a. Make sure it is plugged into Temperature computer's USB port
3. Power up temp logging computer. (may have to click F1 if the computer stays black)
  - a. Click on Briggs Aging IV which is located on the desktop
  - b. Click "Launch Labview"
  - c. Click "No" to extend trial period
  - d. Once Program loads, Click on "window" and select "Show Block diagram"



- i.
- e. On block diagram, double click on box labeled "DAQ Assistant"



- i.
- f. Let it load and then click on "OK"
- g. Let it load again, then close out of "Block diagram"
- h. Click "Run"



- i.
4. Set timers on sandwich box so the engines run at 100% load for 2 minutes, 50% load for 6 minutes and 0% load for 2 minutes.
  - a. Repeat the cycle
5. Check Engine Oil before starting engines
  - a. \*NOTE \* If oil is needed make sure to weigh oil before adding any and make note of how much was added
6. Check and add Fuel if needed
7. Locate and Fill out "Briggs Test Conditions"
8. Fill out "Briggs Engine Log" (located on clipboard behind "Briggs Aging Log")

9. Turn on exhaust blower
10. Configure HVAC appropriately

### **Starting**

11. Follow manufacturer's starting/warm up procedure
12. Switch on Sandwich Box
13. Check engine data every hour and Record following data into "Briggs Aging Log"
  - a. Temperatures at Max Load
    - i. Intake Air
    - ii. Oil Temp
    - iii. Cylinder Head
    - iv. Exhaust Gas
  - b. RPM at Max Load/ Mid Load/ No Load
  - c. Volts at Max Load/ Mid Load/ No Load
  - d. Amps at Max Load/ Mid Load/ No Load
14. Stop all engines and refuel when one runs out of fuel
  - a. Start new "Briggs Test Conditions"
  - b. Fill out "Briggs Engine Log"
15. Stop engine and check oil every 8 hours

## Performance Test Procedure

1. This test can be performed after the unit has been aged for 5 hours and the post aging checks have been performed. This procedure is a modified version of SAE J1444.
2. This procedure is used in conjunction with the “Briggs Performance” recording sheet.
3. The unit must be at ambient temperature and cannot have been run for at least 4 hours.
4. Hook up thermocouple reader and verify that the thermocouples are reading correctly.
5. Plug the unit into the load bank.
6. Make sure the amp clamp (around 1 power wire to the load bank) and voltmeter (one outlet on the unit) and frequency pickup (around 1 power wire to the load bank) are connected. Verify that the amps/volts/frequency are reading correctly.
7. Create a file for storing the frequency information. File name should be “BS1 initial performance Hz” for engine BS1 and “BS2 initial performance Hz” for BS2 etc. Start the VI for recording frequency. Start the engine - Cold engine – no load, move choke to closed position, turn ON ignition switch, pull cord, move choke to open once engine is warm enough to run smoothly.
8. Allow the engine to run for 1 minute with no load. Verify frequency/amps/volts.
9. Follow the loading procedure below while recording the amps/Hz/volts. The units will be checked at 4 load points – No Load, Max load 1750 watts, 3/4 load 1250 watts, 1/2 load 750 watts, 1/4 load 500 watts.
10. For each step apply the load for 20 seconds. Use a stopwatch or timer to track times.
11. Record the volts and amps for each load point at approximately 10 seconds into each step.
12. After the last load point, record the temperatures, shutoff the unit and record the stop time.
13. Stop VI and save file.

**Loading sequence – 26 Load points – 20 seconds each**

1. Max load
2. No load
3. Max load
4. No load
5.  $\frac{3}{4}$  load
6. No load
7.  $\frac{3}{4}$  load
8. No load
9.  $\frac{1}{2}$  load
10. No load
11.  $\frac{1}{2}$  load
12. No load
13.  $\frac{1}{4}$  load
14. No load
15.  $\frac{1}{4}$  load
16. No load
17. Max load
18. No load
19.  $\frac{1}{4}$  load
20.  $\frac{1}{2}$  load
21.  $\frac{3}{4}$  load
22. Max load
23.  $\frac{3}{4}$  load
24.  $\frac{1}{2}$  load
25.  $\frac{1}{4}$  load
26. No load



### **Hot Restart Test Procedure**

1. After the unit has completed "Briggs Performance Procedure" this procedure may be performed.
2. Record max load data before turning off the unit.
3. Shut off the unit.
4. Place box over the unit. Immediately record temp data.
5. After 5 minutes record the temperatures and attempt to restart the unit.
6. Record the number of pulls and how the engine runs.
7. Reapply the load bank and note how the engine runs at max load and record data.
8. Shut engine down after collecting data

## Emissions Test Procedure

# [ MnCAR 4 Stroke SNRE Emissions Test ]

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### Description

This procedure defines how to run an emissions test on a Briggs and Stratton 525 series.

### Requirements

Estimated Time For Task:	[3hrs]
Total Time Before Test:	[1 hour warm up equipment and set up]
Equipment:	[ <ul style="list-style-type: none"> <li>[ ] 1. ECCS Computer <ul style="list-style-type: none"> <li>a. Asset #-----</li> </ul> </li> <li>[ ] 2. Emissions console California Analytical Instruments <ul style="list-style-type: none"> <li>a. Asset #-----</li> </ul> </li> <li>[ ] 3. Magtrol 2WB-65 water cooled eddy current dyno</li> <li>[ ] 4. Magtrol DSP-7002</li> <li>[ ] 5. Task requires 2 technicians</li> </ul> ]
References:	[ ] 1. [Version 1.1 of procedure 10-28-13 [ ] 2. Engine/Tailpipe/Bag Dilute for ECCS version 9.639 [ ] 3. 40 CFR 90.401
Required Contacts:	[ <ul style="list-style-type: none"> <li>• Dr. Bruce Jones (AMET Department) <ul style="list-style-type: none"> <li>○ 507-389-6700 (Office)</li> <li>○ bruce.jones@mnsu.edu</li> </ul> </li> </ul> ]

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	<ul style="list-style-type: none"> <li>• Mr. Paul Steevens (AMET Department)</li> <li>○ 507-389-1176 (Office) Wissink Hall 220</li> <li>○ <a href="mailto:paul.steevens@mnsu.edu">paul.steevens@mnsu.edu</a></li> </ul>
Calibrations Needed:	<b>[Zero and Span Emissions Bench Dyno Load cell]</b>

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## Set up

- [ ] 4. Emission console needs to be warmed up 1 hour with FID(HC analyzer) on.
- [ ] 5. Calibrate Eddy Current dyno load cell- See calibration Procedure
- [ ] 6. Set up the engine to be tested on the Magtrol Dyno
- [ ] 7. Make all necessary connections in the dyno controller, and verify function
- [ ] 8. Determine Data Log file path on the Magtrol Computer

## Procedure

- [ ] 1. Computer log in:



- [ ] 4.
- [ ] 5. Fill out MNCAR CORE log sheet
- [ ] 6. Turn on Emissions Console by opening right hand side lower door and switching white circuit breaker CB1 and CD2 up.
- [ ] 7. Switch on each analyzer individually with the switch on the back side by opening the back doors of the analyzer.
- [ ] 8. Turn on bottle number 26 zero air or if using the ZAG upstairs don't turn on 26
- [ ] 9. Record pressures on clip boards for each tank as used
- [ ] 10. Turn on bottle number 23 FID fuel
- [ ] 11. Turn on bottle number 21 zero nitrogen
- [ ] 12. Turn on bottle number 22 for 100% O2 for ozone have extra bottle
- [ ] 13. To light the FID
  - A. When the analyzers startup they are at the Measurement window
  - B. Go to diagnostic by pressing [F3] and see that oven is at 100C
  - C. Push button [MAIN] to get to the Main menu, and then push [F8] to Ignite and watch the gas pressure build up and voltage climb to show gas is flowing. Not to exceed 8 volts, 9 is max
  - D. From the analyzer main menu push [F3] for Diagnostics and see if burner temp climbs to 300-360 degrees C

- [ ] 14. Wait 1 hour
- [ ] 15. --
- [ ] 16. (Can be completed while waiting for bench warm up) Click on the ECCS icon on the desktop
- [ ] 17. Select yes for PID loop control
- [ ] 18. Click "engine test results" shortcut on the desktop: create folder for tests
- [ ] 19. Copy the test folder address so it can be pasted later
- [ ] 20. Click on the "testing" drop down menu to log on: ECCS, ECCS
- [ ] 21. Click on the "testing" drop down menu and select "data logging"
- [ ] 22. Once in the "Bench Data Logging" window, deselect the "Engine" and "Tailpipe" boxes
- [ ] 23. Click the "Parameters" button within the "Bench Data Logging" window
- [ ] 24. Paste the test folder address into the "data file path" location
- [ ] 25. Fill out the "Data File Name Prefix" for the desired name
- [ ] 26. Select the Sample Rate: 1 sample per second
- [ ] 27. Close "Parameters" window
- [ ] 28. ---
- [ ] 29. **ZERO-SPAN**
- [ ] 30. Turn all bottles on, the blue tape-marked on the pressure gauge represents the bag dilute bench bottles, that need to be on
- [ ] 31. Under the main software window click on the "Bag/Dilute Bench" analyzer to be adjusted. (HC, NO<sub>x</sub>, CO(l), CO<sub>2</sub>, CO(h)) in grey bars
- [ ] 32. Once the Specific analyzer window is opened, check on the range to be selected (the highest range first)
- [ ] 33. Click the Operation Button
- [ ] 34. In the "Operation Control" Window select span
- [ ] 35. Wait for the number in the selected analyzer to stabilize, keep an eye on it to make sure that it is in fact stabilized. The number is in the main software window.
- [ ] 36. Once the number is actually stabilized, click the "Set Virtual Span" button In the "Operation Control" Window
- [ ] 37. Make sure that the number is still stabilized ( no longer going down or up)
- [ ] 38. If stabilization does not occur, check the bottle is on, and pilot light is lit
- [ ] 39. In the "Operation Control" window select "standby"
- [ ] 40. In the "Operation Control" window select "zero"
- [ ] 41. Wait for the number in the selected analyzer to stabilize around "0.00", keep an eye on it to make sure that it is in fact stabilized. The number is in the main software window.
- [ ] 42. Once the number is stabilized click "set virtual zero".
- [ ] 43. Close the "Operation Control" Window
- [ ] 44. You have now Zero and Span calibrated ONE range on ONE given analyzer, this process must be repeated for EVERY analyzer on EVERY range. (HC, NO<sub>x</sub>, CO(l), CO<sub>2</sub>, CO(h)) or the ones that you need
- [ ] 45. Repeat steps 32-43 until this task is completed, takes 30 minutes
- [ ] 46. -

[ ] 47.–

### Testing:

- [ ] 48. Select proper critical flow venturi size: for the 4-Stroke SNRE's :194cfm. Do this by changing the valves upstairs.
- [ ] 49. Turn on the Exhaust Blower that pulls the sample, the switch is located on the south wall upstairs
- [ ] 50. In the "Bench Data Logging" window enter in Technician name and file name.
- [ ] 51. Start the engine, warm it until it reaches thermal stability at each Mode. Each test consists of:
- Ambient sample
  - Mode 1 sample
  - Ambient sample
  - Mode 2 sample
  - Ambient sample
  - Mode 3 sample
  - Ambient Sample
  - Mode 4 Sample
  - Ambient Sample
  - Mode 5 Sample
  - Ambient Sample
  - Mode 6 Sample
- This will test will be repeated twice more
- [ ] 52. Click "Begin" to start Data Logging
- [ ] 53. Click "End" to stop Data Logging
- [ ] 54. Sample at each mode for 4 minutes
- [ ] 55. Record Zero and Span

## Dynamometer Calibration Procedure

### [Magtrol Eddy Current Dynamometer Calibration Procedure ]

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#### Description

[This procedure defines how calibrate Magtrol 2WB-65 water cooled eddy current dynamometer.]

#### Requirements

Estimated Time For Task:	[30 minutes]
Equipment:	<ul style="list-style-type: none"> <li>[ ] 6. Magtrol 2WB-65 water cooled eddy current dyno</li> <li>[ ] 7. Magtrol DSP-7002</li> <li>[ ] 8. Magtrol Computer             <ul style="list-style-type: none"> <li>a) Asset # _____</li> </ul> </li> <li>[ ] 9. 4kg &amp; 2kg calibrated weights</li> <li>[ ] 10. Calibration arms</li> <li>[ ] 11. String for hanging weights]</li> </ul>
References:	[ ] 9. [40 CFR 90.401]
Required Contacts:	<ul style="list-style-type: none"> <li>[ Dr. Bruce Jones (AMET Department)             <ul style="list-style-type: none"> <li>o 507-389-6700 (Office)</li> <li>o bruce.jones@mnsu.edu</li> <li>• Mr. Paul Steevens (AMET Department)                 <ul style="list-style-type: none"> <li>o 507-389-1176 (Office) Wissink Hall 220</li> </ul> </li> </ul> </li> </ul>

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Calibrations  
Needed:

**Dynamometer load cell**

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### **[Set up**

- [ ] 1. Retrieve weights, string, and calibration arms from tool box located under hysteresis dynamometer
- [ ] 2. Boot up Magtrol computer

### **Procedure**

- [ ] 56. Computer log in:
- [ ] 57. Username:
- [ ] 58. Password:
- [ ] 59. Plug dyno in.
- [ ] 60. Ensure dyno communication cables are attached to rear of Magtrol DSP7000.
- [ ] 61. Power up DSP7000 dyno controller.
- [ ] 62. Start "M-Test 7" from the desktop.
- [ ] 63. Select "Load Setup" under Startup tab.
- [ ] 64. Select "EDDY CURRENT.MSF."
- [ ] 65. Switch to Configure Hardware tab.
- [ ] 66. Select channel 1, then change "Display Torque" to N-M.
- [ ] 67. Switch to Configure test tab.
- [ ] 68. Change test type from "Manual" to "Calibration Display."
- [ ] 69. Under the Data Logging section click "Data" and find preferred output folder, then select "Current Folder."
- [ ] 70. Select "Save setup."
- [ ] 71. Select "Overwrite" when prompted.

- [ ] 72. Switch to TEST tab.
- [ ] 73. Thread calibration arms completely into threaded holes opposite each other on dynamometer.
- [ ] 74. Torque reading should be within .01 N-M of 0. If more than .01 N-M out, use flat head screwdriver in hole marked "Zero" in blue box under dyno to bring number as close as possible to 0.
- [ ] 75. Hang 2kg weight on portion labeled "N-M" on arm, starting with CW side. (CW when looking at dyno face).
- [ ] 76. Click "Start test" on Magtrol software.
- [ ] 77. Torque should read approximately 10 N-M with 2kg weight attached.
- [ ] 78. If not within .01 N-M of 10, use flat head screwdriver inserted into hole labeled CW in blue box under dyno to dial number in as close as possible.
- [ ] 79. Remove 2kg weight from CW arm and hang 4kg weight from same position on CW arm.
- [ ] 80. Torque should now read within .01 N-M of 20 N-M. If not, adjust CW setting in blue box.
- [ ] 81. Remove string and 4kg weight from CW side.
- [ ] 82. Repeat process with 2kg and 4kg weights on CCW side, adjusting if necessary.
- [ ] 83. When CCW side is calibrated, remove weight, string, and both calibration arms and return to toolbox under hysteresis dynamometer.]



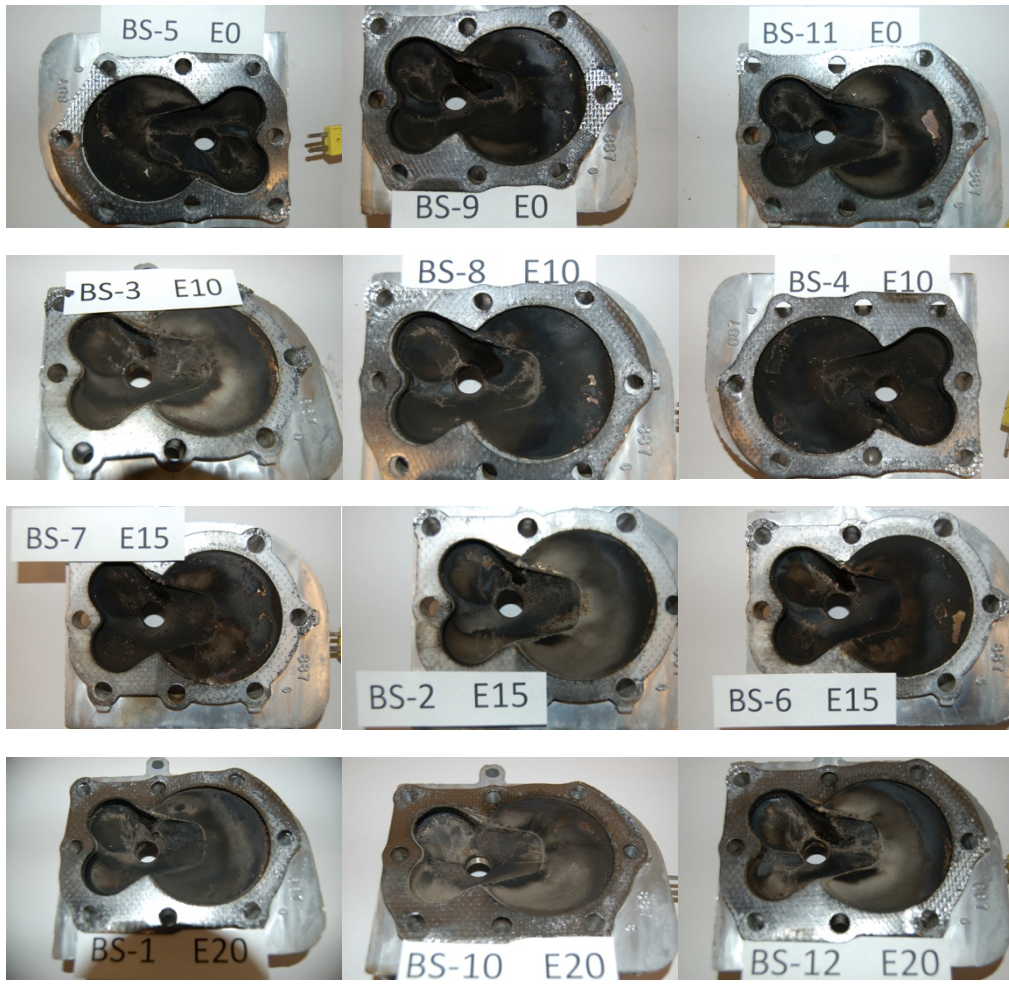
## Aging Notes

- BS-2, running on E15, was showing signs of poor performance during the 30-31.7 hr. mark of aging. The engine would not achieve high idle, nor would it exhibit acceptable performance when loaded( half or full). Up until this point the engine exhibited acceptable and consistent performance. The engine was taken out of aging and the carb was inspected. The carb showed no signs of excessive buildup or sediment. The fuel passageways looked clear. Slight air was forced through some passageways (blowing on them), and the carb was reinstalled. The engine was placed back in aging and showed acceptable performance once again.
- BS-3 sheered the exhaust studs off at 15.3 hrs. The muffler was replaced with part number 394569S and an array of piping.
- BS-11 Leaked oil at 16.4 hrs. from the oil drain tube.
- BS-11 Sheared coupler bolts at 20 hrs, coupled to genhead E, the coupler was also damaged, and the engine stand weld broke. The exhaust studs stripped from the head. The stand was repaired, the coupler was replaced, the muffler was replaced with part number 394569S.
- BS-10 sheared a coupler bolt, and broke a coupler. At hour 29.
- BS-1, at hour 34, backed the screw out of the throttle blade. The screw ended up resting on the intake valve, while the throttle blade was stuck in the intake runner. A new screw was "loctited" in and was peened.
- BS-3 rounded the keyway on the PTO shaft. The keyway on the coupler was subsequently damaged as well. A new keyway was cut on the PTO shaft on the engine as well as the coupler.
- BS-2 lost all of its oil at 90.8 hours due to the oil drain braking while the engine was running. It was shut down before all oil was lost. Weighed-in oil amount = 526g. Engine was started up and seemed to operate normally.
- BS-4, during midlife testing (62.5hrs) seems to be substantially low on power. Also emissions show that it may be low on compression.

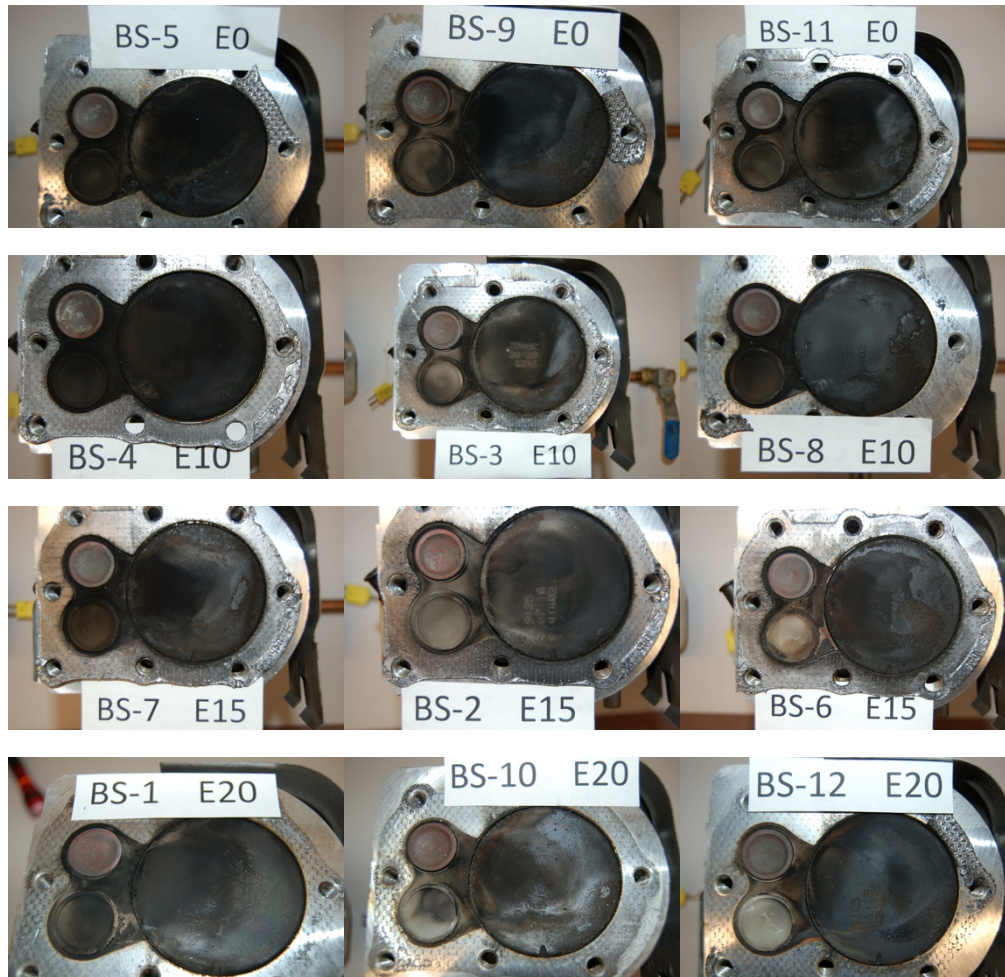
## Disassembly Pictures Carburetors



### Cylinder Head



Piston/Valves





## Disassembly Measurements

Engine Measurement Sheet E-0 Engines				
Part Measured	Specification	BS-5	BS-9	BS-11
<b>Crankshaft</b>				
Armature Air Gap	0.006-0.010"	0.010	0.015	0.010
<b>Valve Tappet Clearance</b>				
Intake	0.005-0.007"	0.015	0.010	0.005
Exhaust	0.007-0.009"	0.015	0.013	0.005
<b>Valve Seats</b>				
Seat Width (Intake)	0.047-0.063"	0.099	0.095	0.095
Seat Width (Exhaust)	0.047-0.063"	0.980	0.095	0.090
Margin (Intake)	1/64" (0.016" min)	0.045	0.047	0.054
Margin (Exhaust)	1/64" (0.016" min)	0.050	0.046	0.047
<b>Valve Guide Diameter</b>				
Intake	N/A	0.252	0.253	0.253
Exhaust	N/A	0.253	0.252	0.254
<b>Valve Stem Diameter</b>				
Intake	N/A	0.246	0.246	0.247
Exhaust	N/A	0.247	0.247	0.247
<b>Bore</b>				
Standard Bore	2.5615-2.5625"	2.562	2.560	2.562
<b>Ring End Gap</b>				
Compression Rings	0.035" (max)	0.007	0.008	0.006
Oil Ring	0.045" (max)	0.020	0.025	0.020
<b>Piston Pin</b>				
Piston Pin Outside Diameter	0.489" (min)	0.490	0.490	0.490
Piston Pin Bore Inside Diameter	0.491" (max)	0.491	0.491	0.491
<b>Crankshaft Journal</b>				
Magneto Journal	0.873" (min)	0.876	0.875	0.875
Crankpin Journal	0.996" (min)	1.000	0.999	1.001
PTO Journal	0.873" (min)	0.874	0.875	0.874
<b>Cylinder Bearing</b>				
Magneto Journal	0.878" (max)	0.876	0.876	0.876
PTO Bearing	0.878" (max)	0.877	0.876	0.876
<b>Connecting Rod</b>				
Crank Pin Bearing	1.001" (max)	1.002	1.000	1.002
Piston Pin Bearing	0.492" (max)	0.491	0.491	0.491
<b>Spark Plug</b>				
Spark Plug Gap	0.030"	0.030	0.030	0.030
<b>Piston</b>				
Piston Skirt	N/A	2.561	2.560	2.558

Engine Measurement Sheet E-10 Engines				
Part Measured	Specification	BS-3	BS-4	BS-8
<b>Crankshaft</b>				
Armature Air Gap	0.006-0.010"	0.013	0.010	0.016
<b>Valve Tappet Clearance</b>				
Intake	0.005-0.007"	0.013	0.010	0.008
Exhaust	0.007-0.009"	0.017	0.013	0.005
<b>Valve Seats</b>				
Seat Width (Intake)	0.047-0.063"	0.063	0.074	0.094
Seat Width (Exhaust)	0.047-0.063"	0.100	0.098	0.094
Margin (Intake)	1/64" (0.016" min)	0.047	0.052	0.044
Margin (Exhaust)	1/64" (0.016" min)	0.047	0.042	0.050
<b>Valve Guide Diameter</b>				
Intake	N/A	0.249	0.251	0.249
Exhaust	N/A	0.254	0.253	0.252
<b>Valve Stem Diameter</b>				
Intake	N/A	0.247	0.248	0.246
Exhaust	N/A	0.246	0.247	0.246
<b>Bore</b>				
Standard Bore	2.5615-2.5625"	2.560	2.561	2.565
<b>Ring End Gap</b>				
Compression Rings	0.035" (max)	0.030	0.007	0.008
Oil Ring	0.045" (max)	0.022	0.018	0.022
<b>Piston Pin</b>				
Piston Pin Outside Diameter	0.489" (min)	0.490	0.490	0.490
Piston Pin Bore Inside Diameter	0.491" (max)	0.412	0.492	0.492
<b>Crankshaft Journal</b>				
Magneto Journal	0.873" (min)	0.875	0.875	0.874
Crankpin Journal	0.996" (min)	0.998	0.999	0.999
PTO Journal	0.873" (min)	0.875	0.875	0.875
<b>Cylinder Bearing</b>				
Magneto Journal	0.878" (max)	0.877	0.873	0.878
PTO Bearing	0.878" (max)	0.876	0.876	0.874
<b>Connecting Rod</b>				
Crank Pin Bearing	1.001" (max)	1.004	1.002	1.002
Piston Pin Bearing	0.492" (max)	0.492	0.494	0.493
<b>Spark Plug</b>				
Spark Plug Gap	0.030"	0.030	0.030	0.030
<b>Piston</b>				
Piston Skirt	N/A	2.559	2.599	2.558

Engine Measurement Sheet E-15 Engines				
Part Measured	Specification	BS-2	BS-6	BS-7
<b>Crankshaft</b>				
Armature Air Gap	0.006-0.010"	0.016	0.010	0.010
<b>Valve Tappet Clearance</b>				
Intake	0.005-0.007"	0.005	0.005	0.005
Exhaust	0.007-0.009"	0.005	0.005	0.005
<b>Valve Seats</b>				
Seat Width (Intake)	0.047-0.063"	0.085	0.092	0.102
Seat Width (Exhaust)	0.047-0.063"	0.094	0.090	0.102
Margin (Intake)	1/64" (0.016" min)	0.056	0.046	0.049
Margin (Exhaust)	1/64" (0.016" min)	0.049	0.045	0.045
<b>Valve Guide Diameter</b>				
Intake	N/A	0.250	0.249	0.250
Exhaust	N/A	0.252	0.250	0.251
<b>Valve Stem Diameter</b>				
Intake	N/A	0.246	0.246	0.246
Exhaust	N/A	0.246	0.246	0.246
<b>Bore</b>				
Standard Bore	2.5615-2.5625"	2.562	2.562	2.561
<b>Ring End Gap</b>				
Compression Rings	0.035" (max)	0.008	0.010	0.008
Oil Ring	0.045" (max)	0.021	0.021	0.023
<b>Piston Pin</b>				
Piston Pin Outside Diameter	0.489" (min)	0.489	0.489	0.490
Piston Pin Bore Inside Diameter	0.491" (max)	0.491	0.492	0.492
<b>Crankshaft Journal</b>				
Magneto Journal	0.873" (min)	0.873	0.874	0.875
Crankpin Journal	0.996" (min)	0.997	0.999	0.998
PTO Journal	0.873" (min)	0.874	0.875	0.875
<b>Cylinder Bearing</b>				
Magneto Journal	0.878" (max)	0.877	0.876	0.876
PTO Bearing	0.878" (max)	0.879	0.877	0.876
<b>Connecting Rod</b>				
Crank Pin Bearing	1.001" (max)	1.001	1.001	1.001
Piston Pin Bearing	0.492" (max)	0.491	0.491	0.491
<b>Spark Plug</b>				
Spark Plug Gap	0.030"	0.030	0.030	0.030
<b>Piston</b>				
Piston Skirt	N/A	2.559	2.559	2.558

Engine Measurement Sheet E-20 Engines				
Part Measured	Specification	BS-1	BS-10	BS-12
<b>Crankshaft</b>				
Armature Air Gap	0.006-0.010"	0.006	0.010	0.012
<b>Valve Tappet Clearance</b>				
Intake	0.005-0.007"	0.005	0.007	0.005
Exhaust	0.007-0.009"	0.005	0.005	0.005
<b>Valve Seats</b>				
Seat Width (Intake)	0.047-0.063"	0.097	0.093	0.100
Seat Width (Exhaust)	0.047-0.063"	0.097	0.133	0.106
Margin (Intake)	1/64" (0.016" min)	0.051	0.049	0.047
Margin (Exhaust)	1/64" (0.016" min)	0.054	0.037	0.054
<b>Valve Guide Diameter</b>				
Intake	N/A	0.252	0.254	0.253
Exhaust	N/A	0.252	0.254	0.253
<b>Valve Stem Diameter</b>				
Intake	N/A	0.247	0.245	0.246
Exhaust	N/A	0.247	0.245	0.246
<b>Bore</b>				
Standard Bore	2.5615-2.5625"	2.562	2.561	2.561
<b>Ring End Gap</b>				
Compression Rings	0.035" (max)	0.005	0.008	0.009
Oil Ring	0.045" (max)	0.020	0.022	0.022
<b>Piston Pin</b>				
Piston Pin Outside Diameter	0.489" (min)	0.489	0.488	0.489
Piston Pin Bore Inside Diameter	0.491" (max)	0.489	0.490	0.492
<b>Crankshaft Journal</b>				
Magneto Journal	0.873" (min)	0.874	0.874	0.874
Crankpin Journal	0.996" (min)	1.000	0.997	0.997
PTO Journal	0.873" (min)	0.874	0.875	0.874
<b>Cylinder Bearing</b>				
Magneto Journal	0.878" (max)	0.875	0.875	0.876
PTO Bearing	0.878" (max)	0.875	0.875	0.876
<b>Connecting Rod</b>				
Crank Pin Bearing	1.001" (max)	1.001	1.001	1.001
Piston Pin Bearing	0.492" (max)	0.490	0.490	0.491
<b>Spark Plug</b>				
Spark Plug Gap	0.030"	0.030	0.030	0.030
<b>Piston</b>				
Piston Skirt	N/A	2.558	2.558	2.559



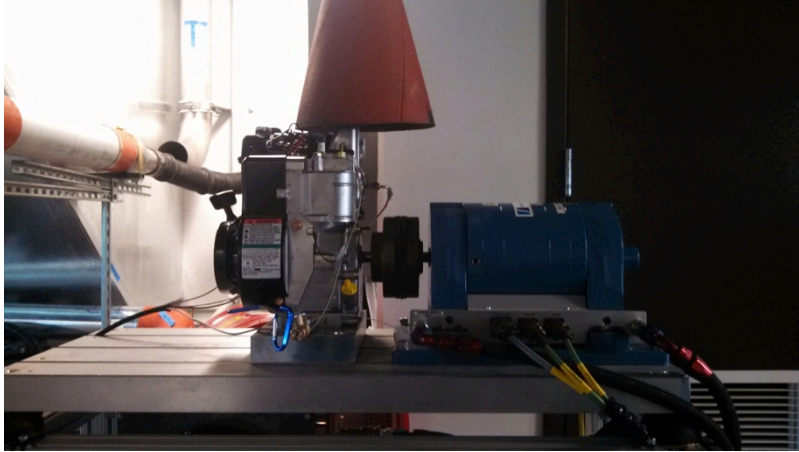
## General Pictures



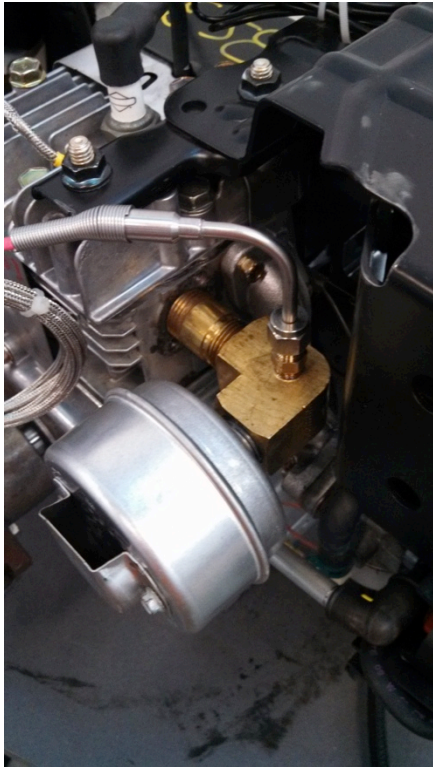
Picture 1 shows the aging apparatus.



Picture 2 shows the engines on the aging apparatus and the load being switched by the circuitry.



Picture 3 shows the engine being tested on the dynamometer.



Picture 4 shows a retrofitted muffler after the original had failed.