FACT-Vol. 12, Solid Fuel Conversion
for the Transportation Sector
ASME 1991

TECHNICAL OVERVIEW OF VEGETABLE OIL AS A TRANSPORTATION FUEL

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ABSTRACT

The esters of vegetable oils are renewable, alternative fuels which have potential as direct replacements for diesel fuel in compression ignition engines. Vegetable oils have energy contents about 10 percent less than diesel on a mass basis. They have higher molecular weights, viscosity, density and flash point than diesel fuel. When vegetable oil esters are compared to diesel fuel in engine tests, power and fuel consumption are in nearly direct proportion to the energy content of the fuels. Thermal efficiencies have been shown to be slightly higher, thought to be a result of the oxygenation of the fuel.

Long term engine tests with the methyl ester of winter rape (MEWR) have shown that engine performance, wear and injector coking are equal to or surpass that when the engines are fueled with diesel. Some oil dilution has been observed, but it is not sufficient to be of serious consequences.

Limitations to vegetable oil use are costs and potential production. Costs are driven by the value of the by-products (meal and glycerol); the value of which would likely drop as use of vegetable oil esters increased. Production of vegetable oil esters is limited by available land area. It is estimated that 65 percent of the total U.S. agricultural land would be required to grow the vegetable oil required to replace the diesel fuel used in U.S. transportation. Idle crop land (conservation reserve and set aside) could be used to produce 24 percent of the diesel used in transportation.

Use of vegetable oil esters have positive environmental consequences. Use of these fuels is most desirable when these environmental factors are most beneficial. Engine smoke is reduced by as much as 66 percent at full power; a benefit which might be of use in reducing city smog. However, gaseous emissions such as NO_x are essentially unchanged. CO_2 production from the engine is offset by CO_2 utilization in growing the plant, a fact which has potential for reducing global warming. The fuel is essentially sulphur free and so produces no sulphur dioxide in combustion and thus potentially could reduce the acid rain problem. The fuel is biodegradable and has less severe consequences than does petroleum based fuels when they are spilled into the environment.

INTRODUCTION

Many studies have shown that vegetable oils such as soybean oil, sunflower oil, safflower oil, cottonseed oil, peanut oil and rape oil have potential as alternative fuels for diesel engines. However, this is not an entirely new concept; history records that Rudolph Diesel, the inventor of the engine that bears his name, used vegetable oil fuel in his engines as early as 1900. In the intervening years, readily available, inexpensive and abundant supplies of petroleum based fuels have provided little incentive for experimenting with alternative, renewable fuels. The energy crisis of the 1970's sparked a renewed interest in the use of vegetable oils as fuels (Peterson, 1986). The most promising form of vegetable oil for use in compression ignition (CI) engines is that of an ester (methyl, ethyl or butyl) (Zhang et al., 1988; Sims, 1985,; Wagner et al., 1984; Goering et al., 1982; Kaufman and Ziejewski, 1984; Clark et al., 1984; Quick and Woodmore, 1984; Mora, 1985; Melville, 1987; Mosgrove, 1987; Fort et al., 1982).

It has recently been reported that a 10 million liter per year methyl ester of rape oil for diesel fuel plant has been built in Austria. Several engine manufacturers have extended their engine warranties to cover operation on this fuel. Development of the technology for vegetable oil fuels makes it possible to provide energy for agriculture from renewable sources located close to the area where it can be used.

Vegetable oils are fatty esters of glycerol (triglycerides) and have the structural notation as shown in Figure 1.

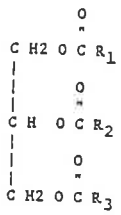

Figure 1. Vegetable Oil's Structural Notation.

R_1, R_2, and R_3 represent the hydrocarbon chain of the fatty acids. R_1, R_2, and R_3 may be the same, depending on the particular oil, but ordinarily are different in chain length and in the number of double bonds present. Shorthand notation for fatty acid consists of two numbers, separated by a colon; the first indicates the total number of carbon atoms, the second the number of double bonds. The most commonly encountered fatty acids in vegetable oil are: lauric 12:0, palmitic 16:0, Stearic 18:0, oleic 18:1, linoleic 18:2, linolenic 18:3, erucic 22:1 and ricinoleic 18:1. All are found in different amounts in vegetable oils, except for ricinoleic which occurs only in castor oil and erucic which occurs in rapeseed and crambe.

This paper will discuss the technical issues surrounding the use of vegetable oils for diesel fuel substitutes which are: Properties of vegetable oils relative to diesel fuel, Fuel evaluation in short term performance tests, Fuel evaluation in long term test cycles, Environmental impact of using vegetable oils as fuel, Processing the methyl ester of winter rape oil (MEWR), Potential production and Economics.

A. PROPERTIES OF VEGETABLE OILS RELATIVE TO DIESEL FUEL.

Over 350 oil bearing crops have been identified, the most predominantly considered of these as fuel substitutes are sunflower, safflower, soybean, cotton, winter rape, canola and peanut. In 1981, 19 percent of the U. S. cropland was planted to vegetable oil crops: 14.7 percent was devoted to soybeans, 3.1 percent to cottonseed, 0.8 percent to sunflower and 0.3 percent to peanuts. Each of the other species were produced in very small quantities. The U. S. is the largest oilseed producing nation (35% of the world production in 1980-81.) In 1981, the U.S exported 363 million gallons of vegetable oil, equivalent to 11 percent of the diesel fuel used in agriculture.

All of the vegetable oils have energy contents similar to diesel (94 percent of the energy content on a volume basis), but vegetable oils are many times more viscous. This high viscosity causes injector pattern problems and is thought to be at least in part responsible for difficulties experienced with engine life.

Goering et al. (1982) presented data on eleven alternate fuels. Vinyard et al. (1982) reported many of the relevant properties of five types of vegetable oils. Needham and Doyle (1985)compared sunflower oil with other alternate fuels. Vander Griend et al. (1989) focused on properties of rape oil and its esters relevant to modeling combustion in a diesel engine.

The relevant vegetable oil properties are determined by the theory of compression ignition combustion. The fundamental process is spray formation. Current theory of the spray atomization which occurs in diesel engines emphasizes the influence of surface waves on droplet breakup. The surface tension of the fuel is critical because of its influence on the stability of these waves. Secondary parameters are the density and viscosity of the liquid. In dense sprays, O'Rourke (1981) showed that the coalescence of the droplets competes with droplet breakup to determine the size distribution in the spray. Again, the surface tension is an important property in this process. The next stage of compression ignition combustion is droplet vaporization. The preceding spray formation is important, as well as the specific heat and thermal conductivity of the fuel. Vapor pressures and heat of vaporization are important for many fuels, but the low volatility of vegetable oils makes their boiling and critical temperatures significant parameters as well.

Table 1 lists the values of these properties for the neat vegetable oil, MEWR and No. 2 diesel additional properties are given in Vander Griend et al. (1989).

Table 1

Properties of Methyl Ester Compared with #2 Diesel and Neat Rapeseed Oil

Test	Rapeseed Methyl Ester	No. 2 Diesel	Neat Rapeseed oil
Cetane rating	54.4	47.8	42.6
Flash Point, °C	*	80	274
Cloud Point, °C	-2.2	-12.2	-11
Pour Point, °C	-9.4	-28.9	----
Viscosity, (cs)			
@40°C	6.2	3.2	46.68
@100°C	2.4	1.3	----
Specific Heat, C_p J/g/C @100°C	2.47	1.7	2.43
Conductivity W/m/C @100°C	0.17	0.11	0.15
Surface Tension mN/m @100°C	25.4	22.5	28.1
Sulfur (%, wt)	0.031	0.32	0.022
Heat of Combustion			
kJ/kg (gross)	40,600	45,300	40,400
Btu/lb (gross)	17,500	19,500	17,370
Specific gravity	0.874	0.852	0.906

* No flash was observed.

Note: Analysis conducted by Phoenix Chemical Laboratory, Inc. Chicago, IL.

Specific heats of the rape oil and its MEWR were determined by the Dynatech R/D Thermophysics Laboratory using a copper drop method. The surface tensions of #2 diesel fuel, Rape Oil, and MEWR were measured by Vander Griend et al. (1988) using the ring method (ASTM D971-50.) using a DuNouy interfacial tensiometer. The results of these two tests are presented in Figures 2 and 3.

The lines for Figure 3 are from linear regressions over six data points. The curve of hexadecane and a curve typical of diesel fuels are included for comparison. The lines for Figure 2 are from linear regressions over eight data points. Hexadecane data from TRC Thermodynamic Tables (1978) are included for comparison. Symbols are scaled representations of a 95% uncertainty interval calculated from the data of three replicates.

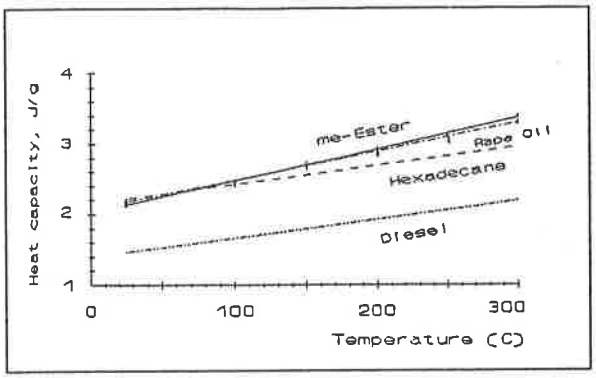

Figure 2. Specific Heats (Data by Dynatech

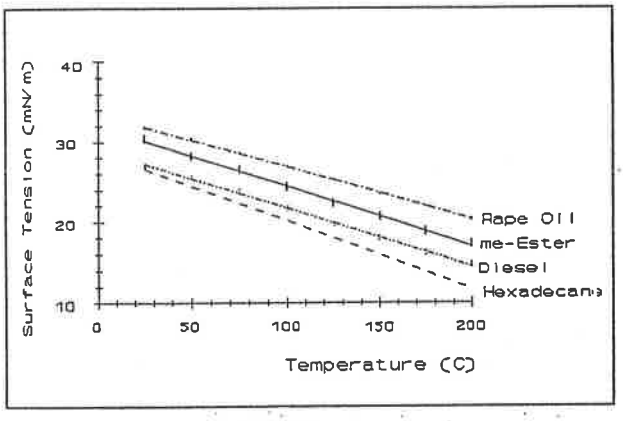

Figure 3. Surface Tensions

Measurement of droplet sizes for the vegetable oil fuels was done by Vander Griend et al. (1988) by capturing the droplets in an immersion liquid for microphotometry. The use of an injection system from a commercially produced engine insured droplet sampling with nozzle geometries (90 μm radius) and pressures typical of engine conditions and also produced the required pulsed, intermittent spray. Ambient fluid density was matched to values representative of the engine chamber through the use of a pressurized spray chamber. Samples were taken at 90, 300 and 575 KPa chamber pressure in a carbon dioxide atmosphere. An injector pump speed of 1500 RPM was used. Samples were photographed with an SLR camera mounted on a Unitron microscope. Droplet diameters were obtained by digitizing three surface points on each droplet. Diameters were segmented into 12 partitions of 20 μm each (0 to 20, 20 to 40, ...).

The vegetable oil and the MEWR have a tendency to form bimodal size distributions. Of special interest is the fact that most of the distributions show at least some probability in the 50 to 70 μm range which is the maximum probability of conventional fuels (Hiroyasu and Kadota, 1974). The existence of droplets smaller than the nozzle radius (90 μm) shows that breakup processes can act upon these fuels. Therefore, the size distributions of droplets from these fuels will be influenced by the fuel properties which affect the breakup mechanism -- surface tension, density, and viscosity.

The interpretation of the properties of rape oil and MEWR with current theory of diesel engine combustion as reported by Vander Griend et al. (1988) gives a perspective on the potential of these alternate fuels. The important parameters are those which affect spray formation and vaporization. Several observations are useful;

1. The slightly higher surface tension of rape oil and MEWR produce droplet size distributions with Sauter Mean Radius double those of conventional fuels when injected under engine conditions.

2. The alternate fuels have higher heat capacities than diesel -- approximately 50% greater specific heats and 3% greater densities at initial injection temperatures.

3. The pressure dependence of the boiling points of most fuels implies that supercritical behavior is possible.

4. To reach critical temperature, diesel requires enough energy to heat it to 385°C, MEWR must reach 419°C, and Rape Oil must be heated to 492°C.

5. At a temperature of 279°C, below the critical point of any of the fuels, the vapor pressure of MEWR reaches that of diesel -- over 200 KPa. At this temperature, the predicted vapor pressure of Rape Oil is 0.4 KPa.

Therefore, sprays of rape oil and MEWR can be characterized by their large droplets with higher heat capacities than conventional fuels. However, the MEWR shows a potential for subcritical vaporization rates similar to those of diesel, while rape oil vapor is only formed at much higher temperatures.

B. FUEL EVALUATION IN SHORT TERM PERFORMANCE TESTS

In a summary of 22 short term engine tests conducted at 12 locations worldwide (Quick, 1980) in which vegetable oil was compared to diesel as a fuel, peak engine power on the vegetable oil fuels ranged from 91 to 109 percent of that produced when the same engine was operated with diesel fuel. In these tests, 16 of the 22 reported peak power equal to or exceeding that when the engines were operated on diesel. Fuel consumption is generally slightly higher reflecting the reduced energy content of the vegetable oil. Thermal efficiencies are also generally reported to be slightly higher than for diesel fuel.

Peterson et al. (1987) ran a series of short term engine tests to evaluate the effects of transesterification of winter rapeseed oil on injector coking. The results showed the transesterification treatment to decrease the injector coking to a level significantly lower than that observed with no. 2 diesel.

C. FUEL EVALUATION IN LONG TERM TEST CYCLES: NEAT VEGETABLE OILS

While short term test results are almost always positive, longer term tests with the neat vegetable oils lead to severe engine deposits, ring sticking, injector coking and thickening of the lubricating oil.

Polymerization of the vegetable oil in the ring belt area causes the rings to seize, associated with an increase in blow-by, and increase in the viscosity of the lubricating oil and resulting catastrophic failure of the engine.

In a North Dakota study where tractors were operated on farms over a three year period with alkali-refined, winterized sunflower oil/no. 2 diesel fuel blends the engines operated a total of 7616.9 hours and burned a total of 145,891.8 liters of fuel (German et al., 1985). Three tractors were fueled with 25% sunflower oil/75% diesel and three with 50% sunflower oil/50% diesel. All engines were turbocharged, direct injection diesel engines. Two were intercooled and one used a fuel and a lubricating oil additive. One engine experienced a camshaft/valve train failure. Most deposits were found on engines fueled with the 50% sunflower oil; a significantly lower level of deposits were found on pistons from engines fueled with 25% sunflower oil. The lowest average amount of deposits were found on pistons fueled with only no. 2 diesel fuel. No injector coking problems or ring sticking problems were encountered. Bearing wear was normal.

They concluded that use of a 25% sunflower oil/75% No. 2 diesel fuel blend or a 50% sunflower oil/50% diesel fuel blend as a substitute diesel fuel cannot be recommended. However, under emergency conditions, a 25/75% blend of alkali-refined, winterized sunflower oil/diesel fuel could be used as a diesel engine fuel. The operator must be aware that reduced engine life would occur.

D. FUEL EVALUATION IN LONG TERM TEST CYCLES: DIRECT INJECTION VS. INDIRECT INJECTION ENGINES

Problems associated with using vegetable oils have been observed to be much less severe in indirect injection engines; i.e., those with pintle type injectors and precombustion chambers, than in their direct injection counterparts. One test in South Africa reported on an engine installed in an agricultural tractor and subjected to extended service life power takeoff drive (pto) tests using the manufacturer's cycle. After 1800 hours no problems were observed and no injector coking was evident. The general condition of the engine components at the completion of the test was such that the manufacturer issued a warranty on their indirect injection engines for operation on sunflower oil. (Fuls et al., 1984). This and other tests has shown that vegetable oil can be used successfully in unmodified, indirect injection engines. The worldwide trend in engine design is away from the indirect injection engines toward direct injection engines because of their increased fuel economy. Most tractors made in the U.S. are of the direct injection type while most of the small import tractors are indirect injection.

E. FUEL EVALUATION IN LONG TERM TEST CYCLES: TRANSESTERIFIED VEGETABLE OIL FUELS

Einfalt and Goering (1985) evaluated the methyl ester of soybean oil, Wagner et al. (1984) investigated three types of soybean oil esters (methyl, ethyl and butyl), Kaufman and Ziejewski (1984) evaluated methyl ester of sunflower oil and Zhang et al. (1988) evaluated methyl esters of winter rape oil in 200 hour EMA test cycles. They concluded that the performance of the esters of soybean oil did not differ greatly from diesel. The brake power was nearly the same as with diesel fuel while the specific fuel consumption was higher than diesel. Based upon crankcase oil analysis, engine wear rates were low but some oil dilution did occur. Carbon deposits inside the engine were normal with the exception of intake valve deposits.

Although most researchers agree that vegetable oil ester fuels are suitable for use in CI engines, a few contrary results have also been obtained. Vinyard et al. (1982) reported an extensive coking problem while using degummed sunflower ethyl ester. The ester produced unacceptable coking levels after only 50 hours of operation under part load even when diluted with up to 30% diesel fuel.

The results of these studies point out that most vegetable oil methyl esters are suitable as diesel substitutes but that more long term studies are necessary for commercial utilization to become practical.

University of Idaho 1000 Hour Tests

Tests at the University of Idaho have shown that use of the MEWR is equivalent to diesel fuel in direct injection, diesel engines.

Three engines, one fueled with 100% methyl ester of winter rapeseed oil (100 RE), one with a 50% number 2 diesel - 50% methyl ester (50RE-50D2) of winter rapeseed oil blend, and one with a reference fuel of 100% number 2 diesel (100 D2), were investigated in both 200 hour Engine Manufacturer's Association (EMA) test Cycles (Zhang et al., 1988) and in 1000 hour test cycles using the EMA test procedure for alternate fuels (EMA, 1982). It was found that methyl ester of winter rapeseed oil was equivalent to number 2 diesel when compared on the basis of long term performance and engine wear. The primary factors which were evaluated included engine brake power and torque, injector tip coking, and engine component wear (based on oil analysis). The only noticeable adverse effect of the ester fuel was a slight decrease in engine oil viscosity.

Yanmar 3TN75E-S diesel engines (3-cylinder, 4-stroke, naturally aspirated,direct injection) were selected as the test engines. Each has a bore and stroke equal to 75 mm a displacement of 994 cc, a compression ratio of 17.6:1 and a one-hour power rating of 16 kW at 3000 rpm. These engines were chosen because their direct injection design is typical of most diesel engines used in agriculture today.

The 1000 hour test cycle was run to evaluate the engine durability effects of long term usage of 100RE and 50RE-50D2 in comparison to 100D2. The test was performed on three identical engines simultaneously and controlled by the microcomputer based data acquisition and control system. At 50 hour intervals, oil samples were taken from each engine's crankcase and analyzed by a commercial lab for wear metal concentrations and viscosity changes. The crankcase oil was changed at 100 hour intervals.

At 100 hour intervals, the test was halted to run the following tests with each engine running on its respective test fuel:

Constant throttle - variable speed torque test
Injector performance check
Cylinder compression check

Also each of these 100 hour intervals, the injectors were visually examined for coking and ranked on a scale of 1 to 10 by comparison with pre-ranked injector photographs from previous tests to give a qualitative record of injector coking over the duration of the test. The injectors were also

periodically photographed and digitized to provide a quantitative record of injector coking.

All engine service and maintenance was performed as specified in the manufacturers service manual.

The methyl ester of winter rape oil used in the test was produced as described by Peterson et al. (1989).

Fuel Consumption

The engine fueled on 100D2 consumed 3607 liters of fuel while the engines fueled on 100RE and 50RE-50D2 consumed 3701 and 3589 liters of fuel, respectively.

Engine Performance

The observed trends in power over the course of the experiment are shown in Figures 4 and power curves measured at the conclusion of the test as Figure 5.

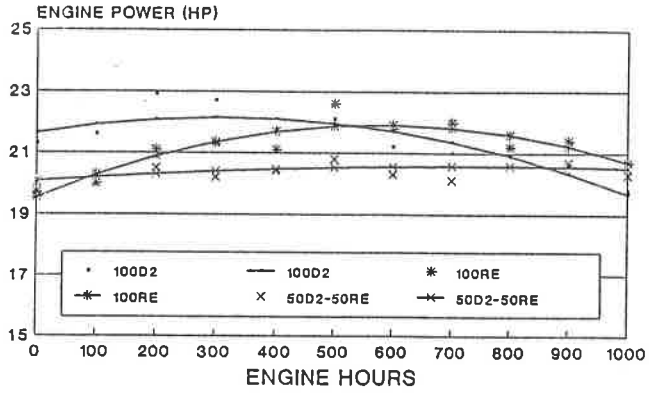

Figure 4. Maximum engine power at 100 hour intervals during the 1000 hour endurance test.

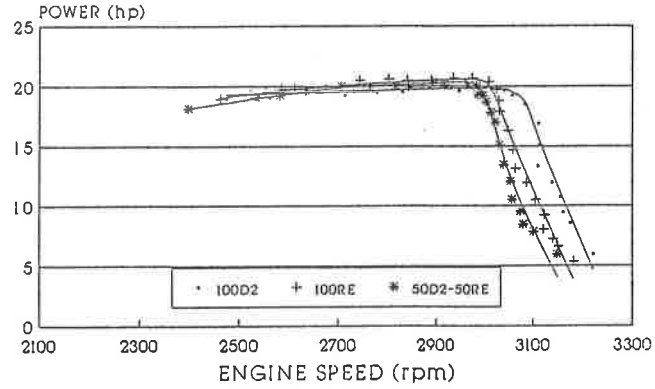

Figure 5. Power curves at 1000 hours of the 1000 hour endurance test.

The test began with the 100D2 providing the most power and the 50RE-50D2 second and the 100RE having the lowest power output. The 100D2 fueled engine reached its peak power output after 200 hours and gradually declined from there. The 100RE fueled engine reached its peak output at 500 hours while the 50RE-50D2 fueled engine reached its peak at 800 hours. It was noted that from the 500 hour mark on the 100RE fueled engine produced more power than the 100D2 fueled engine and from the 800 hour point on the 50RE-50D2 fueled engine also produced more power than the 100D2 fueled engine. (The 100RE fueled engine produced more power than the 50RE-50D2 engine from the 200 hour mark on.)

The torque output followed the same general trend as the power output with the only major difference being that the 100RE fueled engine started out with a slightly higher torque than the 50RE-50D2 fueled engine. Another notable difference is that the 100RE fueled engine produced a "flatter" power curve than the 100D2 and 50RE-50D2 fueled engines.

Oil Analysis

No major problems with viscosity were observed. A slight decrease in oil viscosity was observed with the ester fueled engine, but throughout each 100 hour interval the viscosity, remained within the allowable limits (SAE 25 - SAE 45) for SAE 30 motor oil. This decrease can most likely be attributed to fuel dilution of the crankcase oil. The diesel engine experienced increases in oil viscosity near the end of the test but still remained within the allowable limits for SAE 30. This increase can possibly be attributed to increasing levels of oxidation and nitration from the worn engine. The viscosity data at each oil change is shown in Figure 6.

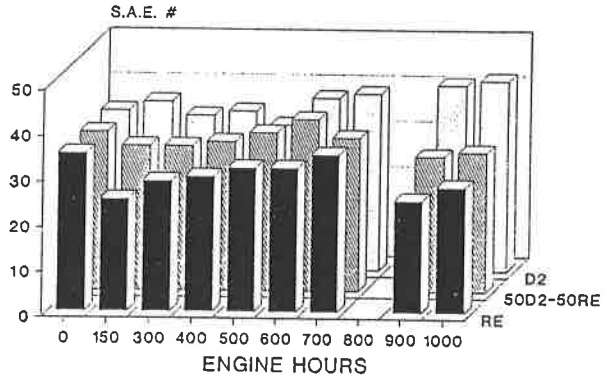

Figure 6. Oil viscosity at 100 hour oil change points.

Engine wear was evaluated on the basis of the concentrations of four wear metals in the lubricating oil. The metals, and their primary source, used as the wear basis are as follows:

1) Iron - cylinder wear
2) Aluminum - piston wear
3) Chromium - ring wear
4) Lead - bearing wear

Wear metal concentration results were somewhat surprising in that the 100D2 fueled engine consistently produced higher concentrations of iron, aluminum, chromium, and lead in the crankcase oil than did the 100RE and 50RE-50D2 fueled engines, however all were well within the allowable limits. Wear analysis results for iron are shown in Figure 7.The 100RE fueled engine consistently had the lowest wear metal concentrations of the three engines. This could possibly be attributed to the lower peak pressures and slower rate of pressure rise observed in the combustion of methyl ester of winter rape (Vander Griend et al., 1988).

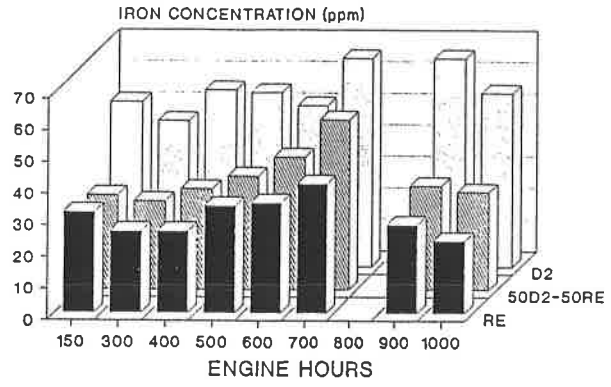

Figure 7. Concentration of iron in engine oil wear metal analysis at 100 hour oil change intervals.

Injector Coking

The coking results from the qualitative visual ranking method and quantitative digitizing method were very similar. Only the digitizing method results are presented. The injectors were photographed and digitized at 200, 600, 800, and 1000 hours. Following the 800 hour inspection the injectors were cleaned and reset to the manufacturers specifications for opening pressure. As such the 1000 hour results are essentially duplication of the 200 hour results The results are graphically shown in Figure 8.

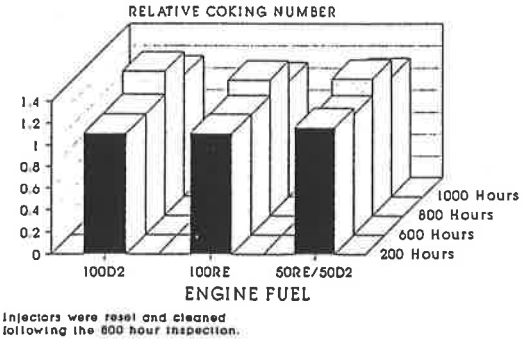

Figure 8. Relative injector coking measured by digitizing photographs of injectors at 200 hour intervals.

At the 200 and 600 hour points there were no significant differences in the coking levels of the different fuels. However, between the 600 and 800 hour marks a very significant increase in coking occurred for all of the fuels with the 100D2 showing the largest increase in coking.

After being cleaned (after the 800 hour inspection) and operated for an additional 200 hours the injector coking level was essentially equivalent to that observed after the first 200 hours of operation.

No significant difference was noted between the coking levels of any of the fuels. The cause of the rapid increase in the coking level between 600 and 800 hours is unknown.

F. ENVIRONMENTAL IMPACT OF USING VEGETABLE OILS AS FUEL

Fatty acid esters have surprisingly good emissions characteristics. Mittelbach et al. (1985) found that emissions of two different methyl ester fuels derived from rape seed oil gave significantly lower total particulates and lower polynuclear aromatic hydrocarbons than #2 diesel fuel. However, combustion of methyl ester fuels produced higher levels of NOx emissions and aldehyde emissions than did #2 diesel fuel. Similar results have been reported by Geyer et al. (1984), Mills and Howard (1983), and Feldman (1988). Particulate production (smoke) has been shown to be reduced by from 50 to 66 percent at full power. Additional long term engine tests, cold starting tests, and studies of gaseous emissions are needed before vegetable oil fuels can be commercialized. Both engine modification and fuel modification have potential for enhancing engine heat release rates and further reducing exhaust emissions.

Vegetable oils are also more environmentally friendly in case of a spill. The fuel is not water soluble and is not carried into the soil and will biodegrade. Tests comparing the effect of spills on the environment are in the planning stage.

Vegetable oil contains no sulphur which decreases the acid rain problem and CO_2 production in the exhaust emissions can be balanced against CO_2 utilization by the vegetable oil producing plant resulting in little or even a net loss in CO_2 with implications for reducing global warming.

G. PROCESSING THE METHYL ESTER OF WINTER RAPE OIL

Transesterification of vegetable oils involves reacting an alcohol with the oil in the presence of an alkaline or acidic catalyst as shown in Figure 9. With methanol, a methyl ester and glycerol are produced.

Hoffman (1989) gave the following description of the transesterification process, " An ester is the condensation product of an acid and an alcohol. Transesterification may be either an acidolysis, where the acid component of an ester is replaced by another acid, or an alcoholysis, where the alcohol component of an ester is replaced with a different alcohol."

Vegetable oils are esters of fatty acids and glycerol. In this work, the transesterification being studied is an alcoholysis where the glycerine component of a vegetable oil is replaced by an alcohol.

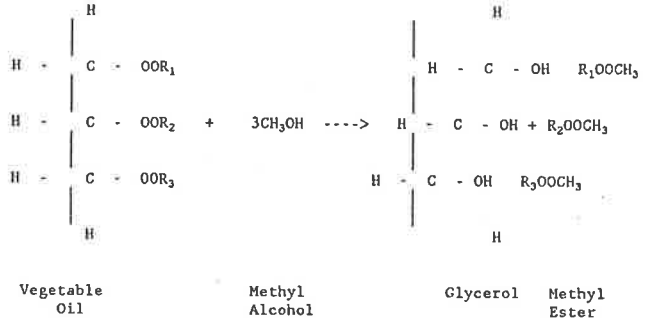

Figure 9. Vegetable Oil Transesterification.

Equipment

Extracting and Processing - All of the oil used in the University of Idaho studies has been extracted with a small oil extraction plant consisting of a mechanical screwpress manufactured by CeCoCo of Japan. The plant has a capacity of 45 kg per hour and generates about 19 liters of oil per hour. For a complete description of the process see Peterson et al. (1983) and Peterson et al. (1989).

The esterification plant was designed for a 756 L capacity. Typically 605 L batches have been produced. The components of the system are: a 1096 L cone bottom, cross-linked polyethylene tank; an R. S. Corcoran Co., New Lenox, IL, model 2000D Centrifugal pump (75 -95 L/min capacity). This pump is compatible with methanol, vegetable oil, and KOH solutions, fluid viscosities from 0.65-55.0 centistokes and is explosion proof. A 0.2 kW lab mixer with 3.4:1 gear reduction (1725 r/min motor speed and 514 r/min rotor speed). The mixer should have an explosion proof motor. A 0.75 kW portable gear pump with totalizing meter is used to transfer the raw vegetable oil and the finished ester to the bulk storage tanks.

The polymer tank and system pump (Corcoran pump) are mounted on a 1.2 m by 2.4 m steel platform with caster wheels and fork lift eyes. PVC pipe and fittings are used for all plumbing components. Two hand operated charge pumps are used to prime the centrifugal system pump. All of the reaction, settling, washing and separating takes place in this one tank. The methanol and KOH are mixed in a smaller 190 L tank prior to being transferred to the large tank. All processing is at room temperature. Wiping down equipment with alcohol prior to the process is important to remove moisture.

Ingredients:

756 L batch:

756 L raw, filtered rape oil
170 L methanol
7.30 kg KOH

Reaction Process:

The reaction produces two liquids, methyl ester and its by-product, glycerol. The KOH is dissolved into the alcohol and the mixture pumped into the vegetable oil with the mixer operating. After 4 to 6 h the mixer is removed from the tank. The system pump lines are removed. The tank is covered, and the mixture is allowed to settle for 12 h or more to allow the glycerol to settle to the bottom.

The glycerol is then drained from the bottom of the tank. Approximately 165 L of glycerol will be drained from the tank from a 756 L batch. This is approximately equal to the amount of methanol used, thus the amount of ester produced is about the same as the amount of vegetable oil used in the batch. A distinct color change from dark brown to yellow will occur when all the glycerol has drained off.

Washing:

Enough cold water is added to raise the level of ester in the tank 200 to 250 mm. This creates a "cushion" of water between the ester and the drain. The outlet constant head drain tube (a tube connected to the outlet of the tank) is placed at the level of the ester. Water is sprinkled into the tank from a common lawn sprinkler at the approximate rate of 375/L/h for 20-30 h.

Once finished the MEWR will have a milky yellow color. After washing, let the mixture sit for 3 to 4 days. The water will settle to the bottom leaving a clear layer of MEWR. At this time, the interface between the MEWR and water should be visible as a white layer.

Glycerol:

Caringal (1989) proposed two schemes for glycerol recovery. His process B, which was vacuum evaporation, was recommended. It had an 86.29 percent glycerol recovery and produced 98.2 percent glycerol. He reported a price of $0.336 per kg for glycerol.

The process described has been used successfully to produce the MEWR oil. Conversion has been 98 percent and above. All of the problems encountered have been mechanical in nature (leaks, failure to prime the pump, etc.) Handling large quantities of methanol constitutes an explosion and fire hazard and is the biggest major element of concern in implementing the process. The relatively large quantities of water used constitute a disposal problem. Methods to recover the methanol and purification of the glycerol need scale-up and implementation to improve the economics of the system.

No attempt has been made to define the process for any other purpose than for fuel use. Transesterification is used only as a method to lower the viscosity of the vegetable oil to a more suitable level for use as a fuel.

H. POTENTIAL PRODUCTION

The United States is almost totally dependent upon petroleum for its liquid energy source. Stout (1984) reports that 71.5 percent of our total energy is from oil and natural gas while only 2 percent comes from biomass. In 1989, the U.S. used about 3.2 million barrels/day of distillate fuel and 7.4 million barrels/day of gasoline. For agriculturally produced renewable fuels to make a significant contribution to this mammoth energy use would require the use of every foreseeable alternative energy source which can be developed.

As of 1982, the active crop land in the United States consisted of 150.7 million hectares; an additional 8.46 million hectares of crop land was idle. If it is assumed that each hectare of vegetable oil is capable of producing 960 liters of oil. (rapeseed at 2300 kg/hectare is equivalent to 960 liters of oil and approximately 1385 kg of meal.) On this basis, if all available crop land were put into rape production approximately 152,800 million liters of fuel per year could be produced. This is equivalent to 1.6 times the annual consumption of diesel use in transportation.

Computations of the land actually available for vegetable oil production are complicated. Certainly land must be available for domestic production of food. It is also logical to assume that some production of food for export will continue to be needed. In 1990, 13.8 million hectares were in the conservation reserve program and 9.8 million hectares were in the set-aside programs (USDA. 1990). These two sources of idle crop land could produce 22.6 billion liters of vegetable oil per year or 24 percent of the diesel used in transportation. An estimate of additional crop land potentially available for vegetable oil production was made by comparing crop production for several of the major crops with domestic use. Any production over domestic use was

termed excess and using the national average production for that crop an estimate of excess crop production land of 25.6 million hectares was calculated (Peterson et al., 1990).

Providing sufficient liquid fuel to replace U. S. petroleum imports, and because of recent world events, that from the Arab Opec countries of Kuwait and Iraq is of especially high priority. These imports are reported in Peterson et al. 1990. The U.S. Distillate Fuel and Gasoline Fuel Use and the Hectare/Day equivalent for vegetable oil fuel is shown in Table 2.

Table 2
U. S. Gasoline and Distillate Fuel Use and Acres of Vegetable Oil Equivalent (Based on 100 Gal/Acre) (USDOE, 1989)

	Barrels/Day	Hectares/Day Equivalent	% of Total U.S. Crop Land per Year
Gasoline	7,436,000	N.A.	
Distillate			
Residential and Commercial	770,000	127,322	29.2%
Industrial	570,000	94,251	21.6%
Transportation	1,750,000	289,370	66.3%
Electric Utilities	70,000	11,574	2.6%
Total Distillate	3,150,000	520,866	119.7%

Vegetable oil has potential as one segment of the alternative energy picture. Realistically, vegetable oil could be used to replace the 12.8 billion liters of diesel used per year in production agriculture. To do this would require 8%-10% of our agricultural land. About 1 out of every 4 hectares of cropland in the U. S. would be required to replace the oil imported from Iraq and Kuwait in 1989,. Reductions in land required would result from improved oil production which might occur through improved varieties or selection of higher yielding cultivars. Figure 10 shows how the required crop acreage would decline as yield improves.

In addition to the oil produced, a vegetable oil crop such as winter rape also produces considerable biomass. Peterson (1988) estimates that in addition to the meal, 2270 kg of biomass normally left on the field at harvest is produced. The energy equivalent of these by-products is estimated at 21 barrels/hectare of diesel. The meal can also be used as a high protein livestock feed. However, if a major shift of acreage occurred into production of vegetable oil crops for energy it is likely that these by-products would be used for direct combustion or for production of ethanol. Utilization of the entire crop for energy leads to the concept of "energy" crops. Agricultural policy makers need to seriously consider how to include these energy crops in the farm program and to encourage their development.

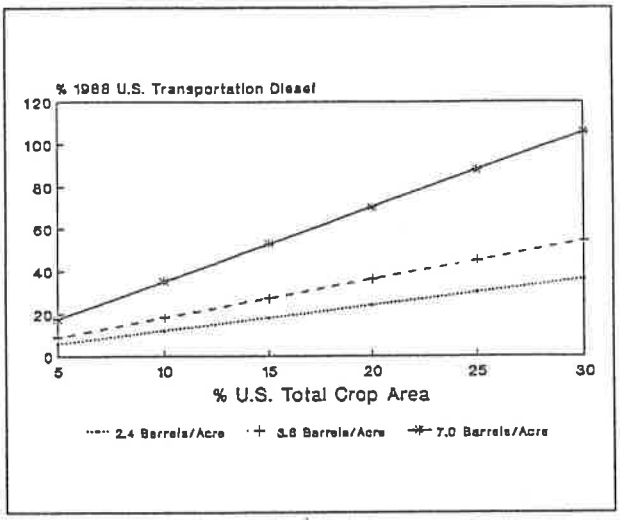

Figure 10. Production of ester of rape oil at varying seed yields of 2,000, 3,000 and 6,000 lbs/acre

I. ECONOMICS

Economics:

Two University of Idaho graduate students, Melville (1987) and Caringal (1989) have made zero profit analysis of the cost of MEWR.

Melville (1987) estimated the production cost of the ester as $0.31 per L and $0.425 per L for a COOP sized unit and Farm sized unit respectively. The farm size unit processed 78.6 t of seed per year producing nearly 34,000 L of ester per year (enough to meet the diesel demand of an average sized farm.) The COOP sized unit processed 1480 t of seed per year producing 655,000 L of ester per year (enough to supply approximately 20 average sized farms.) Melville (1987) assumed prices of glycerol at $0.93 per kg ($0.42 per lb), methanol at $0.159 per L and meal at $110.23 per t.

Caringal estimated MEWR production costs at $0.346 per L by considering raw rape oil at $0.44 per kg methanol at $0.158 per L and KOH at $1.00 per kg. He based his calculations on a plant processing 10 metric tons of rape oil per day.

Alcohol has been made successful as an additive to gasoline by certain tax breaks. In some cases, these breaks amount to approximately $0.0264 per L of fuel produced containing at least 10 percent alcohol. Since each liter of alcohol can be blended to produce 10 L of fuel, the subsidy is essentially $0.264 per L. A subsidy of this magnitude would make the MEWR an economically attractive fuel. Subsidies for on-farm use could take the form of such things as allowing winter rape, as a total energy crop, to be grown on set aside or CRP land. If the crop were grown solely for energy, there would be no impact on food or feed markets and farmers would be able to meet some energy needs from their own productive capacity.

CONCLUSIONS

Based upon evaluation of engine performance, wear (oil analysis), and injector deposits as indicators of engine durability, methyl ester of winter rape oil appears to be at least equivalent to number 2 diesel.

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A major disadvantage for the methyl ester of winter rape oil at this time is its relatively high cloud and pour points which complicate its use in cold weather. Also, the tendency towards fuel dilution of the lubricating oil could become a problem in some applications.

The major limiting factors for use of vegetable oil are economics (cost) and potential production. Cost is largely driven by the value of the by-products (meal and glycerol). Production is limited by available agricultural acreage.

Environmental impacts for vegetable oil fuels are potentially less than for using diesel fuel. Future research will concentrate on identifying those uses for vegetable oil fuels where the environmental attractions are enough to overcome the economic restraints.

ACKNOWLEDGMENTS

This paper was supported in part by USDA/ARS Research Agreement No. 58-43YK-7-0045.

Approved as paper No. 9135 of the Idaho Agricultural Experiment Station.

Disclaimer Statement

This report contains a summary of research results. This is not to be construed as a recommendation for the use of any alternative fuel mixture mentioned. The engine operator is responsible for all decisions concerning use of alternate fuels. Production of the ester involves the use of certain hazardous materials, the competence of the personnel involved and suitability of available equipment must be considered before attempting to reproduce this work in any form.

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