Biofuels for the Fishing Industry: An Investigation into the Use of Pure Plant Oil as a Replacement for Marine Diesel

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February 2008

Release 1.5

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1 Executive Summary

The use of pure plant oil (PPO), also known as vegetable oil, as a diesel fuel extender or as a total fuel substitute is known. The concept gained popularity during the fuel crisis in the 1970's although engine technology at this time was relatively basic. The concept today has two primary drivers for land transportation: cost reduction and environmental footprint. The use of recovered and suitably processed used cooking oil (UCO) can offer further substantial atmospheric carbon dioxide (CO_2) mitigation together with a reduction in other regulated exhaust pollutants, such as sulphur dioxide, as well as additional cost savings compared to virgin PPO,. Regenatec has developed technology which retro-fits to diesel engines and allows them to be fuelled by diesel or PPO or UCO. This technology is found in products being sold to owners of land based vehicles, both commercial and domestic. Initial trial work performed by Regenatec on land based vehicles has shown promising results.

This project investigated the use of PPO in a trawler, the Jubilee Quest, based in Grimsby, UK, operated on PPO during the Autumn of 2006. The aim of this trial was a technical investigation of the technology and PPO: it was not designed to be a commercial deployment. The use of PPO (and even UCO) is currently commercial unviable in UK marine applications due to the economies of scale enjoyed by the petrochemical industry. (The use of PPO and UCO is only viable for land based vehicles because of a duty rebate currently enjoyed by bio-fuels.) As biofuels start to scale and when the environmental costs of fossil fuels are fully reflected in the cost of the product, it is anticipated that biofuels will become economically viable.

As a key part of this project, Regenatec developed their technology into a system to be used at sea by a trawler. Their dual tank system is under electronic control to automate the use of PPO in a diesel engine. This has significant advantages over existing, less sophisticated technology. The engine is started on conventional marine diesel (or biodiesel) and then automatically switches over to the lower cost, more environmentally friendly PPO. The automation greatly improves the ease of use for unskilled operators and removes the potential for engine damage when compared to manual control.

Additionally, Regenatec is heavily involved in fuel additive work investigating what fuel additives commonly used to enhance the technical and environmental performance of mineral diesel are applicable to PPO and UCO. This work is being undertaken under Confidentiality Agreement in conjunction with a leading mainstream additive manufacturer. An 'additive pack' was not fully developed and therefore not available for field deployment during this project. However, lab work and land based field trials in this area have provided encouraging feedback.

This project attracted considerable media interest including coverage on BBC Television's Working Lunch programme. Regenatec have received a large amount of technical and commercial enquiries since this programme aired.

Although the converted trawler functioned satisfactorily initially, in terms of emissions, fuel consumption and motive power, mechanical failure of certain key parts did result. Whilst the use of PPO may have been a contributing factor, the general state of the vessel's engine and previous history of failure of these components (when operated exclusively on diesel) suggests it would be erroneous to conclude failure was solely attributable to the use of PPO.

Regenatec believe that with the vessel's engine in appropriate mechanical health and the use of PPO together with additives now developed would result in satisfactory technical performance with superior environmental credentials. Regenatec's work with Oxford Brookes University, Brunel University, Millbrook , as well as with various fuel additive manufacturers and existing commercial vehicle customers further back up this view.

Based on this project and the company's on going land based vehicle trials with key commercial customers, research and product development into the use of pure plant oils (PPO) as a replacement for mineral diesel continues. Appropriate academic and commercial strategic relationships have been established to push deeper into the combustion science and understanding of the long term effects of using various grades and types of pure plant oils. Regenatec is highly confident in delivering a conversion technology and pure plant oil biofuel that achieves the same maintenance & service regimes as conventional diesel but with superior carbon and technical performance to biodiesel in the high use, high consumption diesel engine sector. The company sees the primary barrier of PPO technology becoming a wide scale commercial reality is that of a suitable fiscal policy. It is unrealistic to expect a nascent biofuel industry to compete directly against an entrenched competitor, in the form of the petrochemical industry, which enjoys a century head start. Additionally, policy is required that is able to differentiate between the merits of various biofuels and support in an appropriate manner those that are truly sustainable and ethical. Only when this is in place, with visibility of a long term policy commitment, will it allow companies such as Regenatec to attract greater UK investment and ultimately deliver low technology to the market place.

2 Introduction

2.1 Background & theory of biofuels

The earth's climate is changing and there is now scientific, social and political recognition that this very likely as a result of mankind's greenhouse gas (GHG) emissions. Carbon dioxide (CO_2) is arguably the most widely known and publicised GHG but it by no means the most potent GHG. The use of mineral oil in transportation, including fishing, accounts for some 20% of anthropogenic CO_2 globally and around 20% in the UK[1]. The carbon intensity of the fishing industry is particularly acute, being identified in the Stern Report as the 6th most carbon intensive industry in the UK[2].

Transport has become the main driver for increasing global demand for mineral oil, which is predicted to grow by 1.3% per year until 2030, reaching some 116 million barrels (~19 billion litres) per day, up from 84 million barrels per day in 2005. The transport sector relies almost exclusively on mineral oil, which is predicted to become increasingly scarce and costly in the next few decades and supplies of which are vulnerable to interruption.

Biofuels – fuels derived from plant materials – have the ability to address carbon dioxide accumulation and security of supply. On first pass they appear to be carbon

[1] Sustainable Biofuels: Prospects & Challenges, Royal Society, January 2008
[2] Stern Report, published 2006

neutral: the carbon they admit to the atmosphere when being burnt is offset by the carbon dioxide they absorb when growing. They are also viewed as renewable, as supplies can be grown as needed. As they can also be grown in a variety of environments they offer the possibility of increasing supplies from areas where mineral oil is not present, thus increasing security of supply.

It should be noted that the term ‘biofuel’ is used to cover a very large range of products derived from an equally diverse range of feedstocks. As such, the potential GHG savings vary: each biofuel must be assessed on its own merits. For accuracy, each assessment must include the environmental and economic aspects of the biofuel. Growth of plant, fertilizer & irrigation requirements, transportation to and from point of refinery, the refinery process itself (including process chemicals, energy and process by-products) distribution to consumers, end use profile and the potential for pollution must all be considered.

As covered recently in the media, biofuels will have major implications for land use with associated social, environmental and economic impacts. The biofuel industry must be careful that unintended consequences do not significantly reduce or even override the expected benefits.

2.2 Growth of the Sector – Environment

Biofuels have the potential to play an ever increasingly important part of the overall approach to the issue of climate change and energy supply. However, biofuels currently have a limited ability to replace fossil fuel oil and should not be regarded as a so called 'silver bullet' solution. Progress toward a sustainable solution requires an integrated approach, which combines biofuels with other developments such as more efficient engine and vehicle design, development of commercially viable hybrid and fuel cells. Policies that reduce demand for energy and encourage behaviour change are also key in helping biofuels meet market demand.

The attractiveness of alternative renewable solutions to the incumbent non-renewables relies heavily on policy support. The hydrocarbon fossil fuel industry enjoys massive economies of scale having had over a century to grow to its current size with no external competition. Competition has been internal, thus refining & evolving the industry into a formidable advisory for the alternative energy industry to take on. It has - and continues to - produce some the most profitable companies the world has seen. Biofuels are a nascent industry. It is impossible to compete directly on unit energy cost (on a per joule basis) against such a massive, incumbent industry. Whilst the true costs of non-renewable energy in terms of the social cost of carbon, renewable energy will require fiscal support at a policy level in order to allow it to compete. Growth is therefore directly linked to support in the near term.

Existing policy frameworks, whist an encouraging sign that governments wish to promote an alternative to fossil fuels remain flawed. The European Directive on Biofuels with its targets of 5% of transport fuels from biofuels by 2010 and 10% by 2020 focus only on supply targets. Existing policy remains critically flawed as it remains separate from the level of GHG reduction a biofuel achieves. Thus no direct incentive currently exists to invest in systems, processes and technologies that deliver ever lower greenhouse gases which also take into consideration the wider environmental, social and economic impacts.

Biofuel technologies are still at an early stage of development. These technologies continue to build on the immense progress that is occurring in the fundamental understanding of the biological, thermal, chemical and carbon systems involved. This ever growing knowledge can support a hugely diverse portfolio of solutions for the environmental and socially beneficial exploitation of biofuels.

The diversity of options should be encouraged and prevent a premature narrow focusing onto a small set of solutions. Regenatec's pure plant oil (PPO) technology and related fuel additive science is just one such solution. Although a 'niche' solution, it is none the less and important niche – that of high consumption, return to base diesel engines. In the UK, these account for less than 2% of diesel engines but account for over 22% of carbon dioxide emissions from this sector[3].

[3] UK Department of Transport

2.3 The Technology

Regenatec has developed a dual tank system under electronic control to automate the use of plant oils in a diesel engine. This has significant advantages over existing, less sophisticated technology. The engine is started on conventional marine diesel (or biodiesel) and then automatically switches over to, more environmentally friendly PPO. The automation greatly improves the ease of use for unskilled operators and removed the potential for engine damage when compared to manual control.

The conversion technology and layout topology developed for the trial vessel is described in detail in the Appendix (see Scoping Report).

2.4 Attraction to Fishing Industry

The use of PPO to the fishing industry is attractive, or likely to become attractive, to the fishing industry for the following key reasons: potential cost savings and environmental superior performance.

At the time of commencing the project (May 2006), mineral diesel had increased in price by over 100% in the previous 18 months to approximately 26p / litre, leading to financial hardship amongst certain operators in the fishing sector. Unfortunately, even with this level of price increase the use of PPOs in UK marine applications still remains unviable if viewed strictly from a financial viewpoint. This is because the UK taxes fuel according to use: marine fuels are exempt fuel duty, thus making there per litre cost considerably cheaper than their land based equivalent. Any increase in mineral oil price is felt more heavily than on land as the fuel duty, which forms the significant part of the of UK land fuel cost, effectively reduces the percentage ‘raw material’ component cost of the total price. However, it is highly likely that at some future point the cost of a fuel will be directly linked to the impact that a fuel has on the environment. It is the view of Regenatec that this likely to made up of two primary components:

The Jubilee quest being refuelled with PPO

- The overall GHG profile of the fuel and,
- Emission properties with respect to air quality (i.e. particulate smoke mass and gasses that are known to have a detrimental impact via inhalation such as NOx, carbon monoxide etc).

As it currently stands, marine diesel fuel oil enjoys a disconnect from these factors. Financial viability of PPOs is likely to come initially from the use of recovered used cooking oils and tallows (see Section 5.4).

3 Methodology

3.1 Temperature Data Collection

As the visocisty of PPOs is critical to their sucessful use it is necessary to know the effects that the ship's topology might have on the PPOs temperature. In order to achieve this a number of self-contained, data logging thermometers were affixed to the engine, genset and surrounding environment. These data loggers were set to capture the local temperature of the surface they have been fixed to. The loggers were fixed in the following locations:

sensor no.	location	temperature data captured
1	Upper level of day running tank	Maximum in-tank fuel temp
2	Lower level of day running tank	Minimum in-tank fuel temp
3	Main fuel tank under engine room deck	Nominal fuel temp (as affected by thermal contact to the sea)
4	Plastic switch box in engine room	Ambient engine room temperature
5	Genset fuel lift pump	Temperature of generator lift pump
6	Genset fuel injection pump	Temperature of generator injection pump
7	Drive engine fuel injection pump	Temperature of drive engine pump
8	Drive engine thermostat	Temperature of drive engine coolant thermostat
9	Exernally mounted behind wheel house	External ambient tmeperature

Temperature data logger fixed to switch box in engine room to capture ambient temperature (4). Loggers were set to capture the temperature at 60 minute intervals. Each logger holds approximately 5 months worth of data.

3.2 Fuel & Additive investigation

The Automotive Department of Oxford Brookes University were commissioned to provide lab based assessment of PPOs and appropriate technical grade used cooking oil (UCO) including a basic fuel additive pack for two of the oils under test. The following is an executive summary produced by Geoff Goddard, Head of the Automotive Department.

> Testing of four grades of vegetable oil has established that the engine will operate successfully on all four oils. To establish the optimum injection temperature for each fuel, tests were run at a range of fuel temperatures with the engine performance, in cylinder combustion profile, and the tailpipe emissions being monitored at carefully controlled torque and speed settings. This test programme ensured that all the major engine performance testing was carried out at a running point where the fuel temperature, improved the fuel vaporisation, and combustion stability, combined to deliver the best combination of combustion efficiency, and best combination of performance and emissions.
>
> Of the four fuels tested the best results were obtained when running on RG179U, which demonstrated good combustion stability at all the injection temperatures employed. The refined soya oil produced a combustion instability when run at higher oil temperatures. These oils all have a slightly lower calorific value than the reference diesel fuel used in all back to back tests, hence to achieve an identical power output then slightly more PPO has to be consumed. However this is partially compensated for by the slight increase in peak combustion pressures achieved as all these vegetable oils burn more rapidly than the diesel. In terms of emissions characteristics the CO and CO_2 emissions are only shifted by the change in consumption, but the NO_X values fall dramatically when running on the vegetable oils. This is a major advantage for the emissions characteristics of running on vegetable oils, particularly as the effective carbon emissions can be declared very low as this is countered by the growing of the fuel in the first place.
>
> Clearly, even when heated all these oils have a significantly higher viscosity than the reference diesel fuel, so fuel pump and injector pump drive torque requirements will be increased. On most engines this will not be significant as the drive systems employed are robust designs which can easily accommodate this increase without any change to the service life of the drive system, however some poorly designed engines may use a narrow belt to drive the injector pump which would potentially need changing at a higher frequency than that dictated by its current service life.
>
> All testing has been undertaken using a single cylinder research diesel engine but has been meticulously carried out using a reference fuel to establish a stable datum in all tests for direct back to back comparisons with each test fuel. The rigorous control of all the operating parameters, for example controlling the engine oil temperature within less than one degree etc, has ensured that we have established the actual performance differences between each test fuel and the reference fuel. These differences have proved stable over our operating range and we have no reason to doubt that they will remain similar at any other operating point within an engines running range.
>
> During all testing we have monitored the condition of all the mechanical components within the fuel system and the working cylinder and have not noted

any problems due to the fact that we are operating for long periods on vegetable oils. Some have questioned the lubrication properties of the fuel as they have heard of other fuels such as methanol or ethanol which can generate much faster rates of wear and in the case of methanol are even used as seizure enhancers in some production assembly processes. However vegetable oils with their higher viscosities have more in common with lubricants, and indeed many successful engine oils have been entirely based on vegetable sources.

All the fuels were run in back to back tests in a single cylinder research engine with a reference grade of diesel fuel (CARCAL RF73A93, product number: 16875). This is used as the reference fuel for all such research testing within the University Thermodynamic Laboratories.

- Geoff Goddard, Oxford Brookes University.

The full report extends to several hundred pages due to its high graphical content. This is available in electronic form from Regenatec, subject to Non Disclosure Agreement.

4 Results

4.1 Pre Conversion 'Hot Oil' Test

The Jubilee Quest performace on PPO was intially assessed in a relatively quick and simple way: the introduction of suitably warmed oil directly into a warm engine. Large diesel engines, by virtue of their thermal mass and design, have the ability to effectively self heat the oil introduced to their injection pump. The warmed, excess fuel leaving the engine's injection pump, if returned to a suitably small fuel reservoir, serves to maintain the cycle of warm PPO being fed to the engine.

This was sucessfully perfomed on the main drive engine (a Caterpillar). The engine's normal diesel feed was temporily removed from the marine diesel supply and fed from a pre-warmed 22 litre fuel tank containing suitably processed base used oil to Regenatec's RG179 standard (see Appendix). The return feed was returned directly to this tank, thus creating a self-heating closed looped fuel supply.

The engine was found to tickover and rev normally, with no undue or erroneous noise or vibration. A slight drop in indicated fuel pressure was noted on the engine mounted gauge; this is to be expected with the pressures associated with the temporary local fuel loop created as part of this test. The engine was 'hot oil' tested for approximately one hour.

Emission results on engine during warm up (indicated temp <70°C):

Fuel: Marine Diesel

Emitted Gas	Tickover (750 rpm)	Revved (1,300 rpm)
CO	0.11	0.1
CO_2	2.1	3
O_2	18.45	18.5
NO	327	324
NO_x	346	425
COk	0.75	0.74

Fuel: Processed Oil (RG179U)

Emitted Gas	Tickover (750 rpm)	Revved (1,300 rpm)
CO	0.27	0.26
CO_2	1.9	2.4
O_2	18.48	17.82
NO	56	77
NO_x	64	74
COk	1.89	1.3

After allowing the engine to warm for approximately 45 minutes, the engine was then held at a high level of revs (approximately 1,300rpm) to capture the difference between the two fuels.

Extended Rev at 1,300rpm

Emitted Gas	Diesel	RG179U
CO	0.04	0.05
CO_2	7.4	7.7
O_2	10.75	10.26
NO	1076	1386
NO_x	1123	1483
COk	n/a	n/a

note: these above results should be viewed as merely indicative – not absolute or even repeatable. In order to accurately measure emission performance, an engine should be allowed to operate continuously for a minimum of 5 hours. The short time allowed between fuels as part of this exercise would have resulted in erroneous data. That stated, it is however fair to assume that final performance will be consistent with the results obtained: i.e. that overall, plant oils will give comparable emmisions to that of mineral diesel.

The ship's generator did not form part of the hot oil test.

4.2 Post Conversion Results & Sea Trials

Due to the relatively small budget available for a project of this nature and a sample size of one (i.e. a single vessel was used) any results that are a specific function of the vessel's technical status cannot be completely removed from the results obtained. A baseline performance on diesel versus performance on PPO after conversion can be obtained. Results are likely to be part subjective as opposed to completely objective.

4.2.1 Bollard Pull Test

A standard bollard pull test was performed to establish 'real world' power performance. Four to five runs were performed on diesel and then this was repeated on PPO. The vessel was tied to the dock by a strain gauge and then engine revs built up until maximum power is achieved. On the test Regenatec witnessed, the Jubilee Quest pulled 6 tonnes on diesel which was then matched by PPO. The captain stated that when the Quest was first commission she pulled 8 tonnes. During the pull tests no detectable signs of difference (i.e. noise, vibration, engine revs or visible smoke) were noted. The captain did state that the vessel had been down on power for at least six months prior to Regenatec's conversion. On successful completion of this test the ship's captain was happy to sign off the vessel for sea trials.

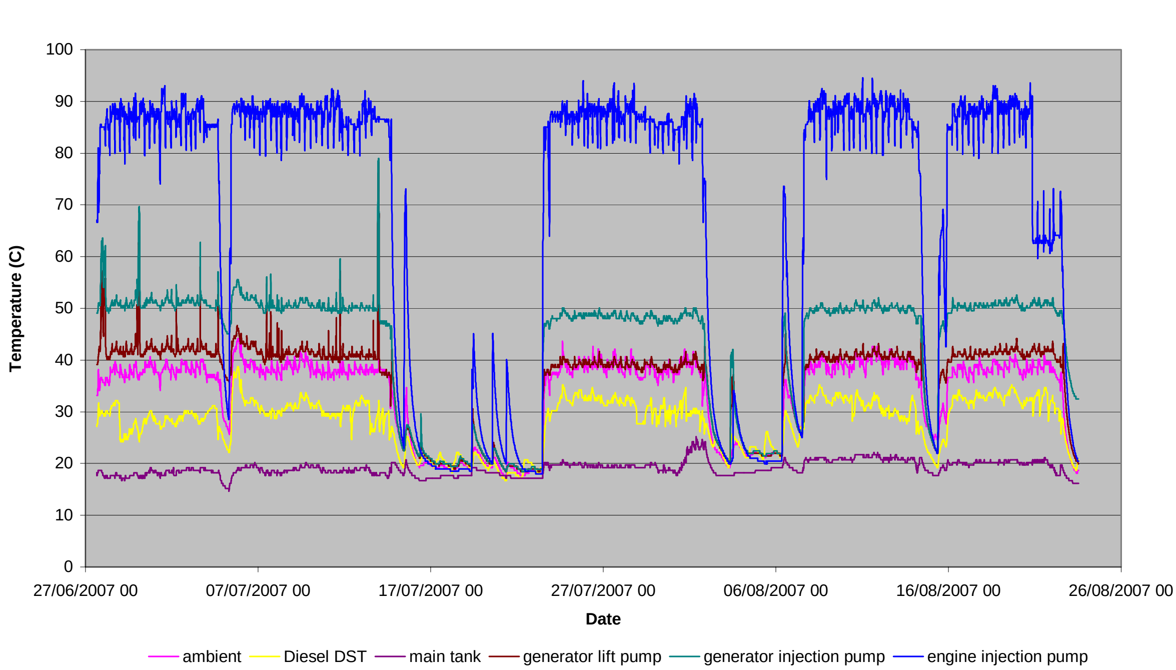
4.2.2 Fuel Consumption

Sea trials took the form of using the vessel in normal commercial activity, i.e. guard ship duty, towing and fishing. It is hard to accurately spot measure fuel consumption per se of a fishing vessel due to variables that are hard to measure and quantify against the simple metric of fuel used over a given period of time. Factors such as wind speed, tide, state of sea, air temperature, vessel load and even age of engine all affect measurement. Fuel consumption monitoring took the form of comparing consumption records over a number of sailings with the captain passing comment on whether, in his experience, anything was abnormal. No detrimental comments were received.

The sea trials were featured by BBC television's Working Lunch programme. A short film was made for the programme featuring comments on performance from the captain. These can be viewed online at: www.regenatec.com/media/tv/jubilee_quest.php

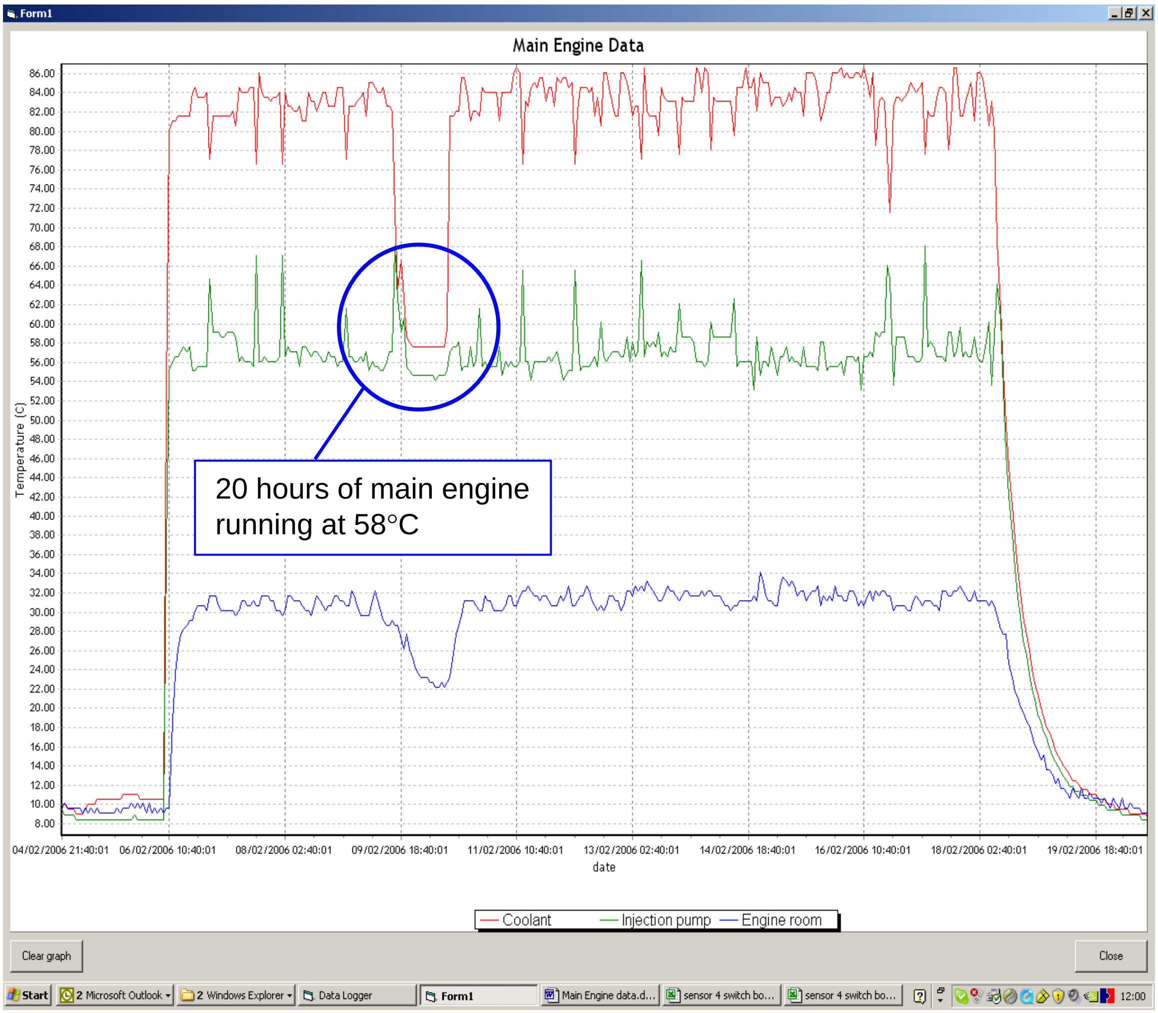
4.2.3 Engine Monitoring During Sea Trials

From Regenatec's land based experience, it is known that the temperatures of certain key components on the engine, as well the fuel oil, are critical to successful and reliable operation on PPO. Hence the reason to collect temperature data on critical points on the main drive engine, generator and other points considered important, as detailed in Section 3.1.



Many thousands of data points were collected by the DCS. A typical plot of the data collected is shown above (Chart 1). This particular chart shows the temperatre in the engine room (ambient), diesel daily service tank (DST), main diesel tanks together with temperatures for the generator and main drive engine injection pumps. A consistant and predicatable temperature of key engine components and engine coolant is critical. From an initial look at the above, it can be seen that there is reasonable consitancy and predicatablity – but also a large percentage of relative variation in some of the traces.

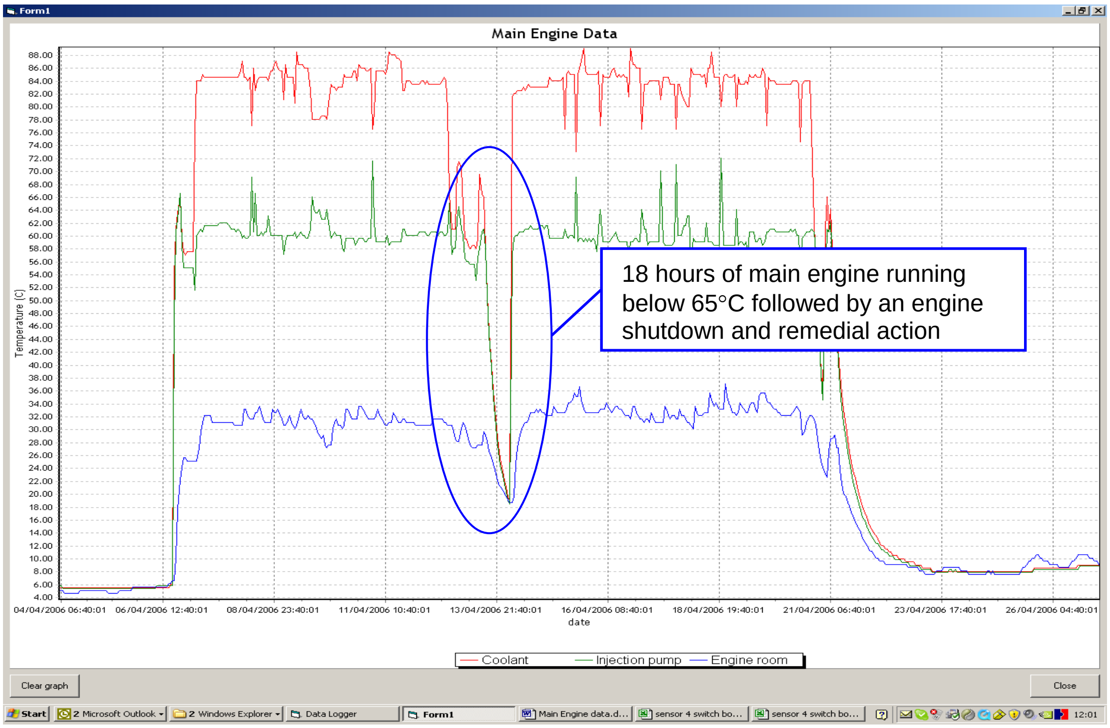
On the follow trace, which show the two key main engine temperatures of coolant and injection pump, there can clearly be seen a large drop of nearly 30°C in engine coolant temperature. This situation continued for approximately 20 hours of operation before normal operating levels were resumed. The level of cooling around the main engine was such that the ambient temperature within the engine room was clearly affected: a drop of approximately 10°C was recorded during the transient period.



Approximately one month later in May 2007 more anonomolous main engine temperature activity was noted. The following chart shows several days of transient coolant temperature activity. As before, it can clearly be seen to have affected the engine room ambient temperature but, more critically, fuel injection pump temperature has been adversely affected. A drop of approximately 10°C was measured at the injection pump. The absence of clear information from the ship's crew as to what activity was taking place means an assumption has to be made as to the cause. A loss of coolant feed to the fuel system heat exchange would cause the observed drop in injection system temperature, but it is unclear as to what situation would prompt the crew to take such action. Additionally, the routing of cooler than desired fuel is possible as part of a manual override configuration but once again, it is hard to imagine a situation why this would happen for a short period of time and then be rectified in the space of a single sailing without any comment to Regenatec. Unfortunately the sensor that would permit deeper investigation and possibly resolve whether a manual override was attempted (Sensor 8: drive engine thermostat) was found to missing at the time of a ship visit to collect temperature data.

4.2.4 Turbo Failure

On a subsequent sailing it was reported that the Jubilee Quest had suffered a failure of the main engine turbo charger. The following chart captures this period of activity. Prior to failure, it can be seen that, once again, the main engine experienced an erratic period of below normal coolant temperature. Again the injection pump can also be seen to experience a degree of temperature deviation.



From Regenatec's work with land based vehicles it is known that injection temperature of a PPO is critical to its correct vaporisation. Additionally if the combustion chamber is below nominal operating temperature then it is possible that not all PPO will be combusted in the time available. This could result in unburnt PPO being ejected out of the cylinder in to the exhaust system. By the nature of a turbo charger's intimate connection to the exhaust gas stream, unburnt PPO could find its way into the turbo charger. Due to the extreme conditions within a turbo charger (rotational speed and temperature) tolerance to any contamination is very low. It is proposed, based on the temperature data collected and the examination of the failed turbo charger that the root cause failure may have been unburnt PPO entering the turbo charger as a result of sub-optimal injection and in cylinder conditions.

As part of a through examination in order to ascertain root cause failure, the main engine cylinder liners were also removed and examined. A large amount of scoring was observed, indicative of lack of lubrication around the cylinder ring set. If an excessive amount of unburnt PPO were entering the cylinder then it could, by the action of blow-by, be forced onto the piston rings. Once here, due to chemical incompatibility polymers could form, thus reducing lubricity (see Appendix for comments from Oxford Brookes University).

It is worth noting that no abnormal behaviour was reported in the ship's generator and this functioned without reported fault on PPO.

5 Conclusions

5.1 Success

The trial can be considered a success with regard to the fact that a modern fishing vessel was modified, with minimal disruption to normal vessel operating patterns, to operate on PPO. The proposed fuel system layout by Regenatec for the vessel was implemented on time, in budget and functioned without any reported issues. The vessel passed a standard bollard pull test to the satisfaction of the ship's captain when operating on PPO. Emission testing performed as part of the hot oil tests showed comparable levels of pollutants when compared against standard marine diesel fuel oil. The carbon mitigation was calculated at c.80%[4].

5.2 Failures

A failure of the vessel's turbo charger unit occurred during operation on PPO, as covered in Section 4.2.4. Within the limited confines of this trial it is likely that this occurred due to unburnt PPO entering the exhaust gas stream & subsequently entering the turbo unit. With abnormally large transient deviations in engine coolant and fuel system temperatures the PPO was subjected to conditions not experienced on land based applications or as part of the Oxford Brookes University combustion work. It is Regenatec's view that whilst some degree of temperature transients are likely, in some cases possibly larger than those experienced on land applications, those seen on the trial vessel were abnormal and indicative of a poorly functioning coolant system. It was revealed during the trial that the vessel had historically suffered from overheating and that at least one thermostat had been removed. This appears to have resulted in a period of overcooling followed by re-insertion of the thermostat(s). From the data collected it was evident that thermal control of the vessels main engine was still an ongoing issue.

5.3 Fuel Additive Programme

It should be noted that the engine's previous turbo failure, start of trial lower-than-when-new power delivery and long term cylinder scoring marks are indicative of an engine that has been operated for some time in sub-optimal conditions.

During the sea trials, Regenatec made considerable headway in its parallel land based fuel additive work as a result of signing an NDA with a leading fuel additive manufacturer. This partnership, in conjunction with work at Oxford Brookes University, has yielded a nascent fuel additive pack technology programme. This has resulted in a first generation proprietary additive pack that will make PPO more tolerant to the conditions experienced in trial vessel's main engine.

It should be noted that the ship's generator functioned without reported fault on PPO for the duration of the trial.

5.4 Cost Benefit Analysis of PPO Technology

Until the environmental cost of mineral fuels are reflected in their price it is unlikely the renewable fuels are likely to be able pure only per litre costs or equivalent unit energy basis. The petrochemical industry has over 100 years to achieve vast economies of scale. They have become a model for vertical integration: controlling

4 Based on data from International Energy Agency

the supply chain from bore well to wheel and maximising profits wherever in the chain value occurs as the markets change.

The biofuel industry is a nascent one with no single ‘magic bullet’ solution. It is unlikely that the industry will produce a one size fits all, highly flexible product such as mineral oil. From road tars to aviation fuel, from petrol through to marine grade diesels and plastics, mineral oil produces thousands of products. Even the methanol required to produce biodiesel on a large scale is derived from mineral oil!

Biofuels will lower their cost base given time. However the competition is large, powerful and can afford to be patient. Only with government support via fiscal incentives that promote renewable fuel sources, proportional to the GHG & emission savings, whilst simultaneously penalising mineral oil fuel for its impact will the renewable market grow.

On a purely cost per litre basis PPOs cannot compete against marine diesel. At the time of writing, marine diesel is c.40p per litre – technical grade PPO being twice that. However, it should be noted that this project was designed to be a technical evaluation of the technology, not a commercial deployment. That said, once confidence in the technology has been proven, it will be possible to start exploring alternative oils, namely used cooking oils (UCOs), tallows and in the medium term non-food oils such as jatropha. These *can* offer a saving over marine diesel: lower quality tallows through to higher quality used oils range in cost from <10p per litre to approximately 30p per litre. This exploratory work will need to take into account further vessel modification to cope with the higher viscosity of used oils. Additional fuel additive science work, backed up by lab based verification, will be needed to ensure emissions are within acceptable limits and there exists no long term detrimental effects on an engine.

5.5 Practical Aspects for the Marine Sector

Once a PPO based fuel can be made available at the right price, the roll out across a significant part of the fishing fleet could be quite rapid. The Regenatec system was retro-fitted to the trawler in under one week. This means that the roll out would not be restricted by the rate of fleet replacement. In fact initial anecdotal evidence even suggests the use of PPO based fuel may even lengthen engine lifetime.

The retro-fit system even takes advantage of the existing multiple fuel tanks on a typical trawler. In the trials one tank was used for diesel and the remaining three stored the PPO fuel. Just one additional daily service tank had to be added.

The PPO based fuel with the correct additive pack will freeze at about -10 degrees centigrade. This is not an issue to be concerned about as north sea temperatures rarely get below 5 degrees centigrade although some care may be needed regarding the insulation of the fish cold store if its adjacent to a fuel tank.

Another big advantage of this technology and fuel is that no new fuel distribution infrastructure is needed. During the trials the fuel was simply delivered up to quayside on a road-going fuel tanker and then pumped directly into the trawler. It may be beneficial to invest in some sort of quayside PPO storage facility but this would only be to simplify delivery logistics.

5.5.1 The Business case

The conversion costs would be quite significant but due to the immense fuel consumption of such vessels, any per litre cost saving on the fuel will quickly pay this investment back.

The pull tests showed the PPO fuel delivered similar power and (hence) consumption to that of diesel. A “typical” ten day voyage can consume up to 13,000 litres of marine diesel. If it is assumed that a vessel can make twenty voyages in one year, the annual fuel consumption should be of the order of 260,000 litres. The current estimated cost to convert a trawler is about £30,000 which means if a fuel saving of 10p per litre can be delivered, the conversion would pay for itself in about 14 months. If a saving of 15p could be delivered, this payback could be achieved in just over 9 months! This would then enable annual fuel savings of between £26,000 and £39,000.

5.5.2 Brand Benefits

In addition to the above direct financial benefit there exists the huge potential for positive PR and brand benefit. One only has to look at the success of Fairtrade products to see what is possible. Clearly there are significant parts of the market who will pay a premium to purchase eco-friendly, ethical and sustainable produce. In addition to the catch volumes being at a sustainable level, the carbon footprint of the fishing process would need to be accounted for. Thus a reduction in the carbon footprint of ~80% would go along way to making the fishing process as a whole, sustainable.

Market testing could quantify the benefit of adding value to the catch but current evidence suggests this benefit is unlikely to be zero. It could also confirm the type of branding which works best: “Caught on plant oil”, “Totally sustainable Fish”, “Member of the Low carbon fishing partnership” etc. Those fishermen using this low carbon technology could club together to sell directly to the public in an “organic farmers market” model. They may prefer to work with certain restaurants and food retailers as an additional route to market.

5.5.3 The Public Perception of Biofuels

How the public view biofuels is key to deriving any brand or PR benefits from their use. Over the last few months various reports have been published, including the Parliamentary Cross Party Environmental Audit Committee and the Royal Society, in which questions have been raised regarding the net environmental benefit of some biofuels. The media at large has exaggerated this storey and with a few selected quotes from NGOs promoted the idea that “all biofuels are bad”.

The reality is that both biofuel reports do concede that biofuels can have a major impact in tackling climate change. However, when change of land use, fertilizers, mechanical harvesting, feedstock processing into fuel, fuel distribution etc are all taken into account, many biofuels have a significantly reduced impact and some even have a negative impact on the environment. Regenatec would generally agree with this analysis which is why they have invested heavily in securing supply agreements of traceable feedstock from non-rain forest areas and in developing their technology which enables the use of minimally processed PPO. Their on-going biofuel R&D programme is making good progress in sourcing other low carbon, ethical, sustainable feedstock to produce PPO biofuels from, such as used oils and non-food jatropha grown on marginal land.

After presenting "results so far" of this project at a public meeting, Regenatec received over 400 e-mails, all from The Biofuel Watch, an anti biofuel NGO, calling for an end to the project. The e-mail their members sent contained many errors and misunderstandings. An automatic reply was then set up and the following text was e-mailed to every sender:

Sent:	*25 June 2007 12:17*
Subject:	*RE: Please abandon plans to convert UK fishing fleet to biofuels from Argentinean soya*

You recently sent an email to a number of parties involved in trialling biofuels for the fishing industry in the UK. We thank you for your interest in the project - this response clarifies some facts about the project, and underlines the wider environmental and sustainability issues which we take very seriously.

Only one vessel has been converted to explore the technical feasibility of operating on Straight Vegetable Oil, a renewable alternative to marine diesel. This is a research project, not a commercial deployment of the technology nor is it necessarily a precursor to fleet-wide deployment. In parallel we are investigating the feasibility of the production of biodiesel from waste vegetable oil, which emphasises the point that sustainability and wider ethical issues are important to us and are being given serious consideration as part of this project.

The vegetable oil sourced for the project comes from a reputable supplier in Argentina, who is a member of a rainforest preservation charity - their commitment to sustainability is an important factor in choosing them as suppliers.

We believe it is important that we carry out this research into sustainable and environmentally friendly biofuels. Alongside this, we are also committed to reducing fuel use overall in the UK fishing industry and are financing and managing a number of other research projects investigating this, not to mention work in training and educating fishermen in best practice.

Regenatec is investing heavily in R&D to ensure that they are one of the first companies in the UK to be able to offer low carbon, ethically sourced, non-food oils such as Jatropha and oil from algae. It is these low environmental impact, non-food oils that will ultimately supply heavy users of diesel fuel.

Invitation to discuss this subject further
If there is enough interest, Regenatec and Seafish would like to host an open seminar on Milton Business Park where the project, the ethics and sustainability of oil being used and the likely outcome of the project can de discussed in more detail.

Please indicate your interest in such an event by sending your name and contact telephone number to project@regenatec.com. A date will be arranged to suit the majority.

In the meantime if you would like any further information, please do not hesitate to contact us directly.

Regards,
Mike Lawton
Founder & CEO

Of the 400 replies sent out only 3 responded to our invitation to meet and discuss the facts further.

5.6 Present Viability and Demand for PPO Technology

5.6.1 Marine Sector

With no differential cost saving between marine diesel and PPO there will no demand for PPO technology in the commercial marine sector. Whilst it is probably true to say that most fishing vessel owners are aware of the impact their high consumption of fossil fuels is having on the environment, it would be unrealistic to assume that they will voluntarily switch to a higher cost fuel in order to lessen this impact. The technology will become viable in the marine sector when a tangible fuel saving exists. Viability is defined as a fuel differential saving that provides a sensible return on investment for the cost of converting a fishing vessel. This can came about via two routes:

- Further technology development to allow the use of UCOs & tallows (although the volume produced in the UK is likely to be a limiting factor) and,
- Fiscal and policy mechanisms to make the use of biofuels financially viable to the industry.

It should also be noted that in the situation of under supply of PPO fuel, market forces will push the consumption towards the segment providing the best return to the supplier. This means that as the PPO fuel market grows, if significant uptake in the marine sector is to be achieved, fiscal policy would need to give a better return to the supplier than the road transport sector.

5.6.2 Other Applications

In other sectors, nascent PPO technology enjoys growing adoption, driven not only by tangible fuel savings but also a desire to reduce dependence on non-renewable energy. In addition to growing numbers of retro fit conversions to private and commercial vehicles, Regenatec is working with UK bus builders the Optare Group and Alexander Dennis Limited. This has resulted in the delivery of a number of factory fit vehicles as part of ring fenced exploratory trials. Uptake of the technology is not driven purely by costs savings – early adopting corporates understand the contract winning advantage of being 'greener' than a competitor and are successfully passing on higher costs (if they exist) to customers. This is particularly true in the local authority and municipal contracts sector where tangible examples of corporate social responsibility are expected and increasingly form part of the bid process.

UK's first factory fit PPO powered bus as a result of Regenatec's work with Optare.

Regenatec is also working closely with Dennis Eagle, the UK's largest builder of refuse vehicles. A new Generation EURO5 vehicle has been converted and is acting as a joint demo unit of DE's product and Regenatec's fuel system. Comments from Dennis Eagle's Chief Executive and from lead customer, SITA plc can be seen in a short film on Regenatec's home page (www.regenatec.com).

Outside the UK, power generation is potential a very large sector for the technology. Regenatec is due to start trials in India shortly with a large hotel chain that operates a high number of large generators (>250kW) to provide power for its 5 star hotels. The hotels also generate a significant amount of high quality UCO which ultimately they wish to fuel their generators with. Regenatec is also in exploratory discussions with an Indian Diesel engine manufacturer over the possibility of factory fitting. In a country such as India the attraction is to use indigenously produced non-food oils such as Jatropha and Pongamia. These offer a financially more attractive alternative to diesel.

5.7 Future Application of PPO Technology

No government will argue that mineral oil will not eventually run out. It's a non renewable product and the world's consumption continues to increase, so arguments are largely reduced to when will wells run dry – not if. Of course, the world is never likely to actually run dry of mineral oil, it will simply become 'economically exhausted' – it will cost too much to extract the remaining hard to reach stocks when compared to alternatives.

Therefore it's reasonable to argue that non-renewable energy sources are likely to increase in cost over time, whilst renewable sources, aided by fiscal policy and technology development, are likely to fall. Early adopting customers that see an advantage to their business by being a 'first mover' in their sector (likely to be image enhancement rather cost saving initially) will pull the technology into the market place. Once de-risked and into the 'comfort zone' of more traditional operators, uptake will be more widespread. Strong fiscal incentives and policy will then need to follow to bring the market at large on board.

The diesel engine will be around for many decades to come. It is a well liked, easily understood and cost effective way of delivering motive power. There is no immediate commercially viable replacement on the horizon for the large commercial diesel engine. Indeed, this situation is likely to remain so for at least another 10 – 20 years in the UK, with diesel-electric hybrids being the next logical step. In developing countries, where engine technology lags Europe by around 5 – 10 years, the replacement cycle is likely to be far longer.

5.8 Conclusion & Recommendations

On a sample size of one it is impossible to draw any statistically meaningful conclusions. The fact that the main drive engine suffered a failure of its turbo charger unit and that a credible engineering root cause for the failure can be traced back to the combustion properties of PPO when engine conditions deviate from the norm does not completely explain all the observations made during the trial. It should also be noted that the Jubilee Quest had previously suffered a turbo failure some 12-14 months prior to conversion for PPO trials and had undergone an engine rebuild, testament to the fact that turbo units can - and do - fail.

It is clear that governments are increasingly demonstrating their commitment to GHG abatement via fiscal measures. The European Commission plans for its revised Renewable Energy Directive to include a binding target for biofuels to make up 10% of road fuels by 2020. In the UK, this gains further momentum with the introduction of the Renewable Transport Fuel Obligation (RTFO) in April 2008 RTFO which initially has a voluntary target for a 50% average carbon saving by 2010/11.

The recently published Royal Society Biofuels Report states a long-term market and appropriate support for biofuels is needed if those with the highest greenhouse gas savings are to be developed. Long-term support for biofuels is needed to encourage the development of those with the highest greenhouse gas savings. As the report states, "unquestionably large uncertainties surround biofuels…and the life-cycle analyses of them needs to be improved'.

As stated earlier in this report, linking the environmental cost of carbon to a fossil fuel is likely to make some biofuels financially viable. It is Regenatec's opinion that this will eventually happened when a political expedient mechanism can be found. This view is in part confirmed by a contributor to the Royal Society report's Working Group. Dr Jeremy Woods of Imperial College, London argues the RTFO should include a mandatory greenhouse gas target of 50% minimum saving. The Report itself calls for carbon pricing to be extended to transport fuels on a CO_2-equivalent basis, but it questions whether such a tax would impact significantly on the economics of biofuels. According to Exxon Mobil, a $100 per tonne carbon tax would only add 25 cents to the cost of a US gallon of petrol[5], although the reader could be forgiven for assuming a bias in such comments.

Regenatec remain confident that a renewable, low carbon and crucially financially viable fuel can be delivered to the UK fishing industry that is compatible with existing fishing vessel diesel engine technology. From the initial, exploratory work performed

[5] ENDS Report 391, pp 36-40

as part of this trial, it is clear that further research is required. Regenatec is confident that it can replicate its land based success at sea. However, this will require further fiscal support to fund the required research, development and field evaluation for the conversion technology and fuel additive science.

Based on this project and the company's on going land based vehicle trials with key commercial customers, research and product development into the use of pure plant oils (PPO) as a replacement for mineral diesel continues. Appropriate academic and commercial strategic relationships have been established to push deeper into the combustion science and understanding of the long term effects of using various grades and types of pure plant oils. Regenatec is highly confident in delivering a conversion technology and pure plant oil biofuel that achieves the same maintenance & service regimes as conventional diesel but with superior carbon and technical performance to biodiesel in the high use, high consumption diesel engine sector. The company sees the primary barrier of PPO technology becoming a wide scale commercial reality is that of a suitable fiscal policy. It is unrealistic to expect a nascent biofuel industry to compete directly against an entrenched competitor, in the form of the petrochemical industry, which enjoys a century head start. Additionally, policy is required that is able to differentiate between the merits of various biofuels and support in an appropriate manner those that are truly sustainable and ethical. Only when this is in place, with visibility of a long term policy commitment, will it allow companies such as Regenatec to attract greater UK investment and ultimately deliver low technology to the market place.

Appendix

1. Marine diesel fuel & RG179 specification
2. Technical Scoping Report
3. Cylinder Liner Investigation

Marine Diesel and RG179 PPO Specification

		Marine Gas Oil [6] BS2869 (Pt: Class A2& D)			RG179 [7]		
Property	**Units**	**Min**	**Max**	**Test Method**	**Min**	**Max**	**Test Method**
Density @15°C	g/ml	0.82	0.875	ASTM D 4052/IP 365			
Appearance @15°C		Clear	Clear	ASTM D 4176			
Colour		red	red				
Distillation @ 760mm	hg. (deg C)			ASTM D 86/IP 123			
50% Vol Rec		240	340				
Vol Rec @ 350°C	(%)	85.0					
Flash Point (P.M.)	(Deg C)	60		ASTM D 93/IP 34			
Sulphur	(%wt)		0.20	IP 336			
Copper Corrosion	(3hrs @ 100°C)		1	ASTM D 130/IP 154			
Cloud Point	(deg C)		3 (S)/-2(W)				
Cold Filter Plugging Point	(deg C)		-4 (S)/-12(W)	IP 309			
Cetane Index OR	45			ASTM D 976			
Cetane No.	45			ASTM D 613			
Viscosity @40°C	(cST)	1.5	5.0	ASTM D 445/IP 71			
Ash	(%wt)		0.01	ASTM D 482/IP 4			
Water	(%vol)		0.05	KARL FISCHER			
Sediment	(%wt)		0.01	ASTM D 473/IP 53			
Carbon Residue 10% Bottoms	(%wt)		0.20	ASTM D 4530			
Total Acid No.	(mg/KOH/g)		0.10	ASTM D 974/IP 139			
Strong Acid No.	(mg/KOH/g)	Nil	nil	ASTM D 974/IP 139			

[6] ISO fuel specification data supplied by Rix Maritime
[7] specification from lab profiling

Jubilee Quest Scoping Report

issue draft 1.0

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1 Executive summary

The use of pure plant oil (PPO), also known as vegetable oil, as a diesel fuel extender or as a total fuel substitute is known. The concept gained popularity during the fuel crisis in the 1970's although engine technology at this time was relatively basic. The concept today has two primary drivers: cost reduction and environmental footprint. The use of recovered and suitably processed waste vegetable oil can offer substantial atmospheric carbon dioxide (CO_2) mitigation together with a reduction in other regulated exhaust pollutants, such as sulphur dioxide. Initial trial work performed by Regenatec on land based vehicles has shown promising results.

This project is designed to investigate the use of suitably processed used vegetable oil as well the use of fresh PPOs.

Regenatec has developed a dual tank system under electronic control to automate the use of plant oils in a diesel engine. This has significant advantages over existing, less sophisticated technology. The engine is started on conventional marine diesel (or biodiesel) and then automatically switches over to the lower cost, more environmentally friendly PPO. The automation greatly improves the ease of use for unskilled operators and removed the potential for engine damage when compared to manual control.

contents

2 Scope

This document is designed to describe the fuel layout system of the Jubilee Quest Fishing vessel and the practical steps required for conversion for operation on Regenatec's pure plant oil technology. This pilot investigative project is part of biofuel investigation programme being sponsored by Defra via an FIFG Grant, under control of Sea Fish Ltd.

3 Introduction

The Sea Fish Industry Authority (Seafish) wishes to investigate the potential use of biofuels in fishing vessels. The large fuel price increases of over 100% in the last 18 months is leading to financial hardship amongst certain operators in the fishing sector. Increased awareness of the environmental damage created by fossil fuels usage is also leading to fishermen seeking ecological viable alternatives.

As part of the biofuels programme, transesterified biodiesel will be explored by the Camborne School of Mines, Cornwall.

The Jubilee Quest, based in Grimsby, has been selected as the pilot vessel to trial Regenatec's diesel engine conversion technology to explore the use of PPO.

The vessel is equipped with two diesel engines:

Main Drive Engine
Caterpillar 12-litre, 450Hp, normally aspirated non-common rail.

220-230v ac Generator
Cummins 2.5-litre, XXkW, normally aspirated non-common rail.

Due to the joint use of a common fuel system on the vessel, both diesel engines will be converted as part of this investigation.

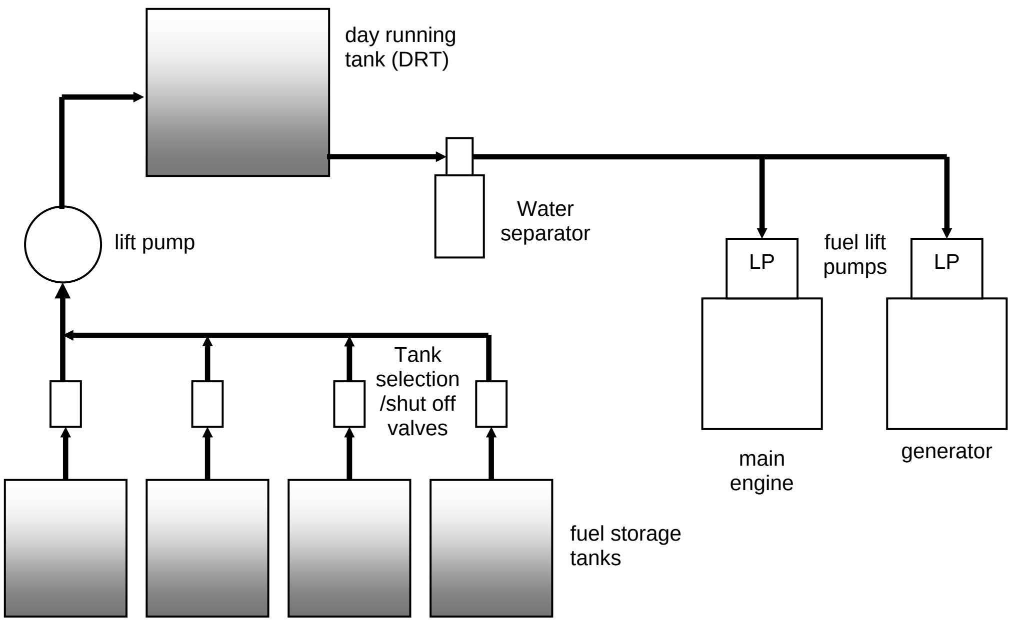
4 Existing Fuel Layout

The vessel has four main fuel storage tanks located in the hull of the vessel. These are equal in size and have an approximate capacity of 6,000 litres each, giving a total capacity of 24,000 litres (approximately 24 tonnes). The Jubilee Quest typically consumes 12 to 15 tonnes of fuel per voyage.

The layout of the four main fuel tanks is such that they must be drawn on in roughly equal measure to ensure the stability of the vessel is not compromised, i.e. drawing exclusively on the tanks that compromise the port side would cause the vessel to list.

Marine diesel fuel is drawn from a selected tank via a fuel selection valve and transferred to the day running tank (DRT) in the engine room itself. Transfer to the day running tank is achieved via electric lift pump. The transfer is automatic: the DRT has two float switches, one determining the upper fuel position (tank full) and a lower switch determining tank low. As fuel is burnt the fuel level in the DRT drops and at the tank low position the transfer pump is started automatically filled until the upper float is activated and the transfer pump shut off. The DRT has a capacity of approximately 1,000 litres.

The DRT is situated slightly above the level of the main drive engine and generator, thus fuel is fed under the effect of gravity to these engines, via a water separation unit located immediately on the outlet of the tank. Gravity fed fuel means that the lift pumps on these engines perform very little or no actual lift work.



5 Proposed Layout

The proposed fuel layout of vessel is shown on page 9. One of the four main fuel storage tanks remains as a store for conventional mineral marine diesel fuel. The remaining three are now given over to holding PPO.

5.1 Initial Vessel Warm Up Sequence

The vessel is started as normal on marine diesel. This is supplied from an additional diesel start up tank that is fitted in the engine room – possibly alongside the existing DRT. Diesel fuel flows from the this tank, via an additional water separator, to a Fuel Select Valve (FSV), one for main engine and the generator, respectively.

With the FSVs set to feed diesel fuel to the engines, via a heat exchanger, it can be appreciated that the engines can be started. Once the engine has fired, unburnt fuel will be continuously ejected from the engine's lift pump. Normally this would be allowed to return to the DST, but is now forced to recirculate back to the engine due to the position of the Purge Valve (PV). Thus a circulating loop of warming fuel is created, the loop being topped up as fuel is burnt by the engine.

It can be appreciated that as the diesel fuel is being heated by the engine's coolant via the heat exchanger, the circulating loop of fuel is warming toward coolant temperature (approximately 80°).

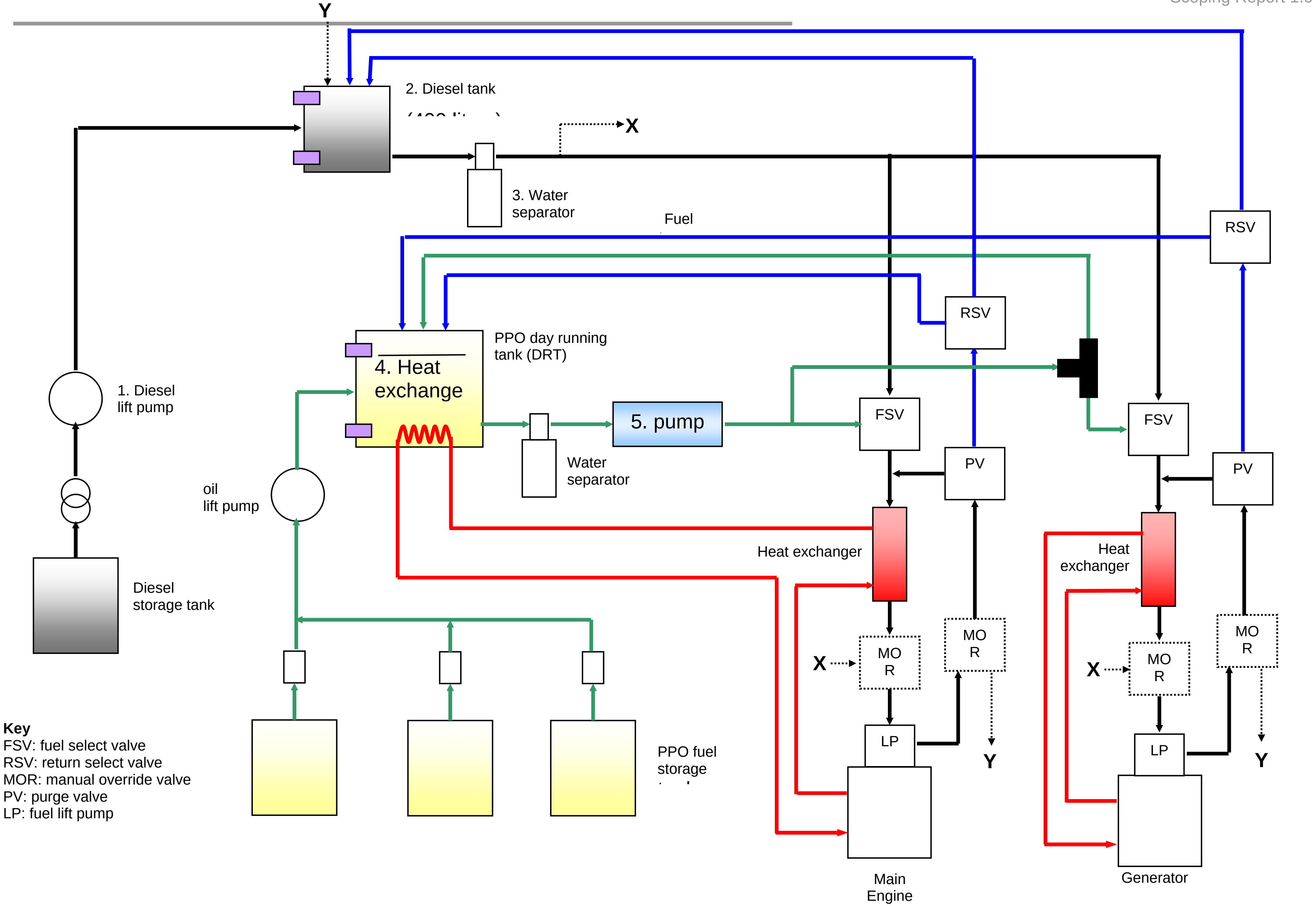
Engine coolant is also circulated via a heat exchanger located in the DRT, such that heat energy is imparted to the PPO. This has the effect of reducing the viscosity of the PPO.

The temperature of the diesel fuel in each recirculating loop is monitored by the control electronics. At the appropriate trigger level, the FSV will be activated to change state. This then has the effect of introducing PPO into the recirculating loop of warmed diesel fuel. After a short period of time (approximately 10 minutes), the recirculating fuel loop will have blended from 100% diesel to 100% PPO. The engine is now operating on PPO.

Due to the higher viscosity of the PPO (some 6 times that of mineral diesel at 40°C) it will be necessary to deliver PPO to the lift pumps of both the main engine and the generator. Without additional pump support (5), it is anticipated that the engines will experience fuel starvation and subsequent power loss.

5.2 Manual Override

It is the intention to leave as much of the existing fuel layout system undisturbed such that in the event of failure of the conversion technology, a manual override can be exercised. This will then allow the vessel to operate on diesel, such that a return to port under its own steam will be possible. To permit this, the conversion topology incorporates a number of manually operated override valves (MOR). When operated, these will return the main engine and genset back to open loop diesel operation under normal control.


Y
2. Diesel tank
X
3. Water
separator
Fuel
RSV
RSV
PPO day running
tank (DRT)
4. Heat
exchange
1. Diesel
lift pump
5. pump
FSV
FSV
Water
separator
PV
PV
oil
lift pump
Heat exchanger
Heat
exchanger
Diesel
storage tank
X
MO
R
MO
R
X
MO
R
MO
R
LP
LP
Y
Y
PPO fuel
storage
Main
Engine
Generator
Key
FSV: fuel select valve
RSV: return select valve
MOR: manual override valve
PV: purge valve
LP: fuel lift pump

6 Baseline Engine Monitoring

Temperatures associated with the main drive engine & genset and how these vary in response to the ambient enviornment and the type of fuel being burnt are critical to understanding engine performance and stress.

In order to establish the baseline performance of the Jubilee Quest, a number of self-contained, data logging thermometers were affixed to the engine, genset and surrounding environment. These data loggers have been set to capture the local temperature of the surface they have been fixed to. The loggers have been fixed in the follwing locations:

Sensor No.	Location	Temperature Data Captured
1	Upper level of day running tank	Maximum in-tank fuel temp
2	Lower level of day running tank	Minimum in-tank fuel temp
3	Main fuel tank under engine room deck	Nominal fuel temp (as affected by thermal contact to the sea)
4	Plastic switch box in engine room	Ambient engine room temperature
5	Genset fuel lift pump	Temperature of generator lift pump
6	Genset fuel injection pump	Temperature of generator injection pump
7	Drive engine fuel injection pump	Temperature of drive engine pump
8	Drive engine thermostat	Temperature of drive engine coolant thermostat
9	Exernally mounted behind wheel house	External ambient tmeperature

Temperature data logger fixed to switch box in engine room to capture ambient temperature (4). ALL loggers have been set to capture the temperature at 90 minute intervals. Each logger will hold approximately 25 days worth of data.

7 'Hot Oil' Test

A relatively quick and simple way to assess a diesel engine's ability to operate on pure plant oil is to simply introduce warmed oil directly into a pre-warmed engine. Large diesel engines effectively self heat the oil introduced to the injection pump, by the action of fuel compression. The warmed, excess fuel leaving the engine's injection pump, if returned to a suitably small fuel reservoir, serves to main the cycle of warm oil being fed to the engine.

This was sucessfully perfomed on the main drive engine. The engine's normal diesel feed was temporily removed from the marine diesel supply and fed from a pre-warmed 22 litre fuel tank. The return feed was returned directly to this tank, thus creating a self-heating closed looped fuel supply.

The engine was found to tickover and rev normally, with no undue or erroneous noise. A slight drop in indicated fuel pressure was noted on the engine mounted gauge – but this is to be expected with the pressures associated with the temporary local fuel loop. The engine was 'hot oil' tested for approximately one hour.

Emission Results on engine during warm up (indicated temp <70°C)

Fuel: Marine Diesel

Emitted Gas	Tickover (750 rpm)	Revved (1,300 rpm)
CO	0.11	0.1
CO_2	2.1	3
O_2	18.45	18.5
NO	327	324
NO_x	346	425
COk	0.75	0.74

Fuel: Processed Oil (ETF-RVO)

Emitted Gas	Tickover (750 rpm)	Revved (1,300 rpm)
CO	0.27	0.26
CO_2	1.9	2.4
O_2	18.48	17.82
NO	56	77
NO_x	64	74
COk	1.89	1.3

After allowing the engine to warm for approximately 45 minutes, the engine was then held at a high level of revs (approximately 1,300 rpm) to capture the difference between the two fuels.

Extended Rev at 1,300rpm

Emitted Gas	Diesel	Veg Oil
CO	0.04	0.05
CO_2	7.4	7.7
O_2	10.75	10.26
NO	1076	1386
NO_x	1123	1483
COk	n/a	n/a

Note: the above results should be viewed as merely indicative – not absolute or even repeatable. In order to accurately measure emission performance, an engine should be allowed to operate continuously for a minimum of 5 hours. The short time allowed between fuels as part of this exercise would have resulted in erroneous data. That stated, it is however fair to assume that final performance will be consistent with the results obtained: i.e. that overall, plant oils will giver lower emissions than mineral diesel.

3. Cylinder Liner Investigation

History received (Lee Ackrell, Regenatec Principal Engineer email, 1 March 07)

a) *It is a Caterpillar 3412C marine diesel engine*

b) *The history I have to hand is that the engine was rebuilt (I'm assuming liners and pistons as well) 24 months ago. Running hours since rebuild would be in the order of 10,000 to 15,000 hours. The engine was down on performance by 25% for the 6 months preceding the conversion to PPO. The conversion was performed and comparative power testing done between PPO and diesel, the results showed no difference between the two fuels. The engine has run on 8,000 litres of soya oil then was put back on to diesel. The turbo failed after running on diesel for a further 1,000 hours (approx) damaging the cylinder head. Upon removal of the cylinder head the bores were noticed to be glazed.*

c) *We are also aware that the engine cooling system was severely compromised with first overheating during trawling and then over cooling by the removal of the engine's thermostat.*

d) *The lube oil is monitored regularly by the vessel's operator (including lab testing) however when we got a sample of the oil independently tested it was found to have a very high TBN number, in the region of 80. I'm not sure when the oil was changed prior to this failure.*

Brief summary of findings

Liner has excessive wear at top ring reversal point. However, there are no (vertical) scoring marks or scuffing in the liner. It seems, the engine had excessive blow-by that resulted in build-up of excessive hard carbon between the rings zones. However, it is difficult to identify the reason for the excessive blow-by with out analysing the conditions of the rings and knowing the wear before vegetable oil was used. The surface underneath piston crown shows the sign of excessive heating.

Geoff Goddard comments:

The loss of 25% of engine performance before the change to the Regenatec fuel is a major indicator of something seriously wrong with the engine long before the switch to the new fuel. As Stephen has noted the bore has worn considerably producing a large step at the top ring and completely removing the original honing marks in the region of the ring travel.

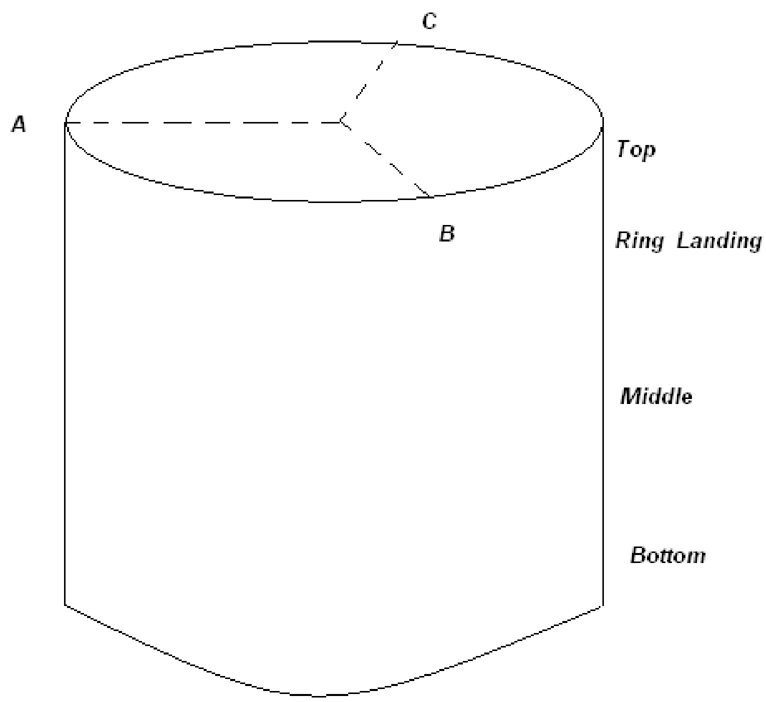
However the piston skirt is virtually unmarked but the combination of ancient carbon build up and the accumulation of wear particles within the rings which we have not been shown, has clearly trapped the rings leading to excessive blow-by and the resulting massive loss in performance.

How can this occur when running on normal fuel? The life of the cylinder bore is governed by the compatibility of the piston ring material and the cylinder liner material and their relative hardness values combined with the effects of the operating *temperature on oil film formation and stability. In many diesels the mistake is made to take a very hard (long life) ring specification e.g. titanium nitride hardened stainless steel rings, and then to run them in a soft cast iron liner bore, resulting in very rapid bore wear while the rings remain largely unscathed. Very hard rings were developed for use in chromed liner bores, or hard spheroidal graphite liners. With a soft liner like this one I would expect to find a much softer ring in use e.g. cast iron, to ensure compatibility between the surfaces.*

The problems of the rate of carbon build up on the original fuels may be due to the source and grade of this fuel as these engines were designed for normal heavy road haulage applications e.g. Kenworth trucks where they are operating on normal pump diesel not on a marine diesel

.

I do not believe any conclusions about the effects of the Regenatec fuels on engine life can be drawn from examining components from an engine that was already worn out before the fuels were introduced. (GG)



Approximate dimensions (mm) measured using micrometer;

	Top	Ring Landing	Middle	Bottom
A	137.20	**137.38**	137.26	137.27
B	137.20	**137.29**	137.27	137.34
C	137.20	**137.43**	137.31	137.35

Figure 1Excessive wear: ring landing area

Figure 2 Overall liner surface looks healthy apart from ring landing area

Figure 3 Fingerprints for excessive blow by- possibly due to excessive wear of rings and liner at the ring landing area, hard carbon build-up between top and bottom ring

Figure 4Excessive carbon build-up

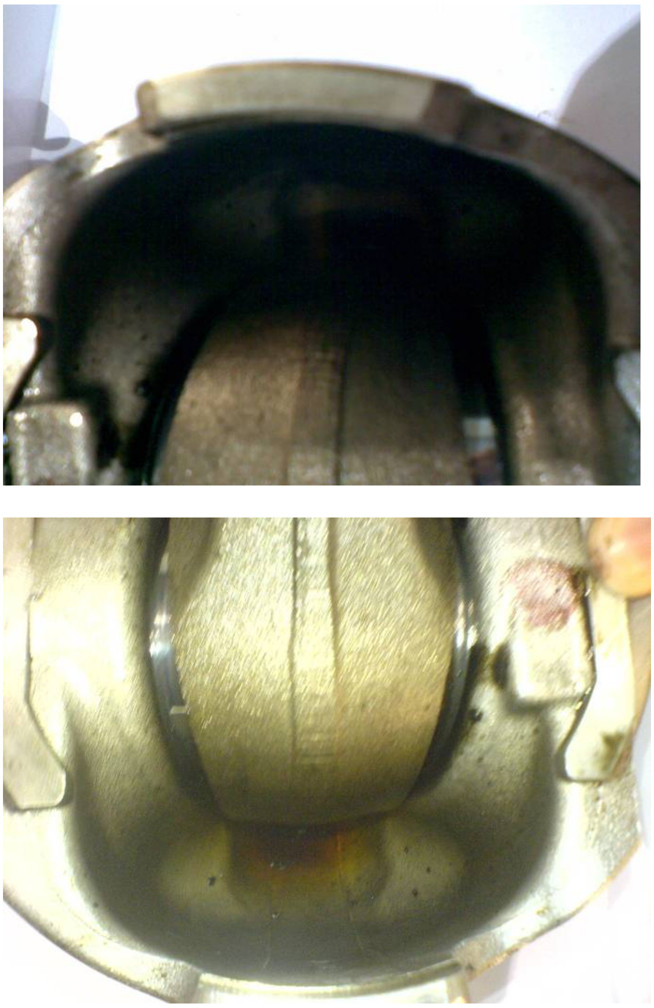


Figure 5 Fingerprint for Overheating: under the piston crown