Winter Rape Oil Fuel for Diesel Engines: Recovery and Utilization[1]

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ABSTRACT

Although vegetable oil cannot yet be recommended as a fuel for general use, considerable progress in recovery and use of rapeseed oil (*Brassica napus* L.) for diesel operation has been made. Operation of a small-scale screwpress plant (40 kg/hr) was demonstrated. Maintenance of screw and end rings was a major problem. The plant has operated with a recovery efficiency of 77% and has processed 10,100 kg of seed in 230 hr. High viscosity of the rapeseed oil and its tendency to polymerize within the cylinder were major chemical and physical problems encountered. Attempts to reduce the viscosity of the vegetable oil by preheating the fuel were not successful in sufficiently increasing the temperature of the fuel at the injector to be of value. Short-term engine performance with vegetable oils as a fuel in any proportion show power output and fuel consumption to be equivalent to the diesel-fueled engines. Severe engine damage occurred in a very short time period in tests of maximum power with varying engine rpm. Additional torque tests with all blends need to be conducted. A blend of 70/30 winter rape and No. 1 diesel has been used successfully to power a small single-cylinder diesel engine for 850 hr. No adverse wear, effect on lubricating oil or effect on power output were noted.

INTRODUCTION

Agricultural production in the United States requires 8.3 billion liters of diesel fuel to produce crops from 138 million hectares of cropland. In Idaho, 155 million liters of diesel fuel are required to produce crops from 2.7 million hectares of cropland. Between 55 and 60 liters of diesel fuel are required for each hectare of crop production.

The possibility of using vegetable oils as a direct substitute for diesel fuel is one of several concepts for on-farm production of fuel. Vegetable oils show promise of providing all the liquid fuel needed on a typical farm by diverting 10% or less of the total acreage to fuel production (1-4). The meal remaining from the fuel extraction can be a source of high protein livestock feed replacing the soybean meal currently imported into the Pacific Northwest. Further, the extraction and processing of vegetable oil is a simple low energy process that makes use of equipment not unlike that with which farmers are already familiar.

Winter rape (*Brassica napus*) is adapted for production in the Palouse region of Northern Idaho and Eastern Washington. Current production, however, is less than 3000 ha. Dwarf Essex, the cultivar currently produced, is a nonedible variety produced only for industrial use of the oil. The oil contains ca. 50% erucic acid and the meal contains high levels of glucosinolates which break down in the intestines of livestock to form toxic byproducts (Appelquist and Ohlson, 1972). Bettis (5) provides a detailed description of winter rape.

Even though the total acreage of winter rape is presently small, the adaptability of the crop, yield of oil per acre, and low iodine number make it an attractive source of emergency fuel to guarantee the continued agricultural production of the area in case of a petroleum shortage. The varieties of winter rape presently grown are high in erucic acid, high in glucosinolates, and the oil produced has a viscosity ca. 17 times that of diesel fuel. These factors present problems requiring special consideration if winter rape is to be used economically and reliably as a fuel.

Recent interest has focused attention on winter rape because of its high oil content (45%) and its high potential yield, in excess of 5000 kg/ha, in experimental trials. Current commercial average yields in the Palouse are close to 2000 kg/ha. Agronomic optimization of the crop through breeding and management appear to have great opportunity.

Tests of vegetable oils as diesel fuel replacements have been generally satisfactory in short-term tests but have resulted in undesirable combustion chamber deposits in long-term tests. Evidence suggests that the best means of reducing these deposits may be through use of the more saturated vegetable oils such as high erucic or oleic oils.

This paper discusses the experimental tests in progress at the University of Idaho investigating extraction and use of high erucic acid winter rape for use as a blend with diesel fuel. The program is interdisciplinary, involving plant scientists, chemical and agricultural engineers, animal scientists and agricultural economists seeking solutions to production, extraction and utilization of both oil and meal.

EXPERIMENTAL

The winter rape oil used in these tests was processed with a CeCoCo expeller operated by the University of Idaho. Filtering the sediment was the only additional processing. The oil was evaluated to determine: (a) fatty acid composition, (b) specific gravity, (c) viscosity, (d) heat of combustion, and (e) ash content. The oil was also evaluated in short-term engine tests to determine its effect on engine performance. Three cycles of long-term (830 hr) test have been conducted to evaluate potential effects on engine life.

Fatty acid composition was determined on a Packard-Becker model 419 gas chromatograph with a flame ionization detector. Physical characteristics were evaluated in

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accordance with ASTM procedures for petroleum products. Viscosity was measured in Cannon-Fenske viscometers and heat of combustion in a Parr model 1241 bomb calorimeter with an adiabatic jacket.

Short-term engine tests were conducted on a Ford 4-cylinder, 2.8 L, direct-injection diesel engine with hole type injectors. The engine was connected to a General Electric cradled dynamometer. The engine fuel system was modified by adding an additional spin-on fuel filter and a 3-way, hand-operated, two-position directional control valve which allowed rapid switching between the No. 2 diesel used as a standard and the test fuel. The vegetable oil fuel was used to power the engine for 20 min, during each of the three replicates. An identical diesel fuel test was conducted both before and after each vegetable oil test. Switching between tests was done under load in all cases. The fuel filter on the test oil line was changed for each new vegetable oil blend. Data collected included (a) dynamometer load and rpm, (b) fuel consumption at 5-min intervals and (c) temperature of the incoming air, oil, engine coolant, fuel and exhaust. Similar procedures were used for varying power and torque performance tests.

Two Yanmar model TS70C, 376 cc, single-cylinder, water-cooled, diesel engines with precombustion chambers and pintle type injectors were used for long-term tests. Three cycles, two with diesel fuel, two with linoleic safflower oil, and one each with a 70% winter rape/30% No. 1 diesel fuel blend with and without a dispersant additive have been conducted.

Test cycle No. 1 used 100% safflower in one engine and No. 2 diesel in the second engine. Test cycle No. 2 used the same fuels, only the engines were reversed. Test cycle No. 3 used 70% winter rape/30% diesel in one engine and 70% winter rape/30% diesel with DuPont FOA-2 (6) additive in the second engine. Before and after each test, the engines were completely disassembled to measure clearances and weigh critical components such as bearings and rings.

The engines were connected to electric generators with resistor banks for load units. The engines were operated at wide-open throttle with the load cycled on and off at 15-min intervals. Once each day the engines were stopped for general maintenance and were stopped for longer periods at irregular intervals for convenience of running the tests. For example, when the Mount St. Helens volcano erupted, the engines were shut down to avoid possible damage due to ash fallout. The total time of the tests was determined from the first test and was simply the time at which the safflower-fueled engine would no longer start which occurred at 830 hr. This time has been repeated for the other two tests for comparison purposes.

A three-cylinder Ford model 4600 tractor also was operated on 100% linoleic safflower oil for 150 hr over a 15-month period. The tractor was first operated on a 50/50 mixture of sunflower oil and diesel beginning Dec. 27, 1979. Then on June 6, 1980, the tractor's main tank was filled with 100% linoleic safflower oil, which was used as the principal fuel until August 1981 when the engine was disassembled for inspection. The tractor was used for ca. 120 hr for general farm work and the remainder on short-term demonstrations in many areas of Idaho. Engine inspection included an evaluation of the diesel injector pump by a commercial pump repair firm (1).

RESULTS AND DISCUSSION

Chemical Properties

Vegetable oils consist primarily of triglycerides with fatty acid chains 16 to 22 carbons in length. The composition of winter rape is shown in Figure 1. Classification of the vegetable oils by their predominant fatty acid results in three groups:

Group 1: Sunflower and linoleic safflower have high concentrations of linoleic acid.

Group 2: Oleic safflower and spring rape are high in oleic acid.

Group 3: Winter rape is high in erucic acid.

The safflower oil was chosen for the first tests because of its low viscosity. The winter rape blend was chosen because the erucic acid has only one double bond and therefore reduced oxidation and polymerization rates. The diesel fuel was added to the winter rape to reduce the viscosity to acceptable levels.

The problems of fuel deterioration during storage and incomplete combustion are much more severe for vegetable oils than for commercial diesel fuels. Both problems result from the unsaturated structure of vegetable oils. Points of unsaturation, especially conjugated double bonds, are very susceptible to polymerization and gum formation. Gum forms by oxidative polymerization during storage and by a more complex oxidative and thermal polymerization at the high temperatures and pressure preceding combustion. These gums escape complete combustion and form carbon deposits at the injector nozzle tip interfering with the injection spray pattern, eventually causing the rings to seize. They also enter the lubricating oil causing an increase in lubricating oil viscosity and lubrication problems.

Gum formation is also a problem in commercial diesel fuels and is reduced by the addition of antioxidants and dispersants. In commercial diesel fuels, gum formation is mainly a storage problem. Storage deterioration in vegetable oils has been characterized by measuring viscosity at 240 C vs time. Viscosity is proportional to the degree of polymerization and at 240 C gives a rapid measure of the rate of polymerization or gum formation. Results of these measurements showed the rate of gum formation by a high linoleic (75-85%) oil is about five times that of a high oleic (ca. 75%) or high erucic (ca. 50%) oil (Fig. 2). The addition of 100-200 ppm diesel fuel antioxidants did not reduce the rate of gum formation. The rate of viscosity increase was reduced slightly by the addition of dispersants. The rate of gum formation was reduced by more than a factor of 100 in a nitrogen atmosphere. Long-term shortage of vegetable oils may require anaerobic conditions to eliminate gum formation.

In a compression ignition engine the conditions during and preceding combustion are very complex. The fuel/air mixture is quite heterogeneous with regions of fuel alone and regions of fuel vapor, of air alone, and of vapor/air mixtures. Both oxidative and thermal polymerization can occur under these conditions. Rates of thermal polymerization become significant at temperatures above 300 C. Gum formation at high temperatures can be reduced by optimizing the fuel composition. Thermal polymerization does not occur by a free radical polymerization and should have a higher activation energy than oxidative polymerization. This implies that the best means of reducing gum formation at high temperatures is the use of more saturated vegetable oils.

Engine torque tests are being used along with the laboratory bench tests for polymerization and oxidation to screen the oil blends and additives. The torque tests are conducted by adding load to the engine at full throttle so as to drop the rpm in 200-rpm steps. The engine is operated for ca. 10 min at each step so a total test requires ca. 45 min to complete. Following the test, the injectors are removed from the engine and deposits on the injector are measured. These tests are in progress; results thus far show differences between the types of vegetable oils and only minor improvements due to the additives tested.

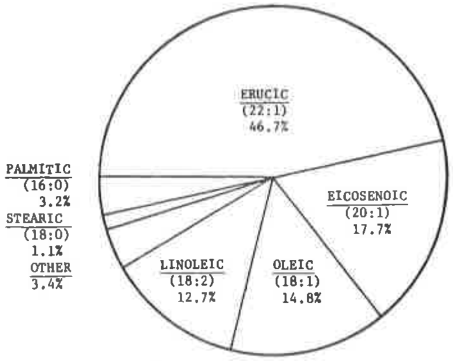

FIG. 1. Approximate fatty acid composition of winter rape (*Brassica napus*). (Numbers in parenthesis are the number of carbons: unsaturated bonds).

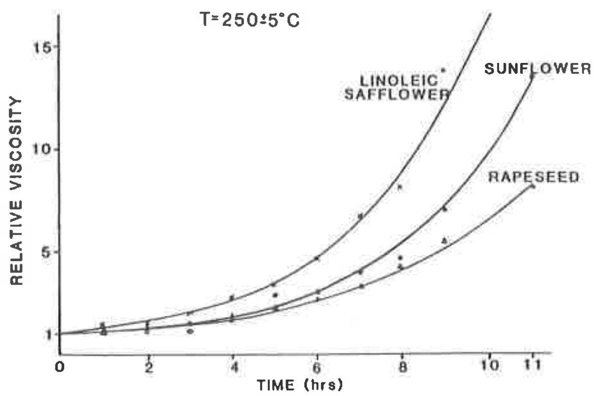

FIG. 2. Oxidative polymerization rates of three vegetable oils.

Physical Properties

The physical properties determined at the University of Idaho are shown in Table I. The vegetable oils are 7-9% heavier than diesel fuel; contain only 94-95% as much energy; have viscosities 11-17 times higher than that of diesel fuel; and the ash content was found to be less than diesel in all cases except for the spring rape.

Viscosity/temperature relationships for the vegetable oil/diesel blends have been developed (Fig. 3). Actual measurement of the fuel temperature at the injector on two engines, one air-cooled and one water-cooled, has shown temperatures of 85 C to be typical. In selecting a blend of oil for the long-term engine tests, temperatures of the fuel at the injector were used to compare the viscosity of the blend with diesel fuel recommended viscosities. Diesel fuel was added to bring the viscosity of the blend close to the upper limit (13.1 cSt) set as the emergency fuel specification published by the Cummins Engine Company (7). Referring to Figure 3, note that a temperature of 140 C would need to be reached by 100% winter rape to equal the viscosity of the 70% winter rape/30% diesel mixture at 85 C (actual injector temperature); whereas comparing the fuels at 40 C would indicate a fuel temperature of the 100% winter rape of only 82 C to obtain equal viscosities. Heating to raise the temperature of the fuel at the injector pump did not result in a corresponding increase in injector fuel temperature. It was found that the rapid transfer of heat away from the injectors to the engine head and away from the fuel lines prevented the fuel temperature at the injector from increasing significantly. A 77 C increase in fuel temperature at the injector pump resulted in only 25 C increase at the injector.

Oil Recovery

Oil recovery of vegetable oils for food and industrial markets is a common practice, carried on successfully in many locations with a variety of vegetable oil sources. Nearly all previous recovery data reported have been concerned with large-scale processing in plants operated by highly technical professionals. The concept of extracting oil by pressure with a screwpress is well known, as are the various associated processes (8-10).

Rapeseed, the most promising fuel oil in the Pacific Northwest, is characterized by small seed size and high oil content. The hulls are important to act as supporting material during extraction which increases oil yield but they lower feeding value (8). Some authors prefer crushing of the seed before pressing, whereas others are of the opinion that "cracking prior to flaking is unnecessary and redundant" (9). The objective of crushing is to roll to a flake thickness of 0.2 mm with 0.25-0.30 mm the maximum thickness tolerable.

There is general agreement on the following discussion of screwpress operation (8-10).

The mechanical screwpress has five elements: the main worm shaft and worm, drainage barrel, choke mechanism, motor transmission and bearings, and the loading system. The press is designed to exceed a pressure of 1000-1400 kg/cm^2 on the seed and should reduce the oil content from 42-45% in whole seed to 14 or 15% in the processed meal.

TABLE I

Physical Characteristics of 5 Vegetable Oils and No. 2 Diesel

	Higher heat of combustion		Kinematic viscosity		Specific gravity		Ash	
Oil	kJ/L	Ratio[a]	cSt (37.8 C)	Ratio[a]		Ratio[a]	(%)	Ratio[a]
Sunflower	36327.0	0.94	34.9	12.0	0.92	1.08	0.0046	0.37
Linoleic safflower	36379.0	0.94	32.3	11.1	0.93	1.09	0.0074	0.60
Oleic safflower	36032.0	0.94	42.1	14.5	0.92	1.08	—	
Winter rape[b]	36330.0	0.94	51.0	17.6	0.91	1.07	0.0043	0.35
Spring rape[c]	36543.0	0.95	39.0	13.4	0.92	1.08	0.0984	7.9
No. 2 diesel	38498.0	1.00	2.9	1.00	0.85	1.00	0.0124	1.0

[a]Relative to No. 2 diesel.
[b]High erucic acid variety winter rape.
[c]Low erucic acid variety spring rape (canola).

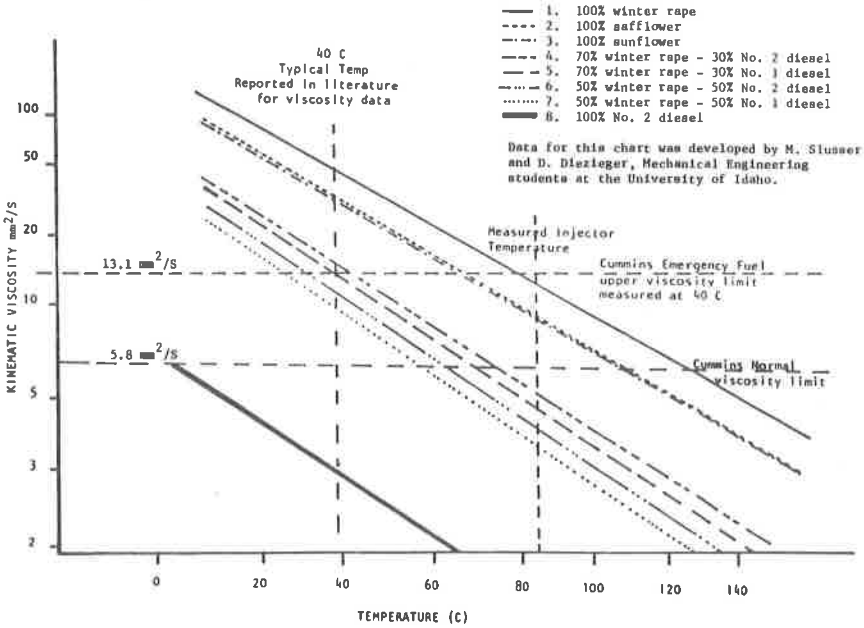

FIG. 3. Viscosity vs temperature for vegetable oil blends.

Power requirements are ca. 1 kW per metric ton of daily capacity. Cooking temperatures range from 77 C to 105 C with hold-up times of 15-20 minutes. Longer times promote protein degradation. The minimum temperature for myrosinase inactivation is 80 C.

Most commercial plants today use a mild pressing operation in which approximately half or more of the oil is removed avoiding high pressure. The remainder of the oil is solvent extracted.

Crude rapeseed oil has small amounts of phosphatide called "gums" and free fatty acids which should be removed by hydrating with steam or hot water.

Filtration is ordinarily by settling and then forcing through a plate and frame filter system.

Cooking is done for the following reasons: breakdown of oil cells, coagulation of protein to facilitate oil separation, reduction of affinity of oil for solid surfaces, insolubilization of phosphatides, increased fludity of oil, destruction of molds and bacteria, and inactivation of the enzyme myrosinase. The last is essential for oil and meal to be free of hydrolysis products from the glucosinolates.

The quality of both oil and meal are markedly affected by the method of cooking (8). The protein of the meal is often extensively denatured in the cooker, which improves feeding value, but too much heating can cause losses in amino acids. Lysine, an essential amino acid, is the most heat sensitive. Overcooking darkens the oil and increases refining loss. Heat treating can also lower the oxidation stability of the oil, which would affect storage life and the amount of antioxidant additives needed for both oil and meal. Free fatty acid content of the oil is also affected by temperature, moisture and hold-up time.

Straight screwpressing has the advantages of simplicity and lower investment costs and the disadvantages of high power consumption, wear and tear on equipment, residual oil in meal and high temperatures.

Information on the operation of small-scale plants is much less readily available. Although the basic theory is the same, more problems with quality control, efficiencies and handling and storage of seed, oil and cake are inevitable. Personnel have less training, and equipment must be manufactured as inexpensively and simply as possible.

Several individuals report operating small screwpresses (2,11; J.L. Butler, personal communication). The presses generally are used only for short periods for demonstration and are not complete operating plants intended for more-or-less continuous operation.

Bulletins describing processing equipment are available from several firms (12-14). The smallest is ca. 40 kg/hr capacity. Seed preheaters and some handling equipment are also described. Research papers or data on the operation of small units, the range of oil quality expected and economics of scale could not be found in the recent literature. Morgan and Schultz (15) in a special report for the American Chemical Society state that "simple, low-cost extraction equipment is needed." They further state that "the literature in key technical area – oil seed agronomy, oil extraction and conversion, and diesel utilization – is incomplete, especially for less well-known species."

The University of Idaho has developed an automated extraction plant using a press of 40 kg/hr capacity. A seed preheater-auger, seed bin, meal auger, oil pump, oil storage and oil filtration equipment complete the system. The complete system is automated and instrumented. The press, preheater, oil filtering system and auger are tied into a central panel where energy use is measured and the process controlled. Most of the equipment, with the exception of the screwpress, has been constructed locally. Extracted oil weight, meal weight, process temperatures and input energy are recorded during operation. The system requires a minimum of supervision; however, the person collecting data has been with the system during all of its operation thus far.

The plant has processed 10,100 kg of seed and produced over 4000 L of oil in 230 hr of operation. An average extraction efficiency of 77% has been obtained to date. Sediment in the oil has averaged only 1% by weight, the oil left in the meal has been 15.3%. The power required for the total system has been 0.16 kW hr/L.

Oil filtering is accomplished by letting the processed oil settle for 48-72 hr in special settling tanks, then pumping the oil through a three-stage filtration system consisting of a recleanable prefilter, 20-micron filtration and then 4-5 micron throw-away final filter. Analysis has shown the filtered oil as clean as ramdom samples of No. 2 diesel fuel.

The filtration system is technically adequate to provide oil of high enough quality for use in diesel engine tests. However, the cost of the throw-away filters is 2.5-3 ¢/L. Thus far, materials in the cleanable prefilters have not had a sufficiently small mesh to extend significantly the life of the final 4-5 micron filter.

Additional materials, including metallic and plastic materials of smaller sieve sizes, will be tested. Final filter life as determined by pressure drop through the filter and total cost of filtration per liter of oil are the evaluation criteria.

This automated processing plant is an important part of the total vegetable oil program at the University of Idaho. In addition to providing valuable data on small-scale screw-press extraction, it also:

– provides all of the oil used in the engine testing program;

– provides all of the meal used in the animal nutrition studies;

– is used for long-term storage studies with meal, oil, and oilseeds;

– provides data used by Agricultural Economics on cost budgets for on-farm processing plants; and

– is used with the breeding program to supply oil samples, meal samples, and extraction data on experimental varieties. A recent study compared four varieties of safflower, two winter rape varieties, and one sunflower variety. Significant differences existed in every category and demonstrated the value of the plant as a research tool (Tables II-IV).

After ca. 1400 L of oil had been expressed with the oilseed expeller, mechanical difficulties were encountered. The screw would continually score against the tapered end bushing rendering the press inoperative. At first, this was thought to be caused by foreign material, such as small metal scraps, contaminating the seed. Precautions were taken to prevent this problem, including screening the seed and incorporating a better magnetic metal trap, but the problem persisted. Various methods of rebuilding the screw and tapered bushing were explored at this time. The end bushing was first rebuilt with brass, then a steel insert and finally a spray powder hard facing technique. None of these methods worked satisfactorily. The auger, made of manganese steel, responded well to the spray powder buildup and a turning and polishing operation. The tapered end bushing was then bored out to the base cast iron and the resulting combination has worked well for the remaining 6000 kg of seed processed. Bushing problems on the drive have also been corrected. Since these problems have been corrected, 2700 L of oil have been produced with an overall efficiency of nearly 85% and a yield of 0.422 L/kg.

It should be noted that screw failure during the processing of 1 Mg of seed results in $0.20-0.30 extra cost per liter

TABLE II

Crop/Cultivar Processing Experiment – Oil Content

	Oil content		
	Whole seed (%)	Meal (%)	Extraction[a] (%)
Safflower			
S-208	35.9 e[b]	14.0 bc[b]	73.5 bc[b]
S-112	36.4 e	12.5 c	76.5 b
UC-1	36.7 e	10.3 d	75.0 b
S-541	38.8 d	12.7 c	75.5 b
Winter rape			
Dwarf Essex	45.9 a	14.4 b	83.4 a
Sipal	41.5 c	13.0 bc	86.5 a
Sunflower			
Hybrid 894	44.4 b	16.1 a	69.9 c

[a]Percent of oil in whole seed that was extracted. Each data point represents the average of five replications, 18 kg per sample.
[b]Means within a column not followed by the same letter differ at the 0.05 level of probability by Duncan's multiple range test.

TABLE IV

Crop/Cultivar Processing Experiment – Power Requirements

	Press power requirements[a]		
	kW hr/hr	kW hr/ton	kW hr/gal
Safflower			
S-208	2.98 a[b]	45.0 a[b]	0.66
S-112	3.06 a	44.8 ab	0.63
UC-1	3.00 a	44.9 ab	0.63
S-541	2.92 a	45.9 a	0.61
Winter rape			
Dwarf Essex	1.82 c	30.2 c	0.30
Sipal	2.20 b	30.6 c	0.33
Sunflower			
Hybrid 894	2.02 bc	39.4 b	0.49

[a]Power data is for the press motor only and does not include power for preheating.
[b]Means within a column not followed by the same letter differ at the 0.05 level of probability by Duncan's multiple range test.
Each data point represents the average of five replications, 18 kg per sample.

TABLE III

Crop/Cultivar Processing Experiment – Oil Extraction

	Oil extraction			
	lb/ton	gal/ton	time/ton (hr)	Sediment (%)
Safflower				
S-208	525 f[a]	67.7	15.1 bc[a]	6.95 a[a]
S-112	550 e	70.9	14.7 bc	2.91 bc
UC-1	545 e	71.1	14.5 bc	2.52 bcd
S-541	580 d	74.7	15.7 bc	2.58 bcd
Winter rape				
Dwarf Essex	760 a	100.1	16.7 b	1.01 cd
Sipal	715 b	93.2	13.9 c	0.89 d
Sunflower				
Hybrid 894	615 c	80.2	20.4 a	2.91 b

[a]Means within a column not followed by the same letter differ at the 0.05 level of probability by Duncan's multiple range test.
Each data point represents the average of five replications, 18 kg per sample.

of oil to replace or rebuild the screw.

The byproduct meal from an extraction plant has potential for livestock feed. However, the high glucosinolate content of varieties of winter rape presently grown in the Palouse area is potentially harmful to livestock.

Thomas (16) gave the following report on the feeding value of rapeseed meal.

> "Rapeseed meal (RSM) and safflower meal (SM) contained 30.7 and 25.8% crude protein (CP), 21.7 and 8.7% ether extract and 25.2 and 42.3% acid detergent fiber, respectively. RSM had a total glucosinolate concentration of 78.3 μmol/g. True metabolizable energy (TME) values were determined with RSM, SM, and soybean meal (SBM).
>
> "Respective TME values were: 3.68 (RSM), 2.51 (SM), and 3.23 (SBM) kcal/g. In a feeding trial we found that SM can replace up to 50% of the SBM protein in diets for broilers; however, Dwarf Essex RSM was not satisfactory. There is a need for the development of a low glucosinolate variety of winter rape if the by-product is to be fed to poultry."

Utilization in Diesel Engines

It has been reported that Rudolph Diesel, the inventor of the compresion ignition engine, used peanut oil for fuel in a 1900 demonstration. Reference to vegetable oil as a potential fuel has occasionally appeared in the literature since that time with many different types of oils being mentioned. However, not until the energy crisis of 1974 was there serious interest into nonpetroleum based alternative fuels such as vegetable oils. Several researchers have reported results of engine tests with vegetable oils (2, 3, 11, 17-19). They generally concur that short-term tests are equivalent to diesel fuel but mechanical problems occur in long-term testing. In most instances, the oil used in these tests is "food grade" obtained from large commercial extraction plants. It is generally at least crude degummed.

Bruwer (17), in South Africa, reported on sunflower seed oil as a fuel and concluded that in short-term tests it was comparable to diesel fuel. In long-term tests, lubricating oil problems, sticking piston rings and injector atomization patterns all contributed to engine mechanical difficulties. A more recent news release from South Africa (20) indicates that they have successfully operated an air-cooled, precombustion chamber diesel engine for 2300 hr at a constant 70% load on 100% sunflower oil. They suggest that this is a major breakthrough in the quest for using vegetable oil as a fuel.

Various tests each using sunflower, safflower and/or winter rape as fuels have shown results similar to those of Bruwer (2, 3, 21). Blends of 20% sunflower oil/80% diesel could probably be used now (22). All express caution, since premature use before testing is complete could result in severe engine damage and a voiding of manufacturer warranties.

Deere and Company (23) has reported tests with sunflower and peanut oil and blends with No. 2 diesel fuel. Injector deposits and filter plugging were problems. A trend to slightly higher HC, CO and particulate emission were considered to be a result of using a fuel system optimized for diesel fuel. NO_X emission were not significantly changed.

Caterpiller Tractor Co. (24) has initiated extensive tests using vegetable oil fuels as well as other alternative fuels. They have found a distinct advantage for precombustion chamber engines operated at near full load. Caterpiller has extended their warranty on some engines operating on up to 10% vegetable oil, but only in Brazil. This demonstrates acceptance by a major manufacturer of the general concept of vegetable oil based blends. If vegetable oil were extended to all diesel fuel consumers, agriculture would have difficulty providing even 10% of the amount currently used in the United States.

Volkswagen do Brazil (19) has tested vegetable oil in the Volkswagen Passet, which has a prechamber diesel engine, with a 30% salad oil blend with diesel, 100% salad oil and processed methyl esters of the vegetable oils. Their tests strongly support the choice of monoesters, in place of straight vegetable oils, as the best diesel fuel alternative. However, the extra cost and high crystalization temperature (0 C) are problems with esters (24). Incomplete removal of the catalyst used in the transesterification process can result in severe fuel system corrosion when the ester is used in the engine (25).

The literature verifies that vegetable oil can be used as a direct replacement for diesel fuel in existing engines with no modificiations if used only for short periods. However, modifications to both engines and fuels such as precombustion chambers, improved lubricating oils and identification of acceptable blends or modifications of each vegetable oil type and appropriate additives may be needed before vegetable oils can be safely recommended for general use.

Short-term performance tests. Three sets of performance data were developed: maximum power and fuel consumption at rated engine rpm, varying power and fuel consumption at rated engine rpm, and maximum torque and varying engine rpm.

During the maximum power and fuel consumption tests (Table V), power output of the engines did not vary significantly for the different oil blends, although there was a general tendency for power to increase by 2-3% at the 50/50 blends. Fuel consumption by volume was the same as for diesel fuel and thus was higher for vegetable oils on a weight basis. Thermal efficiency was also higher for the vegetable oil fuels. Differences in engine performance are so small that in actual operation an operator would not detect which of the different fuels was in use. Data from the varying power test is shown in Table VI.

Torque tests were conducted with sunflower, linoleic safflower and winter rape. Various blends of the oils with diesel were included in the tests. Torque, horsepower and brake specific fuel consumption (BSFC) were measured in 200-rpm steps from 2200 to 1000 rpm. The test engine was severely damaged during these tests. Operating the engine with 100% sunflower oil under load at reduced engine rpm severely gummed the piston rings, causing an almost immediate loss of power and an increase in engine blow-by. This experience causes the authors to believe that maximum torque tests are an essential part of endurance test cycles and should be included in test procedures. Since this damage occurred early in the tests, considerable differences in engine power between the beginning and the ending test cycles on diesel were observed in the test data. Torque tests, with inspection of the injector as the evaluation criteria, are being used as a fuel blend screening tool as described earlier.

Long-term engine screening tests. These tests thus far have included 1660 hr on 100% linoleic safflower oil (two 830-hr tests), and 850 hr on 70% winter rape/30% No. 1 diesel with and without DuPont FOA-2 dispersant additive added at the rate of 150 ppm. Power, fuel consumption and wear data are shown in Table VII.

Measurements and weights showed about twice the wear rate for the safflower-fueled engine compared to the diesel-fueled engine. The safflower-fueled engine also showed more carbon in the combustion chambers and additional varnish and carbon buildup on the injector nozzle.

For the test durations indicated and for the particular

TABLE V

Diesel Engine[a] Performance Using Vegetable Oil and Vegetable Oil/Diesel Mixtures as a Fuel

	100% Winter rape	75% Winter rape	50% Winter rape	25% Winter rape	100% Diesel
kW	28.9	29.4	29.6	29.2	28.2
Fuel (kg/hr)	9.7	10.4	10.3	9.9	9.3
Fuel (L/hr)	10.6	11.7	11.7	11.4	11.0
BSFC (kg/kW hr)[b]	0.33	0.35	0.35	0.34	0.33
BSFC (kW hr/L)[b]	2.72	2.54	2.56	2.56	2.58
Exhaust temperature (C)	692	704	715	710	690
Energy kJ (kJ/kg)	39923	41170	42517	43850	45292
Thermal efficiency (%)	26.8	24.7	24.3	24.2	24.1
Fuel weight (kg/L)	0.91	0.90	0.89	0.86	0.85

[a]Information in this table was obtained on a 2.8 L Ford 4-cylinder, 2200 rated rpm diesel engine.
[b]BSFC is brake specific fuel consumption and is a measure of work output per unit of fuel used.

TABLE VI

Power, Fuel Consumption and Thermal Efficiency Measured in a Varying Load Test with Winter Rape/Diesel Blends as Fuel

	100% Diesel			25% Winter rape		
% Load	Power (kW)	Fuel use (kg/hr)	Thermal efficiency (%)	Power (kW)	Fuel use (kg/hr)	Thermal efficiency (%)
100	27.8	9.4	26.8	29.8	10.1	25.7
75	21.0	6.8	27.8	22.3	7.1	27.6
50	13.9	5.1	24.8	15.2	5.2	25.3
25	7.1	3.6	17.7	7.5	3.8	17.3
0	1.3	2.5	7.6	1.2	2.7	3.9
	50% Winter rape			75% Winter rape		
% Load	Power (kW)	Fuel use (kg/hr)	Thermal efficiency (%)	Power (kW)	Fuel use (kg/hr)	Thermal efficiency (%)
100	29.7	10.1	24.8	29.1	10.2	23.3
75	22.3	7.1	26.6	22.0	7.1	25.5
50	15.0	5.3	23.7	14.6	5.2	23.0
25	7.5	3.8	16.7	7.4	3.7	16.3
0	1.0	2.7	3.0	1.1	2.5	3.7
	100% Winter rape					
Load	Power (kW)	Fuel use (kg/hr)	Thermal efficiency (%)			
100	28.3	9.6	23.5			
75	21.0	6.9	24.3			
50	14.2	5.2	21.7			
25	7.1	3.7	15.3			
0	0.9	2.8	2.6			

Engine used was a 2.8 L direct-injection 4-cylinder diesel with hole type injectors manufactured by Ford (the data is typical of the other vegetable oils tested).

engine used, the winter rape blend is clearly superior to the linoleic safflower as a fuel. In all cases where the safflower oil has been used, the engines have suffered severe degradation, primarily as a result of ring gumming, lubrication oil thickening and some injector gumming. None of these problems were found in the engines fueled with winter rape oil. Some gumming was noted on the upper piston land although it had not progressed to a point where it had any effect on engine performance.

Oil analysis data confirmed the results of engine measurements as shown in Table VIII. A tendency for the oil to thicken was noted in the 100% safflower tests. A ratio of beginning to final lubricating oil viscosity of 2.6 was noted for the safflower engine, 1.6 for the diesel engines, and an increase of only 1.4 and 1.6 for the winter rape blend and winter rape blend with additive, respectively.

The oil analysis also indicated excessive oxidation, high iron, aluminum, chromium, silver, molybdenum, tin and lead for the engine operated on linoleic safflower. The engine fueled with winter rape blend was equivalent to diesel in nearly all of these factors. No engine maintenance problems would have been detected by the oil analysis data dur-

TABLE VII

Power, Fuel Consumption and Wear Data from Long-Term Screening Tests Using Single-Cylinder, 376 cc, Precombustion Chamber Yanmar TS706 Test Engines

	Test #1		Test #2		Test #3	
Engine no.	11	22	11	22	11	22
Fuel	100% Safflower	100% Diesel	100% Diesel	100% Safflower	70% Winter rape/ 30% Diesel	70% Winter rape/ 30% Diesel
Additive	None	None	None	None	None	DuPont FOA-2
Hours of test	830	830	883.4	837.8	853.8	851.0
Compression change (%)	–	–	-6	-10	-6.2	-3.1
Power drop (%)	–	–	+5[a]	+2[a]	4.5	2.7
Fuel consumption (L/hr)	0.83	0.79	0.79	1.36	0.87	1.06
Stuck rings	2	0	0	2	0	0
Ring #1, Δg[a b]	0.173	0.124	0.123	0.150	0.169	0.260
Ring #2, Δg	0.078	0.039	0.054	0.262	0.086	0.188
Ring #3, Δg	0.037	0.029	0.042	0.380	0.047	0.098
Oil ring, Δg	0.022	0.034	0.038	0.107	0.048	0.121
Rod bearing, Δg	0.088	0.026	0.059	0.138	0.014	0.019
Piston, Δg	0.00	0.09	0.32	0.00	0.10	0.40
Upper cylinder wear, (mm)	0.025	0.025	0.010	0.028	0.013	0.025

[a]These data are not directly comparable because of changes in the fuel setting.

[b]Numbers are change in weight of component between start and finish of test in grams.

TABLE VIII

Oil Analysis Data for Long-Term Endurance Tests (850 hr) with 376 cc Displacement Single-Cylinder Precombustion Chamber, Yanmar Diesel Engines (data by Montech, Inc., Spokane, WA)

	100% Safflower	70% Winter rape/ 30% diesel	70% Winter rape/ 30% diesel w/FOA-2 additive	100% diesel
Avg hrs on oil	104.7	105.4	104.2	110.4
Viscosity (cSt @ 38 C)	291.5[a]	143.6[b]	166.2[b]	182.8[a]
Fuel dilution[c]	N	N	N	N
Oxidation[c]	M-E	N	M	N
Silicon (dirt)[d]	21.6	13.8	20.8	8.0
Iron	131.5	37.4	70.6	37.9
Copper	5.25	4.4	6.00	3.2
Aluminum	34.0	8.4	16.2	7.9
Chromium	5.49	2.2	3.9	2.5
Magnesium	19.75	20.2	20.2	18.5
Silver	0.75	0.2	0.5	0.03
Molybdenum	4.25	1.00	2.2	0.5
Tin	19.1	4.4	9.6	4.0
Lead	18.3	8.2	9.8	10.1

[a]Oil used was Delo 400 SAE 30 with initial viscosity of 113.0 cSt @ 40 C.

[b]Oil used was Delo 300 SAE15w-40 with initial viscosity of 101 cSt @ 40 C.

[c]N = Normal, M - marginal, E - extreme.

[d]Values given are in parts per million.

Figures reported are the average of data collected at the end of each oil change or ca. 100 hr.

ing the long-term endurance cycle using winter rape as a fuel.

It would appear from the oil analysis, wear measurement and engine performance that the fuel additive was detrimental to the engine. This engine had more oil consumption throughout the tests, which may have been a function of the seating of the rings. Replication of the test is in progress to see if a trend develops on the effect of the additive. The additive did appear to decrease drastically fuel filter plugging.

Although the test data show that use of a winter rape blend may be feasible, additional testing will be required with many types of engines before it can be recommended for general use. Anyone contemplating the use of vegetable oil in a diesel engine should be aware of the possible consequences and be prepared to assume the risks.

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