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Paper No. 88-1562
AN ASAE MEETING
PRESENTATION

DIESEL ENGINE DURABILITY WHEN FUELED WITH METHYL ESTER OF WINTER RAPESEED OIL

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Written for presentation at the 1988
International Winter Meeting of the
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Hyatt Regency Chicago
in Illinois Center
December 13-16, 1988

SUMMARY:

Methyl ester of winter rapeseed oil was compared with diesel no. 2 and a 50-percent blend each of rapeseed oil and diesel no. 2 in 2 replicates of EMA screening tests. Based on these tests Winter Rape Methyl Ester was found to be an excellent potential alternative fuel.

KEYWORDS:

Methyl Ester, Diesel, EMA Test, Durability, Alternative Fuels

American Society of Agricultural Engineers

St. Joseph, MI 49085-9659 USA

DIESEL ENGINE DURABILITY WHEN FUELED WITH METHYL ESTER OF WINTER RAPESEED OIL

by

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ABSTRACT

Methyl ester of winter rapeseed oil is more suitable as a diesel fuel substitute than pure rapeseed oil. The ester has a lower viscosity and a higher cetane rating. This paper reports on two replicates of 200-hour EMA (Engine Manufacturer's Association) screening tests which were performed to evaluate engine durability when methyl ester of winter rapeseed oil is used as fuel.

Three engines, one fueled with methyl ester of winter rapeseed oil and two with reference fuels of No. 2 diesel and 50:50 diesel-winter rapeseed oil blend, were investigated in those 200-hour tests. It was found that the methyl ester of winter rapeseed oil and diesel fuel did not show significant differences when compared on the basis of performance and durability. Factors evaluated included engine brake power, engine thermal efficiency, carbon deposits, injector tip coking, engine oil deterioration, and wear of engine components. The only noticeable adverse effect of the ester fuel was an increase in lubricating oil dilution. Results from the engine fueled with the winter rapeseed oil diesel blend showed signs of potential durability problems including carbon deposits in the combustion chamber, injector tip coking, and an increase in metal concentration in the lubricating oils.

INTRODUCTION

Previous studies on the use of unrefined vegetable oil fuels have revealed their vast potential as an alternative to diesel fuel as well as their many handicaps (Peterson, 1986). Tests conducted worldwide have shown that short-term performance indicators (power output, torque, and brake thermal efficiency) of numerous vegetable oils are comparable to those of diesel. Long term usage however, normally leads to fuel related problems which include severe engine deposits, injector coking, and ring sticking. In a number of cases, a modification of the vegetable oils, typically through transesterification to form a methyl, ethyl, or butyl ester of the oil, has been used as a means of reducing the long term effects.

This paper reports the effect of Winter Rape Methyl Ester (in comparison with 100% diesel and a diesel-rape oil blend) on engine durability as observed in replicated trials of an "EMA 200 Hour Test Cycle". Both trials were conducted with direct injection, naturally aspirated diesel engines.

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LITERATURE REVIEW

A renewed interest in use of vegetable oils as a fuel source has developed as a result of the energy crisis of the 1970s (Peterson, 1986). For use as a fuel in internal combustion engines, one of the most promising forms of the plant oils is in that of an ester. Research, to date, has focused on the use of methyl, ethyl, and butyl esters of vegetable oils (Sims, 1985; Wagner et al., 1984; Goering et al., 1982; Kaufman and Ziejewski, 1984; Clark et al., 1984; Quick and Woodmore, 1984; Mora, 1985; Melville, 1987; and Mosgrove, 1987). Typically research has shown that the transesterification process improves the fuel qualities of a vegetable oil and makes it more suitable for use in a diesel engine. Studies with soybean oil, sunflower oil and winter rape oil have shown significant improvements in viscosity and surface tension (Vander Griend, 1988). The degree of improvement appears to vary, however, with the type of ester (methyl, ethyl, or butyl) and the type of vegetable oil. In a comparison of these three esters of soybean oil, it was found that the fuels varied very little in regards to fuel properties, while for tallow oil, of the three, the methyl ester was remarkably similar to diesel (Sims, 1985). Clark et al. (1984) reported that engine deposits were comparable in amount, but slightly different in color and texture, with the methyl ester of soybean oil engines experiencing greater carbon and varnish deposits on the pistons. Measurements of engine wear and fuel injection system tests showed no abnormal characteristics for any of the fuels after 200-hour tests. Engler et al., (1983) found little advantage in use of partial transesterification of vegetable oils.

Short Term Engine Performance Test

Peterson et al. (1987) ran a series of short term engine tests to evaluate the effects of the transesterified and propane fumigated winter rapeseed oil on injector coking. From the tests he found that injector coking could be remarkably reduced with transesterification but results of fumigation treatments were inconclusive.

Based on engine performance tests with methyl ester of soybean oil, Pischinger et al. (1982) reported that the power and torque output between the methyl ester fuel and the diesel fuel differed only marginally. Much lower smoke emission was observed with the ester fueled engine than the diesel fueled one. The injection pump delivers a little more fuel with ester than with diesel. Since the ester has a lower value of heat of combustion, the volumetric fuel consumption is increased, whereas, the energy specific consumption is nearly the same.

Long Term Engine Test

Einfalt and Goering (1985) evaluated the methyl ester of soybean oil in a tractor engine for a total of 578 hours. They noted that as a diesel engine substitute fuel, the ester fuel appeared promising. The brake power output was almost the same as with diesel fuel. The specific fuel consumption was higher. Engine wear rate, based on the results of bearing metal content in the lubricating oil, was low. Carbon accumulation inside the engine was normal except for that on the intake valves. Crankcase oil dilution occurring under light load caused the oil viscosity to decrease to unsafe levels.

Similar research was conducted by Wagner et al. (1984). Three types of esters of soybean oil were investigated in EMA 200-hour tests. The effects on engine performance, engine oil deterioration, and engine wear were examined. They concluded that engine performance with esters of soybean oil did not differ a great extent from that of diesel fueled engines. The engine oil analysis showed that wear metal levels in the oil for each engine might be considered to be normal throughout the 200 hour tests. The viscosity of the lubricating oil continued to drop within the 100-hour oil change interval for all esters. Engine wear was found to be normal after 200 hours for all fuels. The methyl and butyl ester fuels resulted in greater amount of deposits on the pistons than did the diesel fuel.

Kaufman and Ziejewski (1984) evaluated the methyl ester of sunflower oil in an EMA 200-hour screening test in direct injected diesel engines. The engine performance with the methyl ester as fuel was satisfactory throughout the entire test. No significant effect on injector coking and engine performance were observed. Lubricating oil consumption showed comparable levels to those found with diesel fuel. No abnormal wear of any engine part was found. However, some difficulties were experienced with engine starting.

Even though many researchers agree that the ester fuels are suitable for substituting for diesel fuel, a few contrary results have also been obtained. Vinyard et al. (1982) reported that when the degummed sunflower ethyl ester fueled a diesel engine, a serious coking problem occurred. Even if the ester was diluted with 30 percent diesel fuel, an unacceptable level of coking occurred after 50 hours under part load.

The results from these previous experiments show that (1) transesterification of plant oils can improve the fuel properties and make them more suitable for fueling the diesel engine; (2) most types of methyl esters appear qualified for diesel engine fuel use; (3) pre-combustion chamber engines are more suitable for using methyl esters as fuel; (4) only the completely esterified oils are comparable to diesel fuel; (5) the fuel properties of the esters will be varied with the types of plant oil. and (6) before the esters become practicable for diesel engine utilization, further studies are necessary.

OBJECTIVES

The objectives of this study were:

1. To evaluate engine durability as measured by the EMA engine screening test when the methyl ester of winter rapeseed oil is used to fuel a direct-injected, compression ignition diesel engine as compared to 100 percent No. 2

diesel fuel and a blend of 50 percent unmodified rapeseed oil and 50 percent diesel. This evaluation is based on the following standards:

a) Engine performance
b) Engine Wear
c) Condition of internal engine components
d) Accumulation of deposits inside the engine
e) Analysis of lubricating oil

2. Define potential problem areas for prolonged use of high erucic acid rape methyl ester.

MATERIALS AND METHODS

A. Equipment

Three Yanmar 3TN75E-S diesel engines (3-cylinder, 4-stroke, naturally aspirated, direct injection design) were selected as the test engines. Each has a bore and stroke equal to 75 mm, A displacement of 994 cc, a compression ratio of 17.6:1, and a rating of 14.5 kw at 3000 rpm. These engines were chosen for their direct injection design and combustion chamber configuration which is common to most diesel engines in current agricultural applications.

Three test stands, designed and built at the University of Idaho (Peterson and Wagner, 1982), were used to load and monitor the test engines. Each uses a hydraulic dynamometer which consists of a Hydreco gear pump (cradled for torque measurement) coupled directly to the engine clutch shaft. A Sperry-Vickers electronically modulated relief valve (EMRV) was used to control the pressure on the pump output, thereby providing the capability to set and maintain any engine load (torque) with a voltage input. A constant volume flowmeter, which measures the time for a known volume of fuel to be consumed by the engine, and a magnetic pickup, which measures engine speed at the clutch shaft, have been incorporated into each stand. Throttle control was provided by a DC gearhead motor attached to the throttle lever of each engine. Each test stand is capable of manual control at the stand, or remote control by a data acquisition/control system.

The data acquisition/control system consists of an HP 85 microcomputer and 3054 DL Data Logger. The system capabilities include control of engine speed and load as well as measurement of engine torque, speed, horsepower, fuel consumption, and temperatures (exhaust, crankcase oil, fuel, and hydraulic oil).

B. Fuels

The fuels used in this study were 100% methyl ester of winter rape oil (100RE), 100% No. 2 commercial grade diesel (100D2), and a 50% winter rape oil - 50% No. 2 diesel blend (50WR-50D2) mixed on a volume basis. The 100RE was produced in a bench-scale transesterification process (Melville, 1987) by the Chemical Engineering Department for the first EMA test and in a pilot plant process (Mosgrove, 1987) by the Agricultural Engineering Department for the second test. Both processes produced methyl ester with a purity in excess of 99%. Number 2 diesel, used as a control, was obtained from a local commercial dealer. Winter rape oil, used in the 50WR-50D2 blend and in production of the 100RE, was produced with an extraction plant developed by the Agricultural Engineering Department. Properties of the test fuels, as determined by a commercial lab, are displayed in Table 1 and in Figures 1 and 2.

C. EMA Test Cycle

This research adopted the Engine Manufacturer's Association (EMA) standard 200-hour screening test to investigate engine durability (EMA, 1982). This standard was created by the EMA for alternative fuel research purposes. The 200 hour test cycle, outlined in the standard, was designed to initiate durability problems in a reasonable amount of time.

The test utilizes four engine load cycles (1 set) over a three hour period as a test basis. The standard calls for five consecutive sets (15 hours of continuous engine operation) followed by a nine hour period (minimum) during which time the engines are shut down and allowed to reach ambient temperature. This is repeated until 200 hours are logged on each engine. The load cycles specified for each set are shown in Table 2.

The four load conditions used in the study were:

1. Rated condition: Operating at full throttle, a load is applied to the engine until speed decreases to, and is maintained at, 3000 rpm. Torque and horsepower are then measured and averaged over the 60-minute duration.

2. Maximum torque: Operating at full throttle, a load is applied to the engine until speed decreases to, and is maintained at, 2550 rpm. Torque and horsepower are then measured and averaged over the 60 minute duration.

3. High idle: The load is set at 80 n-m and the throttle varied to achieve a 3.6 kw output at 2700 rpm for 30 minutes.

4. Low idle: At no load, the throttle is varied to achieve a speed of 1250 rpm for 30 minutes.

The following data (averaged over the duration of the cycle) was measured and collected for each load cycle of every set:

- Engine speed
- Torque
- Horsepower
- Fuel consumption
- Crankcase oil temperature
- Exhaust gas temperature
- Fuel temperature
- Ambient temperature

PROCEDURES

Two, 200 hour EMA test cycles were run to evaluate the effect of 100RE on engine durability. In both tests, three fuels were evaluated (100RE, 100D2, and

50WR-50D2) in three identical engines. The engines, controlled throughout the test by the data acquisition/control system, were run simultaneously and subjected to the same loading and operating conditions.

Prior to each EMA test, all three engines were disassembled and wearing surfaces measured and recorded (the engines were new prior to test 1 and completely rebuilt prior to test 2). Following reassembly and a short break-in period on 100D2, the test was begun and conducted as per the EMA test cycle standard using the three test fuels. At 50 hour intervals, the test was halted to run the following tests for each engine operating on its respective test fuel:

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

Engine service and maintenance was performed as specified in the engine service manual. Both EMA tests were conducted in the same manner except for the following conditions:

1. In test 1, the engines were run for five 3-hour sets on a daily basis. In test 2, they were run for three 3-hour sets. This change was made to accommodate the work schedule of those available to run the tests. Two shift operation is difficult in our laboratory.

2. Processing of 100RE for test 2 used an extended washing phase for catalyst removal, increasing the ratio of wash water volume to fuel volume by a factor of 2.

3. The engine operating on 50WR-50D2 in test 2 was outfitted with a diesel purge system, allowing operation on 100D2 for a five minute warmup and five minute shutdown period.

4. Rotation of each fuel with respect to engine number and test stand number between tests insured that each fuel was evaluated in a different engine on a different stand.

Following completion of each 200 hour EMA test, all three engines were systematically disassembled, their wear surfaces measured, and their respective components compared visually for damage, general condition, and deposits. An evaluation of each fuel was then made based on three factors:

Engine Performance
Engine Wear
Engine Component Condition

Weighting each factor equally, a comprehensive evaluator, known as the "Engine Durability Factor," was obtained for each fuel by taking an average of the three values.

The "Engine Performance Factor" represents an average of two parameters: engine brake power and engine thermal efficiency at rated load conditions. To derive a value for each parameter, the fuel with the best performance for that parameter was given an arbitrary value of 1.0 and the remaining two fuels given percentages of 1.0 based on their relative performance.

The "Engine Wear Factor" represents an average of the relative concentrations of four metals found in the lubrication oil at the conclusion of the EMA tests. (An inverse relationship is used, so that the lower the metal concentration with respect to the other fuels, the higher and more desirable is the engine wear factor.) Iron concentration was chosen as an indication of cylinder wear, chromium concentration as an indication of ring wear, aluminum concentration as an indication of piston wear, and lead concentration as an indication of bearing wear. To derive a value for each of the four concentration parameters, the fuel with the lowest concentration for that parameter was given an arbitrary value of 1.0. The remaining two fuels were assigned values equal to a percentage of 1.0 based on the inverse of their relative concentrations.

The "Engine Component Condition Factor," qualitative in nature, was difficult to define. It represents the condition of the combustion chamber components with respect to deposits, excessive visible wear, and ability to perform their function. Five components were evaluated: 1) Injectors, 2) pistons, 3) rings, 4) cylinders, and 5) valves. The values for the injector condition represents a comparison of the quantity of carbon deposits on the injector tip as measured using photo micrograph techniques by Melville (1987) in test 1 and Mosgrove (1987) in test 2. Again, an inverse relationship was used so that the fuel with the least injector coking was given a value of 1.0 and the remaining two fuels assigned values equal to a percentage of 1.0 based on the inverse of their relative measure of injector coking. Values for the other four component condition parameters were derived using a visual grading technique. Each component was graded on four criterion; a) deposit quantity, b) deposit nature, c) visible wear, and d) general condition. For each criterion, one of five values was assigned (1.0 = good, 0.75 = fair, 0.50 = nominal, 0.25 = poor, and 0.00 = severe). The value for each component was then established as the average of the four criteria grades. The value of the "Engine Component Condition Factor" represents an average of the five component values.

RESULTS AND DISCUSSION

Results from tests 1 and 2 were very similar and, as such, are reported together. Tables 3 through 8 display the raw data and their normalized values for engine performance, wear, and component condition. Table 9 shows a summary of the evaluations, resulting in a single "engine durability factor" which indicates the overall effect of a fuel on an engine. Following is a description of the observed test results.

Engine performance was virtually indistinguishable among the three fuels, both from an operators standpoint and from an evaluation of the data (Figure 3). Consistent with short term results from past studies, power and thermal efficiencies for both tests were nearly equal among the fuels, indicated by the close similarity of their normalized performance values.

Lubricating Oil Viscosity

Figure 4 shows the average variation in oil viscosity with test time. The lubricating oil was changed before the EMA tests and after the first 50 hours run during the tests. It can be observed that the viscosity of lubricating oil in 100RE fueled engines decreased with time within the oil service interval,this effect was only observed in test 2. The viscosity of the lubricating oil in the 100D2 fueled engine increased somewhat within the oil service periods during the first test, and remained essentially constant in the second test. The effect of fuel type on lubricating oil viscosity was statistically significant. This decrease in oil viscosity in methyl ester fueled engines is verified by the results obtained by the other researchers. Wagner et al. (1984) found that for the methyl, ethyl, and butyl ester, the viscosity of lubricating oil continued to drop within the entire 100-hour oil change intervals.

Oil Analysis

Engine wear, based on the concentration of four metals in the lubricating oil, appears to be sensitive to fuel type, as seen in Tables 4 and 5. In both tests, wear for 100RE appears to be similar to that of 100D2 (equivalent in test 1 and slightly worse in test 2) and most pronounced for 50WR-50D2. Consistent between the two tests are the observations that bearing wear (lead concentration) appears to be higher and piston wear (aluminum concentration) lower in the 100RE fueled engines than 100D2. Metal concentrations are the highest in every case except one for the 50WR-50D2 fueled engines. The wear values give a comparative value of wear per component for each fuel. Figures 5-8, show the relative concentrations of Iron, aluminum, chromium, and lead in the lubricating oil.

Injector Nozzle Coking

In the EMA tests, the injectors were pulled from the engines after every 50-hour operation interval for deposit checking. The photo micrographs of the injector tips after 50 hours and 200 hours testing are shown in Figures 9 and 10. In both tests it was found that injector coking after 50 hours was worse than that after 200 hours. This fact implies that there is a critical level of injector coking for each test fuel. When the critical deposit level is reached, no more carbon mass is built-up. The critical coking level on the injectors of the 100RE fueled engines appeared to be very similar to that of the 100D2 fueled engines. From Figures 9 and 10, it can be observed that the injector coking level of the 100RE fueled engine was slightly lighter in the first test than in the second test. The other fuels did not show such a change. As mentioned earlier, the time of ester washing during the transesterification process was different for the two tests. Instead of 10 hours for the first case, a 20 hours washing time was used in the 100RE preparation for the second test. The longer time of ester washing may have attributed to the lighter injector coking in the second test.

Two different methods were applied for quantitative analysis on the injector tip coking conditions in the two tests. The method used in the first test was the photo micrograph injector silhouette weight determination as described by Melville (1987). The second test used the method of digitizing the photo micrographs as described by Mosgrove (1987). Because of two different analysis methods being used, direct comparison could not be made between the two tests. By defining the average coking amount on injector tip in the 100RE fueled engines at the 200-hour point as one unit, the relative coking amount might be compared. This analysis confirmed that heavier tip cokings were formed after the 50-hour test in all six test engines. It also showed that the injector tip coking was worse in 50WR-50D2, better in 100RE, and best in 100D2. The average relative injector tip coking in the 100RE fueled engines was only 8 percent higher than that in the 100D2 fueled engines. However, the average relative injector tip coking was about twice as much in the 50WR-50D2 fueled engines as in the 100RE fueled engines. Figure 11 shows these comparisons. It indicates that the transesterification of winter rapeseed oil will eliminate or greatly reduce the engine injector tip coking problem, and result in a condition very similar to that of 100D2 fuel.

Component Condition and Measurements

Condition of the combustion chamber components, like engine wear, varied with respect to the type of fuel as seen in Tables 7 and 8. The quantity of deposits found in the 100RE fueled engines was very similar to those of the 100D2: slightly lighter on the valves and valve ports and slightly heavier in the ring belt of the pistons and the portion of the cylinder wall above ring travel. The 50WR-50D2 engines had considerably higher levels of deposits in all components, particularly in Test 1 and where the deposits interfered with proper seating of the valves and smooth operation of the pistons within the cylinders. The deposits for the 100RE engines were a bit grainy in nature giving them a more abrasive quality than the soft, sooty deposits of 100D2. Deposits of both fuels, however, more acceptable than those of 50WR-50D2 which were characterized by thick, hard, flakes and small areas of sticky, polymerized oils. Neither 100RE nor 100D2 had any signs of abnormal visible wear or damage to any component. The engines operating on 50WR-50D2 displayed signs of considerable wear in the forms of piston scuffing (tests 1 and 2) and cylinder scoring (test 1) and resulted in components at the tests' end that were substandard in condition. Of special interest in the evaluation of 50WR-50D2 were the observations that in both tests some of the compression and scraper rings had begun to "stick" within their ring grooves and signs of "blowby" past the exhaust valves was evident. An indication of the relative condition for each of the fuels is portrayed by the component average values. Figures 12 and 13 show the relative wear for the combustion chamber group and the crankcase group based on the amount of measured wear compared to the manufacturer's wear limit. Note that the relative wear in all cases is less than 20 percent of the allowable wear.

Relative Durability

Table 9 summarizes the relative engine durability factors for Tests 1 and 2. The similarity of all three fuels with regard to performance is indicated by their performance factors being nearly equal in both tests. Based on the observations of wear and component appearance, it is believed that a sharp decline in performance for 50WR-50D2 was forthcoming in both tests while 100RE and 100D2 gave no indications of potential failure. A comparison of the wear factors shows 100RE to be nearly equivalent to diesel in that respect and greatly advantageous over 50WR-50D2. Likewise, a comparison of the condition factors shows 100RE to be nearly equivalent to 100D2 and again, advantageous over 50WR-50D2. An average of the three evaluation factors results in an "Engine Durability Factor" for each fuel. Using 1.0 as an optimum value, this factor provides a relative measure of expected engine durability for long term use of each fuel. As can be noted, the results are very consistent between tests, showing 100RE to be roughly equivalent to 100D2, and both fuels being superior to 50WR-50D2, Figure 14.

Inconsistencies between the results of the two tests were minimal. Use of an extended washing phase in the processing of 100RE greatly reduced the presence of the processing catalyst found in the deposits. This resulted in a more desirable deposit (less abrasive) but had no conclusive effect on wear or performance. Likewise, use of a "diesel-purge" system in conjunction with 50WR-50D2 resulted in a favorable change in deposit quantity and nature, yet again, no effect was noted with reference to performance or wear. Fuel dilution of the lubricating oil by 100RE, a problem common to methyl ester fuels, was noted in test 2. The oil, changed once at 50 hours of operation, was then run to the tests end but sampled and analyzed at 50 hour intervals. The dilution observation was made at the test conclusion after 150 hours of operation on the lubricating oil. No signs of dilution were evident at any other lube oil analysis interval, nor was it evident in the engine operation or durability evaluation.

CONCLUSIONS

Based on evaluations of engine performance, wear, and combustion chamber component condition as indicators of engine durability, Winter Rape Methyl Ester appears to be equivalent to number 2 Diesel and vastly superior to a blend of 50% Winter Rape Oil and 50% Number 2 Diesel. As such, 100RE is a desirable emergency fuel substitute for diesel. Additional research focused on emissions and the long term effects of 100RE is necessary to realize all of the implications of its use.

Prior to a practical utilization of 100RE for everyday use however, an effort must be made to identify and correct its undesirable traits. Fuel dilution of the lubricating oil, the foremost drawback, may be avoided (though not corrected) by using a shortened oil change interval. Three other characteristics demanding investigation are relatively high cloud and pour points (eliminating use of 100RE in low temperature applications), its poor compatibility with various materials, and its requirements for long term storage.

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TABLE 1. PROPERTIES OF FUELS
BASED ON ANALYSIS OF SAMPLES SENT TO PHOENIX
CHEMICAL LAB. INC., CHICAGO, ILLINOIS.

PROPERTIES	100RE	100D2	50WR-50D2
Cetane Rating	54.4	47.8	42.3
Flash Point (C)	83.9	80.0	89.4
Cloud Point (C)	-2.2	-12.2	-11.1
Pour Point (C)	-9.4	-28.9	-17.8
Viscosity (cs) @ 40C	6.0	3.2	10.2
@ 100C	2.39	1.26	3.13
Heat of Combustion kJ/kg (Gross)	35375.5	38536.6	37537.2
Density (kg/L)	0.874	0.852	0.879

TABLE 2. EMA LOAD CYCLES

CYCLE	SPEED (rpm)	TORQUE (kw-m)	POWER (kw)	DURATION (min)
1	RATED	--	RATED	60
2	85%	MAX	95%	60
3	90%	28%	25%	30
4	IDLE	0	0	30

TABLE 3. ENGINE PERFORMANCE, TEST 1
BASED ON AVERAGES OVER ENTIRE TEST CYCLE

	POWER AT RATED CONDITIONS		THERMAL EFFICIENCY AT RATED CONDITIONS	
TEST FUEL	AVERAGE POWER	PERFORMANCE VALUE	AVERAGE POWER	PERFORMANCE VALUE
100RE	15.0 kw	0.94	33.0%	1.00
100D2	16.0 kw	1.00	32.8%	0.99
50WR-50D2	15.0 kw	0.94	33.0%	1.00

TABLE 4. ENGINE PERFORMANCE, TEST 2
BASED ON AVERAGES OVER ENTIRE TEST CYCLE

	POWER AT RATED CONDITIONS		THERMAL EFFICIENCY AT RATED CONDITIONS	
TEST FUEL	AVERAGE POWER	PERFORMANCE VALUE	AVERAGE POWER	PERFORMANCE VALUE
100RE	15.4 kw	1.00	32.9%	1.00
100D2	14.9 kw	0.97	32.7%	0.98
50WR-50D2	15.2 kw	0.99	30.4%	0.92

TABLE 5. ENGINE WEAR, TEST 1.
BASED ON METAL CONCENTRATIONS FOUND IN THE
LUBRICATING OIL AT THE CONCLUSION OF THE TEST CYCLE

	IRON		CHROMIUM		ALUMINUM		LEAD	
TEST FUEL	CONC.	WEAR VALUE	CONC.	WEAR VALUE	CONC.	WEAR VALUE	CONC.	WEAR VALUE
100RE	55 ppm	1.00	5 ppm	1.00	6 ppm	1.00	4 ppm	0.25
100D2	60 ppm	0.92	7 ppm	0.71	11 ppm	0.55	1 ppm	1.00
50WR-50D2	87 ppm	0.63	7 ppm	0.71	25 ppm	0.24	11 ppm	0.09

TABLE 6. ENGINE WEAR, TEST 2.
BASED ON METAL CONCENTRATIONS FOUND IN THE
LUBRICATING OIL AT THE CONCLUSION OF THE TEST CYCLE

	IRON		CHROMIUM		ALUMINUM		LEAD	
TEST FUEL	CONC.	WEAR VALUE	CONC.	WEAR VALUE	CONC.	WEAR VALUE	CONC.	WEAR VALUE
100RE	87 ppm	0.79	1 ppm	1.00	4 ppm	1.00	9 ppm	0.22
100D2	69 ppm	1.00	1 ppm	1.00	8 ppm	0.50	2 ppm	1.00
50WR-50D2	74 ppm	0.93	11 ppm	0.09	41 ppm	0.10	24 ppm	0.80

TABLE 7. ENGINE COMPONENT CONDITION, TEST 1.
BASED ON COMBUSTION CHAMBER COMPONENTS AT TEST CONCLUSION

	DEPOSIT QUANTITY	DEPOSIT NATURE	VISIBLE WEAR	GENERAL CONDITION	COMPONENT AVERAGE
100RE					
INJECTORS	1.00	--	--	--	1.00
PISTONS	1.00	0.75	1.00	1.00	0.94
RINGS	0.75	0.75	1.00	1.00	0.88
CYLINDERS	0.75	0.75	1.00	1.00	0.88
VALVES & SEATS	1.00	0.75	1.00	1.00	0.94
100D2					
INJECTORS	0.99	--	--	--	0.99
PISTONS	0.75	1.00	1.00	1.00	0.94
RINGS	1.00	0.75	1.00	1.00	0.94
CYLINDERS	1.00	1.00	1.00	1.00	1.00
VALVES & SEATS	1.00	1.00	1.00	1.00	1.00
50WR/50D2					
INJECTORS	0.66	--	--	--	0.66
PISTONS	0.25	0	0.50	0.50	0.31
RINGS	0.25	0	1.00	0	0.31
CYLINDERS	0	0	0.50	0.75	0.31
VALVES & SEATS	0	0.50	1.00	0.50	0.50

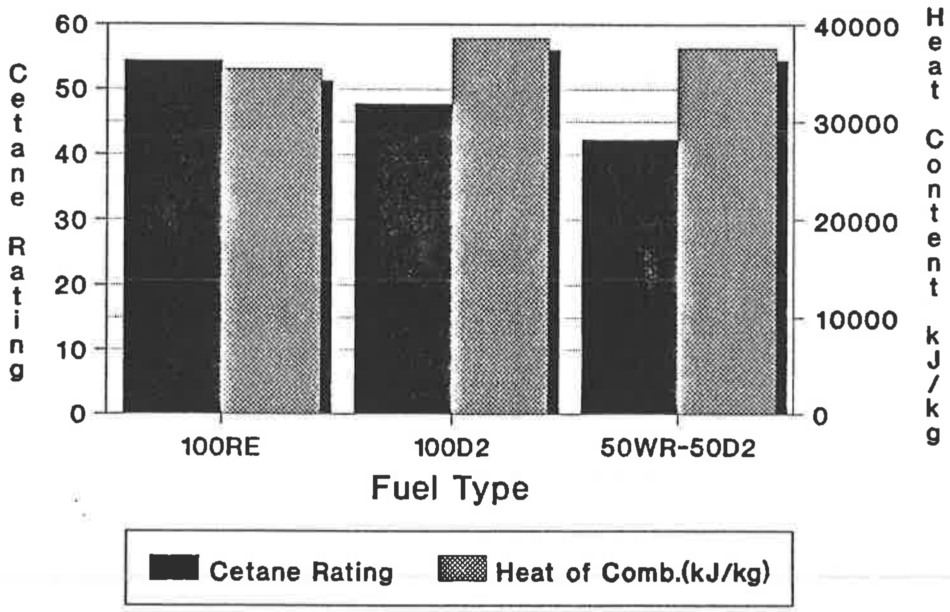
TABLE 8. ENGINE COMPONENT CONDITION, TEST 2.
BASED ON COMBUSTION CHAMBER COMPONENTS AT TEST CONCLUSION

	DEPOSIT QUANTITY	DEPOSIT NATURE	VISIBLE WEAR	GENERAL CONDITION	COMPONENT AVERAGE
100RE					
INJECTORS	0.86	--	--	--	0.86
PISTONS	1.00	1.00	1.00	1.00	1.00
RINGS	0.75	1.00	1.00	1.00	0.94
CYLINDERS	0.75	0.75	1.00	1.00	0.88
VALVES & SEATS	1.00	1.00	1.00	1.00	1.00
100D2					
INJECTORS	1.00	--	--	--	1.00
PISTONS	1.00	1.00	1.00	1.00	1.00
RINGS	1.00	1.00	1.00	1.00	1.00
CYLINDERS	1.00	1.00	1.00	1.00	1.00
VALVES & SEATS	0.75	1.00	1.00	1.00	0.81
50WR/50D2					
INJECTORS	0.38	--	--	--	0.38
PISTONS	0.25	0.25	0.50	0.50	0.38
RINGS	0.50	0	1.00	0	0.38
CYLINDERS	0.25	0.25	1.00	1.00	0.63
VALVES & SEATS	0.25	0.50	1.00	0	0.44

TABLE 9. ENGINE DURABILITY FACTORS, TESTS 1 AND 2.

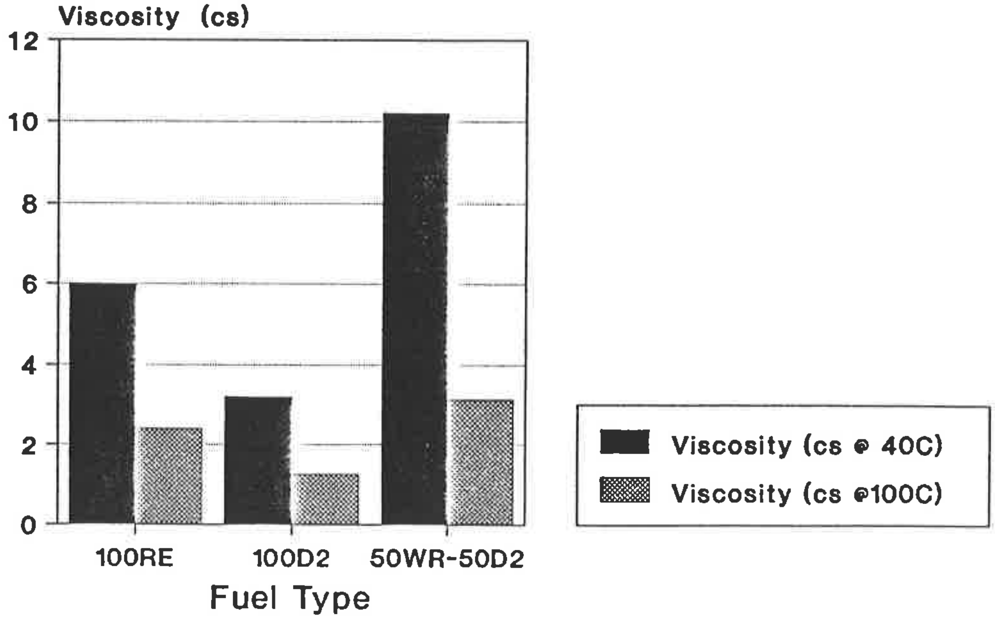
	TEST 1			TEST 2		
	100RE	100D2	50/50	100RE	100D2	50/50
PERFORMANCE						
BRAKE POWER	0.93	1.00	0.93	1.00	0.97	0.99
THERMAL EFF.	1.00	0.99	1.00	1.00	0.99	0.92
PERFORMANCE FACTOR	0.97	1.00	0.97	1.00	0.98	0.96
INTERNAL WEAR						
IRON CONCENTRATION	1.00	0.92	0.63	0.79	1.00	0.93
CHROMIUM CONCENTRATION	1.00	0.71	0.71	1.00	1.00	0.09
ALUMINUM CONCENTRATION	1.00	0.55	0.24	1.00	0.50	0.10
LEAD CONCENTRATION	0.25	1.00	0.09	0.22	1.00	0.08
WEAR FACTOR	0.81	0.80	0.42	0.75	0.88	0.30
COMPONENT CONDITION						
PISTONS	0.94	0.94	0.31	1.00	1.00	0.38
RINGS	0.88	0.94	0.31	0.94	1.00	0.38
CYLINDERS	0.88	1.00	0.31	0.88	1.00	0.63
VALVES/SEATS	0.94	1.00	0.50	1.00	0.81	0.44
INJECTORS	1.00	0.99	0.66	0.86	1.00	0.38
CONDITION FACTOR	0.90	0.97	0.42	0.94	0.96	0.44
ENGINE DURABILITY FACTOR	0.90	0.92	0.60	0.90	0.94	0.57

FIGURE 1



Fuel Properties
1987 EMA Test Cycles

FIGURE 2



Fuel Properties
1987 EMA Test Cycles

FIGURE 3

Fuel Efficiency

Average of Two EMA Test Cycles
Engines At Rated Power

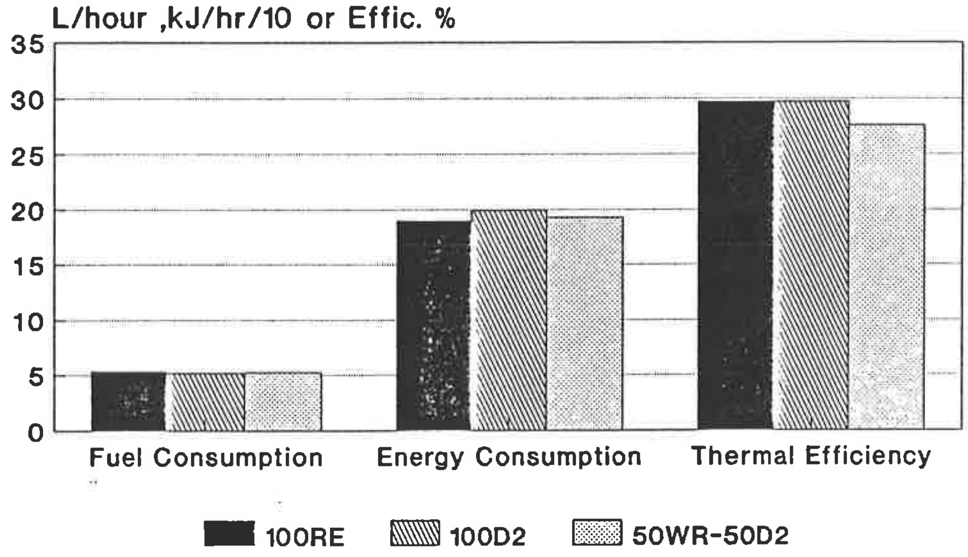


FIGURE 4

Lubrication Oil Viscosity

Average of Two EMA Tests

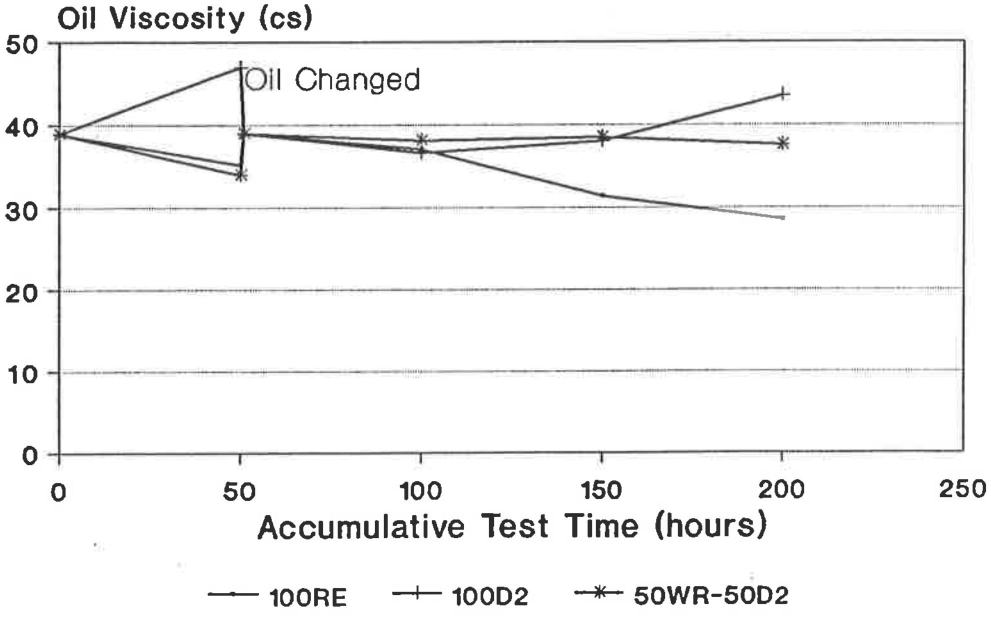


FIGURE 5

Wear Metal Concentration
Average of Two EMA Tests
Iron (PPM)

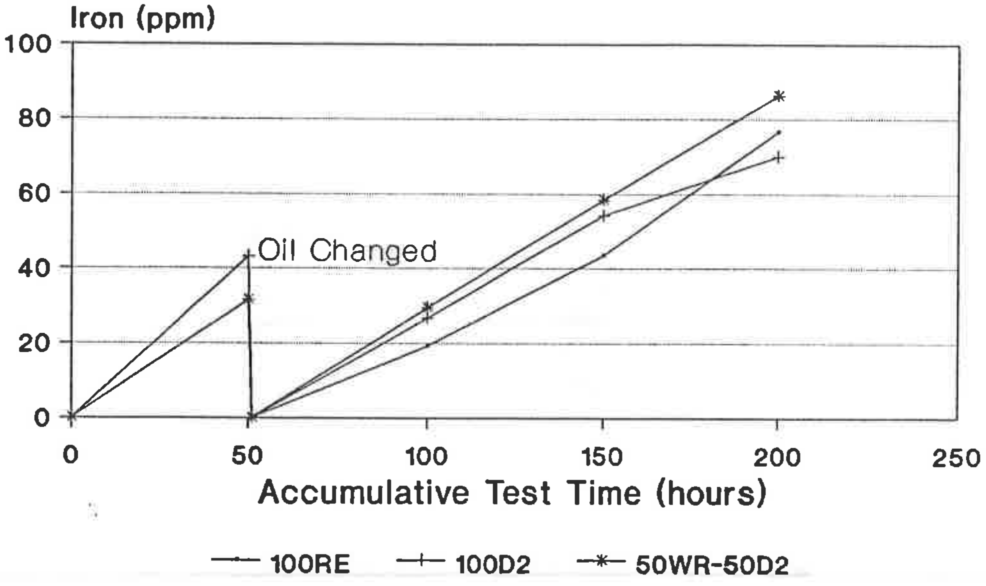


FIGURE 6

Wear Metal Concentration
Average of Two EMA Tests
Chromium (PPM)

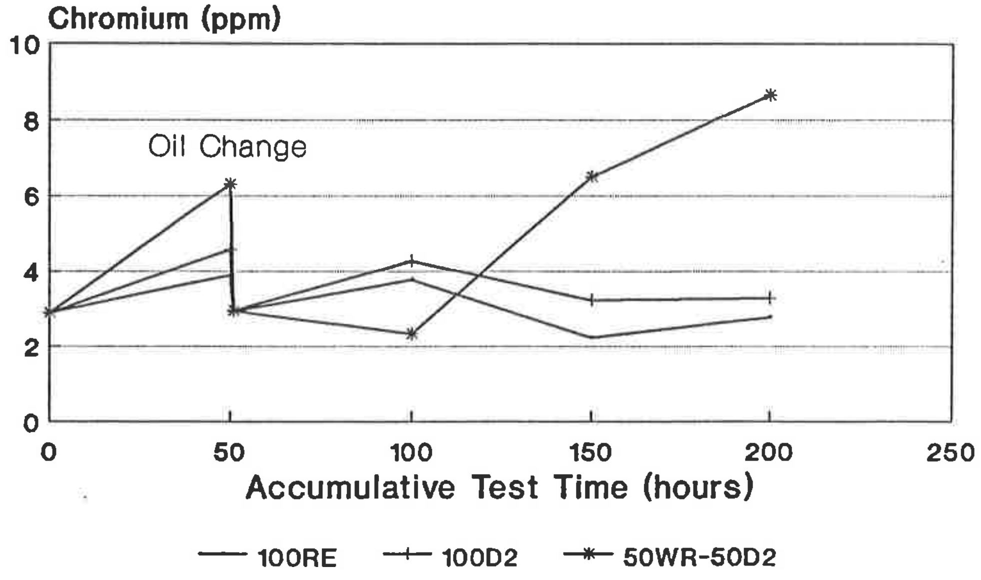


FIGURE 7

Wear Metal Concentration

Average of Two EMA Tests
Aluminum (PPM)

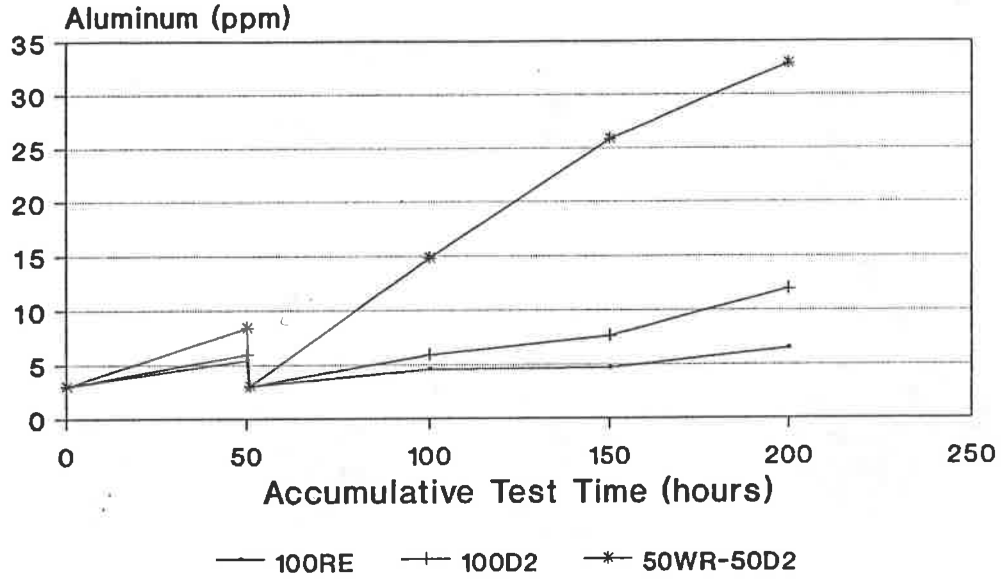


FIGURE 8

Wear Metal Concentration

Average of TwoEMA Tests
Lead (PPM)

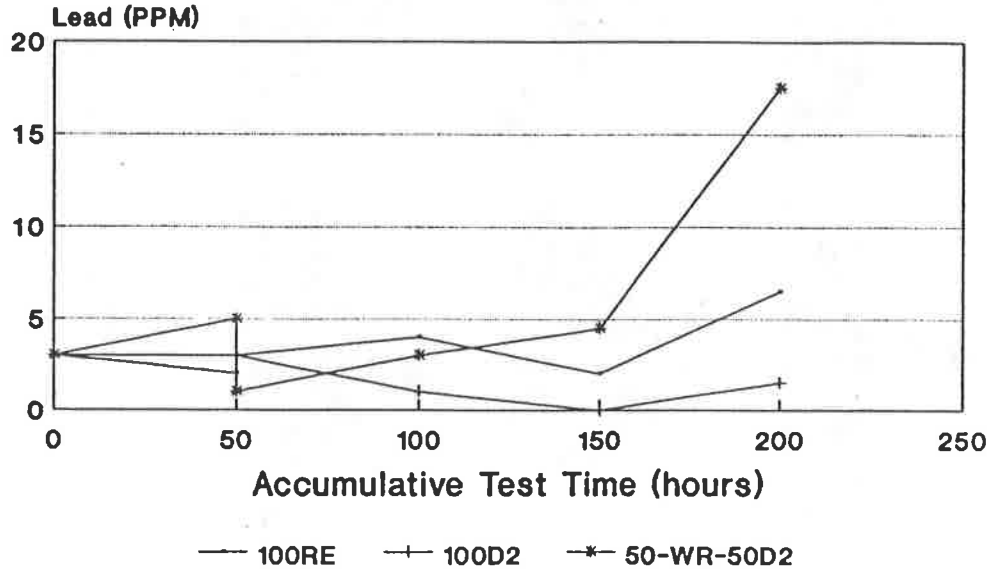
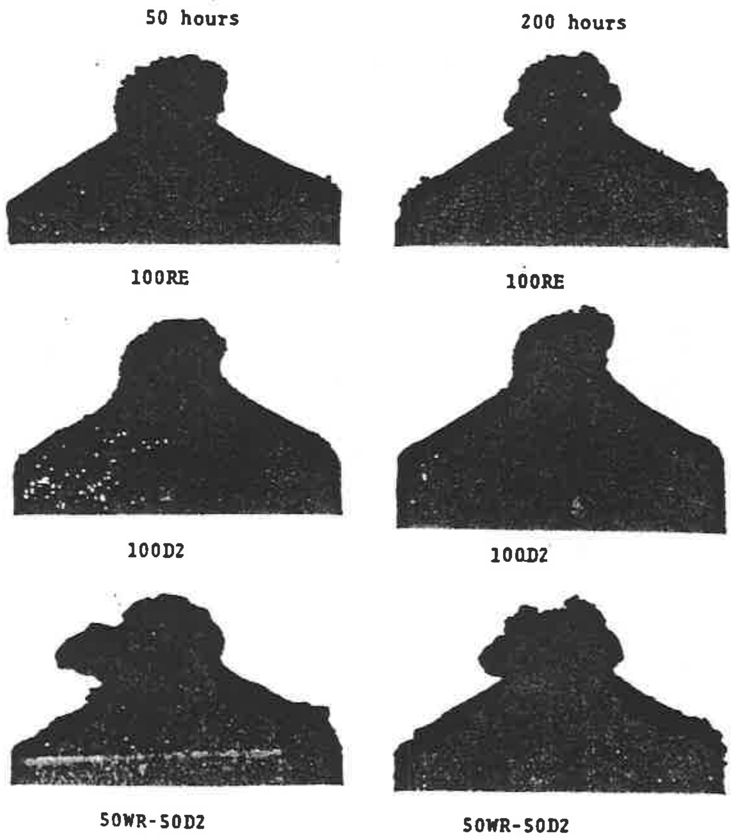
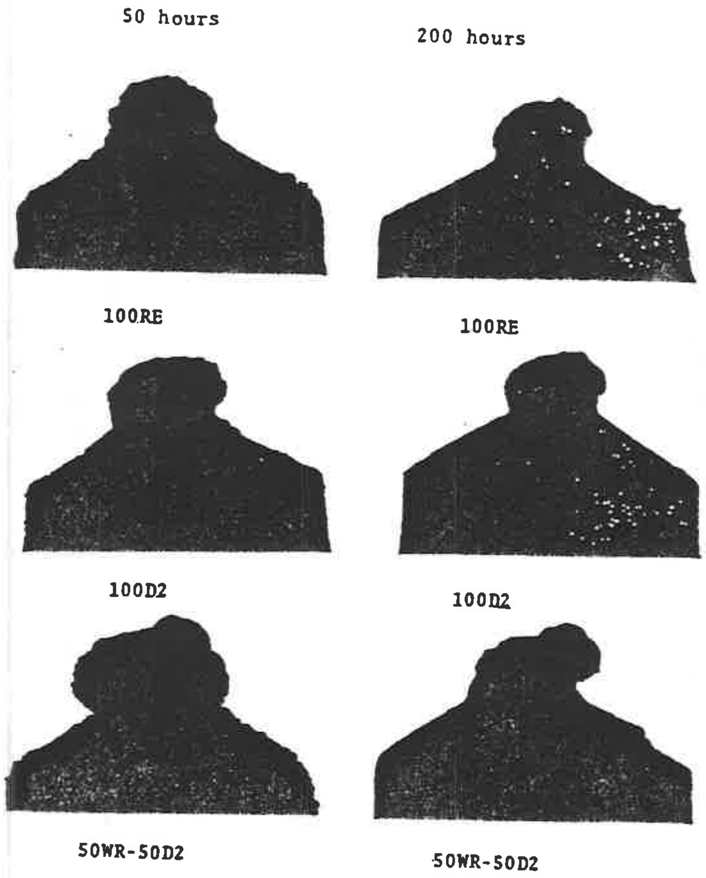


FIGURE 9



Typical micrograph photos on injector tips (test 1). Photos taken after 50 and 200 hours run by David Milville (1987).

FIGURE 10



Typical micrograph photos on injector tips (test 2). Photos taken after 50 and 200 hours run by Donald Mosgrove (1987).

FIGURE 11

Injector Tip Coking

Average of Two Orientations
Two EMA Test Cycles

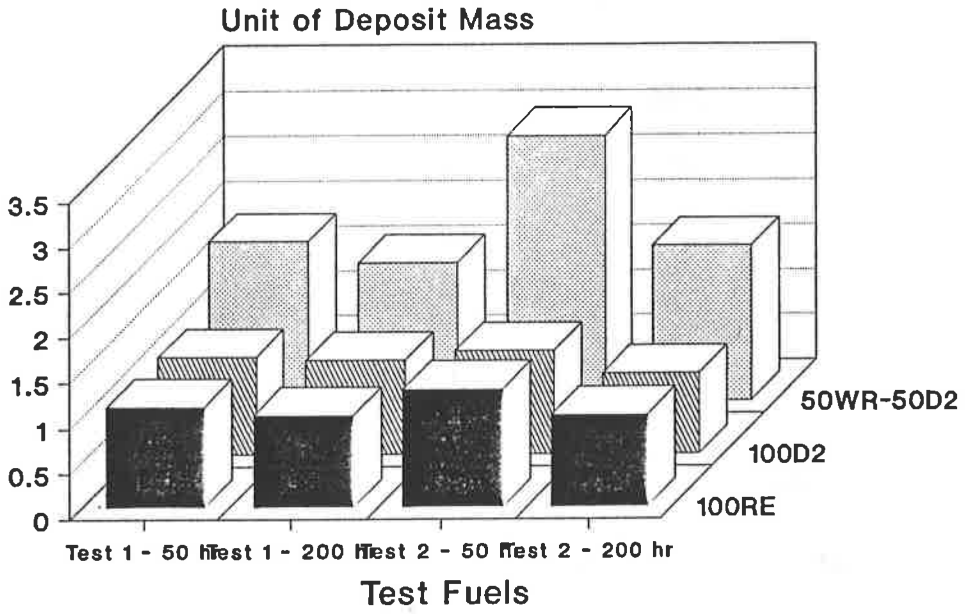
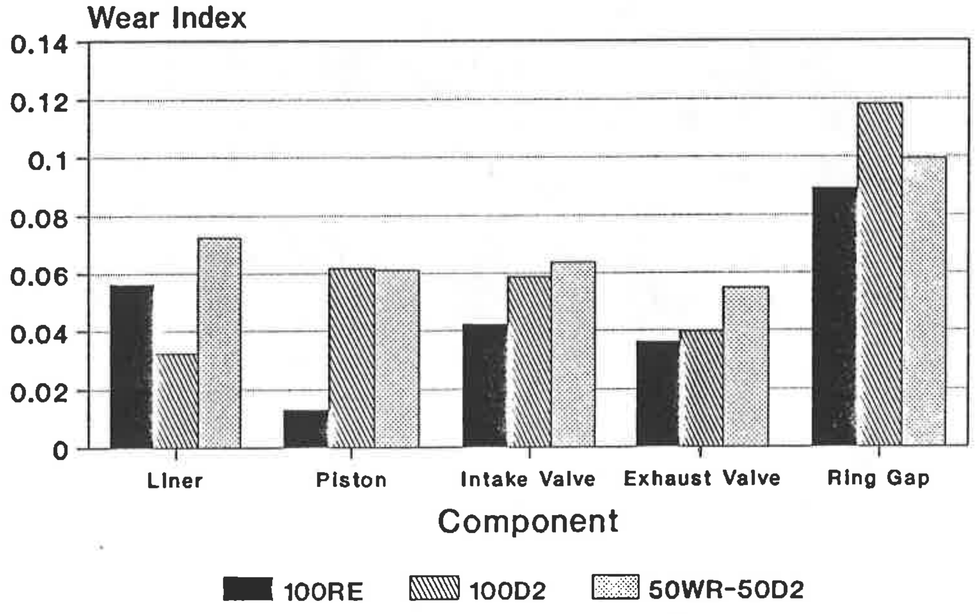


FIGURE 12

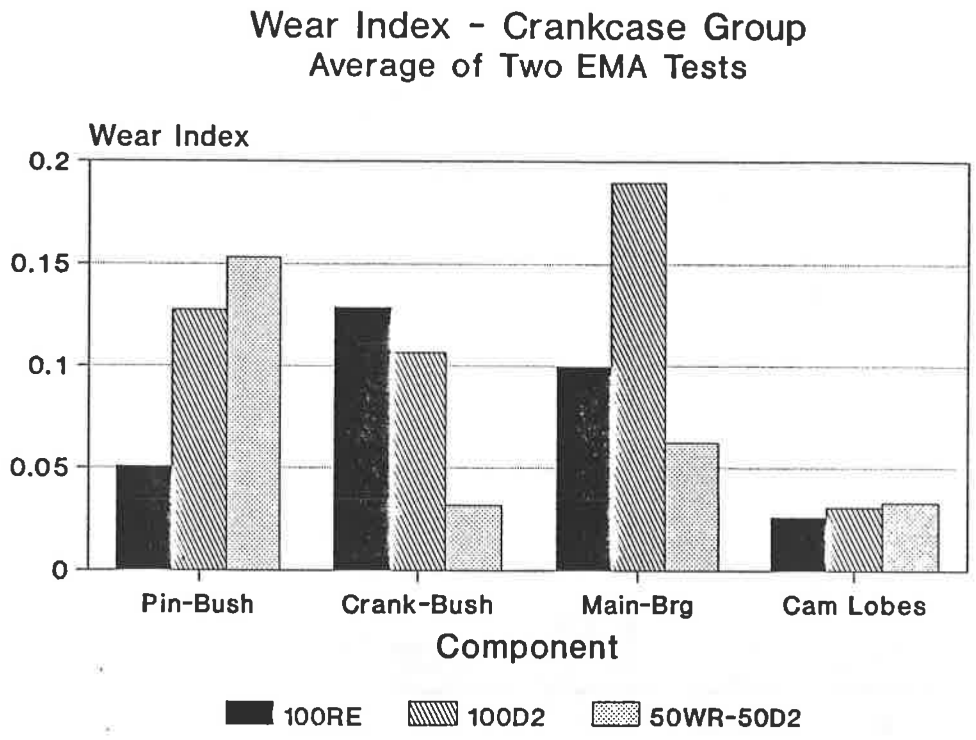
Wear Index - Combustion Chamber Group

Average of Two EMA Tests



Wear Index = actual wear / manuf. limit

FIGURE 13



Wear Index = actual wear / manuf. limit

FIGURE 14