INSTITUTE OF APPLIED SCIENCES

THE UNIVERSITY OF THE SOUTH PACIFIC

UTILIZATION OF COCONUT OIL AS A FUEL FOR PETROLEUM DIESEL AND KEROSENE SUBSTITUTION

IAS TECHNICAL REPORT NO. 81/1

by

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South Pacific Commission Regional Technical Meeting on New and Renewable Sources of Energy, Papeete, French Polynesia, 28 September to 1982.

The utilization of coconut oil as a fuel for diesel engines has been trialed in many of the island countries of the Pacific. In all cases, the engines operated successfully for at least a short period. The economic potential for using coconut oil as a fuel has been greatly increased by a continuing decline in international prices for copra and coconut oil. In almost all island countries of the Pacific, the foreign exchange income from export of coconut oil or copra is less than that outgoing from the importation of petroleum diesel fuel. Coconut meal from the coconut oil extraction process is a valuable byproduct. This meal is high in protein and may contribute to livestock industries. Coconut oil is currently produced in a number of island countries of the Pacific and processing plant for its production is available on an "off-the-shelf basis".

Coconut oil may be used directly as a fuel for standard unmodified diesel engines or mixed in any proportion with petroleum diesel fuel. Mixing with petroleum fuel minimizes the problem of the formation of solid particles in the coconut oil during the cooler months. Diesel fuel must be free from solid particles. These form in coconut oil in the temperature range 25-20C (68-77 F), with purer grades of oil

The Philippines is reported to be mixing 20 per cent refined coconut oil with bulk petroleum diesel fuel. The potential for saving foreign exchange and the rejuvenation of the coconut industry in the Pacific provides much incentive for using coconut oil or "COCOHOL" as a fuel. Expansion or introduction of high yielding oil palms may greatly increase indigenous liquid fuels. The factors responsible for the formation of engine injector deposits are not fully understood. As operation of engines on coconut oil with poor injection characteristics may lead to failure of engine components, it is recommended that coconut oil only be used as a fuel at locations where trained expertise is available for regular monitoring of engine performance.

Production of "COCOHOL" from chemical combination of coconut oil and ethanol, will also yield glycerol as a valuable byproduct. "COCOHOL" is equal or better than petroleum diesel fuel and may be used in domestic appliances fueled by kerosene (paraffin). The performance of "COCOHOL" is equal to kerosene in "pressure" appliances. It is a much safer fuel than kerosene due to a lower volatility and a higher flame flash point.

INTRODUCTION.

Island Nations of the Pacific have faced increasing difficulties with their balance of payments in recent years due to a general increase in the price of imported petroleum fuels and a general decrease received from their principal exports. For many of the nations, the outflow of foreign exchange for petroleum fuel alone, exceeds the total export revenue. A significant export commodity for most of the countries is copra or coconut oil. Copra is particularly significant as a traditional cash crop in isolated rural areas, some of which may not have any other cash income.

Latest international prices available at the time of writing this report place the average London price of copra at US$268 a tonne on August 30, 1982. This is a decrease of US$47 from the price of US$315 on July 5, 1982. From the most recent price, must be subtracted the cost of handling and freight from the Pacific. As a guide, the deductions of the official Silsoe formula as applied in Fiji, yield an unsubsidized price of US$110 tonne for copra landed in the capital city of Suva, based upon a London price of US$274. From the official Fiji price in Suva of US$110, must be subtracted the cost of freight from more isolated islands of the Fiji group, reducing the unsubsidized return from copra to less than US$100 per tonne. (This is less than US10 cents per kilogramme or 5 cents per pound.) Whereas the validity of the Silsoe formula is open to debate, the freight components from smaller pacific ports is likely to be greater than from Suva. The unsubsidized return from copra within the Pacific is not likely to be greater than 10 cents per kilogramme or 5 cents per pound based upon current and international prices in the intermediate future.

A return of US$100 per tonne is less than the economic and social costs of production of copra in many areas of the Pacific. The larger producers of Fiji and Papua New Guinea currently have subsidy schemes which raise the price to an excess of US$300 and $200 respectively.

Part of this subsidy is recovered from price stabilization arrangements within the Lome convention of the EEC. As these price stabilization schemes are based upon average prices within the immediate preceeding years, the general downward trend in copra prices (which still continues) translates into decreased returns from the EEC stabilization scheme. It is possible that the removal of subsidy schemes for copra may see the virtual collapse of the copra and coconut industry in most areas of the Pacific. This has been the case in some areas which currently do not have a subsidy scheme.

In the case of Fiji, downward movements in the international price of sugar have been buffered by longer term biparty price agreements which yield a return much greater than current international prices for a significant proportion of the crop. It is possible to establish a buffer price for copra and coconut oil which would be much greater than the unsubsidized return on copra of approximately $US100 per tonne. This buffer price could be based upon the energy equivalent of coconut oil as compared to imported diesel fuel. Studies with diesel engines from 6 h.p. to 350 h.p. have shown beyond doubt that the experimental combustion efficiency of coconut oil is the same as that for petroleum distillate. However, the energy content of coconut oil on a volume basis is approximately 90 per cent of that of distillate. When burnt at the same efficiency, approximately 10 per cent more coconut oil is required on a volume basis. The density of coconut is greater than that of petroleum diesel fuel, which largely compensates for the energy difference on a volume basis. To a good approximation, a tonne of coconut oil will yield the same energy as a tonne of petroleum distillate when used to fuel a diesel engine.

The landed price of petroleum diesel fuel in bulk is approximately US$350 tonne (approximately 30 cents per liter). Duty and handling costs increase this price at all outlets. All regional governments could offer copra producers a coconut oil equivalent price of $350 per tonne and finance the complete cost rom savings from imported petroleum distillate. The recovery of coconut oil from copra is in the range 60 to 70 per cent depending on the species of coconut and the effi iency of the milling operation. If the lower value of 60 per cent is used, the minimum price which can be paid to copra producers is US$210 per tonne. This is more than double the return from current interna onal export prices and could be fi anced completely from savings on imported fuel.

Rel ting the current international pric s for copra and coconut oil to the landed price of imported petroleum distillate, leaves no doubt that coconut oil is an economical fuel in many areas of the Pacific at the present time. Social, economic and agricultural factors must be considered as to whether sufficien c pra can be produced wit in island countries of the Pacific to justif the r latively simple processing to obtain coconut oil as a fuel. A detailed c nsideration o these factor is outside the scope of these di u sio s. The tech logy fo produc ion of coconut oil from copra is l es ablished and e uipment available from a number of sources as an off-the-shelf item. As an approximate figure, a complete p ant to ro ess 50 kilogramme of copra per hour can be landed in the Pacific from Japan for US$20,000. Such a plant would produce approximately 32 liters of diesel fuel equivalent per hour from 50 kilogrammes of copra. In dd tion, approximately 20 kilogramme of a valuable animal ood in the or of coconut meal would be available as a byproduct.

The technology for production of coconut oil from copra is well established. Within my knowledge, copra mills are already established in the region in Fiji (4 miles), Papua New Guinea (at least one mill), with one mill in Kiribati, Tonga, and Vanuatu. Aga n within my knowledge, coconut oil has been used to fuel diesel engines for hundreds of hours in the Philippines, Papua New Guinea, Fiji,

Western Samoa and Vanuatu and hort term runs hav been made in

Tuvalu, Solomon Islands and Islands of Micronesia. In all cases the engines operated successfully for at least the initial period. Technical problems arose with longer term running in some of the cases. In the remainder of this presentation, I will discuss these technical problems in relation to diesel fuel technology, so that the potential of coconut oil as a fuel may be considered within current technical perspectives.

DIESEL ENGINE REQUIREMENTS

The modern diesel engine, named after its inventor, was original designed to utilize powdered coal as a fuel. It is unlikely that such a corrosive material would ever have been successful. Since that time, engine design has been largely determined by the availability of a liquid petroleum fraction less volatile than that required for spark ignition internal combustion engines. In the spark ignition (or petrol engine), the fuel is vaporized and mixed with air in a carburettor prior to being drawn into the engine cylinder, where the combustion process is started by an externally initiated spark. In the diesel (or compression ignition) engine, air alone is compressed in the engine cylinder and liquid fuel injected at high pressure as a fine droplet spray into the hot compressed air. Combustion commences at "hot" spots within the cylinder. The position and shape of the injector nozzle from which the droplet spray enters the cylinder is of a major importance in determining the combustion characteristics.

A major criteria of engine design is to prevent combustion pressure induced vibrations or "knock" in the engine. This has lead to the widely used "octane" rating for petrol or 'cetane' rating for diesel fuels. The number of variable factors controlling "knock" in diesel engines is much greater than in spark engines. For modern diesel engines designed for distillate fuel, three important fuel characteristics which are importaat in determining the rate of the combustion process and hence the possibility of "knock" are:

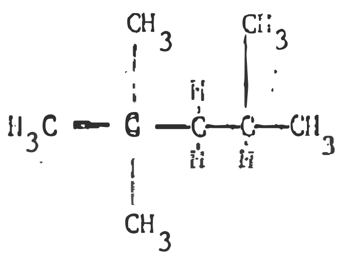
1) the chemical nature of the fuel molecules (measured by the cetane rating);

II) the volatility of the fuel, which determines how fast it vaporizes in the engine cylinder;

III) the viscosity of the fuel which influences the injector characteristics and mixing characteristics with air in the cylinder.

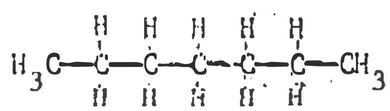
Other criteria of diesel fuels are that they should be sufficiently volatile when the engine is cold so that some of the fuel will combust and start the engine. They should not form corrosive materials on combustion. The very high pressures of the liquid fuel injection system demands high precision engineering in the injector pump and diesel fuel must be free from solid particules. Solid particles should not form in the fuel on standing due to reaction with air, the container or by cooling to lower temperatures.

Most petroleum fuels are a mixture of many different chemical hydrocarbon carbon compounds. High octane fuel is associated with chemical molecules having "branching" in the carbon chain, whereas as high cetane fuels are associated with long chains and no branching in the molecule. Standard examples are shown below.



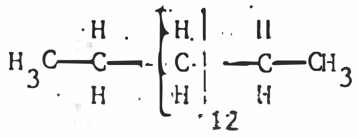
ISOOCTANE

OCTANE NO = 100



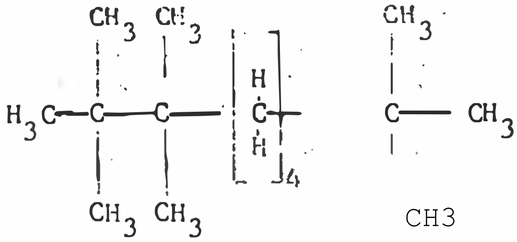
HEPANE

OCTANE NO. = 0



CETANE

CETANE No. = 100

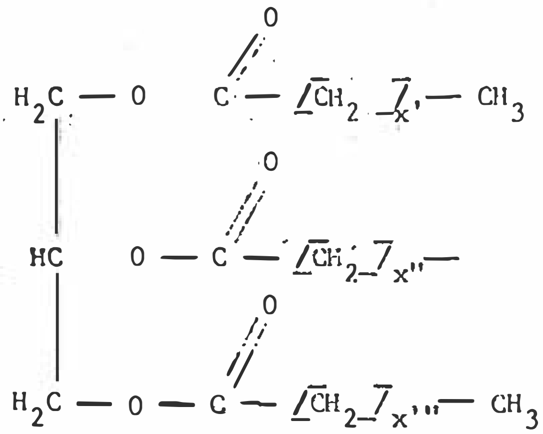


HEPTANETRYLNONANE

CETANE No. 15

CHARACTERISTICS OF VEGETABLE OILS

Vegetable oils molecules consist of three carbon chains containing 8 to 22 carbon atoms chemically combined with a molecule of glycerol as shown below.



x', x'', x''' = 6 to 20

Vegetable oils are not pure compounds, but consist of many different types of molecules containing carbon chains of different length in the triglyceride molecule. The range of carbon atoms in the carbon chain and the average number of carbon atoms per molecule is characteristic of the vegetable oil. The only difference between molecules of vegetable oils is the number of carbon and hydrogen atoms in the carbon chain.

Properties of some selected vegetable oils are shown in table 1. The average length of the carbon chain is represented by the saponification value. The higher the saponification value, the lower the average carbon chain length. Rapeseed oil has the lowest saponification number with a predominant chain length of 22 carbon atoms. Coconut oil has the highest saponification number and the lowest predominant carbon chain with 12 carbon atoms. The other significant value is the iodine value. This is a measure of the chemical unsaturation in the carbon chain and determines whether the oil is "saturated" or "unsaturated". Linseed, peanut and sunflower oil are unsaturated oils, while rapeseed, palm and coconut oil are relatively saturated oils. Unsaturated oils are reactive and readily form films and varnishes. This is a desirable characteristic of linseed oil in the paint industry. It may be noted that coconut oil is the most saturated oil with the shortest predominant carbon chain, both desirable fuel characteristics as discussed below.

VEGETABLE OILS AS DIESEL FUELS

As the carbon chain of the triglyceride vegetable oil molecule is very similar to the carbon chain of petroleum diesel fuels, it is not surprising that diesel engines will operate on virtually all vegetable oils. The presence of oxygen atoms in the triglyceride molecule slightly reduces the heat output and hence the energy per unit mass compared to petroleum hydrocarbon molecules. However, it also slightly reduces the oxygen demand on combustion and may enable vegetable oils to combust more easily in engines in some circumstances. Properties of diesel fuel are compared with vegetable oils in table 2. Petroleum specification values which have been determined for vegetable oils are limited. Values do not appear to have been reported for coconut or palm oil as the required facilities are generally beyond the capability of laboratories in developing countries.

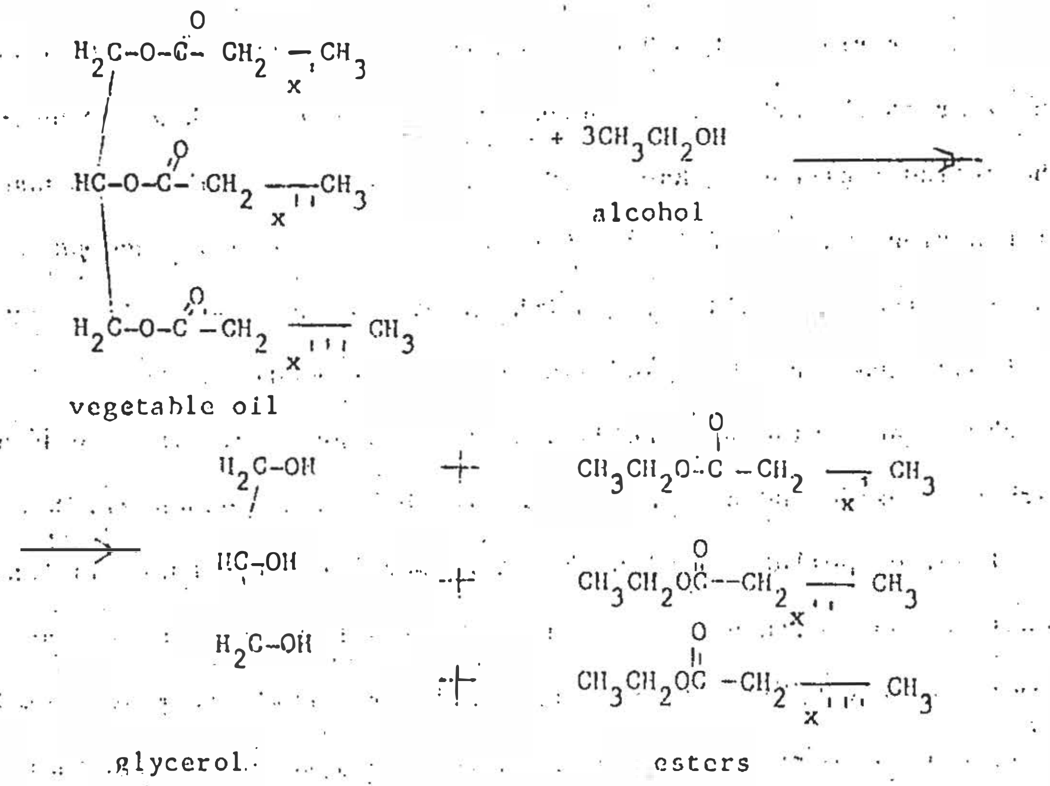
Several hundred reports have now been published on the use of sunflower and rapeseed oil as a fuel, up to a in which the fuel characteristics of linseed, peanut, safflower, soybean and olive oil are reported, while the number of different investigations generating values for coconut and palm oil as a fuel is possibly less than 10. All recent reports originate in the Pacific area from centres in developing countries with the addition of the James Cook University of North Queensland.

Sunflower is a crop of warmer cereal lands and investigators in the United States, South Africa and Brazil have been active in reporting the fuel characteristics. As with all vegetable oils, sunflower oil will operate diesel engines with equal efficiency to petroleum distillate in the initial period. Following prolonged running, the majority of investigators report extensive injector deposits and formation of gums and varnishes on pistons and piston rings. A decrease in the specific fuel consumption leads to possible sticking piston rings, contamination of the lubricating oil with non-combusted vegetable oil, severe loss of lubricating oil properties and permanent damage to the engine on continued operation. The formation of gums and varnishes within the cylinder and the rapid loss of lubricating oil properties is most likely due to the reactive nature of the unsaturated bonds in the carbon chain of sunflower oil. The general recommendation is that sunflower oil should not be used for continued operation as a diesel fuel.

Rapeseed is a crop of the cooler cereal lands and reports have originated in the United States, New Zealand, Australia and recently from Europe. Whereas some reports have outlined problems similar to that found with sunflower oil, recently a number of centres have reported continuing operation of farm tractors with refined rapeseed oil for up to 1000 hours per tractor. In general, deposits and lubricating characteristics have remained similar to engines operating on petroleum distillate. With one type of injection system, the injector pump has seized while operating with rapeseed oil. This was ascribed to close clearances within the pump. Increases the clearance between the pump and the plunger to the maximum specifications, appears to have remedied this problem.

Reports in which other vegetable oils have been used as fuels are generally similar to that of sunflower oil. Unsaturated oils lead to injector deposits, cylinder gums and varnishes, poor combustion, contamination of the lubricating oil with non-combusted vegetable oil fuel and subsequent severe loss of lubricating oil properties. The main cause of the problems is the injector deposits which lead to poor fuel atomization and combustion. The buildup of these deposits is largely ascribed to polymerization of the vegetable oil molecules initiated by the unsaturated carbon chains.

Each vegetable oil triglyceride molecule consist of three carbon chains containing 8 to 22 carbon atoms. By chemical reaction of vegetable oils with methanol or ethanol, free glycerol may be formed and each carbon chain joined individually to part of the methanol or ethanol molecules. This process is shown below for ethanol.



It may be seen that whereas the triglyceride which makes up the vegetable oil contains three long carbon chains, these form three separate molecules in the ester products with glycerol being the other product. Whereas the triglyceride may contain between 27 and 65 carbon atoms, the corresponding esters produced from ethanol contain 10 to 24 carbon atoms respectively. The number of carbon atoms per molecule of ester is approximately one third that in the triglyceride. Compared to the vegetable oil, the ester have a greatly reduced boiling temperature, solidification point and viscosity and an increase in the vapour pressure. The esters are similar to the long chain hydrocarbon molecules which are the preferre diesel fuel molecules.

It is only very recently that longer term running trials have been reported at a conference on vegetable oil fuels held at Fargo, Dakota, USA, in August of this year. The Volkswagon Company of Brazil has carried out extensive tests with the ester prepared from sunflower oil and methanol. Diesel engines produced in Brazil for light commercial vehicles were used for the trials. Six engines were tested for 1400 hours under rigorous bench test conditions. At the end of this period, the wear of the crankshaft journal main bearing, the big end bearing, the cylinder/piston, exhaust and intake valve stem guides and the piston rings was determined. For all wear measurements except the intake valve stem guide, wear with the methyl sunflower oil ester as fuel was equal or less than that with petroleum diesel fuel. The wear of the intake valve stem guide was slightly greater. The level of carbon monoxide and nitrogen oxides in the exhaust gases was determined. The level of pollutants with the sunflower oil ester fuel was less or equal to those with petroleum fuel. A Diesel Passat vehicle has completed 40,000 kilometers using sunflower methyl ester as a fuel. Driveability, performance, engine noise, cold starting and fuel consumption remain comparable to those with petroleum fuel.

Similar results are reported from South Africa where a Perkins 4.236 diesel engine in a Massey Ferguson tractor has completed 1300 hours operation fueled by sunflower oil ethyl ester. The tractor is still performing as would be expected with petroleum fuel. The engine was dismantled and inspected after 1200 hours. The carbon deposits on the injector tips were comparable to that experienced with diesel fuel with all the holes still unobstructed. Horning marks on the cylinder walls had not been worn and were still clearly visible. Valve seating surfaces appeared clean and in sound condition. Only slight carbon deposits were evident on the cylinder walls above the first compression ring travel.

It may be noted that relative iodine numbers are not changed by converting a vegetable oil to the methyl or ethyl ester. The reactive double bonds present in the molecule of sunflower oil remain in the ester. It would appear that the greatly decreased viscosity, and increased volatility and cetane number of the ester compared to sunflower oil lead to much more efficient engine injection and combustion so that polymerization cannot occur on the injector tip. Injector deposits and subsequent poor combustion do not appear to be a problem. However, on extended engine operation without an oil change (in excess of 150 hours), both of the above studies reported loss of dispersive properties of the lubricating oil. Within the period between 150 and 200 hours of operation with the engine oil, no wear or abnormal results were observed.

At this stage it is informative to refer to Table 1. Sunflower oil, which has a high iodine value and relative large molecular size, has not been found to successfully fuel diesel engines over an extended operating period. Rapeseed oil, which has a low iodine number, but large molecular size, has successfully fueled several vehicles in excess of 1000 hours, but injector coking and injector pump problems have been reported from some studies. Both palm oil and coconut oil have lower iodine values and lower molecular size than most vegetable oils. Coconut oil has the lowest iodine number and smallest molecular size of all the vegetable oils. The lower molecular size increases the volatility and decreases the viscosity. A low iodine number is indicative that there are few double bonds in the carbon chain to act as centres for polymerization and reactions with the lubricating oil.

On this basis, coconut oil might be expected to be the vegetabl oil which would cause least problems when used as a fuel in diesel engines. By comparison with rapeseed oil, it might be expected that diesel engines could be operated successfully on coconut oil. Due to the particular interest of Pacific Island Countries in coconut oil, all documented studies known to the author in which coconut oil has been used as a diesel fuel are outlined in the following section.

COCONUT OIL AS A DIESEL FUEL

The longest term vehicle running trials with coconut oil fuel have been conducted by Professor Ibarra Cruz, previously of the University of Philippines and more recently the Manager, Energy Research and Development Centre, Philippine National Oil Company. Initial trials were done with a ASTM-CFR stationary diesel engine. In seventy-five experimental runs, the thermal efficiency with crude coconut oil was 33.3 per cent with an average indicated horse power of 6.83, compared to a thermal efficiency of 32.4 per cent and indicated horse power of 6.84 with petroleum diesel fuel. Similar results were obtained with a "DUCATI IS-11" single cylinder diesel engine, commonly used in the Philippines for motor boats. Crude coconut oil was used to fuel a "ISUZU" diesel engine of a passenger Jeepney. 64 trips were made with crude coconut oil over a distance of 7742 kilometers. The thermal efficiency was 11.3 and 12.1 kilometers per kilocalorie for coconut oil and petroleum diesel fuel respectively. The only problems reported was that the coconut oil solidified overnight during the cooler weather. A limited fleet test was carried out with seven buses equipped with M.A.N. diesel engines and five buses with either Hino or Fiat engines. A mixture of 30 per cent coconut oil with 70 petroleum fuel was compared with buses operating on 100 per cent petroleum fuel. The sum of the distance travelled during the trials was 40,000 kilometers. Buses operating on the coconut oil diesel fuel obtained average fuel efficiencies the same as when operating on 100 per petruleum fuel within the experimental variation. The only problem reported was clogged fuel filters due to the formation of slimes in the fuel from the presence of water.

The Department of Works and Supply in Papua New Guinea have carried out extensive tests with coconut oil in a 13 horse power indirect injection Yanmar diesel engine. This engine was run on coconut oil fuel under controlled conditions in excess of 200 hours under the direction of Mr Laurie King. Fuel injection is by means of a single hole injector closed by a pintle pin. The major problem encountered during the trials was the formation of extensive deposits around the injector hole. These lead to poor atomization and a decrease in the efficiency of combustion as shown by increase in the fuel consumption. Poor combustion of the fuel resulted in hard deposits being formed within the cylinder and sticking piston rings. The deposits on the piston rings lead to one of the rings breaking causing extensive scoring of the cylinder wall

A number of variations were investigated in order to minimize the formation of deposits on the injector. A proprietary fuel detergent was mixed with 50 per cent coconut oil and petroleum diesel fuel. Injector deposits were reduced, but not below the level at which inefficient combustion occurred. The pintel pin was shaved to increase fuel bypass. By this means, the temperature of the injector orifice might be expected to be decreased and the rate of shutoff of the fuel after injection should also be increased. Although this measure did reduce the rate of injector deposits, again these were of sufficient levels to cause inefficient combustion. The injection pressure was increased from 140 atmospheres to 170 atmospheres in order to increase the efficiency of fuel atomization and also increase fuel bypass with subsequent injector cooling. No reduction in injector deposits was observed as the relative increase was considered too small. The engine cooling in the vicinity of the injector nozzle was increased by the use of a second water cooling system. This modification was also found to decrease the injector deposits, although not to a level at which they did not cause reduced combustion efficiency. Tests were carried out with 10 per cent ethanol coconut oil mixtures. Reduction in injector deposits were observed, although carbon deposits in the cylinder increased. Problems were also encountered with vapour locks in the fuel line. A fuel of 20 per cent kerosene and 80 per cent coconut oil fuel gave similar results to coconut oil-petroleum fuel mixtures. Since the trials in Papua New Guinea, reports have been published for the effect of injector cooling with sunflower oil fuel. The results are similar to that with coconut oil fuel. Although injector deposits may be reduced in some cases, this reduction is not sufficient to eliminate the problem of decreasing efficiency of fuel combustion as injector deposits increase. None of the many modifications to the fuel or the engine investigated with coconut oil as a fuel in Papua New Guinea were sufficient to prevent the build up to injector deposits. The subsequent poor combustion due to the decreasing fuel atomization will lead to permanent engine damage if steps are not taken to periodically physically remove the deposits from the injector opening.

The Electric Power Corporation of Western Samoa has carried out trials with coconut oil fuel over a number of years under the section of Mr John Worrall. These results are of much interest as coconut oil was used to fuel a 420 BHP Mirless type J6 stationary diesel engine driving an electric generator. This is probably the largest engine fueled by coconut oil fuel. It was found over an eight hour period that the engine gave the same thermal efficiency as diesel fuel at standard load conditions for the engine and was slightly less efficient (5 per cent) when operating with coconut oil fuel at light loads. Subjective comparisons with this engine indicate that it produced less smoke and less noise with coconut oil, has similar exhaust and cooling water temperatures, but was slightly more difficult to start as compared to petroleum diesel fuel. The major problem has been frequent blockage of the engine oil filter when operating on coconut oil or coconut oil diesel fuel mixtures. A number of tests have been carried out with coconut oil fuel in 3 litre truck and land cruiser engines for he vehicles in normal use. The major problem during these trials was the formation of solid particles in the fuel, blockage of fuel filters and difficult starting after overnight cooling. The thermal efficiency of the coconut oil was approximately 20 per cent less than that of petroleum diesel fuel. The trials were not conducted for a sufficient period for the non-combusted coconut oil to cause any serious deterioration of engine lubrication. Operators of the vehicles reported that the engine running was smoother with coconut oil than petroleum fuel once the engine is operating at normal temperatures.

The longest term for which an engine has been run regularly on coconut oil wou d appear to be 18 months. This is the period that Mr Keith Barlow of Vanuatu has been operating a Ford 60 horse power stationary diesel engine on a mixture of 50 per cent coconut oil and petroleum diesel fuel. The engiine continues to operate satisfactorily after this period. A smaller 10 horse power Southern Cross engine has been operating satisfactorily over a two-year period on 100 per cent coconut oil fuel, although this engine has only been used intermitantly in the last six months. The coconut oil which is used as a fuel for these two engines is oil produced in Vanuatu and rejected as being below export grade fo d quality unrefined coconut oil. The only modification to these engines is to preheat the fuel with exhaust gases and careful filtration prior to the engine filter.

Further evidence for the better fuel qualities of coconut oil compared to other vegetable oils has been reported by Perkins Engines Ltd in the United Kingdom. In a series of short term tests, they investigated fuel injector nozzle coking, fuel system deposits and lubricating oil gelation of a number of vegetable oils including coconut oil. Using engine noise as a criteria for cetane numbers, they obtained values 40 per cent greater than normally obtained from ignition delay methods. From ignition noise measurements, cetane value of 60 for rapeseed oil was obtained compared to usual range of 50-60 quoted for petroleum diesel fuel. Many operators who have trialled coconut oil as a fuel, quote it is "quieter" than petroleum diesel fuel. On this basis, the cetane number for coconut oil may be greater than 60. The engine trials by the Perkins Engine Company were run at "worst" conditions for engine coking. This was continuous running under part load. Within a 10 hour period, extensive nozzle deposits, cylinder gums and varnishes were formed with sunflower oil, slight deposits with very little cylinder deposits with coconut oil and virtually no deposits from heated animal tallow from which the slight amount of unsaturated fats had been removed. From these results, it was concluded that problems in the use of vegetable oils as diesel fuel were largely due to the unsaturated bonds (as measured by the iodine number). The use of ethyl esters of saturated and unsaturated vegetable oils was also briefly investigated. Compared to the unchanged triglyceride oils, all injector deposits were greatly reduced. However with a highly unsaturated ester, injector deposits were formed. With relatively saturated esters from coconut oil and animals fats, virtually no injector deposits were observed. The conclusion of the Perkins Engine Company is that the ester physical characteristics very closely resembling conventional petroleum diesel fuels, but with better combustion characteristics due to the absence of the non-carbon chain aromatic compounds present in petroleum fuel.

Trials with various vegetable oils in a 6 horse power indirect injection Yanmar diesel engine have been carried out at the University of the South Pacific over a number of years. These trials were initiated by Professor James Ward of the James Cook University of North Queensland and more recently have been directed by myself. During this period, most helpful correspondence has been maintained with most of the investigators whose results are outlined above. Vegetable oils which have successfully fueled the stationary engine for short period include coconut, sunflower and soyabean oil. These fuels have been used as 100 oil and in admixture with various ratios of petroleum diesel fuel

and also to a lesser extent with kerosene.

In one of these trials, the engine was operated continuously under partial load with a 50 per cent mixture of crude coconut oil and petroleum diesel fuel. At the start of the trial, the thermal efficiency of the coconut oil fuel was the same as that of 100 per cent petroleum fuel. After 130 hours of continuous operation, the efficiency of the coconut oil fuel had decreased by 11 per cent compared to the start of the trial. Immediately following this period, the specific fuel consumption of petroleum fuel was measured in the Engine. It was found that this had decreased by 16 per cent compared to the start of the trial. The injector was removed from the engine and found to have extensive "trumpets" around the nozzle. These were removed and the injector surface polished. The injector was replaced in the engine and the specific fuel consumption of the coconut oil fuel and petroleum diesel fuel determined. Compared to the coked injector, the fuel efficiency had increased by 5 per cent and 8 per cent respectively for coconut oil and petroleum fuel respectively.

The fuel efficiency remained less than that at the start of the trial, so the engine was partly dismantled. It was found that holes connecting the injector pre-chamber with the combustion chamber itself in the cylinder were partly blocked with solid particles. These particles were removed and the engine reassembled. When the fuel efficiency of the coconut oil and petroleum fuel was again determined, these had returned to the values prior to the extended running trial. It may be concluded that the engine had been returned to its original condition. Of interest is the fact that with a coked injector, the decrease in fuel efficiency with coconut oil fuel is less than that with petroleum diesel fuel, although neither are satisfactory.

When the engine was partly dismantled, the upper cylinder walls and piston surface were also inspected. No heavy deposits or scoring were seen on these surfaces. Similarly, there were no heavy deposits on the value surfaces or in the outlet manifold. Small samples of the lubricating oil were withdrawn from the sump while the oil was still hot after each 20 hours of operation during the trials. The used oil samples were analysed by atomic absorption spectroscopy for the major wear metals of iron, chromium, lead and copper. A regular increase was found during the period of the trial, but no greater than would be expected for an engine operating on petroleum fuel. The dispersive properties of the oil were qualitatively examined. These remained within specification for used oil under petroleum fuel operation. As discussed previously, the specific fuel consumption for coconut oil fuel had increased by 11 per cent at the completion of the trial. It would appear that non-combusted fuel was not causing serious degrading of the lubricating oil at the time the trial was discontinued after 130 hours of continuous operation. The lubricating oil was changed at this time.

The deposits in the pre-combustion chamber were not black and shiny as would be expected from polymerized carbon deposits. They were predominantly a red-brown colour, characteristic of metallic silica deposits, particularly of iron. The deposits were similar in appearance to those obtained when a sample of the vegetable oil was combusted in air in a static system to a temperature of 775 C. The amount of non-combustible ash deposits was determined in the crude coconut oil and a number of other oil samples. These results are shown in Table 3. The highest value was that for the crude coconut oil taken from near the bottom of the 200 litre drum. This contained 0.121 per cent non-combustable ash. Samples from the top of the drum had 0.047 per cent ash. Specification for petroleum fuel are less than 0.01 per cent ash. These results are similar to ash contents of crude rapeseed and peanut oil obtained from Dunedin and Townsville respectively. Standard commercial alkali refining of these crude oils reduced the ash contents to 0.008 per cent and 0.02 per cent for refined coconut oil and rapeseed oil respectively. These value may be compared with a ash content of 0.001 and 0.004 per cent for two samples of partly esterified coconut oil, which has been previously called "COCOHOL". The impurities, forming the major constituents of the ash in crude coconut oil, are removed as part of the bottom glycerol layer by a simple decantation in the preparation of "COCOHOL". It would appear that the ash impurities in coconut oil are selectively absorbed in the more polar glycerol bottom layer. A similar effect is found in reverse when petroleum diesel fuel is added to crude coconut oil. Impurities in the coconut oil tend to separate as a slimy solid. This material is particularly effective in blocking fuel filters. In the trials above, it was necessary to pre-filter the mixture of crude coconut oil and petroleum diesel fuel to minimize blockage of the engine fuel filter. For the pre-engine filtration, frequent changes of the filtering element was required. The process for the preparation of "COCOHOL" requires less sophisticated industrial plant than that for the standard alkali refining process. The loss of coconut oil is also less than that of the standard alkali refining process. No coconut oil is lost in fact, but part is converted to glycerol, which may form a valuable byproduct. Industrial glycerol currently has a value five times that of coconut oil, compared to a relatively low value soap stock as the byproduct from the alkali refining process.

"COCOHOL" is the product formed by partial esterification of coconut oil after separation of the glycerol fraction by decantation. The major constituent is the ester, although depending on the conditions under which it is prepared, it also contains unchanged coconut oil, alcohol and some glycerol. The solidification point is generally less than 15C compared to greater than 20C for coconut oil itself. The ester and coconut oil making up the major constituents of the mixture are not soluable in water. Addition of water to the mixture results in the formation of a separate layer, containing largely the added water with the small amounts of ethanol and glycerol from the mixture. The effect of water on the mixture is not unlike the effect of added water to petroleum diesel fuel itself. The viscosity of "COCOHOL" depends on the conditions of preparation, but it is generally similar to petroleum diesel fuel itself. The flash point is largely dependent upon the amount of unreacted alcohol, as the ester itself has a flash point higher than that of petroleum diesel fuel.

Limited trials have been conducted with "COCOHOL" in the indirect combustion Yanmar diesel. Within the experimental error, the thermal efficiency is the same or slightly greater than that with petroleum diesel fuel. After 20 hours continuous operation on partial load, there was no decrease in the thermal efficiency. Only a light coating of a uniform carbon coating was formed on the injector, similar in appearance to those with petroleum diesel fuel. A problem which occurred during these trials was the removal of the glue attaching the paper fuel element of the engine fuel filter to a metal holder. This process occurred within one or two hours of passing the "COCOHOL" fuel through the filter. A similar process was found with two other standard Yanmar filters. Discussios with Mr Ron McLeod in New Zealand, following the use of partially esterified rapeseed oil as a fuel for a short period in a Datsun sedan, indicate a similar problem with removal of the adhesive from the fuel filter. With the Datsun vehicle, the adhesive subsequently caused gumming in the injectors. Esters in general are much more effective solvents than hydrocarbons, and more extensive materials testing trials are required before esters can be used with confidence as a fuel.

CONCLUSION AND RECOMMENDATIONS

There is no doubt that vegetable oils will successfully fuel diesel engines. Coconut oil has the best characteristics as a fuel of all common vegetable oils. The engine trials which have been carried out with coconut oil are limited. Conclusions from these trials would suggest that the only short term problem with coconut oil fuel is possible clogging of the engine fuel filter. This problem is easily remedied by changing the filter element. The rate at which the engine filter clogs may be minimized by efficient pre-filtration of the coconut oil fuel. A standard portable filter as used by electricity authorities in the region for the filtration of transformer oil is well suited for this purpose.

Partial solidification occurs when coconut oil is cooled to temperatures below 25C for an extended period. A mixture of the coconut oil with diesel fuel reduces the temperatures at which solid forms. A 50 per cent mixture with petroleum diesel fuel has a solidification point below 15C. The effect of water on the mixtures is not fully understood. Small amounts of water will dissolve in the mixture. Larger amounts of water form a separate layer with the separation of solid particles in some instances.

Longer term running of the engine with coconut oil fuel may produce deposits on the injector(s) of the engine. These deposits may lead to poor fuel combustion and contamination of the lubricating oil with unburnt fuel. Chemical reaction between the vegetable oil and antioxidants in the engine oil may lead to loss of lubricating properties in the oil and subsequent permanent damage to the engine. No damage is done to the engine if the injectors are cleaned on a regular basis with regular changes of the engine oil.

Engines for which injector coating has been significant have been small single cylinder indirect injection engines. Although not as closely monitored as the small engines, there has been no evidence for injector deposits leading to poor combustion with larger direct injection engines in stationary engines, light commercial vehicles or in buses. Careful monitoring of a number of larger diesel engines operating on coconut oil is required so that factors controlling the formation of injector deposits are better understood. Should international prices for coconut oil remain at present levels or decrease, these trials can be done with an economic saving compared to the utilization of petroleum diesel fuel at many centres in the Pacific Islands. It is not recommended that crude coconut oil be used directly as a fuel, just as the use of crude petroleum oil is not recommended. However, the use of filtered coconut oil under technical supervision is economically and technically feasible at the present time.

At a small price premium, less than that for alkali refining of vegetable oils, the coconut oil may be chemically reacted with alcohol to form a fuel mixture containing largely the ester. The ester of coconut oil is better fuel for diesel engines than petroleum diesel fuel itself. The Perkins Diesel Engine Company has suggested it will extend all guarantees to engines operating on ester fuels. The esters of coconut oil may also be used as a kerosene substitute in domestic appliances such as pressure lamps and stoves and in wick stoves. In these applications, the esters are a much safer fuel than kerosene due to a higher flash point and lower volatility. The esters cannot be used in wick (Hurricane) lamps as the combustion is too eficient leading to a non-incandescent flame. These esters may be transported and stored in the region as for petroleum diesel fuel or kerosene at the present with a much greater fire safety factor.

TABLE 1. VEGETABLE OIL CHARACTERISTICS

OIL	SOLIDIFICATION POINT (C)	IODINE VALUE	SAPONIFICATION VALUE
COCONUT	20-25	10	268
PALM	30-35	54	199
RAPESEED	-10	98	175
SUNFLOWER	-17	125	189
PEANUT	3	93	192
SOYBEAN	-16	130	191
LINSEED	-24	179	190

TABLE 2. DIESEL OIL CHARACTERISTICS

CHARACTERISTIC	PETROLEUM DIESEL	SUNFLOWER OIL	COCONUT OIL	"COCOHOL"[a]
K. viscosity (40C) $mm^2 s^{-1}$	2-4	30-34	24-28	3-6
Cetane numer	40-60	30-40 or 60[b]	>60[b]	>60[b]
Cloud Point (C)	-9	-6	25	2-6
Calorific value (MJ l^{-1})	38	36	35	33
Flash Point (C)	60-70	320	-	-
Ash (%)	0.02	0.05-0.4	0.05-0.15	0.001

[a] ethyl esters coconut oil

[b] estimate from engine noise levels

TABLE 3. VEGETABLE OIL MEASURED ASH LEVELS

TABLE 3.

OIL	ORIGIN	ASH (%)
CRUDE COCONUT	FIJI	0.05-0.12
ALKALI REFINED COCONUT	FIJI	0.008-0.071
CRUDE PEANUT	QUEENSLAND, AUST	0.08
CRUDE RAPESEED	NEW ZEALAND	0.10
ALKALI REFINED RAPESEED	NEW ZEALAND	0.02
PROCESSED PALM	SOLOMON ISLANDS	0.006
COCOHOL	FIJI	0.0008-0.002