Long Term Performance of a Sunflower Oil/Diesel Fuel Blend

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It has been recognized for many years that vegetable oils could be burned in compression ignition engines. However, they have not been accepted as a viable substitute for diesel fuel because of inexpensive and abundant supplies of petroleum-based fuels. The world petroleum situation of the past several years has focused attention on the need for development of alternate fuels. Research efforts have been started to determine the feasibility of using vegetable oils as diesel fuel substitutes (1-7).

The purpose of this project was to study the effects of a 50 percent blend by volume of sunflower oil in #2 diesel fuel used in a diesel test engine of current design. Specifically, this investigation covered the effect of the fuel blend on engine durability and the functioning of the different fuels in the diesel engine injection system.

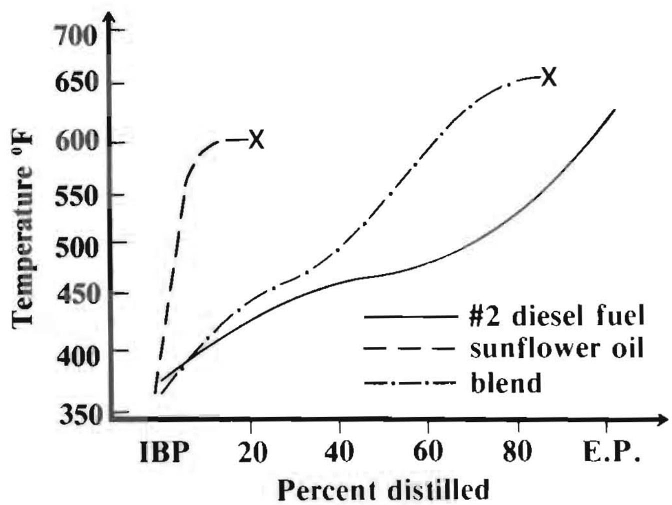
FUEL PROPERTIES AND CHARACTERISTICS

The fuels used in these tests were #2 diesel fuel and a blend by volume of 50 percent alkali refined sunflower oil and 50 percent #2 diesel fuel. Fuels were obtained from commercial sources. No additives were used. All fuels were filtered through a 5 micron filter.

Samples of all fuels which were used in the tests were analyzed using American Society of Testing and Materials (ASTM) standard procedures for petroleum fuel products. Results presented in Table 1 show several important properties of the fuels which, along with chemical characteristics, influenced engine performance and long term engine operation. The API gravity of the alternate fuels was found to be lower than the #2 diesel fuel. The viscosity of the sunflower oil was significantly higher than that found for the #2 diesel fuel. The #2 diesel fuel had the highest heating value of the tested fuels. Cracking was observed at a relatively low percentage level for the alternate fuels particularly for pure sunflower oil (Fig. 1).

Table 1—Test Fuel Properties

	#2 Diesel	100% Sunoil Refined	50% Diesel 50% Sunoil
API Gravity @ 60°F			
Degrees	35.3	22.1	29.1
Cetane Rating	48.0	31 7	38.2
Heating Value, BTU/lb			
Gross	19,232	16,974	18,411
Net	18,157	15,914	17,272
Pour Point, °F	-35	-9	-9
Cloud Point, °F	-18	--	-4
Viscosity (centistokes)			
32°F	6.42	187.68	71.66
100°F	2.40	34.33	17.37
160°F	1.48	14.93	8.21



I.B.P.—Initial Boiling Point
E.P.—End Point
X—Cracking observed, distillation discontinued

Fig. 1—Fuel distillation curves.

The sunflower oil used for this test was unusually high in linolenic acid content (Table 2). Due to problems encountered while performing this experiment, the sunflower oil was re-analyzed after completion of the endurance test and found to contain 17 percent linseed oil. This would explain the high linolenic acid content of the test fuel since linseed oil has a linolenic acid content of 60 percent. For this test, the authors simply ordered their test fuel by specifying alkali refined sunflower oil on the purchase order. The supplier did not deliver what they had ordered.

APPARATUS AND PROCEDURE

For testing purposes, a four-cylinder Allis Chalmers diesel engine was selected because of its typical design,

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relatively small size, and low fuel consumption. Engine and fuel injection system specifications are presented in Table 3.

Table 2—Sunflower Oil Chemical Analysis

Acid value, mg/g		0.13
Iodine value, g/g		142.3
Saponification Value, mg/g		191.3
Fatty Acid Distribution		
Palmitic	C16	6.2
Stearic	C18	4.5
Oleic	C18:1	18.0
Linoleic	C18:2	65.2
Linolenic	C18:3	5.5
Erucic	C22	0.7

Table 3—Engine and Fuel Injection System Specifications

Description	Specification
	Engine
Engine model	433I, intercooled, turbocharged
Type	Four-stroke cycle
Combustion system	Direct injection, high swirl, toroidal combustion chamber
Displacement	200 in³
Bore	3.87 in
Stroke	4.25 in
Compression ratio	14.1:1
	Fuel Injection System
Fuel injection pump	Stanadyne Roosa Master type DB2
Injection nozzle	Robert Bosch,
Nozzle opening pressure	4250 ± 50 psi
Nozzle assembly	Four orifices = 0.32 mm Spray cone angle = 160° Sac length = 0.04 in Sac diameter = 0.04 in

Fuel consumption was measured on a weight basis with a Cox Instrument Fuel Consumption Weight System, Type 402.

A Bosch Model EFAW 68A Smokemeter was used to analyze exhaust smoke. Three smoke samples were taken and the average reading was recorded.

The dynamometer used to load the engine was a Dynamic Absorbing Dynamometer, Model 1014 D.G. The dynamometer was equipped with an electronic digital output for torque and RPM. A continuous test cycle of three minutes at high idle and 10 minutes at peak torque was used. Fuel injection line pressures were measured at the nozzle with a Kistler Model No. 607F122 piezo-electric pressure transducer. The pressure output signals were conditioned with a charge amplifier and displayed on an oscilloscope simultaneously with timing marks sensed by a magnetic pickup on the flywheel.

RESULTS

No significant problems with engine operation were encountered during the test on diesel fuel. However, problems with plugged fuel filters, carboned nozzles, and stuck piston rings were experienced while operating on the 50/50 (v/v) blend of sunflower oil and diesel fuel.

Fuel Filter Problem

The fuel pressure before the injection pump should be maintained at 3-4 psi, according to the manufacturer's specifications. When the pressure dropped below this limit, the fuel filter was changed. During 500 hours of testing with #2 diesel fuel, the fuel filter was changed once after 230 hours of engine operation. Before the blend test the pure sunflower oil was pumped from the bottom of a storage tank, filtered through a 5 micron filter and blended with #2 diesel fuel. Using this fuel mixture, the fuel filters on the engine would plug after 15-20 hours of operation. After 345 hours, a new fuel mixture was prepared from sunflower oil pumped from the top of the storage tank and filtered through a 5 micron filter. Filter life was extended to about 40 hours. The last test fuel mixture was prepared after 531 hours of testing from sunflower oil pumped from the top of the storage tank and filtered through a 3 micron filter. An unscheduled termination of the engine test (piston failure at 604 hours) did not allow positive determination of the effect of prefiltering the sunflower oil through a 3 micron filter.

Injection Nozzle Carbon Buildup and Effects

During 604 hours of testing with the blended fuel, the injection nozzles were changed eight times. The changes were made after experiencing a 5 percent drop in power accompanied by a very high level of exhaust smoke (above 5 Robert Bosch smoke units) and engine instability.

The effect of injection nozzle operating time on engine performance for the 50/50 blend using the first set of injection nozzles is presented in Fig. 2.

At the start of the 50/50 blend test, the power output was 3 percent higher and fuel flow was 13 percent higher than for #2 diesel fuel. This translated to a 6 percent increase in specific fuel consumption (SFC). In addition, exhaust temperature was 5 percent higher for the 50/50 blend. As the tests proceeded, engine performance losses were observed. The injection nozzles were changed when power loss did not allow the engine to continue on the test cycle. As can be seen in Fig. 2, engine performance loss between 60 and 79 hours was caused by fuel filter plugging. After changing the filter element at 79 hours of engine operation, the power output and fuel flow increased. Changing the injection nozzles after 112 hours of operation increased the power output to the initial level, decreased the smoke level, and decreased the exhaust gas temperature. A reduction in SFC was caused by increased power output because the fuel flow did not change. The outcome was similar for the other replaced injection nozzle sets.

The major problems with the injection nozzles were a drop in the nozzle opening pressure and abnormal carbon buildup. On initial installation, nozzle opening pressures were adjusted within close limits (about ± 1.0

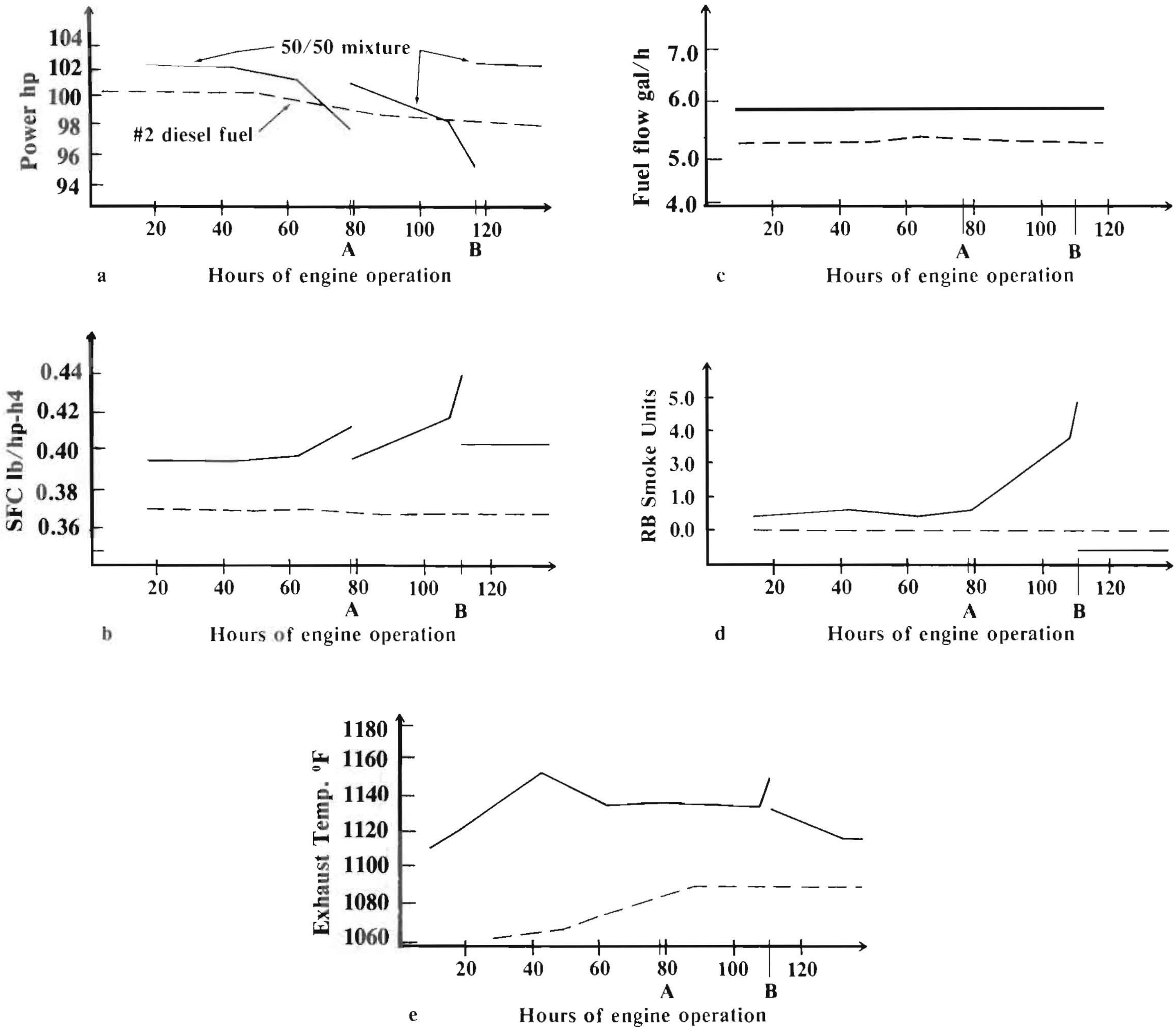


Fig. 2—Effect of injection nozzle operating time on engine power, specific fuel consumption (SFC), fuel flow, exhaust gas temperature, and smoke level at 2300 RPM with a 50/50 mixture of sunflower oil and diesel fuel. Point A indicates fuel filter replacement. Point B indicates injection nozzle replacement.

percent) of the nominal pressure setting of 4250 psi. The nozzle operating time with the blend varied from 5 hours to 123 hours. During this time the nozzle opening pressure dropped about 10-15 percent as a result of the nozzle springs taking a set; there was slight wearing of various valve, spindle, and spring contact surfaces; and carbon deposits formed on the seat and needle. The highest drop in nozzle opening pressure was almost 20 percent. The loss of opening pressure for all nozzles was not equal, which affected fuel distribution between cylinders.

After a short period of time, the test on the 50/50 mixture showed excessive carbon buildup on the nozzle tip (Fig. 3). Partly responsible for the carbon buildup on the nozzle are the following: (1) the sunflower oil tendency to polymerize, (2) a small quantity of fuel which remains at the nozzle tip after the end of the main injection, and later (3) injection nozzle "micro" reopenings, (4) secondary injection and (5) needle sticking.

Some of the fuel which remains in the nozzle tip after the end of the main injection is observed to leave the nozzle tip owing to fuel evaporation at the high temperatures and the high gas flow (9). The fuel trapped between injections undergoes decomposition from high temperatures. This decomposition of the fuel occurs at a temperature of 660°F (350°C) and is influenced by the chemical composition of the fuel and the presence of catalytic materials, one of which is carbon (10).

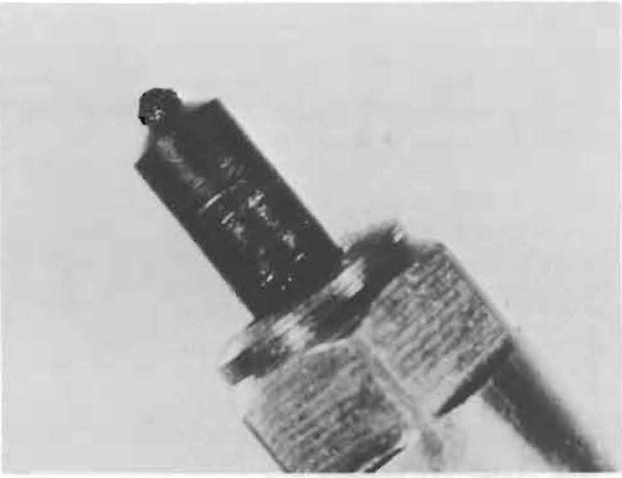


Fig. 3—Injection nozzle tip after 24 hours of testing with a 50/50 sunflower oil/diesel fuel mixture.

The carbon did not build up equally around the nozzle tip of the 32 nozzles which were tested. The carbon distribution shows a pattern which was consistent in all tested nozzles. The nozzle orifice on the intake valve side was almost clean. There was no carbon buildup on the surface and much less inside the orifice. The remaining nozzle surface showed considerable carbon buildup which extended into the orifices. It is very possible that air swirl movement had an influence on the carbon distribution of the nozzle tip. There are also different angles between the nozzle holes and the main axis of the nozzle tip. The different angles could cause differences in dynamic flow through the orifices. This could cause a difference in injection velocity and flow pattern of the injected fuel resulting in a variation of fuel spray configuration (11).

Carbon deposits developed inside the nozzle orifices causing a decrease in the orifices' diameter and affecting smoothness of the orifices' surfaces. Inspection showed a reduction in orifice diameters for all tested nozzles. For each nozzle, three orifices exhibited a reduction of inside diameter from 0.0125 inch to 0.0108 inch. The orifice on the intake valve side showed a reduction of inside diameter from 0.0125 inch to 0.0118 inch. This translates to a total hole area reduction of approximately 25 percent.

Maximum injection line pressure and residual line pressure increased due to the reduction in orifice diameters caused by the carbon deposits (Figs. 4 and 5). The increased maximum line pressure caused a higher rate at which the fuel was injected into the combustion chamber and thus affected the rate of pressure rise. Higher residual line pressure, in addition to the decrease in opening pressure, increased the possibility of secondary injection. Maximum injection pressure at 2300 RPM increased from 6500 psi for a clean nozzle to 9000 psi for a carboned nozzle and at 1800 RPM from 6000 psi (clean nozzle) to 7000 psi (carboned nozzle). Residual line pressure went up from 2900 psi to 4500 psi at 2300 RPM and from 2500 psi to 3000 psi at 1800 RPM. The residual pressure waves for the carboned nozzle also occurred sooner than for the clean nozzle. Therefore, for the carboned nozzle, successive residual line pressure waves occurred at higher combustion chamber pressures, increasing the possibility of needle micro-reopening and secondary injection.

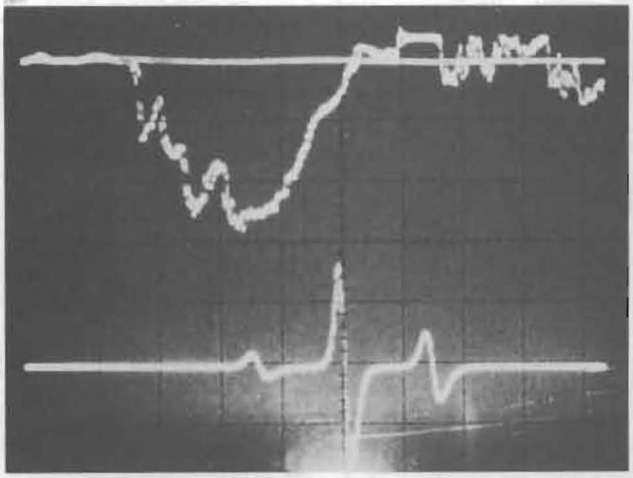


Fig. 4—Timing mark (1) and injection line pressure (2) at the nozzle for 50/50 sunflower oil/diesel fuel mixture after 2 hours of operation. Nozzle opening pressure = 4250 psi. Engine speed = 2300 RPM. Nozzle has four orifices with a diameter of 0.0125 in.

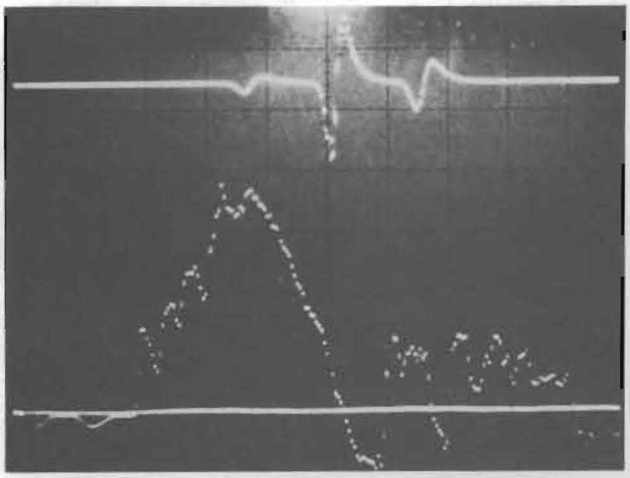


Fig. 5—Timing mark (1) and injection line pressure trace (2) at the nozzle for 50/50 sunflower/diesel fuel mixture after 108 hours of engine operation. Nozzle opening pressure = 4000 psi. One nozzle orifice completely plugged. Two orifices have a diameter of 0.01/in. One orifice has a diameter of 0.012 in. Engine speed = 2300 RPM.

This phenomenonon does not affect the specific fuel consumption, but it can cause the formation of carbon deposits on the nozzle tip. The formation of carbon deposits on the injector needle (Fig. 6) and seat may cause poor seating with consequent dribble.

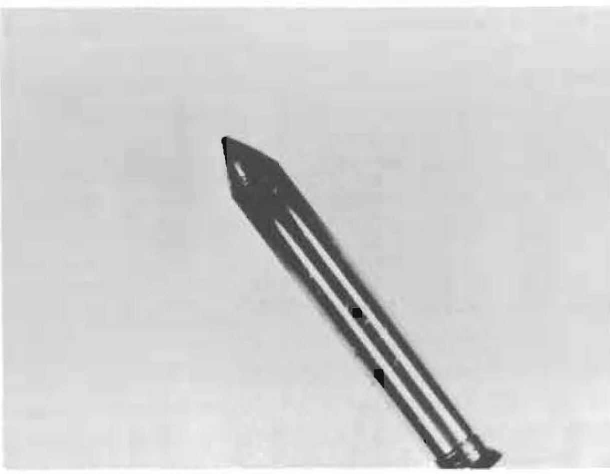


Fig. 6—Carbon buildup on the injection needle after 25 hours of testing with a 50/50 sunflower oil/diesel fuel mixture.

The pressure shapes during the beginning and the end of the injection have a great influence on the fuel inlet characteristics to the combustion chamber and therefore may cause the fuel to burn more rapidly and completely. For both injection nozzles (clean and carboned) the pressure shapes during the beginning and final injection states were fairly steep to assure an injection process free from pronounced dribble. However, when secondary injection occurred, the fuel entered the combustion chamber with a velocity too low for proper atomization. Also, the fuel was introduced late in the engine cycle when decreased available oxygen and decreasing gas temperature reduced the possibility of burning the carbon particles.

During the test a sudden change in the exhaust smoke level from 3.5 to 0.8 Robert Bosch smoke units was noticed. This was most likely caused by needle hang up. Varnish buildup on the needle over an extended period of time caused the needle movement in the housing to become difficult or impossible. It is feasible that high temperature and clean fuel loosened up the needle and returned smoke to a normal level.

Carbon Buildup in the Intake Port

After 250 hours of testing, excessive carbon buildup on the cam side of the intake ports was noticed (Fig. 7). This phenomenon was caused by many factors: 1) the sunflower oil tendency to polymerize, 2) the combustion process in the second stage of combustion and afterburning (especially at light load), and 3) the effect of valve timing. The combustion must be completed early in the expansion stroke so that the temperature is high enough that oxygen can react with the carbon monoxide, hydrogen, and soot to form the desired products. If the combustion occurs later in the expansion stroke, less time is available before the exhaust valve opens and the temperature has dropped to a value too low for rapid oxidation.

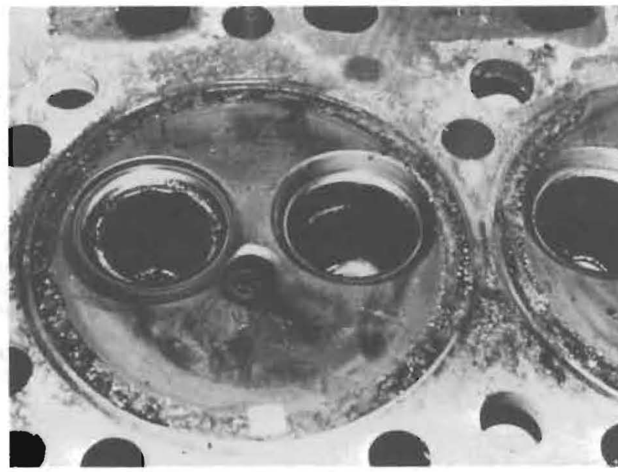


Fig. 7—Carbon buildup on the intake port after 250 hours of testing with a 50/50 sunflower oil/diesel fuel mixture.

The valve timing chosen for a particular engine is generally a compromise of scavenging and the effect on power and torque curves, maximum permissible temperatures of internal working parts, and overall engine efficiency. The value overlap was 36° in this test engine. The quantity of air flow through the cylinder during the overlap period is a function of P_e/P_i (exhaust pressure/intake pressure) and the exhaust gas kinetic energy. In a turbocharged diesel engine, P_e/P_i exceeds unity under the conditions of a suddenly increased load. This encourages exhaust gas to flow through the cylinder into the intake port during the valve overlap period and cause carbon buildup.

Lubricating Oil Analysis, Oil Consumption, and Blowby

The crankcase oil used during the test was Allis Chalmers Power Lube 15W-40 (oil category CD). During 500 hours of engine testing on #2 diesel fuel, seven oil samples were taken and analyzed by Analysts Maintenance Laboratory, Inc. These tests indicated that the condition of the oil was satisfactory. During 600 hours of engine testing on the 50/50 mixture, six oil samples were analyzed by this laboratory. The oil analysis results indicated abnormal oil conditions (Table 4). Excessive iron content for samples up to 233 hours of testing and abnormal aluminum content for the sample taken at 233 hours of the test indicated that the cylinder liners and piston rings were wearing. Also, at 233 hours an excessive total amount of solids (both suspended and nonsuspended) contamination was found. The two oil samples taken after the engine was rebuilt (245 hours) had a normal iron and aluminum content but still had too high a percentage of total solids. The viscosity value was acceptable for the sample taken after 50 hours of operation (14 cSt at 212°F) but was abnormally high for the sample taken after 100 hours of operation (21 cSt at 212°F).

TABLE 4—Spectrochemical Analysis of Lubricating Oil Samples Taken During 600 Hours of Engine Testing on a 50/50 Sunflower Oil/Diesel Fuel Mixture

Sample Number	Total Hours of Engine Operation reference	Hours of Engine Operation on the Oil Sample	Iron	Lead	Copper	Chromium	Aluminum	Nickel	Silver	Tin	Silicon	Boron	Sodium
1	0	0	3.30	1.41	0.07	0.0	1.16	0.0	0.17	0.0	12.6	2.90	36.5
2	64.0	58.0	101	19.4	18.8	9.42	9.60	1.69	0.0	2.96	10.7	9.04	28.6
3	157.0	93.0	131	32.8	22.9	8.86	7.68	2.09	0.30	0.0	9.52	8.36	27.4
4	203.0	46.0	85.6	21.0	14.2	7.04	9.59	2.43	0.30	0.0	10.1	8.66	31.6
5	233.0	76.0	173.0	47.3	23.0	10.7	19.3	3.01	0.30	0.0	13.1	8.66	30.2
6	529.0	44.0	46.4	12.3	6.17	5.48	3.46	0.99	0.35	0.0	6.22	3.01	34.6
7	586.0	56.0	53.1	15.1	9.90	5.67	3.75	0.39	0.26	0.0	11.3	3.21	33.1

Sample Number	Phosphorus	Zinc	Calcium	Barium	Magnesium	Titanium	Molybdenum	Cadmium	Antimony	Fuel Dilution Diesel % Vol	Total Solids % Vol	Water % Vol	Viscosity cSt @ 100°C
1	1802	1571	1687	2.25	399	0.0	0.09	0.37	0.0	< 0.5	< 0.1	< 0.05	Max 16.8
2	940	1065	2248	4.46	133	0.0	0.22	0.38	3.94	< 0.5	1.0	< 0.05	—
3	1759	1307	1827	1.54	360	0.0	0.09	4.10	0.0	1.0	24.0	< 0.05	20.5
4	2232	1683	2089	0.0	533	0.0	1.41	1.52	0.0	< 0.5	5.0	< 0.05	13.1
5	2310	1684	2216	1.54	452	0.0	0.40	2.76	0.0	0.5	25.0	< 0.05	21.5
6	1308	1479	1583	6.28	429	0.0	0.0	1.12	11.4	< 0.5	5.0	< 0.05	14.3
7	1400	1626	1805	1.49	460	0.0	0.89	0.83	0.0	< 0.5	5.0	< 0.05	15.5

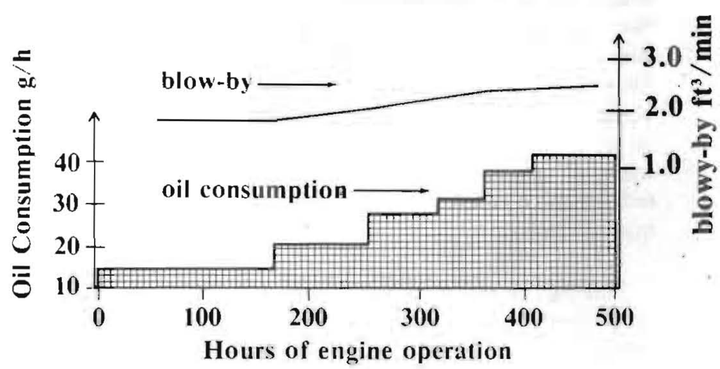
The lubricating oil consumption for the 500 hour test on #2 diesel fuel was very good (0.00051 lb/hp-hr), (Fig. 8). For the 604 hour test on the 50/50 blend, the mean oil consumption was even better (0.00020 lb/hp-hr), (Fig. 8). The lubricating oil analysis (high percentage of total solids and high viscosity) suggests that combusted and noncombusted fuel may have traveled between the piston and cylinder wall into the crankcase causing the apparent low lubrication oil consumption rate.

Blowby stayed at a satisfactory level most of the time during the engine test on the 50/50 blend (Fig. 8). The only reading that showed increased blowby occurred at 200 hours. At this time, the blowby had increased from 2.7 cfm to 4.4 cfm (75 L/min to 125 L/min). This was most likely caused by a temporary loss of sealing of the piston rings.

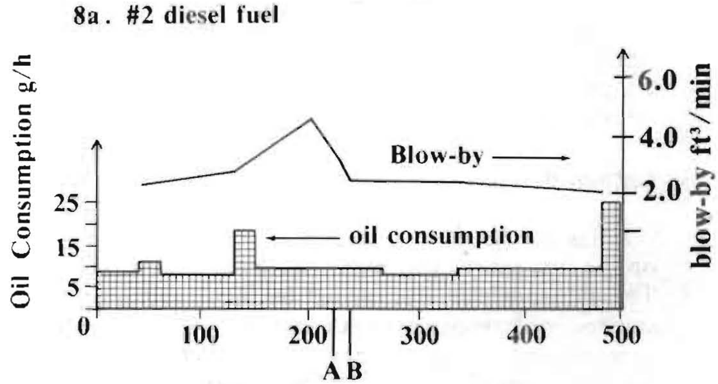
Condition of Pistons, Liners, Rings, and Bearings

After 500 hours of operation on #2 diesel fuel, a worn valve guide (only one) and excessive carbon buildup on the topland of the pistons were found. It is possible that the carbon buildup was a result of the extended period (3 minutes) of operation at high idle.

After 245 hours of engine operation on the 50/50 blend, piston rings #2 and #3 were stuck and the #4 ring (oil ring) was broken on the #1 piston (Fig. 9). The cylinder was gouged out on the major and minor thrust side and was scratched throughout (Fig. 10). The top of



8a. #2 diesel fuel



8b. Blend (50% Sunflower oil and 50% #2 diesel fuel)

Fig. 8—Oil consumption and blowby while using #2 diesel fuel or a 50/50 sunflower oil/diesel fuel mixture (measured at 75 kW).

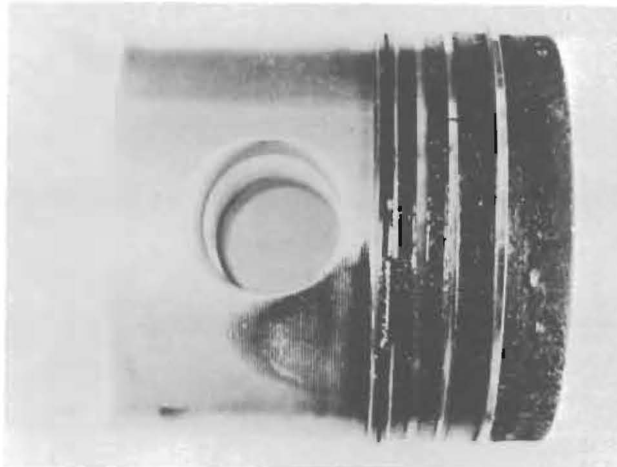


Fig. 9—Carbon buildup on the piston. Rings #2 and #3 are stuck. Ring #4 (oil ring) is broken after 245 hours of engine operation with a 50/50 sunflower oil/diesel fuel mixture.

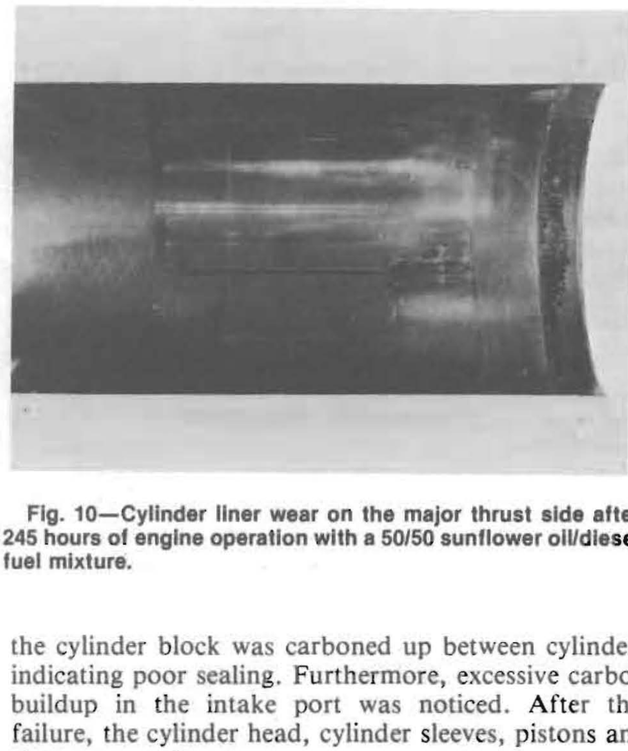


Fig. 10—Cylinder liner wear on the major thrust side after 245 hours of engine operation with a 50/50 sunflower oil/diesel fuel mixture.

the cylinder block was carboned up between cylinders indicating poor sealing. Furthermore, excessive carbon buildup in the intake port was noticed. After this failure, the cylinder head, cylinder sleeves, pistons and rings were replaced.

After 604 hours on the 50/50 mixture, a piston failure, which was not caused by the fuel, ended the test. All pistons showed heavy carbon buildup around the ring groove on the top land. Normal carbon buildup on the second land was observed. Carbon and varnish residue on the third and fourth land was also evident (Fig. 11). Piston ring side clearance was measured after the test and after cleaning. The top ring side clearance increased from 0.003 inch to 0.005 inch. The second rings were all stuck and could not be measured. For the third ring, a large change of inside clearance occurred only on the #4 piston where side clearance increased from 0.0016 inch to 0.0039 inch. The oil ring showed no change. The comparison between initial and final (604 hours) measurements of the piston groove and piston rings did not show significant changes. Ring face wear was evident especially for the third ring on the #4 cylinder where the radial thickness changed from 0.176 inch to 0.174 inch and the gap changed from 0.012 inch to 0.021 inch.

Fig. 11—Carbon buildup on the piston and a stuck #2 ring after 604 hours of engine operation with a 50/50 sunflower oil/diesel fuel mixture.

Cylinder sleeves had some skirt scratches throughout the inside diameter on the major and minor thrust side. Also, very light random polish tracks were visible. Under high magnification, it could be seen that the hone marks were deeper than the scratches. Some scoring was caused by the piston rather than the rings as indicated by the scratches extending below the lowest level of ring travel and by the smearing of metal on the sides of the piston. Overall, cylinder sleeves were in very good condition and showed less wear than when the engine was run on #2 diesel fuel.

Except for light scratches in the #1 and #5 lower main bearings, they were in very good condition. The #2 upper rod bearings showed light edge loading while the #1 and #4 upper rod bearings showed completely removed overlay on the bearing surface in spots. Further, on the #3 upper rod bearing, fatigue failure and a 1 inch visible crack could bee seen (Fig. 12).

Turbocharger and Fuel Injection Pump Comdition

After 233 hours of engine operation, an engine instability problem (especially at a lower speed) led to inspection of the turbocharger. The turbine end journal bearing was seized on the turbine shaft due to inadequate lubrication. The shaft showed signs of severe oil coking (Fig. 13). The thrust collar and thrust bearings were mechanically in good condition, but they were discolored by oil coking. The failed turbocharger was replaced by a new one. At the end of the test (604 hours) on the 50/50 mixture the second turbocharger was inspected and again oil coking on the shaft was seen.

Although failure at this point was not imminent, future life for this turbocharger could not be predicted. The center housing of the turbocharger was coated with a soft carbon that seemed to build up, flake off, and rebuild (Fig. 14). In comparison, the center housing of the turbocharger after the run with #2 diesel fuel had a hard, thin carbon coating.

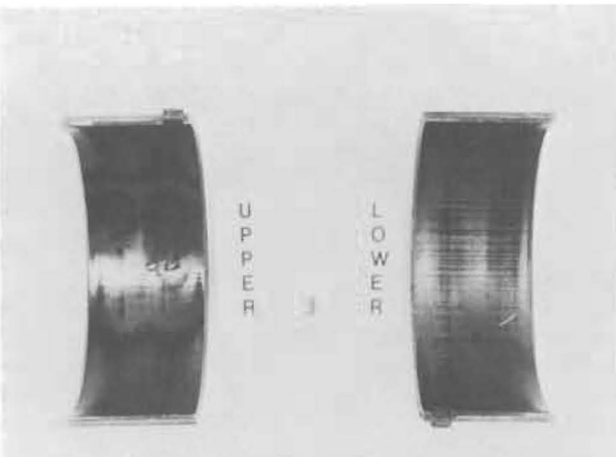


Fig. 12—Fatigue failure and partially removed overlay on the bearing surface of the #3 upper rod bearing after 604 hours of engine operation with a 50/50 sunflower oil/diesel fuel mixture.

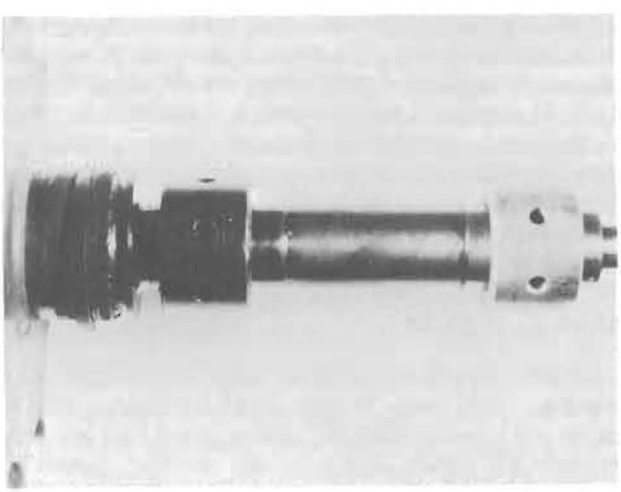


Fig. 13—Turbine and journal bearing seized on the turbine shaft. The shaft shows signs of severe oil coking after 233 hours of engine operation with a 50/50 sunflower oil/diesel fuel mixture.

Two injection pumps were used during the test with the 50/50 blend. The first injector pump had 192 hours of operation. The second injector pump had 402 hours of operation. Inspection of the pumps did not show any significant wear. However, all parts were coated with a sticky layer of sunfloer oil which could affect operation of the mechanical governor, transfer pump regulator, and automatic advance system. It is possible that the sunflower oil coating buildup did not occur during engine operation but during the two-month interval between the end of the test and the injection pump inspection.

Fig. 14—Center housing of the turbocharger coated with soft carbon after 233 hours of engine operation with a 50/50 sunflower oil/diesel fuel mixture.

SUMMARY AND CONCLUSIONS

1. Researchers of vegetable oil fuel for diesel engines should measure the fatty acid distribution of their test fuels. This should be done to check that they have received the fuel as specified and to further establish the relationship between injector nozzle coking tendencies and the iodine number of vegetable oils used as diesel fuel.

2. During the test with the blend of sunflower oil and #2 diesel fuel, the engine fuel filters would plug after 20-40 hours of operation. It is possible that prefiltering the sunflower oil through a 3 micron filter will solve the problem.

3. The injection nozzle operating time on the blend was short and erratic with variations from 35 hours to 123 hours. During this time the nozzle opening pressure dropped 10-15 percent. Excessive carbon buildup on the nozzle tip and inside the orifices was experienced.

4. The carbon distribution on the injection nozzle tip shows a pattern which was consistent in all tested nozzles. The nozzle orifice on the intake valve side was almost clean. There was no carbon buildup on the surface and much less inside the orifice. The remaining nozzle surfaces showed considerable carbon buildup. The carbon deposits inside the orifices caused a significant decrease in orifices diameter and effected smoothness of the orifices surfaces. For each nozzle three orifices had a reduction of inside diameters from 0.0125 inch to 0.0108 inch. The orifice on the intake valve side showed a reduction from 0.0125 inch to 0.0118 inch. This translates to a total reduction in cross-sectional area of approximately 25 percent.

5. Reduction in orifice diameters due to carbon deposits caused an increase in the maximum injection

line pressure and the residual line pressure. The increased maximum line pressure caused a higher fuel injection rate into the combustion chamber which controls the rate of cylinder pressure rise. A higher residual line pressure in combination with the decrease in opening pressure increased the possibility of secondary injection.

6. Excessive carbon buildup on the intake ports on the cam side was seen after 250 hours of testing with the 50/50 fuel blend.

7. Analysis of lubricating oil indicated abnormal oil conditions while testing the 50/50 fuel blend. Excessive iron and aluminum content were experienced until the #1 cylinder was changed at 246 hours. An excessive total amount of solids contamination (both suspended and nonsuspended) was found. The viscosity was acceptable for the sample taken after 50 hours of operation (14 cSt at 212°F) but was abnormally high for the sample taken after 100 hours of operation (21 cSt at 212°F).

8. The lubricating oil consumption for the 604 hour run on the 50/50 blend was very good (0.00020 lb/hp-hr). Also, blowby stayed at a satisfactory level.

9. All pistons showed heavy carbon buildup around the ring groove on the top land after 604 hours of testing with the 50/50 blend. The second rings were stuck on all pistons.

10. The initial and final measurements of the piston groove and piston rings did not show any significant changes.

11. Cylinder sleeves were in very good condition and showed less wear than when the engine was run on #2 diesel fuel.

12. The rod bearings were in good condition. There was light edge loading and removed overlay on the bearing surfaces in spots. One upper rod bearing showed a fatigue failure.

13. A failed turbocharger was replaced after 233 hours of engine operation on the 50/50 blend. The turbine end journal bearing was seized on the turbine shaft due to inadequate lubrication. The shaft showed signs of severe oil coking.

14. Long term tests with fuel and engine modifications will be performed to further investigate the previously experienced problems.

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