

RENEWABLE OIL FUELS AND DIESEL ENGINES AS  
COMPONENTS OF SUSTAINABLE SYSTEM DESIGN

by

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## CHAPTER ONE – STUDY BACKGROUND

### Introduction

“You see, we should make use of the forces of nature and should obtain all our power in this way. Sunshine is a form of energy; wind and sea currents are manifestations of this energy. Do we make use of them? Oh no! We burn forests and coal, like tenants burning down our front door for heating. We live like wild settlers and not as though these resources belong to us.” **Thomas A. Edison, 1916 (European Forum for Renewable Energy Sources, 2000, n.p.)**

“The use of vegetable oils for engine fuels may seem insignificant today. But such oils may become in the course of time as important as petroleum and the coal tar products of the present time.” **Rudolph Diesel, 1912 (Tickell and Tickell, 1999, p. 23)**

### Research Question

"Are renewable oils (RO), as fuels in unmodified compression ignition (diesel) engines, a technically and economically feasible component of sustainable system design, in both developing and developed countries?"



## Definitions

Some of terms and concepts in this thesis may not be familiar to the reader. These are explained below.

### Renewable Oil Fuel (RO)

In this thesis, renewable oil (RO) fuel is defined as *oil that can be annually renewed primarily by solar inputs, can be made suitable for long term use in diesel engines, and is liquid at atmospheric pressure in a temperature range of at least 0-100 degrees Celsius.*

As used in this thesis, “RO” is the broad category of renewable oil, consisting of the following RO fuel subcategories:

- Straight Renewable Oil (SRO)
- Biodiesel

Further explanation of the subcategories is provided in later sections.

### Recovered Renewable Oil (RRO)

Renewable oil that can be used in the form of *either SRO or biodiesel fuel*, as these are defined above, can consist of either new renewable oil (e.g. straight from oilseed presses) *or* “recovered renewable oil” (e.g. spent renewable oil from restaurant deep fat fryers and grease traps, household kitchens, and

wastewater treatment facilities, that has been collected and processed for reuse). RO can also consist of a blend of new and recovered feedstocks.

### Renewable Oil Fuel System (ROFS)

Although the term renewable oil fuel system could be taken to mean the entire production distribution and use of RO fuel (especially since this thesis places an emphasis on sustainable system design), the term is not used in this way. Instead, the term refers to an auxiliary fuel system that is added to a supply SRO to a specific diesel engine. A ROFS, as defined for the purposes of this thesis, is the combination of fuel tanks, hoses, filters, heaters, switches and valves that allow the use of unmodified SRO in an unmodified diesel engine. Waste engine heat is captured and used in a ROFS to heat the SRO, thereby reducing its viscosity to make it suitable for use as fuel in many diesel engines. Details of the ROFS are provided in later sections.

### Sustainability and Sustainable System Design

There have been many attempts to define sustainability, but essentially sustainability means using only the amount of resources needed in the present, such that resources may remain available in sufficient quantities for

future generations. This is admittedly an anthropocentric definition.

However, the more sustainable human activities become, the more the biosphere in general will benefit. A recognition that humans are not separate from the ecosystem in which they live and that this ecosystem is complex and interrelated is central to the concept of sustainability.

All forms of life on the planet, including humans, derive their well being from continuous, cyclical operation of an incredibly complex ecosystem that has provided a storehouse of resources. Many of these resources are self-renewing, at various time scales, using the sun's energy. Human desires for economic wealth and peaceful civil society are completely dependent on adequate supplies from this storehouse of natural resources. Humans have only recently begun to accept that the activity of their own ever-growing numbers will eventually destroy the functioning ecosystem that sustains them unless change occurs.

Sustainable system design recognises the limits imposed by the natural system. A systems approach is used to provide services that people desire, without exceeding what is known of those natural system limits. Viewing a design problem as part of an interrelated system of provision of services, rather than in isolation, generally reveals opportunities for greater efficiency.

Conducting a complete sustainable system review can reduce demand for a given service. This demand reduction process determines the system size that

is truly needed. If demand is reduced, system size is reduced, and it may be that a new paradigm thereby emerges which allows the use of materials, technology and resources previously considered too scarce or expensive. Such demand reduction and related paradigm shifting is essential in meeting human demands for services in a sustainable way.

The human population of the planet is projected to grow from the current six billion to nine billion by 2050 (United Nations, 1998). In light of this growth in population, substitution of renewable for non-renewable resources, and ever-increasing efficiency of resource use, will be necessary.

The general purpose of the research for this thesis was to examine RO-based alternative diesel engine fuels from the viewpoint of sustainable system design and to attempt to determine the extent to which the fuel/engine combination might meet the demands of that particular design philosophy. A combination of literature review and applied research was determined to be the most appropriate approach.

### **The Diesel Engine: Technical Advantages, Problems of Widespread Use**

The Compression Ignition (Diesel) Engine and Petroleum (Petrodiesel) Fuel

Diesels range in size from tiny model aircraft engines to those used in motorcycles (Royal Enfield, 2000), cars, trucks, buses, locomotives and ships.

Other applications of diesel technology include electrical power production (generator sets or “gensets”), refrigeration and heating of goods in transit (Thermo King, 2000), self-powered agricultural equipment and water pumping systems. Diesels are used to run equipment in the search for more of the very fossil fuel on which they are normally operated. A small air-cooled diesel was even specially modified to drill ice cores at elevations as high as 21,000 feet as part of a sampling expedition to the Puruogangri ice cap in China in September 2000 (Diesel Progress, 2000).

Diesel engines are ubiquitous in society precisely because they are the most efficient and cost-effective prime mover available. This efficiency is primarily due to the high compression ratio that is used to create heat and cause spontaneous ignition of diesel fuel (Kennedy, 2000). Because they must be built to withstand the very high internal forces of high compression, diesel engines cost more than other engines. Greater fuel efficiency, reliability, and longevity justify the extra cost.

There is a correlation between the amount of fuel burned per unit of work and the exhaust emissions an engine generated. The diesel engine is inherently more fuel-efficient than gasoline engines. Therefore, certain exhaust emissions, including those that are routinely tested for in emissions tests modelled on USA Environmental Protection Agency standards (often referred to simply as “regulated emissions”, are lower for diesel engines than

for gasoline engines of comparable age, condition and capability. These regulated emissions include total hydrocarbon (THC), carbon monoxide (CO) and nitrogen oxide (NO<sub>x</sub>). This is true even if the diesel engine *is not* fitted with a catalytic converter and the gasoline engine *is* fitted with a catalytic converter. Greater fuel efficiency that reduces the amount fuel required, reduced CO<sub>2</sub> emissions compared to gasoline engines, and reductions in “regulated emissions” explains why the diesel engine is considered to be a more environmentally acceptable engine than the gasoline engine in some regions of the world, especially in Europe (Diesel Progress, 2001).

However, diesels operating on fossil fuel derived petroleum diesel (petrodiesel) fuel emit unacceptable levels of particulates. These are unburned hydrocarbons, the black soot associated with diesels. These particulate emissions pose recognised cancer, respiratory and cardiopulmonary risks to human health. Other emissions and environmental, socio-political and economic concerns also exist in relation to the use of this fuel/engine combination. These issues are discussed in more detail in the following sections.

New technology such as hydrogen fuel cells, efficient photovoltaics, wind turbines and many other renewable energy service providers will eventually replace the diesel engine. However, the cost of these still exceeds that of

diesel technology, sometimes by a wide margin. Millions of diesel engines that already exist or will be manufactured over the next few decades are likely to remain in service for many years. The problems posed by the current fuel/engine combination cannot be ignored, but economically and technically feasible substitutes must be made available before abandonment of that combination can occur.

The remaining sections of this chapter are intended to provide further insight into the problems posed by human reliance on diesel engines, and the possibility that may exist to at least partially mitigate these problems through substitution of petrodiesel with renewable oil as fuel for the diesel engine.

### Direct Injection and Indirect Injection Diesel Engines

New diesel engines are much cleaner than earlier versions due to changes in their design that result in more complete combustion of the fuel. Direct injection diesels are gaining in prominence over earlier indirect injection types. In direct injection, the fuel is injected at very high pressure directly into the main combustion chamber. Indirect injection types use lower pressure to inject fuel into either a “pre-chamber” or swirl chamber attached to the main combustion chamber.

## Diesel Exhaust After-Treatment Technology

Diesel exhaust after-treatment technology, such as particulate traps and catalytic converters exists but has not yet seen wide application. Such devices will be brought into much wider use in coming years and will greatly assist in addressing the problems associated with diesel exhaust emissions. To function properly, this end-of-pipe solution requires that most of the sulphur normally found in petrodiesel be removed. However, the fuel injection pumps and injectors on diesel engines are complex, expensive, precision devices. They are solely dependent on the fuel that passes through them for lubrication. Sulphur normally found in petrodiesel provides the necessary “lubricity” (the ability to provide lubrication) for these pumps, but also causes elevated sulphur dioxide emissions. RO fuels provide excellent lubricity to fuel injection pumps and contain virtually no sulphur. They therefore represent a possible solution to the above dilemma.

The introduction of new diesel engine technology, exhaust after-treatment and sulphur reduction in petrodiesel fuel provide only partial answers to the problems posed by widespread use of the petrodiesel fuel /diesel engine combination. This will be discussed further in later sections.



## Embodied Energy and Economic Necessity of Existing Stock of Diesel Engines

The embodied energy of diesel engines includes the energy used to extract and process resources for manufacturing the existing stock, the energy used in the actual manufacturing process, and the energy used in transporting the existing equipment to the site. Additional energy would be used in removing, transporting, and recycling the old engines into new ones. Emissions are related to energy use. Therefore embodied energy and recycling energy used represent historic and potential emissions. The sum of such embodied energy, and requirements for new energy use to perform recycling, must be included in the decision-making process concerning potential replacement of functioning engines.

## Scale and Scope of Diesel Engine Use

Diesel engines play a major role in the current world economy. Globally, there are approximately 200 million diesel engines in use, and 20 million new engines are built each year (Harris, 1999). Their durability and economy mean that the engines currently in service may not need replacement for decades. In fact, economic circumstances usually dictate that that the longest possible service life be obtained from what is a very large initial investment. Many users of existing diesel engines simply cannot afford to replace them until they are completely worn out and can no longer be rebuilt. This is

especially true in developing countries. This dictates that very economical approaches for emissions reduction should be used if available. RO fuel substitution could be such an economical approach.

Demand for new diesel engines will also continue to grow, since diesels are less expensive and/or capable of providing power more consistently than turbines and other replacements such as wind power or photovoltaics, and more fuel-efficient, durable and reliable than spark-ignition gasoline or natural gas engines (Harris, 1999).

#### Environmental / Health Effects Related to Diesel Exhaust Emissions

The operation of millions of diesel engines on petrodiesel fuel contributes to a number of environmental and human health concerns. Health effects are most severe when diesels are operated in large numbers in densely populated areas. Diesel exhaust emission sources that are most obvious in the urban environment include trucks, buses, and diesel automobiles. However, there are also many other types of diesel powered equipment that operate on a regular basis in densely populated urban areas, including most construction, landscaping, maintenance and backup electrical generating equipment. Local topography and weather conditions can make the problem of petrodiesel exhaust emissions in urban areas even worse.

In addition to the local effects that are most noticeable, petrodiesel exhaust emissions from diesel engines also contribute to pollution of the global atmosphere.

The California Environmental Protection Agency's Air Resources Board declared diesel exhaust emissions (from diesel engines operating on petrodiesel) to be a toxic air contaminant in 1998 (Air Resources Board, 2000). The USA and many other governments around the world are moving forward with measures to reduce harmful diesel exhaust emissions (Samet, Dominici, Zeger, Schwartz, and Dockery, 2000).

General concern about diesel exhaust emissions is illustrated in the following quotes:

“...reliance on diesels comes at the unacceptable price of human health and clean air. Diesel particulate exhaust has been declared a carcinogen by the World Health Organisation, the National Institute for Occupational Safety and Health, and the California Air Resources Board. Diesel engines account for approximately 26 percent of the total hazardous particulate pollution in the air and 66 percent of particulate pollution from motor vehicles. Particulates are linked to increased asthma emergencies and to thousands of premature deaths in the

United States every year. Diesel vehicles also emit high amounts of nitrogen oxides, a major component of smog and acid rain.” (Natural Resources Defense Council, 2000, n.p.).

At the time of this writing, the USA federal Environmental Protection Agency has, after over a decade of study, taken a position on the carcinogenic effect of diesel engine exhaust when operating on typical petrodiesel fuel. Such exhaust emissions have been characterised as “likely to be carcinogenic”(Dieselnet, 2000, n.p.).

#### Particulate Matter Emissions from Diesel Engines Operating on Petrodiesel

Diesel engines operating on petrodiesel are a major source of a number of emissions of concern, including particulate matter (PM). PM<sub>10</sub> (particulate matter 10 microns or less) and the fine fraction PM<sub>2.5</sub> (2.5 microns or less) have been clearly identified as contributing to increased premature human mortality and morbidity (Samet et al., 2000).

PM<sub>10</sub>, regardless of source, has recently been declared a toxic substance under the Canadian Environmental Protection Act (Environment Canada, 2000). A number of other disorders are increasingly being linked to diesel exhaust emissions in both laboratory and epidemiological studies. These health effects include contributions to asthma, bronchitis, and

cardiopulmonary disease (Natural Resources Defense Council, 2000). In addition to the human hardship, the economic cost can be measured in terms of lost productivity and increased health care costs. Environment Canada has attributed over 70% of total PM emissions from the transportation sector to the exhaust of diesel engines, excluding air transport and marine transport which also rely heavily on petrodiesel (Environment Canada, 2001).

### The Role of Fine Particulate Matter in Diesel Exhaust in Regard to Climate Change

It is also becoming apparent to researchers that fine particulates in the exhaust from diesel engines operating on petrodiesel may have both a positive and negative effect concerning climate change. Fine particulates composed of carbon black, for example, absorb heat, whereas those of other composition reflect heat. A reduction in the amount of carbon black (soot) as a component of diesel exhaust emissions could therefore assist in reducing the overall heat-trapping potential of those emissions, and thereby assist in efforts to mitigate anthropogenic, climate altering contributions of pollutants to the atmosphere (J. McTaggart-Cowan, personal communication, 2001).

## Atmospheric Transformation and Deposition

In addition to the carcinogenic or toxic constituents of the particle itself, other toxics adhere to it once it is emitted to the air, and thus the particle is an exposure pathway for other contaminants of concern, such as PAH's (Environment Canada, 2001). These adhered materials could be from the exhaust emissions stream, or could be present in the atmosphere from other sources and then be added to the emitted particles via atmospheric transformations. Once adhered, there is the additional concern that new compounds can be formed by interactions between the chemicals of the particle itself, adhered exhaust stream chemicals, and additional adhered chemicals present from other sources present in the atmosphere. The final composition and effects of such compounds are very difficult to predict, and could produce additional health and environmental effects as they move through the atmosphere and are eventually inhaled, or deposited into the water or onto the soil. The issue of atmospheric deposition to water serves as a reminder that the separation between contamination of air, water, water, soil and species exists only in the human mind. The issue of arctic contaminants, and the following quote regarding pollution in the Great Lakes further illustrate this:

“Atmospheric deposition is a significant source of certain toxic pollutants entering the Great Lakes. In fact, as much as 90 percent of some toxic

loadings to the Great Lakes are believed to be the result of airborne deposition” (Delta Institute, 2000, n.p.).

PM is a serious diesel engine emissions problem.

### Carbon Dioxide (CO<sub>2</sub>) Emissions from Diesel Engines

Reliance on diesel engine technology has reached a level such that some emissions contribute to environmental impacts at the global level, as opposed to the local air quality level. Carbon dioxide emissions from diesel engines operating on petrodiesel are lower than for equivalent gasoline engines, due to the inherent efficiency of the diesel engine. In that regard, the diesel can be considered to be superior to the gasoline engine, and a route via which carbon dioxide emissions could be reduced. Despite this, the global contribution of carbon dioxide to the atmosphere from diesels is still significant, due to heavy reliance on diesel technology. Therefore, a CO<sub>2</sub> neutral, renewable fuel suitable for use in the diesel engine is needed.

### Sulphur Dioxide (SO<sub>2</sub>), Nitrogen Oxide (NO<sub>x</sub>) and Polycyclic Aromatic Hydrocarbon (PAH) and Carbon Monoxide (CO) Emissions from Diesel Engines

The following exhaust emissions from diesel engines operating on petrodiesel fuel are also of particular concern:

- Sulphur dioxide, a source of PM<sub>2.5</sub> and the cause of acid precipitation (J. McTaggart-Cowan, personal communication, 2000),
- Nitrogen oxide, a cause of acid precipitation and a precursor to the formation of ground-level ozone and PM<sub>2.5</sub>, major constituents of urban smog (J. McTaggart-Cowan, personal communication, 2000)
- Polycyclic aromatic hydrocarbons, which may pose a cancer risk (Environment Canada, 2001)

## **Renewable Oil – A Traditional Renewable Fuel - and Potential Alternate Fuel for the Diesel Engine**

### Historic Use of Renewable Oil as Fuel

Humans have used renewable oils have for thousands of years. An example is the oil lamp. Versions of such lamps remain commercially available to this day, even in developed countries such as the USA (Lehman's, 2000). The



following quote illustrates the centuries-old connection between humans and renewable oil, referring in this case to olive oil:

“Olive oil is one of the oldest lamp fuels known to man...a native of the Mediterranean...used and cultivated in that region since prehistoric times”  
(Corliss, 2000, p. 1).

Renewable oil fuels were also used in early versions of the diesel engine – the engine actually predates the widespread availability of inexpensive fossil fuel. When Rudolph Diesel first displayed his engine at the 1900 World Exhibition in Paris, he used peanut oil as the fuel.

The era of cheap petroleum meant that renewable oil was abandoned as a fuel for diesel engines, at least for the past several decades. The modern diesel fuel injection system co-evolved with less viscous petrodiesel, a by-product of gasoline distillation, which from the early part of the twentieth century to present became so inexpensive that there was little motivation to research and use alternatives (Tickell and Tickell, 1999).

Like many new products, inexpensive and abundant petrodiesel was introduced to the market without regard for the possibility that negative consequences could arise from its large-scale use over time. Growing awareness of these negative consequences has rekindled interest in the use of

renewable oil fuels. The long history of renewable oil use in cultures around the world may partly account for the current popularity of the idea.

Renewable oils are often an easily obtained resource, crushed from the seeds of plants grown nearby. The sun is the only true provider of renewable energy. The close connection between renewable oil and the sun is apparent and easily appreciated – the oil is literally *stored solar energy*, created solely by photosynthesis. The need for fertile soil and adequate water to produce the oil is also easily appreciated. The technology of pumping, transporting and refining fossil fuels has broken the link between people and the cycles of nature, by allowing profligate use and extremely rapid depletion of a non-renewable, finite and ancient resource. The appeal of renewable oils lies in the perception that their appropriate production and use may be one way to restore that connection.

### Renewable Oil as Fuel in Diesel Engines

Renewable oils are considerably more viscous than petrodiesel. If the viscosity is reduced to approximately that of petrodiesel, they can be used as fuels in diesel engines without modifications to the engine or fuel injection system. There are, at present, two approaches to such viscosity reduction – referred to in the balance of this thesis as the “**Renewable Oil Fuel System**” (**ROFS**) approach and the “**biodiesel**” approach.

There are advantages - as well as economic, logistic and technical challenges - to either of these two approaches. This is especially true when they are considered within a sustainable system design framework, which places additional demands on any design.

#### Renewable Oil Fuel System (ROFS) Viscosity Reduction Approach

If vegetable oil is heated to approximately 70° C, its viscosity is reduced enough that it can be used in many fuel injection pumps and diesel engines. Coincidentally, this is the approximate operating temperature of the engine. The engine generates a great deal of surplus heat. If the engine is liquid cooled, the circulating coolant can be routed through a heat exchanger and surplus heat then used to reduce the RO fuel viscosity.

The basic operating procedure of a ROFS is as follows:

- The engine is started on petrodiesel (or biodiesel).
- A fuel switching solenoid valve is used to switch to vegetable oil once operating temperature is reached.

The injector pump, filter, and injectors must be purged of RO by once again operating on petrodiesel or biodiesel before the engine is shut off for more than a short period of time (this varies with ambient temperature).

This approach allows use of straight renewable oil (SRO) in an auxiliary fuel tank for a large proportion of the time the engine is operated. “Straight renewable oil” simply means any renewable oil that has not undergone transesterification or blending with other substances.

### Biodiesel Viscosity Reduction Approach

Alternatively, RO can be converted via “transesterification” (a chemical process explained in further detail in later sections). The resulting reactants are alkyl ester (“biodiesel”) and crude glycerine. Biodiesel can be produced in large quantities in efficient but capital-intensive process plants. It can also be made in small batches with very inexpensive equipment and minimal training.

Biodiesel has other uses in addition to diesel engine fuel. It can be used as a kerosene substitute in lamps, heaters and stoves and is an excellent paint remover, penetrating oil/lubricant, rust inhibitor, and degreaser. The glycerine by-product can be used to make soap (Tickell and Tickell, 1999).

Biodiesel production starts with SRO. Required biodiesel process inputs such as methanol, sodium hydroxide and labour (or its replacement with specialised equipment), represent costs that make biodiesel more expensive than SRO. Biodiesel can be used in blends with petrodiesel or used “neat”

(100%) in any diesel without modification to the engine itself or the need to add auxiliary tanks, switches or lines as is the case with SRO fuel in a ROFS. Biodiesel is non-toxic, has a high flash point, and biodegrades in approximately half the time of petrodiesel (National Biodiesel Board, 2000).

These advantages are offset to some extent by the cost of biodiesel. Since SRO is currently *less* than the cost of petrodiesel, and biodiesel cost is two to three times *greater* than petrodiesel (in North America), there could be operating cost advantages to the use of SRO in a ROFS, if the ROFS system cost could be minimised. This “cost –versus-convenience” factor necessitated some investigation of both approaches for this thesis.

#### Emission Reduction Potential of Renewable Oil

Obviously, given the above facts, a pollution prevention strategy for the reduction of diesel particulate emissions, especially of fine particles, is needed. The chemical composition of diesel exhaust emissions must also be addressed. RO fuels have been investigated for their potential in reducing emissions and appear to offer advantages over petrodiesel fuel. Both the literature review and the research project behind this thesis were intended to gain a better understanding of the potential of RO in this regard.

## Other Concerns and Risks of Fossil Fuels and the Potential Role of RO in Reducing Such Risks

Diminished air quality, acidic precipitation, toxic chemical transport, climate change impacts and health effects as a result of exhaust emissions are serious issues, but are not the only concerns in regard to the general dependence on fossil fuels. Fossil fuels are not evenly distributed around the globe, which means they must often be transported great distances from source to market. This increases the potential for soil and water contamination at any point in the extraction; bulk transport, refining, distribution, and storage supply chain. Such releases are frequent and are a major cause of soil, groundwater and surface water pollution (J. McTaggart-Cowan, personal communication, 2000). In Canada, an estimated 10,000 m<sup>3</sup> of crude oil are released into the environment from oil well blowouts and spills each year (National Environmental Indicator Series, 2000).

Since fossil fuels are both non-renewable and unevenly distributed, greater risks are taken over time to ensure a steady supply. These risks are of both a technical and political nature. The current pattern of supply tends to be a source of regional and international conflict, and certainly results in economic disparity. “Have” countries prosper while “have-not” countries, lacking their own reserves, or the means to buy from others at market prices,

fall behind in terms of economic development. Even when fossil fuels like petrodiesel are available, prices often strain the budgets of many purchasers, who may have no other energy source that can so effectively and conveniently meet their needs.

Even in cases where countries can afford to purchase supplies of fossil fuels from other regions of the world, this activity carries with it a higher cost and greater risk than is often perceived. The costs of military protection of fossil fuel shipments and military interventions such as the Gulf War, for example, are paid from general tax revenue, not added directly to the fuel purchase price, as they should be. A reduction in the demand for fossil fuels, through conservation and efficiency measures, coupled with the creation of a locally-based renewable fuels infrastructure, has the potential to lessen the conditions which lead to international conflict.

In addition to the international political risks involved in the acquisition and transport of fossil fuels, the high cost of spill cleanup and remediation of contaminated sites, coupled with liability and due diligence concerns, have increased the financial risks involved in the use of liquid fossil fuels.

Environmental and financial risks could be greatly reduced through the use of renewable oil as a replacement for liquid fossil fuels (Blondeau, Pon, Bresciani, and Reaney, 1997).

The cleanup costs of releases of fossil oil to the environment are often passed on to society. In economic terminology they are “externalities”. Such costs are not factored in to the initial price of the fuel and are among the many subsidies society allows for fossil fuels in exchange for artificially low prices. For example, subsidies to fossil fuel industries have been estimated to be in excess of \$20 billion per year in the USA alone (Hawken, Lovins, and Lovins, 1999).

The recent spill of approximately 1,000,000 litres of petrodiesel and bunker ‘C’ fuel oil from the tanker Jessica is a case in point. The tanker was delivering the fuel to the Galapagos Islands area, to be used primarily in the many tour boats that transport tourists to the “fragile ecosystem, one populated by species found nowhere else in the world and an inspiration for Charles Darwin's theory of evolution” (Cable News Network, 2001, n.p.).

The Jessica was not insured against environmental contamination:

“Shipping authorities have confirmed that the Jessica was not insured for environmental contamination... International shipping rules require such insurance for vessels carrying 2,000 tons of fuel, while the Jessica had only 300 tons aboard, Galapagos park officials said” (Cable News Network, 2001, n.p.).



Various tax-supported organisations were called upon to assist in dealing with the spill, including the United States Coast Guard (Cable News Network, 2001).

In this particular case, biodiesel, which poses much less of a threat to sensitive marine environments in the case of a spill than does petrodiesel (von Wedel, 1999), should have been the fuel of choice. The case illustrates that society currently allows and subsidises an activity that carries with it significant environmental risk – the transport of fossil fuels.

Renewable oil fuels are safer than petrodiesel (von Wedel, 1999), and would be a better choice in areas such as the Galapagos. They could be supplied to local or regional prioritised markets including sensitive marine areas and densely populated urban areas. Locally produced, renewable fuels could reduce risk and, at the same time, contribute to local economic and social development by creating ongoing employment opportunities and by retention of locally generated energy-related profits. In this way, economic multiplier effects could also occur.

Alternative fuels could be of value in allowing the diesel engine to remain in use within sustainable system and thereby allow society to continue to benefit from its versatility, convenience, compact size, power, longevity, efficiency and reliability. However, to address the concerns outlined above,

and to be considered a worthy substitute for petrodiesel and truly a component of sustainable system design, any proposed alternative diesel engine fuels should meet at least the following suggested criteria:

- Renewable (derived from a source that captures solar energy on an ongoing, short cycle of one year or less).
- Capable of being produced inexpensively and easily from low cost, local sources in most regions of the world (preferably from a source normally considered to be a “waste stream”).
- Result in reduced emissions compared with petrodiesel.
- Result in no detrimental effects to the engine and preferably provide greater injector pump lubricity, without containing sulphur.

As noted above, concern about petrodiesel emissions has intensified in the last few years. Some governments, including Canada, are now responding by requiring refiners to reduce the sulphur content of petrodiesel (Environment Canada, 2000). In some cities, there are now outright bans on diesel engines. For example, Hong Kong has recently passed legislation to replace some 18,000 diesel taxis with propane powered vehicles (Addison, 2000). Another example is recent legislation announced by the South Coast Air Quality Management District, the organisation responsible for air quality in an area of southern California that has some of the worst smog in the United States.

This agency has recently created new public fleet rules. These require all “new vehicles purchased or leased by public fleets be powered by natural gas, methanol, electricity or fuel cells” (Dieselnet, 2000, n.p.).

Diesel engine manufacturers and other proponents claim that this is an unfair approach. Compared with gasoline-fuelled engines, diesels will perform the same unit of work on less fuel. Because of this inherent efficiency, some emissions, such as hydrocarbon (HC) emissions are actually lower for diesels than for gasoline engines of similar capability, age and condition (B. Coupland, personal communication, 2000). Because a diesel must withstand tremendous explosive forces, they are more heavily built and therefore last longer than gasoline engines. This makes more efficient use of the embodied energy of the materials used. Diesels are therefore desirable in some respects. The conflict between efficiency and emissions must be successfully resolved. Sustainability criteria add the need to maximise efficient operation and renewability and local production of fuel. If the conflict is not resolved, the following outcomes can be expected:

- Pressure to reduce or ban diesel engines will intensify, and more diesel bans will occur. The advantages of the diesel could be sacrificed in the effort to reduce emissions by switching to other engines.

- Alternatively, the diesel engine will *not* be banned or restricted in many other areas, nor the fuel switched to a cleaner alternative. Emissions and other problems with petrodiesel and fossil fuels in general, mentioned above, will increase.
- Conversions to natural gas use in diesels will likely be legislated in some areas. In some respects, natural gas is not considered to be as safe as RO. It is lighter than air and normally disperses, but this does not always occur. “Natural gas vapours at low temperatures (from leaks of cryogenic LNG or CNG cooled by thermodynamic expansion) are dense and can form clouds of flammable vapour concentrations” (Toy, Graham and Hammitt, 2000, p.3). Conversions are very expensive compared to the use of RO (especially as biodiesel), particularly for mobile applications. Natural gas technology for use as a diesel fuel substitute, without loss of power or fuel economy, is not yet proven in large-scale applications over the longer term. Very strong demand is forecast for natural gas, as power plants are converted or constructed to burn natural gas instead of coal, as more natural gas is used for home heating, and as the use fertilisers, chemicals and plastics derived from natural gas continues to increase. Therefore, natural gas may not be as inexpensive in the future as has been assumed. Regulations requiring the use of natural gas solely for the purpose of

reducing emissions, if equally effective and much less expensive options exist, would be inequitable and economically unsound.

None of these outcomes represent the best solution to the problem at hand, which would be to retain the efficiency of the diesel, yet achieve reduced emissions using a reasonably priced, locally produced, renewable fuel.

### **Potential Causes of the Problem/Opportunity**

#### **Market Penetration of Diesel Engines**

The world “population” of diesels has grown quickly since the 1950’s. In fact, the diesel engine is a victim of its own success. Having displaced the steam engine almost entirely within a few decades, it has now become the engine of choice in a wide range of applications. A largely unnoticed but essential part of the functioning of the global economic system, and now also recognised as a major contributor to environmental and health concerns, the issues surrounding the diesel have yet to be dealt with. Thus, there is a rapidly emerging opportunity for companies that can successfully address this challenge.

## Petrodiesel Pricing

Petrodiesel continues to increase in price due to:

- Supply controls by the oil producing states.
- Increases in taxation (sometimes as a result of environmental protection policy).
- The need for more expensive exploration, extraction, transportation and refining processes as reserves become depleted and regulations require reduced sulphur content.
- General growth in demand due to increased reliance and population increase

As petrodiesel prices increase, an opportunity is being created for alternative, renewable, CO<sub>2</sub> neutral, naturally low sulphur fuels.

## Future Demand for Diesels and Implications of Diesel Engine Longevity

Factories that make the materials for diesel engines, and those actually engaged in diesel engine manufacturing have already or will in future be required to clean up their own operations. The cost of this and costs related to

provision of cleaner diesel engine designs, exhaust after-treatment devices, and cleaner burning fuels will combine to drive up the cost of diesel engine use. However, the features offered by diesels, in combination with a competitive price compared to competing products, will continue to drive sales of new diesels. These new engines, and the existing stock, are very likely to remain in operation for decades. Therefore, the lifetime emissions of an individual engine must be taken into consideration and realistic arrangements made to minimise the impacts of their use.

#### Petrodiesel Substitution with Renewable Oil

If the negative effects of diesel engine use can be reduced via an approach that places due emphasis on local production and appropriate, affordable technology, it may be possible to consider both diesel engines and renewable oils to be worthy components of a sustainable system, at least during the transition to replacement technology. Cleaner liquid fuels for diesels are likely the least expensive and easiest to implement option until more advanced technologies such as fuel cells become commercially viable, or the price of natural gas systems is reduced. Even when fuel cells are viable, they will require a source of hydrogen, and, as is discussed in later sections, this hydrogen could be derived from renewable oil.

#### Sustainable System Design and Diesel Engine Use

Efficiency of overall application design is critical in the effort to create more sustainable use patterns of diesel engine technology. Sustainability criteria include not only emission minimisation but also the need to maximise efficient operation and renewability and local production of fuel. In transportation applications, various transportation demand management and fleet logistic technologies strategies should be used along with more efficient vehicle designs, such as hybrid electric vehicles that are built with lightweight materials (Rocky Mountain Institute, 2000). In applications such as stationary generators, the electrical demand should be examined for conservation opportunities. In short, a holistic energy efficiency and conservation approach should be taken in conjunction with a switch to renewable fuels. This approach would make the best use of the available renewable fuel resource, which, like any other natural resource, has limited capacity to be continuously renewed without resulting in environmental degradation.

Current inefficiency of designs, applications, and user habits, made possible by the abundance of inexpensive fossil fuel available until now, are not congruent with the challenge of sustainability. Examination of the entire consumption pattern of a materialistic society, heavily dependent on long-distance transport made possible by diesel technology and inexpensive,



subsidised fossil fuel, is a critical part of the sustainable system design process.

## CO<sub>2</sub> and RO

Since carbon dioxide is captured when plants are growing and is later released when RO is burned, RO is at least neutral in carbon dioxide emissions. A recent comprehensive life cycle analysis of biodiesel found that each kilogram of biodiesel used represented the *consumption*, not production, of up to three kilograms of carbon dioxide (Tickell, J. and Tickell K., 1999). Other studies have been more conservative in their findings on this subject, but it is commonly accepted that the fuel is at least CO<sub>2</sub> neutral. GHG emission reduction strategies could therefore benefit from the use of this CO<sub>2</sub> neutral fuel. This is one of the major strengths of RO fuel, along with substantial particulate reductions and the virtual absence of sulphur mentioned above.

## RO and Fuel Cells

Emerging technologies including the hydrogen fuel could make use of RO. Onboard fuel reformers produce hydrogen from liquid fuels, for use in the fuel cell. It is usually proposed that these will run on gasoline or methanol, but fuel reformers have been also been successfully operated on diesel fuel,

kerosene, and renewable oil in the form of biodiesel (Northwest Power Systems, 2000).

## **CHAPTER TWO – LITERATURE REVIEW**

### **Review of Organisation Documents**

The sponsoring organisation, Neoteric Biofuels Inc., was formed in response to perceived economic, environmental, technical and socio-political factors that favour the renewable oil products and services contemplated in this study. Because the company has been in existence for only a short time, a limited number of corporate documents exist that serve to support or amplify the problem under study. The company was created quickly, on a very small scale, without a formal business plan. A formal business plan was under development at the time this thesis was written.

## Review of Supporting Literature

### Overview

A review of the literature on renewable oil fuel approaches was undertaken. The intent was primarily to examine use of RO fuels in diesel engines, either as SRO or as RO-derived biodiesel. A peripheral study of the use of RO-derived biodiesel in other devices and applications, and the potential for use of the biodiesel production by-product, crude glycerine, was also undertaken.

A large number of studies have been written on various technical and economic aspects of RO, (particularly for biodiesel), and these provide a good base of information. The field is, however, changing rapidly. Technical breakthroughs in various prime mover technologies, RO/biodiesel production, and government support for renewable energy and changes in environmental regulations all have the potential to suddenly enhance or reduce prospects for RO fuels. Organisations such as the National Biodiesel Board (National Biodiesel Board, 2000) and the National Renewable Energy Laboratory (National Renewable Energy Laboratory, 2000) in the USA, and the Austrian Biodiesel Institute (Austrian Biodiesel Institute, 2000) maintain excellent

technical reports, research study databases, and newsletters. These are made available through online databases at the organisations' web sites.

Information on the ROFS approach is not nearly as easily located. It seems that relatively little work has been done on this in comparison to biodiesel.

It is often assumed that there could not possibly be enough renewable oil produced to meet the needs of the current fleet. This conclusion rests on a number of existing-paradigm assumptions. It assumes:

- There can be no large increases in the availability of renewable oil from existing agricultural land.
- No new sources of RO can be found.
- Recovery and reuse of waste vegetable oil cannot result in any significant additions to available supplies of oil that can be used for fuels.
- Only one replacement renewable energy source will eventually displace petrodiesel.
- More efficient ways of using and conserving available supplies of fuels cannot be found.

This assumption is challenged by the portions of this thesis concerning sustainable system design; precision farming; potential RO feedstocks; new

technology that enables more efficient use of the diesel; new technology that is poised to completely replace the diesel; sustainable system design; transportation demand management; and the general economic and psychological reasons for over-reliance on diesel technology.

#### Internet Discussion Group and Web Site Resources for RO

Several active discussion groups on the topic of RO fuels in diesel engines also exist. Generally, there seems to be a high level of interest in the concept of using RO fuels both as SRO and biodiesel.

Many individuals are interested in learning how to make their own fuel and often purchase a diesel vehicle specifically for use of RO. The general perception seems to be that making RO fuels for a diesel engine is less complicated, legally and technically, than producing home made ethanol fuel for gasoline engines.

The level of technical sophistication achieved in both home made ROFS and home made biodiesel processors can be quite impressive, even though the materials themselves are often salvaged and very simple. For example, some processors include arrangements for methanol recovery via distillation columns and excellent instrumentation. Processors are often made from discarded pails, drums, old appliances and water heaters. Safety precautions

are usually emphasised, although some resources do not adequately address the need for caution in the use of the chemicals involved in making biodiesel.

## **RO – Recent Research**

### **Particulate Matter (PM) Reduction**

Although not always the case, in general it appears that the use of RO fuels in diesel engines reduces particulate matter in exhaust emissions compared to those from petrodiesel fuel. Literature review of various biodiesel emissions studies often reported PM reductions in the 30%-60% range compared to petrodiesel. For example, Peterson and Auld (Peterson and Auld, 1991) identified PM reductions of up to 60% or more in the literature. Petrodiesel quality and sulphur content, specific test engine type and condition, specific emissions test equipment and methodology, and the characteristics of various RO fuels account for the variation in results. In any case, PM reduction is significant in most cases, and is considered one of the major strengths of RO fuels for diesel engines.

PM reduction by the use of RO fuels could assist in more rapid adoption of particulate traps. These end-of-pipe pollution control devices are widely proposed as a solution to diesel PM emissions, and are very effective.

However, because of current emission levels, they tend to fill with trapped material and require maintenance more quickly than is desirable (Mayer, 1998). A large reduction in the volume of PM reaching the trap would likely extend the maintenance interval considerably, thereby making the use of these devices more acceptable to diesel engine operators.

The Ontario Soybean Growers' Marketing Board recently sponsored research on the option of blending biodiesel with petrodiesel. Such blends reduce overall cost compared with use of 100% ("neat") biodiesel. Generally, the results were positive for some emissions as indicated by the following quote:

"In the first study, carried out at Environment Canada's Environmental Technology Centre Ottawa, tailpipe emissions of various blends of biodiesel and conventional fuel were evaluated on a light-duty diesel pickup truck. Results showed that hydrocarbon emissions were lower for all the biodiesel blends compared to the emissions of the conventional baseline fuel. Similarly, results also revealed a 40% reduction in fine particulate emissions (particles less than 2.5 microns in diameter) with the use of biodiesel blended fuel compared to the conventional fuel. This is an important finding since

these ultra fine particles can be inhaled deeply into the lungs and are considered a significant health concern” (Ontario Soybean Growers’ Marketing Board, 2000, n.p.).



## RO Emissions of Polycyclic Aromatic Hydrocarbons (PAH)

A recent study on PAH and *n*PAH emissions concluded that, for the engines tested, neat (100%) biodiesel fuel produced much less PAH and *n*PAH than the standard diesel fuel.

Biodiesel *without* a catalytic converter resulted in emissions in the same range as petrodiesel *with* a catalytic converter. When biodiesel was combined with a catalytic converter, the emissions were further reduced, by a wide margin, compared with the petrodiesel/catalytic converter combination (Pan, Quarderer, Smeal, and Sharp, 2000). This study provides support for the idea that biodiesel, combined with catalytic converters, would be a relatively inexpensive method of reducing a wide range of diesel engine emissions by a significant amount.

The following quote comments on the results of the same study:

“PAH and *n*PAH compounds have been identified as potential cancer causing compounds. All of the PAH compounds were reduced by 75 to 85 percent, with the exception of benzo (a) anthracene, which was reduced by roughly 50 percent. The target *n*PAH compounds were also reduced dramatically with biodiesel fuel, with 2-nitrofluorene and 1-nitropyrene reduced by 90 percent, and the rest of the *n*-PAH

compounds reduced to only trace levels. All of these reductions are due to the fact the biodiesel fuel contains no aromatic compounds.” (Weber, Howell and Hammond, 2000, p.4).

### Smog Forming Potential of RO

The USA’s National Biodiesel Board has stated that:

“The ozone forming potential of the speciated hydrocarbon emissions (for biodiesel) was nearly 50 percent less than that measured for diesel fuel” (National Biodiesel Board, 2000, n.p.).

### Health Effects

Biodiesel has been found to be biodegradable and non-toxic. It is the only alternative fuel to date to have successfully completed the Tier I and Tier II Health Effects testing requirements of the USA Clean Air Act Amendments of 1990 (National Biodiesel Board, 2001).

### Carcinogenicity

A recent study by the University of California also determined that the cancer that biodiesel reduces cancer-causing risks associated with petrodiesel by 90 percent. (Environmental News Network, 2001)

## Energy Balance

A recent life cycle assessment of biodiesel by USA National Renewable Energy Laboratory researchers concluded that the energy balance of biodiesel production from oilseeds is far better than that of petrodiesel. The authors report that the energy efficiency of soybean biodiesel and petrodiesel are very similar (80.55% and 83.28% respectively), yet “biodiesel yields around 3.2 units of fuel product energy for every unit of fossil energy consumed in the life cycle. By contrast, petroleum diesel’s life cycle yields only 0.83 units of fuel product energy per unit of fossil energy consumed” (Sheehan, Camobreco, Duffield, Graboski, and Shapouri, 1998, p.31).

The energy balance for SRO is inherently even more favourable than that of biodiesel, since energy is used in biodiesel production for heating, pumping and mixing and both are derived from the same RO feedstocks. The ROFS uses *normally wasted engine heat* to accomplish the same goal of viscosity reduction.

The very large difference in energy balance between petrodiesel and RO is easily explained. The net *loss* of energy in petrodiesel production is accounted for by the need to distil petrodiesel from crude oil, whereas the *positive* energy balance of RO represents energy of the sun, *as that solar energy was converted by nature, directly to an almost ready-to-use fuel*. It is vitally important to understand that it is the ability to capture solar energy *on a sustainable basis* that differentiates renewable from non-renewable energy sources. Storage of solar energy as fats and oils, via photosynthesis, is a very effective, natural process. The ability to easily access and process that natural product at a low energy cost, and use it in technological devices of widely varying complexity to accomplish goals of performing work, or providing heat and light, is what made RO a traditionally useful fuel. The energy balance of RO reflects this ease of use.

### Kyoto Protocol Implications for RO Fuels

As mentioned above, RO is a CO<sub>2</sub> neutral fuel. The collapse of the recent COP-6 Kyoto Protocol ratification talks in The Hague, Netherlands has demonstrated the resolve of negotiators from Canada and the USA, as well as some other countries, to include GHG emissions trading as a mechanism to meet protocol obligations. It appears that CO<sub>2</sub> emission reduction credits will

emerge as a recognised tradable commodity. Since RO use results in quantifiable CO<sub>2</sub> reductions compared to petrodiesel, it should be possible to attach a CO<sub>2</sub> credit value to RO used as fuel in a diesel engine.

Another component of the Kyoto Protocol that may come into wider and accepted use is the Clean Development Mechanism (CDM). This allows developed countries to invest, for example, in suitable projects in developing countries that reduce GHG emissions and thereby earn credit to be applied against domestic GHG emissions in the developed country. RO use in diesel engines in developing countries may provide CDM-related opportunities if it can be demonstrated that such use meets the necessary criteria.

## **Economic and Technical Feasibility of RO**

### **Overview**

From the literature review, it is apparent that the economic feasibility of RO fuels is dependent on the technology used for processing and the capital cost of required equipment per unit of output; cost of feedstocks; relative price of petrodiesel in a given region; and subsidies that apply to either RO or to petrodiesel. The technology for processing RO into SRO or biodiesel (either a ROFS or a biodiesel processor) is discussed in later sections.

The following sections provide information on some of the RO feedstocks that are commonly used or proposed. Other economic and technical considerations are also presented in the following sections.

### Recovered Renewable Oil (RRO)

Recovered renewable oil (RRO) from the waste vegetable oil generated by restaurant fryers, animal fats from the rendering industry, and grease collected from grease traps, households and wastewater are all sources of recovered renewable oil. Such collection and reuse schemes have resulted in reduction of this material going to landfill sites (Pacific Biodiesel, 2000) and have reduced demands on existing wastewater treatment facilities (Cleaner Production Centre Austria, 2000).

RRO supply is not a problem at present since there is still so much RRO sent to landfill and into sewers. For example, over 11.3 billion litres per year of RRO is generated in the USA alone (Tickell, J. and Tickell, K. 1999).

According to a University of Toronto Innovations Foundation news release concerning a biodiesel joint venture between that organisation and the Canadian firm “Biox”, there is, in Canada, “estimated to be 1 billion litres of oil and grease per year which could be converted into fuel (Innovations Foundation, 2000, n.p.).

## Agricultural RO Feedstocks

Renewable oil can be derived from agricultural and marine sources or from animal fats, and it is commonly proposed that crops such as rapeseed (from which Canola was derived) or soybeans would be sources of supply. However, it must be recognised that petrodiesel is currently used on such a large scale that it would be impossible to substitute RO from agricultural sources to any great extent. Even researchers who generally advocate the use of RO fuels express this current reality:

“However, we must remember that in Canada for vegetable oil to replace just the (petrodiesel used in the) highway transportation industry it would (be necessary to) produce eleven times the (current) acreage for that market alone. To even think that vegetable oil could remove fossil fuels from the marketplace would be very unrealistic”(Faye, 1999, n.p.).

This point appears valid, at least for *the current set of operating conditions*. It often leads to the conclusion that RO should be targeted toward niche markets (Faye, 1999) or blended with petrodiesel, where it is an excellent lubricity additive and replacement for sulphur at as little as a 1% blend (Ontario Soybean Growers’ Marketing Board, 2000). However, it is not logical to state that a renewable energy cannot supply current needs, so and

that, therefore, energy needs must continue to be met by a system that relies on rapid depletion of non-renewable energy sources. Non-renewable means just that - fossil fuels are finite.

Renewable oil is certainly available in much lesser quantity than fossil fuels at this time, but could potentially be available indefinitely. Using renewable oil from plants is only one of many emerging renewable energy options that could be used to replace current reliance on broad application of the diesel engine/petrodiesel combination. Fossil fuel could certainly be used much more efficiently and sparingly, extending the time horizon for which supplies would be available at a reasonable price. This is likely to occur to some extent, but will not make fossil fuels renewable or sustainable, since they are formed over millions of years, not in single growing seasons or even over mere decades.

The amount of renewable oil that could be produced is subject to many factors, such as available land, water, fertiliser, crop species, growing season and existing market demand. Increasing the available supply of RO from industrialised agriculture, as it is currently practised, could be problematic. There is a potential conflict between production of crops for use as energy, as opposed to food. Although agricultural crops are already sold for a wide variety of non-food uses, the consumer is mostly unaware of this, and people often respond negatively to the use of crops that they perceive as potential



food sources being burned in engines. This may be a selective negative bias, but is nonetheless a valid criticism, considering the need to nourish an increasing human population.

An attempt to increase the supply of RO through intensive and expanded cultivation of oilseeds could also inadvertently cause the loss of habitat and soil-rejuvenation functions provided by suitable agricultural land that is not currently under cultivation. It could encourage over-use of soil (depleting it of organic matter and increasing erosion), over-cropping of oilseeds (versus good crop rotation practice that helps maintain soil fertility and minimise crop diseases) and increased dependence on fossil-fuel derived chemical fertiliser, chemical pesticides, and genetically modified crops. It could also encourage further rainforest clearing, use of unsuitable, poorly drained, or drought-prone land, groundwater-depleting and wasteful irrigation practices, loss of topsoil, and desertification.

These negative results must be avoided in the production of RO for fuel.

Awareness of the potential for negative impacts, and of the need for a sustainable system approach to the issue, could assist in the development of policies and incentives that allow the many advantages of RO fuels to be fully realised. Examples of the sort of economic effects, feedstocks, agricultural techniques and by-product applications to be considered in planning such a system of production are provided in the sections that follow.

## Effect on Crop Prices of RO Fuels and Potential Outcome

The use of crops as fuel could support crop prices, per unit of output, at a higher level. If prices were supported in this way, output per unit of land could be lower, yet income would remain the same. This reduced crop output requirement per unit of land could allow greater experimentation with sustainable agricultural techniques and unproven crops, reduce reliance on artificial yield-stimulating inputs that are usually based on fossil fuels, reduce the need for irrigation and generally result in more sustainable practices and lower input costs.

Additionally, on-farm use of petrodiesel could be replaced by self-supply of RO fuels. A small percentage of the land under cultivation could provide the fuel requirements of the entire operation at lower cost than via the purchase of petrodiesel.

Also, when oil is pressed from oilseeds, for example, the “presscake” or oilseed meal can be used as livestock feed. Manure could later be returned to the soil to help maintain fertility. The presscake can also be returned directly to the soil as a fertiliser:

“The press cake which remains after oil extraction by the expellers is a very good organic fertiliser, with mineral composition comparable to that of chicken manure. This has great value for agriculture in the

Sahelian countries, since soils there are rapidly depleted of humus and chemical fertilisers are very expensive” (Henning, 1998, n.p.).

Another way of closing the loop in RO production cycles is to use potassium hydroxide as the base when RO is converted to biodiesel. Components of potassium phosphate fertiliser can then be recovered from the heavier fraction that settles to the bottom of the biodiesel reactor vessel (Tickell and Tickell, 1999). This could be collected and sold as commercial fertiliser.

#### RO Fuel Crops as Part of Urban and Peri-Urban Agriculture and Urban Greening

There is increasing interest in the use of plants in urban spaces to produce useful crops (Cityfarmer, 2000). Plants can also be effectively used in the urban environment to, reduce the extent of impervious cover, reduce runoff, erosion and watercourse sedimentation, absorb carbon dioxide and produce oxygen (D. Palidwor, personal communication, 2001).

If RO and its fertiliser by-products were produced in urban and peri-urban spaces, the “ecological footprint” (Institute for Resources and Environment, 2000, n.p.) of the urban area could be reduced, since the fuel burned in the area’s vehicles could be produced from the urban area itself, rather than relying on fossil fuel imports or RO imports from other agricultural land to

meet this requirement. Rooftop plots and vacant land could be used for fuel production, the possibility of introduction of contaminants to urban-grown food could be avoided (Agricta, 1999), and the harmful effects of diesel exhaust emissions in the urban environment could be mitigated by the use of the RO fuel so derived. Permanent employment in production and processing of such crops could be created. The RO from such urban crops could be added to that collected as RRO for processing as RO fuel.

### Feedstocks from Inedible Oils

Around the world, there are a number of sources of RO that do not rely on usual food oils or do not rely on annual field crops. Examples include oil from the honge (Indian beech) tree, and *Jatropha curcas* (physic nut).

Honge oil is being used in India to operate diesel engines for water drilling and pumping, without prior conversion of the oil to biodiesel. The tree provides a crop every year and can be used as a windbreak, a “living fence” and provide sticks for fences and other uses. (The Week, 2000, n.p.).

*Jatropha curcas* plants produce oil that can be detoxified but is normally not edible oil. This oil is suitable for RO fuel. (Biomass Project Nicaragua, 2000).

Austrian biodiesel experts assisted in the establishment of a biodiesel plant in Nicaragua, which uses *Jatropha* oil:

“In 1991 the Austrian Technical Co-operation for Development discovered a new natural resource in Nicaragua. Within a project on biomass the tropical oil plant *Jatropha curcas* was tested as possible crop. This plant is very frugal, does not need intensive cultivation and guarantees high earnings in oil. The negative aspect is that the plant is unfit for consumption because of poisonous substances.

Nevertheless, the plant, which is domiciled in tropical areas, is an ideal raw material for the production of biodiesel. Within a co-operation with our institute, basic questions on analytic and chemical levels were treated, which finally led to the implementation of a biodiesel plant in Nicaragua. The crop of 100,000 square kilometres is processed in this plant.” (Cleaner Production Centre Austria, 2000, n.p.).

### Rapeseed/Canola

Rapeseed oil (or the derivative, Canola oil) is well suited to use in a ROFS or as biodiesel. It was the earliest biodiesel feedstock in agricultural co-operative biodiesel plants built in Austria in the late 1980's (Körbitz, 2000).

Canola oil yield per hectare is usually in the range of 1 tonne per hectare (Tickell and Tickell, 1999), but yields of up to 2.9 tonnes per hectare have been achieved in Northern Germany using so-called “precision farming” techniques (Körbitz, 2000).

Precision farming does not automatically imply greater intensity of inputs to generate higher yields. Rather, it can result in much more intelligent application of the same amount of fertiliser and pesticide that is currently applied uniformly across a field regardless of need in a particular area.

Precision farming can be defined as:

“An information and technology based farm management system to identify, analyse and manage variability within fields for optimum profitability, sustainability and protection of the land resource” (Prairie Geomatics, 2000, n.p.).

The technique uses Global Positioning System (GPS) receivers mounted on the roofs of tractors, which provide precise location information to a Geographic Information System (GIS). The GIS, working from a database of field information from satellite data and soil tests for the same small areas of the field, directly controls application rates of fertiliser and pesticides for small areas of fields, as the equipment travels over them. This is in contrast to the usual method whereby decisions about application rates are applied to entire large fields.

Strategically located and carefully monitored intensive plots with produce destined for non-food markets, as a small percentage of overall land use adapted to organic production destined for food markets, might be superior to the current agricultural system. The current system tends toward over-application of inputs with insufficient attention to siting, need, or end use of the crop, and deals with a land base that is too large to easily allow intensive management. The potential yields of even the most suitable agricultural crops, grown using the best production methods, are much less than the potential yields of RO extracted from algae.

## Algae

Some types of algae have been identified as having potential to supply significant quantities of RO. Algae use large quantities of CO<sub>2</sub> to support rapid growth. This can be supplied from power plant flue gas (Kadam and Sheehan, 1996). Algae can also use nutrients found in wastewater.

From 1978 to 1995, U.S. National Renewable Energy Laboratory scientists conducted the Aquatic Species Program. Emphasis in the early years was on hydrogen production from algae, but shifted to algae oil production over time when it appeared those algae was a promising feedstock for biodiesel production. The program was ended in 1995 as the result of a decision to

allocate available funds for alternative fuels research to the area of ethanol production. The most productive and useful strains of microalgae were catalogued and are now held in a collection at the University of Hawaii. The yields from algae ponds, on saline soils unsuited to conventional agriculture (in the New Mexico desert), dwarfed that of oilseeds production on productive soils. Yields of RO per hectare were up to forty times more than what even high-yielding oilseeds such as Canola can produce (National Renewable Energy Laboratory, 1998).

Algae can also be produced at wastewater treatment plants. Algae produced from the nutrients in wastewater and the CO<sub>2</sub> from industrial processes appears to be a promising combination to reduce the cost of production and land requirement of biodiesel (National Renewable Energy Laboratory, 1998).

The establishment of algal oil production could be a very significant new source of RO. Recently, it has also been discovered that hydrogen can be produced directly from algae (University of California Berkeley, 2000). This may result in a general renewed interest in the use of algae as a source of both RO and hydrogen.

The literature also appears to support the idea that algae production might be accomplished in some parts of Canada, using greenhouse “polytunnels”



(polyethylene over hoop frames), CO<sub>2</sub> injection supplemental heat. Heat and exhaust from gensets, cogeneration units or fuel cells might supply supplementary heat, water vapour and CO<sub>2</sub>.

If diesel engines were used to power a genset in this scenario, it is possible that the exhaust would have to be treated to reduce emissions prior to routing the exhaust into the greenhouse where the algae would be produced. If this proved necessary, the technology to do so appears to exist. A similar process of using the exhaust from natural gas engines was used at a greenhouse complex in Denmark. Correspondence with the technical staff at Haldor Topsøe, the engineering firm responsible for that design, confirmed that the same emission control equipment used in that case could be adapted for use with RO:

“As we expect that there are only traces of SO<sub>x</sub> and a maximum content of 5mg/Nm<sup>3</sup> of soot/particulate matter in the exhaust gas of the fuels specified, we see no obstacle to implementation of a GREENOX unit on a "Bio-Diesel" engine” (N. Christoffersen, personal communication, 2001).

Employment

More labour is typically required to produce renewable fuels than is the case for fossil fuels. This could assist in job creation, crucial to the “social” aspect of sustainability.

RO fuels production and use creates a wide range of employment opportunities in agriculture, RO processing, plant and equipment design, engineering and construction, vehicle and engine conversion, collection logistics, distribution and research.

While some jobs require skilled workers, and are short-term positions that exist only during the design and construction phases, many other permanent jobs are created. A recent study on the employment prospects for the renewable energy industry in the European Union concluded that:

- Renewable energy is more labour intensive than conventional energy technologies in delivering the same amount of energy.
- Renewable energy technologies use less imported goods and services than conventional energy technologies, so their use provides great stimulus to both direct and indirect employment in domestic manufacturing.
- The agricultural industry has spare labour market capacity and can expand to exploit the emerging market in supplies of biomass fuel.

(European Forum for Renewable Energy Sources, 2000)

## Research on SRO in Direct and Indirect Injection Engines

Literature review revealed that some research, development and commercialisation has occurred for designs that allow for SRO use, without heating and without any use of petrodiesel. These change the engine injection system, require substantial changes to the engine, or use a completely redesigned diesel engine (Elsbett, 2000).

Some research exists on the effects of SRO fuel on unmodified direct injection diesel engines. The conclusion was that, for direct injection engines, vegetable oil or vegetable oil / petrodiesel blends could not be recommended since piston ring sticking and other problems resulted over the longer term (Peterson and Auld, 1991). However, it does not appear that the RO was heated prior to injection in that particular study, nor that RO was tested in indirect injection engines in that particular study.

Other researchers have also concluded that without RO heating and without biodiesel purging cycles at start-up and shutdown, SRO fuel will tend to cause problems with direct injection diesel engines (B. Hertz, personal communication, 1999).

Indirect injection diesel engines are considered to be more tolerant of SRO. One study in South Africa, on an indirect injection type, installed in a tractor,

concluded that there were no problems after 1800 hours of extended-service-life power takeoff drive (PTO) tests. These tests followed the manufacturer's cycle. No problems were observed and injector coking did not occur. In fact, the study resulted in extension of the manufacturer's warranty to include the use of straight vegetable oil (Peterson and Auld, 1991).

The diesel industry is moving toward direct injection, but millions of indirect injection engines are in use and will continue in use for many years. A number of manufacturers continue to produce indirect injection engines, particularly those based in developing countries. It appears that in hot climates, for certain indirect injection engines, SRO could be used - even without any sort of pre-heating ROFS.

### Cold Weather Use of SRO Fuel

Some researchers, perhaps those working where cold winters occur, tend to be less supportive of the use of SRO. As Tickell and Tickell note:

“In the words of one researcher, the idea of heating the vegetable oil fuel supply was dropped because “the entire distribution and storage system would also require heating, a clearly impractical and expensive approach”” (Tickell and Tickell, 1999).

It was this comment that originally inspired the research into SRO use in a ROFS for this thesis. It is certainly easier to use SRO in hot climates, where it will remain liquid and flow easily. However, there may be more opportunity to extend the useful range of ROFS into colder climates than is generally recognised. Waste heat is generated by the engine even in very cold ambient temperatures. Theoretically, then, it should be possible to capture that waste heat and use it in a ROFS to heat the RO. The design of a ROFS requires the use of petrodiesel for start-up and shutdown even in moderate temperatures. Winter petrodiesel is readily available in cold climates for this start-up and shutdown cycle. Bulk delivery and bulk storage of RO fuels in cold climates would represent challenges, but the actual costs of this may not be prohibitive when compared to the increasing cost and liability potential of petrodiesel delivery and storage.

It may seem that biodiesel is better suited to cold climates than is SRO. However, biodiesel will plug fuel filters at higher temperatures than petrodiesel unless blended with petrodiesel or unless pour point depressants are added. This adds additional cost to biodiesel. It also means that emissions

and other environmental benefits may be sacrificed due to blending biodiesel with winterised petrodiesel for cold weather use. Research into making biodiesel more useful in cold temperatures is ongoing but at the present time the use of additives or blending with petrodiesel are the only options for cold weather biodiesel use. SRO, heated in a ROFS, could be as viable an option as winterization of biodiesel, for use in cold climates.

### Biodiesel Production Techniques and Potential Impact on Commercial Prospects for ROFS

The question of whether to use biodiesel or a ROFS hinges on the cost of production of biodiesel, versus that of a payback time for a ROFS.

Transesterification processes have traditionally been batch processes.

However, much more efficient continuous processes that allow use of low-cost recovered renewable oil (RRO) and animal fats, incorporate solvent recovery, and produce a high-quality and high value glycerine by-product are now emerging (University of Toronto, 1999). ROFS would lose some of their appeal if biodiesel production cost were to be reduced substantially by new processes that allowed regional production at low cost.

### Effects of Biodiesel / Petrodiesel Blends on Sustainable System Design

Low level lubricity additives derived from RO, if widely used in petrodiesel, are an effective means by which to restore lubricity to winterised petrodiesel and sulphur-reduced petrodiesel. These RO-based additives are, therefore, an enabling technology in a transition to petrodiesel fuel that results in lower emissions (e.g. SO<sub>2</sub> emissions) and allows use of catalytic converters to reduce other emissions. Wide acceptance and use of RO for this purpose, however, would use much of the available supply of RO feedstocks.

The result would be a dilution of the potential benefits of RO fuels to the point that they would not be considered a component of sustainable system design. RO, in this case, would merely encourage greater fossil fuel use by reducing emissions of petrodiesel on a unit basis, and would accomplish almost nothing in terms of establishing renewable energy systems or sustainability.

Higher percentage blends of biodiesel and petrodiesel result in useful emissions reduction. However, RO as an effective component of sustainable system design rests on a premise of its use as fuel almost exclusively in the diesel engine, rather than as a minor component of a fuel blend with petrodiesel. If RO fuels were blended with petrodiesel, especially as low percentage lubricity blends, the desired sustainability-related outcomes as outlined in this thesis would not occur.

## Fuel Specifications and Manufacturer's Warranties

Fuel specifications have been created for biodiesel in a number of countries, including Austria, Germany and the USA. These fuel specifications were needed in order to enable engine manufacturers to confidently extend warranties to biodiesel. Most warranty coverage extension to the use of biodiesel has occurred amongst European manufacturers or European subsidiaries of manufacturers based elsewhere. For example, Volkswagen AG has extended warranty coverage for biodiesel use for all models manufactured since 1996. Discussion with a Volkswagen sales representative in Canada indicated that biodiesel use was not, however, covered by the vehicle warranty in Canada. Many other manufacturers extend warranty coverage to the use of biodiesel or biodiesel/petrodiesel blends in Europe, but this varies widely according to model and model year. Also, special maintenance schedules are sometimes required, including more frequent lubricating oil changes (Cleaner Production Centre, 2000). The USA's National Biodiesel Board has prepared the following summary of the current state of warranty coverage by Original Equipment Manufacturers:



“...Ford and Chrysler have begun biodiesel research initiatives, with Ford’s efforts being the most advanced. Ford is conducting independent compatibility testing in anticipation of providing diesel engines certified to operate on biodiesel. Chrysler has included biodiesel in its compatibility specifications. Most major diesel engine manufacturers have affirmed that use of B20 in their equipment will not void their warranty and are actively working with industry on research and development activities. Moreover, the Fuel Injection Equipment manufacturers have issued letters recognising biodiesel’s significant role as a renewable lubricity additive” (National Biodiesel Board, 2000, n.p.).

### Global Status of Biodiesel Plants and Commercial Sales of Biodiesel

Commercial sales of biodiesel are underway in a number of countries, notably Italy, Germany, Austria, France, and the USA. Successful collection systems are being used in a few locations (e.g. Graz, Austria) to collect fats and oils from households and food service facilities. Such RRO would otherwise enter the wastewater stream, create a treatment problem and represent a cost to taxpayers (Cleaner Production Centre Austria, 2000). By collecting RRO and converting it for use as fuel, a double environmental and economic benefit is realised. The RRO does not clog sewers and enter the watershed,

and is used instead to reduce emissions to the air from local diesel engine use.

It seems that other cities could benefit from this experience. For example, at the same time that Hong Kong has attempted to deal with disastrous diesel emissions by switching taxis to propane power, hotels and restaurants complained that the \$400 million spent annually on dealing with wastewater grease is ineffective in preventing blocked sewer pipes and polluted water (Ehrlich, 2000).

Fats and oils from a variety of sources, including those with high free fatty acid content are now being used in sophisticated multi-feedstock biodiesel plants that allow rapid and precise custom blending for maximum profitability and proper seasonal fuel performance (Biodiesel International, 2000).

The industry has grown rapidly over the last several years and it appears that this trend will continue.

Recent Corporate, Non-Governmental Organisation (NGO) and Government Support for Renewable Energy Technology

Government, NGO and corporate support for alternate and renewable energy varies widely around the world, but is gaining momentum. For example, in

British Columbia, the provincial government's Green Economy Initiative (Green Economy Initiative, 2000) provides grants and tax credits in support of a broad range of environmental technology, including renewable energy.

The Canadian federal government's Technology Early Action Measures (TEAM) program is a \$56 million component of the comprehensive Climate Change Action Fund and supports projects that reduce greenhouse gas emissions (Climate Change Action Fund, 1999).

The USA federal government's Department of Energy has recently increased subsidies for renewable fuel use and research, including direct support for Environmental Protection Agency registered producers of biodiesel (Biodiesel Bulletin, 2000). Also in the USA, fleet owners who might otherwise be required to purchase alternative fuel vehicles can instead apply fuel credits earned from using biodiesel (S. Spence, personal communication, 2001).

Whereas biodiesel in that country has been used primarily for research and environmental demonstration until this time, it is anticipated that this rule will make the purchase of biodiesel for fleets the least expensive means by which fleet managers can comply with federal regulations.

Corporate and NGO initiatives that generally support renewable energy have the potential to stimulate research and development and eventual market demand for RO fuels in diesel engines. A number of large petroleum

companies have moved further toward acceptance of alternate and renewable energy as a part of their business. The Canadian-based energy resource company, Suncor, recently announced the creation of a 100-million dollar fund for the research and development of alternate and renewable energy (Suncor, 2000).

The Shell Foundation, initially endowed with \$30 million (USA funds) has announced the Sustainable Energy Program (SEP), in support of projects by non-profit groups and researchers that:

- Reduce environmental impacts of fossil fuel use
- Increase access to energy by “encouraging non-governmental organisations, community groups, small entrepreneurs and local businesses to find new ways to supply cleaner energy and improved energy services to poor people” (Shell Foundation, 2000, n.p.).

These initiatives indicate a growing readiness amongst government, NGO and business leaders to explore renewable energy options and to provide financial support for development of those options. This support has a direct bearing on the potential for RO fuels to compete with petrodiesel in terms of relative cost.

Comparison of RO with Petrodiesel and Natural Gas as Diesel Engine Fuels

Table 2.1 summarises the comparison between petrodiesel, natural gas (NG), and renewable oil as generally found in the literature that was reviewed:

**Table 2.1 – Comparison of RO, Natural Gas, and Diesel Engine Fuels**

| Attribute   | Petrodiesel | NG   | Renewable Oil |
|---|-------------|------|---------------|
| Production by community or individual   | No          | No   | Yes           |
| Uses existing delivery infrastructure from production centres to local refuelling stations  | Yes         | No   | Yes           |
| Can use a waste stream as feedstock   | No          | Some | Yes           |
| Conversion cost   | Nil         | High | Low or nil    |
| Renewable   | No          | Some | Yes           |
| CO <sub>2</sub> neutral   | No          | No   | Yes           |
| Positive Energy Balance on LCA basis  | No          | No   | Yes           |
| Biodegrades harmlessly if spilled/released  | No          | No   | Yes           |
| Compact liquid form at atmospheric temp and pressure  | Yes         | No   | Yes           |
| Convenient for use in cars and light trucks   | Yes         | No   | Yes           |
| Negligible SO <sub>2</sub> emissions  | No          | Yes  | Yes           |
| Naturally Oxygenated  | No          | No   | Yes           |
| High cetane number (good ignition characteristics)  | Yes         | No   | Yes           |
| Reduced PM emissions  | No          | Yes  | Yes           |
| Contains aromatics  | Yes         | No   | No            |
| Enables use of Catalytic converter and particulate trap for further reductions in emissions | No          | Yes  | Yes           |
| Non-toxic if ingested/inhaled   | No          | Some | Yes           |
| Safe flash point  | No          | No   | Yes           |
| Supports sustainable local jobs/agriculture   | No          | Some | Yes           |

## **Patent Search / Technology Review**

A review of existing patents related to ROFS and biodiesel was undertaken using the Delphion Internet patent server (Delphion, 2000) and the USA Patent and Trademark Office Internet patent server (United States Patent and Trademark Office, 2000). This provided the ability to search patents issued by the USA and European Union patent offices. Extensive and high quality information concerning the existing technology was available via Internet searches.

### **Biodiesel Patents**

A large number of patents have been issued for biodiesel processes. However, many of these have been issued for processes that require large capital investment. The basic transesterification process is quite simple and has been known for decades.

Three recent developments concerning patented processes and equipment for the production of biodiesel and related products that are noteworthy include:

- A modular containerised “Continuous Trans Esterification Reactor” (patent # PCT-AT98/00284), manufactured by “Energea” in Austria (Energea, 2000).

- The ongoing effort toward patenting and commercialisation of a continuous process by Biox, Inc. (T. Haig, personal communication, 2001).
- An additive for winterised diesel fuel based on Canola oil, but that is not biodiesel, developed jointly by Agriculture and Agri-Food Canada's Saskatoon Research Centre, the Department of Mechanical Engineering at the University of Saskatchewan, and Canodev, the marketing arm of the Saskatchewan Canola Development Commission (R. Button, personal communication, 2001)

The first two are efficient processes that can use RRO and other low cost feedstocks. They create the potential for a large number of smaller, regional and local biodiesel plants to put into operation globally, in the near term.

The third development mentioned above has the potential to introduce RO-based diesel additives to a wide audience and build awareness of the potential for greater use of RO as a fuel for diesel engines.

## Patented and Non-Patented ROFS

USA - Ward

USA patent number 5,662,090 was issued September 2, 1997 to J.L. Ward. The patent discloses a heat exchange system for using vegetable oils as engine fuel.

Electric fuel preheating described for initial starting of the engine in cold climates. From the description, it seems that this is a single-fuel system, to be operated only on vegetable oil.

## Lohmann

A German patent on a ROFS also exists, and the system is being manufactured. The device is a high quality system and the company, “Biocar®”, has installed the system on various makes and models of automobiles as well as on agricultural equipment as far afield as Japan. The latest system cost is roughly \$2000.00 Canadian dollars, FOB Germany. It is a sophisticated ROFS that allows precise, automated mixing of biodiesel or petrodiesel and SRO to arrive at a viscosity acceptable to the engine’s fuel injection computer. The patent is owned by G. Lohmann, and is patent number [DE19635220A1](#). The inventor is actively building and installing these systems and is also supplying well-filtered waste vegetable oil for use within the device (Lohmann, 2000).

## Diesel-Therm Bio



Another German invention is the “Diesel-Therm Bio” (Diesel-Therm, 2000). This is a small device that does not heat the RO until just before the filter and injection pump. A fuel switching valve, instantaneous electric heating element, and auxiliary fuel tank are provided. There is no provision for heating the RO within the auxiliary tank, so the device is probably best suited to new RO and for use at moderate ambient temperatures, so that the unheated oil can flow from the tank to the heater. Used RO becomes quite viscous at lower temperatures and might not be suitable for use with this device.

#### Jonsson

Jonsson describes a sophisticated, automated ROFS device designed for cold weather use. The system has been used on a Volvo diesel car and a John Deere tractor, both in Sweden. No patent is indicated. Most of the components used are of European origin (Jonsson, 2000).

#### Tickell

Tickell and Tickell provide detailed instructions on ROFS construction and installation. The design recommends a custom fabricated aluminum tank with a copper heating loop, and the use of a secondary fuel heater ahead of the fuel filter (Tickell and Tickell, 1999). Most of the manufactured components recommended are of North American origin.

## Carven

Carven has apparently commenced sales of a ROFS kit made in the USA that consists of “a heated tank, heated filter, necessary hoses/hardware, electric switch and installation, use and trouble shooting manual” (Carven, 2000, n.p.). The kit retails for six hundred USA dollars It is not recommended for direct injection engines (Carven, 2000).

## CHAPTER THREE – CONDUCT OF RESEARCH STUDY

### Research Methods

Initial literature review indicated that the Renewable Oil Fuel System (ROFS) approach might emerge as the preferred direction for further research by the thesis sponsor. Therefore, as originally conceived, the study was divided into four phases with emphasis on ROFS, as follows:

- Phase I - development and testing of a basic proof-of-concept ROFS.
- Phase II - data collection phase with emission tests, oil analysis, timed acceleration runs, fuel consumption and general operating characteristics monitored and recorded.
- Phase III anticipated that a ROFS could prove to be the favoured option, and that a second generation, pre-commercialisation design would be built, installed and tested in a similar fashion to the first version.
- Phase IV anticipated that the second generation ROFS might be eventually commercialised, and emphasis was placed on production considerations and early stages of marketing activity.

## ROFS and Biodiesel Comparison

Part way into the study, it became clear that both the ROFS and the biodiesel approaches were of potential value for specific applications. To determine the respective advantages and disadvantages, first hand experience in both approaches was ultimately considered desirable. Two phase I proof-of-concept ROFS, and a small biodiesel batch plant, were built. General principles from the literature were used in the design of all of these, but innovative approaches were used in an attempt to reduce cost, make use of commonly available materials, and/or make technical improvements. Subsequent testing tended to focus on SRO more than biodiesel. This was because the literature review and patent review had confirmed that there was a great deal of information and research pertaining to biodiesel, but not as much on the use of SRO, particularly when used as described in a ROFS.

## Quantitative and Qualitative Data

A range of tests was conceived to compare the ROFS and biodiesel approaches.

Both quantitative and qualitative tests were used to collect data.

Quantitative tests were best suited to generate useful data on emissions and

effects on performance, fuel economy and engine reliability and durability.

Qualitative observations and impressions were considered to be of value as well, and were useful in examining operational characteristics, potential user and public acceptance and interest, market potential and other economic and social components of the research question.

A description of the research methods used follows. Findings are presented in chapter four.

## Quantitative Research Methods

### Exhaust Emission Testing

Quantitative exhaust emission testing was performed at the Pacific Vehicle Testing Technologies Ltd. facility in Burnaby, British Columbia, Canada, using a chassis dynamometer and a standard test procedure known as Constant Volume Sampling (CVS).

The use of a chassis dynamometer allowed computer controlled brake resistance and thereby simulated the conditions of actual driving. A test driver followed a programmed driving trace on a computer monitor.

The standard test procedure was followed. As with all CVS testing, the exhaust gas was diluted with filtered ambient air, such that the total volume flow of exhaust gas plus dilution air was kept constant.

The driving cycle normally used in emissions testing in the USA and Canada is standardised and is called the “EPA75” or “FTP”. It includes a 12-hour cold soak, followed by a “cold transient phase”, a “stabilised phase” and a “hot transient phase”.

The test facility was located several hundred kilometres from the researcher's home. The vehicle was driven to the site on petrodiesel, with the return trip made on SRO. Time and budget limitations meant the overnight "cold soak" could not be performed. All the tests had to be performed in a matter of hours, on a hot engine. Therefore, only the "Hot 505" portion of the test cycle was performed.

There are published standards, based on this test, to which particular model years and classes of vehicles must conform. Test results for the various RO-based fuels and petrodiesel were compared against the applicable standards for the 1982 model year. The results are presented in chapter four.

The following fuels were used for the emissions tests:

- Premium diesel (Turbo/Shell "SuperDiesel™"):

A low sulphur diesel with an additive package from Knox Petroleum claimed to reduce visible smoke by up to 50%, according to the product literature and independent tests.

It is important to note that this premium diesel was the baseline (reference) petrodiesel, not "regular diesel" as sold in Canada at the time of the tests.

The comparisons of various RO fuels were made against the best petrodiesel fuel commercially available in Western Canada at the time of the tests.

- New Canola Oil. This was as supplied for restaurant fryers, and contained an anti-foam agent.
- Recovered Renewable Oil (RRO). This consisted primarily of used Canola oil from restaurant deep fat fryers. This was pre-treated by heating almost to its smoke point to remove any water and to reduce viscosity, and then filtered to less than one micron.
- Soygold™ brand biodiesel.

The test procedure was as follows:

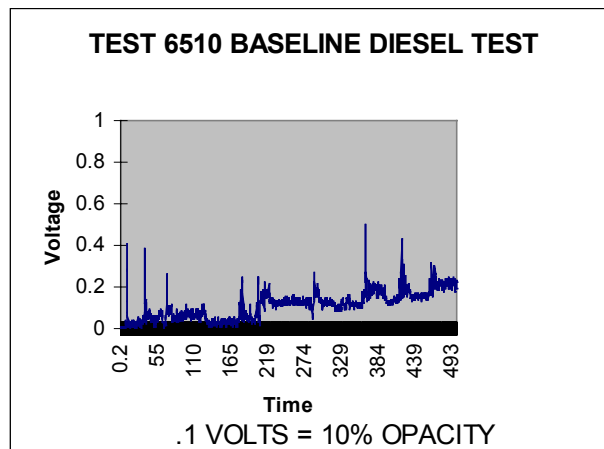
The engine was brought to operating temperature by operating the vehicle on the dynamometer prior to the start of the first test. The fuel switching solenoid valve was checked to ensure that it was operating correctly. The RO fuels were supplied to the engine via the auxiliary tank. A given fuel was poured into the auxiliary tank. Prior experience with the ROFS indicated that five minutes allowed adequate time for each fuel to reach the cylinders. Therefore, the test driver operated the vehicle for five minutes under simulated driving condition as indicated by the computer-generated driving trace. Following this, the driving trace was followed once more and the results recorded.



After a given fuel was tested, it was pumped from the auxiliary tank and replaced with the next fuel, and the five-minute purge segment and subsequent test were performed. While some residue of the prior fuel(s) may have remained in the tank, the percentage of such residue entering the engine after the five-minute purge segment was considered unlikely to influence the results. The petrodiesel fuel was supplied to the engine by switching the fuel solenoid valve to draw fuel from the main (original) fuel tank.

Opacity was measured by comparing the amount of light that passed across a 5cm venturi in the test device, through which the exhaust stream was directed. The greater the density of soot in the exhaust, the more a light beam was obstructed. The signal strength information was captured by a light receptor. This was conveyed as an electrical signal, with signal voltage representing percentage opacity. One volt represented a completely obscured light path. Therefore .1 volts represented 10% opacity. An example chart from the tests is provided in Figure 3.1, below:

**Figure 3.1 – Example Opacity Test Chart – 1982 VW Jetta**



Copies of the results for regulated emissions tests and opacity tests are included in Appendix 'C'.

### Power Output

Power output of the diesel engine is very important to the end user.

Horsepower and torque on RO fuels would have to be very close to that of petrodiesel for market acceptance of RO as a fuel. Power output testing was performed at the Pacific Vehicle Testing Technologies facility in Burnaby, British Columbia, Canada. A chassis dynamometer that included a computerised readout of output under load was used. This was the same equipment used for the emissions tests and the readings were taken in conjunction with those tests.

## Lubricating Oil Tests

In all engines a certain amount of oil contamination occurs from fuel products entering the lubricating oil. This contamination problem is especially acute in diesel engines and lubricating oil for diesels must therefore be specially formulated. Diesels are also expensive engines to purchase, repair and replace, relative to gasoline engines. However, they are expected to last longer than gasoline engines. This longevity, and better fuel economy, are what justifies their higher cost. It is therefore necessary to ensure that any alternative fuel does not degrade the lubricating oil to a greater extent than does petrodiesel. Some researchers suggest that SRO can cause ring sticking and lubricating oil thickening over the longer term (Peterson and Auld, 1991).

A lubricating oil monitoring and testing program suited to this study was arranged with Fluid Life Corporation© of Edmonton, Alberta, Canada. The following procedure was used for the lubricating oil tests:

- Drain the lubricating oil and remove the filter. Replace with a standard Fram™ oil filter for the 1982 VW Jetta test vehicle. Replace the lubricating oil with 4.5 litres of Motomaster™ 15W40 Diesel Oil meeting API specifications CH-4 and CF/SJ.

- Sample the lubricating oil at set intervals (500km, 1000km, and 2000km) following engine operation primarily on RO (except for the petrodiesel start-up and shutdown segments of the operation cycle). Use the sampling device supplied by Fluid Life Corporation© to draw samples through the dipstick tube directly into a supplied sample jar. All samples are to be sent by courier to Fluid Life Corporation© within 24 hours of the time the sample is taken.
- At 2000 km, drain oil, remove filter and replace as above.
- Operate engine on petrodiesel alone to purge the engine of RO effects (1000 km).
- At 1000 km, drain oil, remove filter and replace as above.
- Operate on petrodiesel only and sample at 500km, 1000km, and 2000km as above.

This should be considered a very minimal testing program for the effects of RO use on lubricating oil and resultant effects on the engine itself. Sampling over a longer term and more complete analysis is needed. However, such research was beyond the scope and budget of this study.

## Engine Compression Tests

Diesel engines require very high compression to ignite the air/fuel mixture. This compression must not be allowed to deteriorate through premature engine wear. Biodiesel is noted in the literature for its excellent lubricity. It has been shown to reduce the level of engine wear that would eventually result in loss of compression, and it does not cause ring sticking (Peterson and Auld, 1991). Therefore, no compression tests were performed for a biodiesel-fuelled engine. In contrast, since the literature search revealed concerns for SRO use in this regard (Peterson and Auld, 1991), it was considered necessary to conduct compression tests for the SRO used in the ROFS approach.

Longer time frames than those used in this study would be needed to determine if RO fuels cause any problems in this regard, but an interim compression test served as an indicator of any severe wear. The engine compression was checked prior to the installation of the ROFS, and again at the time of the injector inspection, after ten months and approximately 10,000 kilometres of RO use. A licensed mechanic performed these tests.

### Acceleration Tests

Diesel vehicle acceleration is considered to be barely adequate at its best; therefore, there is little tolerance for any reduced acceleration capability that may result from RO fuel use. Acceleration tests were therefore considered

necessary. An assistant used a stopwatch to record 0-90 km/h acceleration for SRO, biodiesel and petrodiesel.

Each test was performed once in each direction under calm conditions on a level, paved surface. The SRO was placed in the auxiliary fuel tank. The petrodiesel was in the original vehicle fuel tank. A dash mounted toggle switch allowed operation of the electric fuel switching solenoid valve (part of the ROFS). To purge the fuel system of the previous test fuel, the vehicle was driven for approximately five minutes at approximately 80 km/h. Tests were repeated later in the study after the replacement of the fuel filters, the addition of a 2-4 psi electric in-line fuel pump (as a booster pump), and the installation of fresh lubricating oil.

### Fuel Economy / Range

The excellent range provided by the combination of energy density of petrodiesel fuel, and the efficiency of the diesel engine is desirable.

Alternative diesel engine fuels such as SRO and biodiesel should not sacrifice this characteristic. Literature review provided ample evidence that biodiesel offers similar fuel economy to petrodiesel. Less information was found for SRO. Therefore, fuel economy tests focused on SRO fuel, used in the ROFS.

Fuel economy calculations were based on vehicle logs for September and

October. The driving cycle was a combination of approximately 50% local trips and 50% highway trips. Paved roads with flat to moderate grades were selected.

### Fuel Cost

The costs of new Canola oil, RRO, commercial biodiesel, biodiesel from the small processor, and regular and premium petrodiesel prices were compared. Prices were adjusted to reflect differences in fuel consumption of the various fuels.

## **Qualitative Research Methods**

### Visible Smoke

Visual observations of visible smoke emissions from the tailpipe were made while starting the engine and when driving the vehicle. Observations were made primarily by looking in the rear view mirror and observing the amount of visible smoke emanating from the tailpipe under conditions that normally cause diesel engines to emit significant amounts of visible smoke. These conditions include cold starts, hard acceleration from a standing start and ascension of steep grades. Occasionally, an assistant standing outside the vehicle also made observations as the vehicle was driven past. These

observations were made primarily for operation on petroleum diesel and SRO, again because less information on this aspect was found in the literature review than was found for biodiesel.

## Exhaust Smell

The smell of RO exhaust is distinctive. It has often been characterised as having a “French fry” smell. Most people reportedly find this to be more pleasant than petrodiesel exhaust. Products of a very long period of evolution, olfaction and taste are perhaps underestimated as a qualitative research tools. The following quotes illustrate this (*Italics added*):

“Both smell and taste require us to incorporate—to breathe in or swallow—*chemical substances* that actually attach themselves to receptors on our sensory cells. Early in evolution, the two senses had the same precursor, a common chemical sense that enabled bacteria and other single-celled organisms to locate food *or be aware of harmful substances*.

The average human being, it is said, can recognise up to 10,000 separate odours. We are surrounded by odorant molecules that emanate from trees, flowers, earth, animals, food, industrial activity,



bacterial decomposition, other humans” (Howard Hughes Medical Institute, 1998, n.p.).

The researcher’s observations concerning the characteristics of exhaust from combustion of RO in the diesel engine were compared to the characteristics of petrodiesel.

### Injector Coking Inspection

Fuel injector coking has been reported as a problem when diesel engines are operated on SRO over longer periods of time. It was hypothesised that the start-up/shutdown cycle procedure, especially using biodiesel or premium diesel, both of which are known to have a solvent cleaning effect on injectors, would alleviate this concern. After nine months and approximately 10,000 km of mostly urban and suburban driving on SRO (mostly Canola RRO) the injectors were removed and inspected by a licensed, qualified mechanic.

The mechanic was very familiar with the vehicle, engine, and fuel injector type. He was considered able to reliably estimate the amount of coking that would typically be expected for petrodiesel and therefore able to detect an unusual condition. Therefore, even though this was a qualitative observation,

it was considered to be a reliable indicator of any injector coking caused by SRO (in this case, primarily WVO) used in a ROFS under typical driving conditions.

### Cold Weather Tests

Cold weather is generally problematic for diesel engines and fuels.

Petrodiesel, SRO, and biodiesel are all subject to “clouding” (the formation of wax crystals) at certain temperatures. Clouding can cause the fuel filter to become plugged and the engine to stop running. SRO and biodiesel both tend to cloud at higher temperatures than petrodiesel. Cloud point and “pour point depressants” (petroleum-based additives) are used in petrodiesel to combat this problem. Similar products have been used to lower the cloud point of biodiesel. The literature review indicated that research into winterisation of biodiesel is active and productive. Winterisation of biodiesel adds further to its cost.

In theory, a ROFS could avoid or reduce this cost of the above RO “cloud point” problem. The start-up/shutdown cycle could be performed with winterised petrodiesel, and the SRO, as always, would therefore be heated prior to use. In an effective ROFS, even RO that had solidified from cold temperatures in the auxiliary tank would be liquefied and made ready for use after a short period of time, since the ROFS uses waste heat from the engine.

Cold weather operability tests were devised for SRO in the ROFS, including:

- Cold start on SRO with and without use of block heater. “Glow plugs” are fitted to many diesel engines as a cold starting aid. Cold starting characteristics using glow plugs alone were compared against the use of glow plugs in combination with ten to twenty minutes of block heater use prior to attempting to start the engine. Such tests were performed after the vehicle had been parked outside overnight, and consisted of the researcher’s observations.
- Normal ROFS operation in cold weather. In this case as well, testing consisted of the researcher’s observations of cold weather use of the ROFS.
- Efficiency of the heat exchanger and efficiency of heat transfer from the heat exchanger into the RO in the auxiliary RO fuel tank. Both of these functions were critical to the proper functioning of the ROFS in cold weather. A comparison was made of the engine’s glycol coolant temperature at full operating temperature, the temperature of the RO in the auxiliary tank, and the temperature of the RO as it exited the heat exchanger.

Cold weather tests were subject to the available ambient temperatures in the researcher’s region. During the test period, the coldest temperature was approximately  $-10^{\circ}\text{C}$ .

## **Materials**

A cornerstone of sustainable system design is the ability to generate a desired level of quality with a minimum of resource throughput. The limited budget for the research behind this thesis required the use of inexpensive, readily available materials. An effort was made to use standard, readily available components and to reuse materials wherever possible. Details of materials used are included in the descriptions of the ROFS and biodiesel processor that were built.

## **Data Gathering Tools**

### **Instrumentation and Equipment**

The test vehicle speedometer, odometer and coolant temperature gauges were used to provide some of the data needed. The coolant temperature gauge did not have a numeric scale, but a small mark indicated the normal operating temperature. This was used as a reference mark to determine operating temperature attainment times under varying ambient temperature and operating conditions. The operating temperature corresponding to this mark was determined by a reading taken with the Sun Instruments infrared sensor gun described below.

Petrodiesel fuel consumption was determined from filling station receipts and corresponding odometer readings. A wooden dowel, with a reference mark indicating the minimum fuel level, was used to take fuel level readings from the RO (auxiliary) tank. Sixteen litres of RO was required to bring the level from this minimum mark to the maximum level at the bottom of the filler opening. Fuel consumption was determined from odometer readings and their relation to fuel filling.

Fuel and engine coolant temperature data were collected using a Sun Instruments infrared sensor gun, a Springfield “PreciseTemp™” self-powered digital thermometer with minimum and maximum temperature memory capability, and a common dial-type pocket thermometer (made in China - manufacturer unknown).

The infrared sensor gun was used to take readings at the top of the flat brass fuel inlet fitting on the fuel injection pump, at the glycol expansion tank, and at the cylinder head. These readings were taken in the summer of 2000, with the engine fully up to operating temperature and idling.

The digital thermometer sensor was later affixed directly to the top of the flat brass fuel inlet fitting on the fuel injection pump using Surebond™ SB-190

adhesive. The sensor and fuel inlet fitting were then wrapped in a layer of “Plyfoil™ SB” aluminum-faced, R-5 “bubble pack” type radiant barrier insulation, in an attempt to isolate the sensor from the ambient temperature of the engine compartment. The sensor lead wire was routed to the interior of the vehicle and the display was mounted inside the vehicle. Since the sensor was mounted directly onto the fuel inlet fitting and this fitting was capable of heat transfer, this arrangement was intended to provide a means of sensing the minimum and maximum temperatures of fuel entering the fuel injection pump over a given period.

The dial type pocket thermometer was used to determine ambient temperature and the temperature of RO in the auxiliary fuel tank at a given time. This provided an indication of ROFS effectiveness for pre-warming of the RO, prior to its entry into the main body of the heat exchanger for further heating.

An older model “Swiss made” (manufacturer unknown) stopwatch was used for timing of acceleration tests.

Exhaust emissions testing was performed using a Horiba™ Instruments Model CVS-46/48 Constant Volume sampler and a roller type chassis dynamometer, at the Pacific Vehicle Testing Technologies facility in Burnaby, British Columbia, Canada.

Engine lubricating oil analysis was performed by Fluid Life Corporation© in Edmonton, Alberta, Canada, using “ICP (Inductively - Coupled Plasma) type and Arc-Spark (Rotrode)” spectrometers for elemental analysis (Fluid Life Corporation©, 2000).

An “autoviscometer” (model D-AV2, developed in-house by Fluid Life Corporation©) was used for measurement of kinematic viscosity. Viscosity was measured at two temperatures (40°C and 100°C) and was considered accurate to within 1.0 % at both temperatures (Fluid Life Corporation©, 2000).

#### Test Conditions Meteorological Data

Effort was made to collect meteorological data including temperature, wind speed and direction, barometric pressure and relative humidity, and to evaluate its effects on performance as part of the detailed vehicle trip logs for September and October 2000.

It soon became obvious that there were no perceptible variations in performance attributable to small variations in meteorological conditions, or if present, that these effects were too slight to be detected by the test methods used. The effort to collect data was discontinued.

## **Construction of a “Proof-of-Concept” ROFS**

Tickell and Tickell describe a ROFS using a trunk-mounted custom aluminum fuel tank fitted with copper loop inside it, to pre-heat the RO. In Tickells’ description, the engine coolant (a glycol/water solution referred to hereinafter simply as “glycol”) travels in one direction toward the auxiliary fuel tank, through a length of heater hose installed for this purpose. The fuel travels in the opposite direction in its own smaller diameter fuel line, within the glycol line. This “hose-in-a-hose” (HIH) concept provides primary heating. Secondary heating is then provided by a small electric or glycol-operated fuel heater of the type normally used on diesel trucks (Tickell and Tickell, 1999).

### **Auxiliary Fuel Tank**

Rather than incur the cost of the custom tank and the cost and added complexity of the fuel heater, a less expensive device, designed by the researcher, was built from a combination of new and surplus components. The HIH concept was used, as well as the suggested automotive type fuel switching solenoid valve. Photographs of this ROFS are presented in figure 3.2, followed by a description of the components and their functions.



**Figure 3.2 Proof-of-Concept ROFS, Auxiliary RO Fuel Tank Assembly**



The main components of the device, (referred to earlier as the “Phase I” or “proof-of-concept” ROFS) consisted of:

- A steel fluid-to-fluid heat exchanger originally manufactured as a diesel fuel heating device by Universal Diesel Liquifier (UDL), in Kelowna, BC.

- Steel fuel tank mounting plate.
- A Galvanised steel “Mercury” brand outboard motor fuel tank.

The UDL heat exchanger was approximately 10cm in diameter and 30cm in length. The steel fuel tank mounting plate was the same length and consisted of a series of vertical, light gauge metal plates on a base of the same material. The vertical sections were cut to the contour of the round UDL, and the piece was mounted, inverted, on the top of the UDL. It was fastened in place with “JB Weld” brand two-part epoxy adhesive. The fuel tank was then mounted to the flat surface provided by the mounting plate, using “Surebond™ SB-190” brand adhesive.

A piece of “Plyfoil™” brand radiant barrier insulation was placed into the corner of the trunk, to later function as an insulation blanket over the entire assembly. This was held in place by a hook and loop fastener to allow easy removal of the insulation for inspection or filter maintenance.

The above sub-assembly was then mounted into the trunk of the test vehicle, behind the passenger side wheel well, using four #14 x 2.54 cm long self-drilling screws.

The inverted file divider provided a flat mounting surface for the fuel tank itself and facilitated heat transfer from the top of the UDL heat exchanger to the bottom of the auxiliary fuel tank. A layer of “Surebond SB-190” adhesive was applied to the surface, and the tank was installed. A large plastic “zip” (electrical type) tie was positioned around a stamped metal fitting on the inner surface of the passenger rear quarter panel and the stamped metal handle of the fuel tank. This provided additional support to the assembly, particularly until the adhesive could cure.

A shutoff valve was installed into the side of the fuel tank, near the bottom, leaving some space for sediment accumulation below the outlet. The mounting point chosen for the assembly sloped downward toward the front of the vehicle. The fuel outlet was therefore located toward the rear of the vehicle, allowing sediment to accumulate toward the front of the tank. This was done to prevent sediment from being drawn into the fuel outlet, which would otherwise cause premature fuel filter plugging. Figure 3.3, below, shows the tank and filter arrangement:

**Figure 3.3 Proof-of-Concept ROFS – RO Fuel Line and HIH**



A hydraulic oil filter mount with a 30-micron hydraulic oil filter (capable of filtering material as small as 30-micron diameter) was added alongside this tank/ heat exchanger assembly. This was installed to trap larger particles and prevent possible filter plugging of the final filter (a 10-micron filter installed just before the fuel injection pump).

Fuel line sections were then installed and clamped into position with automotive type hose clamps. Fuel lines were routed such that RO fuel could be drawn from the RO fuel tank, through the heat exchanger, and through the 30-micron filter. In figure 4.2, the front of the heat exchanger is barely visible below the fuel tank. The translucent plastic fuel line extends from the

front outlet of the UDL. This was formed into a loop to facilitate a connection, and then connected to the fuel filter inlet (out of picture at right hand side).

The short section of translucent hose from the fuel filter outlet was one end of a long section of fuel line, part of the “HIH” assembly. It was routed through the car body to the valve, mounted in the engine bay at the front of the vehicle. The plastic “Y” connector with attached heater hoses shows the method by which the fuel line was branched off the glycol hoses. The branch where the fuel line protruded was capped off by a short section of smaller diameter hose, clamped around the fuel line. This forced the glycol to stop and circulate through the other branch, through the UDL heat exchanger, and back to the engine via a return line. The RO was drawn in the opposite direction to this flow, inside the HIH.

Photographs of the HIH routing are presented in Figure 3.4 below:

**Figure 3.4 – Proof-of-Concept ROFS - HIH and Glycol Return Line Routing**





From the 30-micron filter to the engine compartment, the routing was through the trunk; through an opening cut into passenger side rear wheel well; through another opening cut between the wheel well and the passenger compartment; along the passenger side of the vehicle (inside the passenger compartment); and through a hole cut into the firewall in the front passenger side (into the engine compartment).

The counterflow arrangement within the HIH, described above, resulted in further heating of the RO along the HIH path. The HIH was insulated along most of its path with prefabricated foam pipe insulation, of the type used to insulate water pipes in households. This was fastened with plastic “zip” ties. Clearance in the wheel well area, between the tire and the hoses, was barely adequate, so this short section was not insulated. Instead, a small piece of light gauge metal was placed over the hoses to protect them from contact with the tire. To prevent movement against the sharp edges of the openings

(which were made with an electric jigsaw) hoses were fastened into position and openings sealed with “Surebond SB-190” adhesive.

The test vehicle was not originally equipped with a separate fuel pump, relying instead upon the suction created by the fuel injection pump itself to draw fuel from the fuel tank. This arrangement was retained, at first, for supply of RO to the engine. An electric in-line fuel pump was later added as a booster pump. A photograph of the engine compartment with the ROFS lines installed is presented in Figure 3.5 below:

**Figure 3.5 - Proof-of-Concept ROFS – Engine Compartment**



The insulated section of HIH is visible in the upper left corner of Figure 3.5, with the line supplying hot glycol connected to it with a “Y” connector. The opposite end of that section of heater hose was connected into another “Y” connector, spliced into the original heater hoses supplying glycol to the passenger compartment heater box. The glycol return line from the UDL in the trunk was connected similarly into the other original line that carried glycol from heater box back to the engine. Thus, the ROFS glycol loop was interconnected with the original cooling system, and the vehicle water pump could provide hot glycol to the ROFS.



## Fuel Switching Solenoid Valve

The fuel switching solenoid valve, manufactured by Pollak™ (Pollak™, 2001) and referred to hereinafter as the “Pollak™ valve”, was mounted on the inside of the passenger front fender. The fuel line carrying petrodiesel was routed from the original fuel filter to the Pollak™ valve. A fuel line was connected from the outlet port of the Pollak™ valve to a final filter and then to the fuel injection pump. The positive terminal of the Pollak™ valve was connected to one side of a toggle switch mounted on the dashboard inside the vehicle, within easy reach of the driver. The other terminal of the toggle switch was connected to the battery via an inline-fused connector containing a 10-amp fuse. Thus, when the toggle switch was in the down position, petrodiesel was supplied to the engine. When the toggle switch was in the up position, 12 volt power was supplied to the Pollak™ valve, causing an internal component to close the port admitting petrodiesel to the valve, and simultaneously open the port admitting RO to the valve. The selected fuel could then exit the valve via the single outlet port, and be supplied to the fuel injection pump.

## Fuel Return Line Loop

Diesel engine fuel injection pumps are designed to constantly supply more fuel to the injectors and the pump itself than is needed to operate the engine.

The surplus is collected in return lines and sent back to the fuel tank. In a ROFS, if the Pollak valve were actuated, some surplus fuel would be present in the return lines. Thus, if the engine were operating on RO before switching fuels, some surplus RO would be returned to the original petrodiesel tank or alternatively, some surplus petrodiesel would be returned to the auxiliary RO tank.

It was necessary to keep the two fuels separate from each other, primarily to avoid fuel line and filter plugging with unheated RO (when operating on petrodiesel). Therefore, the return line was cut and routed back into the fuel feed line, such that surplus fuel would be supplied back into the fuel injection pump rather than returned to the original fuel tank. The cut off end of the original return line extending to the original fuel tank was plugged with a suitably sized bolt inserted into the line. A hose clamp was tightened around the outside of the return line and the bolt inside it, to prevent air or contaminants from entering the fuel system.

### Filtration

The 30-micron filter was kept warm by its proximity to the heat exchanger inside the radiant barrier insulation blanket, and by installation of the assembly within the trunk of the car. It was anticipated that warming of the RO in the auxiliary tank and filter, via insulation blanket retention of waste

heat radiated from the heat exchanger, would be sufficient. This avoided the need and expense of filter heaters and a custom fabricated tank with internal copper heating loop. Originally, the final fuel filter used just before the fuel injection pump was an inline automatic transmission oil filter. This was later replaced with a surplus Bosch™ brand filter mount and a fuel filter of the same type used petrodiesel in the original fuel system.

## Cost

The cost of the Proof-of-Concept ROFS used on the 1982 Volkswagen Jetta was approximately \$300 Canadian. A materials list is included in Appendix 'A'.

## Simplified Phase I ROFS - 1988 Ford Truck

A very inexpensive, simple version of a ROFS was constructed and used on a 1988 Ford diesel truck.

The truck engine was a 6.9 litre V8 indirect injection engine, equipped with an after-market turbocharger.

Photographs of this ROFS are presented in Figures 3.6 and 3.7 below:

**Figure 3.6 - Simplified Proof-of-Concept ROFS on Ford Truck**



**Figure 3.7 - Simplified Proof-of-Concept ROFS on Ford Truck - HIH**



Since the truck was equipped from the factory with dual tanks and a Pollak-type valve, a glycol loop was simply added to the cooling system and connected to a home made, surplus copper heating loop mounted beneath (not inside) one of the tanks. "Plyfoil" insulation was wrapped around the assembly. That tank was filled with RO, and the other tank filled with petrodiesel, biodiesel, or blends of the two fuels.

Since the fuel switching solenoid valve was located in the area of the fuel tanks, under the cargo box, both petrodiesel and SRO fuels passed from its outlet port, through the HIH, and into the original factory fuel filter. The insulated HIH assembly provided the only additional RO heating along the path to the fuel filter, other than the copper tubing below (outside) the RO

tank. No heat exchanger was used. The fuel filter was insulated with a layer of “Plyfoil” insulation. A “Springfield PreciseTemp™” digital thermometer sensor was affixed to the fuel injection pump fuel inlet fitting in similar fashion to that described above. The display was mounted inside the vehicle.

### **Construction of a “Low Capital Cost / Low Product Cost” Biodiesel Plant**

Technologically sophisticated biodiesel plants exist that provide economies of scale and maximise conversion efficiency. These are capital-intensive plants and may not always offer an appropriate solution. However, the literature review indicated that the transesterification process could be scaled down quite successfully, such that individuals, using basic and inexpensive equipment, could make good quality biodiesel. This is a rare attribute for alternative fuels for either gasoline or diesel engines, and potentially significant in defining a role for RO fuels in sustainable system design in developed and developing countries.

A visit to another local biodiesel producer offered further evidence that biodiesel production could indeed be very inexpensive and simple. In that case, the individual’s investment was negligible, and the work area was very small (approximately 2.5 metres x 2.5metres x 1.5 metres). The equipment

consisted of a surplus scale, mixer, and plastic pails. The workbench was a piece of plywood supported on bricks, a few centimetres off the floor. In addition to biodiesel, this particular individual was experimenting with the production of soap from the glycerine by-product, using simple moulds to make the bars of soap. It was not difficult to imagine such a simple and inexpensive fuel production “plant” being replicated in homes and villages around the world, with the possible addition of a simple press for the production of oil from oilseeds, such as the “Mafuta Mali” manual ram press (ApproTEC, 2000) or the Taby Pressen electrically operated screw press (Jonsson, 2000).

A small biodiesel processor plant was constructed to gain experience and compare biodiesel production and use with the construction and use of a ROFS. The book “From the Fryer to the Fuel Tank” (Tickell and Tickell, 1999) was used as a reference for the basic design and function of the processor as well as for methods of production.

The total investment was in the hundreds of dollars, the same as the ROFS system. A basic batch type single tank biodiesel processor was built and installed in a small outbuilding. The processor and related equipment and materials were housed in a small wood-frame building, approximately 2 metres x 4 metres. The processor and processor building were such that they

could be constructed in most parts of the world at relatively low cost.

Photographs of the plant are presented in Figure 3.8, below:

**Figure 3.8 – Interior of Biodiesel Processor Building**





## Processor Building Insulation and Liner Material

The building was lined with “Plyfoil” brand radiant barrier insulation (aluminum bonded to polyethylene bubble pack) manufactured by Plyco Corporation in the USA, which provided effective insulation against heat loss and heat gain. The material was approximately 1cm in thickness, and came in a roll. It was compact when shipped, lightweight, fire resistant, and easy to install and keep clean. The bright interior building liner it created eliminated the need for any other interior finish and maximised the effectiveness of a single fluorescent light. This material was also very useful for insulating lines, valves and tanks on both the ROFS and the biodiesel processor equipment.

## Flooring

Heavy galvanised sheet metal was placed over the wood floor to prevent absorption of any spilled materials and allow for cleanup.

## Single Tank Processor

A single tank processor system uses one tank for both mixing the catalysing reactants (sodium hydroxide and methanol, in this case), and then for mixing

the reactants with the RO. The processor tank itself was made from an old wringer washing machine. The agitator was used as a mixer, and the bottom drain provided was used to drain off the glycerine. The tank had a useful capacity of 40 litres. The mixing tank and lid were insulated with “Plyfoil” radiant barrier insulation.

### Miscellaneous

A small, electric oil-filled heater was added for winter use. A rectangular flap was cut into the ceiling insulation to allow venting of vapours to the outside. A reused kitchen counter provided a work surface and storage for supplies. A surplus RV type 12-volt water pump was used to pump the finished biodiesel through an inexpensive “GoldenRod™” brand 10-micron diesel fuel filter, of the type normally used on agricultural diesel fuel dispensing tanks. This was mounted on the wall of the building near the processor.

A small balance scale was used to weigh sodium hydroxide. Litmus paper or aquarium test kits were used for pH tests. A glass kitchen blender was used for mixing batches of sodium methoxide catalyst and for mixing small test batches of RO and catalyst to produce biodiesel and glycerine. Methanol and sodium hydroxide were purchased in bulk from a local industrial supplier.

## **Construction of a “Pre-Commercialisation” ROFS**

Late in the study, the lessons learned from the two “proof-of-concept” ROFS were applied to the design and construction of a third “pre-commercialisation” version. This was fitted into the box of the same Ford diesel truck that was used for the simplified proof-of-concept ROFS. The pre-commercialisation version was designed to be lightweight, inexpensive and easy to install.

### **Pressure Test**

The design was dependent on the strength of a specialised sealant material. Once fully cured, the material was pressure tested to double the working pressure of the cooling system on the truck.

### **Heat Exchanger Efficiency Test**

After fitting the ROFS to the truck box, coolant lines were attached to the heat exchanger. The truck was brought to operating temperature and temperature measurements were made of the glycol coolant, the RO fuel temperature in the auxiliary fuel tank, and the RO temperature as it exited the heat exchanger.

## Other Uses of RO

Others have reported that biodiesel can be used successfully in certain devices intended for use with kerosene or lamp oil. A simple olive oil lamp and a modern wick-type “Kerosun™” brand kerosene heater were obtained to determine if the availability of RO fuels in a given area might allow multiple services (namely, light and heat, as well as diesel engine fuel) from one basic fuel. Such multiple fuel use capability could provide further incentive for the establishment of a RO fuels industry in a given region. In addition, it was also understood to be the case that biodiesel is a good solvent, degreasing agent, and light oil lubricant, and paint remover. Simple tests were devised to determine its effectiveness for these uses.

Biodiesel was used to:

- Clean oil stains from concrete.
- Remove grease from engines.
- Remove adhesive residue from glass.
- Lubricate bicycle chains and sliding doors.
- Remove cured paint from painted wood.
- Remove paint, oil and grease from skin.

## **CHAPTER FOUR – RESEARCH STUDY RESULTS**

### **Results of ROFS and Biodiesel Viscosity Reduction Approaches**

#### **ROFS**

##### **ROFS Heat Exchange Efficiency**

The ROFS was intended to provide the highest heat exchange efficiency possible. The combined effect of pre-heating of RO in the auxiliary tank, primary heating in the UDL heat exchanger, and secondary heating via travel of fuel RO through the heated path of the hose-in-a hose (HIH) was intended to accomplish this.

RO should be heated to a minimum of 70 °C in order to reduce viscosity to less than 20 cSt, a tolerable viscosity for most fuel injection pumps (Tickell and Tickell, 1999). In reality, 80°C might be preferable, since at that

temperature, RO would be approximately 10 cSt, the same viscosity as petrodiesel. However, at least one study on the effects of viscosity reduction of SRO did conclude that 60-70° C was the optimum temperature range for SRO, for diesel engines under moderate load versus full load (Lohmann, 2000).

Since the glycol engine coolant temperature is coincidentally maintained at approximately 80°C, RO can be used as fuel by capturing waste heat from internal combustion.

Since the optimum temperature for proper viscosity is essentially the same as operating temperature of the engine, the objective in ROFS design should be to achieve very high heat exchange efficiency by the time the RO reaches the fuel injection pump. This proved to be more difficult than anticipated.

Temperature measurements were taken once the engine was at operating temperature, using the infrared sensor gun. The maximum glycol coolant temperature with the engine at idle was 67°C at the high point of the cooling system, the coolant expansion tank. The cylinder head temperature at the time was 95°C. Therefore the engine was considered to be operating at near its normal operating temperature. The temperature of the fuel at the fuel inlet into the injection pump was 55°C, despite the effort made to maximise

heat exchange and retain heat by insulating the RO fuel line from the heat exchanger through to the Pollak valve.

The fuel inlet temperature divided by the glycol temperature in the expansion tank indicated a system heat exchange efficiency of 82%. It is likely that higher glycol and fuel inlet temperatures were achieved when the engine was under load, but the glycol temperature would also have been higher when the engine was under load, meaning that efficiency would not have been greater than for the measurements taken at idle.

The temperature readings taken with the Springfield digital thermometer were not considered accurate. Heat loss occurred at speed despite the insulation that was installed. A noticeable drop in temperature was observed on the digital display mounted inside the vehicle as the vehicle was accelerated to driving speeds. The maximum temperature recorded by the digital thermometer sensor on the top of the fuel inlet fitting was 54°C even when the engine was under load.

Despite RO heating being less than ideal, engine did perform well on RO using the ROFS.

## **Production of Biodiesel from Recovered Renewable Oil**

RRO Collection Logistics

Waste vegetable oil was collected from local restaurant deep-fat fryers. Free fatty acid (FFA) content and contaminant levels varied widely. A titration was performed on each batch that indicated the amount of NaOH (sodium hydroxide) to be used in a mixture with methanol to create sodium methoxide, the base needed for transesterification. Some of the oil collected was too heavily contaminated or had too high a FFA content to be used in biodiesel production. This RO was filtered and used in the ROFS instead, as SRO.

### Base-Catalysed Transesterification

The book “From the Fryer to the Fuel Tank” was used as a reference for the design of the biodiesel reactor and for information on the transesterification process (Tickell and Tickell, 1999).

Sodium hydroxide and methanol were mixed to form a strong base, sodium methoxide. This is a caustic solution that creates a significant amount of exothermic heat. Caution and proper safety equipment must be used in this stage of the biodiesel production process. The mixture of sodium methoxide



was added to RRO that had been heated to approximately 43°C. This was then mixed for one hour in the processor tank, and allowed to settle for eight hours. In a successful reaction, glycerine settled to the bottom of the processor with the lighter esters, fatty acid methyl ester (FAME) forming the top layer. A sample is shown in Figure 4.3, below:

**Figure 4.3 – Fatty Acid Methyl Ester (FAME) Biodiesel**



The biodiesel as shown in the top layer in Figure 4.3 was then siphoned off and “washed”. The technique of washing biodiesel is described in the next section.

#### “Washing” Biodiesel

Most researchers now recommend that biodiesel be “washed” to remove impurities such as methanol, free fatty acids, soaps and waxes that are usually present in small quantities after transesterification. A common “washing” method is to sprinkle water on the surface and let it settle to the

bottom. Contaminants attach to the water as it settles through the biodiesel. The pH of the water can be slightly acidified, using vinegar, to neutralise the base-catalysed biodiesel. The process is repeated as necessary. Washing results in significant quantities of wastewater. A sample of washed biodiesel is presented in Fig. 4.4, below:

**Figure 4.4 – “Washed” Biodiesel**



In figure 4.4, the fats and soaps that were removed by washing the biodiesel are visible in the bottom of the sample jar.

An alternative method is the “bubble wash” technique, usually attributed to University of Idaho researchers. In the bubble wash technique, the pH of the biodiesel (above 7) is measured and an acid (usually vinegar) is added to an equal volume of water until the pH is below neutral to the same degree that the biodiesel is above neutral. The biodiesel is added to the water. A compressed air supply attached to a device for producing fine bubbles, such

as is used in aquariums, is placed in the bottom of the container, in the water. This results in a stream of bubbles rising to the surface. Water attaches to the air bubbles, and the two rise through the biodiesel. The air bubbles are released at the surface, and the water droplets re-settle through the biodiesel, attracting and filtering out contaminants. Kac provides a complete description of the technique. (Kac, J., 2000). The final biodiesel is removed with a clear siphon tube and filtered. This technique is recommended by a number of researchers. Either method of washing biodiesel requires some use of heat and mechanical (pumping) energy.

### **Results of SRO and Biodiesel Fuel Use in Vehicle**

#### **Exhaust Emission Testing – Quantitative – Comparison of Fuels**

Certain emissions are included in the standard Environmental Protection Agency test. These are HC, CO, NO<sub>x</sub> and CO<sub>2</sub>. These are expressed in either grams per kilometre (in Canada) or grams per mile (in the USA). Emissions test results are presented in Table 4.3, below:

**Table 4.3 Emissions – Various Fuels – 1982 VW Jetta**

| <b>Horiba™ Analyser - Hot 505 - First Phase of 75 FTP (CFV CVS; metric units)</b> |           |           |                       |                       |               |
|---|-----------|-----------|-----------------------|-----------------------|---------------|
| <b>Summary of Emissions Tests</b>   |           |           |                       |                       |               |
| <b>Test Vehicle - 1982 Jetta</b>  |           |           |                       |                       |               |
| Grams/km  |           |           |                       |                       |               |
| <b>Fuel</b>   | <b>HC</b> | <b>CO</b> | <b>NO<sub>x</sub></b> | <b>CO<sub>2</sub></b> | <b>Test #</b> |
|   |           |           |                       |                       |               |

|  |      |      |      |        |      |
|--|------|------|------|--------|------|
| <b>Premium Diesel - Baseline Test #1</b> | 0.13 | 0.92 | 0.46 | 165.13 | 6510 |
| <b>Premium Diesel - Baseline Test #2</b> | 0.14 | 0.90 | 0.45 | 164.95 | 6511 |
| <b>Canola Test #1</b>                    | 0.15 | 0.93 | 0.47 | 165.89 | 6512 |
| <b>RRO Test #1</b>                       | 0.18 | 1.12 | 0.43 | 165.92 | 6513 |
| <b>Diesel Test #3</b>                    | 0.14 | 0.91 | 0.50 | 172.01 | 6514 |
| <b>RRO Test #2</b>                       | 0.14 | 0.85 | 0.45 | 163.95 | 6515 |
| <b>Biodiesel Test #1</b>                 | 0.15 | 0.91 | 0.48 | 173.60 | 6516 |
| <b>Canola Test #2</b>                    | 0.15 | 0.75 | 0.53 | 180.76 | 6517 |

Although a number of studies in the literature report significant reductions for all these emissions but NO<sub>x</sub>, such reductions did not occur in the emissions tests that were performed.

## Opacity

Opacity is a determination of the amount of soot in the exhaust stream. It is not a direct measurement of particulate matter, which is more difficult to quantify. However, since soot is largely composed of particulate matter, opacity measurement is a useful tool for quickly estimating particulates in a given diesel exhaust stream and comparing that produced from different fuels, while other variables are controlled.

Opacity test results for various fuels are presented in Table 4.4, below. RO fuels reduced opacity, compared to premium petrodiesel, by approximately 50%. Averaging tests 1, 2 and 4 produces the result of an average opacity for the premium diesel fuel of 13.4%, whereas the average of tests 3 and 7 shows an average opacity for SRO of 6.4%.

**Table 4.4 – Opacity – Various Fuels – 1982 VW Jetta**

| <b>Test Name</b> | <b>Test #</b> | <b>Fuel</b> | <b>Average Opacity</b> | <b>Standard Deviation</b> |
|------------------|---------------|-------------|------------------------|---------------------------|
| <b>ALTDESL</b>   | 651           | Baseline    | 11.14%                 | .066                      |
| <b>1</b>         | 0             | diesel      |                        |                           |
| <b>ALTDESL</b>   | 651           | Baseline    | 17.25%                 | .099                      |
| <b>2</b>         | 1             | diesel      |                        |                           |
| <b>ALTDESL</b>   | 651           | New Canola  | 7.5%                   | .048                      |
| <b>3</b>         | 2             |             |                        |                           |
| <b>ALTDESL</b>   | 651           | Diesel      | 11.9%                  | .067                      |
| <b>4</b>         | 4             |             |                        |                           |
| <b>ALTDESL</b>   | 651           | RRO         | 6.3%                   | .041                      |
| <b>5</b>         | 5             |             |                        |                           |
| <b>ALTDESL</b>   | 651           | Biodiesel   | 5.4%                   | .026                      |
| <b>6</b>         | 6             |             |                        |                           |
| <b>ALTDESL</b>   | 651           | New Canola  | 5.3%                   | .028                      |
| <b>7</b>         | 7             |             |                        |                           |

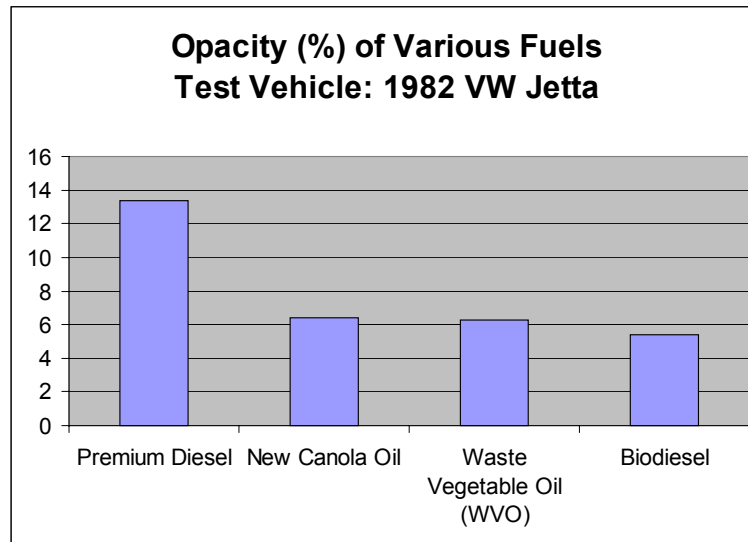
A single factor ANOVA was performed on the opacity data for the various fuels. The ANOVA results are presented in Table 4.5, below:

**Table 4.5 - Anova for Opacity – Various Fuels – 1982 VW Jetta**

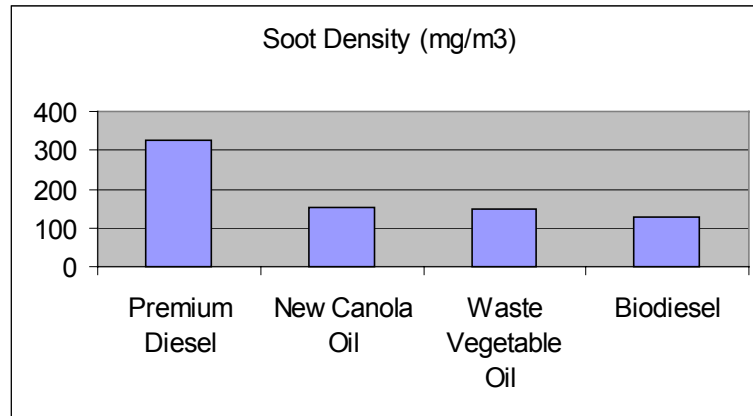
| <b>Anova: Single Factor</b> |              |            |                |                 |                |               |
|-----------------------------|--------------|------------|----------------|-----------------|----------------|---------------|
| <b>SUMMARY</b>              |              |            |                |                 |                |               |
| <b>Groups</b>               | <b>Count</b> | <b>Sum</b> | <b>Average</b> | <b>Variance</b> |                |               |
| <b>ALTDESL 1</b>            | 2500.000     | 278.704    | 0.111          | 0.004           |                |               |
| <b>ALTDESL 2</b>            | 2500.000     | 431.488    | 0.173          | 0.010           |                |               |
| <b>ALTDESL 3</b>            | 2500.000     | 187.872    | 0.075          | 0.002           |                |               |
| <b>ALTDESL 4</b>            | 2500.000     | 297.000    | 0.119          | 0.005           |                |               |
| <b>ALTDESL 5</b>            | 2500.000     | 156.608    | 0.063          | 0.002           |                |               |
| <b>ALTDESL 6</b>            | 2500.000     | 133.912    | 0.054          | 0.001           |                |               |
| <b>ALTDESL 7</b>            | 2500.000     | 131.504    | 0.053          | 0.001           |                |               |
| <b>ANOVA</b>                |              |            |                |                 |                |               |
| <b>Source of Variation</b>  | <b>SS</b>    | <b>df</b>  | <b>MS</b>      | <b>F</b>        | <b>P-value</b> | <b>F crit</b> |
| <b>Between Groups</b>       | 29.419       | 6.000      | 4.903          | 1421.057        | 0.000          | 2.099         |
| <b>Within Groups</b>        | 60.357       | 17493.000  | 0.003          |                 |                |               |
| <b>Total</b>                | 89.775       | 17499.000  |                |                 |                |               |

The Anova in figure 4.5 indicates that the results of the opacity tests are of the same family.

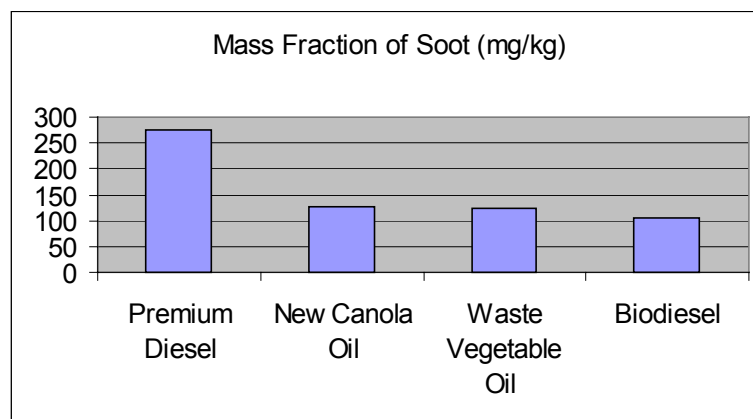
The opacity percentage results are also provided in chart form, in figure 4.4, below:

**Figure 4.4 – Opacity of Various Fuels**

On-line tools such as “Java scripts” are available from “Dieselnet”, a web site specialising in information about diesel emissions (Dieselnet, 2000). These may assist in calculations of particulate matter, based on opacity readings. Averaged opacity readings from the emissions tests were entered gave the results presented in Figures 4.5 and 4.6.

**Figure 4.5 – Soot Density – Various Fuels – 1982 VW Jetta**

Soot density as mg/m<sup>3</sup> reflected the percentage opacity readings.

**Figure 4.6 Mass Fraction of Soot – Various Fuels – 1982 VW Jetta**



The mass fraction of soot, expressed as mg/kg were again calculated using the on-line Java scripts described above, and reflected the percent opacity readings.

The above results indicate that a significant reduction in particulate emissions resulted for all RO fuels, compared to premium petrodiesel.

#### Power Output (Horsepower)

Chassis dynamometer horsepower readings were taken for the various fuels.

These readings were taken during emissions testing (described in later sections). The results are presented in Table 4.1, below:

**Table 4.1 - Horsepower - Various Fuels - 1982 VW Jetta**

| Test # | Fuel / Test Name | Gear Selected   | Avg. Speed km/h | Avg. Horsepower |
|--------|------------------|-----------------|-----------------|-----------------|
| 6511   | Baseline Diesel  | 3 <sup>rd</sup> | 86.98           | 34.7            |
| 6512   | New Canola       | 3 <sup>rd</sup> | 80.18           | 36.5            |
| 6513   | RRO              | 3 <sup>rd</sup> | 78.20           | 36.3            |
| 6516   | Biodiesel        | 3 <sup>rd</sup> | 87.34           | 35.5            |
| 6517   | New Canola, Test | 3 <sup>rd</sup> | 87.33           | 35.7            |

#2

Each fuel was tested for horsepower, in conjunction with the emissions tests.

The procedure is presented in the emissions testing section. There was no significant difference in horsepower between the various fuels tested.

Straight RRO in a ROFS provided the highest horsepower reading of the group, but this was only slightly higher than the other fuels.

#### Lubricating Oil (Crankcase Oil) Testing

A summary of the analyses is presented in Tables 4.2 and 4.3 below. Only the reportable or unacceptable results are shown here. Complete reports are presented in Appendix 'B'.

**Table 4.2 - Lubricating Oil Analysis Summary - Spectro-chemical Analysis (ppm) – SRO Fuel compared to Petrodiesel – 1982 VW Jetta**

|                                | Sample #  | Date     | Sodium      | Potassium   | Iron        | Lead        |
|--------------------------------|-----------|----------|-------------|-------------|-------------|-------------|
| <b>Series I – SRO</b>          |           | Y/M/D    |             |             |             |             |
| 2000 km                        | 12/01-459 | 00/11/28 | 51 <b>R</b> | 14 <b>R</b> | 88 <b>U</b> | 26 <b>R</b> |
| 1000 km                        | 11/07-401 | 00/10/31 | 19          | 8           | 45          | 20          |
| 500 km                         | 10/19-103 | 00/10/14 | 1           | 9           | 20          | 12          |
| <b>Series II – Petrodiesel</b> |           |          |             |             |             |             |
| 2000 km                        | 02/07-584 | 01/02/04 | 6           | 12          | 36          | 5           |
| 1000 km                        | 01/29-478 | 01/01/24 | 8           | 1           | 23          | 2           |
| 500 km                         | 01/12-497 | 01/01/10 | 6           | 3           | 17          | 2           |

R – Reportable U-Unacceptable

Fluid Life Corporation© has predetermined standards for levels of various wear particles from engine components that tend to appear in engine lubricating oil with use. The rating scale is that contaminants are considered to be negligible (normal contamination with use), reportable (for which close monitoring is recommended), and unacceptable (for which the customer is notified immediately and corrective action recommended). This reporting system is based on their expertise in lubricating oil analysis and the known probable sources of contamination, usual rates and levels of contamination observed, and effects of excess contaminant levels on engines.

**Table 4.3 - Lubricating Oil Analysis Summary -Physical Tests- SRO Fuel compared to Petrodiesel – 1982 VW Jetta**

|                                | Sample #  | Date     | Water % | Glycol % | Viscosity 40°C cSt | Viscosity 100°C cSt |
|--------------------------------|-----------|----------|---------|----------|--------------------|---------------------|
| <b>Series I – SRO</b>          |           | Y/M/D    |         |          |                    |                     |
| 2000 km                        | 12/01-459 | 00/11/28 | PR      | PR       | 131.R              | 17.22R              |
| 1000 km                        | 11/07-401 | 00/10/31 | PR      | N        | 123.R              | 16.42R              |
| 500 km                         | 10/19-103 | 00/10/14 | N       | N        | 118.               | 15.58               |
| <b>Series II – Petrodiesel</b> |           |          |         |          |                    |                     |
| 2000 km                        | 02/07-584 | 01/02/04 | N       | N        | 127R               | 16.90R              |
| 1000 km                        | 01/29-478 | 01/01/24 | PR      | N        | 106                | 15.14               |
| 500 km                         | 01/12-497 | 01/01/10 | N       | N        | 113                | 16.05               |

P – Positive N-Negative R – Reportable U-Unacceptable

The physical tests performed by Fluid Life Corporation© are intended to reveal any unusual levels of water or glycol in the lubricating oil and any

unusual viscosity characteristics for the oil itself. A “negative” result is the acceptable end of the rating scale that is used, followed by “positive”, “positive reportable”, and “unacceptable”.

### Series I – SRO Fuel

Reportable amounts of sodium, potassium and lead were found in the 2000-km sample. An unacceptable level of iron was also found in the 2000-km sample. Reportable levels of glycol and water were also found. The glycol, water, sodium and potassium levels indicated a possible coolant leak in the engine. Oil viscosity increased to an unusual level in the 2000-km sample. Fluid Life Corporation© faxed an alert, in advance of the normal procedure of mailing test results, indicating that immediate investigation was warranted and that the presence of water and glycol and the viscosity reported at 40°C and 100°C could cause “dramatic reductions in component life” (Fluid Life Corporation©, personal communication, 2000). Suggested causes of the problem included overheating or a leaking head gasket. This was the last of three samples to be taken after operation on SRO.

Fluid Life Corporation© was contacted for an opinion on the extent to which the unexpected presence of glycol and water in the sample may have

contributed to the reported level of iron and the reported viscosity. A representative replied that both the iron and lead levels, and the viscosity of the oil would “most definitely” have been result of the presence of glycol and water in the sample (M. Laplante, personal communication, 2000).

The oil was changed to begin the 1000 km-purge segment that was conducted before the test on petrodiesel fuel. The engine was inspected for signs of overheating or leaks. A slight indication of an earlier glycol leak was located at the head gasket. The indicator was a green discoloration approximately 1cm x 1cm in size, below a section of the head gasket. This appeared to be minor and was dry.

The cause of the discoloration was suspected to have been an overheating incident earlier in the study (prior to the lubricating oil analysis portion) when the electric radiator fan failed to operate due to a sticking thermostatic fan switch. Immediately after that overheating incident, the metal switch housing was tapped with a small hammer and tested. The switch operated normally, causing the cooling fan to engage, and was returned to service.

Partway through the 1000km-purge segment of the tests, the switch apparently failed again. The fan did not engage as it should have, and the engine overheated on a steep grade. There appeared to be a large amount of white smoke coming from the exhaust and a head gasket failure was

suspected. Fortunately, the cause was later identified as a hole in the underside of a coolant hose, just below the head gasket (the white smoke had come from the coolant hitting the outside of the hot exhaust pipe). All older coolant hoses, and the thermostatic fan switch, were replaced with new items. The cooling system was flushed and an engine block sealant (“Gunk™” brand) was mixed with water and circulated through the system to seal any internal leaks. The block sealant product was then drained from the cooling system per the product instructions, and the glycol / water solution was replaced.

#### Series II – Petrodiesel

Series II results for petrodiesel indicated that the glycol leak repair had been effective. Glycol was not detected. Although either the glycol/water solution or SRO could have caused the oil thickening notices in Series I, it was noted that almost the same viscosity was reported in the third “2000 km” sample from Series II as was found for the third sample in Series I. Therefore, the increase in viscosity in Series I may not have been caused entirely by either the SRO use or by the coolant leak.

Overall, since the results of Series I were likely affected by coolant contamination of lubricating oil samples, the lubrication study was considered to be largely inconclusive and further research was recommended.

#### Engine Compression Test

The engine compression was checked prior to the installation of the ROFS, and again at the time of the injector coking inspection. A very slight loss of compression is normally found over time. A significant reduction in compression coincident with the use of SRO could have indicated a problem with the use of SRO fuel. In fact, the compression readings were actually higher after approximately 10,000 kilometres of operation primarily on SRO. The same mechanic used the same compression test device for both tests. The results are presented in Table 4.4, below:

**Table 4.4 - Engine Compression (PSI) – 1982 VW Jetta**

| Date                      | Odometer<br>(km-<br>corrected) | Cyl. #1 | Cyl. #2 | Cyl. # | Cyl. |
|---------------------------|--------------------------------|---------|---------|--------|------|
|                           |                                |         |         | 3      | #4   |
| <b>Oct. 11,<br/>1999</b>  | 194,905                        | 450     | 460     | 460    | 460  |
| <b>Sept. 22,<br/>2000</b> | 205,694                        | 500     | 490     | 510    | 510  |

New oil had recently been installed in the vehicle, and the engine may have been hotter when tested the second time. These factors might explain the slight increase in compression that was observed.

### SRO Fuel Economy

Using SRO in the ROFS, fuel consumption averaged 5.65 litres per hundred kilometres (50 miles per Imperial gallon) for September and October 2000, the months in which detailed trip logs were maintained. Operating on petrodiesel, fuel consumption averaged 5.23 litres per hundred kilometres (54 miles per gallon).

### Visible Smoke

Hard acceleration up steep grades and full power acceleration from a standing start produced negligible amounts of visible smoke when operating on RO. The same conditions produced moderate amounts of black smoke when operating on petrodiesel.

### Exhaust Characteristics



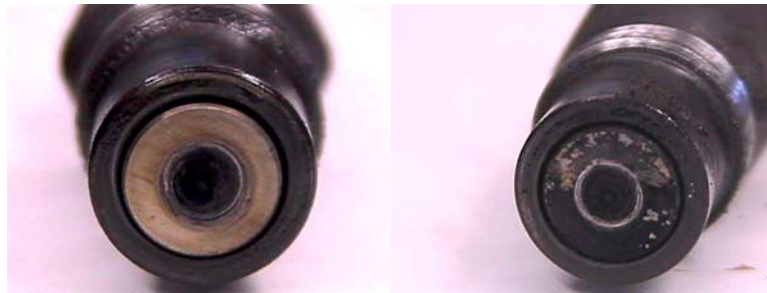
The engine on the test vehicle was in very good condition and did not produce large amounts of visible smoke for any fuel used. However, at times, the exhaust smell was noticeable. It was distinctive and similar to the smell of the exhaust from deep fat fryers. It was considered by the researcher to be less objectionable and irritating to eyes, nose, and throat than petrodiesel exhaust. This was also the general impression of observers (members of the public and acquaintances of the observer) who contributed their casual observations.

### Injector Coking Inspection

Fuel injector coking has been reported as a problem when diesel engines are operated on vegetable oil over longer periods of time. It was anticipated that that the start-up/shutdown cycle, especially using biodiesel or premium diesel, both of which are known to have a solvent cleaning effect on injectors, would alleviate this concern.

After nine months and approximately 10,000 km of mostly urban and suburban driving (conditions which could have led to coking), the injectors were removed and inspected by a qualified mechanic. Photographs of two of the injectors, taken at the time of this inspection, are presented in Figure 4.7 below.

**Figure 4.7 Fuel Injectors – After Approximately 10,000km on SRO – 1982 VW Jetta**



Three of injectors were almost totally free of deposits. Deposits did appear on one injector, shown on the right in figure 4.1. The mechanic's opinion was that the injector might not have been tightened adequately when it was removed temporarily for compression tests the year before, and that a slight leak may have caused the deposits to form.

A visual inspection of the injector spray pattern was performed with an injector tester. A photograph of this test is presented in Figure 4.8 below:

**Figure 4.8 – Injector Spray Pattern Test**



The spray pattern was normal for all four injectors. Overall, the mechanic indicated that the injectors were in good condition, and that no cleaning or other maintenance was necessary. The injectors were replaced without any cleaning or maintenance being performed.

#### Cold Weather Tests - ROFS

Cold starts on SRO were almost impossible without the use of a block heater. Even at temperatures above freezing, if SRO was not purged from the system before shutting the engine off overnight, it was very difficult to start the engine. Repeated use of the glow plugs was necessary in order to start the engine. A short period of block heater use consistently solved the problem.

The engine would start easily after only 15-20 minutes of block heater operation, even if no purging had occurred and the engine had been left completely on SRO overnight. This was the case for temperatures as low as  $-10^{\circ}\text{C}$ .

Normal ROFS operation in cold weather conditions to  $-10^{\circ}\text{C}$  also proved to be greatly improved by the use of the block heater for at least 20 minutes prior to starting the engine. The time required to bring the engine to operating temperature (and enable the ROFS) was reduced by half.

#### Cold Weather Operation on Biodiesel

Biodiesel was tested in a 50/50 blend with petrodiesel. There were no problems with this mixture down to  $-10^{\circ}\text{C}$ .

#### Use of ROFS with Recovered Renewable Oil (RRO)

RRO was obtained from a local collecting company that had collected the material from restaurants. The material was believed to contain a large percentage of Canola oil, the predominant frying oil in the region. The RRO was obtained from a large silo collection tank that was kept constantly heated at approximately  $60^{\circ}\text{C}$ . The tank drain valve was approximately one metre from the ground. This allowed solids and water to accumulate at the

bottom of the tank, below the valve. The material was therefore free of major contaminants. A quantity of approximately 10 litres was added to the auxiliary tank and the vehicle was then operated on the RRO for the journey from the collection facility to the researchers home, a distance of approximately 100 kilometres. The engine operated normally on this trip.

Shortly after this trip, problems occurred with the fuel-switching valve, which began sticking partway between fuels so that the vehicle was actually operating on a blend of petrodiesel and RRO. The design of the valve prevented complete purging of RRO. The 30-micron filter was not purged as part of the shutdown procedure, since it was upstream of the Pollak valve. Like the Pollak valve, RRO occasionally cooled overnight, plugging the filter. Since the filter was in close proximity to the UDL heat exchanger, and the entire assembly was insulated, the filter would become warm enough that flow would begin after 10-20 minutes of operation on petrodiesel. 10-micron water separating fuel filter was used for a short test, in place of the 30-micron filter. This plugged easily and did not release when the RRO was warmed. It was removed and the 30-micron filter was reinstalled.

## ROFS Faults

Some problems did occur with the original ROFS. The first problem was plugging of fuel filters as described above. The second problem was with air

entering the fuel system via the numerous connections that were used for the ROFS. Fuel starving occurred if the filters became plugged. This resulted in partial or complete stalling when attempting to switch fuels for operation of the engine on SRO.

The test vehicle was not originally equipped with a booster fuel pump, but relied solely on the fuel injection pump vacuum to draw fuel from the tank. If fuel was not delivered and the engine was allowed to stop running from fuel starvation, it was not possible to restart the engine without pressurising the main fuel tank with a small amount of compressed air and bleeding the fuel system. This forced fuel from the tank and allowed restarting of the engine. The addition of a 2-4 psi 12 volt electric fuel pump solved this particular problem. Later changes to the fuel filtering system, combined with more careful attention to RO fuel quality and pre-filtering prior to placement in the fuel tank prevented further problems for warm weather operations. Cold weather operation remained somewhat problematic, and was identified as an area for future research.

Air in the fuel system was caused by both the difficulty in obtaining airtight seals at all the connections needed for the ROFS, and by the use of a return line loop. The return line loop prevented the usual return of fuel to the fuel tank and the usual venting system. Therefore, small amounts of air that entered the fuel system tended to accumulate and cause poor idling. This

problem was not completely solved. Elimination of as many connections as possible in ROFS design did improve the situation to some extent.

### Acceleration Tests

An assistant used a stopwatch to record 0-90 km/h acceleration times. Each test was performed once in each direction under calm conditions on a level, paved surface. Tests were repeated later in the study after replacement of fuel filters, the addition of a 2-4 psi electric in-line fuel pump (as a booster pump), and with the installation of fresh lubricating oil. Results were very similar to the first acceleration runs. The vehicle and tires were at normal operating temperature for both tests. Only regular petrodiesel and SRO were compared. Results are presented in Table 4.5 below.

**Table 4.5 Acceleration – Petrodiesel vs. SRO – 1982 VW Jetta**

|                            | Date     | Petrodiesel        | SRO                |
|----------------------------|----------|--------------------|--------------------|
|                            | MM/DD/YY | 0-90 km/h<br>(sec) | 0-90 km/h<br>(sec) |
| <b>Test #1, Run<br/>#1</b> | 10/10/00 | 18                 | 18                 |
| <b>Test #1, Run<br/>#2</b> | 10/10/00 | 18                 | 18                 |
| <b>Test #2, Run<br/>#1</b> | 12/15/00 | 17                 | 19.5               |
| <b>Test #2, Run<br/>#2</b> | 12/15/00 | 18                 | 19                 |

SRO acceleration times were very close to those for petrodiesel fuel. Ambient temperature was not recorded but was in the range of 0° C to +10° C for both tests. The road surface was flat, smooth, dry asphalt pavement for both tests. The difference in acceleration might have been due to a partially plugged SRO fuel filter (the 30-micron hydraulic oil filter) that was not part of the petrodiesel fuel delivery path. A partly plugged fuel filter would have caused



a restriction in fuel flow, which would translate into a slight difference in available power under the full load condition of maximum acceleration from a standing start.

### Gradeability

Part of the driving cycle included a moderate grade, approximately two kilometres in length. The grade could be approached at speeds of 100km/h, using the overdrive (5<sup>th</sup>) gear. In the latter part of the study, it was noted that while on petrodiesel, the vehicle had sufficient torque to maintain at least 95 km/h to the top of the grade in overdrive, but that this could not be achieved on SRO (either new Canola oil or RRO). For SRO, the top-of-grade attainment speed was approximately 90km/h and downshifting from overdrive to 4<sup>th</sup> gear was often necessary. Since the dynamometer horsepower readings were the same for all fuels earlier in the study, this slight difference in gradeability might have been due to a partially plugged SRO fuel filter (the 30-micron hydraulic oil filter), as described in the acceleration results section above.

In any case, the available power on SRO was adequate and this result was not considered to be a significant difference in gradeability. Discussions with owners of other diesel and gasoline powered 4 cylinder, five speed

automobiles indicated that the need to downshift to 4<sup>th</sup> gear, on the grade used for the tests, was not unusual.

#### Biodiesel Fuel Use in VW Jetta and Ford Truck

The general performance using biodiesel in the main fuel tank in place of petrodiesel (i.e. not in the ROFS) seemed to be at least on a par to petrodiesel. This comparison was not extensive or quantified, however, to the same extent as the comparison of SRO and petrodiesel.

#### Results of Simplified Proof-of-Concept ROFS Installed in Ford Truck

There were no problems with the use of biodiesel in the original fuel tank in warm weather.

The HIH, without the use of a separate heat exchanger, combined with the rate of fuel flow demanded by the 6.9 litre diesel truck engine, did not provide adequate SRO temperature rise and viscosity reduction in cold weather. The practice of using biodiesel within the ROFS instead of SRO was adopted in cold weather to overcome the inadequacy of the simplified ROFS design.

This practice made the best all season use of the simplified ROFS. It allowed the least expensive fuel (SRO) to be used in warm weather, avoided the usual

problems with high biodiesel cloud point, and used a fuel (biodiesel) that was more easily and quickly warmed for use than SRO in winter (i.e. biodiesel).

### **Results of Pre-Commercialisation ROFS Tests**

#### **Pressure Test**

The device was tested to double the working pressure of the truck's cooling system. No leaks were found initially, but a critical seal later burst when the unit was in service. At the time of this writing, the device was being redesigned to eliminate need for the seal.

#### **Heat Exchanger Efficiency Test**

The results of the heat exchanger efficiency test are presented in Table 4.6 below:

**Table 4.6 Pre-Commercialisation Version ROFS Heat Exchanger Efficiency Test**

|                                    |                     |
|------------------------------------|---------------------|
| <b>Ambient Temperature</b>         | 0 <sup>0</sup> C    |
| <b>Glycol Coolant Temperature</b>  | 76.6 <sup>0</sup> C |
| <b>SRO Temperature – Exchanger</b> | 13.2 <sup>0</sup> C |
| <b>Inlet</b>                       |                     |
| <b>SRO Temperature – Exchanger</b> | 43.5 <sup>0</sup> C |

|               |
|---------------|
| <b>Outlet</b> |
|---------------|

Heat rise between the heat exchanger inlet and outlet was 30.3<sup>o</sup> C. Maximum potential heat rise was 63.4<sup>o</sup> C. Therefore, the heat exchanger efficiency was 47.79%. This result was less than anticipated, and was due to the plastic material used as heat exchanger tubing. The heat exchanger components represented a compromise of cost, efficiency, ease of assembly, and durability rather than heat exchanger efficiency alone. Upon exiting the heat exchanger itself, the RO travelled through the hose-in-hose (HIH) along the rest of its path to the fuel injection pump and the HIH provided the additional heating required. Future designs will use metal as the heat exchange material rather than plastic in order to obtain better heat exchanger efficiency. Improved heat exchanger design will allow the ROFS to operate more efficiently in cold weather.

#### Other Uses of Biodiesel – Results

Biodiesel proved to be an excellent replacement for lamp oil and kerosene. The fuel seemed to be as effective as kerosene for heating and lighting purposes, with less objectionable odour than kerosene. Biodiesel was also considered by the researcher and research assistant to be effective as a non-toxic and biodegradable concrete floor oil stain remover, engine degreaser,

adhesive residue remover, light oil lubricant, paint remover, and hand cleaner.

## **Study Conclusions**

### **Emissions**

Emissions research comparing RO and petrodiesel is complicated by many factors that result in scientific uncertainty. The results of diesel exhaust emissions research, and actual emissions of engines in use, reflect this problem.

Factors that add complexity to the issue are:

- Engine type, age, and application
- Maintenance of the engine (e.g. Lubricating oil changes; fuel, air, and oil filter changes)
- Cold start practices (e.g. use of engine heaters to reduce emissions on cold starts)
- Other operator practices and skills (e.g. proper gear selection to maintain optimum power and minimise emissions of unburned fuel, excessive idling)
- Presence or absence of exhaust after-treatment technology
- Type and characteristics of RO fuel (e.g. many types of RO exist, from many sources; new RO versus RRO; SRO versus biodiesel; heated SRO versus unheated SRO)

- Quality of petrodiesel fuel and availability of ultra low sulphur petrodiesel and other emissions-reducing petrodiesel products

The emissions tests performed resulted in emissions profiles that were very similar for SRO and biodiesel. Other than opacity reduction, emissions for the RO fuels were not significantly lower than the emissions for the premium petrodiesel that was tested. Since many studies have reported reduced emissions for RO, compared with petrodiesel, this was not the anticipated result.

The product literature, for the premium diesel selected, claimed reductions in “visible smoke” (i.e. opacity), cleaner injectors with regular use, and a package of additives designed to inhibit corrosion and carbonisation within the engine. The fuel was used almost exclusively as the start-up and shutdown fuel for several months prior to the tests, as well as during the tests. This may have resulted in cleaner injectors and combustion chambers than those in the engines used in other studies.

If deposits existed in the engines used in other studies, and if those studies used regular petrodiesel, the two factors combined could have resulted in higher levels of emissions for the petrodiesel tests. The solvent effect of biodiesel, in particular, is well documented. Therefore, if deposits existed in a

test engine, those deposits could have been removed by conditioning runs between petrodiesel emissions tests and biodiesel emissions tests. The end result in such a case would be a greater indicated difference between petrodiesel and biodiesel emissions.

### Use of Premium Petrodiesel for Emissions Tests

It is possible that the use of regular petrodiesel instead of premium diesel may have produced results indicating lower emissions for RO than for petrodiesel. Petrodiesel quality and varies widely around the world. Some countries will require cleaner petrodiesel fuel sooner than others will, and the ability to enforce such regulations also varies. Therefore, RO should be compared against the expected petrodiesel quality in a given region. As has been noted, premium petrodiesel was used in the emissions tests for this study because it is expected that it more accurately represented the petrodiesel product that will soon be in wide use in Canada.

### Regulated Emissions and Non-Regulated Emissions

All of the RO-based fuels tested reduced opacity by roughly 50%. This was consistent with the 30-60% reductions in opacity reported in the literature from a number of studies. Opacity is an indicator of the level of particulates emitted. Particulates are the most harmful component of diesel exhaust. For

that reason, the particulate matter reduction potential of RO, even without considering any of its other positive attributes, would seem to justify its use if it is economically feasible to do so.

Non-regulated emissions were not part of the emissions tests for this study. This was due to the fact that the test facility test procedure was designed to generate results for regulated emissions. Time and budget constraints for the emissions tests did not allow for modification of the test procedure to test for non-regulated emissions.

#### General Performance of Diesel Engines on ROFS and Biodiesel

In general, diesel engine performance on RO fuels was very similar to that of petrodiesel. The noticeable lack of visible smoke and the less objectionable odour of the exhaust when operating on RO fuels were regarded by the researcher and the research assistant to be valuable attributes of RO fuel. Cold weather did pose challenges for the use of SRO in the proof-of-concept ROFS, but these were not considered to be insurmountable.



## **CHAPTER FIVE – RESEARCH IMPLICATIONS**

Research implications exist internally, for the sponsoring organisation, and externally, for society as a whole. These are discussed below.

### **Organisation Implementation**

The original sponsor of this research was a division of an existing company owned partly by the researcher. The early stages of the research attracted the interest of a number of people, and the decision was made to form a new corporation with one interested party. The new company was named Neoteric Biofuels, Inc. The company was formed to take over from the original sponsoring company division, so that a separate corporate entity would exist to explore the commercial potential of ROFS, small-scale biodiesel plants, consulting, and RRO-derived biodiesel. Findings pertaining to the interests of the sponsoring organisation are as follows:

- Renewable Oil Fuel Systems (ROFS) that allow the use of straight renewable oil (SRO) can be produced inexpensively for some applications. They can make use of a waste stream of low value than can represent a disposal cost or problem in some cases (recovered renewable oil, or “RRO”). ROFS use can reduce some emissions compared to operation of

the same diesel engine on petrodiesel, especially emissions of particulate matter and carbon dioxide. RO fuels are non-toxic, biodegrade quickly and have a higher flash point than petrodiesel. They are therefore safer and less environmentally harmful fuels than petrodiesel, while providing almost equivalent fuel economy and performance at marginal engine/vehicle conversion cost. ROFS should be developed further as a potentially commercially viable product.

- Biodiesel production technology is progressing quickly with developers claiming to reduce process costs by 50%. Containerised, compact, multi-feedstock biodiesel plants are emerging. These developments are likely to alter existing assumptions concerning ROFS and biodiesel profitability.
- The cost of petrodiesel fuel should be monitored to determine the products and services that the sponsoring organisation may be able to profitably bring to market.
- The logistics of acquiring RO feedstocks are a factor in determining economic viability of RO fuels, and this must be taken into consideration.
- The specific requirements of potential clients must be properly assessed before recommending the ROFS approach, the biodiesel approach, or a combination of these.
- Direct injection diesel engines, especially those with computerised fuel injection that senses viscosity, are less tolerant of SRO, even if heated in a ROFS, than indirect injection diesel engines. ROFS are also less suited to

applications where the engine is operated extensively at idle and not under load. Engine type and operating conditions should be assessed prior to recommending use of a ROFS versus biodiesel.

- In a ROFS application, it is recommended that winter petrodiesel be used as the start-up and shutdown fuel in cold weather. Either biodiesel or SRO can be used in the ROFS as the main operating fuel once the engine has reached operating temperature.
- Block heater or oil heater use is recommended at temperatures below +5°C. This allows use of SRO fuel to commence more quickly after start-up, resulting in reduced emissions from a cold engine operating on petrodiesel.
- ROFS use with diesel gensets, especially in hybrid systems, could compare favourably against photovoltaics and wind energy alone, providing a source of backup power, and the ability to reduce or eliminate the need for lead-acid batteries. Lead acid batteries remain the most cost-effective battery types, but must be maintained, then recovered and recycled in fairly short cycles (every few years, with present cost-competitive battery technology). The difficulty of recovery and replacement increases with remoteness of the installation. The ROFS could provide a solution by reducing the need for such battery replacement while minimising the need for transport of petrodiesel and minimising diesel engine exhaust emissions.

Some of the above findings have been acted upon by the sponsoring organisation. The ROFS is being developed further, in an effort to improve reliability and performance while keeping system cost low. The pre-commercialisation version may be patentable. This is being investigated. Eventual commercialisation may be possible.

## Societal Implications

The combination of literature review and practical research behind this thesis, taken together, indicated that it should be possible to successfully incorporate renewable oil fuels and associated products (e.g. glycerine soaps, potassium fertiliser, and various non-diesel biodiesel uses, as discussed above) into sustainable system designs in both developing and developed countries. The main findings pertaining to society are as follows:

- A number of diesel exhaust emissions can be reduced substantially at relatively low cost, without the need to replace millions of diesel engines with much more expensive technology (whether new engines or complete technology replacement) before the existing engines are worn out.
- Local and regional agriculture and urban agriculture could be supported as part of the fuel production process, since a wide variety of edible and non-edible oils and fats can be used as feedstocks.
- A problematic urban waste stream consisting of RRO and grease could be turned into a fuel resource that could in turn help improve air quality.
- Jobs for local people (largely in agriculture but also in collection, processing and distribution) can be created in the establishment of this sort of system. Renewable oil fuel processing technology can be simple and is thoroughly scalable, ranging from home-made ROFS and backyard

biodiesel processors to sophisticated fuel systems that work with the most modern diesel engines, and to very large and fully automated biodiesel processing plants

- RO is a candidate for inclusion in programs to develop more efficient vehicles, such as diesel-electric hybrids. It is an enabling technology for new emission control technology to further reduce emissions, since it is virtually sulphur free.
- RO can be used to provide fuel for the technologies that will replace the diesel engine, such as microturbines (Capstone Turbine Corporation, 2000), and fuel cell fuel reformers, in place of gasoline and methanol.
- In addition to being a substitute for diesel engine fuel, renewable RO or biodiesel can be used to fuel heating, lighting and cooking appliances, replacing kerosene. It could replace the use of wood for heating. Since the collection of firewood is increasingly problematic in many developing countries, causing desertification and hardship for those involved in firewood collection (often women), this is an important feature. The glycerine by-product of biodiesel production can be made into soap. The potassium recovered from biodiesel made with potassium hydroxide makes a good fertiliser, as does the press cake from oilseed pressing. Biodiesel is also an environmentally friendly industrial solvent and degreaser. All of these products are of significant value in sustainable system design in both developed and developing countries.

- Oil-bearing crops are not necessarily derived only from edible oilseed crops and thus do not necessarily reduce the amount of food available. Feedstocks can include oil from algae (which can be many time more productive than other crops, including the best oilseeds), oils from many different plants and trees, and animal fats that are unfit for human consumption.
- It is possible to visualise a farmstead, village or region becoming more self-reliant, deriving most of its energy needs and a number of lubrication and cleaning products needs from local, renewable sources. This would lead to reduced reliance on outside suppliers of energy, whether in non-renewable fossil fuel form, or in the form of other, more expensive renewable energy technologies. Thus, jobs and money can be kept within local and regional economies rather than exported to afar and products can be used where they are produced, reducing the need for transportation in both directions. This process of localisation of energy production and consumption could help to reduce the need for income with which to purchase fuel. It could provide an appropriate technology business opportunity for many, dispersed, small-scale RO producers in the developing world. The low cost of manually operated presses such as the Mafuta Mali (“Oil Wealth”) oilseed press, developed in Kenya (ApproTEC, 2000), and the ability to produce both ROFS and biodiesel processors from inexpensive surplus parts, could make such enterprises

viable. Such a local production and consumption system could help to reduce the migration of rural residents forced to seek employment in cities due to high energy costs and lack of opportunity in rural areas. Producers closer to urban areas could also earn money processing RO fuel for sale in the city. RO use in the cities of the developing world would have the additional benefit of reducing the very high emissions from older diesel engines whose owners simply cannot afford to replace them with newer and less polluting diesels or other technology.

#### Dissemination of RO Information

In order to translate the potential of RO fuels into reality, useful information about RO must be economically made available to a globally dispersed and diverse audience. The ability to transmit digital photographs, drawings, and full-motion video over the Internet is rapidly improving, as is the general availability of Internet-connected computers. It is likely that inexpensive and helpful sources of information for those interested in producing their own RO fuel will continue to improve and have an impact on both awareness and actual global use of RO fuel in diesel engines.



The Internet presence developed for Neoteric Biofuels, Inc., as one of the deliverables for this thesis, (Neoteric Biofuels, Inc., 2000), provides an example of the use of full motion video, text, photographs and machine-based translation.

## Summary

ROFS and biodiesel both appear capable of being reliable fuels that offer benefits to society in terms of sustainability. The potential appears to exist for RO to help improve quality of life, to lessen the environmental impact of diesel engine use, and to reduce conflict stemming from reliance on fossil fuels. Overall, the research question can be answered in the affirmative, with two caveats:

- That demand-side management, the capacity for energy conservation and energy efficiency gains, and the entire operating environment of the energy sub-system be considered prior to responding to any assumed need for energy.
- That an outcome of sustainable system design should be a system that is flexible and allows for changes in the state of technology. The technology that best addresses a need at present may only be a transitional measure. The system should anticipate and allow for the reality of constant changes in relevant technological, economic, and social-political factors.

## **Future Research**

Although it appears renewable oil has good potential as an alternative fuel for diesel engines, and might be produced and used in a sustainable way, a number of areas require further research. These are listed below.

### **Life Cycle Analysis (LCA) of ROFS**

Evolving LCA techniques could provide an acceptable framework on which to base important decisions concerning diesel engine and petrodiesel fuel use. This work appears in the literature for biodiesel (Sheehan, et al., 1998), but a sustainability-centred LCA for the ROFS would be useful.

With properly chosen indicators, such an LCA could give a truer picture of whether or not new technology to replace existing diesels is required in all cases. For example, such an LCA could investigate comparisons, from emissions and sustainability perspective, between continuing to use old and new diesel engines, with RO fuel substitution, versus other renewable energy options such as wind, photovoltaics, or fuel cells.

Such a study could be of benefit in situations where economic realities dictate that existing diesel engines remain in service for the longest possible time. It could also assist in acceptance of RO for GHG emission reduction credits.

### Lubricating Oil Studies

Based on the fact that some manufacturers already offer warranty coverage for biodiesel meeting fuel specifications, the use of biodiesel does not seem to adversely affect lubricating oil. The same may or may not be true for engines operated on RO via the ROFS approach, especially when SRO is used over the long term. More advanced and longer-term lubricating oil studies are needed to determine whether or not the use of SRO combination results in undue degradation of lubricating oil or causes other problems inside the engine that could be revealed by such lubricating oil analysis.

Total Base Number (TBN) testing was recommended by Fluid Life Corporation© as a test methodology that would be useful for future research. TBN is a measure of reserve alkalinity. Acidity increases due to oil oxidation, and when this reaches a predetermined level, the oil is considered to have lost its ability to provide proper lubrication or provide necessary protection against corrosion (M. Laplante, personal communication, 2001).

Also, new formulations of RO-based lubricating oil are beginning to appear. Formulations have been developed for gasoline engines, and there is some work being done on RO-based lubricating oil for diesel engines (personal communication, J. Garmier, 2000).

The combination of RO fuel and RO lubricating oil is an interesting area for future research. The possibility of using such RO-based lubricating oil as fuel after it is drained from the crankcase would be another area worth investigation. Finally, the use of existing synthetic oils might avoid concerns about lubricating oil thickening, if that is in fact a problem.

Another area that requires further research is the effect on lubricating oil of the combined use of biodiesel and SRO. SRO may cause lubricating oil thickening, but biodiesel can cause lubricating oil *thinning*. Therefore, there could be an offsetting effect if biodiesel was used as the start-up/shutdown fuel in a ROFS arrangement, and this could alleviate the concern of effects on lubricating oil viscosity changes from RO fuel use.

## Economic Feasibility

Many factors determine the economic feasibility of RO. Oilseed crop prices are less predictable over time than petrodiesel prices, making profitability forecasts difficult. RRO markets already exist (supplying the animal feed and cosmetics industries, among others), and in some areas where collection schemes have already been set up to serve these markets, introduction of an RO fuel market will compete with the existing use. This could cause upward pressure on RRO prices. Collection and processing costs and economic blends of RO feedstocks at a given time must be optimised.

The sale of glycerine by-product is often relied upon to help lower the overall cost of biodiesel. However, it is often the case that the glycerine from RRO is not of sufficient quality for the glycerine market and can become a liability in terms of the cost involved for its disposal. Even if the glycerine is of adequate quality to be sold into the glycerine market, biodiesel production on too large a scale can result in oversupply of regional markets and depress glycerine prices, which has a negative impact on biodiesel plant profitability assumptions (Webber, 1993). Investigation of potential markets for the glycerine component should be researched further.

### Cold Weather Operability

Cold weather operability for diesel engines and petrodiesel fuel has always been somewhat challenging, and the same is true for both biodiesel and SRO.

In a ROFS, a certain minimum temperature must be achieved to make SRO flow, but it may not be necessary to maintain this temperature at all times, throughout the entire distribution and storage system. For example, once it is in the fuel tank of the ROFS, RO can be allowed to thicken or even solidify, since it will be heated and liquefied again prior to use by the ROFS.

ROFS that operate properly in cold weather with a minimum of modifications and additional components pose a design challenge. This is one of the main areas for improvement in future versions of ROFS devices. If successful, this line of research could place the ROFS in a superior position over biodiesel for cold weather use, since biodiesel tends to cloud or gel at higher temperatures than petrodiesel, but a ROFS using waste engine heat to heat the SRO could theoretically operate in very cold ambient temperatures.

For example, even if the RO in a storage tank had completely solidified in winter, a diesel engine in the Arctic could be started on a small amount of winter petrodiesel and create waste engine heat, allowing use of RO within minutes. The entire mass of RO need not be heated before switching to RO. A small amount of heated RO, near the outlet of the storage tank, would be sufficient to begin operation on RO, then more fuel could be liquefied, and flow maintained, in a self-stoking cycle.

Once heated, the RO could be used to run the engine for days or weeks on end before shutting down on petrodiesel for maintenance. This coincides with the way in which gensets and diesels are often used. Transporting petrodiesel in the north is an expensive process that carries a high potential liability. The shipment of SRO as the majority of the fuel to be used in the many gensets that exist would seem to be a good application for a ROFS designed for those conditions.

Another approach to achieve better cold weather ROFS performance seems to be the use of biodiesel or biodiesel/SRO blends within the ROFS in winter months, as was discussed previously. Biodiesel in the ROFS in winter provides a less viscous fuel that only needs to be warmed slightly for successful use. Therefore, even a marginally effective ROFS would provide sufficient heat for the biodiesel to be used within minutes of starting the engine, even in very cold temperatures, whereas it would take longer to heat a solid mass of SRO. SRO could be used in warm weather in the ROFS, and replaced with biodiesel in the winter. The biodiesel, in this case, would not need to be winterised, and the cost of such winterisation could be avoided.

Preliminary research also indicted that a 30% biodiesel blend with RRO containing a high level of free fatty acids and other contaminants resulted in a thinner product that was less susceptible to solidification than the unblended RRO itself. An initial separation of fats occurred within 24 hours

and these settled to the bottom of the container. A photograph of such a blended product, with the initially separated fats at the bottom of the container, is presented in figure 5.1, below:

**Figure 5.1 30% Biodiesel / SRO Blend with Settled Fats**



The remainder of the blended product appeared to be stable over several months' storage, as further separation did not occur. Such a blended product, decanted after initial settling, could have lower viscosity and better resistance to solidification in cold weather than SRO itself. Therefore, it could be a useful cold weather ROFS fuel without incurring all of the higher cost of biodiesel use. Further research in this area could be useful in determining technical and economic feasibility of cold weather ROFS use.

Products are available for winterisation of biodiesel for use without a ROFS.

Effective biodiesel pour point depressants must be added to biodiesel for cold



weather use. Pour point depressants such as Lubrizol ® 7671 (Lubrizol, 2000) have been formulated for use with biodiesel and RO. Samples should be obtained and tested with RO and biodiesel.

### System Cost and Effectiveness

Continuous improvement in the design of low cost, effective ROFS and biodiesel plants at various scales is needed, so that both can be successfully deployed for use in both developing and developed countries.

### Specialised Biodiesel Processors

Some manufacturers are developing continuous-process biodiesel plants that can use RRO and animal fats as well as new RO. Although very expensive at present, these plants could have a significant impact on this emerging industry due to their efficiency. It may be possible to adapt or licence some of the technology used, and combine it with other devices such as small oil-extraction screw presses. Packaged and containerised, this would allow complete and efficient “turn-key” plants, suitable for large farms, fleets, and community or regional biodiesel production (Energea, 2001).

## ROFS Application for Air Cooled Diesel Engines

ROFS that can be used with the many air-cooled diesel engines that exist is an area for further research. Air-cooled engines do not offer the ability to capture waste heat as do liquid cooled engines since there is not hot glycol/water mixture that can be used as a heat transfer medium for RO viscosity reduction. Alternative sources heat for the ROFS approach include direct solar heating of the fuel tank, waste heat from lubricating oil, or exhaust stacks.

## Gensets Operating on RO versus Photovoltaics

A life cycle assessment comparing the economics and eco-efficiency of use of RO in diesel gensets and cogeneration units versus other means of using renewable energy (e.g. wind and photovoltaics) would be useful, as mentioned previously.

## **CHAPTER SIX – CONCLUSIONS**

### **Renewable Oil Fuel System and Biodiesel Approaches - Comparison**

## Selection of Favoured Viscosity Reduction Option – ROFS versus Biodiesel

At the outset, an expected outcome was that the ROFS would emerge as the favoured option, if it could be built inexpensively and perform well, since this would allow the use of unmodified RO, the lowest cost feedstock.

However, the results of the study indicate that both the ROFS approach and the biodiesel approach have merit. The biodiesel approach results in a reliable and convenient fuel once it is made. However, production requires time, energy, and input costs that are not incurred for SRO in a ROFS.

Conversely, a ROFS uses low cost SRO but requires installation and subsequent operator monitoring and control.

In addition to the above, other factors that would likely influence the decision to use one approach over the other include:

- Availability of materials for system construction
- Availability of inputs such as methanol (or ethanol), sodium hydroxide (or potassium hydroxide) for biodiesel production
- Philosophical acceptance or rejection of blends of biodiesel with petrodiesel. Low percentage blends enhance lubricity in low sulphur petrodiesel, and reduce emissions at the 20% biodiesel level. However, the decision must be made as to exactly what is to be accomplished in

establishing biodiesel production. Blends, especially low percentage lubricity blends consisting of only a few percent biodiesel, may increase demand for biodiesel and bolster oilseed prices, but do so by diluting the potential environmental benefit that could otherwise occur if higher percentage blends or neat biodiesel were used instead, for selected applications (e.g. sensitive marine environments and densely populated urban areas). SRO does not blend with petrodiesel, as biodiesel does. Therefore, a decision to implement SRO versus biodiesel is effectively a decision to direct resources toward renewable energy and away from any potential for over-dilution via blending.

Table 6.1, below, provides a summary of some of the key points of comparison between the ROFS and biodiesel approaches.

**Table 6.1 Comparison of ROFS and Biodiesel Approaches**

| Criteria  | ROFS  | Biodiesel   |
|---|---|---|
| Emissions reduction (versus petrodiesel)                      | Yes<br>(some emissions)   | Yes<br>(some emissions)   |
| System/Equipment cost under \$500                             | Yes   | Yes   |
| System/Equipment can be built by semi-skilled people          | Yes   | Yes   |
| Non-toxic   | Yes   | Yes   |
| Biodegradable   | Yes   | Yes   |
| Requires modification of, or addition to, vehicle fuel system | Yes - Obtrusive - Auxiliary tank, fittings, heat exchanger, heating lines, etc. | Yes – Unobtrusive – Rubber fuel system components should be changed |

|   |             |     |
|---|-------------|-----|
|   | lines, etc. |     |
| Can be used for other heating, cooking and lighting appliances  | No          | Yes |
| Can be blended with petrodiesel                                 | No          | Yes |
| Can be used in sub-zero temperatures without special procedures | Yes         | No  |

### **Reliance on Diesel Engines and Strategies for Minimising Negative Consequences of Use**

For society to benefit from the use of RO in diesel engines, the dissemination of the necessary knowledge that already exists, rather than any significant technological breakthrough, is currently the greatest requirement.

Some of this knowledge is technical and economic in nature. It is the knowledge of how to economically build an RO-based energy supply system that results in reliable fuel for existing diesel engines, for other appliances ranging from oil lamps to modern heating and cooking devices, and for other liquid-fuel devices that will eventually replace the diesel engine.

However, such successful dissemination of current and future technical and economic knowledge on the subject would treat only one small part of a much

larger problem. In sustainable system design, demand reduction must take priority, as already mentioned.

The diesel engine is far from perfect, but does serve society through its compactness, efficiency, reliability, longevity and power. It is these very attributes that have led to its overuse. In the final analysis, it is such overuse that must be addressed before the research question can be adequately answered.

Reducing the emissions of an engine, making an engine run on a safer and more equitably available renewable fuel, or making fuel from what is currently a waste stream, are certainly worthwhile and achievable goals. They are, however, small steps compared to the thoughtful re-examination of resource use that is required in order to design sustainable systems.

Along with the capacity of the human race to create tools that can result in changes to the environment comes a responsibility that is only beginning to be understood. Recognition of a responsibility to care for the environment, to understand that there are limits to the “carrying capacity” of the planet (even if these are difficult to quantify) and to consider the needs of future generations, should be given due consideration along with efforts to provide for the needs of the present generation. This sustainability-focused approach

should be applied to the use of the diesel engine as much as to all other human activity.

If a given service that is derived from the use of a diesel engine is truly required, its provision should be via a system that has been designed to reduce negative consequences to the greatest extent possible. From both the literature review and the practical research that was undertaken for this thesis, it appears that there are many advantages to the use of RO fuels in diesel engines in this regard.

It also appears that in many cases it is technically and economically feasible to use RO fuels in most diesel engines, via one or both of the viscosity reduction approaches that have been discussed, and thereby capture those advantages. Either approach can be applied at various scales, capital cost, and labour cost, and can therefore be an appropriate technology in both developing and developed countries. Properly created and operated, it appears that an RO fuels infrastructure could succeed, create jobs and allow local retention of energy profits.

The wide variety of renewable feedstocks that can be used for RO fuels provides considerable scope to develop clean production systems that make use of what are presently considered to be problematic wastes. Innovative

new crops and crop production techniques could add to those already used for renewable oil.

It appears that it will be possible to use RO fuels in the devices that will eventually replace the diesel engine. Investments made in RO fuels infrastructure are likely to yield financial benefits to investors, as well as various social and environmental benefits.

There is, in summary, a reasonable basis to believe that renewable oil fuels in diesel engines can be a successful component of sustainable system design in both developed and developing countries.



## REFERENCES

- Addison, K. 2000. Biodiesel in Hong Kong. Journey to Forever Web Site. Journey to Forever Web Site. URL: [http://journeytoforever.org/biodiesel\\_hk.html](http://journeytoforever.org/biodiesel_hk.html) (visited June 21, 2000)
- Agricta. 1999. Take Your Farm to Town. Agricta Web Site. Spore issue number 81. URL: [http://www.agricta.org/Spore/spore81/spore81\\_feature.html](http://www.agricta.org/Spore/spore81/spore81_feature.html) (visited March 5, 2001)
- Agriculture and Agri-Food Canada. The Health of Our Air: Toward Sustainable Agriculture in Canada. 1999. Agriculture and Agri-food Canada Web Site. URL: [http://res2.agr.ca/research-recherche/science/Healthy\\_Air/2d6g.html](http://res2.agr.ca/research-recherche/science/Healthy_Air/2d6g.html) (visited June 15, 2000)
- Air Resources Board. Particulate Emissions from Diesel-Fueled Engines as A Toxic Air Contaminant. 1998. California Air Resources Board Web Site. URL: <http://www.arb.ca.gov/toxics/dieseltac/dieseltac.htm> (visited June 17, 2000)
- ATG GmbH. 2000. Diesel-Therm Bio. Diesel-Therm Web Site. URL: <http://www.diesel-therm.de/dieselthermbio.htm>
- ApproTEC. 2000. ApproTEC's Oilseed Press Promotion Program. ApproTEC Web Site. URL: <http://www.approtec.org/oil/oilpress.html> (visited January 12, 2001)
- Biodiesel Bulletin. 2000. Bioenergy Program Final Rule Issued. December 2000 Biodiesel Bulletin. National Biodiesel Board Web Site. URL: <http://www.biodiesel.org/default2.htm> (visited January 11, 2001)
- Biodiesel International. 2000. Multi Feedstock Information Page. Biodiesel International Web Site. URL: [http://www.biodiesel-intl.com/rohstoff\\_e/rohstoff.htm](http://www.biodiesel-intl.com/rohstoff_e/rohstoff.htm) (visited December 20, 2000)
- Biomass Project Nicaragua. 2000. Curcas Oil Methyl Ester. Biomass Project Nicaragua Web Site. URL: <http://www.ibw.com.ni/~biomasa/index.htm> (visited January 17, 2001)

Blondeau, J., Pon, G., Bresciani, S., and Reaney, M. 1997. Analysis of Selected Diesel Fuel Markets in Canada: Markets for Canola Biodiesel- Executive Summary. Agriculture Canada, Saskatchewan Research Centre Web Site. URL: <http://res2.agr.ca/saskatoon/fuel.html> (visited June 16, 2000)

Capstone Turbine Corporation. 2000. Hybrid Electric Vehicle Applications. Capstone Turbine Corporation Web Site. URL: <http://www.microturbine.com/applications/hevAppDetails.asp> (visited January 22, 2001)

Carven, J. 2000. Greasecar. Greasecar Web Site. URL: <http://www.greasecar.com/Home.html> (visited January 13, 2001)

Corliss, M. 1999. I Didn't Know That Olive Oil Would Burn! (2<sup>nd</sup> edition). Lehman's. Kidron, Ohio.

Cleaner Production Centre Austria. 2000. Ecodrive in Graz. CPC Web Site. URL: [http://www.cpc.at/english/itc\\_e\\_frameset.html?http://www.cpc.at/fokus/biodiesel/english/](http://www.cpc.at/english/itc_e_frameset.html?http://www.cpc.at/fokus/biodiesel/english/) (visited December 19, 2000)

Cleaner Production Centre Austria. 2000. Biodiesel- Declaration of Car Production Companies. URL: [http://www.cpc.at/fokus/biodiesel/english/fahrzeuge\\_e.html](http://www.cpc.at/fokus/biodiesel/english/fahrzeuge_e.html)

Climate Change Action Fund. 1999. Technology Early Action Measures Backgrounder. Government of Canada Climate Change Action Fund Web Site. URL: [http://www.climatechange.gc.ca/english/actions/action\\_fund/pdf/TEAMbkgrdr.pdf](http://www.climatechange.gc.ca/english/actions/action_fund/pdf/TEAMbkgrdr.pdf) (visited January 11, 2001).

Cable News Network. 2001. Tanker Captain, Crewmen arrested in Galapagos Fuel Spill. Cable News Network Web Site. URL: <http://www.cnn.com/2001/NATURE/01/25/galapagos.spill/index.html> (visited January 25, 2001)

Delphion Intellectual Property Network. URL: <http://www.delphion.com> (visited December 4, 2000)

Diesel Progress. 2000. Reaching New Heights In Power Generation. Diesel Progress North American Edition. Vol. 66 No. 12. Diesel and Gas Turbine Publications, Waukesha, WI, USA

Diesel Progress. 2001. The Return of the Passenger Car Diesel? Diesel Progress North American Edition. Vol. 67, No. 2. Diesel and Gas Turbine Publications, Waukesha, WI, USA

Dieselnet. California ARB Sued Over the Identification of Diesel PM As A Toxic Air Contaminant. Dieselnet Web Site. URL: <http://www.dieselnet.com/news/0001carb.html> (visited June 15, 2000)

Delta Institute. 2000. Atmospheric Deposition of Toxics to the Great Lakes: Integrating Science and Policy. Delta Institute Web Site. URL: <http://www.delta-institute.org/publications/airtoxics.pdf> (visited December 18, 2000)

Elsbett. 2000. Eco-tuning with Vegetable Oil. Elsbett Web Site. URL: <http://www.elsbett.de/tuniinfe.htm> (visited December 21, 2000)

Energiea. 2000. Energiea Web Site. URL: <http://www.energea.at> (visited March 2, 2001)

Environment Canada. 2000. More Initiatives to Clean our Air Announced by the Government of Canada. Environment Canada Web Site. URL: [http://www.ec.gc.ca/press/000621\\_n\\_e.htm](http://www.ec.gc.ca/press/000621_n_e.htm) (visited June 21, 2000)

Environment Canada. 2001. 1995 Criteria Air Contaminant Emissions for Canada. Environment Canada Web Site. URL: [http://www.ec.gc.ca/pdb/ape/ape\\_tables/canada95\\_e.cfm](http://www.ec.gc.ca/pdb/ape/ape_tables/canada95_e.cfm) (visited February 28, 2001)

Environmental Protection Agency. 2000. Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulphur Control Requirements. USA Environmental Protection Agency Web Site. URL: <http://www.epa.gov/otaq/regs/hd2007/frm/f00057.pdf> (visited December 21, 2000)

Environmental New Network. 2001. Seattle Experiments with Green Fuel. Environmental News Network Web Site. URL: [http://www.enn.com/enn-news-archive/2001/03/03022001/biodiesel\\_42246.asp](http://www.enn.com/enn-news-archive/2001/03/03022001/biodiesel_42246.asp) (visited March 5, 2001)

European Forum for Renewable Energy Sources, 2000. The Impact of Renewables on Employment and Economic Growth. European Forum for Renewable Energy Sources Web Site. URL: <http://www.eufores.org/Employment.htm> (visited January 20, 2001)

Ehrlich, J. 2000. Restaurant Body Tables Cheaper Waste Deal. *South China Morning Post* newspaper, Feb. 10, 2000

Faye, Z. 1999. Canola Biodiesel. Canola Information Service Web Site. URL: <http://www.canolainfo.org/html/biodieselframe.html> (visited January 11, 2001)

Fluid Life Corporation©, 2001. Fluid Life Corporation© Web Site. URL: <http://www.fluidlife.com> (visited February 20, 2001)

Government of British Columbia. 2000. Green Economy Initiative. Government of British Columbia Web Site. URL: <http://www.gov.bc.ca/ges/> (visited December 21, 2000)

Harris, N. 1999. Westport Innovations Inc. MEM Business Planning Case. Royal Roads University, Victoria, 76 pp.

Hawken, P., Lovins, A., and Lovins, H. 1999. Natural Capitalism. Little, Brown and Company, Boston, New York, London, 396 pp.

Health Assessment Document for Diesel Emissions, SAB Review Draft.1999. USA Environmental Protection Agency Web Site. URL: <http://www.epa.gov/ncea/diesel.htm> (visited June 15, 2000)

Health Effects Institute. Health Effects Institute Web Site. URL: <http://www.healtheffects.org> (visited June 10, 2000)

Henning, R. 1998. Use of *Jatropha curcas* L. (JCL): A household perspective and its contribution to rural employment creation: Experiences of the *Jatropha* Project in Mali, West Africa, 1987 to 1997. *Jatropha* Web Site. URL:[http://jatropha.org/harare98.htm#Erosion Control and Soil Improvement](http://jatropha.org/harare98.htm#Erosion%20Control%20and%20Soil%20Improvement) (visited January 12, 2001)

Howard Hughes Medical Institute. "The Mystery of Smell: The Vivid World of Odours". 1998. HHMI web site. URL: <http://www.hhmi.org/senses/d/d110.htm> (visited December 1, 2000)

Innovations Foundation, 2000. From Grease to Airplane Fuel. News and Events. Innovations Foundation Web Site. URL: <http://www.innovationsfoundation.utoronto.ca> (visited January 17, 2001)

Institute for Resources and Environment. 2000. Our Ecological Footprint. Institute for Resources and Environment Web Site. URL: <http://www.ire.ubc.ca/ecoresearch/ecoftpr.html> (visited March 5, 2001)

Kadam, K. and Sheehan, J. 1996. Microalgal Technology for Remediation of CO<sub>2</sub> from Power Plant Flue Gas: A Technoeconomic Overview. World Resource Review. Vol. 8(4) December 1996. pp. 493-503. Also at National Renewable Energy Laboratory Web Site. URL: <http://www.nrel.org> (visited January 11, 2001)

Jonsson, B. 2000. Taby Pressen oil presses. Taby Pressen Web Site. URL: <http://www.oilpress.com/skeppsta.html> (visited January 12, 2001)

Kac, A. 2000. The University of Idaho's Bubble Wash Method. Journey to Forever Web Site. URL: [http://journeytoforever.org/biodiesel\\_aleks.html](http://journeytoforever.org/biodiesel_aleks.html) (visited January 23, 2001)

Kennedy, I. 2000. Combustion in Compression Ignition Engines. Course Material for EME 161 Combustion and the Environment. Department of Mechanical and Aeronautical Engineering. University of California Davis. University of California Davis Web Site. URL: <http://fanon.engr.ucdavis.edu/EME161/Ch%206/Chapter%206> (visited January 10, 2001)

Kinast, J. 2000. Biodiesel Multi Feedstock - Phase III. Fats and Proteins Research Foundation, Inc. Executive Summary of Current Projects. FPRF Web Site. URL: [http://www.fprf.org/Page\\_58.html](http://www.fprf.org/Page_58.html) (visited December 20, 2000)

Körbitz, W. 2000. World-wide Trends in Production and Marketing of Biodiesel. Paper presented at ALTENER Seminar "New Markets for Biodiesel in Modern Common Rail Diesel Engines", University for Technology in Graz, Austria, May 22, 2000. Austrian Biofuels Institute Web Site. URL: [http://www.biodiesel.at/courier\\_on/index.html](http://www.biodiesel.at/courier_on/index.html) (visited January 30, 2001)

Lehman's. 2000. Lehman's Non-Electric Catalog. URL: <http://www.lehmans.com> (visited January 8, 2001)

Lohmann, G. 2000. BioCar® Web Site. URL: <http://www.biocar.de> (visited June 21, 2000)

Lubrizol®. Lubrizol Corporation Web Site. URL: <http://www.lubrizol.com> (visited November 28, 2000)

Mayer, A. 1998. Selection Criteria for Diesel Particulate Trap Systems: VERT Experience. Dieselnet Technical Report. Dieselnet Web Site. URL: <http://www.dieselnet.com/papers/9812mayer.html> (visited December 19, 2000)

Natural Resources Defense Council. Earth Smart Cars Campaign, FAQ #7. NRCD Web Site. URL: <http://www.nrdc.org/earthsmartcars/faq.html> (visited June 21, 2000)

National Biodiesel Board. 2001 National Biodiesel Board Web Site. URL: <http://www.biodiesel.org/default2.htm> (visited March 5, 2001)

National Environmental Indicators Series. 2000. Energy Consumption. Environment Canada Web Site. URL: [http://www.ec.gc.ca/Ind/English/Energy/Bulletin/ec\\_iss\\_e.cfm](http://www.ec.gc.ca/Ind/English/Energy/Bulletin/ec_iss_e.cfm) (visited December 18, 2000)

National Renewable Energy Laboratory. 1998. A Look Back at the Department of Energy's Aquatic Species Program: Biodiesel from Algae. NREL web site. URL: <http://www.nrel.gov/publications/> (visited November 29, 2000)

Neoteric Biofuels Inc. 2000. Neoteric Biofuels Web Site. URL: <http://www.neotericbiofuels.com> (visited February 19, 2001)

Northwest Power Systems. Northwest Power Systems Develops Diesel Fuel Processor. Northwest Power Systems web site. URL: [http://www.idatech.com/media/pressreleases/19990714\\_nwpower.html](http://www.idatech.com/media/pressreleases/19990714_nwpower.html)

Ontario Soybean Growers' Marketing Board. 2000. Biodiesel Research Update. Ontario Soybean Growers' Marketing Board Web Site. URL: <http://www.soybean.on.ca> (visited January 9, 2001)

Pan, J., Quarderer, S., Smeal, T., and Sharp, C. 2000. Comparison of PAH and Nitro-PAH Emissions Among Standard Diesel Fuel, Biodiesel Fuel, and Their Blend on Diesel Engines. Southwest Research Institute. 2 pp. National Biodiesel Board Web Site. URL: <http://www.biodiesel.org> (visited December 19, 2000)

Peterson, C. and Auld, D. 1991. Technical Overview of Vegetable Oil as a Transportation Fuel. FACT- Vol. 12 Solid Fuel Conversion for the Transportation Sector. American Society of Mechanical Engineers. National Biodiesel Board Web Site. URL: <http://www.biodiesel.org> (visited January 8, 2001)

Peterson, C. and Reece, D. 1996. Emissions characteristics of ethyl and methyl ester of rapeseed oil compared with low sulphur diesel control fuel in a chassis dynamometer test of a pickup truck. Transactions of the ASAE, **39(3)**: 805-816.

Pollak, 2001. Pollak Web Site. URL:  
[http://www.pollakaftermarket.com/sc\\_app/](http://www.pollakaftermarket.com/sc_app/)  
(visited February 17, 2001)

Prairie Geomatics. 2000. What is Precision Farming? Prairie Geomatics Web Site. URL: <http://www.prairie.mb.ca/precfar00.htm> (visited January 30, 2001)

Royal Enfield. 2000. Taurus Diesel Motorcycle. Royal Enfield India Web Site. URL: <http://www.royalenfield.com/store/gallery.htm> (visited January 11, 2001)

Rocky Mountain Institute. Hypercars. Rocky Mountain Institute Web Site. URL: <http://www.rmi.org/sitepages/pid18.asp> (visited June 21, 2000)

Samet, J., Dominici, F., Zeger, S., Schwartz, S., Dockery, D. 2000. National Morbidity, Mortality, and Air Pollution Study. Health Effects Institute Web Site. URL: <http://www.healtheffects.org/pubs-recent.htm> (visited June 21, 2000)

Sheehan, J., Camobreco, V., Duffield, B., Graboski, M., and Shapouri, H. 1998. An Overview of Biodiesel and Petroleum Diesel Life Cycles. National Renewable Energy Laboratory. NREL web site. URL:  
<http://www.nrel.gov/docs/legosti/fy98/24772.pdf> (visited December 4, 2000)

Shell Foundation. 2000. Sustainable Energy Program. Shell Foundation Web Site. URL: <http://www.shellfoundation.org/sep/about.html> (visited December 21, 2000)

Suncor. 2000. Alternative and Renewable Energy. Suncor Web Site. URL:  
<http://www.suncor.com/greenenergy/index.html> (visited December 21, 2000)

The Week. 2000. Seeds of self-reliance. July 9, 2000. The Week magazine Web Site. URL: <http://www.the-week.com/20jul09/life2.htm> (visited January 17, 2001)

Thermo King. 2000. Transport Temperature Control. Thermo King Web Site. URL: <http://www.thermoking.com> (visited January 11, 2001)

Tickell, J. and Tickell, K. 1999. From The Fryer to The Fuel Tank: The Complete Guide to Using Vegetable Oil as an Alternative Fuel. 2<sup>nd</sup> ed. Green Teach Publishing, Sarasota, FL, 162 pp.

Toy, E., et al. 2000 "Fueling Heavy Duty Trucks: Diesel or Natural Gas?" Risk in Perspective. Harvard Center for Risk Analysis Web Site. URL: <http://www.hsph.harvard.edu/Organizations/hcra/diesel/diesel.pdf> (visited December 18, 2000)

United Nations. 1998. World Population. United Nations Department of Social and Economic Affairs, Population Division. United Nations Web Site. URL: <http://www.popin.org/pop1998/1.htm> (visited January 25, 2001)

United States Patent and Trademark Office. 2000. Internet Patent Server. URL: <http://www.uspto.gov> (visited January 12, 2001)

University of Toronto. 1999. News and Events. University of Toronto Web Site. URL: <http://www.newsandevents.utoronto.ca/bin/19991027b.asp> (visited June 21, 2000)

von Wedel. 1999. Technical Handbook for Marine Biodiesel in Recreational Boats. Cytoculture Environmental Biotechnology. Cytoculture Web Site. URL: <http://www.cytoculture.com/Biodiesel%20Handbook.htm> (visited January 25, 2001).

Weber, J., Howell, S., and Hammond, S. 1998. Biodiesel Marine Marketing Opportunities: Successes and Challenges in the Chesapeake Bay. MARC-IV Consulting. MARC-IV Web Site. URL: <http://marciv.com/about.htm> (visited January 31, 2001)



## Appendix 'A'

### List of Materials – Proof of Concept Renewable Oil Fuel System (ROFS) – 1982 Volkswagen Jetta:

| Qty. |  | Cost (CAD\$)   |
|------|--|----------------|
| 1    | 24 litre metal outboard fuel tank – used | \$20.00        |
| 1    | 'UDL' heat exchanger – surplus           | \$60.00        |
| 1    | 'Pollak' 3-port fuel switching valve     | \$64.58        |
| 1    | Toggle switch                            | \$12.08        |
| 50'  | 5/8" heater hose                         | \$32.72        |
| 20   | Hose clamps                              | \$10.60        |
| 4    | Temro' Y fitting ( for heater hose)      | \$16.32        |
| 1    | 5/8" to 3/4" adapter                     | \$4.33         |
| 6'   | 3/8" fuel line                           | \$9.30         |
| 1    | 3/8" plastic "T"                         | \$3.10         |
| 1    | Roll, 18 GA Red primary wire             | \$3.19         |
| 1    | 20 amp fuse holder                       | \$2.45         |
| 5    | 20 amp fuses                             | \$2.30         |
| 1    | Transmission Filter Kit                  | \$29.26        |
| 1    | JB Weld Epoxy                            | \$7.99         |
| 1    | 1/4" 90 deg. Galvanised Elbow            | \$1.99         |
| 1    | 1/4" Nipple                              | \$1.29         |
| 1    | Shutoff Valve and Fitting                | \$4.88         |
| 6    | 3/4" x 3' Foam Pipe Insulation           | \$3.60         |
| 1    | Roll Electrical Tape                     | \$0.48         |
| 1    | Hydraulic Oil Filter (Line Type)         | \$16.99        |
| 2    | 3/4"-3/8" Hex Bushing Reducer            | \$2.58         |
| 20'  | 3/8" High Temperature Polyethylene Hose  | \$7.20         |
| 1    | Misc. fitting and shop supplies          | \$25.00        |
|      | Total:                                   | <hr/> \$342.23 |

## **Appendix 'B'**

### **Lubrication Oil Analysis Results- 1982 Volkswagen Jetta**

## **Appendix 'C'**

### **Emissions Test Results – 1982 Volkswagen Jetta**

