HySEE Preliminary Processing and Screening

Making and testing a biodiesel fuel made from ethanol and waste french-fry oil

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HYSEE PRELIMINARY PROCESSING AND SCREENING

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HYSEE PRELIMINARY PROCESSING AND SCREENING

by

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INTRODUCTION

Due to increasing environmental awareness, Biodiesel is gaining recognition in the United States as a renewable fuel which may be used as an alternative to diesel fuel without any modifications to the **engine.** Biodiesel fuels can be produced from ethanol and vegetable oil, both agriculturally derived products. As such, they provide several advantages: they are renewable, they are safer, they are biodegradable, they contain little or **no** sulfur and they reduce engine exhaust smoke. Currently, the cost of this fuel is **a** primary factor that limits **its** use. One way to reduce the cost of Biodiesel is to use a less expensive form of vegetable oil such as waste oil from a potato processing plant.

Idaho produces approximately 120 million cwt of potatoes from over 152,000 ha annually. Nearly 60 percent of these are processed., the vast majority being made into french fried potatoes. These operations use mainly hydrogenated soybean oil, some beef tallow and canola It is estimated that there are several million pounds of waste vegetable oil from these operations each year. Additional waste frying oil is available from smaller processors, off-grade oil seeds and restaurants.

One of these processors, produces over 2 billion pounds of frozen potatoes per year at plants in Oregon, Idaho and North Dakota. This company built two ethanol plants in the late 1980's, which use potato waste as the feedstock. One plant provides an opportunity for a Biodiesel facility using waste vegetable oil and ethanol to produce hydrogenated soy ethyl esters (HySEE). The market value of waste frying oils is about **$0.11** per liter ($0.40 per gallon). Ethanol has a plant value of about $0.28 per liter ($1.05 per gallon). It is projected that this facility could produce Biodiesel at only slightly over $0.25 per liter ($1.00 per gallon) making it economically comparable to diesel fuel.

Biodiesel is being demonstrated as a motor fuel in an ongoing project entitled, "Demonstration of the On-the-Road Use of Biodiesel." This project is a cooperative effort between the University of Idaho and the Idaho Department of Water Resources. Hydrogenated soy ethyl ester (HySEE) has good possibilities for use as a diesel fuel substitute because:

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- Biodiesel made from waste french fry oil may be cost competitive with diesel fuel and other diesel substitutes.

- Ethyl Esters may reduce emissions which may help open markets in urban areas.

- Ethyl Esters are made from ethanol and vegetable oil. They are therefore completely biomass derived products.

- Ethanol is less toxic, making it safer to work with than methanol.

This study examines short term engine tests with HySEE and number 2 diesel fuel (D2). Four engine performance tests were conducted including an engine mapping procedure, an injector coking screening test, an engine power study and a 300 hour endurance test In addition emissions testing of HySEE -was conducted at the Los Angeles County Metropolitan Transit Authorities (MTA) Emissions Testing Facility (ETF).

OBJECTIVES

1. Produce 1000 liters of HySEE using the University of Idaho's Agricultural Engineering transesterification process.

2. Perform fuel characterization tests on the HySEE according to the ASAE proposed Engineering Practice for Testing of Fuels from Biological Materials, X552.

3. Conduct short term injector coking tests as reported in Korus, et al. (1985) using HySEE with three replicate runs on a John Deere 4239T test engine. This test includes torque tests and mapping engine performance.

4. Conduct a 300 hour engine durability screening test using the Agricultural Engineering Department's Yanmar TS70C single cylinder diesel engines.

5. Compare regulated **emissions** data including total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO,), nitrogen oxides (NOx), and particulate matter (PM) for HySEE and diesel control fuel.

MATERIALS AND METHODS

Fuel Production

The potato processing company supplied a sufficient amount of waste hydrogenated soybean oil to produce 1000 liters of HySEE. This was produced at the University of Idaho's Agricultural Engineering Laboratory farm scale processing facility using a recipe developed by the Agricultural Engineering Department personnel. Phillips 66 Company low sulfur diesel reference fuel was used as the baseline fuel for the engine performance testing and emissions testing, and D2 from a local vendor was used for the 300 hour endurance engine testing.

Fuel Characterization

The fuels were characterized by evaluating the parameters required in ASAE EP X552. The tests for specific gravity, viscosity, cloud point, pour point, flash point, heat of combustion, total acid value, catalyst, and fatty acid composition were performed at the Analytical Lab, Department of Agricultural Engineering, University of Idaho. The boiling point, water and sediment, carbon residue, ash, sulfur, cetane number, copper corrosion, Karl Fischer water, particulate matter, iodine number, and the elemental analysis were performed at Phoenix Chemical Labs, Chicago Illinois. The high performance liquid chromatograph (HPLC) **and** titration analysis for total and free glycerol, percent of oil esterified, free fatty acids, and mono-, di-, and trigylicerides were performed by Diversified Labs Inc., Chantilly, Virginia.

Engine Performance Tests

All engine performance tests were conducted in the engine performance lab at the University of Idaho. The equipment used and tests conducted are described below. The short term tests were performed with an in-line four cylinder John Deere 4239T turbocharged, direct injected diesel engine. It has a displacement of 3.9 liters (239 cubic inches), a high RPM of 2650, 61 kW (82 hp) at 2500 RPM, and 290 Nm (214 ft lbf) torque at 1500 RPM. It is attached to a General Electric 119 kW (159 hp) cradled dynamometer. The engine was not modified in any way for use with renewable fuels.

A Hewlett Packard data acquisition unit (model 3497-A) and a personal computer were used to collect data every thirty seconds during each of the tests. Torque, power, opacity, fuel consumption, and temperatures of various engine parameters were monitored throughout the testing and saved into a data file.

Fuel Flow Equipment -- The fuel delivery and return lines were adapted with quick couplers for fast and clean changing of the fuels. Individual 19 liter (5 gallon) metal fuel tanks were modified with a fuel filter and flexible fuel lines which could be connected to the engine quick couplers. Fuel flow rate was determined by direct weighing. The fuel containers were placed on an electric 45.4 kg (100 lb) scale accurate to 23 grams (0.05 lb) with RS232 capability.

Opacity Meter -- A Telonic Berkley model 200 portable opacity meter was connected to the data acquisition unit. The opacity meter consists of a light source positioned on one side of the exhaust stream and a photo resistor mounted on the opposite side. The meter provides an output voltage ranging from 0 to 1 .00 volts. One hundred percent opacity (1 .OO volt) corresponds to no light transmission whereas 0 percent opacity (0.0 volts) corresponds to complete light transmission.

Injector Coking Test -- Carbon build-up within the combustion chamber and piston ring groove area is a potential problem with alternative fuels. The injector coking test uses an easily removable part from the combustion chamber (the injector) and a short engine test to determine the carbon deposition on direct injection diesel nozzles. The injector coking tests were performed using the procedure described in "A Rapid Engine Test to Measure Injector Fouling in Diesel Engines Using Vegetable Oil Fuels" (Korus et al., 1985). The engine was operated for ten minutes at each interval for data collection.

Torque Tests -- In addition to the injector coking test, a torque/horsepower test was triplicated. The torque tests were performed with the engine operating from 2600 RPM to 1300 RPM in 100 RPM increments with the same data collection procedure as previously described. The engine was operated for 2 1/2 minutes at each RPM for data collection.

Mapping Engine Performance -- The engine mapping performance test was also triplicated. The engine mapping tests were performed using the procedure described in "Procedure for Mapping Engine Performance-Spark Ignition and Compression Ignition Engines" (SAE J13 12, 1990). The mapping tests were performed at 2500, 2250, and 2000 RPM with loadings of 100, 75, 50, 25, and 0 percent of maximum power. The engine was operated for 5 minutes at each data collection interval.

300 Hour Engine Endurance Test with HySEE and Diesel

Two Yanmar TS70C single cylinder, 4-cycle, horizontal diesel engines were used for this test. These engines have a bore and stroke of 80 mm and 75 mm respectively, a displacement of 0.376 liter, a continuous rating output of 6 horsepower at 2200 RPM and a compression ratio of 21.2 to 1. The engines have a precombustion chamber combustion system and a condenser type cooling system with a cooling water capacity of 2.0 liters. The engines drive alternators which are connected to a pair of electric load banks. A timing circuit switches the load between the engines every twenty minutes. Each engine ran for 300 hours, one with 100 percent HySEE and the other with 100 percent diesel #2 (D2). The testing began June 7 and ran continuously for 150 hours until June 13, with the exception of oil changes. The first 150 hours of testing was with both engines operating at the same load. The second 150 hours they operated at the same high RPM.

Emissions Testing

The emissions tests were conducted at the Los Angeles County Metropolitan Transit Authorities (MTA) Emissions Testing Facility (ETF) with a 1994 Dodge pickup which has a direct injected, turbocharged and intercooled, 5.9 L Cummins diesel engine. This facility has instrumentation to measure all regulated emissions: total hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM). A comprehensive description of this facility is in Peterson and Reece (1994).

PROCEDURES

Fuel Production

The HySEE fuel production process utilizes 70 percent stoichiometric excess ethanol (absolute, 100 percent pure), or a molar ratio of 5.1: 1 ethanol to oil ratio. The total free fatty acids are determined and neutralized with the calculated addition of catalyst. Based on the amount of input oil by weight, 1.3 percent of KOH is used plus the amount to neutralize the free fatty acids. The following equations were used for the quantities processed:

$EtOH = 0.2738 \times Oil$ $\qquad$ $KOH = Oil/85$

where: Oil = desired amount of oil, in liters

EtOH = amount of ethanol needed, in liters

KOH = amount of potassium hydroxide required, in kg

The waste hydrogenated soybean oil is heated to 49 degrees Celsius (120 degrees Farhrenheit). The catalyst is dissolved into the alcohol by vigorous stirring in a small reactor. The oil is transferred into the Biodiesel reactor and then the catalyst/alcohol mixture is pumped into the oil and the final mixture stirred vigorously for two hours. A successful reaction produces two liquid phases: ester and crude glycerol. Crude glycerol, the heavier liquid will collect at the bottom after several hours of settling. Phase separation can be observed within 10 minutes and can be complete within two hours after stirring has stopped. Complete settling can take as long as 20 hours. After settling is complete, water is added at the rate of 5.5 percent by volume of the oil and then stirred for 5 minutes and the glycerol allowed to settle again. After settling **is** complete the glycerol is drained and the ester layer remains. Washing the ester is a two step process which is carried out with extreme care. A water wash solution at the rate of 28 percent by volume of oil and 1 gram of tannic acid per liter of water is added to the ester and gently agitated. Air is carefully introduced into the aqueous layer while simultaneously stirring very gently. This process is continued until the ester layer becomes clear. After settling, the aqueous solution is drained and water alone is added at 28 percent by volume of oil for the final washing.

Engine warm-up and cool-down

Three different engine test protocols were followed using facilities at the University of Idaho. Each test started with a warm-up and ended with a cool-down period. The warm-up period consisted of a two minute interval on D2 at low idle. Then there was an eight minute interval with the fuel to be tested. During this eight minute period there is a gradual increase in load and RPM to the rated horsepower and load. The cool-down period consisted of 10 minutes on D2 at low idle. For both the warm-up and cool-down periods the return fuel line was placed into a separate container.

Engine Durability Screening Test

The two TS70C Yanmar engines used for the engine durability screening test were rebuilt prior to the beginning of the 300 hour test. New cylinder liners, pistons, rings and rod bearings were installed. The cylinder head was rebuilt and the head was thoroughly cleaned of all carbon deposits. The engine oil was changed and sampled every 50 hours of operation. The oil samples were sent to Cleveland Technical Center in Spokane, Washington for analysis. The engine valves were adjusted at each oil change interval during the first 150 hours of operation.

At the end of the 300 hour test the engines were disassembled and inspected for evaluation of the effect of the fuel on engine components. Coking of the pintle injector, precombustion chamber and piston ring grooves were evaluated by inspection.

Emissions Testing

Two problems had to be overcome in developing a test design. The first was that the number of potential test runs was unpredictable. The test facility was scheduled for one week during which time all testing had to be completed. The second hurdle was a tendency for emissions to vary with ambient conditions. A randomized block design with unequal sample numbers was developed. In this design the main fuels were randomized and tested first and tests of fuel blends were included in later **tests** in each block. As it turned out, sufficient time was available to test each fuel and desired blends. Two runs of HySEE were included in the test design. The cycle used was the double arterial cycle of 758 seconds duration. Five test runs were included on the same cycle using Phillips low sulfur diesel control fuel. A Fisher's Protected LSD analysis using SAS (Statistical Analysis System) was carried out for the analysis of the data.

The emissions test procedure was as follows:

1. The test fuel delivery tube was connected to the input lines and the return line was connected to a waste tank. The engine was started and run for 50 seconds.

2. The engine was stopped and the return line was connected **to the** test fuel tank.

3. The engine was restarted and idled for approximately 10 minutes until the MTA technicians were ready to run the test.

4. The vehicle was operated under load until the operating temperatures stabilized.

5. The test was started and the cycle completed.

6. While the technicians were taking data, weighing particulate filters, etc., the fuel was switched to the next fuel to be tested.

RESULTS

Fuel Production

Waste vegetable oil was obtained from the french fry plant owned by Simplot, Inc., Caldwell, Idaho. The waste oil was placed in drums and is solid at normal room temperatures. The oil is heated in the drums by electric heaters and is then transferred into the biodiesel reactor for transesterification. The ethanol-KOH mixture is added to the heated waste grease. The amount of ethanol and KOH must be adjusted upward to account for vaporization of the ethanol as it is heated and the free fatty acid content of the waste oil. Separation of the ester and glycerol is a constant problem. The final product produced in these tests was found to be 92.26% esterified and contained 0.3% glycerine, 0.99% total glycerine. Monoglycerides were 1.49%, diglycerides 4.23% and triglycerides 0.99%. Alcohol content was only 0.012%. The remaining catalyst measured 32 microg/gm.

Fuel Characterization

A complete summary of the fuel characterization data is listed in Table 1 for the HySEE and the reference diesel fuel used for this study. Some comparisons include:

Viscosity - HySEE had a viscosity 1.9 times that of D2.

Cloud and Pour Point - HySEE had a cloud point 19 degrees Celsius higher than D2 and a pour point 23 degrees higher than D2.

Sulfur - HySEE had 1.56 times less sulfur than the low sulfur diesel fuel used for comparison.

Heat of Combustion - HySEE has 12.3 percent less energy on a mass basis than D2. Since HySEE has a 4.1 percent higher specific weight, the energies average 8.2 percent lower on a volume basis.

HySEE has an apparent molecular weight of 306.95 compared to D2 at 198. As the molecular weight increases so do the cetane number and viscosity.

Injector Coking

A visual inspection of the injector tips would indicate no difference between the HySEE and diesel fuel. However, the numerical scales show that diesel has an injector coking index of one and HySEE has an index of 3.05 (for comparison in these tests, Rape Ethyl Ester had an injector coking index of 3.16) The coking index is an average of three runs, four injectors for the four cylinder engine, and two orientations for a total of 24 samples averaged for each fuel (Table 2). The overall injector coking is low, especially when compared with older tests that included runs with raw vegetable oil.

Figure 1 shows a clean injector, an average coked diesel injector, and an average coked HySEE injector.

Torque Tests

Figure 2 compares power and torque for HySEE and diesel fuel. HySEE has a 4.85 percent decrease in power compared to that of diesel at rated load. Peak torque is less for HySEE than for diesel but occurs at lower engine speeds and generally the torque curves are flatter. At 1700 RPM the torque is reduced 6 percent while at 1300 RPM it is reduced only 3.2 percent.

Percent opacity was 19 for diesel fuel at 1400 RPM and only 5 for HySEE at the same load. At the rated load the diesel fuel produced 2.5 times higher opacity than HySEE.

The following table is the average of the completed tests at 1500 **RPM.**

	HySEE	Diesel
Opacity (%)	4.7	11
Power kW (hp)	44 (59.6)	46 (61.7)
Torque N-m(ft-lb)	283 (209)	292 (215)
Fuel Consumption kg/min(lb/min)	0.20 (0.45)	0.20 (0.44)
Fuel Consumption L/hr (gal/hr)	14.1 (3.72)	14.1 (3.73)
Thermal Efficiency (%)	32.7	30.6

At 1700 RPM the torque output for the diesel was 308 N-m (227 ft-lb) and 289 N-m (213 ft-lb) for the HySEE.

Mapping Engine Performance

Figure 3 presents an engine mapping graph for diesel fuel and HySEE at 2500 RPM. Figure 4 is the fuel map for HySEE at each of the three RPM's. Figure 5 is a graph of the thermal efficiency versus brake mean effective pressure. Brake mean effective pressure (bmep) is the theoretical constant pressure which can be imagined exerted during each power stroke of the engine to produce power equal to the brake power and is useful for comparing performance parameters in engines. For a specific engine as used in these tests BMEP is directly related to power so these two graphs also show the fuel consumption as a function of increasing power.

Engine Durability Screening Test

HySEE Engine -- The initial power was set at 2800 watts with the engine operating at 2 100 RPM under a load condition and 2250 RPM under a no-load condition. During the second night of operation the ambient conditions were such that the HySEE gelled and shut the engine down for approximately two hours. A drum heater was added to the drum of fuel, a new fuel filter was installed and the engine was restarted. On June 30, the circuit breaker tripped and 19.4 hours were not logged on the hour meter. The engine was running at full RPM but was not loaded during this time. Ten hours, about one half of the time the circuit breaker was tripped, was added to the end of the test to compensate for the 19.4 hours for which there was no loading. On July 3 the engine shut down again with the probable cause being cold weather gelling the fuel.

During the first one half of the test, when the engines were set at the same load, the engine high RPM under no-load condition was 2300 and under load was 2200 RPM. The engine produced a load of 2820 watts and consumed fuel at a rate of 1.13 L/hr (0.299 gph).

During the second half of the test, both engines were set at the same high RPM's, the engine high RPM under no-load condition was 2270 and under load was 2140 RPM. The engine produced a load of 2950 watts and consumed fuel at a rate of 1.14 L/hr (0.3 gph). For the entire test a total of 340 L (90 gal) gallons of fuel were consumed and 309 hours were logged. The engine was shut down and restarted twice for oil changes.

After completing the 300 hour endurance testing the engine was disassembled and inspected for wear and compared to the engine operating on 100% diesel fuel.

Diesel Engine -- The initial power was set at 2800 watts with the engine operating at 2200 RPM under a load condition and 2300 RPM under a no-load condition.

During the first half of the test, when the engines were set at the same load, the engine high RPM under no-load condition was 2300 and under load was 2200 RPM. The engine produced a load of 2820 watts and consumed fuel at a rate of 0.84 L/hr (0.223 gph)..

During the second half of the test, both engines were set at the same high RPM's, the engine high RPM under no-load condition was 2270 and under load was 2 160 RPM. The engine produced a load of 2860 watts and consumed fuel at a rate of 0.85 L/hr (0.224 gph). For the entire test 255 L (67.5 gal) of fuel were used and 302 hours were logged. The engine was shut down and restarted twice for oil changes.

The HySEE fueled diesel engine consumed 25% more fuel than that of the diesel fueled engine. The HySEE fueled engine shutdown twice, presumably due to cool weather, and produced a significantly greater amount of visible exhaust smoke.

The engine oil analysis for the diesel engine indicated no abnormal conditions. The engine oil analysis for the engine fueled with HySEE at each interval indicated no abnormal conditions except at the 200 hour interval. The engine oil viscosity was reported as being in the SAE 50 range while the base oil is 15 W-40. Figures 6, 7, and 8 are graphs of the viscosity, iron and silicon versus engine hours from the oil analysis. The higher iron concentration may be due to the higher silicon concentration in the HySEE engine.

Engine Disassembiy

At the completion of the 300 hour endurance test the two engines were disassembled and inspected. The first two piston ring grooves of the diesel fueled engine had slightly more carbon build-up than did the HySEE fueled engine. The second two piston ring grooves were identically clean. The top three piston ring groove surfaces for the diesel fueled engine showed more wear than the HySEE fueled engine and the oil. ring (bottom ring) showed more wear. The piston rings were equally free in both engines. The deposits on the piston head were black to gray on the diesel fueled engine and black for the HySEE fueled engine with each having equal amounts of carbon build-up. The HySEE fueled intake valve had more deposits in the stem area than did the diesel fueled engine, other than that the intake and exhaust valves looked similar. No other differences in the engine components were observed.

Emissions Tests

The summary data for the two 100% Hy SEE arterial tests and five 100% diesel tests are shown in the following table.

Fuel	HC gm/mile	CO gm/mile	NOx gm/mile	CO_2 gm/mile	PM gm/mile
Diesel	0.823	3.33	6.27	654.91	0.3050
Diesel	0.757	3.20	6.21	646.75	0.2364
Diesel	0.751	2.90	6.19	651.32	0.2638
Diesel	0.849	3.20	6.25	649.23	0.3124
Diesel	0.837	3.24	6.25	650.16	0.3213
HySEE	0.360	1.69	5.35	655.90	0.3364
HySEE	0.373	1.73	5.26	652.44	0.3200
Diesel Average	0.803	3.17	6.23	650.47	0.2878
HySEE Average	0.367*	1.71*	5.31*	654.17	0.3282

*Numbers followed by an asterisk are significantly different from diesel ($p<.05$).

On the average HySEE showed a slight reduction in NOx, a significant reduction in HC and CO, and a slight increase in PM and CO,. The PM data even though different was significantly variable that it was not significantly different from diesel.,

CONCLUSIONS

A complete set of fuel characteristics for HySEE and diesel are presented. Performance tests demonstrated that HySEE can be used to successfully fuel a diesel engine. In general, the testing performed has shown that torque and power are reduced about 5 percent compared to D2 and fuel consumption is increased 7 percent.

Specific conclusions of this study are:

1. Fuel characterization data show some similarities and differences between HySEE and D2. a) Specific weight is higher for HySEE, viscosity is 1.9 times that of D2 at 40°C (104°F), and heat of combustion is 12% lower than D2. b) Sulfur content For HySEE is 36% less than D2.

2. The average HySEE injector coking index was 3.07 and D2 was 1 .OO. Visually, all injector coking was low especially compared with older tests that included raw vegetable oils.

3. Opacity was decreased by as much as 71 percent compared to D2.

4. At rated load, engine power produced by HySEE decreased by 4.8 percent compared to D2.

5. Peak torque for HySEE at 1700 RPM was reduced by 6 percent compared to D2 while at 1300 RPM it was reduced only 3.2 percent, demonstrating a flatter torque curve characteristic of Biodiesel.

6. The average fuel consumption (g/s) on a mass basis was 7 percent higher than that of D2. The differences in fuel consumption and power reflect the differences in heat of combustion and density between the two fuels.

7. Thermal effkiencies for HySEE and D2 were not significantly different.

8. Emissions tests showed a 54 percent decrease in HC, 46 percent decrease in CO, 14.7 percent decrease in NOx, 0.57 percent increase in CO_2 and a 14 percent increase in PM when HySEE was compared to D2. The HC, CO and NOx differences were statistically significant.

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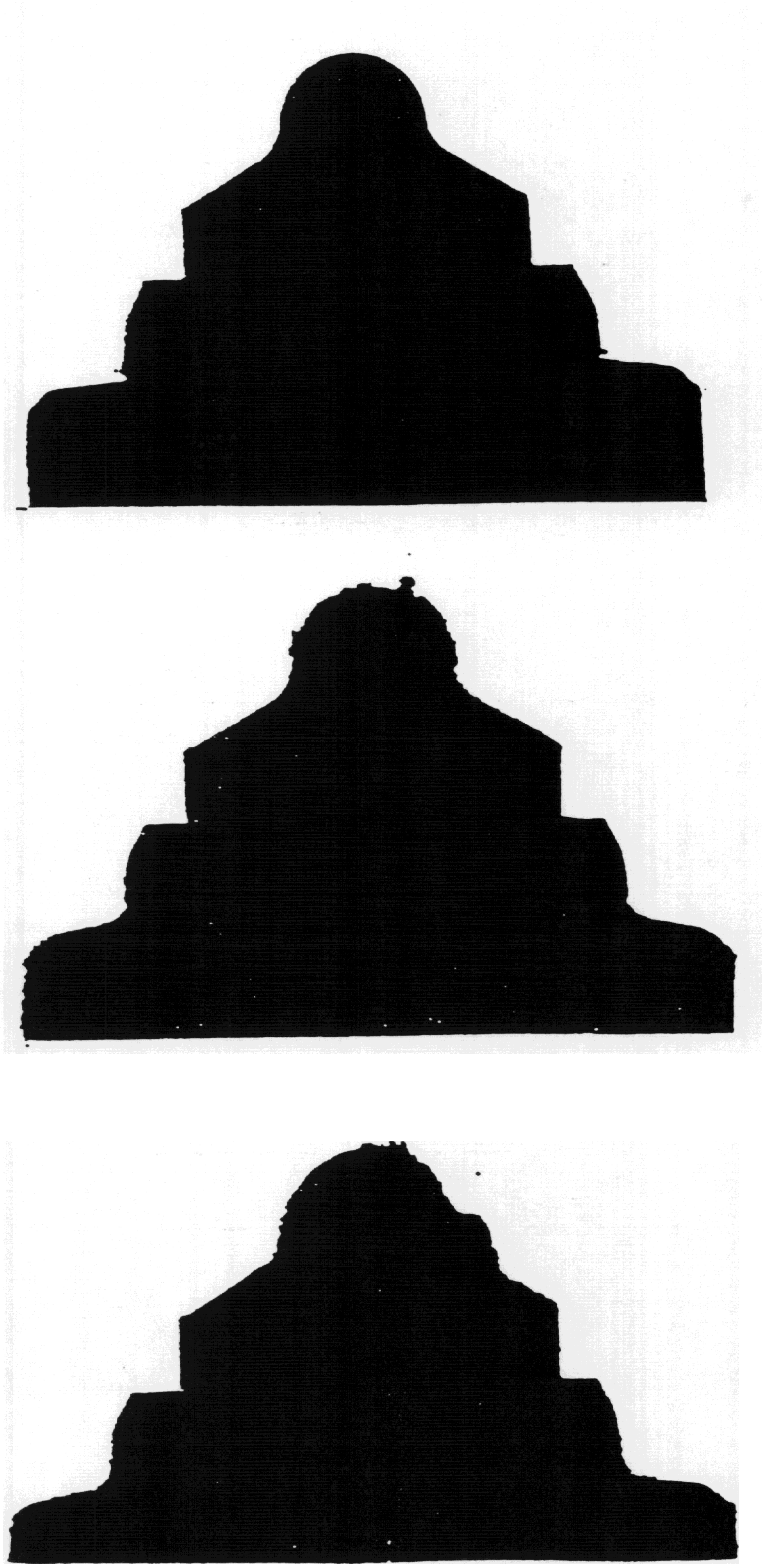
Table 1
Fuel Characterization

	D2	HySEE
Fuel Specific Properties		
Specific Gravity, 60/60	0.8495	0.8716
Viscosity, cs @ 40°C	2.98	5.78
Cloud Point, °C	-12	9
Pour Point, °C	-23	8
Flash Point, PMCC, °C	74	124
Boiling Point, °C	191	273
Water and Sediment, % Vol.	<0.005	co.005
Carbon Residue, % mass	0.16	0.06
Ash, % mass	0.002	0.002
Sulfur, %wt	0.036	0.014
Cetane Number	49.2	61
Heat of Combustion, MJ/kg		
Gross	45.42	40.51
Net	42.9	37.20
Copper Corrosion	1A	1A
Karl Fischer Water, ppm	38	877
Particulate Matter, mg/L		
Total	0.9	6.4
Non-Combustible	<0.1	1.5
Elemental Analysis		
Nitrogen, ppm		12
Carbon, %	86.67	77.72
Hydrogen, %	12.98	12.34
Oxygen, % (by difference)	0.33	9.92
Acid Value	0.128	0.165
Iodine Number	8.6	63.5
Ester Specific Properties		
Percent Esterified		92.26
Free Glycerine, %wt		0.3
Total Glycerine, %wt		0.99
Free Fatty Acids, %wt		0.38
Monoglycerides, %wt		1.49
Diglycerides, %wt		4.23
Triglycerides, %wt		1.42
Alcohol Content, % mass		<1
Catalyst, microgram/gram		32
Fatty Acid Composition, %		
Palmitic (16:0)		10.3
Stearic (18:0)		15.0
Oleic (18:1)		24.6
Linoleic (18:2)		48.6
Eicosenoic (20:1)		0.3

Table 2
Injector Coking Data

	Injector Number	Injector Diameter	Scale Factor	Digitized Injector Area	Digitized Scale Area	Coking Index
HySEE 1	1	15.1	0.000174	95.733	1.66	3.28
	2	15.1	0.000174	97.7624	1.70	4.30
	3	15.1	0.000174	92.4796	1.61	1.63
	4	15.1	0.000174	94.831	1.65	2.82
	5	15.1	0.000174	93.184	1.62	1.99
	6	15.i	0.000174	90.8784	1.58	0.83
	7	15.1	0.000174	93.627	1.63	221
	8	15.1	0.000174	95.6852	1.66	325
HySEE 2	1	15	0.000176	92.029	1.62	2.03
	2	15	0.000176	95.8446	1.69	3.98
	3	15	0.000176	93.0705	1.64	256
	4	15	0.000176	93.4903	1.65	2.78
	5	15	0.000176	95.7044	1.68	3.91
	6	15	0.000176	95.1493	1.67	3.62
	7	15	0.000176	87.9709	1.55	-0.05
	a	15	0.000176	92.9531	1.64	2.50
HySEE 3	1	14.2	0.000196	85.8244	1.69	3.94
	2	14.2	0.000196	87.7791	1.72	5.06
	3	14	0.000202	85.86	1.73	5.37
	4	14	0.000202	83.9996	1.70	4.28
	5	14.1	0.000199	84.7793	1.69	4.03
	6	14.1	0.000199	85.9545	1.71	4.71
	7	14.1	0.000199	80.0059	1.59	1.27
	8	14.1	0.000199	82.7917	1.65	2.88
	Average of all HySEE injectors				1.65	3.05
D2 1	1	14	0.000202	79.1211	1.60	1.41
	2	14	0.000202	78.4036	1.58	0.99
	3	14	0.000202	80.038	1.62	1.95
	4	14	0.000202	80.2352	1.62	2.07
	5	14	0.000202	78.2346	1.58	0.89
	6	14	0.000202	78.3805	1.58	0.98
	7	14	0.000202	77.18	1.56	0.27
	8	14	0.000202	78.154	1.58	0.84
022	1	15	0.000176	90.4685	1.59	1.23
	2	15	0.000176	90.4177	1.59	1.20
	3	15	0.000176	89.3528	1.57	0.66
	4	15	0.000176	85.9857	1.51	-1.06
	5	15	0.000176	89.8264	1.58	0.90
	6	15	0.000176	90.6138	1.59	1.30
	7	15	0.000176	90.6756	1.60	1.34
	8	15	0.000176	90.674	1.60	1.33
	1	14.9	0.000178	89.634	1.60	1.42
	2	14.9	0.000178	88.9961	1.59	1.09
	3	14.9	0.000178	88.6578	1.58	0.91
	4	14.9	0.000178	87.8673	1.57	0.50
	5	14.9	0.000178	88.6331	1.58	0.90
	6	14.9	0.000178	87.985	1.57	0.56
	7	14.9	0.000178	89.5155	1.60	1.36
	a	14.9	0.000178	88.7054	1.58	0.94,
	Average of all D2 injectors				1.58	1.00

Figure 1. Typical injector coking photographs, clean (top), diesel (middle), HySEE (bottom).



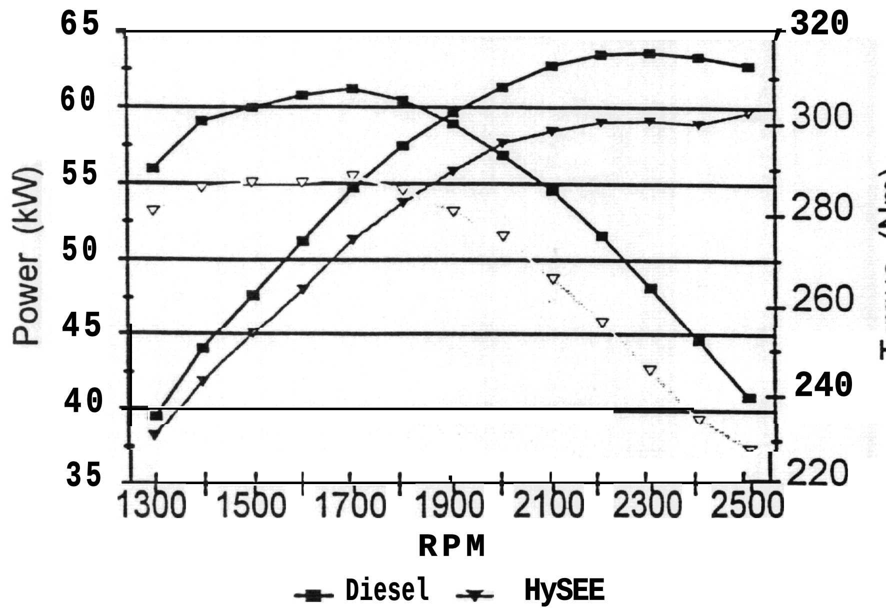


Figure 2. Power and Torque versus RPM

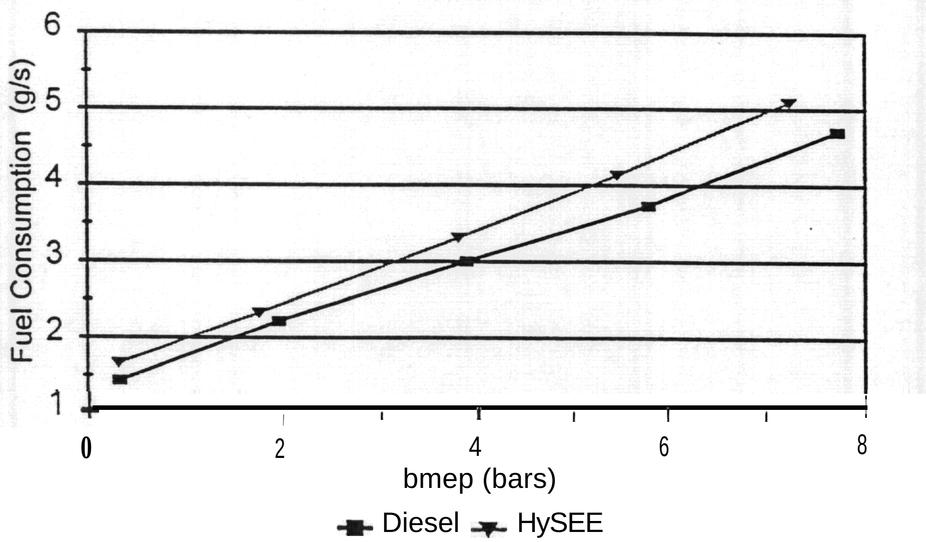


Figure 3. Fuel Consumption versus bmep at 2500 RPM

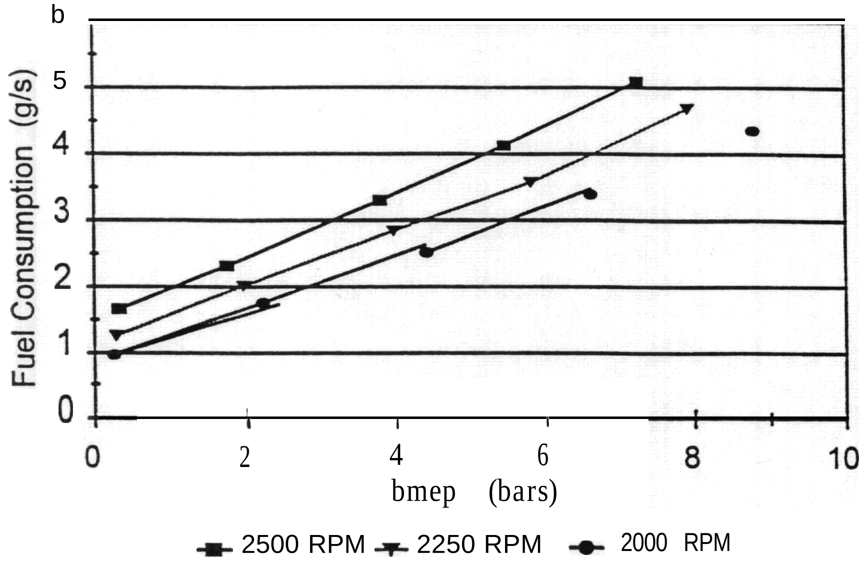


Figure 4. Fuel Consumption versus bmep for HySee at 3 RPM's from Engine Mapping Test

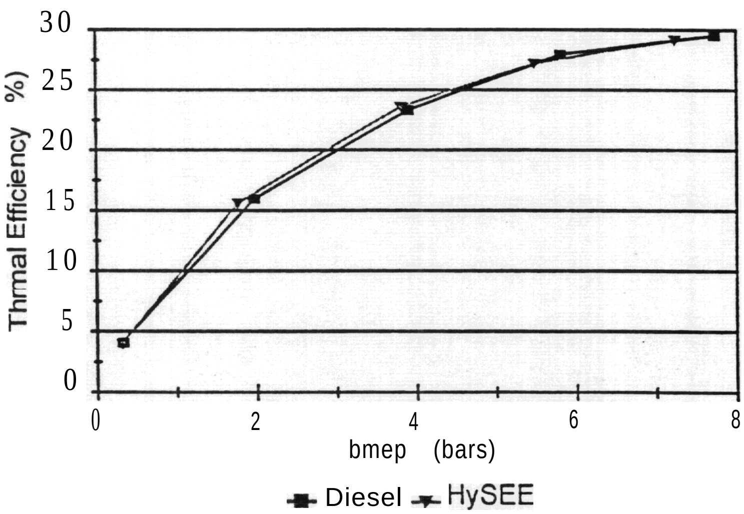


Figure 5. Thermal Efficiency versus bmep
Data is from the fuel mapping test at 2500 RPM

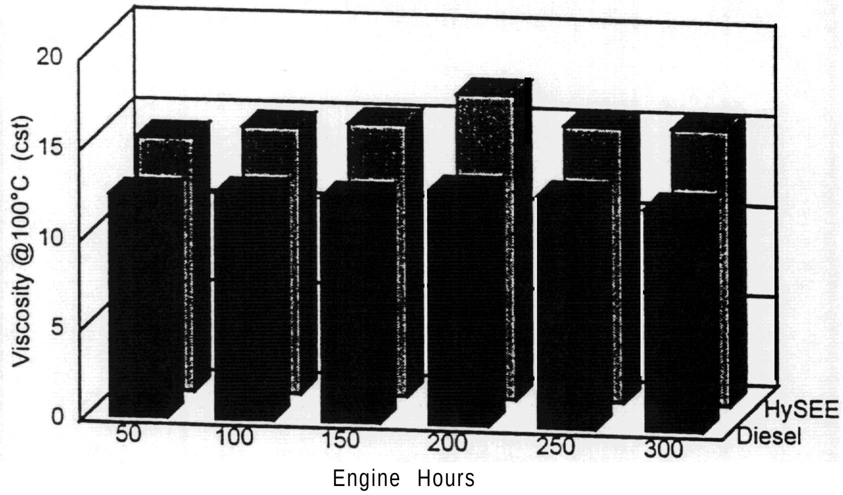


Figure 6. Engine oil viscosity at 50 hour oil change intervals

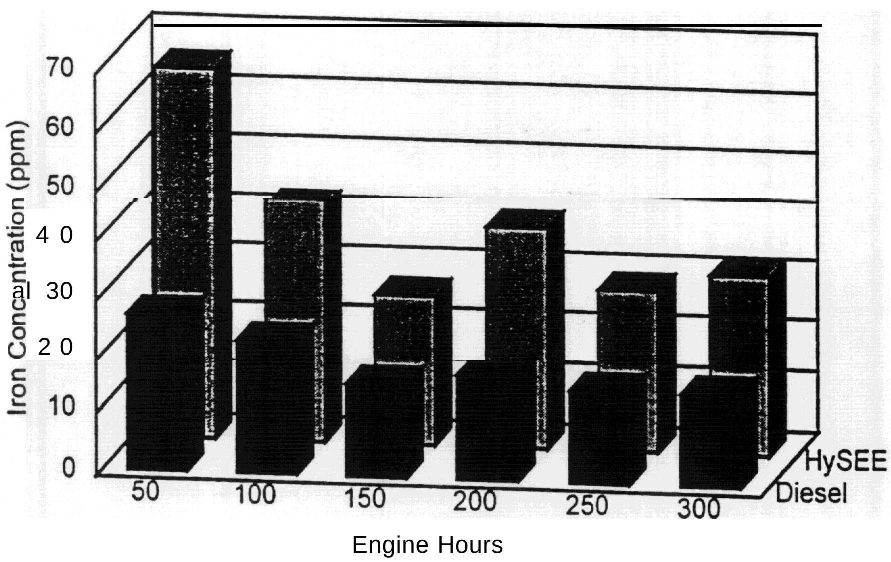


Figure 7. Concentration of iron in engine oil analysis

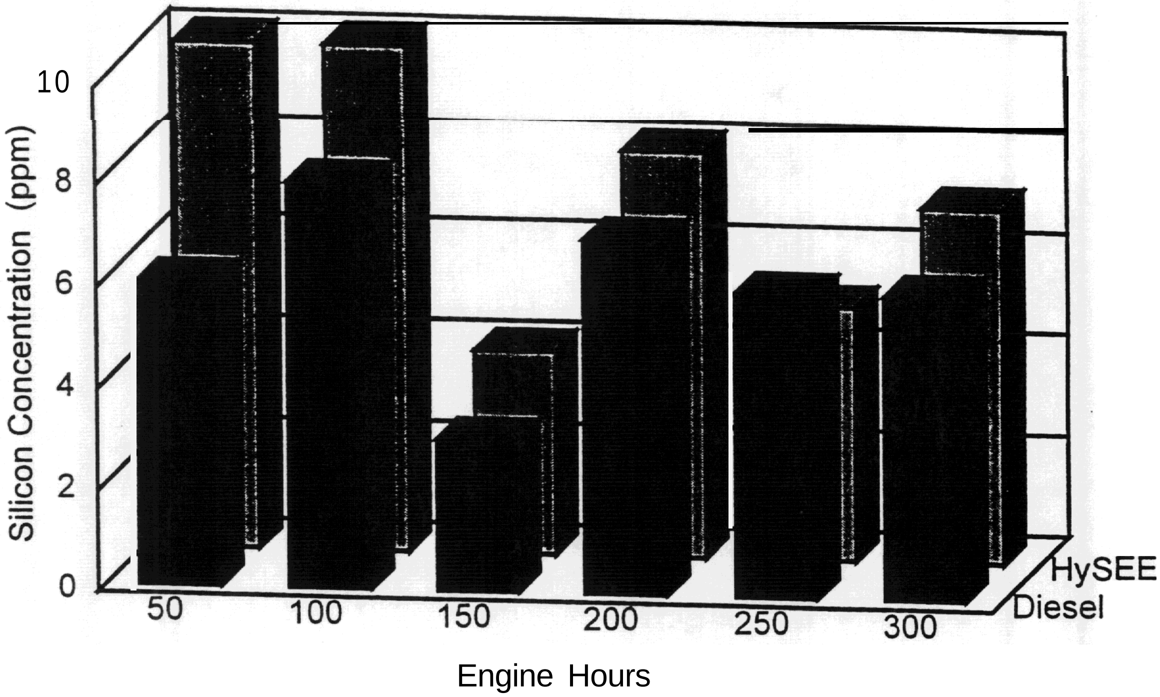


Figure 8. Concentration of silicon in engine oil analysis