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An Investigation on Soybean Oil as an Alternate Fuel in Diesel Engines

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AN INVESTIGATION ON SOYBEAN OIL AS AN ALTERNATE

FUEL IN DIESEL ENGINES

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INTRODUCTION

Background of the Problem

The use of vegetable oils as fuels for diesel engines was not a new concept. As early as 1912, Rudolph Diesel (inventor of the diesel engine) attempted to use the oil derived from an African earth nut as fuel in his diesel engine. His tests showed some promise, but the economics of producing a vegetable oil fuel, coupled with the design of the diesel engine itself, never favored this (Pestes & Stanislao, 1984).

The interest in using vegetable oils as fuel for diesel engines gets renewed during periods of petroleum shortages (e. g., the 1973 oil embargo). Continuing conflicts in the Middle East could affect the availability and price of future imported oil, which increases the need for an alternate source of fuel (Ryan, Dodge, & Callahan, 1984). With the price of diesel fuel having risen 400% in the last 10 years, it was logical for the agricultural sector especially to look for alternative fuels. Since 90% of agriculture's energy need is supplied by diesel power, and agriculture has a possible source of an alternative fuel, vegetable oil fuels were investigated (Pestes & Stanislao).

To date, much of the research conducted on vegetable oil fuels has been performed in countries that have little or no internal petroleum resources (e. g., South Africa, Brazil, Sweden, Canada, and Australia). In the United States, work has been done at universities such as Ohio State, North Dakota State, the University of Idaho, and the University of Alabama. Engine manufacturers like International-

Harvester, John Deere, Caterpillar, and Perkins have also done some work in this area, as well as Southwest Research Institute in San Antonio, Texas (Ryan et al., 1984).

Vegetable oils have good ignition characteristics because of their long-chain hydrocarbon structure (Murayama et al., 1984), and their fuel properties are similar to diesel fuel (Clark, Wagner, Schrock, & Piennaar, 1984). Soybean oil fuel was selected for this study, because it offered certain advantages:

1. Of the various vegetable oils tested, soybean oil had the least tendency to form excessive carbon deposits on injector needles during engine tests of 200 hours or less. Ranked behind soybean oil from best to worst were sunflower, peanut, and cottonseed oils (Pryde, 1984).

2. A positive energy balance is achieved in producing soybean oil, because the need to introduce nitrogen as fertilizer (energy inputs) is reduced, since soybean plants supply most of their own nitrogen through nitrogen fixation (Clark et al., 1984).

Statement of the Problem

The problem of this study was to evaluate the performance parameters and wear rates using a soybean-based fuel in a six cylinder diesel engine.

Statement of Purpose

The purpose of this study was to obtain a fundamental understanding of the use of soybean oil as a fuel in a six cylinder diesel engine.

Statement of Need

The need for this study was based on the following factors:

1. Petroleum is a finite product while vegetable oils are a renewable resource.

Unfortunately, when and if the world's supply of petroleum is used up, it's gone forever. Vegetable oils, however, are a renewable resource with well established crop production practices (Clark et al., 1984). Researchers predict it would only take approximately 10% of the acreage to produce enough fuel for the remaining 90% of the producing acreage (Pestes & Stanislao, 1984).

2. Vegetable oil fuel specifications have not yet been determined.

Interests in vegetable oil fuels faltered because of renewed availability of more economical petroleum. As a result, vegetable oils have not been developed as potential fuels, nor have the necessary physical and chemical properties been defined to make them totally acceptable as a fuel source (Ryan et al., 1984).

3. Information needs to be provided to the customer regardless of whether or not soybean oil is proven a viable alternative fuel.

If diesel engine manufacturers determined that soybean oil should not be used as an alternative fuel, then customers need to know this information, along with the reasons why this fuel isn't recommended. This would protect engine manufacturers against warranty claims issued by those customers who fail to heed the warnings (Adams, Peters, Rand, Schroer, & Ziemke, 1983).

Research Questions / Hypotheses

The following questions were answered as a result of this study:

1. What effects did soybean oil fuel have on performance parameters?

2. Did premature fuel filter plugging occur?

3. Were excessive carbon deposits observed on any of the power cylinder components (i. e., pistons, piston rings, cylinder liners, and valves)?

4. Were excessive carbon deposits observed on fuel injector tips, and if so, were injector spray characteristics altered?

5. Were excessive carbon deposits observed on any additional engine components?

6. Did using soybean oil fuel cause abnormal or excessive wear to the pistons, pistons rings, cylinder liners, and intake valves based on the engine manufacturer's Quality Audit Rating (QAR) manual?

7. It was hypothesized that there would be no statistically significant difference in wear between those power cylinder components (i. e., pistons, piston rings, cylinder liners, and intake valves) tested with the soybean oil fuel compared to those same components tested with diesel fuel.

Assumptions

The following assumptions were made in pursuit of this study:

1. The engine used to conduct this test was representative of other production engines produced of the same model type.

2. The soybean oil fuel purchased for this test was representative of fuel that would be used by a customer.

Limitations

This study was conducted in view of the following limitations:

1. Due to time and budget constraints, only one engine test was conducted.

2. In order to compare test results with the engine manufacturer's QAR manual (see Appendix A), the engine was tested at full load, rated speed conditions. No part-load or cycle tests were scheduled. It was noteworthy that tests conducted in Japan on a Komatsu diesel engine showed carbon deposits accumulated faster at lower engine loads and speeds (Murayama et al., 1984).

3. Only a direct injection diesel engine was used for this study. This item was considered to be a limitation as indirect injection diesel engines are more tolerant of fuel differences than direct injection diesel engines (Ryan et al., 1984).

4. Emissions tests were considered to be not within the scope of this study, but should be considered as a topic for future research.

5. In order to compare test results with the QAR manual, the test duration was only 200 hours.

6. Cylinder peak firing pressure was not measured, because this would have required an additional hole be drilled and tapped into the cylinder head for installation of the pressure transducer. Plans were to sell this engine, therefore, no extra holes were allowed to be drilled into the engine.

Definition of Terms

The following terms were defined to clarify their use in the context of this study:

Aftercooled. Some diesel engines are equipped with an aftercooler. The aftercooler is installed between the turbocharger and the engine's intake manifold. The aftercooler reduces the temperature of the compressed air delivered to it by the turbocharger by 27 to 30° C. This makes the air denser, allowing more air to be packed into the combustion chambers. The result is more power, better fuel economy, and quieter combustion (" Engine Fundamentals," 1979).

Blowby. Blowby is a leakage or loss of pressure, often used in reference to leakage of compression past piston ring between piston and cylinder (Tolboldt & Johnson, 1972).

Catalyst. A catalyst is a substance that acts to change the speed of a chemical reaction without itself undergoing a permanent change in the process (Brown & LeMay, 1977).

Cylinder Liner. In a diesel engine, a cylinder liner is a sleeve or tube installed between the piston and the cylinder wall or cylinder block to provide a readily renewable wearing surface for the cylinder (" Engine Fundamentals," 1979).

Diesel Engine. In this engine, fuel is ignited in the cylinder from the heat generated by compression. The fuel used is an oil, rather than gasoline, and no spark plug or carburetor is required (" Engine Fundamentals," 1979).

Direct Injection Diesel Engine. In a direct injection diesel engine, fuel is sprayed directly into the combustion chamber, that is, on top of the piston (Tolboldt & Johnson, 1972).

Displacement. In an engine, this is the volume of air moved or displaced by moving the piston from one end of its stroke to another. Engine displacement is expressed in liters (or cubic inches), and is the sum of each cylinder's individual displacement (" Engine Fundamentals," 1979).

Ethylene Glycol. This is a permanent type of antifreeze, meaning the solution will not boil away at normal engine operating temperatures. This does not mean, however, that the solution is good for use for more than one season (" Engine Fundamentals," 1979).

Exhaust Density. This is the actual amount of exhaust gases that are passed through the engine's muffler as a result of the combuston process. Exhaust density is also referred to as smoke, and it is measured with a Robert Bosch smoke meter. The units of measure are Robert Bosch Units.

Indirect Injection Diesel Engine. An indirect injection diesel engine (unlike a direct injection diesel engine) has a precombustion chamber, meaning, a portion of the combustion chamber is contained in the cylinder head or cylinder wall and is connected to the space above the piston with a small passage (Tolboldt & Johnson, 1972).

Injection Pump. In a diesel engine, this is a device in which the fuel is metered and delivered under pressure to the injector (" Engine Fundamentals," 1979).

Injector. An injector is an assembly that receives a metered charge of fuel from the injection pump at relatively low pressure, then is actuated to inject the charge of fuel into a cylinder or chamber at high pressure and at the proper time (" Engine Fundamentals," 1979).

Nitrogen Fixation. This is a process that converts atmospheric nitrogen into a form that plants can use (Brown & LeMay, 1977).

Pin Bore. In reference to a piston, these are the two oval-shaped holes that are cast into the piston into which the wrist pin is fitted. The wrist pin is connected to the connecting rod, which is connected to the crankshaft, thereby, allowing the piston to move up and down as the crankshaft is rotated.

Piston Lands. Piston lands are those parts of a piston between the piston rings (" Engine Fundamentals," 1979).

Piston Skirt. This is the part of the piston below the piston rings (" Engine Fundamentals," 1979).

Piston Undercrown. This is the bottom side, or underneath portion of the combustion bowl of the piston.

Plunger. In an injection pump, the plunger generates the high pressure and pumps the fuel to the delivery valve (" Diesel Fuel-Injection," 1981).

Plunger Helix. This is the helical or diagonal straight control edge on the outside of the plunger. The helix is machined into the plunger, and it determines the timing of when the fuel is delivered to the injector (" Diesel Fuel-Injection," 1981).

Scoring. Scoring could be a scratch, ridge, or groove that would mar a finished surface (" Engine Fundamentals," 1979).

Transesterification. This is a process that would reduce the molecular weight (i. e., viscosity) of a vegetable oil fuel to about that of diesel fuel. Alkali metals (e. g. sodium) are used as a catalyst with alcohol (either methanol or ethanol). The metal is dissolved in the alcohol and mixed in a reaction chamber. The mixture is heated to 60 - 80° C for several hours to accelerate the reaction, and then it is cooled. The mixture is then separated into glycerine-water and ester-alcohol, which can be drained. The glycerine is then separated from the water, and the ester-alcohol mixture is separated as well. The ester is dried and filtered until it is pure enough for use. The total amount of time required for this process is two to three days (Vellguth, 1983).

Chapter 2

REVIEW OF RELATED LITERATURE

Gerhard Vellguth (1983) a German scientist at the Institute for Basic Research in Agricultural Engineering stated, " There is no standard method to prove the performance or suitability of fuel in engine tests " (p.5). Based upon a review of the related literature, this statement would appear to be true, as no standardized test procedure for alternative fuel evaluation was uncovered. Methodologies ranged from using single-cylinder engines to complete engines of different types and displacements, and test hours varied from as little as 10 hours to thousands of hours.

Tests conducted by various universities, engine manufacturers, and research institutions have revealed problems such as crankcase oil thickening, loss of power, increased fuel consumption, fuel filter plugging, and carbon deposits on pistons, piston rings, and injectors were encountered when soybean oil was used as a fuel in diesel engines (Adams et al., 1983; Clark et al., 1984; Humke & Barsic, 1981; Jacobus, Geyer, Lestz, Taylor, & Risby, 1983; Mittelbach & Tritthart, 1988; Pestes & Stanislao, 1984; Suda, 1984; Vellguth, 1983). A review of the literature revealed conflicting reports as to what caused these types of problems. For example, Clark et al., (1984) believed the number one problem with using vegetable oils as fuels was their higher viscosity (compared to diesel fuel), while Ziejewski and Kaufman (1983) believed the chemical properties rather than viscosity was the major factor in performance deterioration.

Researchers have proposed several major solutions to the performance and carbon deposit problems. Several researchers recommended using a blended fuel mixture of soybean oil and diesel fuel in lieu of pure soybean oil (Adams et al., 1983; German et al., 1985; Mittelbach & Tritthart, 1988; Suda, 1984). Adams et al. (1984) reported a blend of one-third soybean oil and two-thirds diesel fuel was acceptable for use in agricultural equipment during periods of fuel shortages or allocations. A 50/50 blend or greater was reported to cause thickening of the crankcase lubricating oil. Murayama et al. (1984) reported a blend of 75% diesel fuel and 25% soybean oil was acceptable.

An example of successful test results with a blended fuel mixture was by German et al., (1985). In their study, three tractors equipped with 3.6 L engines operated from 255 to 422 hours with no engine-related problems. These tractors were used to mow grass alongside of highways. Blends of 10%, 20%, and 40% soybean oil was used.

Probably the most interesting reported case of testing a blended fuel was conducted by Mittelbach and Tritthart (1988). In their study, used frying oil was collected from restaurants and households over a period of one year. Food particles were removed, and the frying oil was used to fuel a Volkswagen diesel rabbit. A 50/50 blend of the used frying oil and diesel fuel was tested. Fuel consumption was reported to be the same as with the diesel fuel, and only a feint smell of burnt fat was noticed. A total of 100 liters of fuel was tested with no reported engine problems.

As a final example, since July 1982, the Brazilians have been allowed to use a blended fuel of crude degummed soybean oil and diesel fuel (up to 30% by volume) in earthmoving equipment. The only restriction was this blended fuel had to be used in indirect injection diesel engines (Suda, 1984).

The second major proposed solution was to heat the soybean oil fuel. Pryde (1984) found heating vegetable oil fuels to 145° C lowered its viscosity to that of number two (No. 2) diesel fuel at 40° C, while Murayama et al. (1984) recommended heating vegetable oil fuels to over 200° C to lower their viscosity.

The third major proposed solution was to reduce the viscosity of the vegetable oil fuel through a process known as transesterification (Clark et al., 1984; Jacobus et al., 1983; Pestes & Stanislao, 1984; Vellguth, 1983; Ziejewski & Kaufman, 1983).

Other solutions were proposed by different researchers for solving the performance-related and carbon deposit problems. Adams et al. (1983) reported the soybean oil fuel selected should be degummed oil and not crude oil. Their studies showed degumming minimized deposit formation in the injection pump and fuel filters, but additional refining of the fuel offered no additional benefits. Clark et al. (1984) suggested installing additional fuel filters to reduce plugging, and thus reduce performance deterioration. In addition to these recommended solutions, Vellguth (1983) proposed advancing the injection timing approximately four degrees of the crankshaft compared to manufacturer's specifications. He believed not totally burning a good quality fuel was due to either to a lack of oxygen or a lack of time to allow the air to properly mix with the fuel. Because the required amount of air was present, this meant the amount of time available to mix the air and fuel was inadequate. Therefore the time was extended by advancing the injection pump timing. By doing this, fuel consumption and exhaust density improved, and carbon deposits were reduced on the pistons and fuel injectors.

Chapter 3

METHODOLOGY

In general, the methodology used for this study was to obtain an engine, instrument it, conduct the test, and then the data was collected and analyzed. Additional information regarding each individual procedure used to conduct this study was:

Obtain Engine

A six cylinder, 7.6 L, direct injection, turbocharged and aftercooled engine was purchased from a local engine manufacturer for use in this study (see Appendix B for engine specifications).

Prepare Engine for Testing

Antifreeze (50/50 mixture of ethylene glycol and water) was added to the cooling system, and the crankcase was filled to the full level mark on the dipstick (approximately 21 L) with the engine manufacturer's recommended 5W-30 break-in oil. The engine was installed in a test stand. It was then transported to the test cell area and connected to a General Electric electric dynamometer capable of absorbing 224 kW of power.

Break-In

The engine was run through the engine manufacturer's specified 17 minute production break-in using No. 2 diesel fuel. The purpose of the break-in procedure was to wear-in moving parts to a point where they could withstand higher pressures and loads without scuffing or damaging these parts. The break-in procedure was as follows:

1. The clutch was disengaged, and the engine was started and operated at slow idle (850 rpm), no load for one minute.

2. The clutch was reengaged, and the throttle lever was set to the fully open position (fast idle speed, 2400 rpm). The dynamometer was used to load the engine to 286 Newton meters, or 50% of the engine's rated speed torque. The engine was run for 10 minutes at this condition. During this part of the break-in procedure, oil pressure and coolant temperatures were monitored for any abnormal levels. None were found on this engine.

3. The engine was then run at full load, rated speed (132 kW at 2200 rpm) for five minutes.

4. Finally, the engine was allowed to cool down prior to shutting it off by running the engine at fast idle (2400 rpm), no load for one minute. Once again, any problems observed would have been corrected during this portion of the break-in, but no problems were encountered with this engine.

Baseline Test

A one hour baseline test was run at full load, rated speed with No. 2 diesel fuel to establish initial performance parameters.

Pilot Test

Upon completion of the baseline test, the engine was run with 100% crude soybean oil obtained from Phillips Petroleum Company at full load, rated speed for 200 hours. A test time of 200 hours was chosen because this was considered the minimum amount of running time necessary to provide a reasonable indication of expected life and adequate to screen out any severe problems. It was understood that measured wear would be only a fraction of the initial design tolerance because 200 hours represented only two to four percent of the expected engine life to overhaul.

Data Collection

The following equipment and/or procedures were used to collect the data for this study:

1. A Digital analog-to-digital (A/D) test cell computer was used to automatically record performance parameters such as power, air intake, exhaust, coolant, oil and fuel temperatures, intake manifold, and oil pressure.

2. Validyne transducers with a zero to 500 kPa range, with A/D signal conditioning capabilities were used to monitor the various pressures recorded.

3. Viatran K-type thermocouples were used to monitor temperatures.

4. Air intake and exhaust restrictions were set to the engine manufacturer's required specifications for testing, which was 3.0 kPa intake restriction and 7.5 kPa exhaust restriction. Both air intake and exhaust restrictions were set using butterfly valves located in the intake and exhaust pipes. The air intake restriction was manually controlled at the engine by the test cell operator, and the exhaust restriction was wired into the operator's control console.

5. A wire-wrapped hose was installed at the inlet to the fuel injection pump to measure fuel inlet temperature, and a Barber-Coleman fuel temperature controller with a 30 - 75° C range was used to control fuel temperature.

6. The test cell operator manually checked exhaust density (smoke), blowby, and oil consumption every 24 hours. Exhaust density was checked using

a Robert Bosch smoke meter. Blowby was checked using a Rockwell gas meter, and oil consumption was checked by visually observing the graduations on a sight glass connected to the engine test stand.

7. Every 24 hours, 120 milliliters of oil was drained from the engine crankcase, collected in a plastic sampling bottle, and delivered to the engine manufacturer's oil laboratory to analyze the amount of wear metals in the oil as well as oil deterioration due to changes in viscosity.

Follow-Up

Upon completion of the 200 hour durability test, the following procedures were performed:

1. The instrumentation was disconnected, the oil and coolant were drained from the engine, and the engine was removed from the test cell.

2. The engine was removed from the test stand. It was then installed in a roll-over test stand so it could be disassembled.

3. Engine components were visually inspected, and then the pistons, piston rings, cylinder liners, and intake valves were measured using a Sheffield proficorder linear profile charting system.

4. The engine was rated and demerits were assigned per the engine manufacturer's QAR manual.

5. A local professional photographer was hired to photograph various component parts.

6. The engine was rebuilt to the engine manufacturer's specifications with various new parts.

7. The engine was prepared for storage. Engine parts were lightly coated with clean engine oil for rust prevention, all external openings were covered, and the engine was then stored in the inactive storage area.

Chapter 4

RESULTS

Performance

The initial observed power on the engine with No.2 diesel fuel was 132.4 kW. After switching over to 100% crude soybean oil, the power immediately dropped to 129.5 kW, or approximately a two percent loss of power. The fuel delivery was increased by adjusting the injection pump's fuel screw until 132.5 kW was obtained with the soybean oil (see Appendix C-1 for beginning and end-of-test power check data). At the normal fuel inlet operating temperature of 40° C, the soybean oil fuel could not be pumped through the filters at the normal supply pressure of 137 kPa. The fuel temperature of the soybean oil fuel had to be heated to 50° C to keep the engine running. With the exception of a loss of power due to repeated fuel filters plugging, no problems were encountered with any of the performance parameters being monitored.

Oil Analysis

One oil sample was taken approximately every 24 hours and analyzed at the engine manufacturer's oil laboratory. Results showed no excessive wear metals in the oil, and no excessive increase in viscosity. The engine manufacturer's recommended oil was used, which consisted of a 5W-30 break-in oil for the first 100 hours, followed by 30 weight oil for the remaining 100 hours of the test. As shown in Table 1, the parts-per-million (ppm) of iron was 62, the ppm of lead was eight, and the ppm of copper was seven at the end of the 200 hour test (100 hours on the oil). The engine manufacturer specified ppm of iron should be less than

0.75 ppm per oil hour, and the ppm for both copper and lead should be less than 0.50 ppm per oil hour. All three wear metals met this specification. The specification for percent increase in viscosity was no more than 50% at 100 oil hours. The end-of-test viscosity measured 136 centistokes (28% increase), which was within specification.

Table 1

Wear Metals and Viscosity as a Function of Hours

Test Hours	Oil Hours	Al	Cu	Fe	Pb	Mg	Visc. MM2/S
24	24	6	25	25	9	3	44
54	54	7	23	38	12	3	47
78	78	8	18	49	15	3	50
100	100	9	16	65	19	4	57
101	1	2	3	13	3	1	106
126	26	4	5	18	5	1	110
172	72	7	5	45	7	3	122
200	100	7	7	62	8	3	136

Note. The definitions of the column headings are aluminum is Al, copper is Cu, iron is Fe, lead is Pb, manganese is Mg, viscosity in centistokes is Visc.MM2/S.

One noteworthy item was the ppm of manganese. As shown in Table 1, manganese never exceeded four ppm for the entire test. In studies conducted by

Adams et al., (1983), manganese showed the greatest increase of the wear metals. Manganese is a known catalyst used by the paint and varnish industries to harden plant oils, therefore, its increase could be significant. Manganese would enter the oil as a result of engine wear, since it is a component of steel.

Failures

According to Snyder (1978), a failure is defined as, " any engine deficiency which generates a warranty claim." (p.11). The results of this study showed repeated fuel filter plugging would most likely have generated a warranty claim, with the primary failure mode being a reported loss of power. No oil, fuel, or coolant leaks were observed during test, and no other problems were encountered.

Carbon Deposits

Visual inspection of the engine components revealed excessive carbon deposits were present on all of the power cylinder parts (i. e., pistons, piston rings, cylinder liners, and valves). Figure 1 is a photograph of a typical piston which had excessive carbon build-up on the top of the piston, as well as in the combustion bowl.

Figure 1. A photograph showing excessive carbon deposits on the head and in the combustion bowl of a typical piston.

Also, excessive carbon deposits had accumulated in the numbers one and two compression ring grooves. These grooves were approximately 75% filled with carbon. The carbon was well-packed in the grooves, and it was hard to the touch. The piston skirts, pin bores, and undercrowns were in good condition. No excessive debris scratching, varnish build-up, or evidence of scoring were observed.

Figure 2 and Figure 3 show a typical number one and number two piston compression ring with heavy carbon deposits present on the top side of the rings. Excessive carbon deposits were also observed on the top flange of the cylinder liners (see Figure 4).

Figure 2. A photograph showing the carbon deposits on the top side of a typical number one piston compression ring.

Figure 3. A photograph showing the carbon deposits on the top side of a typical number two piston compression ring.

Figure 4. A photograph showing the carbon deposits on the top flange of a typical cylinder liner.

Figure 5 shows the combustion face of the cylinder head (number two cylinder). Excessive carbon deposits were present on the face of the head and on the head of the intake valve.

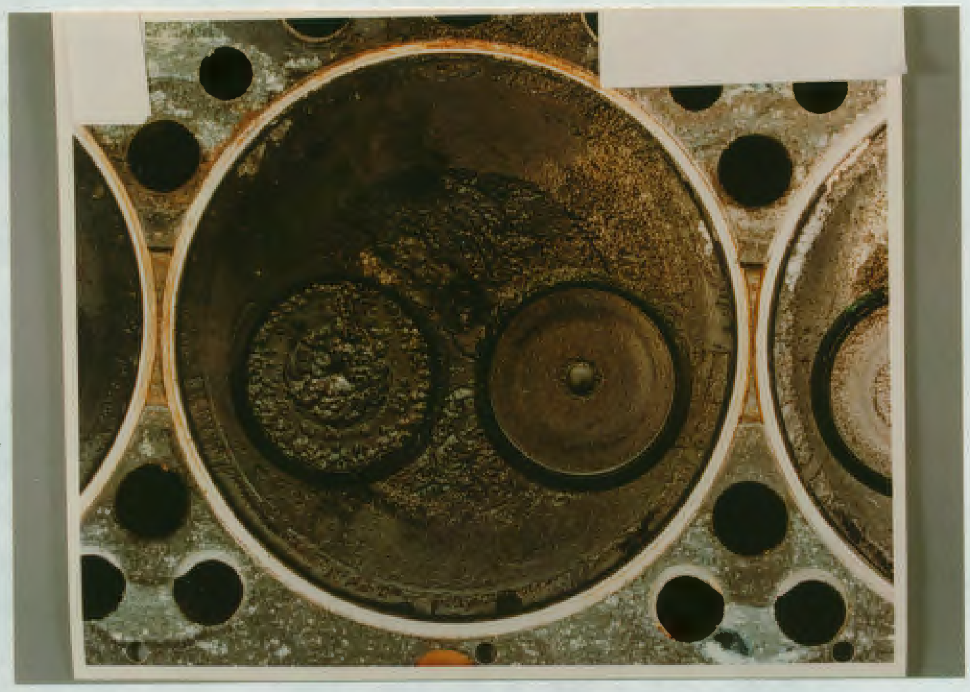

Figure 5. A photograph showing the carbon deposits on the combustion face of the cylinder head and on the bottom of the intake valve.

Severe carbon deposits were also observed on all six fuel injector tips after test. A typical injector and the heavy carbon deposits on the tip is shown in Figure 6.

Figure 6. A photograph showing the excessive carbon deposits on the tip of a typical fuel injector.

As a follow-up check, all six nozzles were tested for opening pressure loss, spray pattern, tip leakage, and plugged spray holes on the test bench. The opening pressure ranged from 25,900 to 27,600 kPa, with the mean opening pressure being 26,700 kPa. The opening pressure specification on a new injector was 29,700 plus 15,000 minus zero kPa. Opening pressure loss was considered normal for 200 hours of testing. No heavy tip leakage was observed, and no spray holes were found plugged.

In addition, the fuel injection pump was disassembled and visually inspected. Deposits were observed on all six plunger helixes and delivery valves (see Figure 7 and Figure 8).

Figure 7. A photograph showing the deposits in the helix of a typical fuel injection pump plunger.

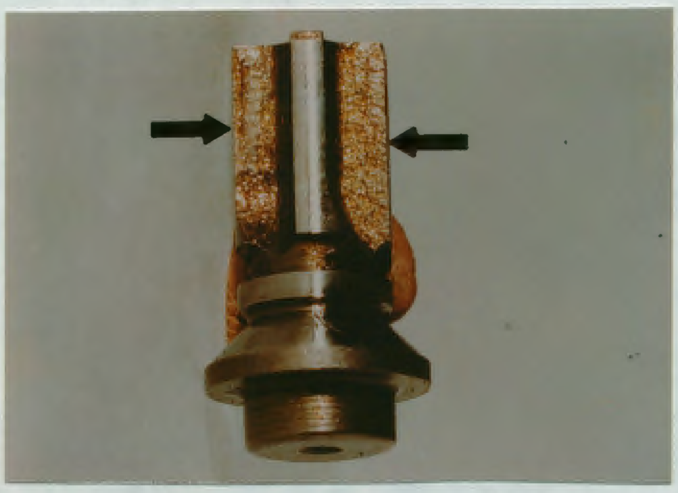

Figure 8. A photograph showing the deposits on a typical fuel injection pump delivery valve.

Also, slight scoring was observed on all six fuel injection pump plungers (see Figure 9).

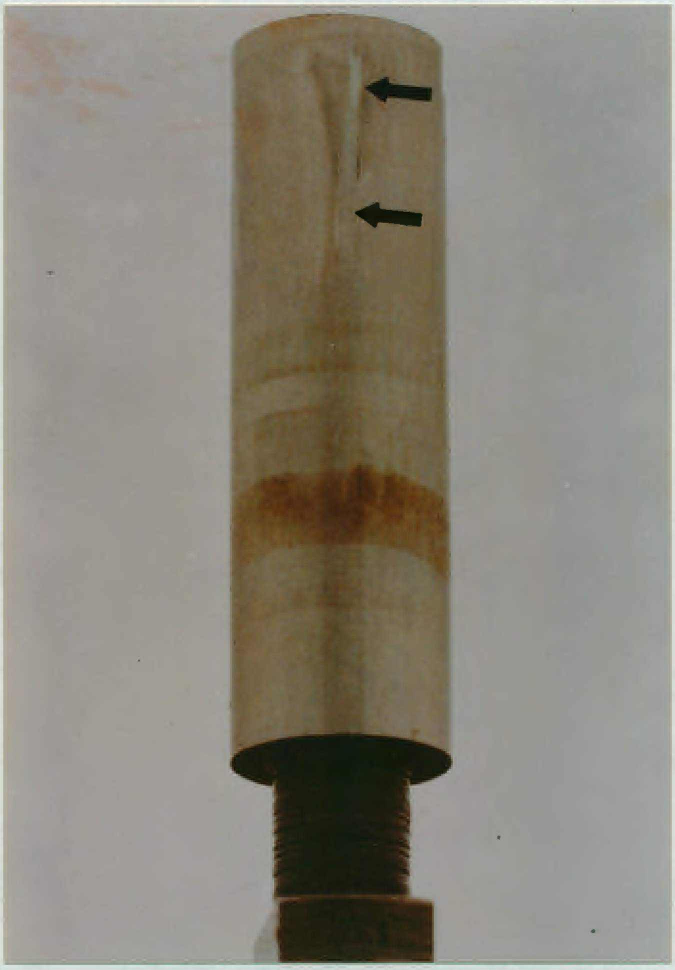

Figure 9. A photograph showing scoring on a typical fuel injection pump plunger.

The remaining fuel injection pump components were not adversely affected by the use of soybean oil as a fuel.

The amount of carbon deposits on all six pistons were rated according to the engine manufacturer's QAR manual. Based upon the manual's categories, these pistons were assigned 30 demerits. The worst rating possible for piston deposits was 40 demerits (see Appendix D-1 for data). Per the QAR manual, the range for a high quality engine was zero to 50 demerits. Carbon deposits on the pistons alone would have used up 60% of the allowable range for a high quality engine.

Component Wear

Proficorder traces were taken after test on the pistons, piston rings, cylinder liners, and intake valves (see Appendix E-1 for data). The amount of wear measured on these parts was compared to standards set forth in the QAR manual. All components measured showed excellent wear characteristics, consequently, no demerits were given under this category.

In addition to comparing wear rates with the QAR manual, the T-test distribution (two-tailed) was used to test the null hypothesis that there was no statistically significant difference between the wear rates of those components (i. e., pistons, piston rings, cylinder liners, and intake valves) tested with soybean oil fuel versus those components tested with diesel fuel. The F-test was first used to distinguish whether or not the variances of the two populations (i. e., parts tested with soybean oil fuel, and parts tested with diesel fuel) were equal (Johnson, 1984). This was done in order to determine what T-test formula should be used. The sample sizes used in the study were $\underline{n}$ = 6 for soybean oil parts and $\underline{n}$ = 36 (six engines randomly sampled, multiplied times the number of cylinders) for diesel fuel parts. The degrees of freedom used for the numerator was five, and the degrees of freedom used for the denominator was 36. At the .05 level of significance, the critical value was determined to be 2.48, with the critical region being to the right on this one-tailed test. This was due to the larger variance being always in the numerator. The formula $F = \frac{S_1^2}{S_2^2}$

was used where S_1^2 was the variance of the soybean tested parts, and S_2^2 was the variance of the diesel fuel tested parts. In all parts evaluated, the calculated F value was not in the critical region, therefore, the variances were considered equal and the following T-test formula was used to test the null hypothesis that there was no statistically significant difference between parts tested with a soybean oil fuel versus parts tested with diesel fuel:

$$t = \frac{(X_1 - X_2) - (u_1 - u_2)}{S_p\sqrt{(1/n_1) + (1/n_2)}}$$

where: $\bar{x}_1$ = mean of part tested with soybean fuel

$\bar{x}_2$ = mean of part tested with diesel fuel

S_p = 0.44096 which was the pooled estimate for the standard deviation for every part evaluated in the study. The formula for S_p was:

$$S_p = \sqrt{\frac{(n_1 - 1) S_1^2 + (n_2 - 1) S_2^2}{n_1 + n_2 - 2}}$$

where: $n_1 - 1$ = the number of degrees of freedom for soybean oil part

s_1^2 = the variance of the soybean oil part

$n_2 - 1$ = the number of degrees of freedom for diesel fueled parts

S_2^2 = the variance of the diesel fuel part

$n_1 + n_2 - 2$ = the number of degrees of freedom, which was the sum of the number of degrees of freedom for the two samples

n_1 = the sample size of soybean oil parts

n_2 = the sample size of diesel fuel parts

The results of the T-test were the null hypothesis was rejected (i. e., there was a statistical difference) on three out of the six parts evaluated. Those parts in which the null hypothesis was rejected were: (a) top piston ring groove wear; (b) second piston ring groove wear, and (c) top compression ring wear. Those parts where the null hypothesis was accepted were: (a) number two compression ring wear; (b) cylinder liner wear; and (c) intake valve seat wear. The calculated T value for the piston rings, cylinder liners, and intake valves was negative, meaning the averages of these parts tested with soybean oil were lower than the averages of these same parts tested with diesel fuel (see Appendix F-1 for data).

Chapter 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Long-range forecasts continue to indicate that as petroleum becomes depleted, increased petroleum-based fuel costs will make alternative fuels more attractive. Vegetable oil fuels are a potential short-range option, because they are a renewable resource. The economics of using vegetable oils as diesel fuel have been examined by various research institutions, universities, and engine manufacturers. The general agreement has been that large-scale usage of vegetable oils was not feasible at the present time as excessive carbon deposits, piston ring sticking, and crankcase oil dilution problems were encountered. However, vegetable oil fuels could be used as an emergency fuel provided precautionary measures such as more frequent changing of the oil and fuel filters, installing a fuel heater, or using a blended fuel mixture of diesel fuel and vegetable oils were used.

A 200 hour durability test was conducted on a six-cylinder, direct injection diesel engine to evaluate performance parameters and wear rates using a soybean-based fuel. Results of this study were a power loss (due to repeated plugging of fuel filters), and excessive carbon deposits on the power cylinder parts could be expected if 100% crude soybean oil fuel were used. While, on the other hand, no piston ring sticking, oil degradation, or significant wear to the engine components were encountered.

Conclusions

It was concluded from the study that the only performance parameters adversely affected by the use of soybean oil fuel was power and fuel consumption. An approximate 13% loss of power was observed every 20 hours due to the soybean oil plugging the fuel filters. In addition, although excessive carbon deposits were observed on the tips of the fuel injectors, opening pressure and spray characteristics were not affected to the point where a deterioration in power was noticed. Although not measured in this study, an increase in fuel consumption would occur if soybean oil fuel were used. The reason for this was the fuel injection pump metered fuel on a volumetric basis, meaning, since the fuel delivery had to be increased with the soybean oil fuel to obtain the same power output as with diesel fuel, the fuel consumption increased.

Excessive carbon deposits on the pistons, piston rings, cylinder liners, intake valves, and cylinder head combustion face could be expected if soybean oil were used as fuel in a direct injection diesel engine.

Based on running one engine test only, no unusual, abnormal, or excessive wear would be expected to the power cylinder parts (i. e., pistons, piston rings, cylinder liners, and intake valves) as a result of running with 100% crude soybean oil.

Recommendations

The following recommendations are made as a result of this study:

1. Crude, 100% soybean oil was not recommended for use in a direct injection diesel engine under any circumstances.

2. Customers should be informed not to use 100% crude soybean oil in their direct injection diesel engines. This would protect the engine manufacturers against warranty claims for customers who fail to heed the warnings.

3 A design of experiments test should be conducted to evaluate those major proposed solutions uncovered in the review of the literature. Variables that need to be tested are: (a) different blends of soybean oil and diesel fuel; (b) a transesterified fuel produced from an "on-farm" situation, and (c) advanced injection pump timing.

4. Additional research and testing is needed to define the fuel properties of all vegetable oils being considered as alternate fuels.

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Appendix A

Worldwide Quality Audit Rating Manual

Appendix A

Worldwide Quality Audit Rating Manual

Introduction:

1. All the items of quality will be rated on a 1 - 10 scale depending on the seriousness, 10 being the most serious. They will be referred to as "demerits." More critical items will have a relative weight multiplier applied per "demerit scoring guidelines" (see next page).
2. The "demerit scoring guidelines" summarize the items to be considered and give the relative weight multiplier. Tables 1 and 2 explain the actual component demerits for performance and durability.
3. Weighted scores will be the demerits times the multiplier.
4. The total demerit weighted score will be matched to a scale which will be divided into four ranges of quality: high, medium, low and unacceptable.

Quality	Score
High	0 - 50
Medium	51 - 100
Low	101 - 200
Unacceptable	201 - >

Demerit Scoring Guidelines

	Relative Weight	Scoring
Objectives	Multiplier	System
Overall Engine		
A. Performance		
• Power	4	0 - 10 demerits per item per
• Smoke	4	Tables 1
• Torque Rise	4	through 4
• Low Speed Torque	4	
• Oil Consumption	4	
Components		
B. Durability		
• Weaknesses	3	
• Failures		
minor	5	
major	10	
• Leaks	2	
• Oil contamination	1	
• Carbon deposits	1	

Demerit Guidelines System - Tables 1 and 2

Table 1

A. Performance

• Power	+ or - 3 - 4.5%	1 - 3
	+ or - 4.6 - 7	4 - 7
	+ or - < or > 7.1	8 - 10
• Smoke		
"T & A"	2.0 - 2.5	1 - 3
	2.6 - 3.0	4 - 7
	> 3.0	8 - 10
"D"	2.5 - 3.0	1 - 3
	3.1 - 4.0	4 - 7
	> 4.0	8 - 10
• Torque Rise		
"T & A"	13 - 16% & 21 - 24	1 - 3
	9 - 13 & 24 - 28	2 - 7
	< 9 & < 28	8 - 10
"D"	10 - 12	1 - 3
	7 - 10	4 - 7
	5 - 7	8 - 10
• Oil Consumption	0.6 - 0.8	1 - 3
	0.8 - 1.0	4 - 7
	1.0 - 1.2	8 - 10
	> 1.2	10

• Low Speed Torque

<u>Demerits</u>

(1000 rpm torque vs	-5 to -10%	1 - 3
rated speed torque, in	-11 to -14	4 - 7
percent)	> -15	10

Components | Table 2

B. Durability

- Weaknesses

Demerits

	Wear (mm per 1000 hrs.)	
Cylinder Liner	0.025 - 0.040	0 - 3
(At top ring turn around)	0.041 - 0.065	4 - 7
	> 0.066	8 - 10
Ring Groove - #1	0.025 - 0.040	0 - 3
	0.041 - 0.065	4 - 7
	> 0.066	8 - 10
Ring Groove - #2	0.025 - 0.040	0 - 3
	0.041 - 0.065	4 - 7
	> 0.066	8 - 10
#1 Ring - Side	0.025 - 0.040	0 - 3
	0.041 - 0.065	4 - 7
	> 0.066	8 - 10
#2 Ring - Side	0.025 - 0.040	0 - 3
	0.041 - 0.060	4 - 7
	> 0.066	8 - 10
Valve Face	0 - 0.125	0 - 3
	0.126 - 0.254	4 - 7
	> 0.255	8 - 10

Wear of Other Items	Will be determined by severity of damage and expected time to failure	
Cracks	Will be demerited by severity of damage and expected time to failure	

- Failures

Minor	- will not cause downtime	1 - 5
	- will cause downtime	6 - 10
Major		10

- Leaks

  Any water, oil, fuel, or air leaks visible or otherwise noticeable, except those resulting from a mechanical failure

- if likely to produce a complaint	1 - 5
- if likely to produce a warranty claim	6 - 10

- Oil Contamination (ppm Fe)

100 to 150 ppm per 100 hours	1 - 6
151 or more ppm per 100 hours	7 - 10

- Carbon Deposits on Piston

- Top Land	10 sq. mm	1 - 3
	10 sq. mm on 3 more pistons	4 - 7
	10 sq. mm or more on all pistons	8 - 10
- Top Groove	50% filled max.	1 - 3
	75% filled max.	4 - 7
	100% filled	8 - 10

- 2nd Land	75% covered max. and 20% contact max.	1 - 3
	75% covered and 60% contact max.	4 - 7
	100% covered and 100% contact	8 - 10
- Undercrown	Light brown	1 - 3
	Dark brown to black	4 - 7
	Black and build-up of measurable thickness	8 - 10

Appendix B

Engine Specifications

Appendix B

Engine Specifications

Engine Model	6466AR07
Configuration	Inline six cylinder, four-stroke/cycle aftercooled, turbocharged
Displacement	7.6 liter
Combustion System	Swirl port, direct injection
Bore x Stroke	116 mm x 121 mm
Compression Ratio	14.9 to 1
Fuel Injection Pump	Robert Bosch AS3000
Injection Nozzle	Robert Bosch - 21 mm major diameter
Nozzle Opening Pressure	27,900 kPa
Nozzle Assembly	Four orifices - 0.36 mm diameter
Spray Cone Angle	155 degrees
Rated Speed and Power	132 kW at 2200 rpm

Appendix C

Beginning and End-of-Test Power Check Data

Appendix C

Table 1

Beginning and End-of-Test Power Check Data

	Start-of-Test		End-of-Test
Observed Parameter	No.2 Diesel Fuel	Soybean Oil	Soybean Oil
Power (kW)	131.3	132.4	132.5
Smoke (R.B.)	0.8	0.8	0.8
Blowby (L/kW-hr)	64	64	63
Fuel Inlet Temp. (° C)	40	40	40
Exh. Temp. (° C)	486	488	490
Air Inlet Temp. (° C)	25	25	25
Oil Temp. (° C)	113	113	113
Coolant Temp. (° C)	93	93	93
Oil Pressure (kPa)	315	315	315
Int. Man. Press. (° C)	105	105	105

Note. The definitions in the parameter column are kW is kilowatts, R.B. is Robert Bosch smoke units, L/kW-hr is liters per kilowatt-hour, Temp. is temperature, ° C is degrees Centegrade, Exh. is exhaust, kPa is Kilopascals, and Int. Man. Press. is intake manifold pressure.

Appendix D

Rating of Carbon Deposits on Pistons per Quality Audit Rating Manual

Appendix D

Table 1

Rating of Carbon Deposits on Pistons per Quality Audit Rating Manual

Top Land	Demerits	Rel. Wt. Mult.	Score
10 sq. mm	1 - 3		
10 sq. mm on 3 or more pistons	4 - 7	1	
10 sq. mm or more on all pistons	8 - 10		10
Top Groove			
50% filled max.	1 - 3		
75% filled max.	4 - 7	1	7
100% filled	8 - 10		
Second Land			
50% covered	1 - 3		
75% covered	4 - 7	1	
100% covered	8 - 10		10
Undercrown			
Light Brown	1 - 3		3
Dark Brown to Black	4 - 7	1	
Black and Build-up of measurable thickness	8 - 10		
		Total Demerits = 30	

Appendix E

Wear Measurement Summary of Components in Millimeters

Appendix E

Table 1

Wear Measurement Summary of Components in Millimeters

Component	Cylinder						Avg.	Std.Dev.
	1	2	3	4	5	6		
Cyl. Liner	0.004	0.004	0.004	0.005	0.003	0.005	0.004	0.0008
No.1 Groove	0.004	0.002	0.003	0.005	0.002	0.003	0.003	0.001
No.2 Groove	0.002	0.002	0.003	0.001	0.003	0.002	0.002	0.0008
No.1 Ring	0.003	0.003	0.004	0.006	0.006	0.005	0.004	0.001
No.2 Ring	0.002	0.005	0.004	0.003	0.003	0.002	0.003	0.001
Int. Valve	0.004	0.004	0.015	0.015	0.028	0.023	0.015	0.010

Note. The abbreviations for this Table are Std. Dev. is standard deviation, Avg. is average, Cyl. is cylinder, and Int. is intake. Cylinder liners were measured on the right hand side, in the top ring turnaround area. Piston grooves were measured on the right-hand side, with the bottom of the groove measured. Piston rings were measured along the bottom side, 180° from the ring gap. Intake valves were measured across the seat.

Appendix F

Summary of F-test and T-test Distributions Comparing Wear Rates Between Parts Tested With Soybean Oil Fuel Versus Diesel Fuel

Appendix F

Table 1

Summary of F-test and T-test Distributions Comparing Wear Rates Between Parts Tested With Soybean Oil Fuel Versus Diesel Fuel

	Avg. Wear (mm)		Variance		F C.V. 2.48*	T C.V. +/- 1.96!
Parameter	Diesel	Soybean	Diesel	Soybean		
Top Groove	0.002	0.003	0.000001	0.000001	1.00	2.27 !
2nd Groove	0.001	0.002	0.000001	0.00000064	0.64	2.32
Top Ring	0.006	0.004	0.000004	0.000001	0.25	-2.38!
2nd Ring	0.004	0.003	0.000004	0.000001	0.25	-1.19
Cyl. Liner	0.005	0.004	0.000004	0.00000064	0.16	-1.25
Int. Valve	0.018	0.015	0.000121	0.0001	0.83	-0.62

Note. * $p < .05$, one-tailed. ! $p < .05$, two-tailed. Definitions for this table are mm is millimeters, C.V. is critical value, Int. is intake, Cyl. is cylinder, Avg. is average