PAPER NO. 85-3572

The Effect of Fumigation and Transesterification on Injector Coking

by

Peter G. Mora
Grad. Res.Ass't.

Charles L. Peterson
Professor

Department of Agricultural Engineering
University of Idaho
Moscow, ID 83843

For presentation at the 1985 Winter Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Hyatt Regency, Chicago Il
December 17-20, 1985

SUMMARY:
A series of short term test cycles with a direct injection CI engine was used to determine the relative merits of fumigation and transesterification in reducing injector coking problems that occur with the use of vegetable oil fuels. Results of fumigation were mixed. Transesterification reduced injector coking to a level not significantly different from that of diesel fuel.

American Society of Agricultural Engineers
St. Joseph, MI 49085-9659

Papers presented before ASAE meetings are considered to be the property of the Society. In general, the Society reserves the right of first publication of such papers, in complete form. However, it has no objection to publication, in condensed form, with credit to the Society and the author. Permission to publish a paper in full may be requested from ASAE, 2950 Niles Rd., St. Joseph, MI 49085-9659.

The Society is not responsible for statements or opinions advanced in papers or discussions at its meetings. Papers have not been subjected to the review process by ASAE editorial committees; therefore, are not to be considered as refereed.

The Effect of Fumigation and Transesterification on Injector Coking

by

Peter G. Mora and Charles L. Peterson*

ABSTRACT

A series of short term test cycles with a direct injection CI engine were used to determine the relative merits of fumigation and transesterification in reducing injector coking problems that occur with the use of vegetable oil fuels. A fixed nominal rate of 10% fumigation with propane was investigated in an attempt to reduce injector coking with Oleic and Linoleic Safflower oils. Variable nominal rates of 5, 10, and 15% propane fumigation were used in an effort to reduce injector coking with Winter Rape oil.

The 10% propane fumigation reduced injector coking caused by Oleic Safflower oil by 64%, to a level not significantly different than diesel fuel. 10% fumigation did not significantly reduce injector coking caused by Linoleic Safflower oil.

The 10% nominal rate of fumigation reduced injector coking caused by Winter Rape oil by 21%; the 15% nominal rate had no significant effect, and the 5% nominal rate increased coking.

Transesterification reduced injector coking caused by Winter Rape by 48%, to a level not significantly different than the injector coking experienced with diesel fuel.

All fuels exhibited power and torque characteristics similar to those of diesel fuel, with the exception of the Winter Rape methyl ester. The slight power and torque decreases experienced with the ester were expected based on its decreased gross heat of combustion.

---

* The authors are former Graduate Assistant and Professor respectively, Department of Agricultural Engineering, University of Idaho, Moscow, Idaho 83843.

INTRODUCTION

The fossil fuels that present day engines have been built around are, by their very nature, of a limited supply. Although projections of future consumption and the quantities of known reserves indicate that there will be enough petroleum for several decades (Sorensen, 1984), the days of cheap crude oil are gone forever. As known reserves of fossil fuels are depleted, more and more money will have to be spent on exploration and the development of new extraction techniques. As always, the consumer of these fuels must pay for these new technologies through higher fuel prices.

Even in these days of plentiful, easily obtainable crude oil, shortages can be created by foreign suppliers; therefore, a more reliable fuel supply is highly desirable. More specifically, a renewable fuel supply is needed; i.e., an inexhaustable supply of energy with which to fuel our energy consuming industries. Hence, the interest in vegetable oils as a substitute for diesel fuel.

The use of plant-derived oil as a fuel should come as no suprise, since petroleum based fuels are also (ultimately) of plant derived origin. In both instances, the plant has acted as a transformer of energy -- chemically converting solar radiation into a concentrated, more usable form.

Diesel fuel and vegetable oil are quite similar. Besides sharing a common origin, they both have about the same density and energy on a mass basis. Vegetable oils in general weigh 7 to 8 percent more than diesel fuel, have 95 percent of the energy (by mass), and are 11 to 17 times more viscous (Korus and Peterson, 1982).

Despite these similarities, vegetable oils are not yet fully compatible with our present CI engines. These modern day power plants owe much of their efficiency and reliability to the quality of fuel that has customarily been specified for their operation. The CI engine has literally been built around tightly specified, high quality diesel fuel (Haddad and Watson, 1984). The entire fuel delivery and injection system found on modern CI engines has been designed for the consistent physical properties attributed to commercial diesel fuel. Combustion chamber design has evolved around its chemical properties.

Alternative Fuels Research

It is easy to see how the introduction of an off-specification fuel such as vegetable oil would cause problems in an engine that has been designed specifically for a certain type of fuel. The problems associated with the use of vegetable oil as a diesel fuel substitute are well documented. Short term tests usually show performance characteristics -- power, torque, and fuel consumption -- close to those of diesel fuel (Peterson et al., 1982; Braun and Stephenson, 1982). Long term tests inevitably lead to severe engine degradation and eventual failure (Peterson and Wagner, 1982).

The series of events leading to engine failure are highly consistent from study to study, a fact that should help overcome the problems associated with these fuels. A review of test results described in the literature provides the following scenario for engine failure.

The first problem to arise when using vegetable oil is usually excessive carbon build up in the combustion chamber. The injectors become fouled. Valves and valve stems sustain heavy deposits, and there is a general degradation of combustion chamber conditions.

As the test continues, the fouled injectors cause poor atomization of the injected fuel. As a result, fuel droplets impinge on the cylinder walls, eventually polymerizing on the piston rings. Deposits of polymerized fuel on the rings causes them to stick in their grooves, effectively ruining their sealing ability.

As more piston rings seize, blowby increases and compression drops. At this point, engine performance decreases noticeably. The increasing blowby results in lubrication oil contamination, characterized by a rapid increase in viscosity. When the lubrication oil becomes contaminated, engine failure is usually "sudden and catastrophic" (Peterson et al., 1983a). It is difficult to maintain adequate lubrication of engine bearings when the engine oil is as thick as axle grease.

Up until now, vegetable oil research has been conducted in four main areas:

1. Mechanical modification of the engine. Research in this area has included shielding, retracting, cooling and coating the injectors; various combustion chamber configurations; the use of a pre-heater for the fuel; and changing the injection pressure, timing, and duration.

2. Selection of desirable vegetable oils. Research here has ranged from selecting types of oils (such as sunflower, peanut, safflower, rape, etc.) to the development of cultivars with good fuel characteristics.

3. Chemical modification of vegetable oils. Research in this field has mostly been aimed at reducing fuel viscosity through formation of methyl and ethyl esters of the vegetable oil fuel. Such esters are much less viscous than the parent oil, with viscosities approaching only double that of diesel fuel.

4. The use of fuel additives. Research in this area has been concentrated in two areas: dispersants have been investigated as a means of reducing viscosity, while surfactants have been used to maintain microemulsions of alcohols and vegetable oils.

It can be seen that while the problems associated with using vegetable oils as a diesel fuel substitute are many, so too are the possible solutions. Triple-fueling and the use of chemically modified vegetable oils, the subjects of this investigation, are among the newest approaches to the problems involved, although the actual principles are decades old.

Fumigation, as used in this study, involves the injection of a mixture of liquid fuels through the conventional fuel injection system, and the induction of a gaseous fuel with the intake air. The majority of fuel energy is in the liquid form, with a small percent of the input energy coming from the inducted gas.

The transesterified fuel used in this study was obtained by chemically reacting methanol and Winter Rape seed oil (Jo, 1984). The reaction was carried out at room temperature with potassium hydroxide as a catalyst. The resulting methyl ester was then blended volumetrically in equal parts with diesel fuel for the engine tests.

Fuel Abbreviation

In the interests of clarity and space, a fuel abbreviation system similar to one used by Peterson, et al. (1983a) will be used. Percentages of fuel blends and auxiliary fuel rates are clearly identified as follows:

AABB + CCDD + EEFFF

AA percent by volume of fuel BB in liquid blend
CC percent by volume of fuel DD in liquid blend
EE percent by weight of auxiliary fuel FFF fumigated into intake air
D2 - #2 Diesel fuel
WR - Winter rape seed oil (Dwarf Essex)
RE - Rape oil methyl ester (obtained from above)
SO - High oleic acid safflower seed oil
SL - High linoleic acid safflower seed oil

LPG - Propane (Liquefied Petroleum Gas)
For example, a fuel blend of 50% winter rape seed oil and 50% #2 diesel with 10% propane fumigation would be designated as:

50WR + 50D2 + 10LPG

It may be noted that all fuel blends used in this study were 50-50 mixtures of #2 diesel fuel and the appropriate vegetable oil.

OBJECTIVES

The objectives of this study were threefold:

1. Determine the effect of propane fumigation on injector coking when used with high erucic rape, high oleic safflower, and high linoleic safflower oils as fuels in a CI engine.

2. Assess the effect of different rates of fumigation on injector coking caused by rape oil.

3. Observe the comparative effectiveness of transesterification and propane fumigation on injector coking when used with Winter Rape oil-diesel fuel mixtures as fuel.

LITERATURE REVIEW

An exhaustive review of the literature related to the use of vegetable oil as fuels is beyond the scope of this study. The literature presented here is selected to provide background on problems associated with vegetable oil fuel use and to provide information related to the potential of fumigation as a means of providing improved combustion in the CI engine.

Vegetable Oils and Their Esters

The desirability of developing vegetable oils as a renewable energy source has led to a wide variety of research programs throughout the United States and the world. The research program at the University of Idaho was among those started by the energy crisis of the mid 1970's. Initial short term tests with safflower, rape, and sunflower oils (Peterson et al., 1982) concurred with other testing of the time, concluding that vegetable oil had performance characteristics similar to diesel fuel. Subsequent long-term endurance testing (Peterson and Wagner, 1982), E.M.A. (Engine Manufacturer's Association) cycle testing (Peterson et al., 1983a), and additive studies (Wagner, 1984) pointed to durability problems, as did the findings of other researchers of the time (Borgelt and Harris, 1982; Strayer and Craig, 1983).

E. F. Fort et al. (1982) reported favorable performance of cottonseed oil and transesterified cottonseed oil in short term performance and emissions tests. Long term testing pointed to problems associated with deposits and poor durability. It was also noted that the tests were conducted at an ambient temperature of 27 degrees centigrade, thus questioning the validity of these tests in colder regions.

Long term endurance testing with sunflower oil at North Dakota State University (Ziejewski et al., 1982) resulted in several problems. Deposits on valves and injectors, ring sticking, and turbocharger failure were reported.

Investigations of sunflower oil conducted by International Harvester Company (Baranescu et al., 1982) found durability and cold temperature operation problems. Further, many of the associated problems were attributed to the modified injection characteristics brought about by the use of fuels more viscous than commercial diesel fuel.

Researchers abroad have reported findings similar to those in the United States. Ventura and Nascimento (1982), and Hugo (1981) reported durability problems with various vegetable oils, and better endurance with esters of the respective oils.

Considerable progress has been made in the selection of potential vegetable fuel oils. Peterson et al. (1981), Peterson et al. (1983b), and Johansson and Nordstrom, (1982) have had considerable success with blends of winter rape oil and diesel fuel.

Peterson et al. (1984) has also had success with a simple fueling regimen. By fueling test engines with diesel fuel just prior to shutdown and subsequent to start up, rape oil fueled engines have experienced 50% greater endurance.

Fumigation and Fuel Blending

The use of multiple fuels in a CI engine may be accomplished by several methods, two of which will be studied herein. Fuel blending mixes the fuels together prior to injection into the combustion chamber by means of the conventional fuel injection system. Fumigation, on the other hand, involves the induction of a portion of the fuel with the intake air while the main fuel charge is injected in the usual manner.

Most previous studies involving the induction of a gaseous fuel into a dual fuel engine were either for the purpose of obtaining additional power from the engine (Miller, 1968; Derry, 1954; McLaughlin et al., 1952), or for utilizing a large quantity of the gaseous fuel (Lalk and Blacksmith, 1982; Bro and Pedersen, 1977; Clark and Bunch, 1962; Mitchell and Whitehouse, 1955). It was usually found that more complete combustion could be obtained with no power increase, or power could be increased with no additional smoke and incomplete combustion.

Carbon monoxide (CO), oxides of nitrogen (NOx), and black smoke in the exhaust gas of a CI engine are indicative of incomplete combustion. Karim et al. (1980) conducted studies involving the fumigation of methane, propane, hydrogen, and ethylene. It was found that the fumigation of these gases resulted in reduced concentrations of CO, NOx, and black smoke at high loads. It was further concluded that propane has "little or no tendency of pyrolisis to liberate soot."

Lyn and Moore (1951), and Lyn (1953) found that propane fumigation decreased ignition delay, smoothed engine knock, and allowed fuels of various, non-optimum cetane rating to be used.

McLaughlin et al. (1952) concluded that propane fumigation of a CI engine reduced smoke and engine deposits through cleaner combustion.

Lalk et al. (1982), and Derry (1954) reported similar findings of reduced smoke with fumigation.

Alcohol has been widely experimented with both as a means of dual fueling the CI engine, and in conjunction with the use of vegetable oils.

Braun et al. (1982) used various blends of diesel fuel, soybean oil, and ethanol to obtain fuels with viscosities approaching that of diesel fuel. 50 hours of testing resulted in no excess carbon buildup. However, some difficulties were encountered in keeping the fuel blend from separating.

Fujisawa and Yokota (1981) developed an injection system that provided mixing of the fuels in the high pressure line between the injection pump and the injector. The high pressure of the line helped maintain the emulsion. In this set up, mixtures of diesel fuel and vegetable oil can be handled by conventional means, with the alcohol being mixed in after the fuel pump.

Shropshire et al. (1983) used various configurations and types of nozzles to fumigate ethanol into a CI engine. Problems encountered resulted partly from the inability of the intake manifold to uniformly distribute the mixture of air, fuel vapor,and liquid fuel.

Being that fumigation and the problems of using vegetable oil fuels are well documented, it seems a logical step to look at these two fields together. Hence, the topic of study covered within appropriately makes use of these concepts as a means of furthering the progress being made in the field of alternative fuels testing.

MATERIALS AND METHODS

The following describes all equipment and the procedures used in the course of this investigation.

Test Equipment

A John Deere 4239T stationary CI engine was used for the torque tests conducted in this study. It is a 4 cylinder, 4 stroke, turbocharged, direct injection engine with a 106.5 mm bore and 110 mm stroke. With a displacement of 3917 cc and a compression ratio of 16.2:1, it has a rated maximum power output of 66 kW at 2500 RPM.

The liquid fuel delivery system incorporated a three way, two position, hand operated valve to allow rapid change from one fuel to another. Additionally, an electric fuel pump was used to facilitate flow of more viscous vegetable oil blends through the fuel filter.

The gaseous fuel induction system consisted of manual and electrical shut-off valves, and a needle valve for flow regulation.

A General Electric dynamometer was connected to the engine to act as a load. The dynamometer has a maximum capacity of 112 kW, and was equipped with a gear on the tail shaft for the purpose of monitoring engine speed. Before testing began, the dynamometer was calibrated by suspending known weights on the dynamometer torque arm. The engine was run at 2200 RPM during calibration to compensate for frictional effects.

Main (liquid) and auxiliary (gaseous) fuel consumption was measured with two digital scales, each one accurate to 0.02 kg. Fuel consumption data was manually recorded.

Engine torque and speed were also manually recorded. Engine speed was monitored by means of a magnetic induction-type RPM pick-up located in close proximity to the gear on the tail shaft of the dynamometer. A Digitec HT series RPM display indicated the engine speed directly in RPM. Torque was measured indirectly by means of a load cell mounted under the torque arm of the cradled dynamometer. A digital multi-meter reading in millivolts was converted to Newton-meters by way of the previously established calibration curve.

Iron-constantan (type J) thermocouples connected to a Digitec Model 590JC Data Logger and Scanner Slave monitored, at 2 minute intervals, several important temperatures, including crankcase, coolant, intake, exhaust, and fuel. The timer and clock display of the data logger also serve to coordinate the test procedures and manual data recording.

Fuels

Table 1 shows the relevant physical and chemical properties of the fuels tested. It should be noted that while 100RE was chemically analyzed, 50RE+50D2 was the fuel used in the tests.

The diesel fuel used was Phillips 2D Reference Fuel. It had a gross heat of combustion of 45,224 kJ/kg.

The gaseous auxiliary fuel was a commercially available mixture of propane and butane commonly called propane. It is a member of the paraffin family of fuels, and has a lower heating value of approximately 45,973 kJ/kg.

All liquid fuel blends used consisted of equal portions of the indicated vegetable oil and #2 diesel fuel. The Winter Rape seed oil was obtained from Dwarf Essex seed. When mixed 50/50 with diesel fuel, the blend had a gross heat of combustion of 42,698 kJ/kg, 5.6% less than the diesel fuel used. The oil was expressed using a CeCoCo expeller operated by the University of Idaho Agricultural Engineering Department. The press processes approximately 55 kg/hr with a mechanical extraction efficiency of about 80%. The oil was stored to allow the particulate matter to settle out and was then subjected to a filtering system with a final mesh size of 4 microns (Thompson, 1983).

The Rape Oil Methyl Ester was supplied by the University of Idaho Chemical Engineering Department. Dwarf Essex seed was processed with the CeCoCo expeller, and transesterified as part of a study involving the transesterification of vegetable oils at room temperature. After final washing, the methyl ester was subjected to the same filtering system as the rape seed oil. The pure ester had a gross heat of combustion of 40,448 kJ/kg, 10.6% less than diesel fuel.

The high oleic and high linoleic safflower oils were obtained from a commercial processor. The Oleic Safflower oil blended with diesel fuel had a gross heat of combustion of 42,349 kJ/kg, 6.4% less than diesel. When blended with diesel, the Linoleic

Safflower fuel had a gross heat of combustion of 42,200 kJ/kg, 6.7% less than diesel.

The fuels involving fumigation used propane to replace part of the liquid fuel. Percent replacement calculations were based on consumption at 2500 RPM. For example, if a baseline test of 50WR+50D2 indicated fuel consumption at 2500 RPM to be 90 kg/hr, the 50WR+50D2+10LPG test would set the auxiliary fuel rate at 9 kg/hr at 2500 RPM. Table 2 summarizes the actual replacement rates. Differences from nominal rates were a result of diminished liquid fuel consumption at lower engine speeds, without a like decrease in the gaseous fuel delivery.

Torque Tests

A torque test was used as described by Wagner (1984) as a means of producing rapid injector coking. In order to keep the results more consistent, a single set of injectors was used, and cleaned after each run. To begin a test, clean injectors were installed, and engine was then warmed up at high idle to operating temperature on the reference fuel. The engine was then loaded, using the dynamometer, to 2500 RPM at full throttle. At this time, the fuel selection valve was switched to allow the vegetable oil blend to be used. After the fuel system was purged of air and the reference fuel, the test was begun.

Data collection took place at 200 RPM increments, starting at 2500 RPM and working down to 1500 RPM by increasing the dynamometer load and keeping the throttle wide open. Each engine speed was maintained for 10 minutes, with data collection occurring every 5 minutes. Two minutes time were allowed between speed settings to adjust the load.

Each vegetable oil was run without fumigation in order to establish a baseline. Baseline fuel consumption and power were then used to calculate fumigation rates and loading.

Torque tests involving fumigation were conducted much the same as the baseline tests with one exception: while baseline tests were conducted at "full governor", the governor was adjusted for each speed setting in the fumigated tests. With the use of auxiliary (fumigated) fuel, adjusting the load alone would have resulted in power outputs higher than the baseline (not to mention the engine's rating). Therefore, both the governor and load were adjusted to maintain torque and power curves identical to the baseline figures. This method allows for partial replacement of the liquid fuel, as opposed to "overfueling".

At the conclusion of each test, the reference diesel fuel was used prior to shutdown of the engine to rid the fuel system of any vegetable oil.

Injector Photographs

After the engine cooled, the injectors were removed and each one photographed at two orientations. A Wild Heerbrugg light microscope and 35mm camera were used at a magnification of 16X. 35mm copy film produced a silhouette image from which 20cm by 25cm prints were made. The area of the coked injectors was measured using a digitizer and microcomputer. An electronic spreadsheet was used to adjust injector areas by subtracting out the area attributed to the injector itself; the remaining area is then attributed to coking. The areas also required scaling to compensate for the slight variations in enlarging that took place in the photographic printing process. All areas reported herein are corrected for scale and have the area of the clean injector subtracted out.

After the areas of all photographs had been calculated, the data were analyzed using SAS*. For the purposes of this study, the mean area attributed to coking was examined to determine if there were any significant differences between fuels. Data input consisted of entering the areas observed for each of the four injectors photographed at the two orientations for each repetition of each fuel, the result being 240 data points. Each data point was specifically labelled as to the fuel, repetition, injector, and orientation from which it was derived. Duncan's multiple-range test was used to find significant differences in injector coking between fuels.

Fixed Rate Fumigation

Part of this investigation involved a fixed rate of fumigation with various liquid fuels. In this study, 10% (by weight) of the fuel consumed in the baseline test was replaced with the auxiliary fuel.

The four fuels tested were: 50SO+50D2, 50SO+50D2+10LPG, 50SL+50D2 and 50SL+50D2+10LPG.

Variable Rate Fumigation

Another part of this investigation involved various rates of fumigation with one type of vegetable oil. Winter Rape seed oil was the oil used in this study. The fumigation rates were calculated as discussed previously. The fuels used were: 50WR+50D2, 50WR+50D2+05LPG, 50WR+50D2+10LPG, and 50WR+50D2+15LPG.

* Statistical Analysis System, SAS Institute Inc. Box 800, Cary, NC 27511

Transesterification

The third part of this investigation involved the use of transesterified Winter Rape oil. The test was conducted in the same manner as the other vegetable oil fuels without fumigation: all speeds were obtained at "full-governor". The fuel used was 50RE+50D2.

Experimental Design

Altogether, 10 fuels were used in this study: Diesel, Winter Rape oil, Winter Rape Methyl Ester (Transesterified Rape oil), Winter Rape oil with 5,10 and 15% propane fumigation, Linoleic Safflower, Linoleic Safflower with 10% propane fumigation, Oleic Safflower, and Oleic Safflower with 10% propane fumigation.

Each fuel was considered a treatment, with each treatment being subjected to three repetitions. The tests, or runs, were conducted in random order by repetition, i.e.,the fuels were arranged in random order, and each used once, for the first repetition. The fuels were randomized again for the second and third repetitions, and the tests carried out to completion. Diesel reference fuel was a treatment in each repetition to examine the effectiveness of fumigation and in reducing injector coking to an acceptable level. A fuel producing injector coking comparable to or less than the diesel reference fuel is desirable.

RESULTS AND DISCUSSION

The areas attributable to injector coking varied widely among the different fuels examined. As can be seen in Figure 1, some treatments had great effect on injector coking; others had little influence. Fixed rate fumigation with Oleic Safflower oil (50SO+50D2+10LPG) and Winter Rape methyl ester (50RE+50D2) resulted in drastically reduced injector coking. Table 3 shows that the coking with these fuels was not statistically different than the coking due to diesel fuel. The 10% nominal rate of fumigation with Winter Rape oil (50WR+50D2+10LPG) reduced injector coking, but not to the level observed with diesel fuel.

The 5 and 15% fumigation rates with Winter Rape oil (50WR+50D2+05LPG and 50WR+50D2+15LPG) resulted in increased injector coking, as can be seen in Figure 1. While the increase for 50WR+50D2+05LPG was quite large, the increase for 50WR+50D2+15LPG was slight, and statistically insignificant (Table 3).

Figures 2, 3 and 4 show typical injector tip photographs. In Figure 2, it can be seen that the injectors used with 100D2, 50RE+50D2 and 50SO+50D2+10LPG experienced very little carbon build up. Figure 3 shows the moderate to severe coking found with the variety of fuels using Winter Rape oil fuel, and Figure 4 depicts the relatively severe coking found with the baseline safflower oil fuels and 50SL+50D2+10LPG.

Fixed Rate Fumigation

The injector coking observed with the use of the baseline fuels (50SO+50D2 and 50SL+50D2) was expected to be quite severe. Of the three vegetable oils involved in this study, these two were clearly the worst in terms of injector coking. Power and torque curves for the baseline and fumigated fuels were identical by design (see Figures 5 and 6).

As can be seen in Figure 7, thermal efficiencies were essentially the same for all vegetable oil baseline runs, diesel fuel and the Winter Rape ester. Figure 8 shows that no differences in efficiency were observed between the baseline and fumigated runs in the fixed rate study.

Fixed rate fumigation of propane significantly reduced injector coking caused by Oleic Safflower oil. The mean injector area attributable to coking for 50SO+50D2 was 771 mm2. The mean injector area attributable to coking for 50SO+50D2+10LPG was 280 mm2, which was not significantly different from the reference fuel injector area of 193 mm2. This represents a 63.7% reduction in injector coking (see Table 4).

Fixed rate fumigation of propane did not significantly reduce injector coking of Linoleic Safflower oil. The mean injector area attributable to coking for 50SL+50D2+10LPG was 653 mm2, which was not significantly different than the 681 mm2 observed for 50D2+50SL.

Propane fumigation appeared to have the most effect on the worst fuel. The 63.7% reduction observed with Oleic Safflower as fuel was the greatest reduction in this study. Some reduction in injector coking could be expected with fumigation due solely to the fact that less coking-prone fuel was used in each test. However, the 12% reduction in liquid fuel observed with the fumigated Oleic Safflower tests does not correspond to the nearly 64% decrease in coking. This decrease must be attributed to factors other than simple liquid fuel reduction.

The 4% increase in coking observed with fumigated Linoleic Safflower must likewise be caused by other factors. The 9.5% reduction in liquid fuel used for these tests would seemingly result in at least a 9-10% reduction in injector coking. As it turned out, no (statistically significant) difference was observed.

The differing results obtained in this fixed rate study must have been effected by the actual mechanisms involved in the burning of these fuels. The differences in saturation of the two fuels appeared to have minimal effect on the baseline tests; both fuels exhibited power and torque curves similar to diesel fuel, and both caused severe coking of the injectors. When operating conditions changed (propane fumigation), marked differences appeared. A more thorough understanding of the combustion characteristics of the fuels involved may help gain insight into why these differences occurred. Unfortunately, it is extremely difficult to evaluate even basic parameters of a fuel, such as ignition delay and rate of combustion. To make things more difficult, these parameters differ from engine to engine, and even within the same engine with changing operating conditions.

To take full advantage of the benefits of propane fumigation, several items would have to be investigated. First, the mechanisms of carbon formation should be more fully understood. Knowing more about this phenomenon, more can be learned about the conditions present in the combustion chamber that are conducive to injector coking. If certain speeds that are conducive to injector coking. If certain speeds and loadings are found to be responsible for carbon formation, selective fumigation under only these conditions may eliminate any ill effects of the fuel. This strategic use of fumigation would maximize benefits with a minimum of fumigated fuel.

Variable Rate Fumigation

The 50WR+50D2 fuel was, by far, the least coking-prone baseline fuel in this investigation. The different rates of fumigation had quite varied effects on the tendency of this fuel to coke the injectors. Again, power and torque curves for the baseline and fumigated fuels were identical by design. Figure 9 shows that efficiencies of the baseline and fumigated tests were essentially the same. The 10% rate significantly reduced injector coking, while the 5% rate significantly increased injector coking. The mean injector area due to coking for 50WR+50D2 was 476 mm2. The mean areas for 50WR+50D2+10LPG and 50WR+50D2+05LPG were 377 and 799 mm2 respectively, both being significantly different than 50WR+50D2 according to Duncan's multiple-range test.

The 15% rate of fumigation did not significantly affect injector coking of Winter Rape oil. 50WR+50D2 and 50WR+50D2+15LPG had mean areas of 476 and 561 mm2, indicating an apparent 17.8% increase in injector coking. This observed increase, however, was not statistically insignificant.

An investigation into the reasons for these widely varied results is suggested for additional study. If only the simple principle of liquid fuel reduction were considered, progressive decreases in injector coking would be expected with increased fumigation rates. This trend was not found. Instead, the results observed must have been influenced by the complex mechanisms of combustion in the combustion chamber. Again, it is difficult to predict the actual conditions that arise inside the combustion chamber, and how fumigation rates influence the chemical properties of the fuels. More insight into the mechanisms involved might be gained in future investigations with the use of exhaust gas analysis. It can then be seen how the addition of fumigated fuel affects the composition of the exhaust products. Any investigation that would help to understand the combustion properties of off-specification fuels would be worthwhile.

Transesterification

Transesterification significantly reduced injector coking caused by Winter Rape oil. 50RE+50D2 had a mean injector area due to coking of 247 mm2, which was significantly lower than the 476 mm2 observed for 50WR+50D2, and not significantly different than the 193 mm2 observed for 100D2. This represents a statistically significant 48% reduction in injector coking, which is perhaps the most important finding of this study. The ester appeared to burn quite well, with a thermal efficiency approximately equal to diesel fuel over the entire operating range of the engine (Figure 7). The power and torque curves are similar in appearance to those of diesel fuel (Figures 5 and 6), with the 2.4% decrease in power at rated speed, and similar small reductions throughout the operating range to be expected, due to the lower fuel content of the ester. This small power decrease could probably be corrected by turning up the fuel pump.

Esters can not yet be claimed the ideal replacement for diesel fuel, due to price, chemical characteristics, and dubious fuel standards. The transesterification process roughly doubles the price of an already expensive parent oil. Pour point and gum content of esters are considerably higher than diesel fuel, making for difficult cold weather operation, and catalyst contamination poses serious problems to the fuel injection system.

CONCLUSIONS

The objectives of this study were to determine the effectiveness of fumigation and transesterification in reducing injector coking when using vegetable oil fuels. A torque test, designed as a screening tool for comparing probable effects on engine life with alternative fuels, was used in this study. The following conclusions are based on the data collected and presented in this paper.

1. A fixed nominal rate of 10% fumigation with propane affected Oleic and Linoleic Safflower oil fuels differently.
   A. Fumigation with Oleic Safflower oil reduced injector coking by 64%, to a level not significantly different from diesel fuel. This was one of the most important results of this investigation.

   B. Fumigation at the 10% nominal rate had no significant effect on injector coking caused by Linoleic Safflower oil. The slight (4%) decrease observed was not statistically significant.

2. The different rates of propane fumigation had widely varied effects on the coking observed with high erucic Winter Rape oil.
   A. A nominal rate of 5% fumigation increased the injector coking observed with Winter Rape oil by 68%.
   B. 10% fumigation with propane reduced the injector coking of Winter Rape oil by 21%.
   C. 15% fumigation did not significantly affect the injector coking of Winter Rape oil. The increase observed (18%) was statistically insignificant.

3. Transesterification significantly reduced the injector coking observed with Winter Rape oil. The 48% decrease in injector coking was one of the most significant findings of this investigation.

RECOMMENDATIONS

Further studies should be conducted. Propane fumigation and the transesterification of vegetable oils shows promise in the field of utilizing alternative fuels. Future investigations could include the following:

1. E.M.A. cycle testing of various fumigation rates used in conjunction with Oleic Safflower oil. Fumigation with Oleic Safflower oil has showed promise in the short term tests conducted in this study. Further

tests of longer duration should be conducted to determine any possible long term benefits to be had. Variations in fumigation rates may lead to the discovery of an optimum rate to minimize injector coking.

2. Short term torque tests with fumigation of other fuels: user produced methane, alcohol, or other renewable fuels. The propane used in this study was a commercially produced fuel. Tests with truly renewable fuels should be conducted to determine the benefits to be had with fumigation of these other fuels. This would also be more in line with the goal of establishing energy independence.

3. E.M.A. cycle testing of transesterified Winter Rape oil. Transesterification of Winter Rape oil was found to greatly reduce injector coking in this short term study. Long term tests should be conducted to discover any benefits that could be had in tests of longer duration.

4. Short term torque tests with esters of other vegetable oils. Since transesterification of Winter Rape oil showed promising results in this study, esters of other vegetable oils should be tested in the same manner. Again, any successes with the short term tests would warrant long term testing.

5. Further studies should be conducted into the transesterification process itself. Less expensive processes should be investigated to make the resulting esters more economically competitive. Further studies should also be conducted into the compatability of esters with engine components.

REFERENCES

Baranescu, R.A. and Joseph J. Lusco. 1982. Sunflower oil as a fuel extender in direct injection turbocharged diesel engines. Society of Automotive Engineers. Paper No. 820260.

Borgelt, S.C., and F.D. Harris. 1982. Endurance tests using soybean oil-diesel fuel mixture to fuel small pre-combustion chamber engines. In Vegetable Oil Fuels, ASAE Publication 4-82. ASAE, St. Joseph, MI 49085.

Braun, D.E., and K.Q. Stephenson. 1982. Alternative fuel blends and diesel engine tests. In Vegetable Oil Fuels, ASAE Publication 4-82. ASAE, St. Joseph, MI 49085.

Bro, K. and P.S. Pedersen. 1977. Alternative diesel engine fuels: An experimental investigation of methanol, ethanol, methane and ammonia in a D.I. diesel engine with pilot injection. Society of Automotive Engineers, Paper No. 770794.

Clark, J.M., Jr. and H.M. Bunch. 1962. Dual fuel combustion of propane in a railroad diesel engine. Southwest Research Institute.

Derry, L.D., E.M. Dodds, E.B. Evans, and D. Royle. 1954. The effect of auxilliary fuels on the smoke-limited power output of diesel engines. Proceedings of Institute of Mechanical Engineers, Vol. 168, No. 9.

Fort, E.F., P.N. Blumberg, H.E. Staph and J.J. Staudt. 1982. Evaluation of cotton seed oils as diesel fuel. Society of Automotive Engineers. Paper No. 820317.

Fujisawa, T. and K. Yokota. 1981. A new look at the utilization of alternative fuels for diesel engines-IDIS. Society of Automotive Engineers, Paper No. 810998.

Haddad, S.D, and N. Watson, (editors). 1984. Design and Applications in Diesel Engineering. Ellis Horwood Limited, Chichester, UK.

Hugo, F. 1981. Sunflower oil as a diesel fuel replacement for the South African research program. In Vegetable Oil as Diesel Fuel, Seminar III. USDA ARM-NC-28. Northern Regional Research Center, Peoria, IL.

Jo, Jaiduk. 1984. Improving storage and use of vegetable oil for fuel. Master of Science thesis, Chemical Engineering, University of Idaho.

Johansson, E. and O. Nordstrom. 1982. Swedish tests on rape-seed oil as an alternative to diesel fuel. In Vegetable Oil Fuels, ASAE Publication 4-82. ASAE, St. Joseph, MI 49085.

Karim, G.A. and K.A. Burn. 1980. The combustion of gaseous fuels in a dual fuel engine of the compression ignition type with particular reference to cold intake temperature conditions. Society of Automotive Engineers. Paper No. 800263.

Korus, R.A. and C.L. Peterson. 1982. Physical and chemical properties of vegetable oils. The Potential of Vegetable Oil as an Alternative Source of Liquid Fuel for Agriculture in the Pacific Northwest. Miscellaneous Series No. 73. Colleges of Agriculture and Engineering, University of Idaho, Moscow, ID 83843.

Lalk, T.R. and J.R. Blacksmith. 1982. Dual-fueling of a single cylinder diesel engine with simulated low-BTU lignite gas as the primary fuel. Society of Automotive Engineers, Paper No. 820316.

Lyn, W.T. and N.P.W. Moore. 1951. Combustion of weak mixtures of methane and propane by pilot oil ignition in a compression-ignition engine. Fuel, Vol. 30, No. 7, p. 158.

Lyn, W.T. 1953. An experimental investigation into the effect of fuel addition to the intake air on the performance of a compression-ignition engine. British Internal Combustion Research Association.

McLaughlin, E.J., P.L. Pinotti, and H.W. Sigworth. 1952. Power booster fuels for diesel engines. Society of Automotive Engineering, Vol. 60, p. 42.

Miller, M.L. 1968. Field modifications of tractors. Agricultural Engineering, March 1968, p. 136.

Mitchell, R.W. and N.D. Whitehouse. 1955. The development and performance of a range of dual fuel engines. Mining Society of Nova Scotia. Transactions, Vol. LVIII, p. 227.

Peterson, C.L., G.L. Wagner, and D.L. Auld. 1981. Performance testing of vegetable oil substitutes for diesel fuel. American Society of Agricultural Engineers, Paper No. 81-3578.

Peterson, C.L. and G.L. Wagner. 1982. Long term endurance tests for determining the effect of fuel blends on engine life. The Potential of Vegetable Oil as an Alternative Source of Liquid Fuel for Agriculture in the Pacific Northwest. Miscellaneous Series No. 73. Colleges of Agriculture and Engineering, University of Idaho, Moscow, ID 83843.

Peterson, C.L., G.L. Wagner, and K.N. Hawley. 1982. Conduct short term engine tests of farm-extracted vegetable oil and vegetable oil-diesel fuel mixtures. The Potential of Vegetable Oil as an Alternative Source of Liquid Fuel for Agriculture in the Pacific Northwest. Miscellaneous Series No. 73. Colleges of Agriculture and Engineering, University of Idaho, Moscow, ID 83843.

Peterson, C.L., G.L. Wagner, K.N. Hawley, and M.C. Hall. 1983a. E.M.A. test cycles: Influence of fatty acid composition on engine deposits. The Potential of Vegetable Oil as an Alternative Source of Liquid Fuel for Agriculture in the Pacific Northwest-II. Miscellaneous Series No. 84. Colleges of Agriculture and Engineering, University of Idaho, Moscow, ID 83843.

Peterson, C.L., J.C. Whitcraft, and K.N. Hawley. 1983b. Field testing of vegetable oils as diesel fuel substitutes-Mitsubishi Bison S6700. The Potential of Vegetable Oil as an Alternative Source of Liquid Fuel for Agriculture in the Pacific Northwest-II. Miscellaneous Series No. 84. Colleges of Agriculture and Engineering, University of Idaho, Moscow, ID 83843.

Peterson, C.L., W.T. Stibal, K.N. Hawley, and P.G. Mora. 1984. Long term endurance testing of vegetable oils as diesel fuel substitutes. The Potential of Vegetable Oil as an Alternative Source of Liquid Fuel for Agriculture in the Pacific Northwest-III. Miscellaneous Series No. 88. Colleges of Agriculture and Engineering, University of Idaho, Moscow, ID 83843.

Shropshire, G.J. and Leonard L. Bashford. 1984. A comparison of ethanol fumigation systems for a diesel engine. Agricultural Engineering. Vol. 65, No. 5, pp. 17-23.

Sorensen, H.A. 1984. Energy Conversion Systems. John Wiley and Sons, New York, NY.

Strayer, R.C. and W.K. Craig. 1983. Long-range engine tests using canola oil as a fuel. In Vegetable Oil as Diesel Fuel, Seminar III. USDA ARM-NC-28. Northern Regional Research Center, Peoria, IL.

Thompson, J.C. 1983. An automated small scale oil seed processing plant. Master of Science Thesis, Agricultural Engineering, University of Idaho.

Wagner, G.L. 1984. Winter rape and safflower seed oils as fuels for compression ignition engines. Master of Science Thesis, Agricultural Engineering, University of Idaho.

Ziejewski, M. and K.R. Kaufman. 1982. Endurance test of a sunflower oil/diesel fuel blend. Society of Automotive Engineers. Paper No. 820257.

Table 1. Chemical properties of fuels tested. Note that 100RE was analyzed, but 50RE+50D2 was used in the engine tests. Analysis was conducted Phoenix Chemical Laboratory, Inc., Chicago, IL.

TEST	100D2	50SO+50D2	50SL+50D2	50WR+50D2	100RE
Cetane Rating	47.8	---	---	42.3	54.4
Flash, F (PMCC)	176	198	198	193	183
Cloud Point, F.	10	8	8	12	28
Pour Point, F.	-20	5	5	0	15
Water & Sediment, %.	Trace	Trace	0.01	0.1	Trace
Ramsbottom Carbon on 10% Residuum, %.	0.17	0.16	0.17	0.18	0.1
Ash, %.	0.01	0.01	0.01	0	0
Viscosity @ 40 C, cs.	3.2	11.25	10.04	10.18	6.7
Viscosity @ 100 C, cs.	1.26	3.31	3.16	3.13	2.39
Sulphur, %.	0.29	0.13	0.12	0.2	Trace
Copper Corrosion, 3 hrs. @ 122 F.	Slight Tarnish,1a	Slight Tarnish,1a	Slight Tarnish,1a	Slight Tarnish,1a	Slight Tarnish,1a
Existent gum, (Steam Jet) mg/100 ml.	21.6	44.9	46.6	40.08	43.9
API Gravity @ 60 F.	33.1	27.8	27.1	28.4	29
Heat of Combustion, BTU/lb. Gross	19443	18207	18143	18357	17390
Particulate Matter, mg/100 ml.	0.2	0.2	0.1	11.31	3.98

Table 2. Actual liquid fuel replacement of the fumigated fuels. Actual percent replacement is based on data collected during three repetitions of the entire test cycle.

FUEL	LIQUID FUEL USED (Kg)	NOMINAL % REPLACED	ACTUAL % REPLACED
50WR+50D2	16.24	---	---
50WR+50D2+05LPG	14.42	5	11.2
50WR+50D2+10LPG	13.82	10	14.9
50WR+50D2+15LPG	12.45	15	23.3
50SO+50D2	16.28	---	---
50SO+50D2+10LPG	14.34	10	11.9
50SL+50D2	16.57	---	---
50SL+50D2+10LPG	15.00	10	9.5

Table 3. Duncan's Multiple Range Test. Means with the same letter are not significantly different.

VARIABLE: AREA

ALPHA=0.05 DF=224 MSE=28978.5

DUNCAN GROUPING		MEAN	N	FUEL
	A	798.92	24	50WR+50D2+05LPG
	A			
B	A	770.97	24	50SO+50D2
B				
B	C	680.64	24	50SL+50D2
	C			
D	C	652.69	24	50SL+50D2+10LPG
D				
D	E	561.02	24	50WR+50D2+15LPG
	E			
	E	476.07	24	50WR+50D2
	F	377.15	24	50WR+50D2+10LPG
	F			
G	F	279.57	24	50SO+50D2+10LPG
G				
G		247.31	24	50RE+50D2
G				
G		192.74	24	100D2

Table 4. Injector coking reduction by treatment.
A comparison of the effects of fumigated and transesterified fuels to the baseline fuels.

TREATMENT	FUEL	COKED AREA (mm)	% COKING REDUCTION
REFERENCE	100D2	193	---
BASELINE OIL	50WR+50D2	476	---
VARIABLE FUMIGATION	50WR+50D2+05LPG	799	-67.8 *
VARIABLE FUMIGATION	50WR+50D2+10LPG	377	20.8
VARIABLE FUMIGATION	50WR+50D2+15LPG	561	-17.8 *
TRANSESTERIFICATION	50RE+50D2	247	48.1
BASELINE OIL	50SO+50D2	771	---
FIXED FUMIGATION	50SO+50D2+10LPG	280	63.7
BASELINE OIL	50SL+50D2	681	---
FIXED FUMIGATION	50SL+50D2+10LPG	653	4.1

* Negative numbers indicate an increase in injector coking

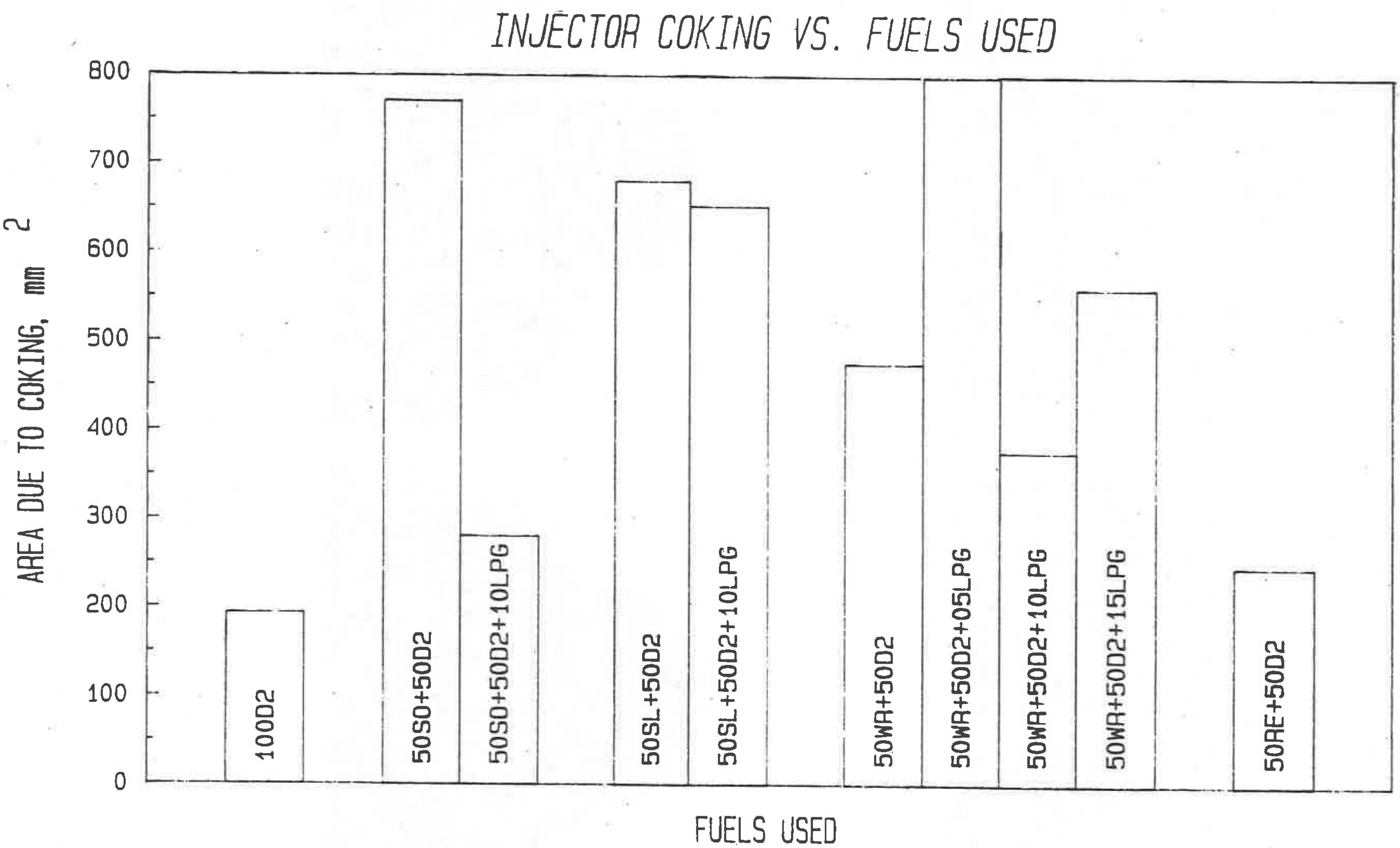
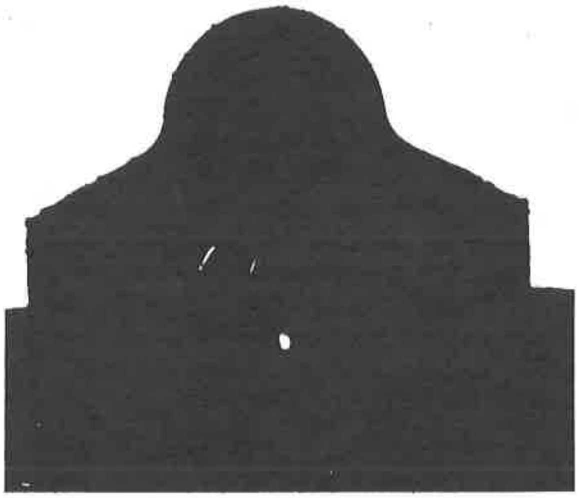
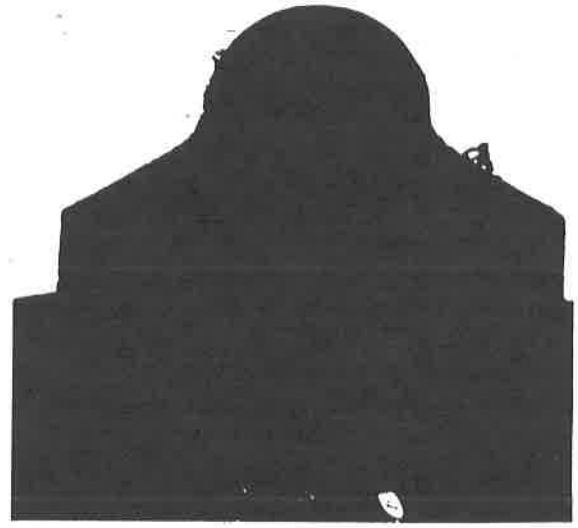


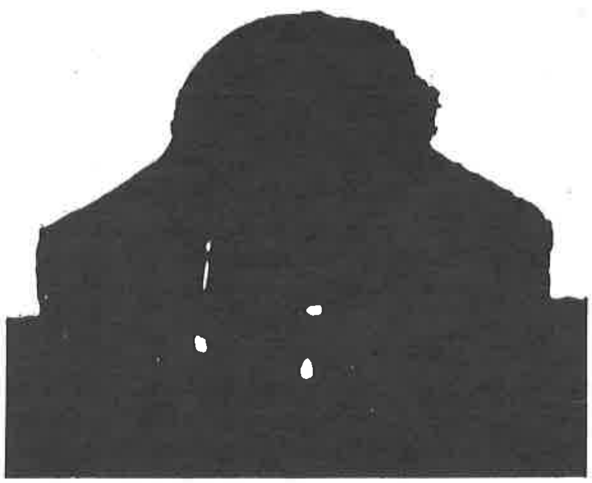
Figure 1. Mean injector areas of the test fuels and the diesel reference fuel.



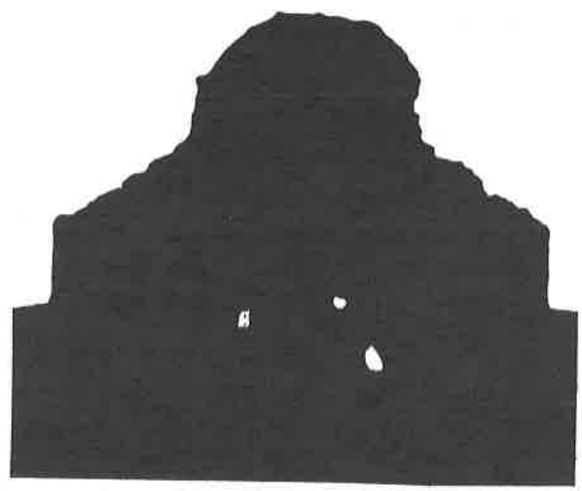
a.



b.



c.



d.

Figure 2. Typical injector photographs. Shown are:
a) Clean injector b) 100D2 c) 50RE+50D2
d) 50SO+50D2+10LPG

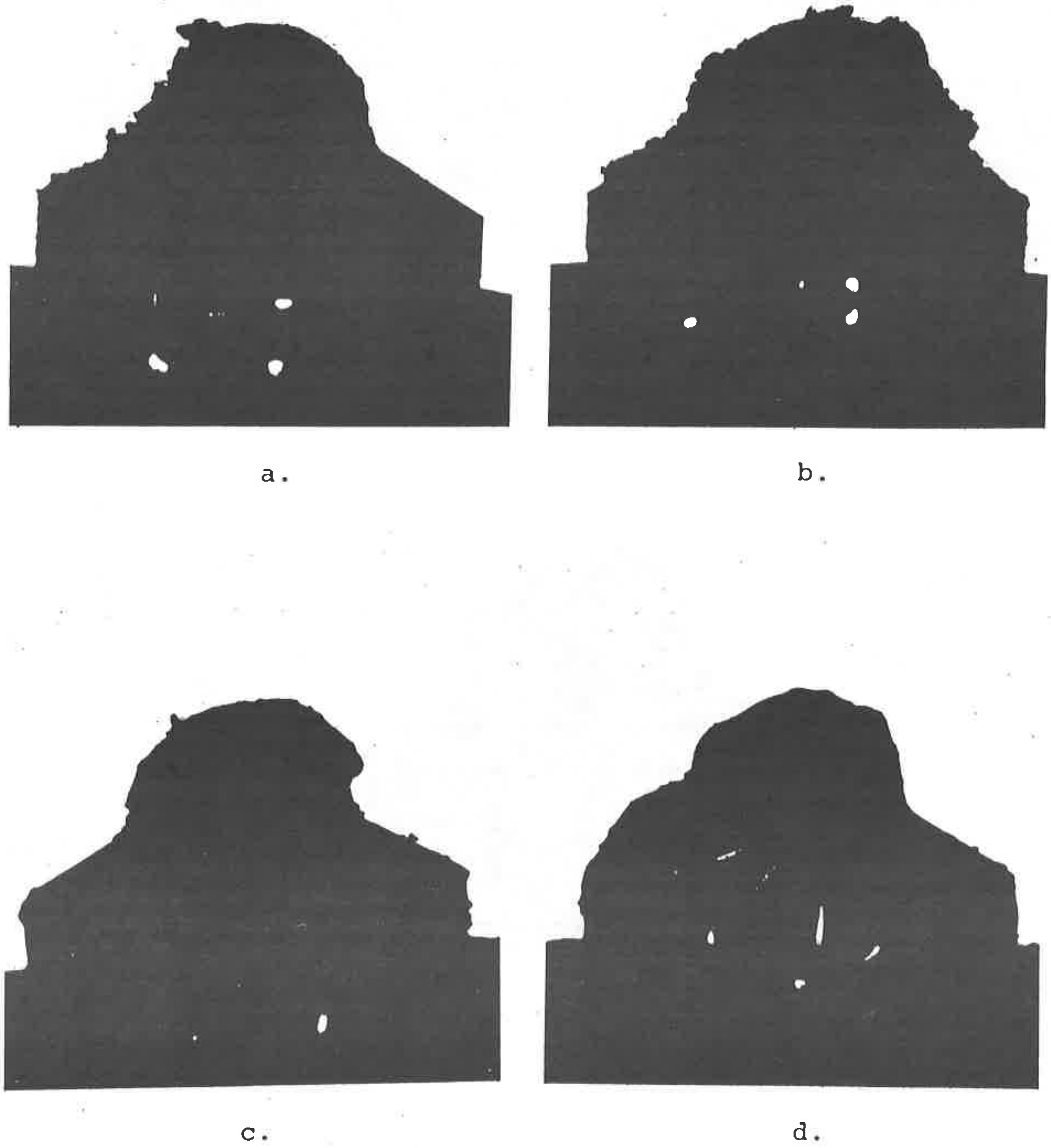
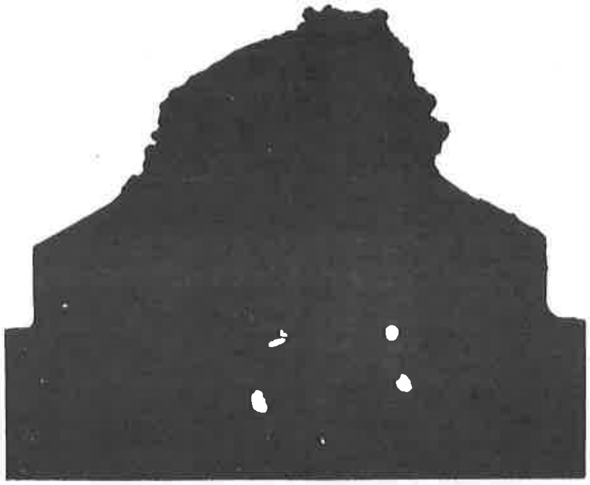
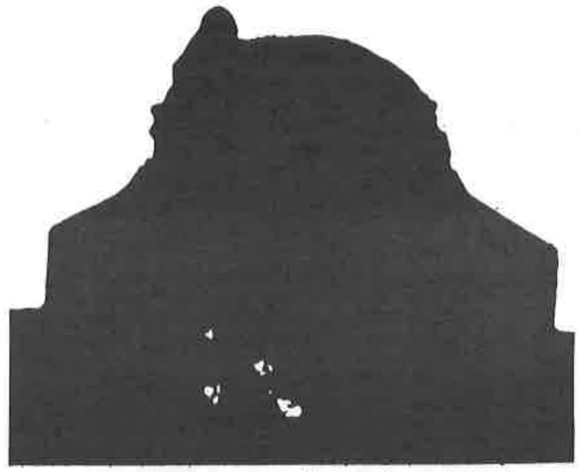


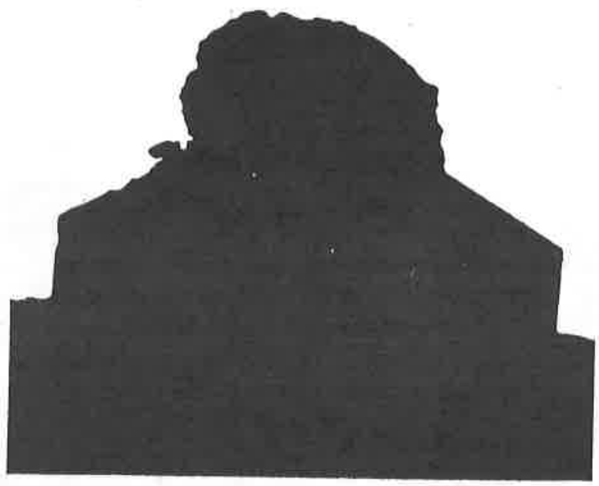
Figure 3. Typical injector photographs showing moderate to severe coking. Shown are: a) 50WR+50D2 b) 50WR+50D2+05LPG c) 50WR+50D2+10LPG d) 50WR+50D2+15LPG



a.



b.



c.

Figure 4. Typical injector photographs depicting severe coking: a) 50SO+50D2 b) 50SL+50D2 c) 50SL+50D2+10LPG

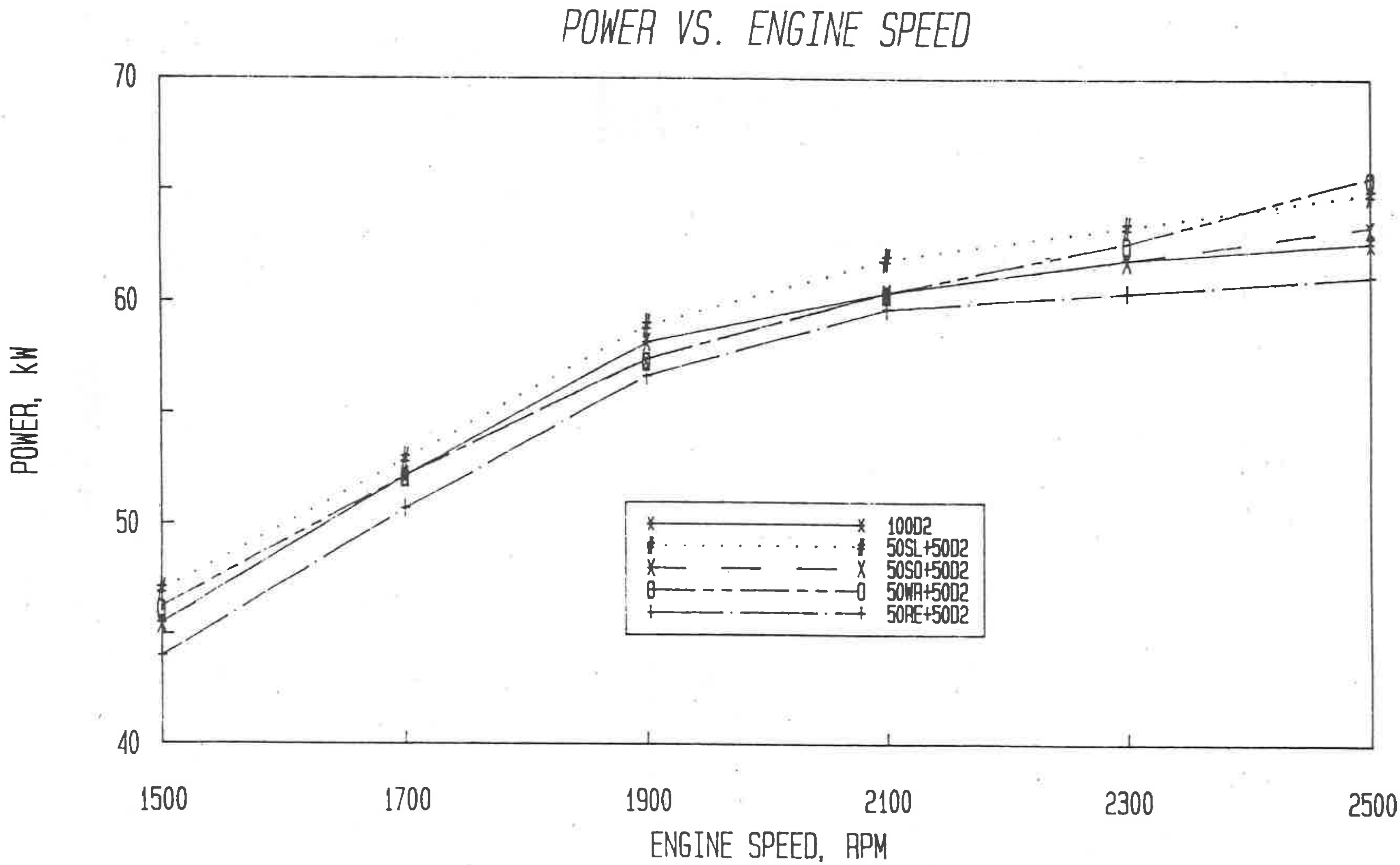


Figure 5. Power curves of the baseline fuels.

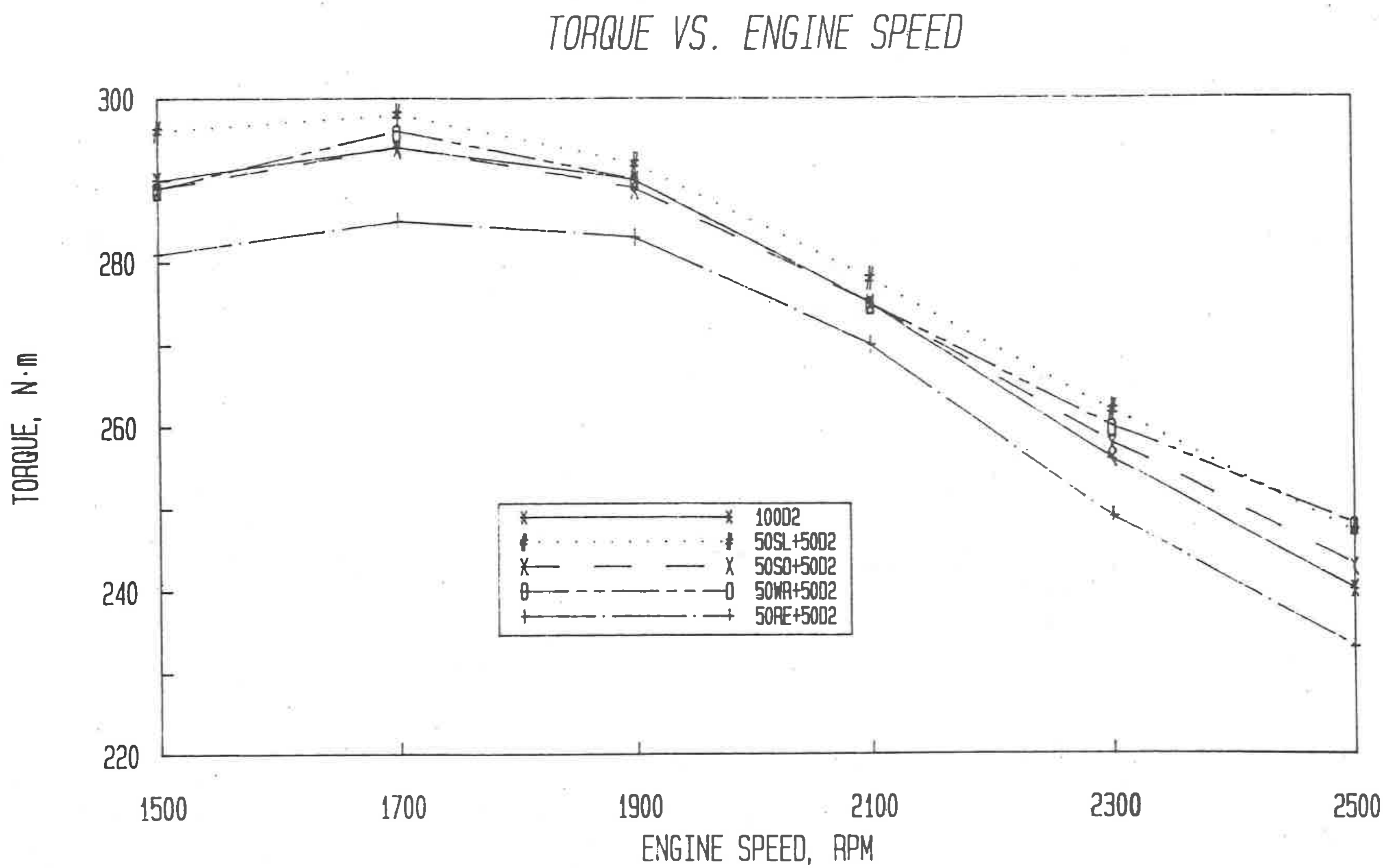


Figure 6. Torque curves of the baseline fuels.

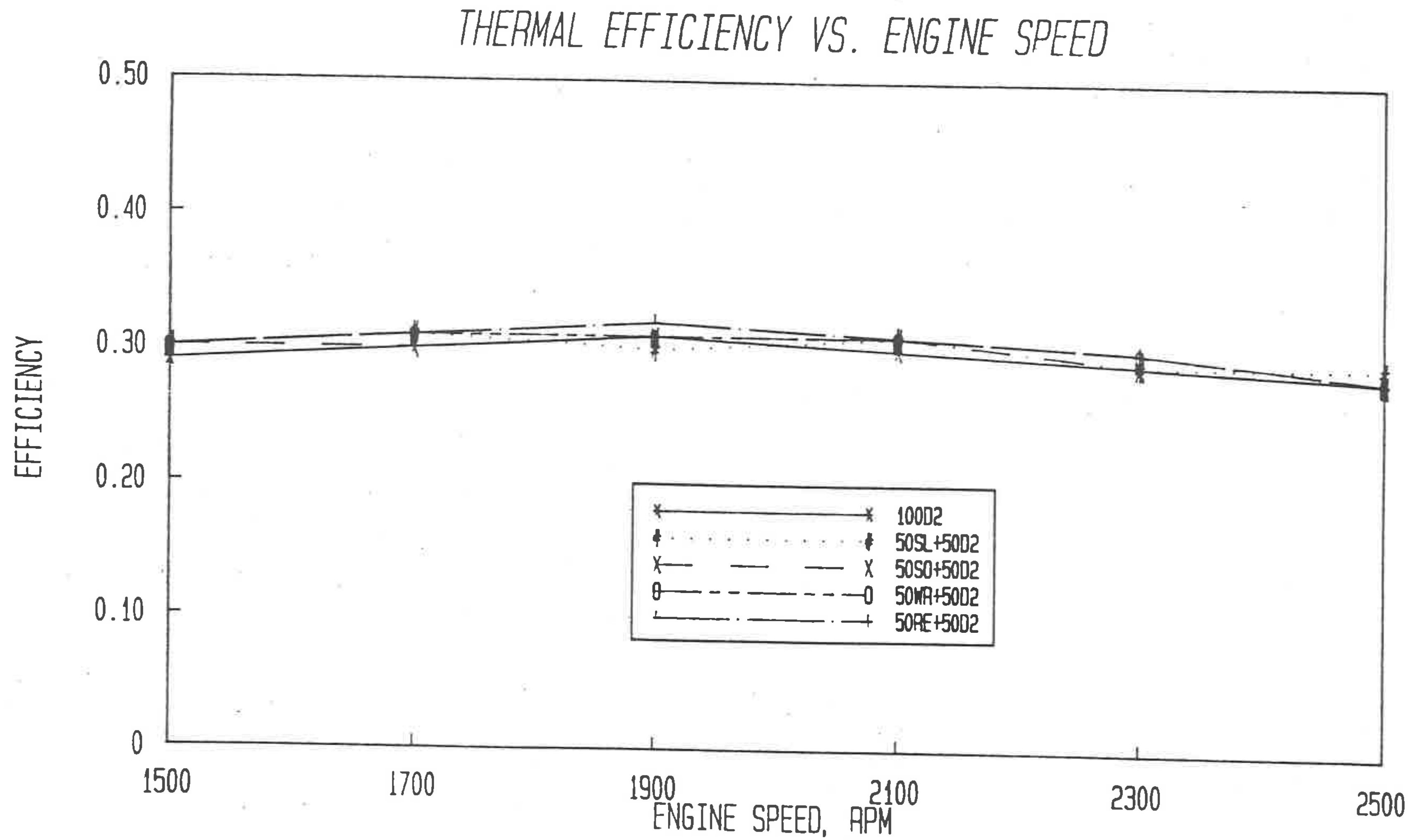


Figure 7. Efficiency curves of the diesel reference fuel, baseline vegetable oil fuels, and the ester fuel.

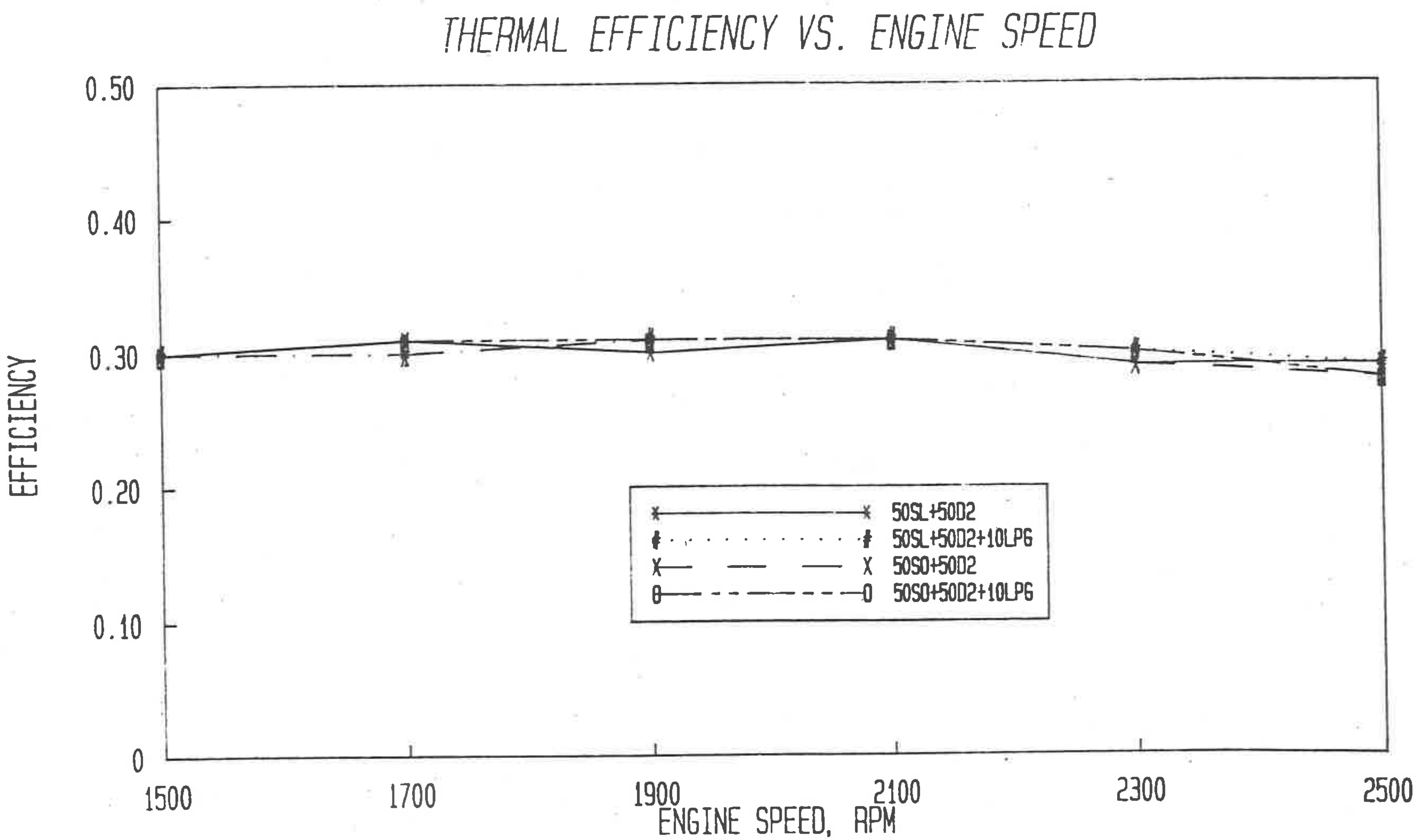


Figure 8. Efficiency curves of the fuels used in the fixed fumigation study.

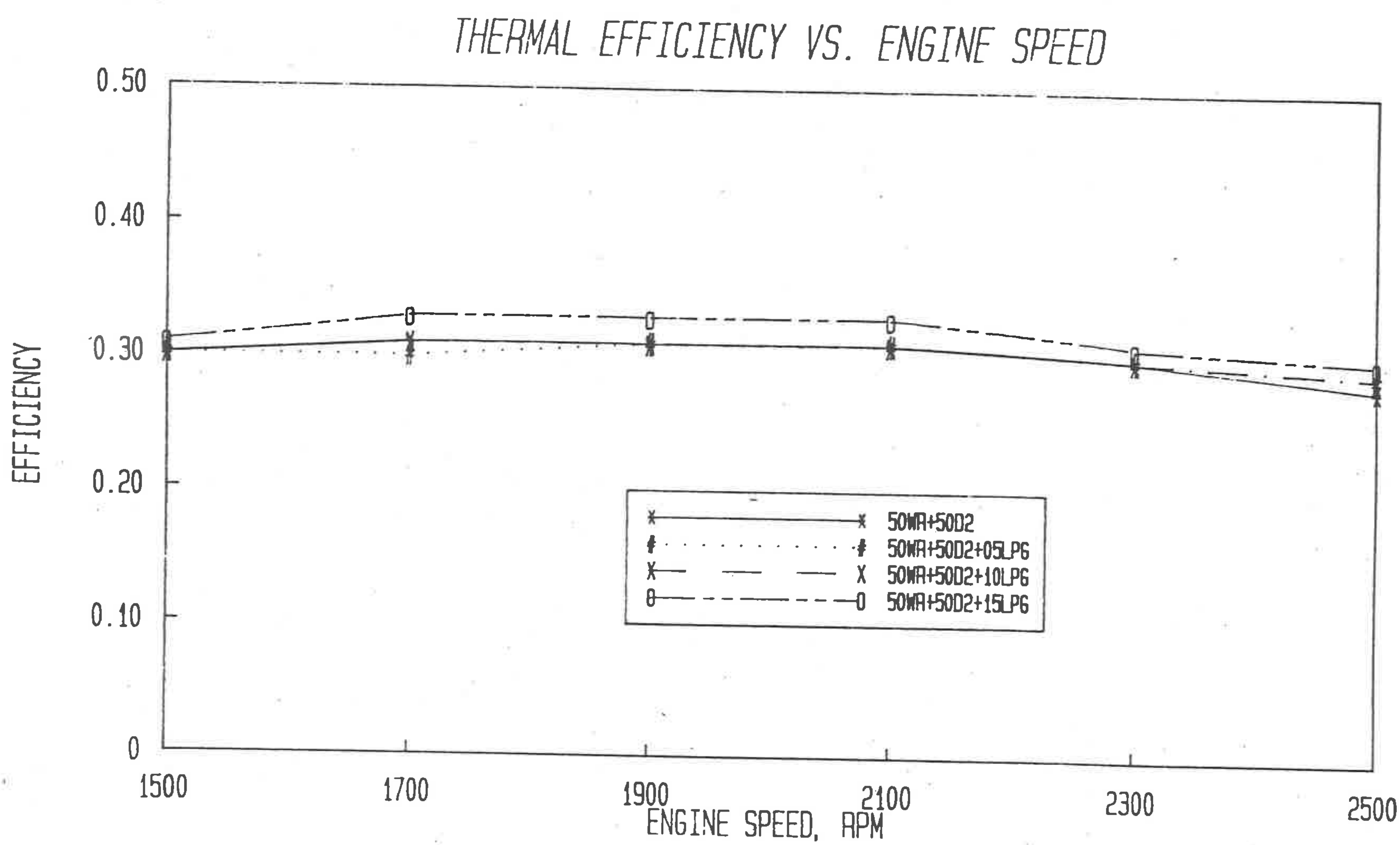


Figure 9. Efficiency curves of the fuels used in the variable fumigation study.