PAPER NO. 84-3082

EFFECT OF VEGETABLE OIL FATTY ACID COMPOSITION ON ENGINE DEPOSITS

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For presentation at the 1984 Summer Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

University of Tennesee, Knoxville
June 24-27, 1984

SUMMARY: High oleic safflower and high linoleic safflower were selected for utilization in an EMA test cycle evaluation of the effect of vegetable oil unsaturation level on engine deposits. In summary, engines operated on the oleic oils did have somewhat less engine deposits at the conclusion of the tests than did the two operated on the more unsaturated linoleic safflower, but both were high in deposits when compared to the engines operated on diesel fuel.

American Society of Agricultural Engineers

St. Joseph, Michigan 49085

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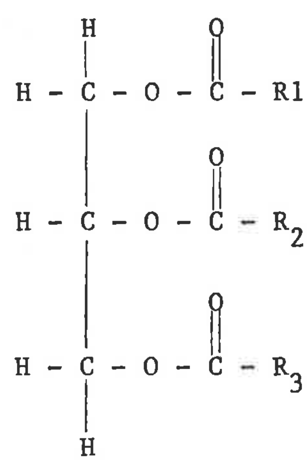
ABSTRACT

High oleic safflower and high linoleic safflower were selected for utilization in an EMA test cycle evaluation of the effect of vegetable oil unsaturation level on engine deposits. Six individual engines, two on diesel, and two on each of the vegetable oils, have been utilized in the tests. The oils were also tested in short term performance test. In summary, engines operated on the oleic oils did have somewhat less engine deposits at the conclusion of the tests than did the two operated on linoleic safflower, but both were high in deposits when compared to the engines operated on diesel fuel.

INTRODUCTION

The first University of Idaho test of a diesel engine on vegetable oil fuel was conducted December 27, 1979 when a diesel tractor was operated on a mixture of 50 percent diesel and 50 percent sunflower oil (Peterson et al. 1983). This was not the first time that a diesel engine has been operated on vegetable oil fuel. In fact, Rudolph Diesel, the inventor of the compression ignition engine, is said to have demonstrated his engine on vegetable oil as early as 1900. This first Idaho test does, however, mark the approximate time of a revitalized interest in renewable sources of liquid fuels. The success of that test has led to more serious investigations. Later work has shown that using vegetable oil as a fuel is very successful in short term tests but is less successful in long term tests. Piston ring seizing, injector coking, increases in oil viscosity and sudden loss of power and degradation of the engine have been problems associated with vegetable oil use.

An understanding of the chemical and physical properties of vegetable oils is essential in improving their application as a liquid fuel. Vegetable oils are water-insoluble, hydrophobic substances which are composed primarily of the fatty esters of glycerol or triglycerides with the following structure.



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where R1, R2, R3 symbolize the even numbered hydrocarbon chains of fatty acids that are usually 16 to 22 carbons in length. By comparison diesel contains hydrocarbon chains that are centered around 16 carbons in length.

Triglycerides contribute 94 - 96 percent of the total weight of the molecule and consequently greatly influence both the physical and chemical character of the glycerides.

The unsaturated fatty acids most commonly encountered in vegetable oils are oleic, linoleic, and linolenic acid. They each have a chain length of 18 carbons, but the number of double bonds they possess are one, two and three respectively. Oleic and linoleic acids are the major components in such vegetable oils as sunflower and safflower. Linolenic acid is found in certain varieties of rapeseed along with erucic acid. Erucic acid, like oleic acid, has only one double bond but its chain length is 22 carbons instead of 18. The composition of the vegetable oils used in the tests reported in this paper are shown in Table 1.

The degree of unsaturation present in these fatty acids and consequently in the triglyceride molecule will be an important consideration in fuel selection.

Vegetable oils are inherently less stable than commercial diesel fuels because of the high degree of unsaturation of vegetable oils and consequent susceptibility to polymerization or gum formation. Both thermal polymerization and oxidative polymerization of vegetable oil will result in the formation of polymeric material. Oils can deteriorate by oxidative polymerization during storage, and by both mechanisms at the high temperature preceding combustion. Initially vegetable oils have viscosities 11 to 17 times greater than that of diesel fuel. High viscosity will result in poor atomization of the fuel as it is injected into the engine causing poor ignition and incomplete combustion. Oxidative polymerization coupled with thermal polymerization can produce extensive gum formation in an engine to the point that it can disrupt, if not halt, its performance by seizing the piston rings. Polymerization of triglycerides in the lube oil due to blowby of unsaturated fuels will increase crankcase oil viscosity. Gum formation in the fuel will leave carbon residues which can then lead to deposits in the combustion chamber and on injector tips disrupting their spray pattern. Thus unmodified vegetable oils have serious drawbacks in their usage as diesel fuel. The reduction, if not elimination, of those drawbacks will be possible once the problems are more thoroughly defined.

The objective of this test was to compare a highly unsaturated vegetable oil, linoleic safflower, with a highly saturated vegetable oil, oleic safflower, and No. 2 diesel to determine the relative improvement which could be expected in engine longevity.

FUEL DESIGNATION SYSTEM

Throughout this report, in the interest of space, a shorthand abbreviation system will be used to designate the fuels. The notation system is described below.

XXAA - YYBB + CCCC
XX = percent of vegetable oil AA in mixture
YY = percent of diesel fuel in mixture
AA = WR for winter rape
   = SL for linoleic safflower
   = SO for oleic safflower
BB = D1 for number 1 diesel
   = D2 for number 2 diesel

CCCC if present indicates additive present in mixture.

CCCC = FOA2 - E.I. Dupont DeNemours and Co., fuel oil additive No. 2, 0.56 ml/gal (150 ppm).

= FOA15 - E.I. Dupont DeNemours and Co., fuel oil additive No. 15, 0.40 ml/gal (105 ppm).

= L565 - The Lubrizol Corporation, Lubrizol 565, 13.6 ml/gal (1300 ppm).

TEST PROCEDURE

Each fuel is tested by a commercial laboratory for comparison with the specifications of diesel fuel. Engine performance characteristics were then determined on a John Deere 4239 TF, 3.9L direct injection, turbocharged, water cooled engine directly connected to an electric dynamometer. Fuel consumption, power, and thermal efficiency were determined at full and part throttle.

Kinematic viscosity was measured with Cannon-Fenske viscometers in a water bath at 37.7°C. Fatty acid composition was determined by conversion of oils to methyl ester and separation of esters in a 6 foot, 1/8 inch O.D. stainless steel column packed with 10% Silar 10C on 100/120 GAS CHROM Q at 180 C in a Varian 1400 gas chromatograph.

Thermal polymerization samples were sealed under vacuum in glass ampoules and heated in an electric furnace. Oxidative polymerization samples were heated in open glass beakers in a forced air convection oven.

Engine performance was characterized by the rate of carbon residue formation on injector tips. Tests were run on the same John Deere T4239 industrial diesel engine with Roosamaster penal type fuel injection nozzles (John Deere part #AR90023) as used for the performance date. A torque test was used to accelerate the rate at which the carbon formed in the combustion chamber. The injectors were removed, cleaned, and reinstalled for each test. A maximum power test was conducted at 2500 rpm on Phillips diesel D-2 control fuel for 10 minutes to check for possible engine damage before each torque test initiated. The speed was reduced at full throttle in 200 rpm increments and at each rpm level, 10 minutes of fuel consumption data was taken. The test was terminated at the 1500 rpm level. The engine was then allowed to cool down by operating at 1800 rpm with no load for 10 minutes. It was then stopped and the injectors pulled. The injector tips were photographed at two orientations using a measuring microscope at 16X with 35 mm copy film forming a silhouette image. The injector tips were then cleaned with observations made on their appearance and how easily the carbon was removed. The injectors were then reinstalled in the engine and the next test started. This whole procedure required about 3 hours time. The pictures of the coked injector tips were enlarged to 8 inch by 10 inch prints and their area measured using a computer digitizer. The silhouette area was compared against a silhouette of a clean tip as a standard and the increase in tip area used as a measure of engine deposits. During each run, ambient, crankcase oil, exhaust turbo inlet, and exit temperatures were recorded at two minute intervals.

EMA TEST ENGINES AND HYDRAULIC LOAD UNITS

Six Wisconsin WD2-1000, 1.0L, direct injection, air cooled, twin cylinder diesel engines rated 15.7 Kw at 3000 rpm were selected as test engines. Engines of this size were required in order to keep the fuel cost within manageable levels for continuous testing and also to keep the test cells as small as possible. Three test cells were constructed which will allow for one-half the engines to be under test and the other half to be undergoing tear down and inspection at all times.

The engines are connected to cradled hydraulic gear pumps. The oil flow is directed through dual pressure, pilot operated relief valves which serve to load the pumps. An electric solenoid valve is used to select the high or low pressure setting of the relief valve or when in neutral to vent the pump at no load. Thus three load settings can be selected. The high and low setting are manually adjustable. After passing the relief valve, the oil is directed through a heat exchanger and back to the reservoir. The heat exchanger has a hydraulically driven fan which is operated whenever the oil temperature exceeds a pre-set value. A hydraulic schematic of the load units is shown as Figure 1.

Each unit has a strain gage load cell for measuring engine torque and weight of fuel in supply tank, an rpm pick-up for engine speed, a pulse-type flow meter which gives a pulse in proportion to flow volume, a DC reversible gear head motor for throttle control, thermocouple transducers for fuel, oil, air, exhaust and load unit oil temperatures and two solenoid valves, one for load control and one to control the cooling fans on the heat exchanger.

The control/data acquistion system, shown in block diagram form as Figure 2, consists of a Hewlett-Packard 85F microcomputer, programmable in HP-BASIC and a 5½ digit precision scanning voltmeter.

The computer controls:
- -engine load
- -engine speed
- -load unit oil temperature

The computer measures:
- fuel consumption
- engine load
- engine speed

The 3054DL comes standard with a digital voltmeter and a programmable current source. Optional capability is provided by 5 plug-in assemblies which include.

1. A 20-Channel relay multiplexer assembly. The multiplexer is useful for 20 channels of dcV, 2-wire ohm measurement of 10 channels of 4-wire measurement. It is also used with the counter assembly to provide up to 20 inputs to the single channel counter. The multiplexer has a maximum of ±170V peak and 50 MA.

2. A 19-channel relay multiplexer with thermocouple compensation. It can multiplex up to 19 thermocouples of 19 dc voltages. Channel 20 on this card provides a reference junction voltage. The card can be used with all thermocouple types through software compensation.

3. A Reciprocal Counter Assembly. Frequency mode 1 Hz-100 kHz or totalize mode 0 to 999,999 events. The device will count up, count down, or measure pulse width down to 18μs. It can be used with the multiplexer as described earlier for multiple channels.

4. A 16-channel actuator/digital output assembly. The actuator contains 16 mercury-wetted relays with a maximum rating of 100 V peak at 1 amp rms and 100 VA. The relays are open and closed on program command.

5. A 350 ohm strain gage/bridge assembly. Ten bridges per card for any mixture of ¼, ½, or full bridge circuits. No minimal adjustment, software is used to measure bridge output, compute strain, and for calibration.

Other options are available. The ones described above are those used to operate the engine test stand.

To run an engine test cycle the program ENTEST is called into the computer and run. It tells when to start the engines and asks for the load cycle parameters, i.e. number of cycle sets, number of cycles in each set, engine speed, load settings (0, 1, 2, or 3) and cycle length. When the engines are started, the computer will bring all three engines to the first cycle's test speed. The load is applied and the first test cycle starts. The engine speed is monitored frequently and adjustments made to attain ±20 rpm of the desired speed. This range of rpm was selected to prevent a "hunting" condition from occurring between the computer and the engine. Load unit oil temperature and crankcase oil temperature are measured 2 to 3 times per minute to ensure that the engines and load units are not overheating. If the load unit temperature goes over 60°C, the computer will terminate the test and print out a warning telling the operator which engine overheated and at what time. Three times during the cycle, power, fuel, consumption, and temperature data are recorded. A summary printout of cycle average power, fuel consumption, and temperatures along with the cycle starting time, length of cycle, and load valve position is reported at the end of each cycle. Some of the software in the program was written by HP for the data logger system. These are subprograms which measure thermocouple temperatuers using software compensation, measure the strain gage bridge circuits, and help debug the system in case of error. Several subprograms of the ENTEST program are shown to help explain programming of the computer.

1. The "RCHECK" subprogram is used to adjust engine speed to the desired level. The computer reads the engine speed and compares it to the desired speed. If the rpm of the engine is too low, the computer activates the dc gear head motor connected to the throttle linkage to increase the fuel flow to the engine. If rpm of the engine is too high, then the motor is reversed and the throttle is closed down. (The amount of time the gear head motor is actuated depends upon the rpm difference between desired and actual engine speed.) By repeating this procedure, the engine speed is adjusted to within the acceptable ±20 rpm of the desired speed.

2. The "LOCHECK" subprogram monitors the load unit oil temperature on each of the three load units. If the temperature exceeds 60°C, the hydraulically driven cooling fan is started using a computer operated solenoid hydraulic valve. When the temperature drops to below 60°C, the fan is turned off. If the temperature continues to rise above 71°C, the engine test is terminated and an operator warning message is displayed showing when the termination occurred and which load unit was responsible.

3. The "CCHECK" subprogram monitors crankcase oil temperatures and terminates the test when it exceeds 120°C. An operator message is also displayed on the computer printout describing the problem and when it happened.

4. The "FUMEAS" subprogram measured the fuel flow to and from the engines using calibrated pulse type flow meters and signal conditioners. A flow meter is located in the incoming fuel line to a float tank where the incoming and return line from the engines are located. The amount of fuel added to keep the float tank full is measured by the flow meter. This data is summarized during the test and presented at the cycle termination. Since installation of this system, it was determined that the flow rates of fuel to the engines were at the low end of the capability of the flow meters when the engines are in the idle setting. Strain gage proving ring type transducers have been installed. These weigh the total fuel in the tank and determine fuel consumption by weight loss per unit time.

5. The subprogram "SC-DEG" was supplied with the 3054DL system to do software compensation on thermocouple temperature measurements. The subprogram inputs are the thermocouple type and its channel connection. The thermocouple voltage is read using the 3497A. The reference junction voltage on the card must also be read and added to the thermocouple voltype.

RESULTS

Four separate sets of data have been collected. First, the fuel data; second, short term performance data; third, injector tip coking data; and fourth, EMA test cycle data.

The fuel data is shown in Table 2. Cetane numbers were not available for the vegetable oil in their variable compression ratio engines. These test data are typical of vegetable oil and similar to that reported previously. High viscosity and gums, slightly lower API gravity, and heat content and cracking during the distillation tests are expected results.

Bulk viscosities of vegetable oils were used as a measure of the degree of polymerization. Relative viscosity measurements for oxidative polymerization at 260 C are shown in Figure 1, Viscosity data was fitted to an exponential model,

$$\nu = ac^{bt} \tag{1}$$

where ν represents kinematic viscosity, t is time, and a and b are constants determined by fitting the data. The oils had specific gravities of 0.92.

Rates of oxidative and thermal polymerization were measured for linoleic and oleic safflower and high erucic rapeseed from 240-300C. Thermal polymerization was negligible below 240C. At 240C., the viscosity of high linoleic safflower oil increased by a factor of 32 over 11 hours in an air environment and shows no change in a nitrogen environment. High erucic acid rapeseed showed a viscosity increase approximately 1/4 that of linoleic safflower for oxidative polymerization at 240 C.

Rates of thermal polymerization showed a stronger dependence on degree of unsaturation than oxidative polymerization. Relative rates of oxidative polymerization of oleic and linoleic safflower were approximartely 1:3 at 260 C. Relative rates of thermal polymerization of the same two oils were approximately 1:30 at 320 C. Relative viscosities of the four vegetable oils for thermal polymerization at 320 C are shown in Figure 2. The trend of thermal polymerization rates of the four oils was the same as with oxidative polymerization indicating that rates of both oxidative and thermal polymerization have similar dependencies on unsaturation. The strong temperature dependence of thermal polymerization rates is apparent from data for thermal polymerization of linoleic acid fitted to equation 1.

The short term test data are summarized in Figure 4. Winter rape is included along with the oleic and linoleic safflowers. Short term performance is nearly identical to the diesel. Winter rape has a slightly higher thermal efficiency but all differences are small. Each of the vegetable oil fuels tested were in blends of 50 percent by volume with Number 2 diesel as the base fuel.

The degree of carbon residue formation on injector tips was measured for 50% (v/v) mixtures of oleic safflower, linoleic safflower, and winter rape with No.2 diesel control fuel. All vegetable oil fuels exhibited significantly greater deposits than pure diesel. The deposits were hard, and their removal required scraping.

There was more carbon deposit with the 50% linoleic than the 50% winter rape mixture by a factor of about 1.7. There was considerable data scatter with the oleic mixture, but the oleic fuel was similar in extent of carbon residue formation to the rape mixture.

EMA test cycle is reported as Tables 3, 4, 5, and 6. All six engine test have been completed but summary data is available for only the first three tests, one engine each on 100D2, 50SO-50D2 and 50SL-50D2.

Table 3 reports the average maximum engine power for the engines broken into 50 hour intervals. The engines operating on the more unsaturated linoleic safflower lost 8.5 percent power, the oleic fueled engine 3.5 percent, and the diesel fueled engine essentially no change.

Table 4 reported the average Brake Specific Fuel Consumption Data again broken into 50 hour cycle intervals. The linoleic safflower engine increased in fuel consumption to more of an extent than did the other two.

Table 5 gives a summary of engine wear data. All wear was minimal and no definite trend is established by the data shown.

Table 6 reports a summary of the oil analysis data. Oil was sampled at 50 hour intervals and analyzed by a commercial laboratory. Some evidence of the source of the power loss in the linoleic powered engines can be seen by the high oil viscosity and high metals content in the oil. It is also evident from the oil analysis data that the oleic fueled engine was also experiencing some problems by the conclusion of the test. Typically, vegetable oil fueled engines degrade rapidly, probably due to an increases in blow-by when a ring sticks and excessive fuel mixes with the lubrication oil. The vegetable oil mixed in the lubricating oil causes a sudden rise in viscosity which causes failure of components. Comments from the observations made during engine tear down are as follows:

<u>100D2</u>

Pistons were clean with all machining marks on top piston land visible. Normal sooty type carbon buildup in head and on injectors that was easily wiped away. Piston skirt had slight varnish. Cylinder barrels had no scoring.

<u>50SO - 50D2</u>

All rings free, black deposits were in ring belt area of piston but wiped off easily. Upper piston land did have carbon but machine marks were still visible. Carbon on top of piston and head surface was quite brittle and flaked off easily. No buildup of hard carbon in oil control rings was visible. Injector deposits were about the same as the linoleic but less crumpets were present. Carbon adhearing to the top of the cylinder barrell was also less than present in the linoleic fueled engines. Cylinder barrels had no scoring.

<u>50SL - 50D2</u>

The top compression ring on both pistons were partially siezed. The top piston land was covered with carbon and machine marks were not visible. The oil control ring had a large amount of carbon buildup. Head surface and injectors have carbon deposits and crumpets around injector openings of 1.6 mm long. Flakes of carbon from head surface were stuck to barrel at head connector area. No abnormal scoring in barrels. Hard carbon in ring area was not easily removed by wiping.

CONCLUSIONS

While the more highly unsaturated linoleic safflower oil did prove to be more detrimental to the engine that did the oleic safflower oil, both were considerably worse than diesel fuel. Linoleic safflower resulted in a power drop of 8.5 percent during the EMA test cycle, oleic 3.5 percent and diesel a slight increase of 0.1 percent. Based on oil analysis, oil viscosity and metals content were higher when engines were fueled with linoleic and oleic safflower than when fueled with diesel. The linoleic fueled engine had ring seizure while the oleic did not; however, considerable presence of polymerization products were observed. In summary, if the results were based on a scale of 1 - 10, with diesel being best rated a 1 and linoleic safflower fuel the worst case rated a 10, the oleic would have to be rated from 6 - 8, somewhat improved when compared to linoleic but still a much less desirable fuel than diesel. The next series of EMA tests will include winter rape and the ester of winter rape. Both of these fuels show promise and may come another step closer to replacing diesel as a satisfactory fuel for agricultural diesel powered equipment.

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Peterson, C.L., G.L. Wagner, and D.L. Auld. 1983. Vegetable Oil Substitutes for Diesel Fuel. Transactions of the ASAE 26(2): 322-327, 332.

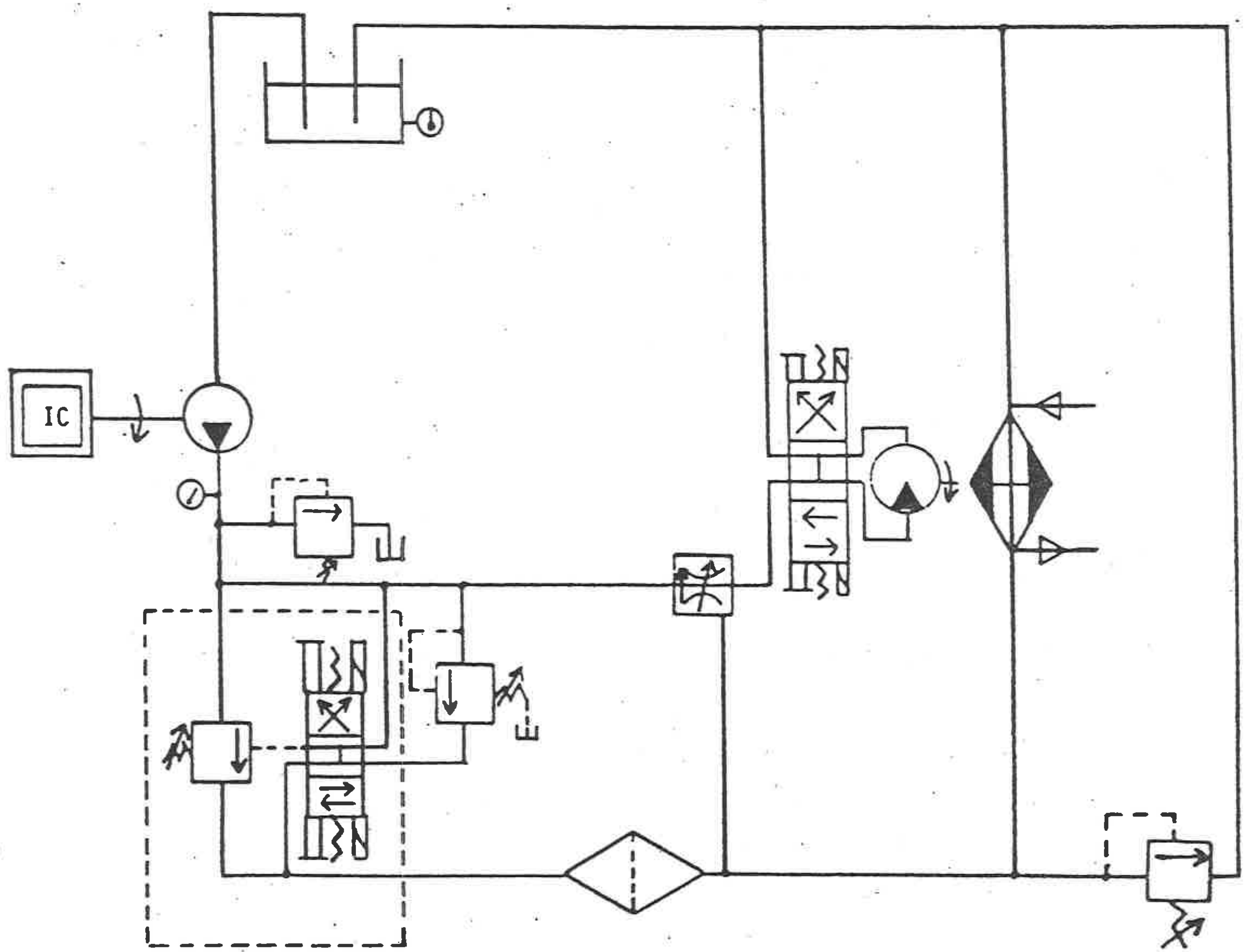
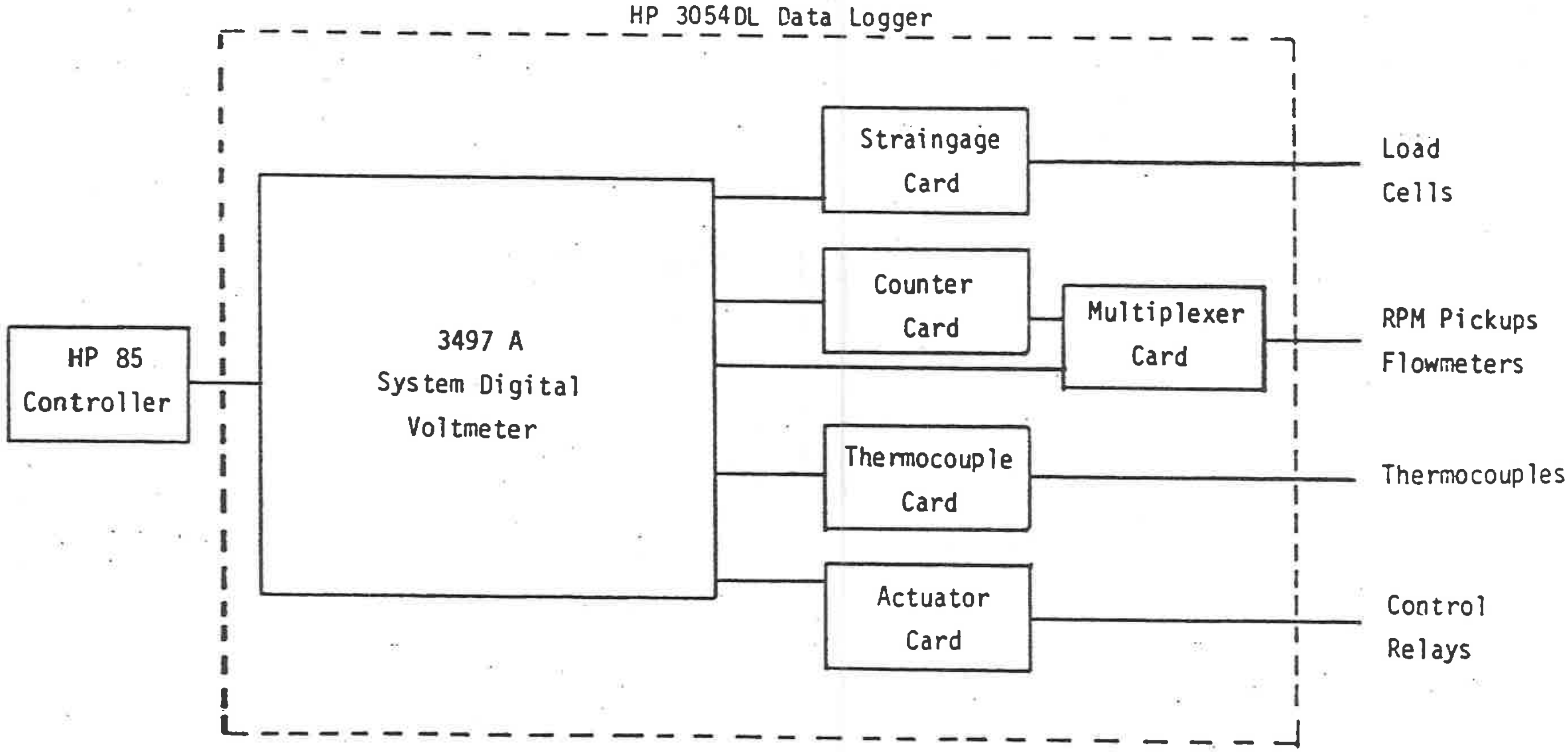


Figure 1. Test Unit Hydraulic Schematic

Figure 2. Block Diagram of HP85/3054DL Data Logger Connections



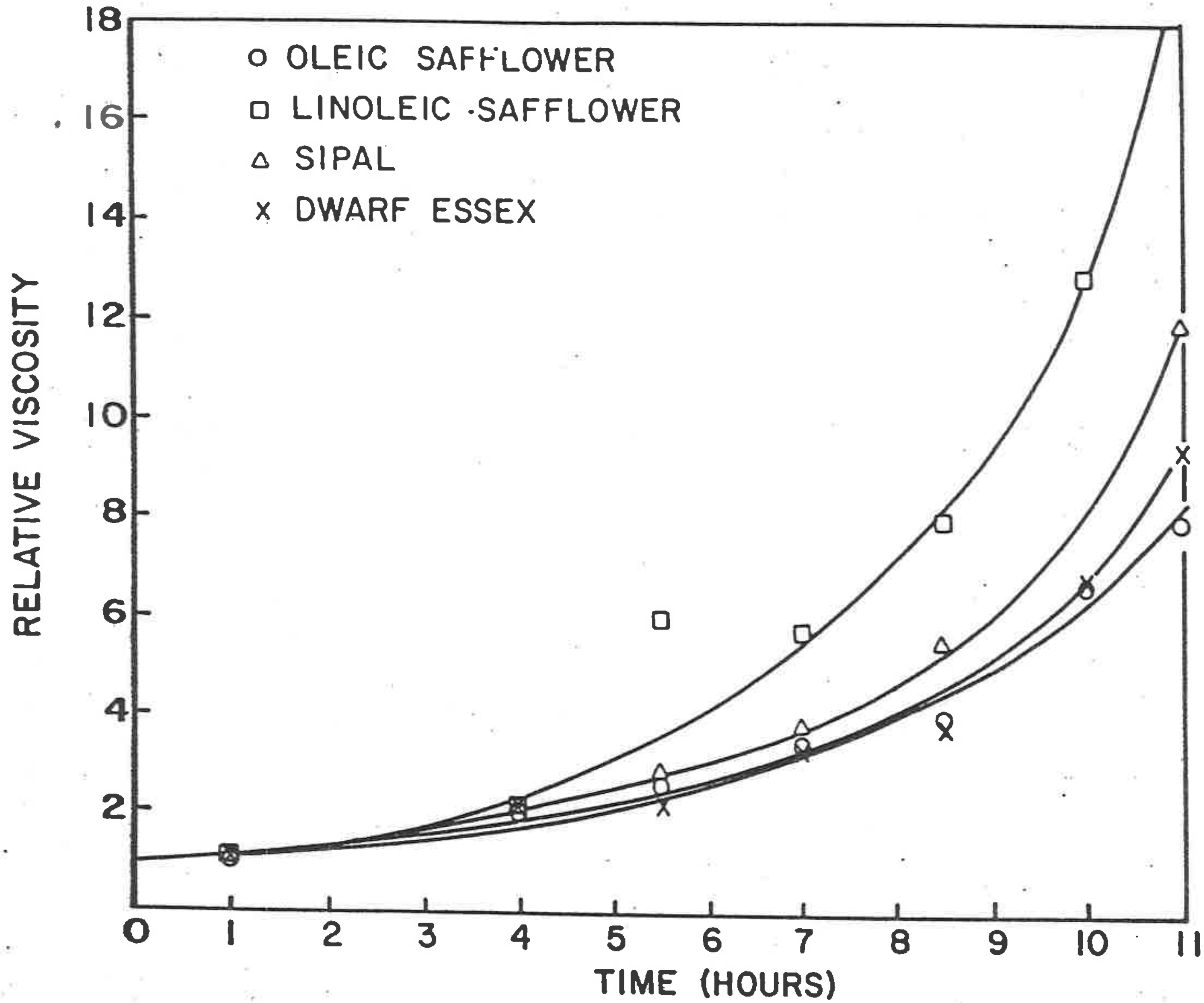


Figure 1. Relative viscosities of oxidized vegetable oils vs polymerization time at 260 C.

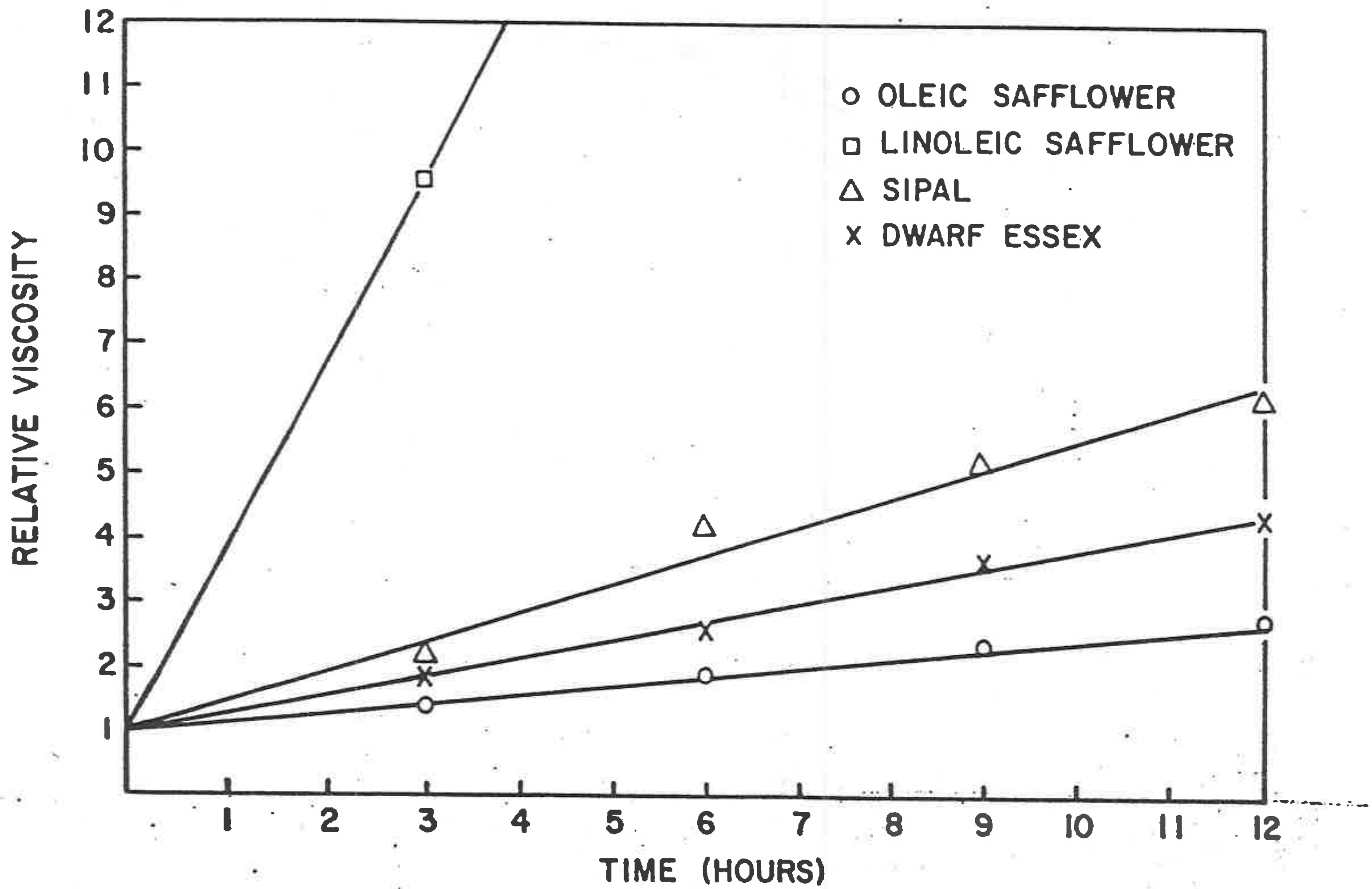


Figure 2. Relative viscosities of thermally polymerized vegetable oils at 320 C.

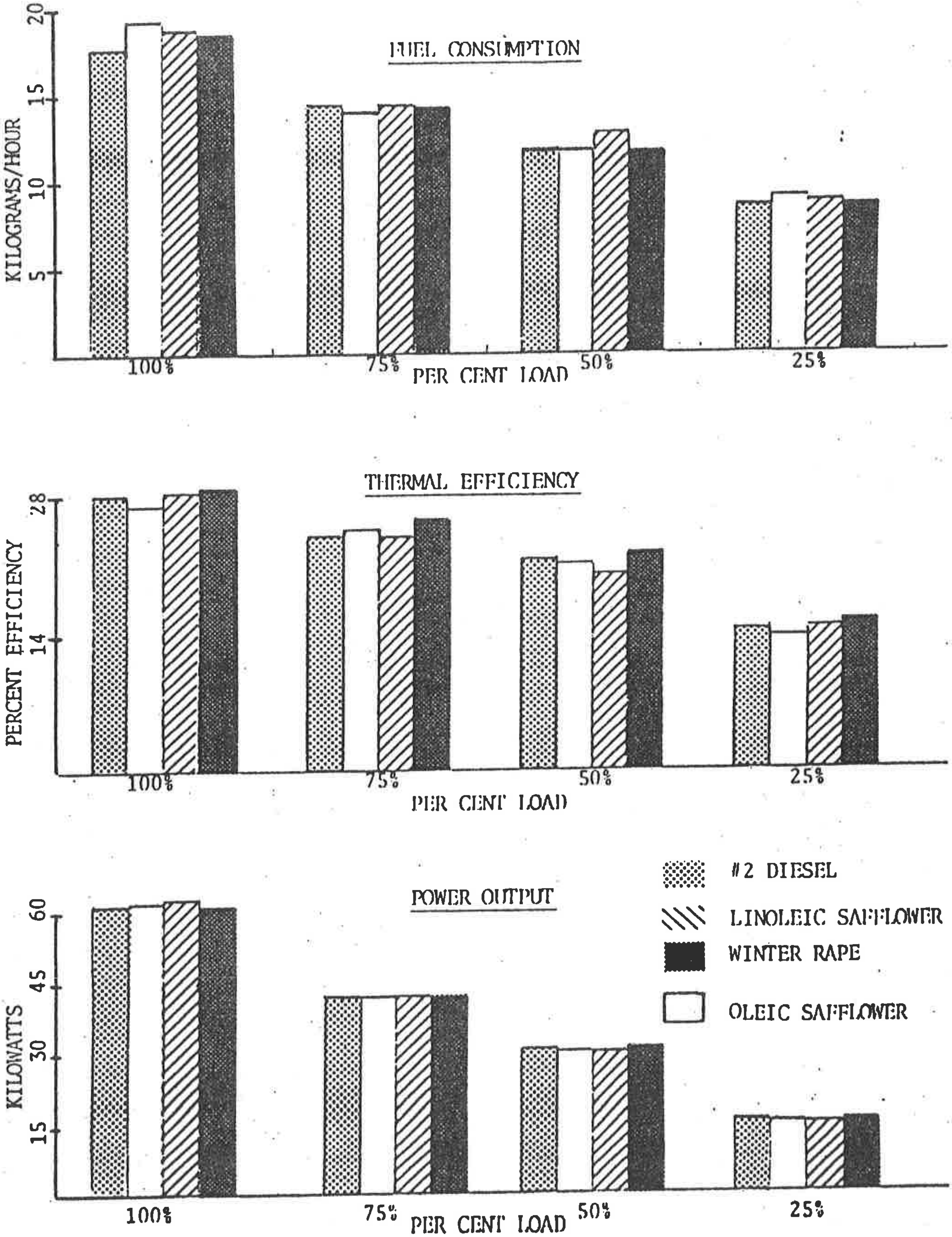


Figure 3. Comparison of 50/50 mixtures of three vegetable oils and diesel fuel to 100% diesel fuel.

TABLE 1. Composition of Vegetable Oils

	Palmitic 16:0	Stearic 18:0	Oleic 18:1	Linoleic 18:2	Eicosenoic 20:1	Linolenic 18:3	Erucic 22:1
	% by weight methyl esters						
Linoleic Safflower	5.87	1.53	8.84	83.76	----	----	----
Oleic Safflower	4.75	1.39	74.12	19.74	----	----	----
Rapeseed (Sipal variety)	4.29	1.26	59.89	21.12	----	13.19	----
Rapeweed (Dwarf Essex variety)	2.97	0.80	13.09	14.09	7.41	9.71	50.72

TABLE 1. Fuel Test Data for the Three Fuels Tested. Tests Conducted by Phoenix Chemical Laboratory, Inc., Chicago, Illinois.

Test	Diesel #2	50% Diesel 50% Oleic	50% Diesel 50% Linoleic
Cetane Rating	47.80	---	---
Flash, °F. (PMCC)	176.00	198.00	198.00
Cloud Point, °F.	10.00	8.00	8.00
Pour Point, °F.	-20.00	5.00	5.00
Water & Sediment, %	Trace**	Trace**	0.01
Ramsbottom Carbon on 10% Residuum, %	0.17	0.16*	0.17*
Ash, %	0.01	0.01	0.01
Viscosity @ 40°C,cs.	3.20	11.25	10.04
Viscosity @ 100°C,cs.	1.26	3.31	3.16
Sulfur, %	0.29	0.13	0.12
Copper Corrosion, 3 hrs. @ 122°F.	Slight tarnish, 1a	Slight tarnish, 1a	Slight tarnish, 1a
Existent Gum, (Steam Jet) mg/100ml.	21.60	44.90	46.60
API Gravity @60°F	33.10	27.80	27.10
Heat of Combustion, BTU/lb. Gross	19,443.00	18,207.00	18,143.00
Particulate Matter, mg/100ml.	0.20	0.20	0.10

*On total sample
**Less than 0.005

Table 1 (Cont'd). Fuel Test Data for the Three Fuels Tested. Tests Conducted by Phoenix Chemical Laboratory, Inc., Chicago, Illinois.

100D2 DISTILLATION, °F.		50SO - 50D2 DISTILLATION, °F.		50SL - 50D2 DISTILLATION, °F.	
Initial Boiling Point	393	Initial Boiling Point	407	Initial Boiling Point	406
5 %	441	5 %	452	5 %	453
10%	458	10%	479	10%	481
20%	482	20%	512	20%	514
30%	498	30%	544	30%	543
40%	512	40%	572	40%	573
50%	525	50%	594	50%	606
60%	539	Cracking at 56%	618	Cracking at 60%	622
70%	554	End Point	618	End Point	622
80%	579				
90%	609				
95%	638				
End Point	656				
Recovery, %	98.0				
Residue, %	1.9				
Loss, %	0.1				

Table 2. Average Maximum Power (kW) for EMA Test Cycle with Three Wisconsin Engines with two Vegetable Oil Fuels and Diesel.

Hours	100D2 Power (KW)	100D2 Change (%)	50SO - 50D2 Power (kW)	50SO - 50D2 Change (%)	50SL - 50D2 Power (kW)	50SL - 50D2 Change (%)
0-50	13.17	---	10.63	---	11.28	---
51-101	14.00	+0.6	10.67	+0.3	10.84	-3.9
102-150	13.72	+0.4	10.73	+0.9	10.53	-6.6
150-193	13.32	+0.1	10.26	-3.5	10.32	-8.5

Table 3. Average Cycle Brake Specific Fuel Consumption (kg/kW-h) for EMA Test Cycle with Three Wisconsin Engines with Two Vegetable Oil Fuels and Diesel.

Hours	100D2		50SO - 50D2		50SL - 50D2	
	BSFC (kg/kW-h)	Change (%)	BSFC (kg/kW-h)	Change (%)	BSFC (kg/kW-h)	Change (%)
0-50	0.349	---	0.414	---	0.367	---
51-101	0.323	- 7.4	0.398	- 4.0	0.433	+18.0
102-150	0.301	-13.8	0.354	-14.0	0.383	+4.0
151-193	0.370	+ 6.0	0.410	- 1.0	0.471	+28.0

Table 4. Engine Wear Data for EMA Test Cycle with Three Wisconsin Engines with Two Vegetable Oil Fuels and Diesel.

	100D2	50SO - 50D2	50SL-50D2
Hours of Test	193	193	193
Fuel Consumed (kg)	486	478	449
Cylinder Wear (mm)	0.0330	NC	0.0180
Valve Stem Wear			
Intake (mm)	0.0025	NC	0.0051
Exhaust (mm)	0.0051	0.0076	0.0076
Valve Guide Wear			
Intake (mm)	NC	NC	0.0051
Exhaust (mm)	NC	NC	0.0100
Piston Ring Weight Loss			
Top (g)	0.0753	0.0803	0.0850
Middle (g)	0.0360	0.0320	0.1170
Oil (g)	0.0519	0.0425	0.0340
Piston Ring Gap Increase			
Top (mm)	0.0510	NC	0.0510
Middle (mm)	NC	NC	0.1270
Oil (mm)	0.0250	0.1270	0.1020
Piston Weight Loss (g)	0.2100	NC	0.0600
Wrist Pin Wear	NC	NC	NC
Injector Opening Pressure Decrease (kPa)	207	345	379

Table 5. Engine Oil Analysis Data for EMA Test Cycle with Three Wisconsin Engines with Two Vegetable Oil Fuels and Diesel.

	FUEL	ENGINE HOURS 0-50	51-101	102-151	152-193
Viscosity	100D2	81.2	141.0	104.1	125.3
(cst @ 40°C)	50SO-50D2	73.1	129.9	126.5	192.9
	50SL-50D2	105.1	164.9	115.2	198.8
Oxidation	100D2	N	M	N	N
(N=normal,	50SO-50D2	N	M	N	M
M=marginal)	50SL-50D2	N	M	M	M
Silicon	100D2	19.0	24.0	10.0	13.0
(PPM)	50SO-50D2	26.0	32.0	27.0	35.0
	50SL-50D2	19.0	30.0	21.0	38.0
Iron	100D2	113.0	214.0	43.0	98.0
(PPM)	50SO-50D2	103.0	185.0	135.0	172.0
	50SL-50D2	117.0	229.0	138.0	185.0
Chromium	100D2	9.5	11.4	5.5	7.8
(PPM)	50SO-50D2	14.2	17.3	16.0	21.2
	50SL-50D2	15.6	18.1	12.5	17.3
Aluminum	100D2	19.0	29.0	10.0	14.0
(PPM)	50SO-50D2	21.0	37.0	30.0	42.0
	50SL-50D2	21.0	31.0	19.0	40.0
Copper	100D2	69.0	86.0	10.0	27.0
(PPM)	50SO-50D2	31.0	41.0	18.0	18.0
	50SL-50D2	51.0	78.0	33.0	25.0
Lead	100D2	12.0	37.0	7.0	9.0
(PPM)	50SO-50D2	13.0	47.0	22.0	26.0
	50SL-50D2	18.0	179.0	46.0	46.0
Tin	100D2	4.0	11.0	3.0	3.0
(PPM)	50SO-50D2	7.0	19.0	20.0	17.0
	50SL-50D2	6.0	17.0	9.0	18.0
Nickel	100D2	6.0	3.0	2.0	5.0
(PPM)	50SO-50D2	12.0	7.0	22.0	32.0
	50SL-50D2	13.0	7.0	17.0	26.0
Magnesium	100D2	50.0	60.0	33.0	39.0
(PPM)	50SO-50D2	39.0	43.0	34.0	40.0
	50SL-50D2	40.0	43.0	35.0	37.0