SOYBEAN ETHYL ESTERS- A RENEWABLE

FUEL FOR DIESEL ENGINES

by

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INTRODUCTION

The search for alternative resources of energy has, for the past ten years or so, recieved widespread attention. Following the Arab oil embargo of 1973, questions were raised as to the future availability and cost of petroleum and the effect it might have on industry and agriculture. Fuel conservation is only a temporary measure to alleviate shortages and therefore, research was immediately established to find substitutes for petroleum fuel.

Most farm equipment is diesel powered and the possibility of using vegetable oils as fuels in compression-ignition engines has been known for a long time. Short term research was done in the 1930's and 1940's but due to the availability of cheap petroleum, little has been done since then. Recently however, renewed interest in vegetable oil prompted the testing of sunflower oil as an extender for diesel fuel in South Africa and Australia. In Canada, canola oil was tested and in Brazil, scientists were conducting research with a variety of vegetable oils. Promising results were obtained but due to practical problems, the widespread use of these oils could still not be recommended.

The purpose of this study was to establish the potential feasibility of soybean oil, in particular, the ethyl ester of soybean oil, as a renewable fuel in diesel engines. Soybean oil was chosen because of the following advantages:

1. It is a renewable resource.

2. Soybean production is an established practice so no new technology

is involved.

3. Through symbiotic nitrogen fixation, fertilizer input is lowered.

4. The oil extraction process yields a high protein meal as a by-product.

5. The fuel energy balance in the production process is positive. One hectare of soybeans yields about 400 liters of oil, while it would require about 56 liters to produce it.

6. Soybean oil esters have fuel properties similar to diesel fuel.

LITERATURE REVIEW

Soybean Production in the US

Soybeans is by far the most important oilseed crop grown in the US. About 28.3 million hectares are grown compared to only 1.6 million hectares of sunflowers. The average yield is taken to be 2.15 metric tons per hectare but experimental plots have shown that higher yields are possible. The US soybean crop provides 12.3 million tons of protein and fat, more than any other single source. Nearly 50% of the crop is exported and soybeans have often been termed "Miracle Crop" or "Gold from the Soil".

The total annual oil production is 6.4 billion liters and the most widely used method of oil extraction is the counter-current solvent plant. Hexane, a petroleum based product, is generally used as a solvent. This method yields an extraction rate of 18-20%, or almost all the oil present in the soybean kernel. Screw press extraction yields only 12-13% oil.

On-farm Oil Extraction

The concept of extracting soybean oil on the farm has been investigated by several researchers. Theoretically, a farmer would need to set aside about 15-20% of his cropland for fuel production to provide him with enough fuel for the next season's crop. This would provide him with insurances against diesel scarcities and give him an extra degree of self sufficiency.

Billet (1981) reports on the development of an on farm expeller type oil press for sunflower seed oil production in South Africa. This press is capable of delivering 50 liters of oil per hour and is a self contained unit mounted on wheels. Seed enters a ripple mill where it is dehulled after which it passes over a sieve to remove the husks by air-flow. The kernels are then fed into the expeller which squeezes out the oil. A settling tank is provided to allow the solids in the oil to settle out.

Tests with a screw press expeller for sunflower oil were also conducted by Smith, Lovely and Buchele(1982). Electric heating coils were used to heat air which was then blown through the seed flow, just prior to entering the expeller. An extraction effiency of 32.4% was obtained at 65 $^{\circ}$C with a meal thickness of 0.75mm. The operation of the plant was simple and once the expeller was set, no further adjustments were needed for a whole day of operation.

Ramsey and Harris(1982) performed tests with a low capacity expeller for soybean oil extraction. An electric grain roaster was used to heat the beans prior to extraction. The highest oil output (0.07 l/kg) occurred at a bean temperature of 77 $^{\circ}$C. This translates into an extraction efficiency of 6.51% or only about one third of the oil present in the beans. The system functioned smoothly with minimal supervision and daily maintenance and lended itself well to automation. The energy ratio for the process, which is defined as the amount of energy present in a unit of oil divided by the energy required to express the same amount of oil, was found to be about 10 at maximum extraction efficiency. The high residual oil in the meal could not be

lowered by recycling it through the expeller. Not only is the oil yield lowered when only an expeller is used, but the meal does not make an ideal protein source for livestock. This is an important consideration when the economics of this process is analyzed. It would seem feasible then, to augment the mechanical extraction process with solvent extraction. Beckel et.al. (1948), reported on the use of ethyl alcohol as a solvent and found it to have certain advantages:

1. Ethanol can be removed from the oil at a lower temperature than higher alcohols.

2. Ethanol gave better results with respect to the color of the oil and meal protein.

3. Ethanol served as a debittering agent for the meal, making it more palatable to livestock.

4. The fire and explosion hazard is less than with hexane.

5. Equipment changes are not necessary.

The most significant fact however, from the farmer's point of view, lies in the fact that ethanol is a biomass derived product and can be produced on farm as well. The purity of the ethanol for oil extraction is not critical and Rao and Arnold (1958) found no significant difference in the extraction efficiencies of 200 proof and 190 proof ethanol. Future research might include the design of a simple, low capacity solvent extractor, suitable for on farm use.

Properties of Soybean Oil

Soybean oil is a member of the triglyceride group of oils typically found in the seeds of peanut, sunflower, castor, cotton, soy and other common plants. Morrison and Boyd (1973) describe the fatty acid composition of soybean oil, as given in Table 1.

Table 1. Fatty Acid Composition of Soybean Oil

Percentage	Fatty Acid
linoleic	50-60
oleic	22-34
palmitic	7-11
linolenic	2-10
stearic	2-5

These fatty acids occur in long chains of mainly carbon and hydrogen atoms attached to the basic triglyceride molecule. The molecular structure of soybean oil may typically look like this:

$$CH_3-(CH_2)_4=CH-CH_2-CH=CH-(CH_2)_7-\overset{\overset{\displaystyle O}{\|}}{C}-O-CH_2$$

$$CH_3-(CH_2)_4=CH-CH_2-CH=CH-(CH_2)_7-\overset{\overset{\displaystyle O}{\|}}{C}-O-CH$$

$$CH-(CH_2)_7-CH=CH-(CH_2)_7-\overset{\overset{\displaystyle O}{\|}}{C}-O-CH_2$$
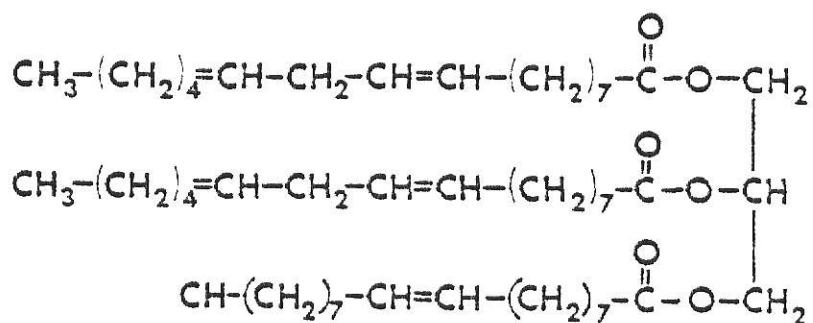
Unlike the structures of the compounds of petroleum oil, soybean oil is not a pure hydrocarbon but rather a partially oxygenated hydrocarbon. The molecular weight of the above molecule is 880.

The presence of double bonds in the fatty acids causes a high degree of unsaturation and reaction with oxygen occurs readily to form a gummy substance. For this reason soybean oil is classed as semidrying with an iodine number between 130 and 135. The iodine value is a measure of the degree of unsaturation; the higher the value, the higher the degree of unsaturation. Linseed oil for example, has an iodine number of 177 and is classed as a rapid drying oil.

The versatility of the triglycerides is manifested by their widespread use in the food, paint and soap industries, to name a few examples. Morgan and Shultz (1981) report that these oils can also be a source of chemical raw materials and aromatic compounds. The conversion of seed oils to benzene, toluene, xylenes, parrafins and olefins, using shape selective zeolite catalysts, has been proven possible on a laboratory scale.

Table 2 summarizes some of the relevant physical properties of soybean oil as compared to #2 fuel oil. From this table it is apparent that the most significant difference between these two fuels lies in their viscosities. The viscosity of any compression-ignition fuel is important because it determines the injection spray pattern and degree of atomization of the fuel in the engine cylinder. Schweitzer (1937) found that a lower viscosity caused a smaller mean droplet size, but a shallower spray penetration. The latter however, is less important than droplet size for favourable combustion characteristics, therefore making the high viscosity of soybean oil undesirable.

Table 2. Properties of Soybean Oil vs #2 Fuel Oil

Property	#2 Fuel Oil	Soybean Oil
Density		
kg/cubic m	845	918
@ 21 C		
Kinematic Viscosity		
cSt 21 C	3.7	62.3
Cetane number	45	37
Heating Value		
MJ/kg	45.5	37.1

The cetane number of a fuel is a measure of its knock characteristics or ignition delay. Soybean oil has a lower value but it is questionable whether this index may be applied to vegetable oils since cetane numbering was developed specifically for the evaluation of petroleum oils. In the case of diesel, special additives are used to improve its cetane rating, while this was not done to any of the vegetable oils tested. Cetane ratings should therefore only be applied as a basis for comparison.

The energy content of soybean oil, on a weight basis, is only about 80% that of diesel. This is due to the fact that soybean oil is not a pure hydrocarbon, but partially oxygenated. Fuel metering in a diesel engine is on a volumetric basis however, so due to a higher density, the energy content of soybean oil, by volume, is about 87% of that of diesel fuel.

Engine Tests with Vegetable Oils

Experiments involving waste cooking oil were conducted by Silvis (1977) to study the operation of a diesel engine on soybean oil-diesel blends. Preliminary work included the measurement of some physical properties of the blends as well as photographing the different injection spray patterns. The blends all had similar patterns to diesel but the pure soybean oil lacked the same high degree of atomization. Its performance was improved slightly by heating the oil prior to injection. Full throttle settings also displayed better patterns than part load settings. The high viscosity of soybean oil was held accountable for these observations.

In the actual engine tests, surging was experienced with a 60% soybean oil blend. Silvis concluded that this was due to a fuel filter flow problem, caused by the higher viscosity of this blend. In general, the blends exhibited superior smoothness of operation to diesel and resulted in better fuel economy and smoke readings.

Strayer and others (1980) tested pure canola oil and found a 3% power loss and a 6% specific fuel consumption increase compared to diesel fuel. No problems were encountered in starting a six cylinder, turbocharged engine on canola oil, either hot or cold. They also noted significantly less smoke than with diesel fuel. No long term engine tests were done but Strayer suspected that the high viscosity of canola oil (roughly comparable to soybean oil), could cause engine deposit buildup and crankcase oil contamination.

Research on sunflower seed oil was conducted by Bruwer and others (1980) and they found similar results to those of Strayer. Maximum power was down by 3% while specific fuel consumption was up by 10%. This is explained by the lower heating value of sunflower seed oil compared to diesel fuel. Diesel knock however, was found to be substantially less audible.

Initial long term tests with a direct injection engine confirmed suspicions about engine deposit buildup and crankcase oil contamination. Under prolonged part-load conditions, carbon buildup around injector nozzles adversely affected combustion to the extent that unburned fuel could be observed in the exhaust system during idling. Unburned fuel also escaped past the pistons (blowby), where oxidation of the seed oil depletes the anti-oxidant additives in the lubricating oil, resulting in polymerization. This can cause solidification of the oil throughout the engine and result, ultimately, in engine failure. Once again, the problem was traced back to the high viscosity of the sunflower seed oil.

Subsequent long term tests with an indirect injection engine showed that deposit buildup does not occur as easily as with a direct injection engine. Indirect injection engines are used mostly in industry and mining, largely because of their cleaner exhaust emmissions. A wider range of fuels can also be used. Ricardo, the inventor of the swirl chamber, stated that the higher surface temperatures in the chamber prevented carbon deposits. This may account for the fact that after 2300 hours of operation on pure sunflower oil, an indirect injection engine showed no abnormal wear or injector tip fouling. Performance was normal throughout the test.

A significant problem with indirect injection engines however, is difficult starting under extremely cold conditions. The cold air, flowing through the throat of the chamber on the compression stroke, is further chilled by a venturi effect, making the use of starting aids such as glow plugs necessary. The poor atomization characteristics of vegetable oils would add to this problem.

From the above, it should be apparent that the single most important problem with vegetable oils is viscosity. A substantial reduction in viscosity prior to injection is required. This could be done by modifying the oil itself, by modifying the engine, or a combination of both. The most logical near term solution is to to modify the oil to match diesel fuel properties so that either fuel may be used in the same engine.

One way to lower the viscosity of soybean oil is by transesterification, a simple and well established process.

Transesterification

Transesterification involves reacting a triglyceride with an alcohol in the presence of a catalyst, to produce glycerol and fatty acid esters. Bradshaw and Meuly (1942) described this process. A typical reaction requires mixing 0.5% sodium hydroxide, on the basis of the oil, into 1.6 equivalents of anhydrous ethyl alcohol. This is added to the oil, heated to about 80 ^{o}C, and stirred until homogeneous. The glycerol begins to separate almost immediately and the reaction is usually 98% complete after one hour. The esters are separated from the glycerol and washed with small amounts of warm water to remove unsettled

glycerol, unreacted alcohol and traces of the catalyst. The esters are stable and non-corrosive, therefore the reaction may be carried out in any convenient, open tank, usually constructed from carbon steel.

A typical reaction occurrs as follows:

$$C_3H_5(R)_3 + 3\ C_2H_5OH \longrightarrow C_3H_5(OH)_3 + 3\ C_2H_5R$$

where R represents the particular fatty acid. From this it can be seen that the molecular weight of the ester is roughly one third that of the original oil, thereby reducing the viscosity.

Wright (1944) found that the materials used in this process should meet certain qualifications for best results. Both the oil and the alcohol must be substantially anhydrous because any presence of water causes soap formation. The acid value of the oil, which is an indication of the amount of free organic acid in any vegetable oil, must be below one for the reaction to take place as described. Soybean oil has an acid value of about two, therefore, in order to neutralize the acids, an excess amount of sodium hydroxide must be added. Because of the resulting soap formation, the reaction mixture becomes viscous, preventing the gravity separation of the glycerol. Similar results are achieved when there is water present in the reaction mixture. Acidification is consequently necessary to promote separation of the layers.

Other esters such as methyl- and butyl esters may be formed but since ethanol can be produced on farm, the focus of this study will be the latter. As stated before, glycerol is a byproduct and may be sold

to offset the cost of the sodium hydroxide catalyst, used in this process.

Engine Tests with Ester Fuels

Preliminary engine tests involving sunflower oil ethyl- and methyl esters have been performed by Bruwer (1980). Dynamometer tests revealed that after 100 hours of operation at 80% of maximum power, the ester fuels actually caused less injector tip fouling than diesel. Consequently, higher brake thermal efficiencies and lower smoke values were recorded. No significant differences were observed between the cylinder pressure diagrams of the esters and diesel.

One problem that came to light though, was that injector needles tended to stick after the engine had cooled off. Long term tests by Hawkins and Fuls (1982) confirmed this problem. They found that the needle sticking was due to the presence of fuel soluble salts of sodium, crystalising on the bearing surfaces. This problem was overcome by using citric acid to adjust the pH, producing an insoluble salt which could easily be stripped from the oil. Apparent exhaust valve burn was observed after 36 hours of operation. Deposits of sodium carbonates prevented proper valve seating causing the valve to burn. The sodium carbonates originated from the catalyst used in the transesterification process and the carbonate group in the citric acid. Using phosphoric acid instead of citric acid solved this problem.

Inspection of the Perkins 4.236 engine after 1100 hours revealed that injector tip fouling was comparable to that of diesel fuel with all the orifices unobstructed. Carbon deposits on the cylinder walls above

the piston ring travel were evident but within acceptable limits. Performance remained normal throughout the 1300 hour test.

Pischinger et. al.(1982), reported on the use of straight methyl ester of soybean oil. Marginal differences in power and torque were observed between diesel and the methyl esters. Fuel consumption was higher but the smoke values were lower. Following a durability run of 1400 hours, the engine was torn down for wear measurement and inspection. No abnormal conditions were noted and combustion chamber deposits were dry, soft and easily removable. The injection equipment showed no signs of excess wear.

In most cases, fuel dilution of the lubricating oil was observed, but did not cause oil polymerization during the normal oil change interval. Siekman et. al.(1982) concluded that oil degradation is determined mainly by the amount of unsaturated fatty acids (linoleic and linolenic) in the fuel. To overcome this, oxidation inhibitors such as BHT (butylated hydroxy toluene) can be added. Hydrogenation can also be employed to saturate the double bonds, but this may not be desirable from the standpoint of viscosity as hydrogenated vegetable oils are usually solids.

Fort and Blumberg (1982), conducted tests with cottonseed esters and found similar results to other researchers. The test cycle consisted of the 200 hour screening test recommended by the Engine Manufacturers Association. A slight reduction in power and an increase in fuel flow occurred, while thermal efficiency remained the same as for diesel. Emissions from the six cylinder, turbocharged engine were not signifi-

cantly different for the cottonseed ester. Engine wear was normal with no evidence of piston scuffing. Deposits in the top ring grooves were evident, however, these were soft and easily removed.

In the light of the promising results obtained with various ester fuels, in a variety of engines, it was felt that a suitable basis existed for comprehensive tests involving soybean ethyl esters. The objectives of this study are more fully discussed in the next section.

INVESTIGATION

Objectives

The objectives of this investigation were twofold:

1. To determine how the physical properties of soybean oil ethyl esters compare with a standard diesel fuel.

2. To perform prescribed medium term tests on a direct injection, turbocharged diesel engine, to determine how engine wear, oil deterioration, exhaust emissions and engine performance for a soybean ester fueled engine compare with a standard fueled engine.

Experimental Equipment

Transesterification

The laboratory scale production of soybean ethyl ester was attempted in order to better understand the process. Crude, degummed soybean oil was supplied by a commercial processing plant, while the ethanol and the sodium hydroxide catalyst were obtained from the university chemical stores. The oil was dried using powdered magnesium sulfate after which 500g of oil was placed in a three necked, round bottom flask. The flask was equipped with a thermometer and a condenser to prevent the alcohol from evaporating. Four grams of the catalyst was dissolved into 120g of ethanol and added to the oil. The mixture was heated to $80^{\circ}C$ and magnetically stirred for about an hour. No separation of the glycerol and the esters occurred. This was suspected to be due to the presence of water in the ethanol. Acetic acid was added in

small amounts and after the addition of about 2.5ml, the separation took place. The mixture was left to settle overnight and then separated. The esters were washed with a small amount of water and filtered.

Since the prime reason for transesterification is to lower the viscosity of the oil, tests were done on the laboratory produced esters to determine how much the viscosity did decrease. These measurements were made according to ASTM D445, using a temperature controlled water bath and Ubbelohde type viscometers. The tests were repeated for pure soybean oil and #2 fuel and the results are shown in Figure 1. A significant reduction in viscosity occurred, bringing the esters much closer to diesel fuel.

Fuel Propeties

In order to fully evaluate the potential of a fuel, complete ASTM tests must be performed. A brief discussion of each test is given.

Cetane number (ASTM D613) is a measure of the ignition quality of the fuel and influences combustion roughness. It can be determined directly by using a CFR engine and measuring the percentage of cetane necessary to give the same knock characteristics as a standard fuel. Alternatively it can be determined by using an equation which includes the fuel's API gravity number and the midpoint temperature in the distillation of the fuel. A high cetane number does not mean better performance, only easier starting, faster warm-up, no diesel knock and reduced carbon and varnish deposits.

Viscosity (ASTM D445) of a fuel is important with respect to the

degree of atomization of the fuel by the injector, as well as the amount of leakage in the injector pump, which is necessary for pump lubrication. Viscosity is determined by measuring the time it takes for a given volume of the liquid to drain through a capillary, and multiplying the time in seconds by the calibration constant for the viscometer.

The heating value of a fuel (ASTM D240) is determined by burning it in a bomb calorimeter. With the water left as vapor the low or net heating value is obtained, while the gross or high heating value is obtained when the water vapor is condensed.

The volatility of the fuel is determined by distillation (ASTM D86), and is an important factor when the engine design, size and speed and load variations are considered. For engines in rapidly fluctuating load and speed situations, a more volatile fuel may be desirable.

The pour point (ASTM D97) is the lowest temperature at which a fuel ceases to flow. This goes hand in hand with cloud point (ASTM D2500). These properties evaluate the fuel's cold weather characteristics.

While not directly related to engine performance, the flash point of a fuel (ASTM D93) is of importance in connection with the safety precautions and legal requirements in fuel handling and storage. The method used is the Pensky-Martens closed tester.

Sulfur content of the fuel (ASTM D129), is of interest because of its corroding effects on fuel lines and injection equipment. A direct method of evaluating corrosion (ASTM D130) is prescribed. Polished copper strips are immersed in the fuel for a specified time, removed,

washed and compared with the ASTM Copper Strip Corrosion Standards.

Ash forming materials (ASTM D482) may be present in fuel as abrasive solids or soluble metallic soaps. The abrasive solids may cause excessive wear in the injector pump, injectors, pistons and rings, while the soluble metallic soaps may contribute to engine deposits.

Water and sediment (ASTM D1796) present in the fuel is objectionable from the standpoint of injection equipment wear. A centrifuge is used to detect the water and sediment.

The gum content (ASTM D381) of a fuel is determined by means of the Williams Pipeline test. Excess gum in a fuel can inhibit fuel flow through the filter, causing loss of power. It can also cause injector needle sticking.

Test Fuels

The test fuels were Phillips #2 Reference Fuel and soybean ethyl ester (trade name ethyl soyate). These fuels were purchased in bulk from Phillips Petroleum and Emery Industries, respectively.

An additive package was added to the ethyl soyate in order to improve some of the fuel properties and to provide a fair basis for comparison with diesel fuel. The additives chosen are currently being used in commercial diesel fuel and consist of Ethyl Distillate Additive-2, Distillate Ignition Improver-3 and Cold Flow Improver-42. The EDA-2 contains an antioxidant, a detergent dispersant, metal deactivator, corrosion inhibitor and an emulsification agent. The DII-3 improves the diesel cetane number by about 5 points. The CFI-42 acts as a pour point

depressant. The treatment rates as specified by Ethyl Corporation were: EDA-2: 0.02% by weight; DII-3: 0.1% by volume; CFI-42: 0.1% by weight.

Test Engine

The test engine was a John Deere 4239TF, direct injection, turbo-charged diesel engine. This engine was chosen because it represents what is being used in agriculture today, yet small enough to keep fuel expenses to a minimum. The engine specifications are given in Table 3.

Table 3. Test Engine Specifications

Specification	Unit	Value
Cylinders	*	4
Bore	mm	106
Stroke	mm	110
Displacement	l	3.917
Compression ratio	*	16.2:1
Rated speed	rpm	2500
Power (intermittent)	kW	70.1
Power (continuous)	kW	57.4
Torque (max.) @1600 rpm	Nm	306

The injection pump was a distributor type pump, supplying fuel to pencil type injectors. The engine came equipped with alternator, starter and oil cooler. A power take-off clutch and an instrument panel were installed. The panel consisted of a starter key switch, vernier type throttle control, ammeter, oil pressure guage, water temperature guage and an accurate hourmeter. A safety feature on the instrument panel

provided engine cut-off should the oil pressure drop too low, or the water temperature rise too high.

To facilitate periodical removal of the engine for evaluation, it was mounted on a two-piece stand, constructed of 100mm channel iron. The lower half remained in-situ, while the upper half provided a stable platform for transportation of the engine. Pillow blocks between the upper frame and the engine mounting brackets dampened vibrations. Engine cooling was achieved via a water-water heat exchanger.

Dynamometer and Instrumentation

A 130 kW Mid-West eddy current dynamometer (Model 1014A), equipped with constant speed or constant load modes of automatic control was used throughout the tests. A Transducers Inc. Model T63H-200 dual bridge load cell was installed in the scale linkage of the dynamometer to provide an electronic signal of engine torque. The load cell signal is recieved by a Daytronic 3270 strain guage conditioner and indicator. Engine speed was determined by a 60-tooth gear, an Electro 3010AN magnetic pickup, and a Daytronic 3240 frequency conditioner and indicator. Copper-constantan thermocouples were used to measure the temperatures of the oil, water, intake air and fuel (at the injector pump). The exhaust gas temperature was measured by an iron-constantan thermocouple.

Air flow measurement was done with a 62.5mm diameter ASME nozzle mounted in a 200 liter fuel drum, which acted as a plenum chamber. The pressure drop across the nozzle was measured by a Setra Systems Inc. Model 239 variable capacitance differential pressure transducer. The discharge coefficient for the flow nozzle was determined by an equation

suggested by Benedict (1966), relating the most probable discharge coefficient to the Reynolds number. A Meriam Model 34FB2 micromanometer was used to calibrate the pressure transducer. Despite the plenum chamber, severe resonance occurred in the air intake system at certain engine speeds. A second, smaller chamber was added downstream of the original drum, which suitably smoothed the output of the transducer. Air filtering was done by an automotive type air filter located at the exit port of the main chamber. The air was ducted by 75mm diameter pvc piping.

The fuel supply system consisted of a three way valve, an auxiliary electric fuel pump, measuring stand and rubber tubing. By switching the three way valve, the engine could either pull fuel straight from the barrel, or from the measuring stand. The measuring stand consisted of a bucket suspended from an Ametek Controls Model BA25-LB load cell connected to a Calex Mfg. Co., Inc. Model 166 Bridgesensor. The load cell output was converted to a frequency output, linearly related to the weight of the fuel in the bucket. The fuel return line from the injectors passed through a heat exchanger before discharging into the bucket. The bucket is initially filled from the fuel barrel using the electric fuel pump.

The turbo boost pressure, turbo inlet pressure and the atmospheric pressure were measured by Setra Systems Inc. Model 204 variable capacitance absolute pressure transducers. Data acquisition was done by a Sym-1 microcomputer based data logger. All the channels were sampled every second, averaged over a three or four second interval and stored in memory, until a minute's worth of data was accumulated. The computer then continually updated its memory so that only the most recent

minute's data was stored. This data could at any time be saved on cassette tape. A Fortran program in the Agricultural Engineering department's computer read the data off the tapes and performed the necessary calculations.

Emissions measurements were done with the following instruments:

1. Beckman 865 infrared carbon monoxide analyzer.

2. Beckman 864 infrared carbon dioxide analyzer.

3. Beckman 402 flame ionization hydrocarbon analyzer.

4. Beckman 955 Chemiluminescence nitrous oxides analyzer.

5. Beckman OM-11 polarographic oxygen analyzer.

The instruments were mounted in a console and plumbed so that zero and span gases could be passed through them for calibration purposes. Probes in the engine's exhaust system facilitated sampling for individual cylinders or for the composite gas of all four cylinders.

Engine Test Procedure

Before any startup, the engine was "blueprinted" by Farmland Industries at Kansas City, Missouri. The following measurements were taken:

A. Engine Measurements.

   1. Crankshaft journals.

   2. Rod bearing weight.

   3. Camshaft lobe height, maximum.

   4. Pistons.

    5. Piston pins.

    6. Piston ring end gap in a standard liner.

    7. Valve guides.

    8. Valve stems.

B. Fuel system.

    1. Injection pump calibrated.

    2. Injectors tested for leakage, chatter, cracking pressure
       and spray pattern.

The engine was reassembled using new gaskets, the valve lash was set and the injector pump statically timed. A break-in period of 50 hours followed, with the engine running at various part load conditions. Commercial diesel fuel was used for the break-in.

The actual engine tests consisted of a 200 hour cycle as recommended by the Engine Manufacturers Association. The test cycle was as follows:

1. 30 minutes at low idle

2. 60 minutes at rated power

3. 60 minutes at peak torque

4. 30 minutes at 25% load and 80% speed.

Five of the above cycles were run, after which the engine was shut down for 9 hours. Maximum performance was checked at the beginning, middle and end of the 200 hour cycle. This was done by applying full rack, and progressively loading the engine using the speed control on the

dynamometer.

The lubricating oil viscosity was checked daily to detect any dilution. Samples were also sent to Farmland Industries for wear metal analysis and deterioration tests. The samples for the reference fuel were taken at 45 hours, 90 hours, 142 hours and 200 hours. The sampling for the ethyl soyate was done roughly every 15 hours to have early warning of any malfunction.

Emissions measurements were made according to SAE J1003 which specifies the following 13 mode sequence:

Mode	Engine Speed	Percent Load
1	Low Idle	0
2	Intermediate	2
3	Intermediate	25
4	Intermediate	50
5	Intermediate	75
6	Intermediate	100
7	Low Idle	0
8	Rated	100
9	Rated	75
10	Rated	50
11	Rated	25
12	Rated	2
13	Low Idle	0

At each mode the emissions were recorded every two minutes for ten minutes. Before and after each test, the instruments were calibrated using the appropriate zero and span gasses.

At the end of each 200 hour cycle, the engine was torn down for evaluation. This included measurement of the wearing parts, rating the sludges, varnishes and carbon deposits, and testing the injectors. The rating of the sludges, varnishes and carbon was done according to CRC test procedures.

Results

Fuel Analysis

Table 4 summarizes the results of the ASTM tests on the reference fuel, pure ethyl soyate and ethyl soyate with additives.

These tests were performed by Farmland Industries, with the exception of cetane number, which was done by Dresser Industries Waukesha Engine Division. A complete distillation curve for each fuel is given in Figure 2. The ethyl soyate was further analyzed by Emery Industries and Table 5 shows the fatty acid composition. The convention used in the formulas of the fatty acids, eg. C18:3 for linolenic, means that there are 18 carbon atoms and 3 double bonds in the acid.

Table 4. Fuel Properties of #2 fuel, Ethyl Soyate and Ethyl
Soyate with Additives

Property	ASTM #	#2 Fuel	Ethyl Soyate	Ethyl Soyate with additives
Cetane	D613	45	48.2	49
Viscosity @ 40°C, cSt	D445	2.49	4.41	4.40
Distillation 90%, °C	D86	338*	344	351
Pour point °C	D97	-6.7	-3.9	-6.7
Cloud point °C	D2500	-	1.1	-2.2
Flash point °C	D93	73.33	160	157
Water and Sediment %vol	D1796	0.10*	trace	trace
Sulfur % mass	D129	0.50*	0.014	0.012
Corrosion	D130	neg	neg	neg
Ash % mass	D482	0.01*	nil	nil
Gum 16 hour	D381	50	19234.2	18402.2
Color 16 hour	-	L1.5	L1.0	L1.5
Heating value MJ/kg	D240	45.5	40.0059	40.0431

* Maximum allowable

Other properties important with respect to the long term storage proper-
ties of the fuel, as well as to how they affect engine performance, are
shown in Table 6. The acid value is a quantitative index of the amount
of free organic acid in a lipid. The saponification value is the amount
of potassium hydroxide required to saponify one gram of oil.

Table 5. Fatty Acid Composition of Ethyl Soyate

Fatty Acid	Formula	% By Weight
Myristic	C14	0.4
Palmitic	C16	10.1
Palmitoleic	C16:1	0.8
Iso-stearic	Iso C18	0.6
Stearic	C18	5.7
Oleic	C18:1	22.2
Linoleic	C18:2	51.2
Linolenic	C18:3	6.5
Behenic	C22	0.2

Table 6. Other Physical Properties of Ethyl Soyate

Property	Value
Acid Value	<0.1
Moisture Content	0.073%
Appearance	clear
Iodine number	123
Saponification value	182.8

Engine Testing

   All test results including engine performance, wear, oil deteriora-
tion and emissions are presented in the appendix and discussed in the
next section. No statistical procedures were used to plot the various
curves due to the obvious consistency of the data.

DISCUSSION

Fuel Properties

It can be seen from Table 4 that ethyl soyate had properties very similar to diesel fuel. The cetane number of ethyl soyate as tested in a CFR engine, was not only significantly higher than the numbers reported for pure soybean oil (Table 2), but higher also than the reference fuel value. A slight improvement was achieved with the additive.

The viscosity of the ethyl soyate, graphically demonstrated in Figure 1, compared very favourably with diesel fuel. No significant improvement was provided by using the additives. Figure 2 shows the distillation curves for the fuels. The ethyl soyate displayed inferior volatility as compared to the reference fuel, although the end point temperatures were very close. Apparent cracking of the ethyl soyate took place above the 85% point.

The pour point of the ethyl soyate with additives showed positive reaction to the treatment and provided a significant lowering of the pour point. This is an important factor when the use of ethyl soyate in cold climates is considered. The cloud point was also lowered slightly. Different teatment rates of the CFI-42 may provide different pour point values and it may be necessary to adjust the rate to a specific climatic requirement.

The flash point of the ethyl soyate was much higher than that of the reference fuel, making it a safer fuel to handle and transport. It is important however, to remove all the free alcohol from the ester if a

high flash point is desired.

The test fuel had only a trace of water and sediment in it, a necessary condition for satisfactory engine performance and durability. Low sulphur and the associated degree of corrosion compared the ethyl soyate very well with diesel fuel. The ash content of the ethyl soyate was also negligible.

A major cause for concern was the high gum number reported for each of the soyate samples. This value represents the number of milligrams of gum per 100 grams of fuel. It can be seen that the gum content of the ethyl soyate was almost 20%, 400 times higher than diesel fuel. This problem manifested itself during the engine tests.

The color of the fuel does not have any effect on engine performance and serves only as a comparison between different fuels. The heating value is a key property affecting engine performance directly. The ethyl soyate had a heating value about 12% lower than the reference fuel. No real difference was observed with the additives. A lower heating value means that an engine will have a higher fuel consumption in order to do the same work.

The fatty acid composition of the ethyl soyate as shown in Table 5, was fairly typical of soybean esters. The characteristically high oleic, linoleic and linolenic fractions have direct relation to the high gum content of the ethyl soyate. Unsaturated double bonds in the fatty acids cause oxidative instability, with resultant gum formation.

The acid value, shown in Table 6 was acceptably low for the ethyl

soyate, as was the moisture content. The iodine value was typical for soybean esters and, as stated before, is also an indication of the degree of unsaturation. The saponification value was within acceptable limits.

Engine Performance

The brake power output at full rack is shown in Figure 3. The maximum power for both fuels occurred at about 2500 rpm with the reference fuel producing a maximum power of 68.6 kW, compared to 65.9 kW for the ethyl soyate. This represents a difference of about 4%. The difference in heating values for the two fuels is 12%. However, the increased fuel consumption with the ethyl soyate would explain the relatively small difference in power output. In terms of megajoules per hour, the ethyl soyate supplied only about 4% less energy than the reference fuel.

Figure 4 shows the torque output at full rack. At 1600 rpm the reference fuel yielded a torque of 315 Nm, while the ethyl soyate yielded 296 Nm at the same speed, a difference of about 6%. Brake specific fuel consumption, shown in Figure 5, was about 12% higher with the ethyl soyate over the 1500 rpm to 2500 rpm range. The higher fuel flow is due mainly to the lower heating value of the ethyl soyate. The fuel temperature at the injector pump was consistently higher by 7°C during the ethyl soyate tests. This could also have influenced the fuel metering by the injector pump. The relative flatness of the BSFC curve demonstrates the efficiency of fuel use in a diesel engine.

Figure 6 shows very little difference in thermal efficiency between the two fuels. The reference fuel achieved a thermal effiency of 35.3%

at 2050 rpm while the ester achieved 34.3 % at the same speed. Thermal efficiency is defined as the ratio of useful mechanical energy output to the chemical energy introduced in the fuel, calculated on the basis of the lower heating value of the fuel. The relatively high efficiencies were achieved mainly as a result of turbcharging. More air is inducted, which drives the combustion to a greater degree of completion.

The fuel air ratio, shown in Figure 7, indicates a richer mixture for the ethyl soyate. This relates once again to the lower heating value of the ester fuel, resulting in a higher fuel flow. Figure 8 shows the full rack exhaust gas temperatures. There was clearly not much difference in EGT for the two fuels.

In general, the ethyl soyate displayed engine performance characteristics very similar to diesel fuel. The small differences were mainly as a result of the difference in heating values. The engine performed smoothly and exhibited no starting problems. There was no audible knock, as indicated by the high cetane numbers reported for the ethyl soyate.

Fuel filter plugging occurred roughly every 50 hours. Peak torque could not be maintained and the engine rpm fluctuated as much as 100 rpm up and down. The filters were replaced whenever this occurred, restoring normal engine performance. Inspection of the filters revealed a gummy substance on the "dirty" side of the filter. This relates to the high gum number reported for the ethyl soyate. It is suspected that gum formation took place after the fuel drum was opened to be used. Emery Industries suggested that the ethyl soyate be stored under an inert

atmosphere to prevent gum formation. Another way to overcome this problem would be the addition of antioxidant additives such as BHT. Prefiltering the fuel is probably the easiest and cheapest remedy.

Emissions

The specific emissions for the two fuels are shown in Figures 9 through 13. Only eight of the thirteen modes are presented in the graphs because of extremely high numbers at low power levels. Figure 9 shows the carbon dioxide level for the ethyl soyate to be slightly higher at the lower speed than for the reference fuel. At 2200 rpm the difference between the fuels was less pronounced. For both fuels the carbon dioxide was higher at 2200 rpm than at 1500 rpm, especially at low power levels. As power increased, the difference due to engine speed was diminished. These effects can largely be explained by the fuel air ratio. The ethyl soyate produced richer mixtures than the reference fuel at any given power setting. A richer mixture would tend to drive combustion towards completion, producing more CO_2. The fuel air ratios for both fuels were higher at 2200 rpm than at 1500 rpm, which explains the difference due to engine speed.

Figure 10 should be examined in conjunction with Figure 9, as the oxygen is also an indication of the degree of combustion. However, the differences in oxygen levels are less apparent than the carbon dioxide levels when the two fuels are compared. Engine speed did show an effect, with the higher speed producing higher oxygen emissions. This is due to the turbocharger inducting an excess amount of oxygen at the higher speed.

Carbon monoxide emissions, shown in Figure 11, were extremely low. The instrument was operating at less than 5% of full scale. This is typical of diesel engines. There was no major difference between the CO values of the two fuels. Although the curves show some trends, it may not be meaningful to draw any conclusions from this data. However, the CO levels for the ethyl soyate correspond to those found for cottonseed esters by Fort and B¹umberg (1982).

In Figure 12 the hydrocarbon emissions, analyzed as equivalent methane, are shown. The ethyl soyate had slightly lower hydrocarbon levels than the reference fuel, with engine speed having no effect. The hydrocarbon emissions of the ethyl soyate at rated power compared well with the findings of Fort and B¹umberg, who tested cottonseed esters. Since the intermediate products of combustion for the ethyl soyate are not known, some questions might be raised as to the applicability of the flame ionization method of hydrocarbon detection.

The nitrous oxides emissions are shown in Figure 13. The ethyl soyate produced consistently higher levels of NOx, while both fuels had higher levels at the slower engine speed. The NOx concentration is mainly a function of combustion temperature, producing higher levels at higher temperatures. For this reason the NOx levels increased with increased power levels. It also explains the fact that NOx was higher at 1500 rpm than at 2200 rpm. At a given power level, the brake mean effective pressure has to be higher for the slower speed, thereby raising the temperature. This, in turn, increases NOx formation. The reason for the difference in NOx levels for the two fuels is less apparent. The higher values for the ethyl soyate may be due partly to higher

ambient temperatures during the tests. It may also be as a result of the ignition delay of the ethyl soyate, with high combustion temperatures existing for a longer period of time. The rated power NOx level for the ethyl soyate was lower than the cottonseed ester value reported by Fort and Blumberg.

'The air fuel ratio was calculated at each mode, using the exhaust gas analysis. Balancing the elements on either side of the combustion equation yielded four equations with five unknowns. The fifth equation was the water-gas equilibrium equation, using an equilibrium constant of 4.3 (Wark 1977). Table 7 shows the calculated air fuel ratios compared to the measured air fuel ratios.

From this table it can be seen that fairly good correlation was found between the calculated and measured air fuel ratios, especially at higher power levels. The value of such an exercise, apart from being an instrumentation crosscheck, may be to determine the molecular formula of an unknown fuel, as demonstrated by Obert (1973). In this case, the molecular structure of the ethyl soyate was known via the fatty acid analysis.

In order to balance the combustion equation, the CO_2, CO and O_2 figures had to be adjusted from a dry gas basis to a wet gas basis. This was necessary because the water in the exhaust gas was condensed out before reaching the analyzers. This was not done in the case of NOx and HC.

Table 7. Calculated Air Fuel Ratios vs Measured Air Fuel Ratios

Mode	meas. AF #2 Fuel	calc. AF #2 Fuel	meas. AF Ester	calc. AF Ester
1	–	106.1	–	95.387
2	120.14	101.67	107.89	91.79
3	63.29	55.29	55.92	48.41
4	40.65	38.06	36.54	32.87
5	30.49	29.31	27.02	24.89
6	24.47	24.04	21.27	20.04
7	–	111.64	–	95.34
8	28.12	26.56	23.81	22.28
9	33.13	31.42	28.28	26.58
10	40.85	38.39	35.63	33.44
11	56.67	51.77	51.11	46.52
12	90.53	78.36	80.74	71.99
13	–	111.4	–	96.61

Some uncertainty about the value of the equilibrium constant for the water-gas equilibrium equation, prompted a recalculation of the air fuel ratios. A different constant was used but no difference in the calculated air fuel ratios could be found. It seems therefore, that calculated air fuel ratios are not sensitive to the absolute value of the water-gas equilibrium constant.

Engine Wear and Deposits

Engine wear was monitored by analysis of the lubricating oil for wear metal levels. In Table 8 the levels of the most important metals are shown for the test fuels.

Table 8. Engine Oil Wear Metal Analysis

Fuel	Hours	Iron	Chromium	Aluminum	Copper	Lead
Reference Fuel	45	12	0	0	3	9
	90	28	0	2	3	12
	142	12	0	0	2	5
	200	38	1	2	4	10
Ethyl Soyate	12	7	0	0	0	22
	30	14	0	0	1	33
	45	18	0	7	1	37
	61	22	0	7	1	41
	92	31	1	2	3	46
	100	35	1	2	4	47
	115	7	0	0	0	5
	129	10	0	2	0	6
	144	13	0	0	2	9
	160	15	0	0	2	10
	174	20	0	0	3	12
	200	30	0	7	4	16

Wear metal levels for the ethyl soyate were considered to be normal throughout the 200 hour test. Initial high levels of lead were of some concern, suggesting that abnormally high wear was taking place on the

bearings. Following the oil change at 100 hours however, the lead concentration returned to normal. It may be that a slightly different alloy was used on the surfaces of the replacement bearings, containing a higher percentage of lead.

The lubricating oil viscosity, monitored over the 100 hour oil change interval, is shown in Figure 14. For both fuels, the initial shear of the oil caused a rapid drop in viscosity during the first 10-20 hours. In the case of the reference fuel, the viscosity then stabilized at about 103 cSt. For the ethyl soyate however, the viscosity continued to drop for the entire 100 hours, which suggests that more oil dilution was taking place. This could eventually lead to oil thickening as the antioxidant additives in the oil become depleted. However, this did not happen during the normal oil service interval.

By adhering to the manufacturer's recommended oil change interval, no problems with oil polymerization should occur, at least not on the short term basis. On the long term, deposits might increase to the point where combustion of the ester fuel will deteriorate resulting in more unburned fuel in the cylinder. This will accelerate oil dilution, so that the oil change interval will be shortened. In an engine with more hours on it, and thus more wear, more blowby will occur. This will also accelerate oil dilution.

Conclusive evidence of engine wear can only be established by physical measurement of the various parts. In Table 9 the average condition for the four cylinders are presented for the base line test and the ethyl soyate test, respectively.

Table 9. Engine Wear

Component	Diesel	Ester
Liner Wear	nil	nil
Piston Wear	nil	nil
Ring Gap Increase, mm First	0.08	0.097
Second	0.038	0.033
Oil Control	0.064	0.051
Wrist Pin Wear	nil	nil
Rod Bearing Wt. Loss, mg	9.1	6.7
Cam Lobe Wear, mm	0.025	nil
Valves Stem Wear	nil	nil
Valve Guide Wear	nil	nil

From this table it is apparent that there was no notable difference in the wear patterns of the two fuels. In both cases the honing marks in the liners were still clearly visible, as were the machining marks on the pistons. The valve stems had faint polishing marks on them, with the valve seat interference angle barely starting to show. Bearing discoloration was only evident on the thrust side of the bearing.

Engine deposits for the test fuels are summarized in Table 10.

Table 10. Engine Deposits

Component	Diesel	Ester
Pistons Top Groove Filling	nil	nil
Skirt Varnish Rating	10.0	10.0
Stuck Rings	none	none
Combustion Chamber	normal	normal
Valves Underhead (CRC) Intake	7.2	8.4
Exhaust	9.0	9.5
Ave. Sludge (CRC)	9.44	9.44
Ave. Varnish (CRC)	9.9	9.9

Deposits for the ethyl soyate appeared to be the same as for diesel, with the exception of the color of the exhaust valve deposits. These deposits were light brown in the ethyl soyate, as compared to black in the diesel tests. The ester carbon deposits were relatively dry and soft, except around the injector bodies. In this area, gum-like deposits made removal of the injectors more difficult.

The injector tips were as deposit free as in the diesel test. There were no obstucted orifices and the spray patterns were unaffected. Cracking pressures declined by an average of about 600 kPa for the ethyl soyate as opposed to about 1400 kPa for the reference fuel test. This was not considered to be an abnormal condition, as injectors tend to wear less rapidly as hours are accumulated. The injector pump calibra-

tion was checked before the diesel test and after the ethyl soyate test. The pump delivery did not change significantly, indicating that no abnormal wear had taken place.

CONCLUSIONS

1. Ethyl soyate with commercial diesel fuel additives has fuel proper-
   ties that compare very well with diesel fuel. The high gum content
   however, is undesirable from the standpoint of fuel filter clog-
   ging.

2. The pour point improver provided a significant drop in the ethyl
   soyate pour point, meriting further experimentation with different
   treatment rates. The high flash point of the ethyl soyate makes it
   safer to handle than diesel fuel.

3. The transesterification process raises the cetane number of the
   vegetable oil to levels comparable to diesel values. This elim-
   inates knock and ensures smooth engine operation.

4. The ASTM fuel tests provide significant insight into the potential
   of a candidate compression-ignition fuel. Following the general
   standards set for diesel fuel, suitable screening of prospective
   fuels may be provided.

5. The interrelation between fuel properties and engine performance
   makes good quality control in the ester fuel preparation mandatory.
   In the on-farm situation, suitable procedures and quality standards
   would have to be prescribed.

6. Engine performance for soybean ethyl esters does not differ to a
   great extent to that of diesel fuel performance. A slight power
   loss, combined with an increase in fuel consumption was experienced
   with the ethyl soyate. This is mainly attributed to the lower

heating value of the ethyl soyate.

7. Emissions for the two fuels were essentially similar, with carbon monoxide too low to provide reliable data. Hydrocarbons for the ethyl soyate were lower than for diesel. Not enough is known about the combustion kinetics of ethyl soyate, to draw any conclusions from this fact.

8. Engine wear for the two fuels were found to be normal after the 200 hour tests. Deposits were comparable with respect to amount, but slightly different in color and texture. Injection equipment showed no difference for the two fuels.

9. Ethyl soyate could be used as an alternative fuel on a short term basis, provided certain fuel quality standards are met. The gum problem needs to be solved to eliminate fuel filter clogging.

10. The 200 hour test cycle, as recommended by the EMA is adequate for the screening of alternative fuels. The long term effects can in no way be established during this cycle. For this reason, failures during this test must be regarded as highly significant, while success can only justify the pursuit of longer term tests.

SUMMARY

The results of this investigation show that a direct injection, turbocharged diesel engine will perform satisfactorily when fueled by soybean ethyl esters. Fuel filter plugging as a result of a high gum content in the ethyl soyate was a constant problem.

These results can only be projected for the short term use of ethyl soyate, such as a temporary diesel fuel shortage.

SUGGESTIONS FOR FUTURE RESEARCH

These tests have shown the short term feasibility of using ethyl soyate as a diesel fuel. However, only the technical aspects were considered. Careful analysis of the economic implications needs to be done before any recommendations can be made. The fuel versus food problem is also of some concern.

Few technical problems were encountered during the screening tests. The high gum levels in the ethyl soyate, which resulted in fuel filter clogging, need to be lowered. Alternative additives to improve the oxidative stability of the fuel may be evaluated. Plant breeders may also be able to perform genetic alterations to soybean varieties in order to change the fatty acid composition of the oil. Higher percentages of saturated fatty acids will reduce the amount of gum formation.

Long term engine tests should be performed, to further analyze the wear patterns and engine deposits of ethyl soyate. These tests should preferably be performed in the field where dusty conditions, varying loads and speeds and the effects of different operators can be studied. This will also provide a fuel performance profile through the seasons to show up any cold weather problems.

In depth study of the combustion kinetics of ethyl soyate will provide better understanding of emission levels and combustion chamber deposits. Gas chromatography analysis of the exhaust gases will reveal the nature of intermediate products of combustion. Time-pressure diagrams of the combustion process will be helpful in this regard as well. Based on the findings of such investigations, the current method

of hydrocarbon detection should be examined, to establish its validity for vegetable oil derived fuels.

Experiments to optimize engine performance with ester fuels may also be conducted. Varying the injection timing may improve the combustion efficiency. The injection pump calibration could also be adjusted to suit the esters better.

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APPENDIX

GRAPHICAL PRESENTATION OF TEST RESULTS
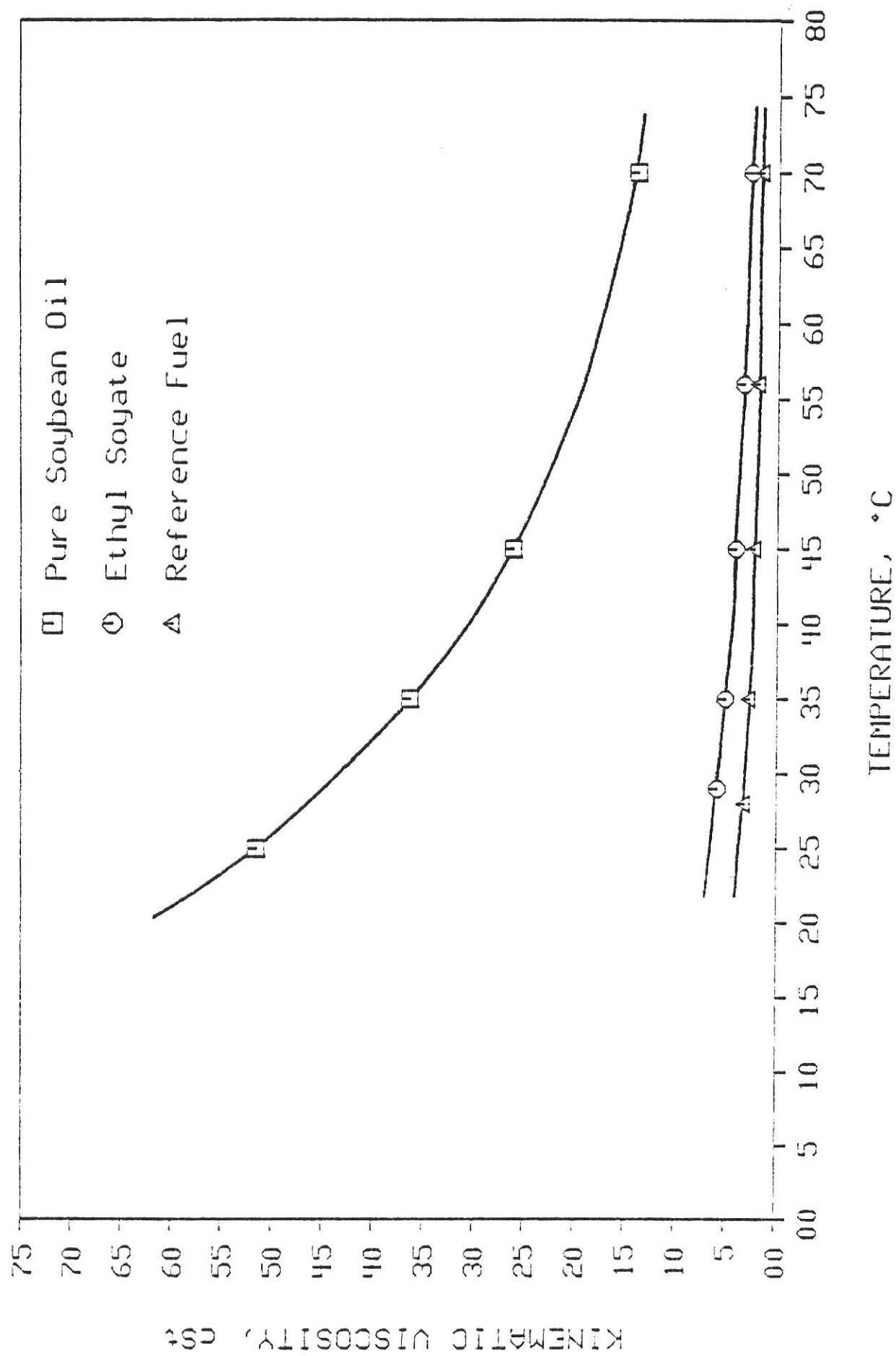
Figure 1. Viscosity versus Temperature for Various Fuels.
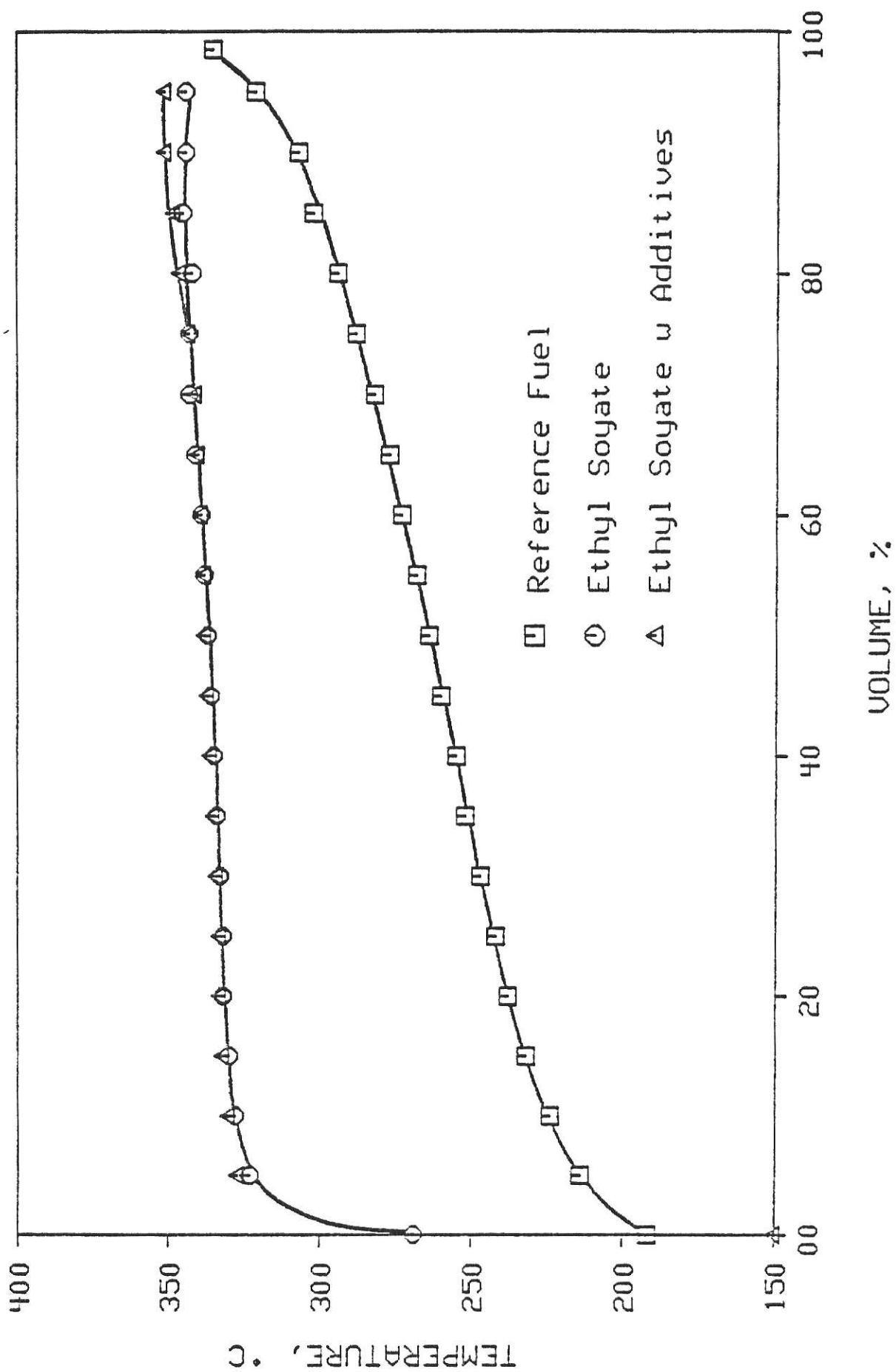
Figure 2. Distillation Curves for Various Fuels.
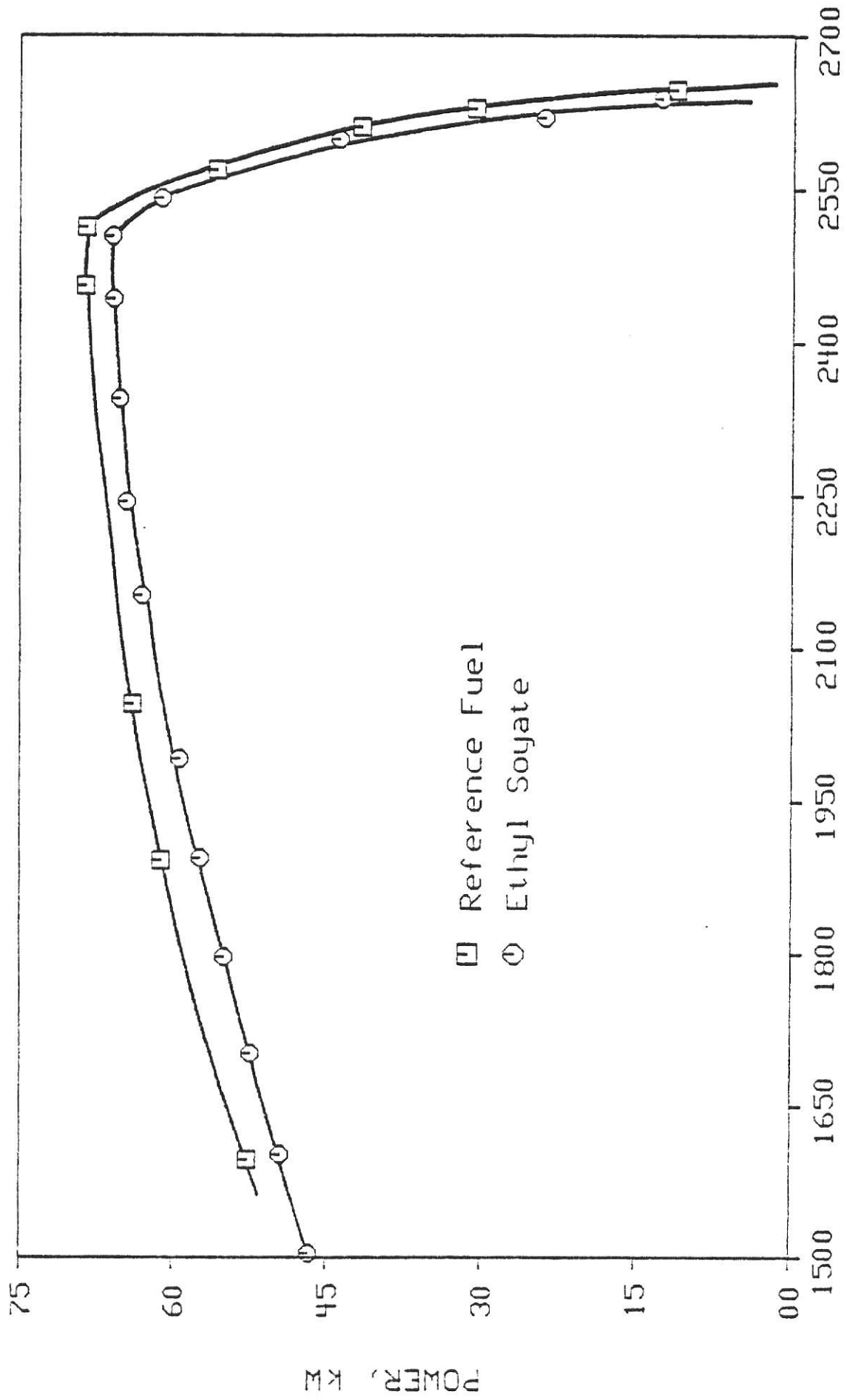
ENGINE SPEED, RPM

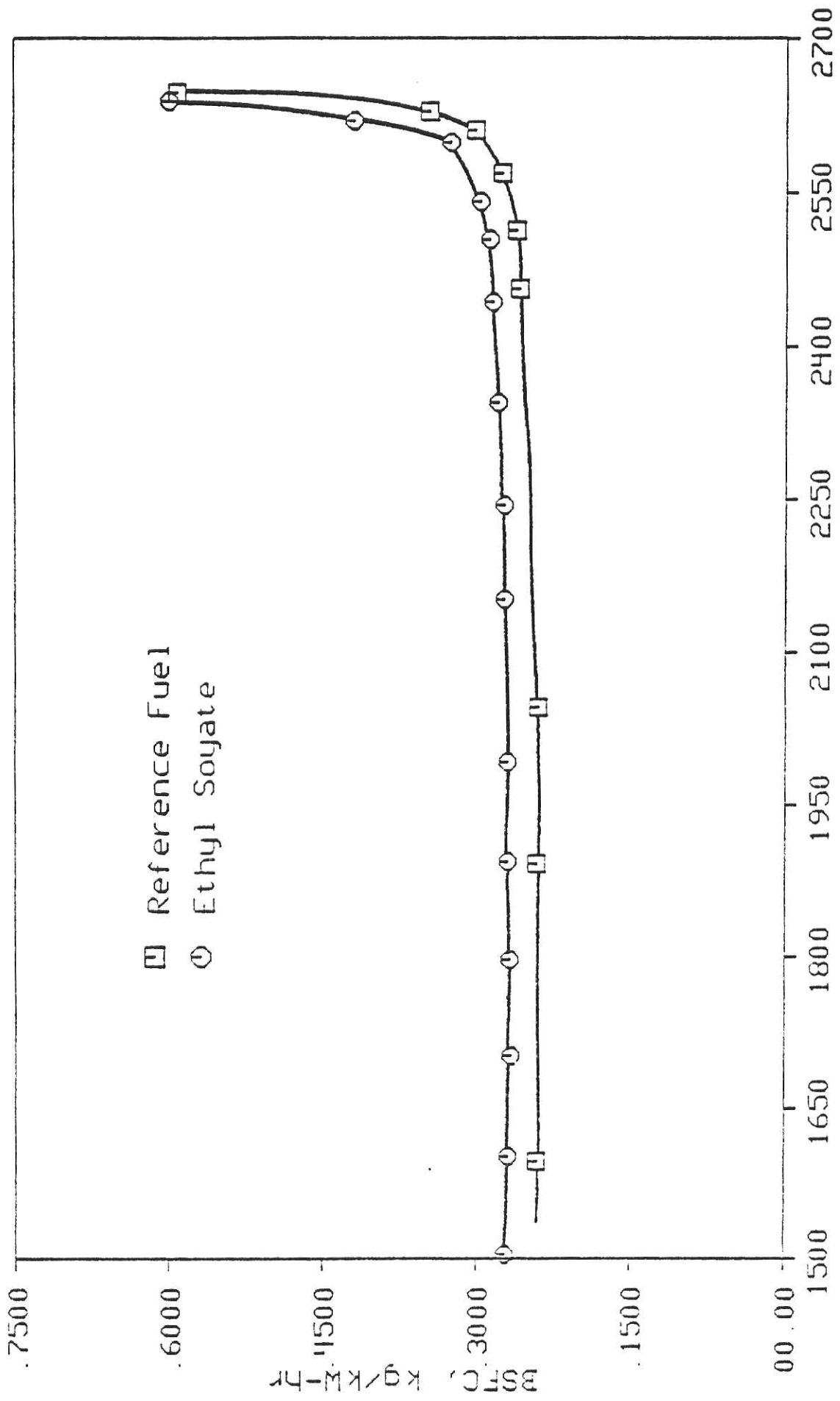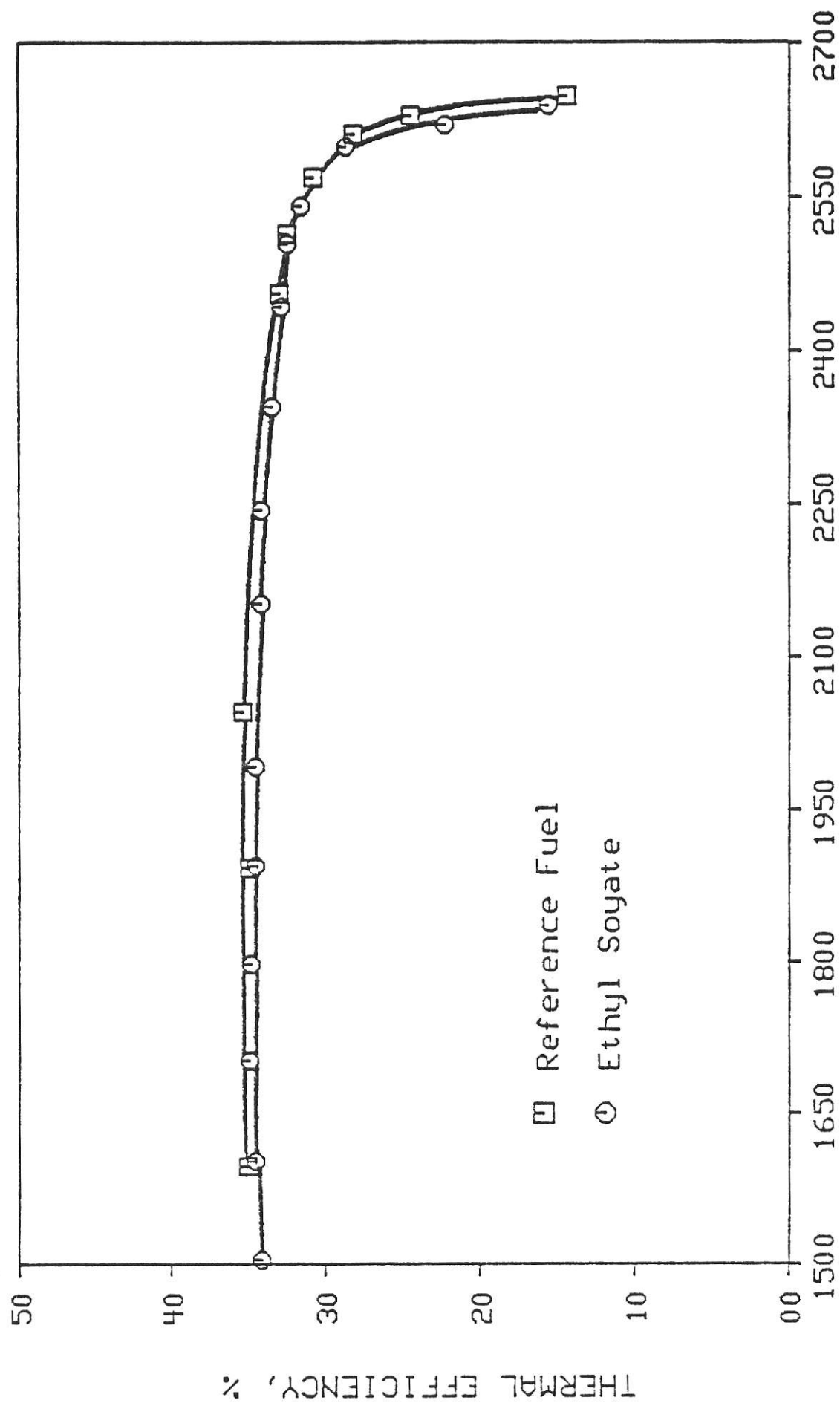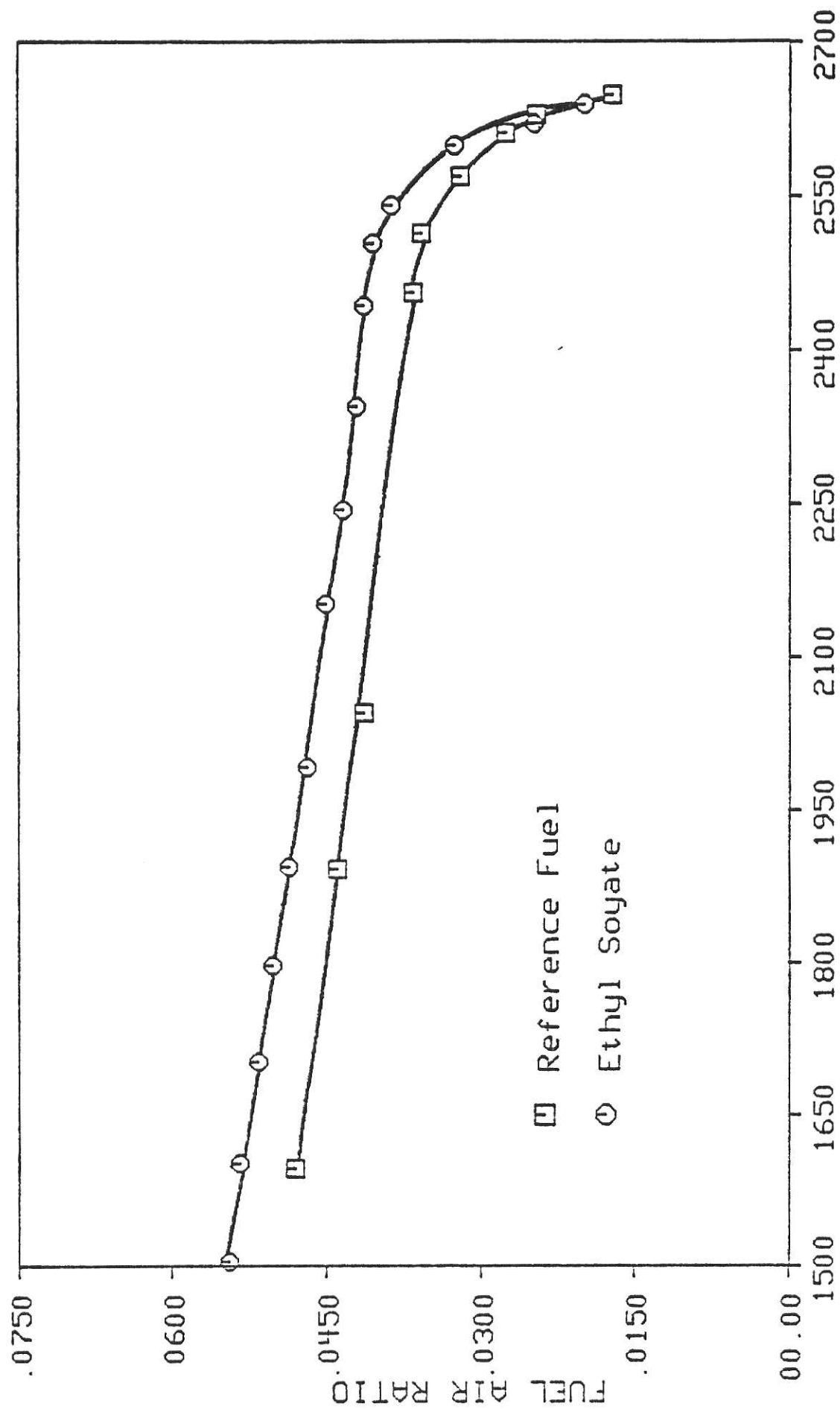Figure 3. Brake Power Output at Full Rack.
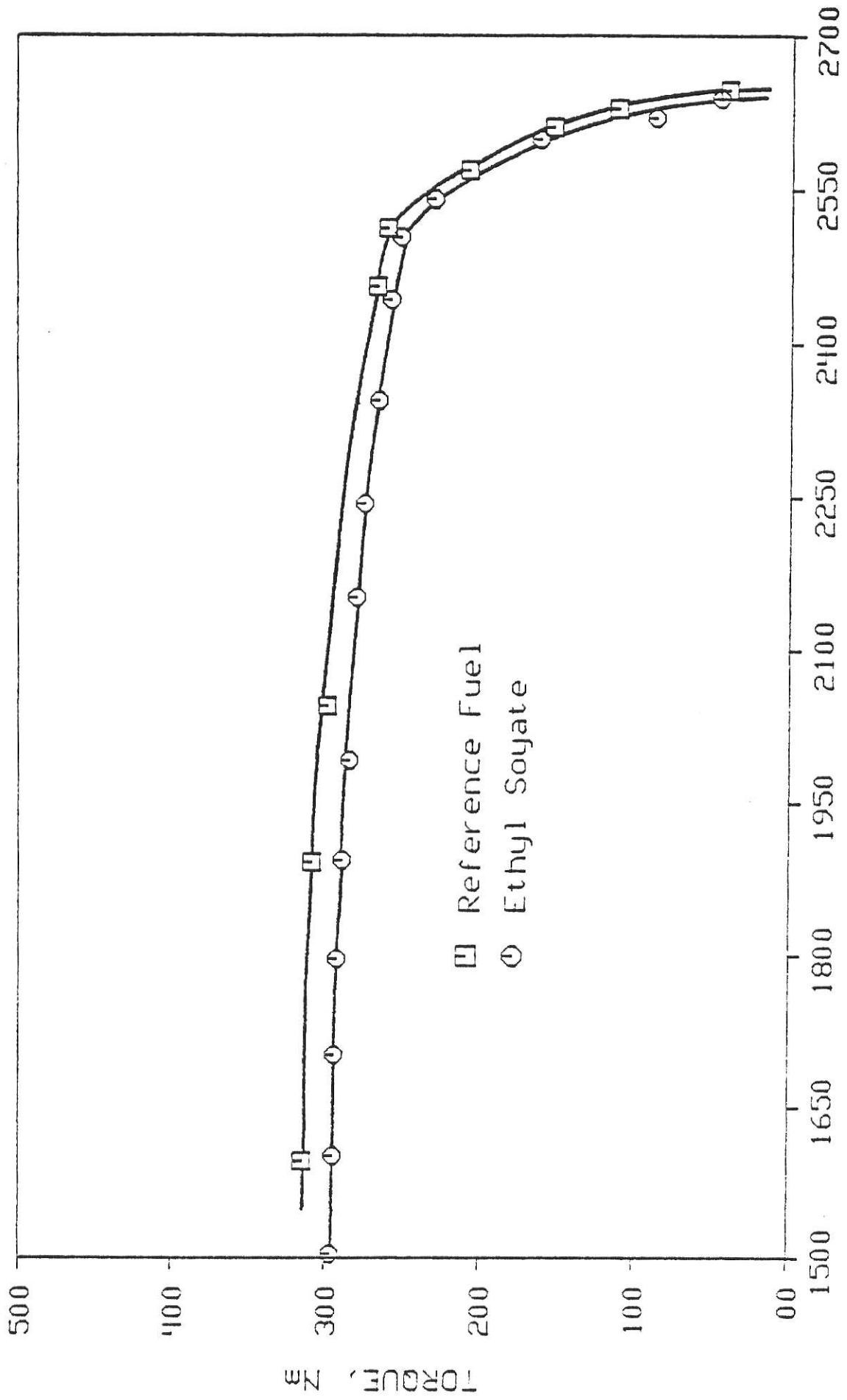
Figure 4. Torque Output at Full Rack.

55

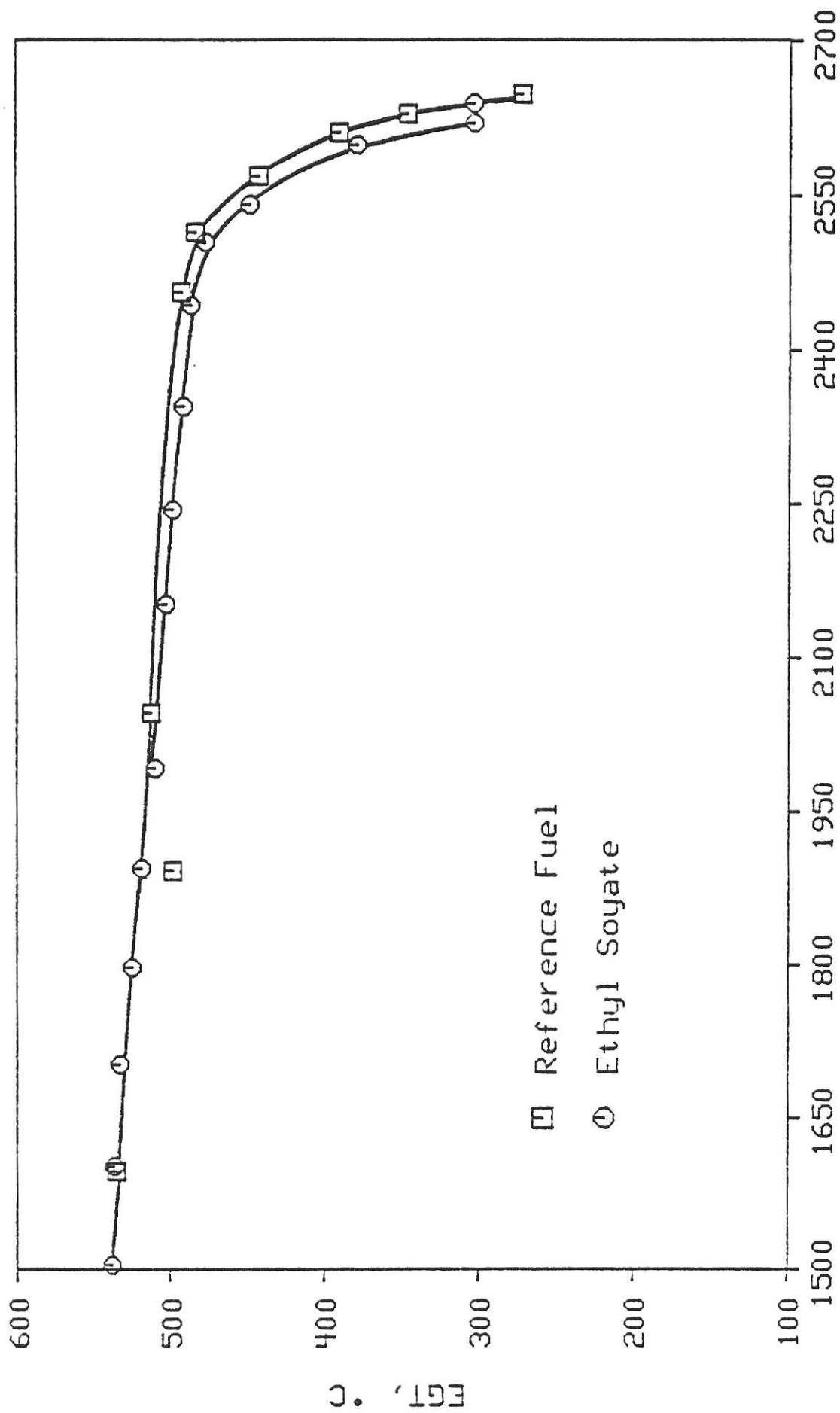Figure 5. Brake Specific Fuel Consumption at Full Rack.

Figure 6. Thermal Efficiency at Full Rack.

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ENGINE SPEED, RPM

Figure 7. Fuel Air Ratio at Full Rack.

ENGINE SPEED, RPM

EGT, °C

☐ Reference Fuel

⊙ Ethyl Soyate

Figure 8.   Exhaust Gas Temperature at Full Rack.
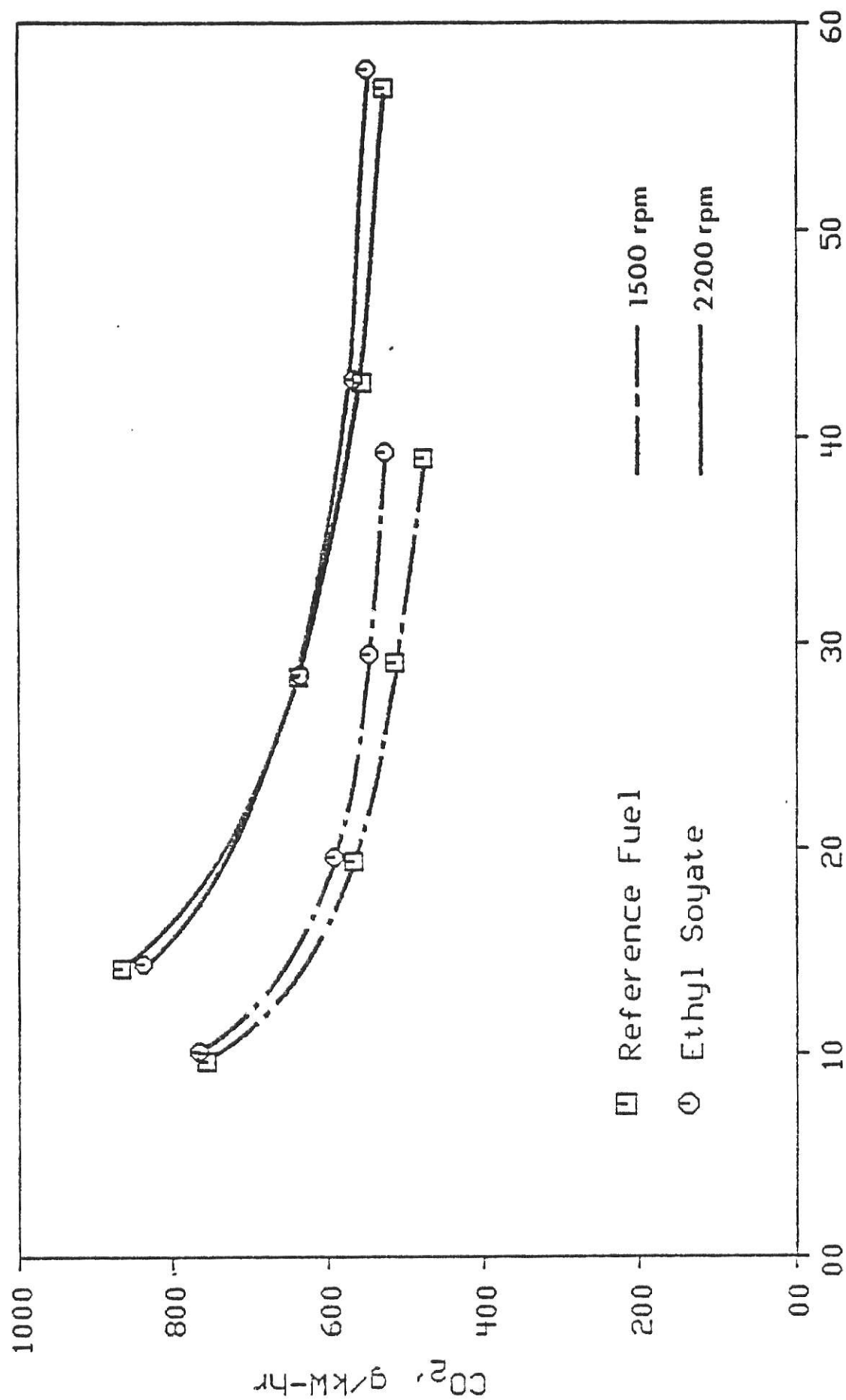
Figure 9. Carbon Dioxide Emissions.
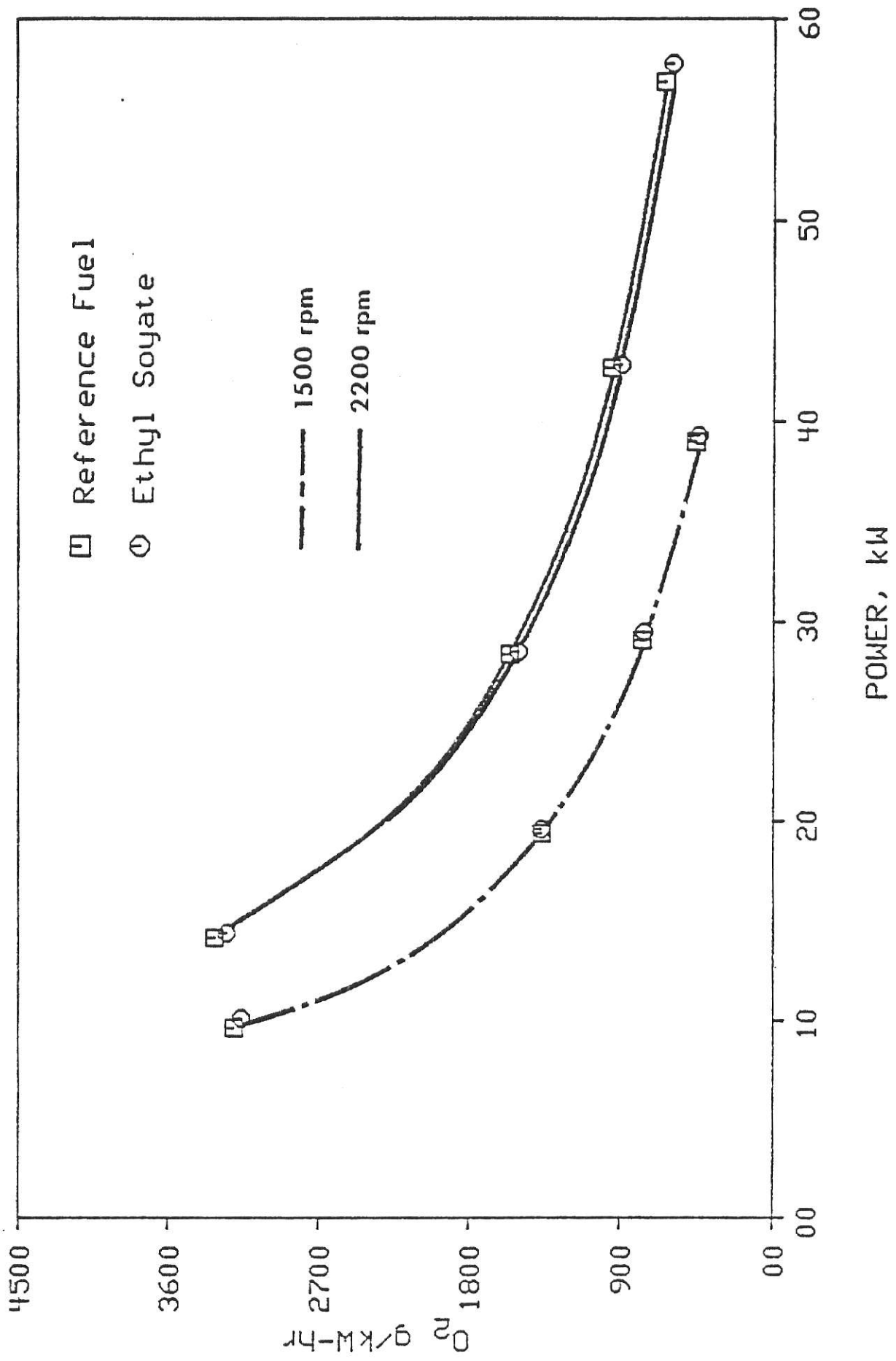
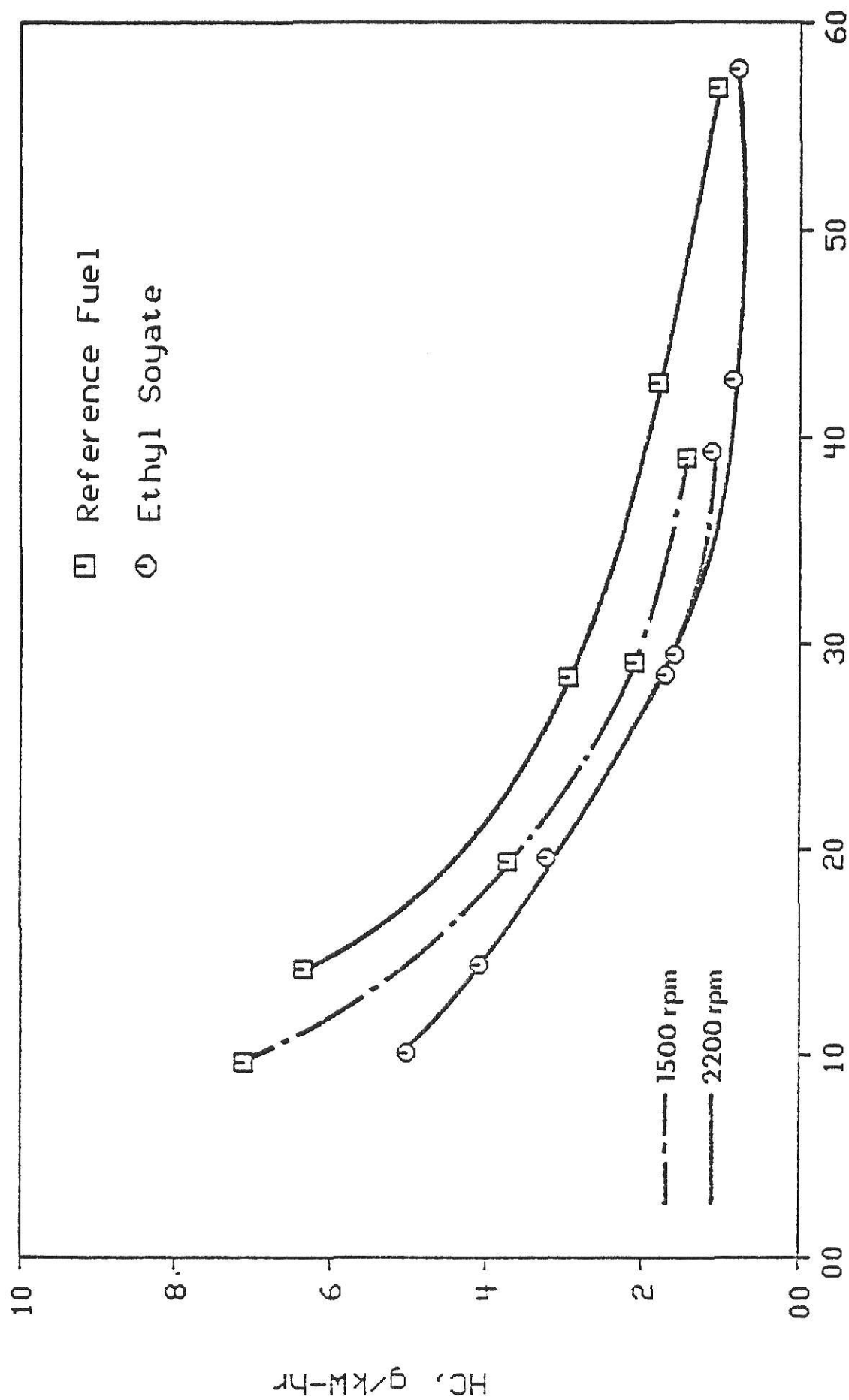Figure 10. Oxygen Emissions.
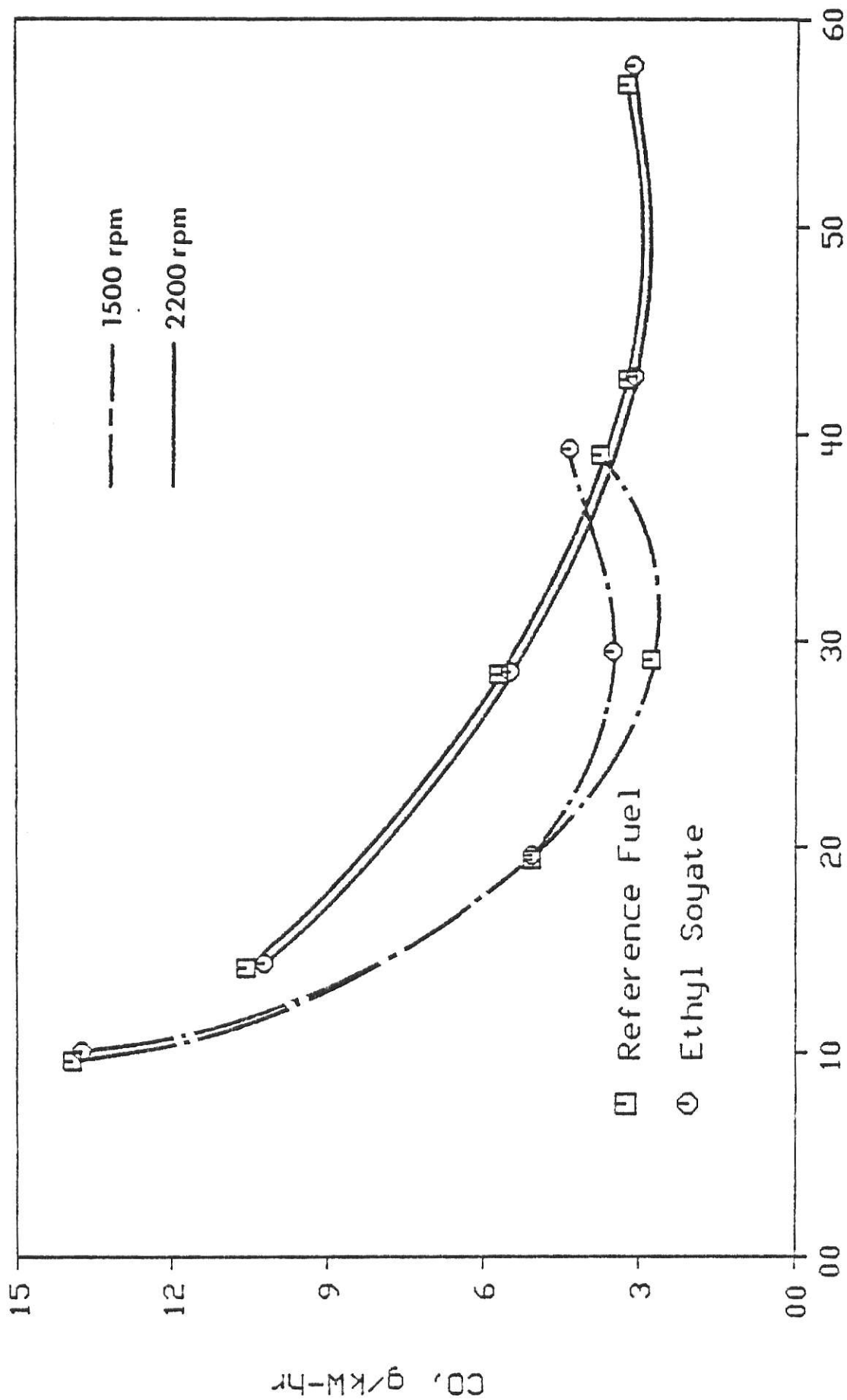
Figure 11. Carbon Monoxide Emissions.

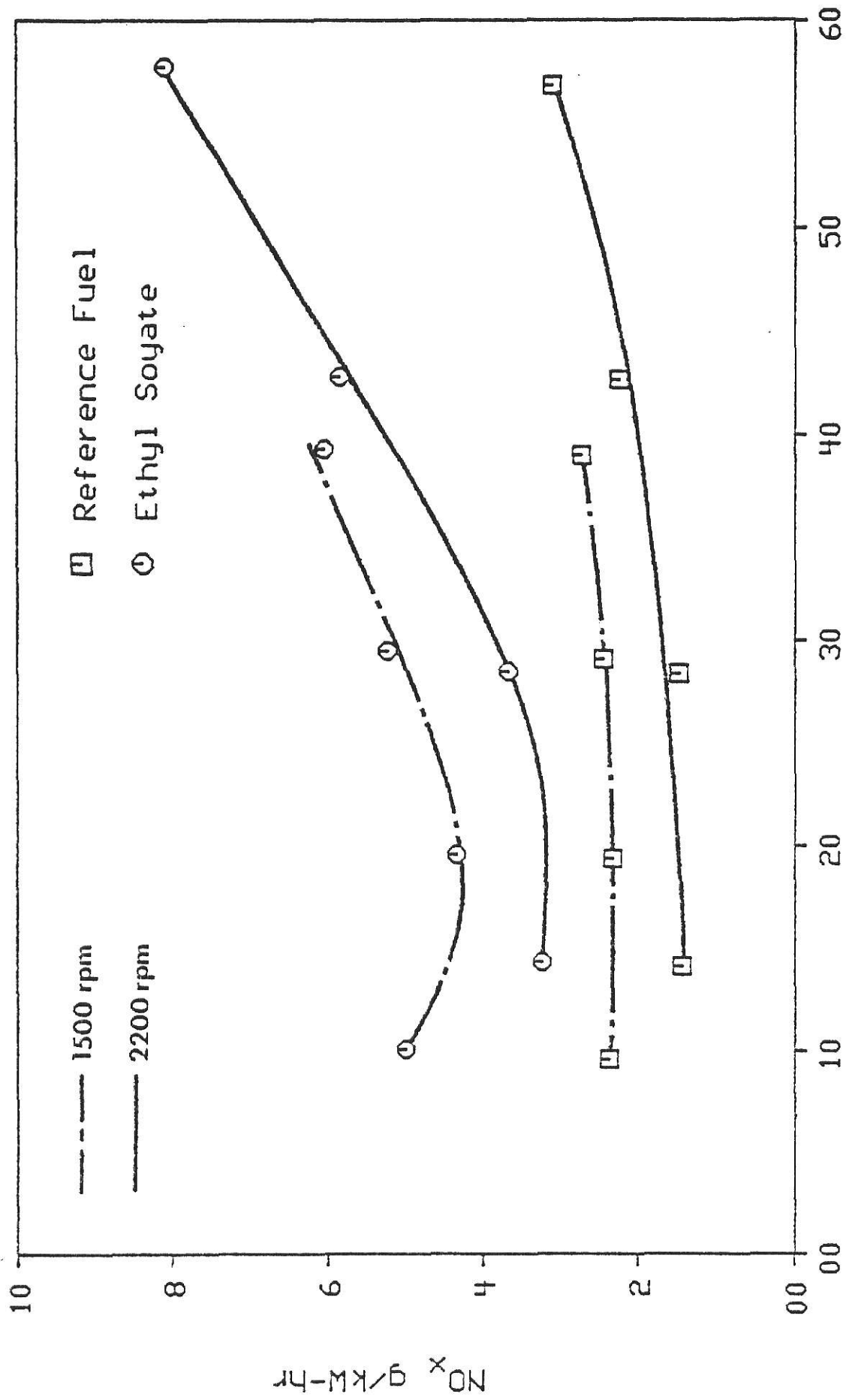Figure 12. Hydrocarbon Emissions.
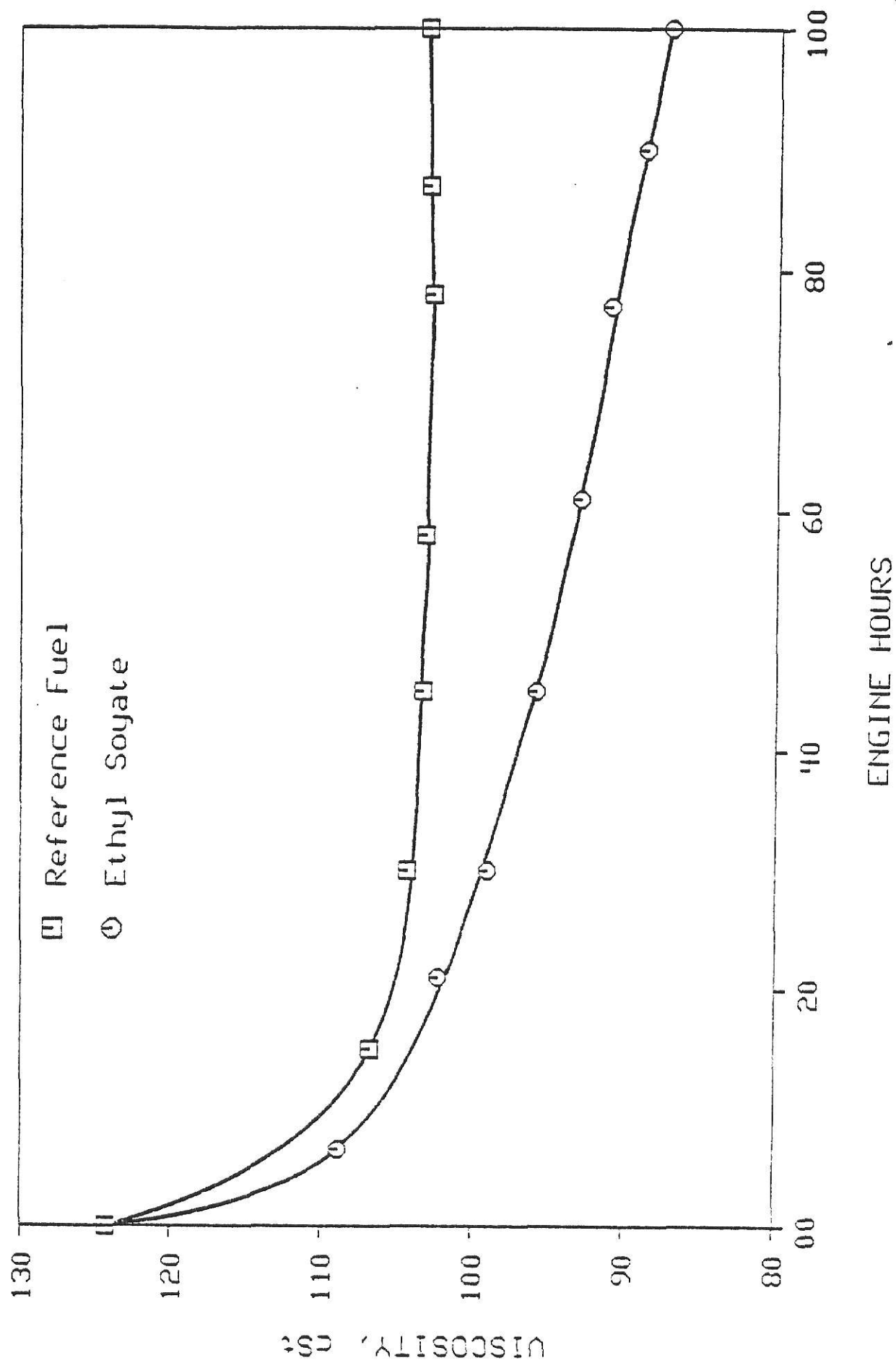
Figure 13. Nitrous Oxides Emissions.

Figure 14. Lubricating Oil Viscosity Drop.

SOYBEAN ETHYL ESTERS- A RENEWABLE

FUEL FOR DIESEL ENGINES

by

PETRUS G. PIENAAR

B.S., University of Pretoria, 1980

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

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Most modern farm equipment is powered by diesel fuel, making agriculture particularly vulnerable to fuel shortages. Renewable, biomass derived fuels have recieved widespread attention as extenders or replacements for fossil fuels. One of these is vegetable oil, typically produced from soybeans, sunflower seeds, safflower seeds and cottonseed, to name a few examples.

The principal problem with using straight vegetable oil in a diesel engine is the high viscosity of the oil. Transesterifying the oil with an alcohol provides a significant reduction in viscosity, thereby improving the combustion properties of the oil.

Complete ASTM fuel tests were performed on soybean ethyl esters to compare its fuel properties with diesel fuel. A commercial diesel fuel additive package was used to improve some of the properties of the ester fuel. A slight gain in cetane number was achieved, while the pour point was significantly lowered. A major problem area is the high gum content of the soybean ester.

Engine tests were performed on a direct injection, turbocharged engine. The test cycle was the 200 hour alternative fuel screening test recommended by the Engine Manufacturers Association. A base line test with Phillips #2 reference fuel was run to provide a means of comparison. The following variables were monitored: engine performance, emissions, lubricating oil deterioration and engine wear and deposits.

A 4% power loss and a 12% higher brake specific fuel consumption was observed for the ester fuel. This was due mainly to the lower heating value of the ester fuel compared to diesel fuel. Emissions for the

ethyl esters were marginally different from diesel emissions. The lubricating oil viscosity was monitored during the oil change interval for both fuels. The viscosity stabilized for the diesel fuel but continued to decline for the ester fuel, indicating that more oil dilution was taking place. Wear metal levels were normal for both fuels, which suggested that no abnormal wear was taking place. This was confirmed when the engine was torn down for evaluation after each test cycle.

No measurable difference could be detected between the wear patterns of the two fuels. Engine deposits were normal for both fuels except for the color of the combustion chamber deposits for the ester fuel. These were light brown as opposed to black.

The only problem encountered during the ester fuel tests was fuel filter plugging. This problem is related to the high gum content of the soybean ethyl esters. Prefiltering the fuel is the most reasonable solution.