WASTE VEGETABLE OIL AS A DIESEL FUEL EXTENDER

by

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We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

January 1987

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ABSTRACT

The possibility of using waste vegetable oil from deep-frying processes as a fuel for long term use in diesel engines was investigated. Research was aimed at using existing technology in terms of engine design in order to utilize a maximum amount of waste vegetable oil as the energy source with a minimum of processing.

A small swirl-chamber diesel engine was selected and used to run the 200-hour test recommended by the EMA for testing vegetable oil-based fuels. A blend of 20/80 (waste oil/diesel fuel) was tested as well as a 50/50 blend.

BSFC data for both blends did not indicate any significant deterioration in engine performance during the 200 hour tests for all the fuels tested. However, the 50/50 blend BSFC data had more spread than the data from the 20/80 or the diesel baseline test. This was attributed to variable amounts of deposits on the injector nozzle throughout this test. Carbon deposits on all other parts of the combustion chamber were comparable for all the fuels tested. Wear of the engine parts was also comparable except for the piston rings. Piston ring wear was greater with diesel fuel and smaller when burning the 50/50 blend. This was attributed to a film of unburned fuel on the cylinder wall that improved lubrication. Lower lubricating oil consumption was also attributed to this film.

The alternate fuel blends completed the 200 hour EMA screening test and could be considered as possible candidates for long-term use in I.D.I. engines.
# TABLE OF CONTENTS

ABSTRACT .......................................................................................................................... ii

LIST OF FIGURES ............................................................................................................... v

LIST OF TABLES ................................................................................................................ vi

ACKNOWLEDGEMENT ........................................................................................................ vii

NOMENCLATURE ................................................................................................................ viii

1. INTRODUCTION ............................................................................................................. 1
   1.1. GENERAL .................................................................................................................. 1
   1.2. OBJECTIVES ............................................................................................................ 3

2. REVIEW OF LITERATURE ............................................................................................. 4
   2.1. STRUCTURE AND PROPERTIES OF VEGETABLE OILS ........................................ 4
       2.1.1. Chemical structure of vegetable oils and diesel fuel ..................................... 4
           2.1.1.1. Vegetable oils ......................................................................................... 4
           2.1.1.2. Diesel fuel ............................................................................................ 4
       2.1.2. Properties of vegetable oils and diesel fuel ............................................... 7
           2.1.2.1. Physical properties .............................................................................. 7
           2.1.2.2. Fuel properties .................................................................................... 10
       2.1.3. Vegetable oil refining ................................................................................... 11
   2.2. VEGETABLE OIL AS A COMPLETE SUBSTITUTE .............................................. 13
       2.2.1. Direct injection engine test results ............................................................ 14
       2.2.2. Indirect injection engine test results ........................................................... 16
       2.2.3. Importance of engine design ...................................................................... 17
       2.2.4. Durability problems, some hypotheses ....................................................... 18
       2.2.5. Reducing viscosity by heating ................................................................... 19
   2.3. VEGETABLE OIL / DIESEL FUEL BLENDS ....................................................... 20
       2.3.1. Direct injection engine test results ............................................................ 20
       2.3.2. Indirect injection engine test results ........................................................... 22
       2.3.3. Effect of engine design .............................................................................. 23
   2.4. MODIFIED VEGETABLE OILS AS DIESEL FUEL SUBSTITUTE ....................... 23
       2.4.1. Transesterification of vegetable oils ........................................................... 24
           2.4.1.1. Process ............................................................................................... 24
           2.4.1.2. Properties of esters of vegetable oil ................................................... 25
           2.4.1.3. Fatty acid esters as fuels ................................................................... 25
       2.4.2. Direct injection engine test results ............................................................ 26
       2.4.3. Indirect injection engine test results ........................................................... 28
       2.4.4. Problems associated with esters of vegetable oils ................................... 28
   2.5. HYBRID FUELS ...................................................................................................... 29
   2.6. WASTE VEGETABLE OIL RESEARCH ................................................................. 30

3. MATERIALS AND METHODS ....................................................................................... 31
   3.1. EXPERIMENTAL EQUIPMENT ............................................................................ 31
       3.1.1. Engine ......................................................................................................... 31
       3.1.2. Engine Dynamometer .............................................................................. 33
<table>
<thead>
<tr>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.3. Measuring Equipment</td>
</tr>
<tr>
<td>3.2. FUELS TO BE TESTED</td>
</tr>
<tr>
<td>3.2.1. Diesel fuel</td>
</tr>
<tr>
<td>3.2.2. Waste vegetable oil</td>
</tr>
<tr>
<td>3.2.3. Alternate fuel blends</td>
</tr>
<tr>
<td>3.3. ENGINE TESTING</td>
</tr>
<tr>
<td>3.3.1. EMA durability screening test</td>
</tr>
<tr>
<td>3.3.2. Engine test procedure</td>
</tr>
<tr>
<td>3.3.2.1. Engine disassembly</td>
</tr>
<tr>
<td>3.3.2.2. Lubricating oil</td>
</tr>
<tr>
<td>3.3.2.3. Engine break-in</td>
</tr>
<tr>
<td>3.3.2.4. Fuel consumption tests</td>
</tr>
<tr>
<td>3.3.2.5. EMA test cycle</td>
</tr>
<tr>
<td>3.3.2.6. 200 hour durability screening test</td>
</tr>
<tr>
<td>3.4. ENGINE CONTROLLER</td>
</tr>
<tr>
<td>3.4.1. Purpose and Objectives</td>
</tr>
<tr>
<td>3.4.2. Equipment available</td>
</tr>
<tr>
<td>3.4.3. Overview of the controller</td>
</tr>
<tr>
<td>3.4.4. Engine speed measurement</td>
</tr>
<tr>
<td>3.4.4.1. Photoelectric frequency generator</td>
</tr>
<tr>
<td>3.4.4.2. Speed measurement</td>
</tr>
<tr>
<td>3.4.5. Latching of the speed reading</td>
</tr>
<tr>
<td>3.4.6. Step motor control</td>
</tr>
<tr>
<td>3.4.7. Semi-proportional control</td>
</tr>
<tr>
<td>3.4.8. Speed setting selector</td>
</tr>
<tr>
<td>3.4.9. Engine load selector</td>
</tr>
<tr>
<td>3.4.10. Engine shut-off circuit</td>
</tr>
<tr>
<td>3.4.11. Operation</td>
</tr>
<tr>
<td>4. RESULTS AND DISCUSSION</td>
</tr>
<tr>
<td>4.1. FUEL ANALYSIS</td>
</tr>
<tr>
<td>4.2. WASTE VEGETABLE OIL ANALYSIS</td>
</tr>
<tr>
<td>4.3. EFFECT OF TIME ON BSFC</td>
</tr>
<tr>
<td>4.4. CARBON DEPOSITS</td>
</tr>
<tr>
<td>4.4.1. Nature of deposits</td>
</tr>
<tr>
<td>4.4.2. Quantification of the deposits</td>
</tr>
<tr>
<td>4.5. WEAR OF ENGINE PARTS</td>
</tr>
<tr>
<td>4.6. LUBRICATING OIL ANALYSIS</td>
</tr>
<tr>
<td>4.6.1. Wear metals</td>
</tr>
<tr>
<td>4.6.2. Viscosity of the lubricating oil</td>
</tr>
<tr>
<td>4.6.3. Lubricating oil consumption</td>
</tr>
<tr>
<td>4.7. ENGINE OPERATION</td>
</tr>
<tr>
<td>5. CONCLUSION</td>
</tr>
<tr>
<td>6. FUTURE RESEARCH</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
</tr>
<tr>
<td>APPENDIX: EMA 200-HOUR SCREENING TEST</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1: Triglyceride molecule synthesis (Goering et al, 1982) ............................................. 8
Figure 2: Typical diesel fuel molecule ......................................................................................... 8
Figure 3: Transesterification process (Pishinger et al, 1982) ....................................................... 8
Figure 4: Typical distillation curves for diesel and corn oil (Goering et al, 1982) ....... 12
Figure 5: Block diagram of the engine controller ......................................................................... 42
Figure 6: Frequency generator ...................................................................................................... 42
Figure 7: Semi proportional speed control .................................................................................... 47
Figure 8: Speed setting selector .................................................................................................... 47
Figure 9: Load selector .................................................................................................................. 50
Figure 10: Shut-off circuit ............................................................................................................. 50
Figure 11: Breadboard circuit of the engine controller ................................................................. 52
Figure 12: BSFC data for the diesel run, step 1 ........................................................................... 57
Figure 13: BSFC data for the diesel run, step 2 ........................................................................... 57
Figure 14: BSFC data for the 20 / 80 run, step 1 ......................................................................... 58
Figure 15: BSFC data for the 20 / 80 run, step 2 ......................................................................... 58
Figure 16: BSFC data for the 50 / 50 run, step 1 ......................................................................... 59
Figure 17: BSFC data for the 50 / 50 run, step 2 ......................................................................... 59
Figure 18: Deposits on miscellaneous parts .................................................................................... 64
Figure 19: Wear of miscellaneous parts ......................................................................................... 67
Figure 20: Piston rings wear ......................................................................................................... 67
Figure 21: Wear iron concentration in lubricating oil ................................................................. 69
Figure 22: Wear aluminium concentration in lubricating oil ......................................................... 69
Figure 23: Wear chromium concentration in lubricating oil ......................................................... 70
Figure 24: Wear copper concentration in lubricating oil .............................................................. 70
Figure 25: Viscosity of lubricating oil at 40°C ............................................................................... 73
Figure 26: Viscosity of lubricating oil at 100°C ............................................................................. 73
Figure 27: Lubricating oil consumption ........................................................................................ 75
LIST OF TABLES

Table I: Fatty acid composition for 12 vegetable oils, % by weight (Goering et al, 1982). ................................................................. 5
Table II: Fatty acids nomenclature (Goering et al, 1982) ................................................................. 6
Table III: Properties of vegetable oils, methylesters of vegetable oil and diesel fuel (Goering et al, 1982; Pishinger et al, 1982; Hawkins and Fuls, 1982) ...... 9
Table IV: Test engine specifications ........................................................................... 32
Table V: Engine break-in procedure (EMA, 1982) ...................................................... 39
Table VI: EMA test cycle (EMA, 1982) ..................................................................... 39
Table VII: Testing conditions for the engine ............................................................... 39
Table VIII: Results of the fuel analysis .................................................................. 54
Table IX: Fatty acid profile of the waste vegetable oil by GC/MS ............................. 54
Table X: Results of the statistical analysis on the BSFC data ................................ 60
Table XI: Diesel fuel savings with the fuel blends ..................................................... 60
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NOMENCLATURE

ASTM: American Society for Testing Materials
BCD: Binary Coded Decimal
BSDC: Brake Specific Diesel fuel Consumption
BSFC: Brake Specific Fuel Consumption
CMOS: Complementary Metal On Silicon
DI: Direct Injection
EMA: Engine Manufacturer’s Association
GC/MS: Gas Chromatograph/Mass Spectrometer
GHC: Gross Heat Content
IC: Intercooled
IDI: Indirect Injection
LED: Light Emitting Diode
OPEC: Organization of Petroleum Exporting Countries
R²: Coefficient of Multiple Determination
SAE: Society of Automotive Engineers
TC: Turbocharged
TTL: Transistor–Transistor Logic
USDA: United States Department of Agriculture
WACL: Weighed Average Carbon chain Length in the fatty acid
WADB: Weighed Average number of Double Bonds in the fatty acid
1. INTRODUCTION

1.1. GENERAL

At the time the compression ignition engine was being developed by Rudolph Diesel in the late nineteenth century, petroleum-derived fuels were relatively expensive in Western Europe. Most of the early testing was done using either kerosene or illuminating gas (methane). Other fuels derived from coal products such as shale oil and coal dust were also burned successfully in the early engines. At the Paris World’s Fair of 1900, a diesel engine was operated wholly on peanut oil and ran as well as the others using different fuels (Nitske and Wilson, 1965).

Shortly after the turn of the century, petroleum-based fuels became more affordable and the diesel engine was adapted to burn these fuels. Since then, for over 80 years, the reliability and efficiency of the diesel engine have improved steadily. This successful development was made possible by the availability of a standardized fuel obtained by petrochemistry. During various periods of petroleum shortages, such as both World Wars, interest was renewed in research for alternate fuels.

During the latest petroleum crisis of the mid-seventies, petroleum products prices were artificially made to increase following the creation of the OPEC. The prices were kept high for about ten years until the latest market readjustments of 1984–1985. During this high-price period, the governments of most petroleum importing countries have made available important funds for alternate fuel research. Vegetable oils resurfaced as an important candidate for diesel fuel substitute and were investigated extensively.

Vegetable oils were studied for many reasons. First, these oils are renewable resources. They are also readily combustible in compression ignition engines. The energy
balance for vegetable oil production is positive, an average output to input ratio of 4:1 has been reported (Goering et al., 1982). Vegetable oils contain no sulfur and the CO₂ produced by their combustion is in equilibrium with their photosynthesis, thus greatly reducing air pollution. The oils have been used as fuels either neat, blended with diesel fuel or in modified form.

Neat vegetable oils were investigated at first since little or no processing was required prior to their use as a fuel. It was found that their long term use as a complete substitute for diesel fuel was only possible in indirect injection engines. For direct injection engines, the oils had to be mixed with large amounts of diesel fuel in order to avoid premature engine failure. The problems encountered when using neat oils as complete substitutes in direct injection engines were heavy carbon deposits on injector tips and in the piston ring grooves. These problems were attributed to the relatively high viscosity of the oils causing improper atomization of the fuel by the injection system leading to incomplete combustion. Since most modern diesel engines use the direct injection system, for better fuel efficiency, research was directed into modifying the oils so that they could be used as total substitutes to diesel fuel for these engines.

The transesterification process, by which an alcohol is used to break the triglyceride molecules in three hydrocarbon chains, was the most successful way to modify the vegetable oils. Encouraging results have been obtained with esters of vegetable oils. However, vegetable oils being more expensive than diesel fuel, the extra cost associated with the process makes these alternate fuels even more expensive than petroleum-derived fuels.

The potential for vegetable oils to replace diesel fuel is rather limited. It has been calculated that about 10% of agricultural land would be necessary in order to
produce the fuel needed on the farms only. (Duke and Bagby, 1982). By growing different species, it would be possible to increase production of these oils but enormous areas of farm land would be necessary in order to produce fuels for out of farm use. The actual price structure of the fuel market would make these fuels interesting only in case of emergency or severe shortages of petroleum resources.

On the other hand, waste vegetable oil from the frying processes is at the moment, relatively inexpensive. Very little research on its use as a diesel fuel substitute or extender has been done and this research project was aimed at filling this void.

1.2. OBJECTIVES

The objectives of this research project were:

1. Determine how waste vegetable oil could be used as a fuel for diesel engines with:
   a. A minimum of processing.
   b. A minimum of engine modifications.
   c. A maximum of energy substitution.

2. Compare the effect of alternate fuels based on waste vegetable oil to diesel fuel in terms of wear, deposits and combustion efficiency.
2. REVIEW OF LITERATURE

2.1. STRUCTURE AND PROPERTIES OF VEGETABLE OILS

2.1.1. Chemical structure of vegetable oils and diesel fuel

2.1.1.1. Vegetable oils

Vegetable oils are made up almost exclusively of triglyceride molecules. Figure 1 displays the synthesis process leading to the formation of a typical triglyceride molecule. Three fatty acids are linked with a molecule of glycerine by ester linkages. These three fatty acids may differ in the number of carbon atoms present in their chain and also in their degree of unsaturation or number of double bonds. A vegetable oil can be characterized by the proportion of different fatty acids present in its molecules.

Table I summarises the composition of some of the most common vegetable oils. Most oils contain a large proportion of fatty acids containing 18 carbon atoms with either one or two double bonds, the C18:1 or C18:2 fatty acids.

Each fatty acid has been identified individually and table II summarizes the names of the fatty acids likely to be found in vegetable oils.

2.1.1.2. Diesel fuel

Petroleum-derived diesel fuels have a very different structure than vegetable oils. The basic difference is that diesel fuel molecules contain no oxygen. The normal structure is the paraffinic straight chain of general formula \( \text{C}_n \text{H} \quad 2n+2 \) as shown in figure 2. Diesel fuel can also contain unsaturated straight chains but their proportion is
Table I: Fatty acid composition for 12 vegetable oils, % by weight (Goering et al., 1982).

<table>
<thead>
<tr>
<th>Veg oil</th>
<th>14:0</th>
<th>16:0</th>
<th>18:0</th>
<th>18:1*</th>
<th>18:2</th>
<th>18:3</th>
<th>20:0</th>
<th>22:0</th>
<th>22:1</th>
<th>24:0</th>
</tr>
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<td>Castor</td>
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<td>1.09</td>
<td>3.10</td>
<td>4.85</td>
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<td>1.27</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Corn</td>
<td>0</td>
<td>11.67</td>
<td>1.85</td>
<td>25.16</td>
<td>0</td>
<td>60.60</td>
<td>0.48</td>
<td>0.24</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cottonseed</td>
<td>0</td>
<td>28.33</td>
<td>0.89</td>
<td>13.27</td>
<td>0</td>
<td>57.51</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>Crambe</td>
<td>0</td>
<td>2.07</td>
<td>0.70</td>
<td>18.86</td>
<td>0</td>
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<td>2.09</td>
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<td>48.28</td>
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<td>0.93</td>
<td>1.32</td>
<td>2.52</td>
<td>1.23</td>
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<td>8.23</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Safflower</td>
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<td>8.60</td>
<td>1.93</td>
<td>11.58</td>
<td>0</td>
<td>77.89</td>
<td>0</td>
<td>0</td>
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<tr>
<td>H.O.Saff.</td>
<td>0.34</td>
<td>5.46</td>
<td>1.75</td>
<td>79.36</td>
<td>0</td>
<td>12.86</td>
<td>0</td>
<td>0.23</td>
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<tr>
<td>Sesame</td>
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<td>13.10</td>
<td>3.92</td>
<td>52.84</td>
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<td>30.14</td>
<td>0</td>
<td>0</td>
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<td>Soybean</td>
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<td>11.75</td>
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<td>23.26</td>
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<td>55.53</td>
<td>6.31</td>
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<td>3.26</td>
<td>16.93</td>
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<td>73.73</td>
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Table II: Fatty acids nomenclature (Goering et al, 1982).

<table>
<thead>
<tr>
<th>FATTY ACID</th>
<th>STRUCTURE</th>
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<tbody>
<tr>
<td>Myristic</td>
<td>14:0</td>
</tr>
<tr>
<td>Palmitic</td>
<td>16:0</td>
</tr>
<tr>
<td>Stearic</td>
<td>18:0</td>
</tr>
<tr>
<td>Oleic</td>
<td>18:1</td>
</tr>
<tr>
<td>Ricinoleic</td>
<td>18:1*</td>
</tr>
<tr>
<td>Linoleic</td>
<td>18:2</td>
</tr>
<tr>
<td>Linolenic</td>
<td>18:3</td>
</tr>
<tr>
<td>Arachidic</td>
<td>20:0</td>
</tr>
<tr>
<td>Behenic</td>
<td>22:0</td>
</tr>
<tr>
<td>Erucic</td>
<td>22:1</td>
</tr>
<tr>
<td>Lignoceric</td>
<td>24:0</td>
</tr>
</tbody>
</table>

xy:z = xy carbon atoms in the fatty acid chain with z double bonds.

*Ricinoleic is a fatty acid containing an OH group.
limited because of the fuel oxidation problem associated with them. A small amount of aromatic molecules can also be present (Liljedahl et al, 1979).

When figure 1 and figure 2 are compared, vegetable oils and diesel fuel appear very different. This suggests that the properties of these oils should be very different from those of diesel fuel.

2.1.2. Properties of vegetable oils and diesel fuel

Table III summarizes some physical and chemical properties related to fuel utilization for different vegetable oils. Properties for some esters of vegetable oils as well as those of typical diesel fuel were also included. Esters of vegetable oil are the product of the transesterification of triglyceride molecules with an alcohol. This process will be discussed later in this literature review.

2.1.2.1. Physical properties

The physical property that distinguishes vegetable oils from diesel fuel is their viscosity. Vegetable oils are typically 20 to 40 times more viscous at room temperature than diesel fuel. Some fuel injection problems are thus to be expected since the design of these systems was made with diesel fuel as the fluid.

Their density is about 8% higher and their cloud and pour point are also generally higher than those of diesel fuel. Some cold weather problems are to be expected from this.

However, esters of vegetable oils have a viscosity much closer to that of diesel fuel. This relatively low viscosity compared to the oils where the esters originate has been the rationale for the investigation on their use as fuels. However, their cloud and pour point are even higher than the vegetable oils from which they are extracted.
Figure 1: Triglyceride molecule synthesis (Goering et al, 1982)

Figure 2: Typical diesel fuel molecule

Figure 3: Transesterification process (Pishinger et al, 1982)
Table III: Properties of 12 vegetable oils (Goering et al, 1982).

<table>
<thead>
<tr>
<th>Vegetable oil</th>
<th>Visc. 38°C (mm²/sec)</th>
<th>Cetane number</th>
<th>gross H.C. (kJ/kg)</th>
<th>Cloud point. (°C)</th>
<th>Pour point. (°C)</th>
<th>Flash point. (°C)</th>
<th>Density (kg/1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castor</td>
<td>297.0</td>
<td>n.a.</td>
<td>37274</td>
<td>none</td>
<td>-31.7</td>
<td>260</td>
<td>0.9537</td>
</tr>
<tr>
<td>Corn</td>
<td>34.9</td>
<td>37.6</td>
<td>39500</td>
<td>-1.1</td>
<td>-40.0</td>
<td>277</td>
<td>0.9095</td>
</tr>
<tr>
<td>Cottonseed</td>
<td>33.5</td>
<td>41.8</td>
<td>39468</td>
<td>1.7</td>
<td>-15.0</td>
<td>234</td>
<td>0.9148</td>
</tr>
<tr>
<td>Crambe</td>
<td>53.6</td>
<td>44.6</td>
<td>40482</td>
<td>10.0</td>
<td>-12.2</td>
<td>274</td>
<td>0.9044</td>
</tr>
<tr>
<td>Linseed</td>
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<td>34.6</td>
<td>39307</td>
<td>1.7</td>
<td>-15.0</td>
<td>241</td>
<td>0.9236</td>
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<tr>
<td>Peanut</td>
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<td>41.8</td>
<td>39782</td>
<td>12.8</td>
<td>-6.7</td>
<td>271</td>
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<tr>
<td>Rapeseed</td>
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<td>37.6</td>
<td>39709</td>
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<tr>
<td>Safflower</td>
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<td>41.3</td>
<td>39519</td>
<td>18.3</td>
<td>-6.7</td>
<td>260</td>
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<td>H.O. Safflower</td>
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<td>49.1</td>
<td>39516</td>
<td>-12.2</td>
<td>-20.6</td>
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<td>Sesame</td>
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<td>-9.4</td>
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<tr>
<td>Sunflower</td>
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<td>37.1</td>
<td>39575</td>
<td>7.2</td>
<td>-15.0</td>
<td>274</td>
<td>0.9161</td>
</tr>
<tr>
<td>M.E. soybean¹</td>
<td>4.5</td>
<td>45.0</td>
<td>33500(net)</td>
<td>1.0</td>
<td>n.a</td>
<td>178</td>
<td>0.885</td>
</tr>
<tr>
<td>M.E. sunflower²</td>
<td>4.9</td>
<td>48.0</td>
<td>41150</td>
<td>-1.0</td>
<td>n.a</td>
<td>121</td>
<td>0.874</td>
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<tr>
<td>Typical diesel</td>
<td>2.7</td>
<td>47.0</td>
<td>45343</td>
<td>-15.0</td>
<td>-33.0</td>
<td>52</td>
<td>0.8400</td>
</tr>
</tbody>
</table>

M.E.: Methyl ester
Cold weather utilisation seems even more limited for these fuels than for the neat vegetable oils.

2.1.2.2. Fuel properties

The flash point of vegetable oils is much higher than that of diesel fuel. Safer handling is to be expected from this. Apparently, the flash point is not directly related to engine performance (Liljedahl et al, 1979). The heat of combustion of vegetable oils is about 88% of diesel fuel. A higher brake specific fuel consumption (BSFC) is then to be expected with these fuels if their brake thermal efficiencies are similar to that of diesel fuel.

The cetane number of most vegetable oils is close to or exceeds the minimum of 40 required for diesel fuel. However, many researchers have reported lower noise levels, the so called "diesel knock", when using vegetable oils as fuels. The cetane rating is a measure of the ignition quality of a fuel and is determined in a standardised single-cylinder variable compression ratio engine. This engine is operated according to a test procedure standardized in ASTM D613. Ryan et al (1984) have suggested that the cetane rating is affected by the atomization and vaporisation processes in the special cetane engine. With the high viscosity fluids, the atomization process was believed to be less efficient. This would cause a longer ignition delay and thus a lower cetane rating for the more viscous fluids. They suggest that real engines are not as sensitive as the cetane engine and that cetane ratings obtained by ASTM D613 do not always reflect the actual behavior of vegetable oils in common engines. By heating degummed soybean oil from 38°C to 145°C, they measured a cetane rating going from 36.6 to 39.3. This was attributed to the lower viscosity of the oil at 145°C resulting in improved spray characteristics and fuel vaporization.
The distillation curve of the vegetable oils is quite different from that of diesel fuel. Figure 4 is a typical distillation curve for both diesel fuel and a vegetable oil, in this case corn oil. Typically, some residue remains in the distillation flask and the oil cannot be totally vaporized.

The sulfur content is very low (less than 0.01%) and low corrosion and sulfur oxide emissions should be expected.

Interesting relationships between vegetable oil composition and their viscosity and heat content have been developed by Goering et al. (1982). These regressions were developed with data from the twelve different vegetable oils of table 1 and are:

\[
\begin{align*}
(2-1): \text{Visc (mm}^2/\text{sec}) &= -73.14 + 6.409 \text{ WACL} - 3.028 \text{ WADB}^2 ; R^2 = 0.98 \\
(2-2): \text{GHC (MJ/kg)} &= 33.74 + 0.3356 \text{ WACL} - 0.07946 \text{ WABD}^2 ; R^2 = 0.90
\end{align*}
\]

For diesel fuel, the GHC can be calculated by equations 2-3 and 2-4 (Liljedahl et al, 1979):

\[
\begin{align*}
(2-3): \text{GHC(MJ/kg)} &= 42.86 + 0.093 \text{ (API-10)} \\
(2-4): \text{API} &= 141.5/\text{Specific gravity at 15.6°C} - 131.5
\end{align*}
\]

2.1.3. Vegetable oil refining

Vegetable oils can be refined to different stages after they are expelled from the organic materials. One process that was found to be important when using vegetable oils as fuels is the degumming process.

Crude vegetable oil contains small portions of compounds that are not triglycerides. One group of compounds is called phosphatides or gums. Gums are soluble in dry vegetable oil but traces of water are sufficient to precipitate them. This
Figure 4: Typical distillation curve for diesel and corn oil (Goering et al, 1982)
has led to fuel filter clogging and deposit problems in many engine tests (Johansson and Nordstrom, 1982; Borgelt and Harris, 1982; Fuls et al, 1984). This is why most engine tests are now being done with degummed oils. The degumming process consists of adding 1% to 3% water to the oil with or without degumming agents such as phosphoric acid (Wiederman, 1981). The oil is then mixed for 30 to 60 minutes at a temperature of around 65°C to dissolve the fat soluble impurities in water. The water and impurities are finally removed by centrifugation.

Another process of interest is hydrogenation. By this process, the number of unsaturations in the fatty acid chains is reduced by adding hydrogen atoms. Many vegetable oils are hydrogenated before they are used for deep-frying purposes. This is in order to reduce thermal oxidation. Hydrogenation usually reduces the number of C18:2 and C18:3 fatty acids by converting them to mainly C18:1 (Ryan et al, 1984). This process, however, raises the viscosity and the cloud point of the oil which makes their use as a fuel more difficult. But it has been observed that the more saturated fatty acids are better fuels than the highly unsaturated ones (Ryan et al, 1984; Quick, 1980).

2.2. VEGETABLE OIL AS A COMPLETE SUBSTITUTE

As mentioned earlier, the capability of vegetable oils to readily burn in diesel engines was recognized a long time ago. This product available off-the-shelf and offering a potential as diesel fuel seemed attractive to alternate fuel researchers. Naturally, early research efforts were directed towards using vegetable oils as a complete substitute to diesel fuel in a wide range of engine designs and sizes.

Short-term performance studies have shown that vegetable oils burn as efficiently as diesel fuel in both direct (DI) and indirect (IDI) injection engines. Power
curves were much the same with variations both ways. The Brake Specific Fuel Consumption (BSFC) was higher due to the lower heat content of the oils. The smoke levels were generally lower than with diesel fuel.

However, in long-term engine tests, the effect of vegetable oils on durability of the DI engines has been mostly disastrous while IDI engines behaved much better.

2.2.1. Direct injection engine test results

Long-term operation of DI diesel engines when using vegetable oils as complete substitutes to diesel fuel has been ruled out by most researchers. Generally after about 30 hours of engine testing, carbon buildup on fuel injector tips have disturbed atomization to a point where serious power losses forced termination of the tests (Pryor et al, 1983; Fuls et al, 1984). If the injector nozzles were cleaned, operation could usually be resumed and the problem would recur again. Carbon deposits on all parts of the combustion chamber were also severe. Often the deposits on piston lands and in piston ring grooves led to ring sticking, severe cylinder liner scoring and subsequent engine failure.

These problems were generally attributed to the relatively high viscosity of the vegetable oils. Fuel injection systems in modern diesel engines are designed to operate with diesel fuel which is a much less viscous fluid. A difference in spray pattern causing more fuel impingement or wetting of the combustion chamber's wall has been suggested by Ryan et al (1984). Poorer atomization has also been suggested to be partly causing these deposits.

One researcher has obtained encouraging results with fuel pre-heating in an attempt to reduce fuel viscosity and this is examined in the last part of this section. In another paper (Elsbet et al, 1983), the authors claimed that the modifications made
on their engine makes operation on vegetable oil possible with no durability problems. The engine was an Elko model 3.80.92T, 3 cylinder, high speed, turbocharged (TC) and intercooled (IC), 1.4 liter engine. The modifications were quite drastic. The compression ratio has been raised from 14.5:1 to 20:1 in order to provide higher temperature at the end of the compression stroke. This was in order to avoid problems of late ignition thought to be associated with low-cetane fuels such as vegetable oils. They also modified the fuel injection system. Individual fuel injection pumps, one for each cylinder, were located in the cylinder head and driven by the overhead camshaft. This has been done in order to provide fuel heating, thus reducing viscosity, and fuel independent lubrication of the pumps. A single jet pintle injector was substituted to the multi-jet needle injector because of the self cleaning action of the pintle nozzles noticed by many other authors (Borgelt and Harris, 1982; Ryan et al, 1984). The problem of sticking rings and lubricating oil dilution was solved by designing a special piston. This piston butts against the liner just above the top ring and has a clearance of less than 1/1000 of the bore in the top land. Substantial cooling of such a piston was, however, required in order to avoid seizing and this was achieved by increased oil cooling. The engine had no conventional cooling system and was entirely oil cooled. Unspecified engine testing has been done with vegetable oil and deposits, blowby and lubricating oil dilution were reported to be comparable to those obtained when burning diesel fuel. Fuel consumption was about 12% higher than with diesel fuel and less smoke and combustion noise were also observed.

It was believed by some researchers that deposits are more substantial on a hot injector tip than on a cool one. Some injector tip cooling tests were done and there was indeed a reduction in injector coking. Van der Walt and Hugo (1982) have judged the reduction to be not worthy of the modifications to the fuel system. Fuls
et al (1984) have reported that cooling injector tips to 80°C on a Perkins 4.236 l DI engine has prevented injector coking when burning degummed sunflower oil. However, they also reported that 1.5 kW of cooling for each injector had to be supplied which was quite substantial.

In light of all these experiments, most researchers have ruled out the use of vegetable oils as long-term fuel for unmodified direct injection diesel engines.

2.2.2. Indirect injection engine test results

The production of IDI engines is now limited to small automotive engines and a few industrial or farm engines. It is relatively easy to install safe and relatively fool-proof cold starting aids in these engines and this is why they are still preferred by automobile manufacturers. Small diesel engines still use this system mainly because direct injection is a little bit more expensive and also because the fuel consumption of these engines is very small to start with.

In this type of engine, the injection and combustion of the fuel occur mostly in a pre-combustion chamber or in a swirl chamber for the latest designs. These chambers are situated in the cylinder head where a relatively high heat transfer takes place between the hot combustion gases and the chamber walls which are kept relatively cool. Pumping losses also occur when the compressed air is forced in the chamber as well as when the combustion gases are expanded back into the cylinder. These two factors, among others, make the IDI engine less fuel efficient than the DI engine. In a direct injection engine, the injection and combustion take place inside the cylinder, often in a cavity in the top of the piston. This cavity is relatively well insulated compared to pre-combustion or swirl chambers and the heat transfer between the combustion gases is smaller making more energy available for expansion work. This
is why D.I. engines are inherently more efficient and consequently their market penetration in the past twenty years so large.

However, IDI engines are more tolerant to a wider range of fuels (Liljedahl et al, 1979). This may be why the use of vegetable oils has proven to be less detrimental to these engines than to DI engines.

In South Africa, encouraging results have been obtained when using degummed sunflower oil (Fuls et al, 1984). A Deutz F3L912W engine has completed the 1300 hour manufacturer's duty cycle with no fuel related problems. Results were such that Deutz Engines is now honouring their factory warranty on the 912W engine when burning degummed sunflower oil. The same authors have also run successfully a Hatz E89G IDI engine for more than 1600 hours as well as a Perkins 3.152 l engine for 300 hours. Testing was in progress for these engines and preliminary results were also good.

However, engine testing results when using blends of vegetable oils with diesel fuel were sometimes not as good as will be seen in the next section.

2.2.3. Importance of engine design

The different behavior of vegetable oils as fuel in DI engines compared to IDI engines stresses the role of engine design. It was also discussed that some modifications to an existing DI engine allegedly led to acceptability of these alternate fuels for this class of engines. However, these modifications would be too prohibitive to do after the actual engine is built and it seems that if one wants to use vegetable oils as complete substitutes to diesel fuel, the IDI engine would be a better choice. Fuel consumption would be higher than with a DI engine of the same power. Nonetheless, it could be argued that short of being state-of-the-art technology, the
IDI can, however, be qualified as appropriate technology for using these oils as fuels.

Direct injection engines are here to stay because of their inherent efficiency advantage. A lot of research has been done on trying to adapt the vegetable oils to these engines and results have sometimes been excellent as we shall see in following sections.

2.2.4. Durability problems, some hypotheses

The problems encountered when using vegetable oils as fuels are mostly related to durability. Three different theories have been put forward by many researchers and they were synthesised by Ryan et al (1984). They are: (a) the high viscosity of vegetable oil degrade the atomisation of the fuel by the injectors thus causing the durability problems; (b) the durability problems come from the chemical structure of the oils which in turn modify the combustion chemistry; (c) the durability problems result from the incomplete combustion, either induced by the spray characteristics or chemically, and the subsequent reaction of the fuel and combustion products on the metal surfaces and in the lubricating oil. Most researchers have indicated that the high viscosity of vegetable oils is the most important factor controlling the durability problems.

In light of this, the trend of the research has been towards reducing the oil viscosity before injection in the combustion chamber. To achieve this goal, many solutions have been proposed and investigated, they are: (a) heating the oil to a temperature where the viscosity becomes near that of diesel fuel; (b) mixing the oil with petroleum fuels, mostly diesel fuel; (c) modifying the chemical structure of the oil with processes such as transesterification with an alcohol or thermal cracking; (d) creating hybrid fuels which are microemulsions of vegetable oil with two alcohols and
Engine testing results with the last three schemes will be examined in the next sections but since the first method involves the use of unmodified vegetable oil it will be examined here.

2.2.5. Reducing viscosity by heating

Short-term tests on two similar Caterpillar model 3306, 6 cyl., 10.2 litre and turbocharged engines were conducted (Ryan et al, 1984). One engine had DI while the other had IDI. The authors made some extensive injection characteristics studies with a special bomb fitted with a fuel injector and a high-speed camera. They found that at 145°C, the four vegetable oils studied (soybean, cottonseed, sunflower and peanut oil) displayed injection spray pattern and penetration similar to diesel fuel at 40°C.

During the engine tests, the fuel injection pump temperature was maintained at 145°C. Statistical analysis of the data revealed a tendency for injector coking in the D.I. engine but not in the IDI engine. When deposits occurred, the composition of vegetable oils was found to be a factor related to the amount of these deposits. For example, the higher the degree of unsaturation in the oil, the larger the amount of deposits.

Long-term testing would be required before any conclusions could be drawn. Major modifications to the fuel system were necessary to insure that the oil at the injector was hot enough and this is why this avenue has not been explored much in the past.
2.3. VEGETABLE OIL / DIESEL FUEL BLENDS

Blending diesel fuel with vegetable oils is a simple way to reduce viscosity of the oil. Triglycerides and diesel fuel are totally miscible and a mixture of the two has a viscosity somewhat intermediate. However, the availability of petroleum-derived fuels is still a constraint and the vegetable oil is then used as a fuel extender and not a fuel substitute. Such a fuel extender may be all that is needed in times of fuel shortages or high petroleum prices. Research has been done in order to see the durability effect of using these blends in actual engines.

2.3.1. Direct injection engine test results

The results of long-term engine tests when using blends of vegetable oil with diesel fuel are almost equally divided between success and failure. As a general rule, and as could be expected, the problems encountered are proportional to the amount of vegetable oil in the blend. The limit at which durability problems rule out the use of a blend seems to be around 20% vegetable oil.

Tests with 10% peanut or cottonseed oil (Mazed et al, 1985) have been successful with a small DI Lister model LT1. The engine completed the Engine Manufacturers Association (EMA) 200-hour preliminary screening test. This test procedure has become almost a standard when testing vegetable oil-based fuels and is described in detail in the chapter on Materials and Methods. In another work, a John Deere 6 cyl., TC, 404 cu. inch engine ran on a blend of 1/3 soybean oil with 2/3 diesel fuel for 600 hours, including 200 hours of EMA testing (Adams et al, 1983). The authors were satisfied with the results and recommended such a blend for long term use. In Sweden, Johansson and Nordstrom (1982) have conducted field tests of a blend containing 1/3 crude rapeseed oil with 2/3 diesel fuel. The blend was tested in
6 different farm tractor engines. The engines were all DI, some were turbocharged. They were operated in normal farm utilisation from 300 to 1200 hours. Carbon deposits were observed on cylinder heads, pistons, rings and valve tulips. The fuel filters had to be changed more often in cold weather. However, the engines operated satisfactorily and field testing was continued in order to accumulate more data on durability.

A three-year field testing programme has been completed recently in the U.S.A. by Kaufman et al (1986). The testing was done on four J.D. 6 cyl. D.I. engines, two were TC and two were TC and IC. Two 6 cyl. J.I. Case engines were also used. These engines were used to power six farm tractors used in normal field work and were operated for an average of 1200 hours. The fuel used was a blend of 25% sunflower oil with 75% diesel fuel in three of the engines. The other three were fueled with a blend containing 50% sunflower oil. Extensive statistical analysis has been done on the results and has yielded: (a) the engines showed no power loss or increased BSFC over the test period; (b) one engine fueled with a 1:1 blend experienced camshaft and valve train failure at 494, 930 and 1096 hours due to valve sticking caused by deposits on the valve stems; (c) heavier carbon deposits in most areas of the combustion chamber were observed with the 1:1 blend; (d) the brake mean effective pressure (BMEP) of the engines had no apparent effect on the amount of deposits; (e) no injector coking or ring sticking problem occurred, but the top ring groove of all engines had larger amounts of deposits than when the engines burned diesel fuel thus increasing wear of the liners. The authors concluded that none of the blends used could be recommended as a long-term fuel for the engines studied. They suggested that the blend containing 25% sunflower oil could be used as an emergency fuel but then reduced engine life has to be expected.
Other research with a blend containing 20% peanut oil with 80% diesel fuel was done by Goodrum (1983). The engine failed the EMA screening test due to fuel-related problems. Also a 25% blend of sunflower oil failed the EMA test because of severe injector coking, injector needle sticking and compression ring groove filling (Ziewjewski and Kaufman, 1983). A large impingement area was observed in the Allis Chalmers 4 cyl., TC and IC engine. This was attributed to a reduction of the injector nozzle hole size caused by the deposits. In a different research programme, Pestes and Stanislao (1984) have tested a blend containing 50% sunflower oil with diesel fuel. Early engine failure caused by piston ring sticking was experienced. Also a blend containing 50% cottonseed oil failed the EMA test after 183 hours (Fort and Blumberg, 1982). Heavy carbon deposits led to piston ring sticking and severe liner scoring in two of the 6 cylinders of the International Harvester 7.1 liter, TC engine.

From all these results, it seems that a mixture of no more than 10% vegetable oil with diesel fuel is the most that DI engines can accommodate without experiencing durability problems. Recognizing this fact, Caterpillar is now honouring their factory warranty on selected engines operating with 10% vegetable oil in Brazil (Peterson et al, 1983).

2.3.2. Indirect injection engine test results

After seeing that some IDI engines have operated for hundreds of hours on 100% vegetable oils, one would expect that blends of vegetable oil with diesel fuel to perform better. But such is not the case for all the tests performed with these blends as will be seen below.

EMA screening tests with percentages of 10% to 25% peanut oil in a Deutz engine have shown no adverse wear or deposit problems (Mazed et al, 1985). A blend
containing 70% rapeseed oil was used to power a small pre-combustion chamber Yanmar TS70C for 850 hours. The authors (Peterson et al, 1983) observed no adverse wear, oil dilution or deposit problems. However, in a different study by Borgelt and Harris (1982), the fuel injector of a small Onan DJA-3.0 litre, air-cooled engine had to be cleaned after 460 hours in order to restore initial power. This was the only problem encountered in the 1000-hour test with a blend of 50% soybean oil with 50% diesel fuel.

2.3.3. Effect of engine design

As in the case of the use of vegetable oil as a complete substitute to diesel fuel, the IDI engines have performed better than the DI engines. The effect of the type of direct injection engine was also important as some engines behaved better with higher proportion of vegetable oil in blend than other engines fueled with a blend richer in diesel fuel.

2.4. MODIFIED VEGETABLE OILS AS DIESEL FUEL SUBSTITUTE

The primary goal when modifying vegetable oils is to reduce the size of the molecules. Many means of attaining this have been developed. The processes are designed as to break free the three fatty acid chains in the triglyceride molecule.

Research efforts in thermal and catalytic cracking, such as used in the petroleum refining industry have been small mainly because of the costs involved by this extra processing. Most research has been directed towards producing gasoline substitutes but some results with producing fuels similar to diesel fuel have been obtained. An excellent review of literature on this topic has been done by Dykstra and Sorenson (1983). The authors suggested that production of diesel fuel by thermal or
catalytic cracking of vegetable oils might even be economically possible by optimizing certain processes already developed. However, very little engine testing has been done with these fuels and their behavior in long-term use is unknown.

Most of the efforts in modifying the structure of vegetable oils have been directed towards a process called transesterification.

2.4.1. Transesterification of vegetable oils

2.4.1.1. Process

The process is well known and documented and was patented by Trent in 1948. The process requires an alcohol and a catalyst. Methanol, ethanol and butanol are the alcohols that have been commonly used. The catalysts used vary from one research project to the next and they include: H₂SO₄, NaOH and NaOCH₃. The chemical reaction is presented in figure 3.

Three molecules of alcohol are required for each molecule of triglyceride. These fatty acids are primarily 16 or 18 carbon chains and the hydrogen atom at the end of the original fatty acid is replaced by a CH₃ group when methanol is used. It is replaced by a CH₂CH₂ group when ethanol is used and by a CH₃CH₂CH₂ group when butanol is used. The chains freed by transesterification are called fatty acid methyl, ethyl or butyl esters.

A very thorough investigation of the process aimed at fuel production has been done by Freedman et al (1984) and the results are summarised here. They suggested using a molar ratio of 6:1 (alcohol:veg.oil) in order to speed up the conversion. The excess alcohol could be used in subsequent reactions and was therefore not wasted. Either 0.5% sodium methoxide or 1% sodium hydroxide, by weight, were effective
concentrations for the catalyst. At a moderate temperature of 32°C, vegetable oils were almost all converted to esters in 1 to 4 hours. They strongly recommended using degummed as well as dry oils. The moisture content had to be maintained below 0.3% in order not to deactivate the catalyst. The glycerol formed in the process has many industrial uses and they suggested that the cost of the transesterification process could be covered by the sale of the glycerol if suitable markets could be found. The use of anhydrous alcohol was recommended and no difference in terms of conversion efficiency was noticed between the three alcohols used in the project.

The glycerol and remaining alcohol were separated by centrifugation from the esters and the remains of catalyst had to be washed from the esters with water. This last process is costly and cannot be avoided since fuel injector needle sticking has occurred even when small residual amounts of catalyst were present in the ester (Hawkins and Fuls, 1982).

2.4.1.2. Properties of esters of vegetable oil

Some properties of esters of vegetable oil are included in table 3. Their viscosity is much lower than that of the oil from which they originate, almost within the range specified for diesel fuel. Their flash point and density are lowered. The heat content is somewhat higher as well as their cetane rating.

2.4.1.3. Fatty acid esters as fuels

Transesterified vegetable oils are still a 100% renewable resource because alcohols can be produced from biomass. All the advantages of a biomass-based fuel are then preserved.

The transesterification process does not need to be complete if the resulting
product is to be used as a fuel. Many researchers have suggested that a 90% conversion of the triglyceride molecules to esters in blend with 10% unreacted or partially reacted vegetable oil is acceptable (Hasset, 1983; Hawkins and Fuls, 1982). Such a mixture can be obtained faster and with a smaller molar ratio of alcohol to triglyceride than the reaction leading to almost complete conversion.

2.4.2. Direct injection engine test results

Long-term durability testing with esters of vegetable oil has produced much better results than when using neat vegetable oil.

In South Africa, where petroleum resources are scarce, extensive engine testing using ethyl ester of sunflower oil has been done by Fuls et al (1984). A 4.236 litre Perkins DI engine has operated more than 1500 hours on the suggested manufacturer's duty cycle. The engine has run without problems and was emitting less smoke and had a higher brake thermal efficiency than when operating on diesel fuel. Lubricating oil monitoring and analysis showed wear rates to be normal or below normal. At the completion of the duty cycle, the engine was disassembled and inspected by factory experts and declared to be in exceptionally good condition. Subsequently, the manufacturer of Perkins diesel engines in South Africa, Atlantis Diesel Engines, declared that they would honour their normal factory warranty on engines burning sunflower ethyl ester as soon as this fuel is commercially available.

Kaufman and Ziejewski (1984) have completed the 200-hour EMA preliminary screening test using a Ford, 4 cyl., TC and IC engine. The fuel used was methyl ester of sunflower oil. Test results showed no deterioration in engine performances or in the fuel injection system. However, some lubricating oil dilution forced more frequent oil changes than suggested by the engine manufacturer. At the end of the
test the engine was disassembled. Less wear and fewer deposits than if the engine had been fueled with diesel were observed. Little carbon on the injector tips was also noticed. The brake specific energy consumption was the same as with diesel fuel and the smoke level was lower.

In New-Zealand there is a surplus of tallow (animal fats) produced. It has been calculated that as much as 12% of the national diesel fuel consumption could be replaced by tallow esters if all exports were diverted to fuel production. Sims (1985) has begun testing blends of 12% tallow esters with 88% diesel fuel. Short-term engine tests were done using a 3.8 l, 4 cyl. Ford engine. The results were reported to be good. Tallow is very saturated compared to vegetable oils and its melting point is around 50°C. This is why a blend with diesel fuel has been investigated.

In another project, a blend of 90% esterified sunflower oil with the remaining 10% composed of partially reacted oil has been tested in a Lister, LT-1, single cylinder D.I. engine (Hasset, 1983). The engine was run at constant speed and load for 100 hours and it was observed that the alternate fuel had the same tendency to foul injectors as diesel fuel.

In Brazil, Volkswagen do Brazil has conducted field tests on a MWM 6 cyl. 5.9 liter, DI engine in normal delivery truck service (Pishinger et al, 1983). The truck was operated for over 130000 km on soybean oil esters. The recommended 5000 km lubricating oil drain interval could not be achieved with the stock engine due to oil dilution problems. However, by simply changing the dimension of the injector holes, lubricating oil dilution by unburned esters could be reduced to acceptable levels. The authors suggested that this modification improved the spray characteristics of the injectors to a point comparable to the stock injector used with diesel fuel. With the original injectors, a maximum of 30% ester blended with 70% diesel fuel could be
used with the same result.

2.4.3. Indirect injection engine test results

Little research has been done on the use of esters of natural fats in I.D.I. engines. This can be attributed to their relative compatibility with unmodified vegetable oils. Pishinger and Falcon (1982) had a 1.6 liter Volkswagen automotive engine complete a 1400-hour duty cycle using methyl ester of soybean oil. 1000 hours of the test were at maximum power and 300 hours at maximum torque. A similar engine installed in a car has also operated for more than 40000 km. No fuel related problems were observed in either engine.

2.4.4. Problems associated with esters of vegetable oils

One major problem is the relatively high cloud point of the esters. Cold weather utilisation would require heating of the fuel tanks.

Esters have also been shown to harden plastics and rubber. However, no problems have occurred to date with the rubber seals used in fuel injection systems. Fuls et al (1984) reported that all seals in the CAV fuel injection system installed on their engine did not show any deterioration after more than 1000 hours of testing with ethyl ester of sunflower oil. Natural rubber seemed to be the most affected.

The esters removed paint like a paint stripper and a resistant paint could not be found (Fuls et al, 1984). All metals showed negligible corrosion when the ester fuels were free of water.

Slight design changes can make a big difference in the use of these fuels as long-term substitutes to diesel fuel in DI engines and very few researchers have tried to make their engine fit the fuel. When fuel-related problems occurred, most research
was directed towards trying to fit the fuel to the engine.

2.5. HYBRID FUELS

Another way of reducing the viscosity of vegetable oils is by creating microemulsions of vegetable oils with two alcohols and water or with one aqueous alcohol and diesel fuel. These alternate fuels have been developed especially for their use in DI engines which have shown durability problems related to the high viscosity of the oils.

Ziejewski and Kaufman (1984) have tested a microemulsion containing by volume: 13.3% of 190 proof ethanol (5% water), 33.4% of 1-butanol and 53.3% of sunflower oil. In these proportions, the emulsion was reported to be stable. An Allis Chalmers model 4331, 4 cyl., TC, IC with D.I. has completed the 200-hour EMA test cycle. However, heavy carbon deposits on piston lands, in the piston ring grooves as well as in the intake ports were noted. Erratic sticking of the injector needles and significant lubricating oil dilution attributed to incomplete combustion were also observed. The authors concluded that this fuel could not be recommended as a diesel fuel substitute.

Another 200-hour EMA test cycle was done using a fuel containing by volume: 50% diesel fuel, 25% soybean oil, 5% of 190 proof ethanol and 20% of 1-butanol (Goering and Fry, 1984). The engine used was a 6 cyl. 3.589 litre TC John Deere engine with DI. Deposits on injector tips led to a significant power loss after the 200 hours. The possibility of using this fuel as a diesel fuel substitute was also rejected by the authors.

Hybrid fuels do not seem to have very good potential as a fuel even if their viscosity is near that of diesel fuel.
2.6. WASTE VEGETABLE OIL RESEARCH

Very little research has been done on the use of waste vegetable oils as fuel for diesel engines. They have nonetheless a distinct advantage over their new oil counterpart in that they are much less expensive, often free to the persons who collect them. The product coming out of the food industry's fryers is not as clean as the new oil and some filtration in inevitable.

One of the few reports on long term use of waste vegetable oil is by Fishinger et al (1981). They used a blend of 20% waste frying oil with 80% no. 1 diesel fuel (by weight). The oil was collected from the campus kitchens and was based on hydrogenated soybean oil. They used a Detroit diesel 6V-71, two stroke, 426 cubic inch engine installed in a campus bus. The bus was operated for 15600 km during a school year. Slightly higher smoke levels were measured at all loads and were attributed to a poorer atomisation of the fuel. Fuel filter clogging was a problem when the temperature dropped below −7°C. No difference in performances and fuel consumption was noticed. After tear down of the engine, deposits were found to be not excessive which was surprising because the engine idled for long periods of time in normal daily operation. No piston ring sticking or injector coking was observed.

Some work on transesterified waste frying oil was reported by Nye et al (1983) and preliminary engine testing with a DI engine has been successful.

Since the price of waste vegetable oil is very low, using the oil as a fuel extender is worthwhile and more research is needed in order to find the optimum blend that can be used in both DI and IDI engines. Blending is necessary if the oil is to be used without modification because the pour point of these oils is usually very high, typically room temperature.
3. MATERIALS AND METHODS

3.1. EXPERIMENTAL EQUIPMENT

Prior to this research, no engine testing facilities were available at the department of Bio-Resource Engineering. Limited funding was also available for the project. An engine test bed, instrumented for the purpose of this research, as well as an electronic engine controller were then built by the author. This apparatus is described in detail here.

3.1.1. Engine

The engine selected for the fuel tests was a small single cylinder, water-cooled, IDI (swirl-chamber) Yanmar model TS60C. The technical specifications are available in table IV.

This engine was chosen for many reasons. The first being the relatively low cost of its purchase, operation and maintenance. The sturdy cast-iron block and cylinder head design, as well as the removable liner were also considered to be important. The relatively slow speed and water cooling ensured a low noise level which was important since the engine test cell was located near a study area.

As seen in the literature review, IDI engines have had less durability problems when using unmodified oils as fuels than the DI engines. It was logical to infer from earlier results of engine testing with new vegetable oil and assume that waste vegetable oils would behave similarly. Thus a larger proportion of waste vegetable oil blended with diesel fuel could probably be used in an IDI engine than in a DI engine.

IDI engines have a higher Brake Specific Fuel Consumption (BSFC) than DI engines. However, if more waste vegetable oil could be used in a blend with diesel
Table IV: Test engine specifications.

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine make:</td>
<td>Yanmar</td>
</tr>
<tr>
<td>Engine model:</td>
<td>TS60C</td>
</tr>
<tr>
<td>Type of engine:</td>
<td>4 cycle horizontal</td>
</tr>
<tr>
<td>No. of cylinders:</td>
<td>1</td>
</tr>
<tr>
<td>Bore x stroke (mm):</td>
<td>75 x 75</td>
</tr>
<tr>
<td>Displacement (l):</td>
<td>0.331</td>
</tr>
<tr>
<td>Continuous rating output (HP/rpm):</td>
<td>5/2000</td>
</tr>
<tr>
<td>1 hour rating output (HP/rpm):</td>
<td>6/2400</td>
</tr>
<tr>
<td>BSFC (g/HP-h):</td>
<td>210</td>
</tr>
<tr>
<td>Compression ratio:</td>
<td>23.1</td>
</tr>
<tr>
<td>Combustion system:</td>
<td>swirl chamber</td>
</tr>
<tr>
<td>Lubrication system:</td>
<td>forced with trochoid pump</td>
</tr>
<tr>
<td>Cooling system:</td>
<td>water condenser</td>
</tr>
</tbody>
</table>
fuel in IDI engines, the energy substitution of waste vegetable oil would be higher than in DI engines. If this substitution is much larger in IDI engines, it could offset the BSFC disadvantage of IDI engines in terms of diesel fuel burned per unit of energy produced.

3.1.2. Engine Dynamometer

The engine dynamometer was a DC generator from a discarded welding unit. This generator was modified for the purpose of the research. The generator load was a fixed resistor cooled in a water bath. At a given speed, the current flowing through this resistor could be varied by changing the generator field current intensity. Three autotransformers as well as a rectifying circuit were used for this purpose. A variation in the field current would indirectly vary the torque necessary to turn the armature at a given speed and thus the load on the engine.

The generator was linked directly to the engine by a flexible coupling. The body of the generator was mounted on bearings concentric with the armature shaft bearings and thus the torque reaction on the generator could be measured directly.

3.1.3. Measuring Equipment

The engine torque was measured on the generator frame using a one metre long arm and a laboratory scale. The scale arm had enough inertia as to dampen vibrations and thus make measurements accurate 0.01 N.m.

The engine speed was monitored electronically to the nearest 5 RPM. The circuit and equipment used to achieve this is described later in the section on the engine controller.
The fuel consumption was measured by gravimetric method. The time required to burn 200.0 g of fuel was recorded.

Atmospheric conditions data were also collected because the BSFC was to be corrected according to SAE standard no. J1349 (June 1983). The dry air temperature as well as the wet bulb temperature were measured in the intake stream of air less than 1 cm from the air filter. The barometric pressure was obtained from Environment Canada's hourly measurements at sea level at Vancouver International Airport less than 6 km away and corrected for the altitude of the test bed.

3.2. FUELS TO BE TESTED

According to the EMA recommendations, a fuel test series should include a 200-hour baseline test of the engine using diesel as the test fuel followed by the 200-hour runs of the alternate fuels to be tested. Alternate fuel testing should be started using the fuel least likely to cause engine damage and following with fuels more likely to cause engine damage.

3.2.1. Diesel fuel

Commercial grade number 2 diesel fuel, marked for off-road use was used in this research as a baseline fuel as well as in the blends to be used as alternate fuels.

The properties of the fuels were determined at a private laboratory and are reported in the results section. The same lot of diesel fuel was used throughout testing.
3.2.2. Waste vegetable oil

The waste vegetable oil used in the blends was obtained from deep fryers of the University kitchens. The waste oil was collected from the same fryer every week for uniformity reasons. After collection, the oil was stored at about 10°C until its utilization. At this temperature the oil was solid. The oil was not filtered until after it was blended with diesel fuel because of its relatively high viscosity at room temperature.

The vegetable oil used was a liquid frying shortening. It contained 100% hydrogenated vegetable oil to which the antioxidant BHT and antifoaming agents were added. The fatty acid content by gas chromatography was determined and appears in table IX.

3.2.3. Alternate fuel blends

Two blends of waste vegetable oil with diesel fuel were selected as alternate fuels. Blends of diesel fuel with waste vegetable oil were easy to make but a mixture of about 40% (by weight) in waste vegetable oil with 60% diesel fuel was cloudy at room temperature. It was arbitrarily decided to use a blend of 20% waste vegetable oil with 80% diesel fuel as our first alternate fuel and if the results were good, we would use a higher percentage.

Following the test with 20% waste oil, results were such that a much higher proportion of oil in the blend was to be used in the next run. For ease of mixing, a blend of 1:1 was selected. However, this blend was cloudy at room temperature and in order to avoid fuel filter clogging problems, it was decided to heat the fuel tank to about 35°C where the blend was not cloudy.

After mixing the raw waste vegetable oil with diesel fuel, the blend was
passed through a screen strainer in order to remove particles of food present in the oil. No further processing was done on the fuel blend before its introduction in the fuel tank.

Properties for the two blends along with those of the diesel fuel are reported in table VIII.

3.3. ENGINE TESTING

3.3.1. EMA durability screening test

Alternate fuel research with vegetable oils had been going on for many years and studies were found to be of limited value because the conditions and procedures were unique to each experiment. In 1982, at the request of the USDA, the Engine Manufacturers Association (EMA), an association of 21 international engine manufacturers, proposed a test procedure. This 200-hour preliminary durability screening test was designed to assess the potential impact on diesel engine durability of using vegetable oil-based alternate fuels (EMA, 1982). The test was designed in a way as to initiate durability problems in a reasonable amount of test time. This was done in order to eliminate some unsuitable fuels rapidly.

Since its publication, this test procedure has been followed in most related research projects and has become almost a standard. The engine test cycle used in this research was also tailored after the EMA recommendations which are available in the appendix.
3.3.2. Engine test procedure

For each fuel tested, a number of operations had to be done either before, during or after the test.

3.3.2.1. Engine disassembly

Before the first EMA 200-hour test and after every test, the engine was disassembled in order to measure the wear of certain parts and the deposits in the combustion chamber.

Each test was commenced with new piston rings and a honed cylinder liner. Dimensions of the liner, piston rings, piston skirt, valves and connecting rod bearings were measured before and after each fuel test. The weight of these parts was also recorded in order to better quantify the wear as well as to evaluate the carbon deposits. The fuel injector was tested for opening pressure as well as for spray characteristics after each fuel test.

3.3.2.2. Lubricating oil

A high detergent SAE classification CD oil was used throughout the fuel test. The 100-hour oil change interval suggested by the engine manufacturer was respected. The oil used was of a SAE viscosity classification 30. Oil samples were taken at 0, 50, 105, 150 and 201 hours for each fuel test and they were analysed for viscosity as well as for wear metal concentrations. A record of lubricating oil consumption was kept for all of the fuels tested. The oil change was done at 105 hours for convenience and to avoid stopping the engine after 10 hours in the seventh day of testing.
3.3.2.3. Engine break-in

Every time the engine was reassembled, it was broken-in with diesel fuel according to the EMA procedure shown in table V.

3.3.2.4. Fuel consumption tests

At least twice a day, the BSFC was measured at two different load and speed settings. One at maximum speed (step 1 in EMA cycle) and one at maximum torque and 85% speed (step 2 in EMA cycle).

3.3.2.5. EMA test cycle

The test cycle used was identical to the one suggested by the EMA. This test cycle lasted 3 hours during which the load and speed of the engine were changed four times as in table VI.

For the Yanmar TS60C engine used in this research, the testing conditions were as shown in table VII.

The continuous power curve for the engine was used because the EMA cycle has two consecutive hours of maximum torque or power. Using the one hour rating curve of the engine would thus have overloaded it. On the other hand, previous engine tests with vegetable oil have shown that carbon deposits problems are accelerated at part load or idle operation. Not operating the engine at its absolute rating would then cause more deposits and thus make the durability problems surface faster.
Table V: Engine break-in procedure (EMA, 1982).

<table>
<thead>
<tr>
<th>STEP</th>
<th>SPEED</th>
<th>POWER</th>
<th>MINUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low idle</td>
<td>idle</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>1/2 rated</td>
<td>idle</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>3/4 rated</td>
<td>1/2 rated</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>rated</td>
<td>rated</td>
<td>55</td>
</tr>
</tbody>
</table>

Table VI: EMA test cycle (EMA, 1982).

<table>
<thead>
<tr>
<th>STEP</th>
<th>SPEED</th>
<th>POWER</th>
<th>TORQUE</th>
<th>MINUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rated</td>
<td>---</td>
<td>Rated</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>85%</td>
<td>Max.</td>
<td>95%</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>90%</td>
<td>28%</td>
<td>25%</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Low idle</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

Table VII: Testing conditions for the engine.

<table>
<thead>
<tr>
<th>STEP</th>
<th>SPEED (rpm)</th>
<th>TORQUE (N.m)</th>
<th>POWER (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>17.46</td>
<td>3.66</td>
</tr>
<tr>
<td>2</td>
<td>1700</td>
<td>17.27</td>
<td>3.07</td>
</tr>
<tr>
<td>3</td>
<td>1800</td>
<td>4.81</td>
<td>0.91</td>
</tr>
<tr>
<td>4</td>
<td>850</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
3.3.2.6. 200 hour durability screening test

Five consecutive test cycles were run every day without stopping the engine. The fifteen hours of running were followed by a 9-hour cold shut down. In a few instances, the engine was not operated the following day and this was still in accordance with the EMA recommendations.

Each durability test was run 201 hours. The extra hour was included in order to avoid stopping the engine immediately after it ran for one hour at maximum torque in step 2 of the 3 hour cycle.

3.4. ENGINE CONTROLLER

3.4.1. Purpose and Objectives

In order to follow the EMA test cycle described in section 3.3.2.5, an automatic controller had to be built for the test engine. It eliminated the need for an operator to be available fifteen hours a day in order to change speed and torque settings four times every three hours. This controller also provided a means of measuring engine speed accurately for Brake Specific Fuel Consumption (BSFC) studies.

For budgetary reasons, the controller had to be relatively inexpensive. It also had to be reliable as well as easy to trouble-shoot and repair. Maximum use of the resources and equipment available in the department was a must in order to keep costs down. Without using state-of-the-art technology, a controller meeting the requirements was built by the author prior to the engine testing phase.

The controller was tested for 100 hours before it was used to control the test engine. It has subsequently been used to control the test engine for more than 800 hours and has operated without any problems.
The theory of operation as well as schematics of the circuitry of the controller are described in the following paragraphs.

3.4.2. Equipment available

1. Frequency Meter: Monsanto Instruments model 101A.
2. Four outlet Programmable Timer: Chrontrol model CD-03.
3. 200 steps/turn stepping motor: Superior electric model MO93-FD07.
5. Power supply for the motor: Power One model HE24, 24V, 6A.
7. Well equipped machine shop.

3.4.3. Overview of the controller

A block diagram of the controller appears at figure 5. The elements of this diagram are described in the following paragraphs.

The heart of the controller was based on a digital logic circuit. Such a circuit was chosen for many reasons: (1) the frequency meter used to monitor the engine speed had a Binary Coded Decimal (BCD) output; (2) handling numbers in BCD is simple and convenient and a lot of BCD logic hardware is available off-the-shelf at relatively low cost; (3) changing a reference number is as easy as setting small Single Pole Single Throw (SPST) switches open or closed, which makes programming the controller easy.
Figure 5: Block diagram of the engine controller

Figure 6: Frequency generator
3.4.4. Engine speed measurement

Measuring the engine speed was necessary for both data acquisition as well as a feedback for the controller. It was made possible by the use of a simple frequency generator and of the frequency meter.

3.4.4.1. Photoelectric frequency generator

A simple linear frequency generator was built and its circuit appears at figure 6. A thin metal disk slotted at regular intervals on its circumference was attached to the engine crankshaft. The infrared emitter diode was positioned on one side of the disk while the detector diode was on the other side.

The rotation of the disk caused the beam to be cut at regular intervals. This in turn caused the voltage drop across the resistor on the detector to vary with a frequency equal to the infrared beam interception frequency. Since the slots on the disk were equidistant, the frequency of the voltage drop across the resistor was varying linearly with the disk rotational speed and thus the engine speed.

3.4.4.2. Speed measurement

The frequency of the photoelectric frequency generator was measured with the frequency meter (Monsanto Electronic Instruments, 1968). By cutting 60 slots in the disk circumference, the readout in hertz (hz) on the meter was equal to the engine speed expressed in RPM. After observing the engine's governor response to minute load variations as well as its accuracy, it was decided that controlling the engine speed to the nearest 10 RPM was the best that could realistically be achieved in order to avoid hunting. The hunting was due to minute inevitable load variations, governor instability and feedback lag.
In the hz/10 mode, the frequency meter reading was in RPM/10 and more than 2 readings per second were generated by the meter. Before a reading is available at the BCD outlet of the meter, a print signal is generated by the meter. This feature enabled us to efficiently transfer the frequency meter reading to the rest of the control circuit.

3.4.5. Latching of the speed reading

In order to make the latest RPM reading generated by the frequency meter available for decision making, some form of short-term memory was required. A simple CMOS device was available to perform this task: the 4042 Quad Latch (Lancaster, 1980). Each 4042 chip can latch four bits of information and thus three chips were used to latch the three BCD four bit words representing the three digits of the RPM reading. A value from 0 to 999 could then be stored.

The print signal from the frequency meter was fed to the three latches and every time this signal dropped to logic 0, the value of the bits at the output ports of the meter were stored and available at the output ports of the latches until another value of the RPM was measured by the meter. At any time, the value of the most recent RPM was used for decision making. The breadboard circuit of the logic part of the controller appears at figure 11 and shows how the latches are related to the rest of the circuit.

3.4.6. Step motor control

A stepping motor was used to vary the speed of the test engine. A worm screw rack-and-pinion drive was built and fitted to the motor in order to convert rotational movement to linear movement. A flexible cable linked the rack to the
governor spring. The stepping motor, by turning one way, would increase the tension in the spring which in turn caused the governed speed of the engine to increase. Turning the other way obviously led to an opposite result.

The stepping motor had 200 steps per turn and the rate of stepping as well as the direction of rotation was controlled via a translator module (Superior Electronic). To obtain a step in one direction or the other, an external signal had to be provided to the translator. Any signal going from logic 1 to logic 0 applied to the clockwise input port caused the motor to step one step in the clockwise direction. A similar signal applied to the counterclockwise port caused the motor to step in the other direction. The stepping rate was equal to the rate at which the input signal dropped from logic 1 to 0. A square wave of a certain frequency would then cause the motor to step at the same frequency in a direction given by which port the signal is applied to.

By varying the signal frequency, it was possible to vary the speed of rotation of the stepping motor and thus the response of the controller.

3.4.7. Semi-proportional control

A semi-proportional, or step-wise, control of the engine speed was relatively simple to design using simple BCD comparators. The 7485 Magnitude Comparator was selected for this purpose (Lancaster, 1981). This comparator can compare the magnitude of a 4 bit word (a single decimal digit in BCD form), and give three different results: A>B, A=B or A<B; where A is the BCD representation of the measured RPM and B is the setting to be achieved by the controller. Since the data to be handled had three decimal digits, three comparators were necessary. From the results of these three comparators, it was easy to design a three speed semi-proportional
control of the stepping motor for both stepping rate and direction.

These three speeds were selected by trial and error. It was found that a rate of 100 steps/sec was sufficient to ensure a fast response in the engine speed. On the other hand, a rate of 3 steps/sec was good for fine adjustments while a 30 steps/sec rate was a good intermediate speed. These three stepping speeds were obtained by generating three square waves of corresponding frequencies. Three 555 TTL timers in astable mode were used as square wave generators, the frequency of a timer could be easily adjusted by a trim potentiometer.

The semi-proportional control circuit in logic form is displayed at figure 7. The logic of the circuit can be easily followed and is left to the reader. The circuit generates a high stepping rate in the right direction if the actual RPM digit for the hundreds is different from the setting. It generates an intermediate stepping rate if the hundreds digit of the actual RPM is equal to the setting but the decade digit is different. It finally generates a low stepping rate in the right direction if only the unit digit of the RPM differs from the setting.

3.4.8. Speed setting selector

The RPM setting value for each step of the engine test cycle had to be made available for decision making to the comparators. This was facilitated by a feature of the 7485 comparator: every input that is not exactly logic 0 is taken by the comparator as being logic 1. Thus we only had to provide a logic 0 signal for all the bits that had a logic 0 value leaving the other bit inputs floating. The setting could be modified by opening or closing an SPST switch for every bit of the three BCD digits of each of the four different settings, in total 48 switches. The outlet of the 4 switches corresponding to the same bit for the four different settings were
Figure 7: Semi proportional speed control

Figure 8: Speed setting selector
connected in parallel while the input side of the switches needed only be isolated by diodes. Referring to figure 8, we can see that a logic 0 at the diodes of a switch battery makes the setting programmed in these switches appear in BCD form at the input ports of the comparators as long as a logic 1 signal is applied to the diode input side of the three other switch batteries.

The load and speed cycle suggested by the EMA consists of four speeds and four loads, one of these loads being zero. The programmable timer available for this research provided only four 115 VAC time controlled relay outlets. Three of these outlets were used for the three non-zero generator field current settings while the fourth outlet was used for the engine shut-off circuit. To render the programmable timer output compatible with the engine controller circuit, a logic output was added to the timer for each of the four relay outlets. The speed setting selection was accomplished by using these logic signals from the timer in this fashion:

setting 1 = 1 . 4
setting 2 = 2 . 4
setting 3 = 3 . 4
setting 4 = 1 . 2 . 3 . 4

Since a logic 0 was needed to activate the proper switch bank, the logic was inverted. Figure no. 8 shows the logic circuit of the speed setting selector. All the necessary circuitry was provided by one 4069 Hex Inverter, one 4011 Quad NAND Gate and one 4012 Dual 4 Input NAND Gate. One 4050 buffer was also used because the CMOS gates were not compatible with the TTL comparator 7485.
3.4.9. Engine load selector

Since the load settings were fixed, it was assumed that a feedback control on the torque would not be necessary since at a given engine speed, the torque reaction on the generator frame is the only function of the field current. Three field current intensities were produced for the three different non-zero load settings of the EMA test cycle. Figure 9 shows the circuit used to achieve this.

Three 115 VAC outlets of the programmable timer were used as a source for the three field current settings. The field current settings were produced by autotransformers and rectified. Isolation of the three autotransformers was done by using double pole single throw (DPST) relays. The solenoid of each relay was activated by the corresponding 115 VAC outlet of the timer while the power for the selected autotransformer came from outlet no. 4 of the timer. No. 4 outlet was energized for the duration of the 15-hour test day and its deactivation at the end of each day prevented current from flowing through the field circuit of the generator as well as provided a way of stopping the engine.

3.4.10. Engine shut-off circuit

The test engine was equipped with an automatic shut-off. Figure 10 shows the circuit used to stop the engine at the end of each test day as well as in the event the oil pressure dropped too low.

3.4.11. Operation

When in operation, new speed settings were achieved in less than 45 seconds. However, due to the peculiarities of the semi-proportional control used, settings with the unit digit of value 0, for example, 200, 180 or 170 for 2000, 1800 or 2000 RPM
Figure 9: Load selector

Figure 10: Shut-off circuit
were hard to maintain without hunting, especially the 200 setting. An RPM reading of 199 for the setting 200 caused the stepping motor to rotate at 100 steps/sec to increase the speed and would overshoot the setting by over 20 rpm. Subsequent decrease of the speed from 202 to the 200 setting would take a relatively longer time since the stepping rate would then be at 3 steps/sec. To avoid this problem, the settings were modified slightly to 201, 181 and 169 instead of the original settings. Since these modified settings were used throughout engine testing and differ by less than 1% from those suggested by the EMA cycle, it was assumed that the effect on the results would be negligible.

The most recent engine speed measurement by the frequency meter was available continuously on a 3 digit Light Emitting Diode (LED) display. Proper operation of the controller could be verified by comparing the frequency meter reading with the value on the controller. Two LED's were used to visually check the stepping rate and direction of the stepping motor.

A regulated 5 VDC power supply was built in the circuit so that it could be powered by external 115 VAC. The entire circuit of figure 11 was mounted on a breadboard plate and most of the connections were wire-wrapped. The whole circuit was fitted in an aluminium box with the proper input and output ports.
Figure 11: Breadboard circuit of the engine controller
4. RESULTS AND DISCUSSION

4.1. FUEL ANALYSIS

The fuels tested in the engine were analysed for a selected number of physical and fuel-related properties. The results of the analysis are presented at table VIII.

As expected, the waste vegetable oil blended with diesel fuel made the alternate fuels more viscous as its proportion went up in the blends. The 50/50 blend was about twice as viscous as the diesel fuel. The pour and cloud points were also higher for the blends. The use of the 50/50 blend without fuel filter heating was impossible because of filter clogging problems. However, the 20/80 blend could be used throughout the summer without heating but winter use would make filter heating necessary since the cloud point of such a blend was 12°C. Also, as expected, the flash point of the blends was higher than for diesel fuel; the alternate fuel blends are thus safer to handle. The sulfur concentration decreased as the amount of waste oil in the blend was increased. This was normal since sulfur was present in diesel fuel only. The fuel density was greater for the blends since vegetable oils are denser than diesel fuel.

The GHC for the diesel fuel was calculated using equations 2–3 and 2–4. Equation 2–2 was also used to calculate the GHC of the waste vegetable oil in conjunction with the fatty acid profile of the oil. The GHC of the waste oil was calculated as being 39504 kJ/kg. The GHC for the two alternate fuel blends were obtained using the mass proportion of each constituent in the blends.
Table VIII: Results of the fuel analysis.

<table>
<thead>
<tr>
<th>Fuel:</th>
<th>Diesel no.2</th>
<th>20 / 80</th>
<th>50 / 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pour point (°C):</td>
<td>-13</td>
<td>-13</td>
<td>-6</td>
</tr>
<tr>
<td>Cloud point (°C):</td>
<td>4</td>
<td>12</td>
<td>room</td>
</tr>
<tr>
<td>Visc. 40°C (cst):</td>
<td>3.65</td>
<td>6.074</td>
<td>13.035</td>
</tr>
<tr>
<td>Visc. 100°C (cst):</td>
<td>1.38</td>
<td>2.048</td>
<td>3.585</td>
</tr>
<tr>
<td>Flash point (°C):</td>
<td>59</td>
<td>65</td>
<td>76</td>
</tr>
<tr>
<td>Sulfur (% weight):</td>
<td>0.32</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Spec. Grav. 15.6°C:</td>
<td>0.8686</td>
<td>0.8778</td>
<td>0.8888</td>
</tr>
<tr>
<td>Gross Heat cont. (kJ/kg): (Calculated)</td>
<td>44851</td>
<td>43782</td>
<td>42178</td>
</tr>
</tbody>
</table>

Table IX: Fatty acid profile of the waste vegetable oil by GC/MS.

<table>
<thead>
<tr>
<th>FATTY ACID</th>
<th>SYMBOL</th>
<th>% BY WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myristic</td>
<td>C14:0</td>
<td>2.5</td>
</tr>
<tr>
<td>Palmitic</td>
<td>C16:0</td>
<td>29.1</td>
</tr>
<tr>
<td>Stearic</td>
<td>C18:0</td>
<td>18.5</td>
</tr>
<tr>
<td>Oleic</td>
<td>C18:1</td>
<td>40.4</td>
</tr>
<tr>
<td>Linoleic</td>
<td>C18:2</td>
<td>8.6</td>
</tr>
<tr>
<td>Linolenic</td>
<td>C18:3</td>
<td>0.9</td>
</tr>
</tbody>
</table>
4.2. WASTE VEGETABLE OIL ANALYSIS

The waste vegetable oil used in the fuel blends was analysed in order to characterize it. The fatty acid profile was obtained by gas chromatography/mass spectrometer. The oil sample was esterified and the fatty acid methylesters were separated. The profile is available in table IX.

Referring to table 1, the composition of the waste oil was quite different from that of neat vegetable oils. The proportion of C18:2 was lower than that of almost all of the natural vegetable oils. However, the proportion of C18:0 in the waste oil was much higher than the neat oils. The proportion of C14:0 and C16:0 was also higher than that of neat vegetable oils. The relatively high proportion of saturated fatty acids present in the waste vegetable oil denotes the fact that the vegetable oils used in the formulation of the frying shortening were hydrogenated. The C18:2 and C18:3 present in the natural vegetable oil were probably converted to C18:1 and C18:0. No measurable amounts of fatty acids containing more than 18 carbon atoms were detected by the GC/MS. The composition of the waste oil was attributed to the formulation of the frying shortening by its manufacturer. This formulation was not available since the information was apparently proprietary. Saturated fatty acids are less sensitive to oxidation and this is one of the reasons why they are preferred for deep-frying processes. As seen earlier in the literature review, some authors consider saturated fatty acids to be better fuels than unsaturated ones.

4.3. EFFECT OF TIME ON BSFC

For each fuel tested, BSFC measurements were taken every 5 to 6 hours of engine operation. The BSFC was measured at two different steps in the EMA cycle: step 1 and step 2. Step 1 was at rated speed and power while step 2 was at 85%
of rated speed and maximum torque. The BSFC data was corrected for atmospheric conditions with the SAE standard J1349 (June 1983).

A statistical analysis, including regression and confidence interval for the averages, was done on the results. The regression analysis was used to verify if BSFC was time dependant. A significant correlation would indicate that fuel efficiency was deteriorating or improving with time. A degree of confidence of 5% was selected to test the hypothesis that the slope of the regression of BSFC vs time was horizontal. Table X summarizes the statistical analysis results for the regressions as well as the confidence interval analysis for the averages. The scatter plots of the BSFC data for the three fuels tested at two different operating conditions appear in figures 12 to 17. The regression line obtained by the least square method is also plotted on the graphs.

Only one of the regressions was significant to less than 5%; the 20/80 test run at step 1. However, the $R^2$ for this regression was only 0.11, which means that the correlation was not good. For the other fuels tested, the BSFC was not time related. No significant deterioration in the fuel efficiency of the engine occurred during the fuel tests.

The average value of the BSFC for each test run could thus be taken as a good estimate of the BSFC of this particular engine when burning the different fuels. The error on the averages was calculated using a confidence of 5% and was included along with the averages in table no. 10. The standard error of the BSFC data for the different runs did not show any difference between the diesel run and the 20/80 run. However, the spread of the data for the 50/50 run was larger than the other fuels tested. This could be explained by two observations made during this fuel test.

First, it was noticed that on a few occasions, on cold mornings, a deposit of solid vegetable oil was present at the bottom of the small tank used for fuel
Figure 12: BSFC data for the diesel run, step 1

Figure 13: BSFC data for the diesel run, step 2
Figure 14: BSFC data for the 20/80 run, step 1

Figure 15: BSFC data for the 20/80 run, step 2
Figure 16: BSFC data for the 50/50 run, step 1

Figure 17: BSFC data for the 50/50 run, step 2
### Table X: Results of statistical analysis on BSFC data.

(Regression of BSFC vs time: BSFC = a + b.time)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Step</th>
<th>a</th>
<th>b</th>
<th>200b</th>
<th>Signif</th>
<th>R²</th>
<th>av. BSFC</th>
<th>Std.err.</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>1</td>
<td>271.27</td>
<td>0.0207</td>
<td>4.14</td>
<td>0.2045</td>
<td>0.03896</td>
<td>273.26</td>
<td>6.2266</td>
<td>1.86</td>
</tr>
<tr>
<td>Diesel</td>
<td>2</td>
<td>267.55</td>
<td>0.0046</td>
<td>0.91</td>
<td>0.7097</td>
<td>0.00389</td>
<td>267.98</td>
<td>4.4911</td>
<td>1.43</td>
</tr>
<tr>
<td>20 / 80</td>
<td>1</td>
<td>278.06</td>
<td>0.0064</td>
<td>1.28</td>
<td>0.6106</td>
<td>0.00749</td>
<td>277.45</td>
<td>4.4274</td>
<td>1.43</td>
</tr>
<tr>
<td>20 / 80</td>
<td>2</td>
<td>273.29</td>
<td>0.0217</td>
<td>4.34</td>
<td>0.0475</td>
<td>0.11065</td>
<td>275.34</td>
<td>3.8973</td>
<td>1.27</td>
</tr>
<tr>
<td>50 / 50</td>
<td>1</td>
<td>289.11</td>
<td>0.0101</td>
<td>2.03</td>
<td>0.6829</td>
<td>0.00497</td>
<td>290.12</td>
<td>8.7979</td>
<td>2.87</td>
</tr>
<tr>
<td>50 / 50</td>
<td>2</td>
<td>285.77</td>
<td>0.0006</td>
<td>0.11</td>
<td>0.9744</td>
<td>0.00403</td>
<td>285.82</td>
<td>6.2377</td>
<td>2.07</td>
</tr>
</tbody>
</table>

### Table XI: Diesel fuel savings with the fuel blends.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Step</th>
<th>BSFC (g/kW-h)</th>
<th>BSDC (g/kW-h)</th>
<th>Saving (%)</th>
<th>Therm. eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>1</td>
<td>273.26</td>
<td>273.26</td>
<td>0</td>
<td>29.37</td>
</tr>
<tr>
<td>Diesel</td>
<td>2</td>
<td>267.98</td>
<td>267.98</td>
<td>0</td>
<td>29.95</td>
</tr>
<tr>
<td>20 / 80</td>
<td>1</td>
<td>277.45</td>
<td>221.96</td>
<td>18.8</td>
<td>29.64</td>
</tr>
<tr>
<td>20 / 80</td>
<td>2</td>
<td>275.34</td>
<td>220.27</td>
<td>17.8</td>
<td>29.86</td>
</tr>
<tr>
<td>50 / 50</td>
<td>1</td>
<td>290.12</td>
<td>145.06</td>
<td>46.9</td>
<td>29.42</td>
</tr>
<tr>
<td>50 / 50</td>
<td>2</td>
<td>285.82</td>
<td>142.91</td>
<td>46.7</td>
<td>29.86</td>
</tr>
</tbody>
</table>
Consumption measurement. This small tank was not heated but the fuel tank and the fuel filter were heated to about 35°C. On those occasions, the engine had to run for a few hours in order for the influx of warm fuel to dissolve the deposit. The first litre or so of fuel burned was depleted in part of its waste vegetable oil and thus contained more diesel fuel. The warm fuel being introduced in the small tank dissolved the deposit and thus the waste vegetable oil proportion would go up to a level higher than the blend until all the deposit was dissolved. For the first few hours of running, the fuel composition would then vary and this could have affected the BSFC data taken during these first few hours, thus causing some larger spread in the data. This theory could explain the variations in the BSFC at around 120 hours. The morning of the ninth day of testing was the coldest and heavier deposits were noticed.

Another observation could explain the spread for the rest of the test data. The fuel injector was removed at irregular intervals during the 50/50 test run in order to observe the deposits on the injector tip. Visual inspection of the nozzle revealed that the amount of deposits found at any time in the test varied and did not follow any pattern. The deposits were not cumulative and seemed to be eroded away once they reached a certain size. The variable amount of deposits on the injector tip would cause the spray pattern to be modified affecting the atomization of the fuel and indirectly, the BSFC data. Figures 14 and 15 show that the BSFC data for the two test conditions behaved in the same manner. They both show a sine wave behavior with maximums and minimums located at the same time in the test cycle. This would indicate that the source of the variation is due to engine burning efficiency and not normal experimental error on the measurements.

From the statistical analysis, it appears that these variations average out and that no long-term effect on BSFC is to be expected. It appears that the self cleaning
taking place on the injector nozzle prevents the BSFC deterioration.

The BSFC's obtained when burning the different fuels were compared to each other in order to quantify the saving in diesel fuel achieved when the alternate fuels were used. Table XI summarizes the BSFC data for the different fuels used. BSDC represents the specific diesel consumption.

The saving of diesel fuel when using the 20/80 blend was around 18% and about 47% when the 50/50 blend was used. These values are lower than the mass substitution values because the waste vegetable oil had a lower heat content than the diesel fuel. More fuel had to be burned in order to provide the same power output.

The thermal efficiencies for the two operating conditions were compared. Within each condition, the values were not significantly different at the 5% confidence level for the three fuels tested.

### 4.4. CARBON DEPOSITS

The carbon deposits were measured after each fuel test on different surfaces of the combustion chamber. The deposits were weighed on four parts: the piston, the exhaust and intake valve tulips, and on the cylinder head. The deposit on the injector nozzle could not be quantified accurately since the mere removal of the injector would cause part of the deposit to fall in the swirl chamber. However, as discussed earlier, the deposits were not cumulative during a test run and a measurement at the end of a test run would not add any substantial information.
4.4.1. Nature of deposits

The deposits formed on the piston top were light and easily removed with solvent or a wire brush. However, their thickness was not uniform. The deposits were thin directly under the three jets of the swirl chamber and the jet pattern was clearly visible. The deposits were the thickest directly under the intake valve. A circular mound of carbon about 3 mm thick and of the same diameter as the valve seat was observed for all fuels tested. However, this mound was somewhat more noticeable when diesel fuel was burned. The rest of the piston top surface was covered by a uniform layer of deposits. Very few deposits were found in the top land and in the piston ring grooves. Traces of deposits were found only in the top ring groove regardless of the fuel tested.

Carbon deposits on the cylinder head surface had the same appearance as the ones on the piston top. They were easily removed with a soft metal scraper after each fuel run. They became somewhat darker as the percentage of waste vegetable oil in the blends went up. No difference in thickness was noticed between the different test runs.

The deposit on the intake valve tulip was quite different from that found on the other parts. The deposits were black, thick, flaky and oily and had the same appearance for all the fuels tested. They were quite hard to remove, even with a wire brush. The oil covering the deposits probably came from the valve guide and since the engine was not equipped with a valve stem seal, this may have caused a relatively large amount of lubricating oil to be aspirated along the valve stem during the intake stroke. The stem to guide clearance was within manufacturer's specifications during all the tests. The presence of relatively large deposits on the intake valve tulip was thus considered to be normal for the engine used. On the other hand, the
Figure 18: Deposits on miscellaneous parts
deposit on the exhaust valve tulip was relatively small for all the test runs. The deposit had a sooty appearance and was easily removed for all the fuels tested.

4.4.2. Quantification of the deposits

Figure 18 summarizes the deposit data for the different fuel test runs. No definite trend could be isolated from the results. The waste vegetable oil blends did not cause more deposits than diesel fuel. No piston ring sticking was observed after each of the fuel tests. The engine used would probably not suffer from this problem when burning blends containing up to 50% waste vegetable oil. The piston rings were all rectangular and did not benefit from the self-cleaning effect associated with Keystone rings.

4.5. WEAR OF ENGINE PARTS

In order to quantify the wear when burning the different fuels, dimensional and weight measurements were taken on parts thought to be affected when the alternate fuels were used.

The first group of parts examined were the parts in direct contact with the combustion gases such as the piston, piston rings, cylinder liner and both valves. The second group of parts were those for which lubricating oil quality was important such as the piston pin and the connecting rod bearings. The test engine was equipped with roller bearings for the crankshaft and no measurements were taken on those since they were relatively hard to remove. They were also thought to be less sensitive to lubricating oil quality than the journal bearings.

Due to its relatively high weight of 1200 g, the cylinder liner could only be weighted to the nearest 0.1 g. For all the fuels tested, no wear was measurable either
RESULTS AND DISCUSSION / 66

by weight or dimensional comparisons. However, honing removed about 0.8 g of metal every time it was done.

Figure 19 shows the amount of wear that was measured for a number of parts during the different fuel runs. For all parts except the piston and the exhaust valve, the wear was smaller as the proportion of waste vegetable oil in the blend went up. However, the diesel run conducted after the 50/50 run did not confirm this fact. The high initial wear of these parts was then attributed to break-in of the new engine during the first diesel fuel run. More wear was observed on the top connecting rod bearing than on the bottom bearing. This is normal since the top bearing insert bears more load than the bottom insert. Both piston and exhaust valve had a higher wear for the 20/80 run. This could not be explained clearly since for the 50/50 run, the wear was smaller. However, the cleaning method was changed from solvent only to solvent and wire brush when the parts were cleaned at the end of the 20/80 run. This may have caused increased abrasion resulting in higher wear and deposit data for this test run.

Figure 20 shows the wear data for the piston rings. Less wear was observed as testing went from diesel fuel to the 50/50 blend. However, the test run with diesel fuel done after the alternate fuels revealed that higher wear was taking place. The last run with diesel fuel was done for the sole purpose of evaluating if the initial high-wear rates for the first diesel fuel baseline test were due solely to engine break-in. This last test run showed that part of the initial wear was indeed due to break-in.

Although the wear of piston rings was reduced for the last diesel test run, it was still higher than the wear observed during the alternate fuel runs. The blend richer in waste vegetable oil caused the least wear, followed closely by the 20/80
RESULTS AND DISCUSSION

Figure 19: Wear of miscellaneous parts

Figure 20: Piston rings wear
blend. Although the results from this single cylinder engine are of limited statistical value, the trend was, however, very consistent.

4.6. LUBRICATING OIL ANALYSIS

Lubricating oil samples were taken at 51, 105, 150 and 201 hours for each fuel test run. A new oil sample was also included in order to provide a baseline. The samples were analysed for contaminants such as wear metals as well as for physical and chemical properties. For clarity, only the results that showed any trend or importance are presented here.

4.6.1. Wear metals

Figures 21 to 24 display the results of the spectroscopic analysis for wear metals. The data represent the difference between the sample concentration in wear metals and the new lubricating oil sample.

The iron concentration was much higher during the first 100 hours in the diesel fuel baseline test than during the same period for the other fuels tested. However, the final diesel test run showed a slightly higher iron concentration than the runs with the two blends. The high initial concentration of iron could then in part be attributed to engine break-in but the wear was nonetheless smaller for the blends. The lowest concentrations of iron were found when the 50/50 blend was used, followed by the 20/80 blend and the diesel fuel. The iron was thought to come mainly from wear of the cylinder liner and the piston rings.

The aluminium concentration behaved in much the same way as the iron concentration. However, the data for the final run with diesel fuel showed a much lower wear that was not very different from that observed for the blends. The
RESULTS AND DISCUSSION

Figure 21: Wear iron concentration in lubricating oil

Figure 22: Wear aluminium concentration in lubricating oil
Figure 23: Wear chromium concentration in lubricating oil

Figure 24: Wear copper concentration in lubricating oil
aluminium was thought to come from the piston and the connecting rod bearings. Since none of these parts were replaced during the experiment, the wear aluminium wear metal data might only show that these parts have reached a stable wear rate.

The piston rings as well as the piston pin were chrome-plated. However, most of the chromium wear metal was thought to come from the rings due to the relatively more severe conditions under which they operate. The piston rings were replaced before each fuel test and the cylinder liner was honed prior to each test. The diesel run done after the blends showed much the same concentration of chromium as the initial diesel baseline test. This fact corroborated the direct wear measurement of the rings. It also confirmed the fact that replacing the rings and honing the liner before each run provided uniform initial conditions for these parts. The chromium concentration measured with the fuel blends was lower than with the diesel fuel. The blends thus caused less wear of the rings.

The copper concentration was high during the first 100 hours of the baseline diesel test. It was relatively constant thereafter and no definite trend could be isolated from the data. The copper was thought to come from the camshaft and piston pin bearings. Since these parts were not replaced during the experiment, the constant wear would indicate that after break-in, no abnormal wear took place during the tests for these parts.

The wear metal associated with parts not in direct contact with the combustion gases did not show any fuel-related dependance after the initial break-in. The wear metals associated with the parts affected by friction in the presence of the combustion gases, mainly the piston rings, showed a dependance on the fuel used. The wear was smaller as the percentage of waste vegetable oil in the blends was higher.
4.6.2. Viscosity of the lubricating oil

The viscosity of each sample was measured at 40° and 100°C and the results are reported in figures 25 and 26. The lubricating oil used for the last diesel run came from a different lot than the one used for the three previous runs. It had however the same label and SAE classification. The slight difference in viscosity was not thought to have affected the wear.

The viscosity at 100°C is the most important for normal engine operation. The recommended viscosity for the Yanmar engine was SAE 30 or 40 for ambient temperatures of between 20°C and 35°C. The specifications for SAE 30 oil viscosity at 100°C is between 9.6 and 12.9 cst; between 12.9 and 16.8 cst for SAE 40 and between 16.8 and 22.7 cst for SAE 50 (Esso, 1977). Although the oil bought was labelled SAE 30, it seems that it really was SAE 40.

At the end of the 200 hour test with the 50/50 blend, the viscosity at 100°C was such that it was greater than the upper limit of SAE 40. However, the wear data did not indicate that a higher wear rate was taking place. Thus, this relatively high viscosity was not thought to be detrimental to engine operation. The data for the viscosity at 40°C for the 50/50 run showed a higher viscosity than for the other fuels which might have caused poorer lubrication during warm up. Again, the wear data did not verify this.

The relatively high viscosity of the lubricating oil for the 50/50 run was attributed to the following factors: lubricating oil dilution by unburned fuel may have taken place causing detergent depletion leading to thickening of the oil; lubricating oil consumption would be lower and oxidation products would be present in larger proportions.
Figure 25: Viscosity of lubricating oil at 40°C

Figure 26: Viscosity of lubricating oil at 100°C
4.6.3. Lubricating oil consumption

Throughout all the tests, a record of lubricating oil consumption was kept and the average oil consumption is presented at figure 27. The lubricating oil consumption was lower for the 50/50 blend test, followed by the 20/80 run and the diesel runs. It was hypothesized that some waste vegetable oil did not burn and that droplets may have come in contact with the combustion chamber walls. These droplets may have acted as additional lubricant for the piston rings, partly explaining why the wear of the rings was lower when the blends were used. The film of unburned vegetable oil on the cylinder liner wall may have improved ring sealing, thus reducing blowby and lubricating oil consumption. Some unburned fuel may have made its way down in the crankcase by the scraping action of the oil control rings. This dilution would cause a lower lubricating oil consumption.

However, from table III, it can be assumed that most vegetable oils have a viscosity of around 35 cst at 38°C. Thus, the mixing of this oil with the lubricating oil would have caused the viscosity at 40°C of the samples to be lower than the new oil. This was not verified and thus lubricating oil dilution by waste vegetable oil was assumed to be minimal. The effect of the waste vegetable oil in the blends seemed to have improved lubrication of the piston rings.

4.7. ENGINE OPERATION

During the fuel tests with the alternate fuel blends, no cold–start problems were encountered even when the engine temperature was down to about 10°C. The engine started as well as when diesel fuel was used and starting aids were never used. The engine was hand started at all times.

When the 50/50 blend was tested, only the fuel filter was heated to about
Figure 27: Lubricating oil consumption
35°C in order to avoid filter clogging by the cloudy part of the blend visible at room temperature. No other heating was provided and the engine was started with cold fuel in the injection system. This did not seem to be detrimental to engine starting or warmup and fuel line heating was thus not necessary.

The combustion noise or "diesel knock" was lower with the blends at a given power setting than when diesel was burned. This was in agreement with previous testing with vegetable oils by other authors. The smoke levels were not measured but at step 2 in the EMA cycle, maximum torque and 85% speed, no visible difference was noticed in the smoke levels. The exhaust gases had a different smell with the alternate fuel blends but were not stronger or obnoxious. The fuel injector opening pressure did not show any deterioration other than the normal time-related drop.
5. CONCLUSION

Two different blends of waste vegetable oil with diesel fuel were compared to diesel fuel in order to determine the effect of these alternate fuels on engine durability. The 200-hour preliminary durability screening test suggested by the EMA was used to test the fuel blends and to obtain a baseline with diesel fuel. Both the 20/80 and the 50/50 blends completed the test with no fuel-related problems and were then considered as being good candidates for long-term use in indirect injection diesel engines. This type of engine was selected because it offered a greater potential for substituting a maximum amount of diesel fuel by waste vegetable oil without any engine modification.

The waste vegetable oil processing was reduced to a minimum. After mixing the oil with diesel fuel, the blend was filtered through a strainer and transferred in the fuel tank. This process was the only operation that had to be done in order to make the alternate fuels acceptable to the engine.

The BSFC did not deteriorate significantly for both fuel blends during the 200-hour test runs. However, the BSFC data obtained during the 50/50 test run showed more scatter than the 20/80 run or the diesel runs. This was attributed to some self-cleaning effect observed on the injector nozzle. Deposits were not cumulative for the whole test and seem to have been broken loose after they attained a certain thickness. The variations in the BSFC data for the 50/50 blend did not indicate any deterioration over the 200-hour test period. The thermal efficiencies of the alternate fuel blends were not significantly different than those observed with diesel fuel. It was then assumed that the engine used in this research project was able to use the alternate fuels as efficiently as diesel fuel.

Carbon deposits on other parts of the combustion chamber were different in
appearance but not in quantity when the blends were used. No piston ring sticking was observed for any of the fuels tested.

Wear measurements showed that all the parts, except the piston rings, had the same amount of wear after each test regardless of the fuel used and this once the initial break-in period was completed. Lubricating oil analysis for wear metal concentrations as well as weighing of the piston rings showed that their wear was higher with diesel fuel than with the alternate fuel blends. The 50/50 blend caused the least wear of the piston rings. This fact and the fact that lubricating oil consumption was lower as the blend got richer in waste vegetable oil were linked. It is believed that a small amount of unburned waste oil was present on the cylinder liner wall. An improved lubrication of the piston rings was attributed to this, thus reducing piston ring wear. Better sealing of the rings and possibly some lubricating oil dilution may explain the lower lubricating oil consumption during the alternate fuel tests.

The 50/50 fuel blend allowed a saving of about 47% in diesel fuel. From the results of previous work, it is unlikely that a direct injection engine could have used a blend containing more than 20% in waste vegetable oil. The efficiency advantage of direct injection engines would not enable them to burn less diesel fuel per unit of power produced with a 20/80 blend than an indirect injection engine burning the 50/50 blend. The use of the indirect injection engine could then be considered as being appropriate technology for burning blends of waste vegetable oil and diesel fuel.

It could be argued that the use of cheap source of energy, such as waste vegetable oil, is a self-defeating innovation since any increased demand for a product usually results in a price increase. In most large population centers, waste vegetable oil is collected and processed into animal feed supplement. The use of these oils as a
partial or total substitute to diesel fuel would be in direct competition with the tallow industry and would possibly cause the price of animal feed to increase. Utilization of these oils as fuels would be interesting only for the company who does the collecting and processing; the oils could be used as a fuel for the fleet of vehicles and in the processing.

In areas where waste vegetable oil is not collected and where it is not used for other purposes, using the oils as fuels would be to consider. These areas are probably relatively remote and conventional fuel prices are probably higher than in the large populations centers, making these alternate fuels even more attractive. In less developed countries where waste vegetable oil collection is probably inexistant, their use as fuels should also be considered. In many of these countries, small diesel engines (usually IDI) are often the prime-movers and fuel prices are high. The use of waste vegetable oils as fuel extenders should then be seriously considered.
6. FUTURE RESEARCH

- The test procedure followed in this research project should be repeated with new frying shortening in order to ascertain the effect of using waste oil vs new oil on engine behaviour.

- More lengthy testing should be done with the 50/50 blend to determine if the proposed self-cleaning effect would take place continuously and prevent deterioration of engine performance.

- Testing should be done with 100% waste vegetable oil using fuel and injection system heating to make the fuel a complete substitute to diesel fuel.

- Testing should be done on larger, multicylinder IDI engines in order to get more statistically sound results.

- Field testing should be done in order to observe the behaviour of the alternate fuel blends in real-life situation.

- Testing of transesterified waste vegetable oil in DI engines as total substitute should be done. Optimization of the transesterification process aimed at fuel production as well as costs analysis should be done to determine the viability of these fuels.
BIBLIOGRAPHY


APPENDIX: EMA 200-HOUR SCREENING TEST

Date: September 1, 1982

Research on/or testing of renewable fuels (i.e. vegetable oils—neat, blended or modified) for diesel engines is in progress or being planned at many locations. Previous studies have limited value because conditions and procedures were unique to each test.

An advisory committee with representation from USDA, agricultural experiment stations, engine (tractor) manufacturers and fuel additive suppliers to advise on procedures for engine tests of renewable fuels has been organized and is coordinated from the Northern Agricultural Energy Center, Peoria.

The Engine Manufacturer's Association (EMA), a trade association of 21 international engine manufacturers, has proposed at the request of the United States Department of Agriculture, a 200-hour preliminary durability screening test to assess the potential impact of alternate fuels on diesel engine durability.

The test is intended for research and development purposes and is designed to try to initiate durability problems in a reasonable amount of test time. Successful completion of the test is no assurance that the fuel will be acceptable. However, the test will eliminate some candidate fuels, and patterns of performance and engine durability will be uniformly evaluated for all test fuels.

The advisory committee has adopted the EMA 200-hour screening test for farm tractor engine studies. Anyone contemplating engine testing of renewable fuels, or in advisory or consultative role to such a project, is encouraged to follow this test procedure:
1. FUEL TEST SERIES:

A fuel test series shall include a 200-hour baseline test of the engine followed by one or more 200-hour tests of alternate fuels for comparison under similar conditions.

2. FUELS TO BE TESTED:

a) Baseline test fuel: Phillips 2D Reference Fuel (P2D).

b) Vegetable oil/P2D blends and modified or hybridized fuels should be specified and tested, starting with the experimental fuel least likely to cause engine damage followed by tests with fuels in order of increasing likelihood of engine damage.

(Note: Commercial grade diesel fuels are not advised by the committee for the official 200-hour screening test because of their variable properties. If commercial diesel fuel must be used, its properties should be extensively tested and reported with the engine test results.)

c) Fuel additives: to be determined and specified.

3. FUEL CHARACTERIZATION AND DESCRIPTION TO INCLUDE:

a) Generic name, degree of refinement, source, percent of total mix for each energy component.
b) Gross caloric value; net caloric value. (May be specified as Btu/lb or Btu/gal.)

c) Viscosity at 100°C and 40°C.

d) Cetane number; Iodine Value; Wax Content; Phosphatide Content; Fatty Acid Profile by gas chromatography.

4. ENGINE WEAR OBSERVATIONS AND MEASUREMENTS:

a) Each 200-hour fuel test to commence with new liners, rings, pistons, injector tips, valves, valve seat inserts and guides. (Other parts to be in good condition.)

b) Dimensions of liners and rings, and weight of rings (and other parts as experience may indicate) to be measured before and after each 200-hour test. Weight to be determined after removal of any deposits.

c) All components of the engine that are likely to be affected by use of the fuel are to be observed, checked, and measured for proper function and for specification tolerances. Included are upper cylinder, cylinder head, induction and exhaust systems, turbo-charger, fuel injection system, and the entire lubrication system.

d) Components such as cylinder heads, injector bodies, valve lifters, cam shaft bearings, and turbo-charger can be cleaned and reused if within manufacturer's specifications.

e) Injector (tips) will be inspected and performance checked after each test.
f) Parts that fail due to non-fuel related causes are to be replaced and the test continued.

g) There are to be no engine or parts modifications during a fuel test series.

5. CRITERIA FOR FUEL/ENGINE FAILURE:

a) Performance: A drop of 5% or more that cannot be corrected with minor adjustments (normal field adjustments) during the 200-hour test. (Injector nozzles may be replaced to complete a test but this would constitute a failure.)

b) Durability:
(1) Failure to complete 200 hours of EMA test cycle for any reason related to the test fuel.
(2) Measurement of blowby during testing is a convenient way of monitoring gross changes in engine performance which may be due to events such as ring sticking. Blowby measurement is optional and if desired, need only be performed periodically (every 50 hours).

c) Lubricating Oil (checked daily after warm-up):
(1) Viscosity: A change of 50% from the new oil value.
(2) Dispersancy: Any indication of failure of dispersion. (Blotter Spot Test acceptable.)

d) Engine life (post inspection): Excessive wear that would extrapolate to a 50% or greater reduction in engine life based on the manufacturer's guidelines and experiences.
Wear inspection should include, but is not limited to:

(1) Piston, ring and liner wear or scuffing
(2) Bearing wear
(3) Cam and follower gear
(4) Valve guttering.

Category b) (2) and c) will allow termination of the test just prior to a total engine disaster.

Category d) will require knowledge of normal engine wear in that area of the world where the alternate fuel is being considered, recognizing geographic variability of diesel fuel quality and the kinds and amounts of impurities.

6. LUBRICATING OIL:

a) High detergent type CD to be used.

b) One lot of lube oil sufficient for the test series should be procured.

c) Physical properties and engine wear contaminants (by chemical analysis) to be recorded at 0, 50, 100, 200 hours.

d) Crankcase level to be checked before each cold start. If oil is low, oil should be added. Records of oil consumption should be kept.

e) Oil and filter change interval to be as recommended by the manufacturer, but not
7. EMA BREAK-IN SCHEDULE (90 minutes):

A new or rebuilt engine is to be broken-in with P2D fuel before each test following a procedure identical to table V of this thesis.

8. POWER AND FUEL CONSUMPTION TESTS:

To be in accord with SAE test procedures.

9. EXHAUST EMISSIONS:

a) Emission measurements for HC, CO, NOx and smoke are optional. If undertaken, measurements should be made before and after each 200-hour test.

b) The following engine operation modes should be used.

(1) low idle speed, zero load
(2) peak torque speed(*) at zero load
(3) peak torque speed(*) at 50% load
(4) peak torque speed(*) at 100% load
(5) rated speed at zero load
(6) rated speed at 50% load
(7) rated speed at 100% load

(*) advertised peak torque speed or 60% of rated speed; whichever is higher.

less than 100 hours.
10. FUEL PRESSURE:

To be monitored continuously and filters replaced as needed.

11. EMA TEST CYCLE (3 hours):

The test cycle is identical to table VI of this thesis. The weighted averaged power is 69%. Turbocharged engines should be tested at their highest power rating (use of derated engines is not advised).

12. PRELIMINARY DURABILITY SCREENING TEST (200 hours):

Five consecutive test cycles are to be run without stopping the engine, followed by a nine hour (or longer) cold shut down (normal interior ambient temperature). Test duration is 200 hours of EMA cycle operation.

NOTE: Engine Manufacturers Association (EMA) and its members disclaim liability from any cause whatsoever related to the use of this test procedure.

(The EMA 200-hour fuel screening test would be only preliminary to many more specific tests were an engine manufacturer to consider commercial applications of its equipment on non-specification fuels.)

Specific further information is available from Northern Agricultural Energy Center, 1815 N. University Street, Peoria, IL 61604.