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The School of Mechanical Engineering

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Diesel fuel additives for mining and industrial equipment

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Abstract

For large scale machinery small improvements in fuel efficiency can translate to significant cost savings. Fuel additives may be one way to reduce the fuel consumption of existing machinery, thus providing economically and environmental benefits. Investigations of possible fuel savings from two diesel fuel additives were conducted. It was determined that controlled tests were required as small changes in operating conditions could conceal the effect of the additives. The additives were tested at different loading conditions with the use of generators coupled to resistive load banks. Different loads were chosen in an attempt to relate additive effectiveness to real engine conditions. The effect of filtering the standard diesel supply was also examined as an addition to the original scope.

Results showed improved fuel efficiency with FTC on a near new engine; however, the improvements decreased as the applied load increased. Nemo showed no measurable effect on fuel consumption in new engines. Both additives showed an improved efficiency with treatment in older engines in the order of 3% to 5%. These results were more erratic than those of the new engines, thus highlighting the difficulty in measuring fuel consumption to a high degree of accuracy in old engines. The results indicated that the savings from FTC were party derived from improved combustion characteristics of the diesel and the remainder from cleaning effects. In comparison to FTC, Nemo was seen to only improve fuel efficiency through cleaning. Filtering diesel to 1-micron showed a small reduction in fuel consumption (~0.5%), however this was within experimental error therefore no definite conclusions can be drawn.

The investigations of this report suggest significant savings can be gained via treatment with either additives on older engines. Furthermore, no short-term negative effects of the additives on engine life were observed through oil sample analysis. Finer filtration of diesel also appears to be beneficial to fuel system longevity, long-term fuel efficiency, and has no negative effects on fuel consumption provided that fuel filters are changed regularly.

Letter of Transmittal

Rick Gillinder
35 Rose Street
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Thursday, 24 November 2005

The Executive Dean,
Faculty of Engineering and Mathematical Sciences
The University of Western Australia,
Crawley, Western Australia 6009

Dear Sir,

It is with great pleasure that I submit this thesis, entitled, "Diesel fuel additives for mining and industrial equipment", as a requirement for the completion of the Bachelor of Mechanical Engineering Degree with honours.

Yours sincerely,
Rick Gillinder

Acknowledgements

First, I would like to acknowledge Pilbara Iron and the CEED department for giving me the opportunity to partake in such a worthwhile project. Also, many thanks to my supervisors, Associate professor Hui Tong Chua and Dr Laurence Spencer and mentors Mr Leith Place and Mr Peter Nicolay for their guidance and encouragement throughout the project.

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Abbreviations

FTC	Fuel Technologies Pty. Ltd. FTC-III combustion catalyst
Nemo	Nemo 2001 Fuel Additive marketed by Shell
CN	Cetane Number
EHN	2-Ethyl Hexyl Nitrate
PM	Particulate matter
ID	Ignition Delay
TDC	Top dead centre (when the piston is its highest point in the cylinder)
NO_x	Nitrous oxides emissions (combination of NO and NO_2)
UHC	Unburnt hydrocarbon emissions
CO_2	Carbon dioxide
CO	Carbon Monoxide
ppm	Parts per million
PPS	Power Proving Systems
EPS	Energy Power Systems
PQ index	Particle qualifier index
BSFC	Break specific fuel consumption (kg/kWh)
kWh	kilowatt hour

1 Introduction

Mining operations consume large volumes of diesel fuel in the order of hundreds of millions of litres per year. Thus, reductions of even a few percent in fuel usage translate to considerable economic and environmental savings. Diesel fuel additives are one possible avenue for improving fuel efficiency. There are two main categories of fuel additives, those incorporated during the refining process and aftermarket additives. Aftermarket additives are products purchased by the consumer, to further alter the fuels' performance and are the focus of this report. Aftermarket diesel fuel additives can be divided into four major categories; engine performance, fuel handling, fuel stability and contaminant control (Chevron, 1998). Additives relating to engine performance are considered in this report as they relate more directly to fuel consumption. The report will assess two main types of fuel additives available, combustion catalysts and cetane improvers combined with detergents (multifunctional additives). The additives chosen for this investigation were FTC an ferrous-picrate combustion catalyst and Nemo a multifunctional diesel fuel additive.

Another aspect of fuel performance that has become of particular interest to Pilbara Iron is fuel contamination. Abrasive particles suspended in the fuel can result in increased fuel system wear and thus decrease the performance of an engine over time. The scope of the investigation was increased to diesel filtration at the request of Pilbara Iron. The duration of the testing did not allow for thorough research into diesel filtration options, however the possible short-term performance benefits of increased diesel filtration were examined. The research conducted in this report was limited by time, cost and availability of equipment, therefore some aspects require further investigation. The areas of further research are highlighted by the report so that all the relevant issues are identified before decisions are made in regards to the introduction of fuel additives.

1.1 Aims

The primary aim of this investigation was to determine whether measurable effects could be realised by treating diesel with either of the two chosen fuel additives and/or improved diesel filtration. As secondary indicators of performance, exhaust emissions and exhaust temperatures were measured. The macroscopic performance of the fuel treatments was the focus of this investigation, rather than alterations to the combustion process. The testing procedure and equipment was chosen to produce comparable results to mining machinery and thus providing useful results for the mining industry.

1.2 Background

The project was a collaborative research effort between Pilbara Iron and the University of Western Australia through Cooperative Education for Enterprise (CEED). Pilbara Iron have investigated fuel additives in the past however, further investigations were warranted (see chapter 3). The initial plan was to conduct additive tests in haul trucks on site, Paraburdoo, Western Australia, and conduct laboratory tests in Perth, Western Australia. However, after investigation on site this did not seem feasible for a number of reasons:

1. The nature of the mining operation resulted in trucks changing haul runs frequently.
2. Legal issues became a problem, as Cummins would not cover the cost of any engine repairs if a breakdown was deemed additive related, not to mention the hundreds of thousands of dollars in lost production. The respective additive producers did have insurance cover, however the time to resolve such legal issues was not available.
3. Issues pertaining to dosing requirements needed considerable time to rectify and modify infrastructure.

Therefore, it was decided to design laboratory tests that could be conducted at the University of Western Australia to test the additive performance with industrial equipment. The results of the tests could then be used to develop a case for large-scale site tests if results were positive. These tests were designed to use diesel machinery similar to that on site as there was some resistance to the usefulness of laboratory tests.

In preliminary research, a number of additives were investigated and additive producers contacted. However, it was not possible to test a large number of additives. For this reason two additives that claimed to work via two common but different mechanism were chosen. Investigations at Pilbara Iron had focused on two main fuel additives: FTC and Nemo. After reviewing this information and other available literature, it was decided to conduct tests on these additives for four main reasons:

1. The tests could build on the knowledge already gained at Pilbara Iron
2. Literature was available to support additives' claims
3. There was no reported negative effects of the additives in past tests for Pilbara Iron
4. Availability of the additives were assured

2 Related Theory

The aim of this report is to determine if the chosen treatments produce a measurable effect on fuel consumption. However, it is necessary to introduce some principles of diesel engines to explain how the possible mechanisms of the additives/filtering may work. The following theory will focus mainly on the aspects of a diesel engine, such as ignition timing, fuel quality and engine cleanliness, which can affect efficiency without engine modification.

2.1 Overview of a diesel engine

There are two main types of internal combustion engines: spark ignition (SI), generally known as a petrol engine and compression ignition (CI), known as a diesel engine. Diesel engines can operate on a variety of fuels, however diesel is the most commonly used fuel. Two main types of reciprocating diesel engines exist: two-stroke and four-stoke. The piston undergoes two strokes of the cylinder per power stroke in the former and four strokes in the latter. Diesel engines are often classed as low or high speed. Engine speeds less than eight hundred revolutions per minute (RPM) are usually considered low speed. The engines considered in this report are high-speed diesel engines, as this reflects mining equipment. These high speed diesel engines are predominantly four stroke (Judge, 1967). The cycles involved in operation of a four-stroke diesel engine are depicted in Figure 2-1.

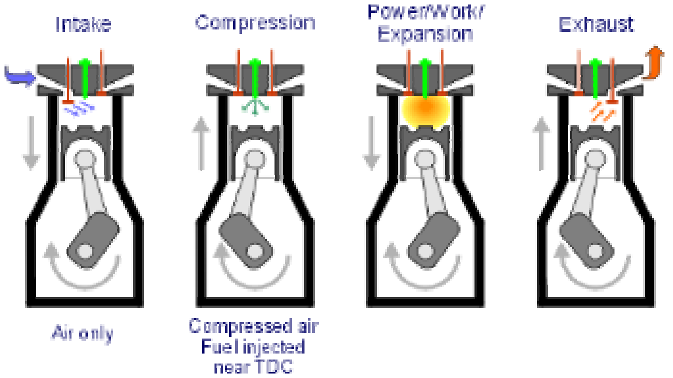

Figure 2-1 The four stages of a four stroke diesel engine.

Adapted from DieselNet diesel engines fundamentals (2001). Note TDC refers to the position at which the piston is at the top of its travel and the connecting rod is dead centre in the cylinder

The main differences between a diesel engine and a petrol engine (SI) are the time at which fuel is introduced into the cylinder, the way in which the fuel enters the cylinder and the initiation of combustion. A diesel engine injects the fuel near the end of the compression stroke, whereas a SI engine introduces the fuel near the start of the compression stroke. Therefore, there is much less time for the fuel to mix with air in a diesel engine and thus the fuel must be injected under high pressure. Furthermore, the diesel engine relies on auto-ignition of the fuel under pressure, where as SI engines require a spark to initiate controlled combustion. There are two common injection methods for diesel engines: indirect injection (IDI) and direction injection (DI). IDI involves diesel being injected into a pre-mixing-chamber before entering the cylinder, whereas the fuel is injected directly into the cylinder in DI. DI usually results in lower fuel consumption however is generally not practical for very high-speed engines (greater that 2500 to 3000 RPM) (Judge, 1967). The engines used in this investigation were DI as those of the Terex haul trucks used on Pilbara Iron sites are DI.

The power output of a diesel engine is limited by fuel that can be effectively burnt within the cylinder, which is limited by the volume of air that can be induced. Boosting the pressure of the air entering the engine, known as supercharging, is common in many modern diesel engines. Supercharging of a diesel engine (generally done via a turbocharger) significantly increases the power output and volumetric efficiency (DieselNet, 2004). The higher thermal efficiency of turbocharged engines results in a lower specific fuel consumption, averaging a 5 per cent reduction at full load and up to 10 to 12 per cent at lower loads (Judge, 1967). Boosting the pressure of the inlet air with a turbocharger causes the air temperature to rise and thus reducing density, for this reason the boosted air is often cooled before entering the cylinder. This process is known as after-cooling (sometimes referred to as inter-cooling). Nearly all engines in large mining and industrial equipment are turbocharged and often after-cooled. For this reason, turbocharged engines were used in the additive and fuel filtering investigation.

2.2 General Diesel combustion theory and Emissions

Two important aspects of diesel engines fundamentals to consider are: diesel engines are throttled by adjusting the air fuel mixture ratio and fuel is injection occurs only a few degrees from TDC. The consequences are dispersion of the fuel is important to ensure a good combustion and there is little time for this dispersion to occur. To achieve this dispersion the fuel is injected at high pressure, via an injector nozzle, allowing the fuel to atomise into fine particles as it enters the cylinder and penetrate into the combustion chamber. In addition, the top of the piston is often designed to enhance turbulent mixing of the fuel and air.

Combustion in a diesel engine initiates from compression of the air fuel mixture in the cylinder. As the piston moves closer towards TDC, the air/fuel mixture reaches its auto-ignition point and combustion commences. The time lag between the start of fuel injection and the start of combustion is referred to as the ignition delay (ID). The combustion of the fuel creates a rise in cylinder pressure that forces the piston to move back towards the bottom of the stroke and thus produces useful work, this process is illustrated by Figure 2-2.

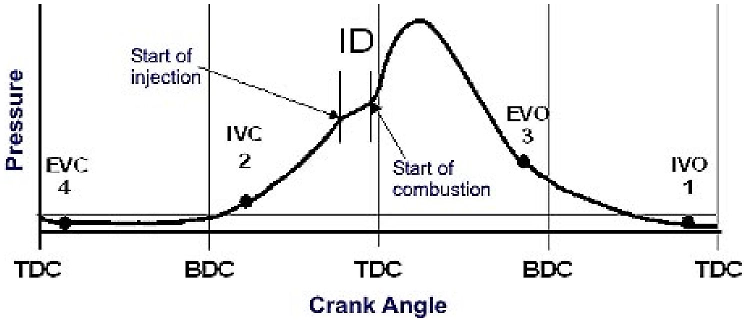

Figure 2-2 Cylinder pressure variation for a 4-stroke diesel engine

EVC-Exhaust valve closes, IVC-inlet valve closes, EVO-exhaust valve opens, IVCO inlet valve opens, ID-ignition delay

During the ID fuel is injected into the cylinder. This fuel has vaporised, mixed to the corrected air-fuel-ratio and is waiting to reach the auto-ignition point for combustion to occur. When auto-ignition commences this fuel rapidly combusts (referred to as pre-mixed combustion) creating a rapid rise in cylinder pressure. As ID increases the volume of fuel that participates in the pre-mixed combustion increases and the greater the rate of heat release and pressure rise. If this rate of pressure rise becomes too excessive, a form of detonation will occur (Judge, 1967). This is known as “Diesel knock”, and can be minimised by reducing the ignition delay through improved fuel properties. However, the ID should not be to greatly reduced, as it reduces combustion efficiency (Judge, 1967). The fuel that does not participate in pre-mixed combustion forms the bulk of the fuel burnt in the cylinder, this is referred to as rate-controlled combustion. A lower heat release peak than that reached in the premixed phase characterises this controlled combustion

(DieselNet, 2001). Figure 2-3 shows the main phases of combustion: ignition delay, premixed and rate controlled (or diffused) combustion.

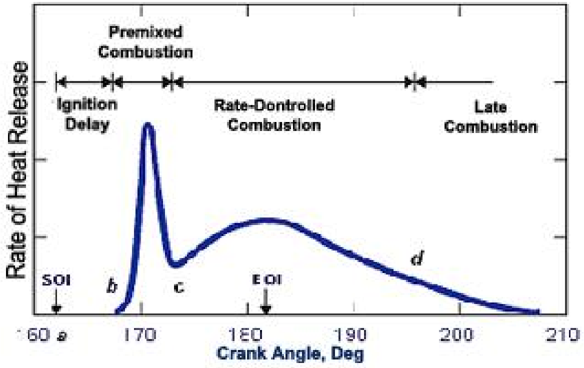

Figure 2-3 The three phases of combustion

Adapted from Combustion in diesel engines (DieselNet, 2001) SOI-start of injection, EOI-end of injection

2.2.1 Exhaust Emissions

Exhaust emissions provide a way of assessing the combustion efficiency of diesel engines. Thus, emissions can be useful in determining additive performance. Emissions should also be checked to ensure these additives do not increase emissions above regulatory standards. Diesel fuel contains a number of different hydrocarbon compounds; however, diesel can be generally represented as C_7H_{13}. If combustion within a diesel engine were perfect, only water and carbon dioxide would be formed, with excess oxygen and nitrogen from unused air. However, in practice complete combustion does not occur and intermediate compounds form. These intermediate compounds are usually a result of insufficient oxygen or temperature in regions of combustion. The main products of incomplete combustion are: carbon monoxide (CO), unburnt or particularly burnt hydrocarbons (UHC), particulate matter (PM) and nitrogen oxides (NO_x).

CO is formed from a lack of oxidants and insufficient temperature. Hence, CO generally occurs in fuel rich regions of the cylinder rich and is therefore present at low concentrations in diesel engines (DieselNet, 2002). Incomplete combustion produces partly decomposed hydrocarbons in the exhaust. The main sources of UHC in direction injection diesel engines can be traced to incorrect mixing of fuel and air, and large fuel droplet sizes at the end of injection (DieselNet 2002). Oxides of nitrogen mainly result from burning small amounts of nitrogen in the in-take air with oxygen at high combustion chamber temperatures. Formation of NO_x becomes significant when the temperature approximately 1600 deg C and can be accelerated by the existence of combustion chamber deposits (Chevron, 1998). NO_x is most prevalent in pre-mixed combustion and NO_x reduction methods act on this early stage of combustion. Unfortunately, these methods generally reduce combustion temperatures and consequently have negative effects of UHC, PM and fuel consumption (DieselNet, 2002). However, increasing the cetane value of a fuel reduces the ID and consequently the NO_x formation (DieselNet, 2002). The black smoke from a diesel engine, known as PM, is formed from over rich or lean combustion and other particles such as dirt or wear metals in the combustion chamber (DieselNet, 2002). PM emissions increase with applied load due to richer conditions (Judge, 1967).

The proportion of the various emissions are dependant on a number of factors (Judge,1976) and discussions of detailed formation are beyond the scope of this report. However, various additive suppliers claim their products reduce certain emissions as they relate to combustion efficiency, although somewhat indirectly. The reported emissions reductions from the various additive technologies are discussed in section 2.5.

2.3 Diesel Fuels

Engine design has the greatest impact on engine performance, however fuel properties can also effect engine performance. The effect of fuel properties on engine power, noise, fuel economy, wear, filter life and emissions are discussed briefly.

Engine Power

Diesel engines are rated by the break power developed at the smoke limit (from regulatory standards). Varying fuel properties within ASTM D 975 standard has little effect on the engine power. However, a loss of power and poor fuel economy may result if the viscosity is outside the recommended range (Chevron, 1998)

Noise

Combustion noise is related to the pre-combustion heat release peak shown in Figure 2-3. The load noise created due to this rapid heat release is known as diesel knock (Judge, 1976). Increasing the cetane value, also known as cetane number[*] of the fuel reduces the ignition delay and hence reduces engine noise (DieselNet, 2002).

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[*] The cetane value of diesel fuel is a measure of it's readiness to combust. A fuel with a high cetane number is characterized by a short ignition delay period (DieselNet, 2002)

Fuel Economy

Fuel economy is related to the heating value (calorific value) of the fuel. Heating value is directly proportional to fuel density when all other properties remain constant (Chevron, 1998). Thus, fuels with lower densities will provide poorer fuel economy. Treating the fuel with aftermarket fuel additives may also have a positive effect on fuel consumption and is the main focus of this report.

Wear

Lubricity, cleanliness and acidity of the fuel are also important properties in regard to wear. Diesel fuels must provide sufficient hydrodynamic and boundary lubrication to prevent excessive surface wear. However, fuels within the ASTM D 975 specification range provide adequate lubrication (Chevron, 1998). If diesel fuel is contaminated with abrasive organic particles it can cause wear to injectors and injector pumps. The most damaging particles for injection systems have been found to 6 to 7 microns in diameter (Chevron, 1998; Judge, 1967). The acidity of the fuel is also another concern for corrosive wear and should be kept within ASTM standards (Chevron, 1998)

Filter Life-fuel stability

Unstable diesel fuels can form soluble gums or insoluble organic particles. These can contribute to injector deposits and fuel filter clogging. The formation of these gums and particles can arise from long-term storage or thermal instability from recirculated, heated fuel. The latter is the case for most diesel engines, injector systems and thus the thermal stability of fuel is quite important. If the diesel fuel supplies are consumed within a few weeks of manufacture long term stability is not a problem (Chevron, 1998). Fuels stored for long periods, may required microbicidal additives to improve fuel stability (Judge, 1976).

Emissions

Table 2-1 summarises the effect of fuel properties on heavy-duty diesel engines

Table 2-1 Effect of fuel properties on emissions

	HC	CO	NO_x	PM
Reduced Sulfur	0	0	0	↓↓… ⇩[b]
Increased Cetane Number	↓↓… 0[a]	↓↓… 0[a]	↓	0
Reduced Total Aromatics	0	0	↓[c]	0
Reduced Polyaromatics	↓	0	↓[c]	↓↓… 0[a]
Reduced Density	↑↑	↑	↓	↓↓… 0[a]
Reduced T95 (Volatility)	⇧	⇧	⇩	0
Increased Oxygenate*	↑	⇩	0	↓

* - tentative results, require confirmation by future work, a - effect disappears on low emission engines, b - smaller effects are observed with low sulfur levels, c -polyaromatics are expected to give a bigger reduction than mono aromatics

Legend: ↑↑ - large effect; ↑ - small effect; ⇧ - very small effect; 0 - no effect

2.4 Additive Claims

Benefits claimed by the two additives, FTC and Nemo, are listed below[†].

FTC-III	Nemo 2001
Reduces fuel consumption	Counteracts injector fouling
Reduces air pollution	Can improve drivability
Lowers maintenance costs	Provides better fuel consumption
Increases engine efficiency	Reduces exhaust emissions
Acts as a biocide in fuel	Prevents against corrosion
	Will not form haze in wet fuel systems
	Has low foaming- for better tank refilling

2.5 Possible mechanisms for improved combustion via additives

2.5.1 FTC

Combustion catalysts generally contain some type of organo-metallic suspension in an organic solvent. The catalyst used in the testing contains ferrous picrate as the organo-metallic compound. Parsons and Germane (1989) suggest the primary mode of action for ferrous picrate additives is related to a reduction in combustion time. It is claimed that the additive forms flat crystalline particles within the air fuel mixture which act as propagating centres to provide multiple flame fronts and thus promote higher rates of flame propagation. In addition to this increase in combustion sites, the decomposition of the

---

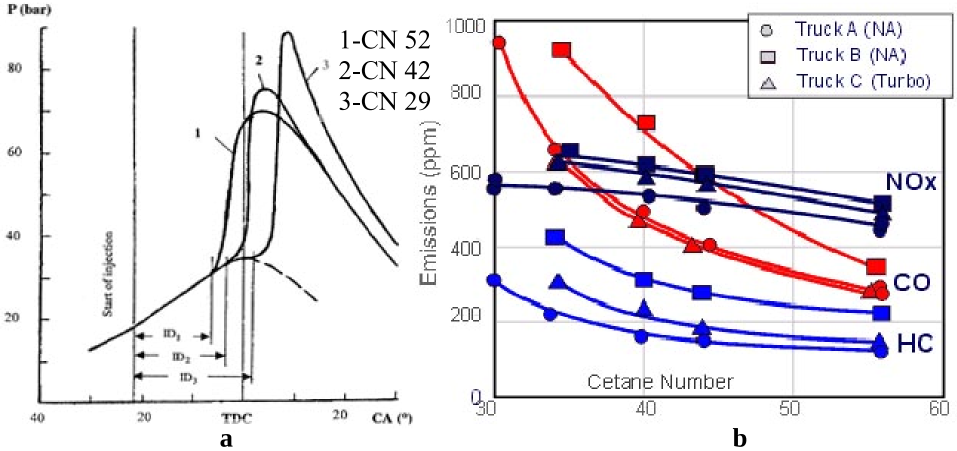
[†] Claimed benefits taken from additive product data sheets

additive provides excess kinetic energy to the local fuel molecules. (Guld 1985). Therefore more fuel combusts when the piston is near the beginning of the power stroke (TDC), thus approaching the ideal cycle (Parsons and Germane,1989). Therefore, providing more a complete and optimally timed combustion is claimed as the overall mode of action of the additive.

FTC has been reported by Millin (2005) of Fuel Technologies Pty. Ltd., to require a conditioning period as the additive is claimed to participate in reactions with carbon build-ups within the engine cylinder before that of combustion Millin (2005). Studies by Parsons and Germane(1989) claim a reduction in hard carbon deposits within the combustion chamber via the alleged improved combustion provide by FTC.

2.5.2 Nemo

Nemo can be referred to as a multifunctional diesel additive as it is designed improve engine performance through more than one mechanism. The additive contains two main components relating to improved fuel consumption; a cetane improver, 2-Ethylhexyl Nitrate (EHN), and a detergent package. The cetane number of diesel fuel is a measure of ignition quality (Chevron 1998). A fuel with a high cetane number is characterized by a short ID period (DieselNet, 2003). Higher cetane numbers are associated with reduced engine noise and reduced PM and NO_x emissions (DieselNet, 2005). Figure 2-4a shows that reducing the ID reduces the height of the pre-combustion-pressure-peak and thus reduces engine noise, as explained previously in section 2.2. A shorter ID may be considered a chemical advance in ignition timing. Authors such as Judge (1967) and DieselNet (2002, 2003) reported that more advanced ignition is favourable for fuel economy. It should be noted however, that advancing the ignition too far can reduce combustion efficiency (Judge, 1967). Heywood (1988) and Guld (1985) state that engines are often designed with ignition timing more retarded than optimal in order to reduce NO_x emissions. However, higher cetane fuels can be used to reduce NO_x emissions without compromising fuel consumption (Garling et al., 1995). As previously explained there is much literature on the benefits of higher cetane fuels in reducing emissions. Figure 2-4b depicts the effect of increasing diesel cetane number on tailpipe emissions.

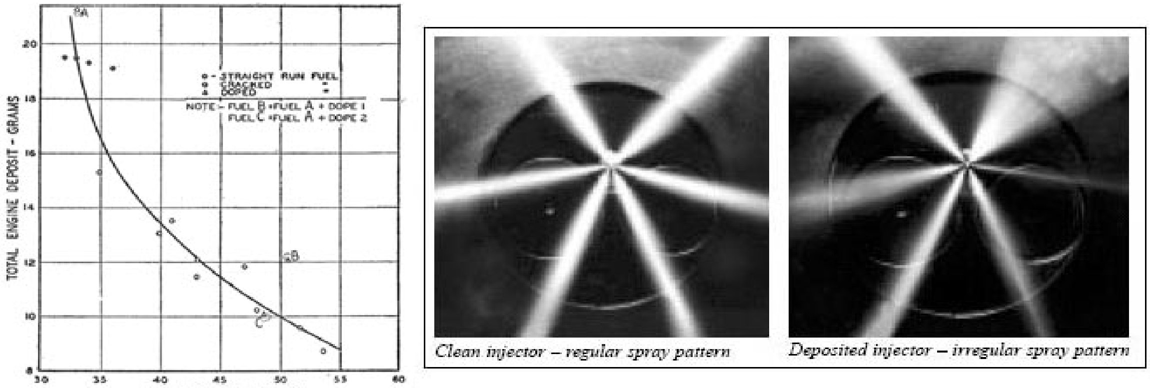


a **b**

Figure 2-4 The effect of cetane number

a) the effect on cetane number (CN) in pre-combustion pressure rise reproduced from İçingür and Altiparmak (2003), b) the effect of CN on tailpipe emissions reproduced from (DieselNet, 2002)

Another quality of increasing the cetane number of diesel fuel is related to injector fouling. A definite relationship exists between the fuel cetane number and the formation of injector deposits (Judge, 1976), see Figure 2-5a. The other reported characteristic of Nemo relating to fuel economy is the detergent package. Detergents play two major roles: keeping fuel injectors clean to maintain optimum fuel atomisation and decreasing the surface tension of droplets during the injection process to enable fine atomisation (White 2005). Figure 2-5b shows the effect of a dirty injector on fuel spray formation. It is quite conceivable that uneven injection may sufficiently affect the air/fuel ratio throughout the cylinder causing the mixture to be too lean in some areas and too rich in others. This will lead to incomplete combustion in those affected areas and thus produce undesirable emissions and an increase in fuel consumption. Cleaning effects of additives have been reported to provide fuel savings of around 3% (Garling et al.1995).



a **b**

Figure 2-5 The effect of cetane number on injector deposits

a) Injector deposit formation with cetane number, reproduced from (Judge, 1976), b) Injector spray patter for a clean injector compared with a dirty injector, adapted from (Chevron, 1998)

2.5.3 Filtered Diesel

Filtering diesel can reduce injector wear by removing a higher percentage of abrasive particles. The existence of abrasive particles in the fuel is of serious concern, as these particles can damage injectors and injector pumps and thus reduce the efficiency of these elements (Judge, 1976). It is quite conceivable that excessively worn injectors and injector pumps would result in a loss in injector pressure, resulting in inefficient fuel atomisation and combustion. Filtering the engines fuel supply before it reaches such components may yield significant savings on both fuel and maintenance costs. It may also be possible to improve fuel consumption by removing combustion inhibiting particles from the fuel supply. However, all diesel engines have multiple fuel filtering systems in place and thus the performance of these filters will affect the performance and requirement of additional filtering. Chevron (1998) states that fuel filters recommended by manufactures have a nominal pore size of 10 microns in diameter, while the most damaging particles have been found to be 6 to 7 microns. Stewart Croft (2005) claims the most damaging particles are those of similar size to the clearances they are passing through, and for today's engines that is 2 to 3-microns. Caterpillar® has released a range of 2-micron fuel filters to be used on all their engines (Taylor, 2005). They claim that with high injector pressures in today's engines, injector pumps and injectors are more susceptible to wear. Cat high efficiency fuel filters claim to remove more than 98% of particles 2-microns and larger. In comparison standard filters only capture particles 15-mircons and larger (Caterpillar®, 2003) Some of the claims of Cat high efficiency filters are: maximum engine performance and fuel economy, reduced exposure to abrasives, reduced wear of injectors and pumps and longer filter life.

Diesel contaminated with water is a problem in diesel engine operation (Judge, 1976). Diesel engines are generally equipped with specially designed filters to remove water. Improved water removal through filtration may yield positive results, for both wear and combustion. It should be noted that the performance of any filtering system is going to be dependant on the contamination of the diesel supplied. Moreover, such filter claims are hard to determine in tests conducted over short periods as those in this investigation.

3 Past Research

3.1 Research with in the Rio Tinto group

There has been a considerable amount of additive research conducted by Pilbara Iron and other Rio Tinto business groups. This literature was reviewed at the commencement of the project. The literature for each additive has been treated separately for simplicity. Note, that the following is only a brief account of the available literature from Rio Tinto as much of the information is confidential.

3.1.1.1 FTC

Fuel consumption tests were carried out on Unit Rig 4000 series haul trucks at Tom Price by Fuel Technology Pty Ltd in 1998. The tests were conducted in static conditioning with the trucks resistive braking elements providing the engine load. The results of these tests show a 6.2% fuel saving at 40% load and a 3.4% saving at 97% load using FTC treated diesel (Fuel Technology Pty Ltd, 1998). It should be noted that these tests only measured fuel consumption at a specific load for 1 hour and the baseline tests were conducted during warmer ambient temperatures that the treated tests. Thus some of the fuel saving could possibly relate to changes in environmental conditions. Note also that the baseline and treated tests were conducted roughly two weeks apart to allow for conditioning of the additive.

Fuel Technology Pty. Ltd. conducted another test on haul trucks in the field at Marandoo using a set 2.2km course with the fuel measured for 11 runs of both treated and non treated trial. Three 4000 series Unit Rig haul trucks were used with one of the trucks being a control variable. An average reduction in fuel consumption of 5.5% in one truck and 3.7% in the other. However, the signal to noise ratio of these results was quite high, for example, the overall standard deviation for latter test was approximately 4.8% for an average 3.7% saving. A 35% reduction in particulate matter was also found. (Fuel Technology Pty Ltd, 2003)

A 12 month trial of FTC fuel additive showed significant efficiency gains at Torong Coal. By comparing the tones shifted per litre of fuel for a 12 month diesel treated period

(November 2002 to October 2003) compared with the previous 12 month period; an efficiency gain of 8.3% was found during the treated diesel 12 month period. (Walker, 2003). These results seem tentative as the fuel consumption is only compared with tones shifted and this increased from one year to the next. Questions arise on how accurately the fuel consumption is actually measured. Furthermore, a change in a haul run or area a shovel is digging in can change the fuel usage/tone produced. That said, this method of assessing fuel consumption does average out a number of variables and if careful monitoring of fuel usage of individual truck performance was conducted to remove outliers, it could be quite useful. The field trials of FTC on Rio Tinto sites appears positive, however the magnitude of inherent error in such field measurements is of some concern.

3.1.1.2 Nemo

Pilbara Iron contracted Vipac Engineers and Scientists to conducted a fuel consumption and emissions tests on Nemo. The tests were conducted on a 6000W Coat Hire lighting tower powered by a 1.4L, 4 cylinder, Kubota engine. Through the investigation a small increase in fuel consumption was found using the Nemo fuel additive. Furthermore, there was a reduction in hydrocarbon emissions and an increase in particle emissions as observed in other studies (İçingür and Altiparmak ,2003) and (Ladommatos, Parsi & Knowles, 1996). The engine used for the trial was reported as 1600hrs old and the loading applied by the lights was around 56%. Thus, these tests were conducted at low load on a relatively new engine. Furthermore fuel injection system on the engine was indirect injection and therefore dissimilar to that of most mining equipment.

3.2 Literature external to Rio Tinto

3.2.1 FTC (combustion catalyst/flame atomiser)

The literature assesses a number of different organo-metals for use as diesel fuel additives. Of these, iron in the form of ferrocene or ferrous-picrate seem the most common.

The Southwest Research Institute conducted an evaluation of a ferrous picrate fuel additive. The investigation found a reduction in fuel consumption of approximately 1.74% on a new 12- cylinder engine in a static test (Markworth, 2002). Furthermore, the effects of the additive were seen to increase with time until approximately 130hrs and thus supporting the notion of a required conditioning time (Markworth, 2002) (shown in Figure 3-1). In contrast to the results of Zeller and Westphal (1992) the study found a decrease in UHC and CO with a slight increase in NO_x emissions.

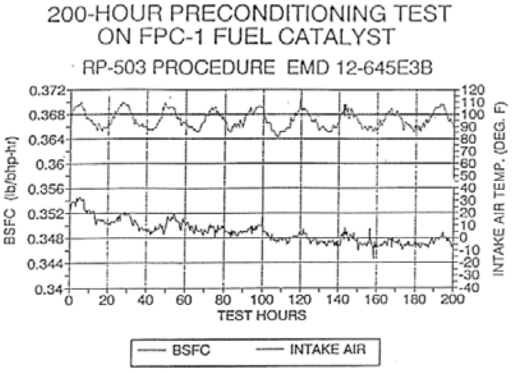


Figure 3-1 Conditioning period of ferrous-picrate catalyst, reproduced from Markworth 1992)

Iron based fuel additives were investigated for their effectiveness on emissions for diesel soot control (Zeller and Westphal, 1992). The report tested two different additives one based on ferrous picrate (the active ingredient in FTC) and a ferrocene based additive. The ferrocene additive was found to reduce particle, hydrocarbon and oxygen emissions however, increase $C0_2$ and NO_x emissions. The ferrous picrate additive was found to have no effect on diesel particulate emissions even at 10 times the recommended concentration and thus tests were abandoned. Unfortunately, Zeller and Westphal (1992) did not record fuel consumption. It is unclear whether Zeller and Westphal allowed a sufficient conditioning period for the ferrous picrate additive.

A report from the Society of Automotive Engines found significant performance savings through use of a ferrous-picrate combustion catalyst (Parsons and Germane,1989). The paper details fuel savings of 2.1% for a vehicle which had been run with the additive since new (baselines were taken with standard diesel) and a 7.35% saving for a vehicle that had not. This result may suggest that a saving of around 2% is derived from improved combustion efficiency and 5% from engine cleaning. Parsons and Germane (1989) reported three separate site base trials found a reduction in hard carbon deposits in the combustion chamber in as little as 10 weeks of operation with the additive. Moreover, continued use of the additive depleted pre-existing hard carbon build-ups so that only soft carbon was left. This soft carbon could simply be wiped away with a rag (Parsons and Germane,1989).

Investigations by Guld (1985) at the Western Australia Institute of Technology found reductions in fuel consumption and increases in engine power in all tests with a ferrous picrate combustion catalyst. The tests were conducted at a variety of concentration rates on a Varimax variable compression engine. These results seem to support the additive claims however, Guld (1985) found exhaust temperatures increased with the additive concentration, which are in contrast to the latest findings of Millin (2005) and Garling et al. (1995)*.

3.2.2 Nemo (Multifunctional diesel additives and cetane improvers)

Nemo is marketed as a multifunctional diesel additive as explained in Related Theory, section. For this reason literature pertaining to cetane boosting additives as well as general multifunctional diesel additive is discussed. İçingür and Altiparmak (2003) studied the effect of different diesel cetane numbers on emissions and performance of a DI diesel engine. They found that increasing the cetane number (CN) from 46 to 61 reduced NO_x and Sulphur dioxide (SO_2) emissions. This reduction can be attributed to the fact that increasing CN reduces the ignition delay, and hence improves combustion (İçingür and Altiparmak, 2003). However, the report references Taylor (1989) who states that by improving CN excessively above normal the ignition delay will be too short for the fuel to completely atomise. As a result, engine performance will decrease and the smoke value with increase. $C0_2$ emissions were seen to decrease for some engine speeds and increase for others while smoke emissions increased with increasing CN. Engine torque and power were seen to improve by about 5% and 4% respectively with increasing CN from 46 to 54.4. The specific fuel consumption is stated to be decreased by increasing the CN, however no figures are given (İçingür and Altiparmak, 2003). The report stated that increasing CN from 51 to 61.5 was insignificant for engine performance.

The results of Ladommatos et al., (1996) seem to agree with that of İçingür and Altiparmak (2003). NO_x reductions were significant for increases of CN up to approximately 50-53 with fixed injection timing. UHC were also found to decrease with increasing CN and

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[*] The research by Garling et. al (1995) was conducted on a multifunctional diesel additive, not a combustion catalyst.

smoke emissions increased. Ladommatos et al., (1996) attribute the decreased NO_x and UHC to the reduction in ignition delay and amount of premixed fuel burnt. The report covers effects of CN on engine emissions, although does not consider specific fuel consumption. The researchers used a cetane improver based on 2-ethylhexyl nitrate (EHN) for there research which is the main ingredient of Nemo (Ladommatos et al., 1996). Gürü et al. (2002) studied the effect of increasing the CN of diesel fuel with manganese additives. They found by increasing the CN from 46.22 to 48.24 decreased exhaust temperatures, O_2 and CO by 0.9, 0.2% and 14.3% respectively[†]. While CO_2 emissions increased by 7.4%. It should be noted however, that the manganese additive decreased the flash point of the fuel by 3° C and the effect of the flash point on emissions compared with cetane is not known.

Many modern fuel additives appear to be based on CN increasing chemicals and injector cleanliness detergents. A report by Garling et al., (1995) states fuel savings of around 3% which have be attributed to improved injector cleanliness on older engines and 2.2% from a standard CN increase. The report by Garling et al, (1995) is not drawn from any one specific trial, instead the data is taken from a number of fleet trials.

3.3 Filtered Diesel

Austin and Goodridge (1952) studied the wear of fuel injection system by various sized particles in detail. Alumina of different sizes, from 2-micron to 12.5-microns, at different concentrations was used to asses the wear of injector pumps and fuel injectors. The results found that:

- Scratch depth was independent of particle size
- Wear depends on total quantity of abrasive not concentration
- Particles of any given size cease to scratch when the total clearance (injector barrel clearance plus worn depth) becomes greater than the particle diameter.

The study found pump plunger and barrel wear was evident with even the small particles sizes (2 and 3 ¼ -micron). The study went on to examine the transmission of different filter types available however, this information is probably less relevant for this investigation and today filters. The work of Austin and Goodridge (1952) highlights the importance of diesel filtration for fuel system life.

[†] Percentage decrease using the absolute temperature scale (deg K)

4 Experimental Methods

4.1 Testing Framework

Laboratory tests at the University of Western Australia Shenton Park Eastern Laboratories were conducted to asses the performance of the two additives chosen, FTC and Nemo, and filtered diesel. These tests used diesel generators coupled to resistive load banks. The first phase of testing was conducted on near new, originally less than 1300hrs, engines. Following this, a second phase of testing with older engines, in excess of 5500hrs[*], were conducted to test possible cleaning effects of the additives on engine performance. Each test comprised of two generators of the same make and model with similar run hours. One of the generators was operated as a control variable to remove environmental effects and variations in fuel quality

Both generators ran for eight hours at 50%, 75% and 100% load on standard diesel to form a baseline. Additive was then introduced into one of the engines while the other continued to be supplied with untreated diesel. A conditioning period was undertaken to allow the additive to integrate into the system. The conditioning period was approximately forty-eight hours, however this was extended to one hundred and twenty hours for FTC. The duration of this conditioning period was based on results from available literature and discussions with the additive suppliers.[†] In the case of Nemo this period was mostly to allow for the action of detergents, where as FTC was reported by Millin (2005) to require time for the additive to remove carbon build-up as the catalyst has a strong affiliation for carbon. Following this conditioning period tests were conducted at the same loads as the baselines with the treated diesel in one engine. This process was repeated for each additive, however a new set of baselines was established for testing of the second additive. These methods were identical for the filtered diesel except no conditioning period was necessary for the filtered diesel.

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[*] The two newer generators A and B were delivered with roughly 1300 and 600 hours respectively and the older generators had 7000 and 5500 hours respectively

[†] Additive suppliers recommended an initial dose of double the normal additive concentration. In light of this advice for the first half of the conditioning period the additive dose was doubled.

4.1.1 Testing Schematic

The flow diagram below (Figure 4-1) depicts the framework used for testing each additive. Note testing followed this framework for both new and old generators on each additive with the following alterations:

- The control variable remains as generator 'B' throughout the testing on the new engines. However, is reversed for each additive for the old generators. This is to allow each additive to act on an "uncleaned" engine.
- The maximum load on the older generators was reduced to 90%, furthermore this load was run first on the old engines to allow any cleaning effects of high load to be removed.

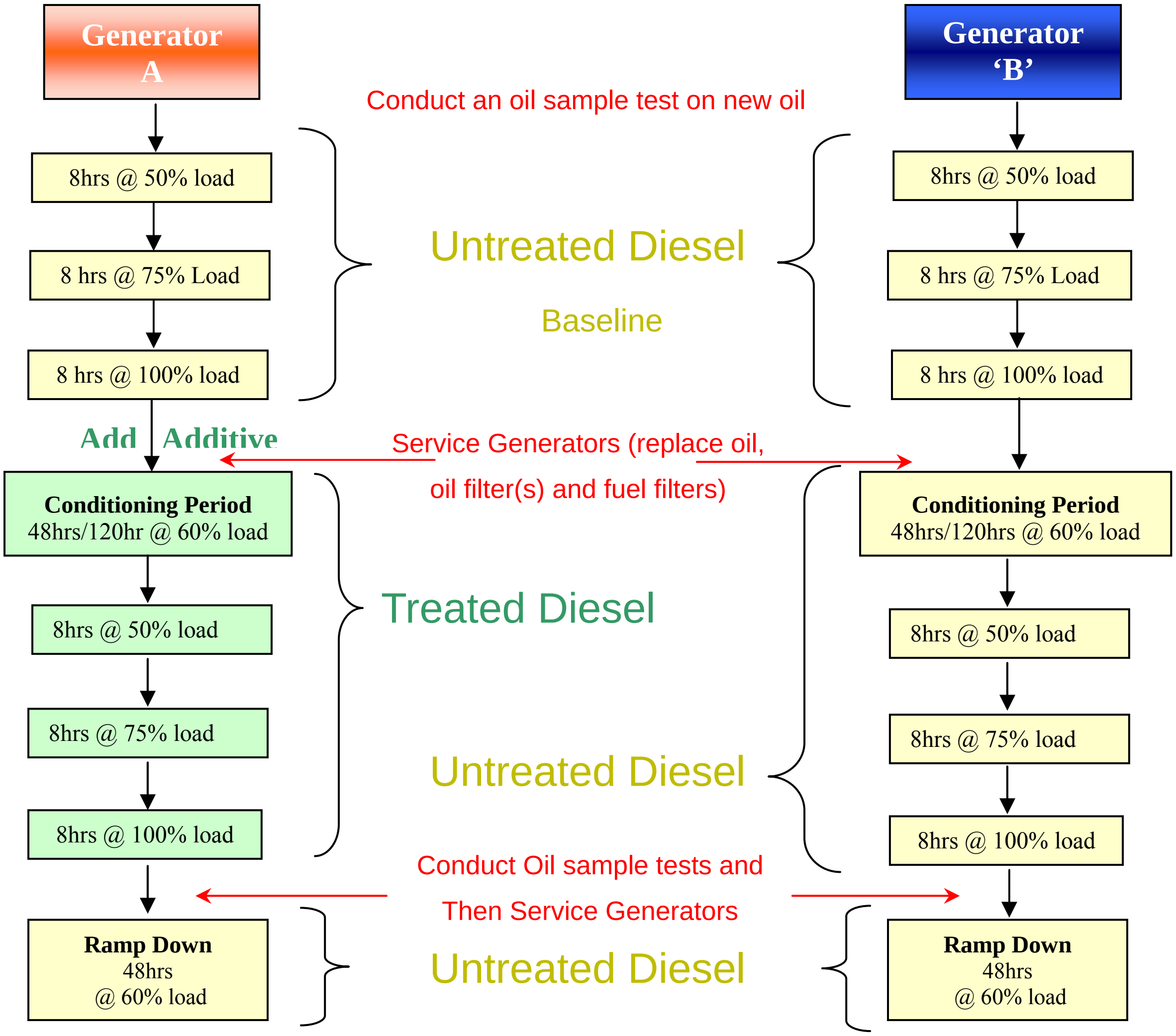

Figure 4-1 Testing Flow Chart (per additive)

The following framework outlines the testing procedure undertaken for the filtered diesel tests. The methodology used was similar to that of the additive testing however, there was no need for a conditioning period as a one-micron filter was connected directly into the fuel line. Fuel samples before and after filtering the diesel were taken to asses the performance and usefulness of filtering the diesel to one micron. The same fuel was used throughout the filtered diesel test apart from the 100% load filtered test.[‡] For this reason a fuel sample was collected from the control generator so that an unfiltered sample of diesel could be compared to a filtered sample at 100% load of same fuel

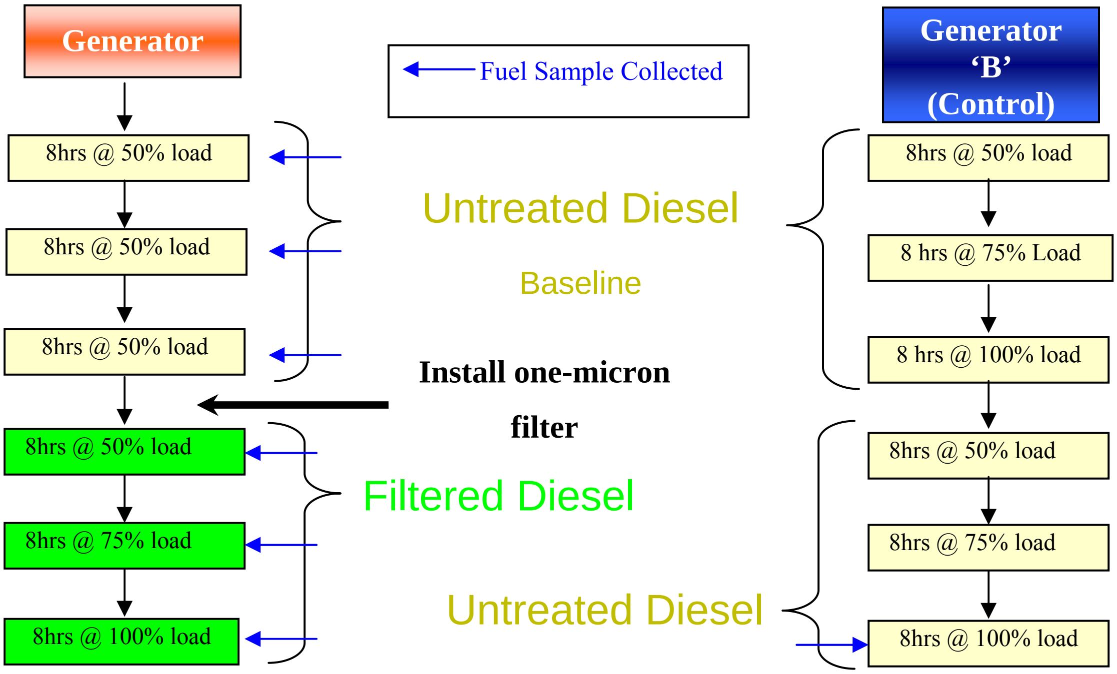

Figure 4-2 Filtered diesel testing framework

The following schematic indicates the overall path of the testing conducted.[§] Each test had an associated baseline so that any permanent changes to engine performance from cleaning for example of one additive would not effect the result of the next additive to be tested. It was found, however, with the new generators no residual affects of the additives were observed. Thus, the existence multiple baselines were not necessary for the new generators.

[‡] The volume of fuel in the generators tanks was not sufficient to complete all the testing. The initial fuel mix at the start of the filtered diesel tests was ~150L of fuel #8 + 400L of fuel #9. At the commencement of the 100% test the fuel level of the original mixture was approximately 150L and ~200L of fuel #9 was added.

[§] Note this schematic does not include repeated tests performed due to equipment failure as only the reliable tests are presented in the results.

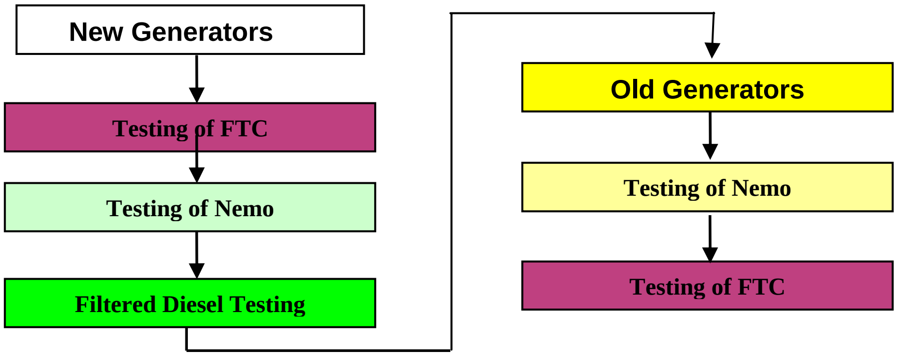

Figure 4-3 Overall testing flow chart

4.2 Experimental Set-up

4.2.1 Equipment

In addition to the generators and load banks, a significant amount of equipment was required for monitoring additive performance. A schematic of the equipment used is shown in Figure 4-4.

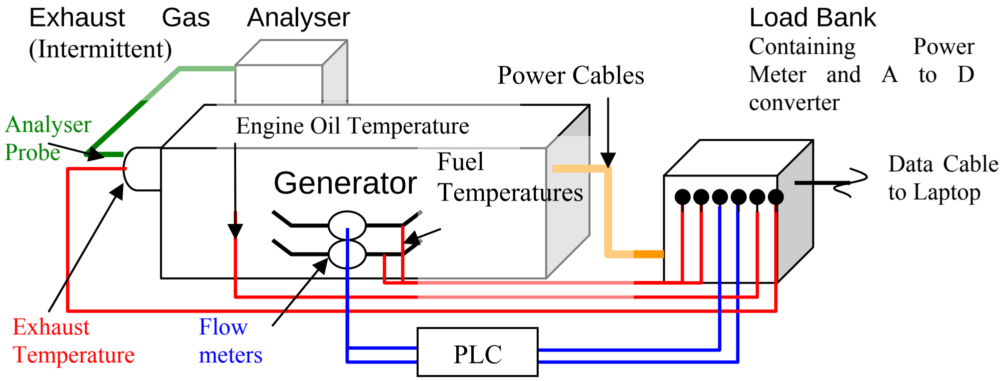

Figure 4-4 Schematic of Equipment

Note two generators and two load banks were used

The following is a brief overview of the equipment used and the relevant function of the different equipment. The Equipment Specifications appendix contains further equipment details. As mentioned earlier, generators were used to evaluate the performance of the additives. The major reason being, generators can be readily hired and provide a convenient way of placing a load on the engine. Resistive load banks capable of supplying up to 600kW in 1kW increments provide the loading for the generators. The first phase of testing used 75kVA Cat Rental generators from Energy Power Systems, and the second phases utilised 100kVA generators also from Energy Power Systems.

Mac Naught M05 positive displacement flow meters measured the inlet and outlet fuel flows (shown in Figure 4-5a). The flow meters provided a pulse output with each pulse represent a certain volume of fuel. The pulse output of the flow meters were analysed on an oscilloscope to check the requirements of the data recording equipment. A program logic controller (PLC) received the output pulses from the flow meters. The PLC then sent a pulse signal to the power meter for every ten flow meter counts. The circuit limits the definition of the flow readings to approximately 6.5mL. However, this method insures all flow pulses are counted reliably, as the PLC is capable of higher pulse detection rates than the power meters. The error created by this recording method is insignificant to the accuracy of the flow meters.

Thermocouples were located in the inlet and outlet fuel lines to calculate the correct fuel density with respect to fuel temperature (Figure 4-5a). Thermocouples were mounted into the sump (Figure 4-5c) and exhaust (after the turbocharger, Figure 4-5b) on each engine. A portable, Landcom series III, exhaust gas analyser was used to measure gaseous tail pipe emissions and a Bosch smoke test unit measured exhaust PM. These units were not designed for continuous monitoring and thus measurements had to be taken by hand.

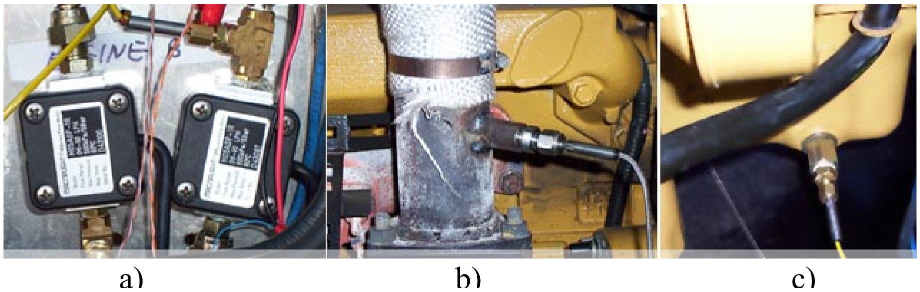
a) b) c)

Figure 4-5 Images of flow meters and thermocouple probes as mounted

a) flow meters and thermocouples attached in line via t-pieces, b) exhaust temperature sensor, c) engine oil temperature sensor

4.2.2 Variables Recorded

The equipment detailed measured a number of variables. Some of these variables were measured directly for assessment of the fuel additives, while others to confirm reliability of the data. The following is a list of the measured variables:

Variables for additive assessment

- Inlet and outlet fuel flow rates
- Inlet and outlet fuel temperatures

- Engine and exhaust temperatures
- Energy produced (kWh's)
- Engine load
- Exhaust emissions (CO, SO_2, NO_2, NO, UHC, H_2S, CO_2, excess air), PM
- Oil samples and fuel samples (for filtered diesel tests)

Variables to confirm data reliability

- Ambient temperature and humidity
- Fuel samples
- Power output characteristics (frequency, voltage, current)

4.2.3 Fuel Storage, Additive Treatment and Filtered Diesel

The first phase of testing used 75kVA generators equipped with approximately 600L fuel tanks. Thus, refilling of diesel was required every 24 to 48 hours depending on applied load.[**] Refilling was conducted with the aid of an electric fuel pump and associated fuel transfer hose from a fuel storage area. This fuel storage area was located inside a secured building for environmental and security reasons. This fuel storage comprised of ten 205L fuel drums located within a bunded area in accordance with health and safety regulations (see Figure 4-6).

Figure 4-6 Bunded Fuel Storage Area

It was rather difficult to source two commercially available generators of the same make and model in excess of 5000 hours. Two such generators of 100kVA were located, however, the fuel tank capacity was approximately 240L. This meant the generators needed to be refilled every 5 to 10 hours, which was not practical. To overcome this problem,

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[**] In general the fuel level should not be allowed to become too low as some engines require fuel circulation for fuel injector cooling. This was less of a problem as Perkins engines were used which do not return large volumes of fuel from the injector rail, however this concern was still taken into consideration. If Cummins engines are used in similar tests, the experimentalist should be especially mindful of this.

external fuel tanks were connected to the generators to increase the time between required re-fuelling.

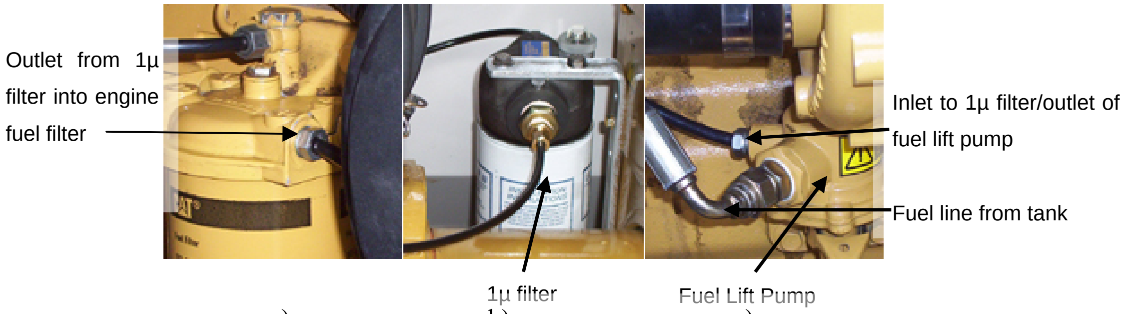
Figure 4-7 Picture of an external fuel tank connected

To ensure adequate mixing of the additive within the fuel, the additives were introduced into the fuel during refilling so that the turbulence created would assist the dispersion process. Nemo was supplied by A S Harrison Pty. Ltd. in two one-litre containers. The volume of additive to be added to the fuel was determined to be 350 mL/1000 L of diesel, from the manufactures specifications. Fuel Technology Pty. Ltd provided FTC in pre-measured containers to treat each 205L drum at a dose rate of 313 ml/1000 L of diesel (1 L/3200 L)[††]

Filtered diesel tests were conducted using an inline one-micron filter. This method was chosen over the bulk filtering of diesel as contaminates in the generator fuel tank may affect the result. The filter needed to be installed on the pressure side of the fuel lift pump and thus the fuel lines had to be altered to accommodate the filter (see

Figure **4-8**).

[††] The treatment rates stated are standard maintenance dosing rates. These dosage rates were used for testing, however the dosage rates were doubled for the first half of conditioning as a cleaning dose.



a) b) c)

Figure 4-8 Connection of one-micron (1μ) filter

a) filter outlet connection to secondary fuel filter, b) 1μ filter connected and mounted, c) filter inlet connected to the outlet of the diesel lift pump

4.2.4 Fuel and oil sampling

The storage requirements prevented all the fuel from being purchased in one batch. Changes to the fuel density and heating value can considerably affect the fuel consumption. As explained a control generator was used to remove these variables, however, fuel samples from each different batches of delivered fuel were taken. These samples were then analysed for density and heating value to determine the variation in these values.

For the filtered diesel testing the quality, or more precisely the particle and water content, of the diesel was a under question. Samples of the diesel before and after filtering were taken to ascertain the affect of the additional one-micron filter and whether it was necessary. The fuel was collected in 100 mL sample containers (provided by Komatsu) from the outlet of the return fuel line. The generators contained a remote tank option via two way valves and hence, samples could be taken from the remove tank return line. Four to five hundred mL of fuel was allowed to flow through the line before collection to flush the system before sampling.

Oil samples were taken for analysis of any negative affects of the additives on engine wear or oil properties. The nature of the testing limited the period of time the oil was exposed to the additives and thus long-term effects could not be tested. Samples were taken with and without additive however, to check any for any dramatic effects of the additives, especially from engine cleaning.

4.2.5 Data Capture

The power meters (contained within the load banks) shown in Figure 4-4 recorded all the measured data. This data could then be down-loaded or viewed in real time on the laptop computer. Data points were logged in fifteen-minute intervals. The flow meter counts were collated for this period and then converted to a value of litres at the end of fifteen minutes. Each temperature reading was recorded every one hundred seconds and the values were averaged over the fifteen-minute period.

4.2.6 Tail Pipe Emissions Recording

Tail pipe emissions were recorded to examine changes in exhaust emissions with fuel treatment and whether relationships between exhaust emissions and fuel consumption from the treatments existed. It was necessary to construct a T-piece that would fit into the exhaust tail pipe to measure gases with the Landcom III exhaust gas analyser. Before the measurement of emissions five to ten minutes was allowed for any residue in this T-piece to disintegrate. Tail pipe emissions were taken at least three times for each test, with the system purged between each reading. Approximately five minutes was allocated for the emissions to settle before recording each reading. Furthermore, emissions were taken at least one hour after the application of the required engine load to allow the engine to reach steady state. Bosch smoke tests did not require this T-piece and could be taken by directly placing the probe in the tail pipe. Two Bosch smoke patches were taken for analysis as any loose carbon in the exhaust may effect the result. A Bosch darkness meter was used to quantify these patches and thus produce a Bosch smoke number.

5 Project Management

This project was mostly experimental research in nature however, required considerable organisation and management. There was not sufficient space for the project on The University of Western Australia's (UWA) Crawely campus and thus, a suitable site had to be found elsewhere. After consultation with Operations and facilities management, Shenton Park field laboratories were chosen as suitable site for the project. The project also required the hire of equipment from outside companies along with skilled labour from contractors. Therefore, coordination of numerous contractors was required for the successful completion of the project. The following is a brief account of the management and organisation required.

5.1 Funding Proposals

The initial project funding allowed for a small laboratory test to re-enforce site testing. Thus, there was not sufficient funding approved for the laboratory testing that eventuated. To overcome this problem a testing plan was presented in detail, with cost estimates of the equipment, fuel testing and fuel required. The funding proposal was drafted in consultation with the project mentors, Leith Place and Peter Nicolay. After discussions with many suppliers, it was decided to hire an equipment package from Power Proving Services so that the one supplier could guarantee the installation of the required equipment. This option was chosen as there was a great deal of ancillary equipment that needed to be mounted to the generators. This decision proved to be invaluable as faulty equipment (from other suppliers/manufactures) caused many project delays.

5.2 Organization of a University site for Laboratory tests

To utilize the UWA Shenton Park facility, it was necessary to consult Mr. Gerald Stack (manager of operations and maintenance), Mr. Michael Bair (manager of the Shenton Park field station), Mr. Jeff Davis (chemical and fire safety officer) and Mr. Grant Wallace (Insurance and risk management officer). With the help of these individuals a specific site was agreed upon and the necessary arrangements such as clearing of space and the provision of keys were conducted. A health and safety document was written and submitted to Mr. Jeff Davis, and the required site modification such as a fuel storage bund were organized.

5.3 Changes to initial experimental plan

An initial project framework was drafted for an application was made for funding. This application contained planed experimental methods, however the variation in the data arising from the research was quite hard to predict. Thus a number of changes were required to be made to the experimental methods to obtain reliable data. Furthermore, the equipment supplied was not to the original project specification. To combat both obstacles the testing framework was altered so that the testing could be conducted to a higher degree of accuracy with the equipment provided, without excessively increasing the project costs. All such decision were made in consultation with mentors from Pilbara Iron.

5.4 Management of Shenton Park operations

The day to day operations at Shenton Park required the coordination of a number of contractors and suppliers. The following list breaks down some of the required areas of management. To improve coordination and simplify accounting issues many of the required services were procured through Power Proving Services (PPS).

5.4.1 Hire and delivery of equipment

Meetings with PPS were conducted in regard to the equipment to be supplied and organizing delivery. As there were numerous equipment servicing requirements and breakdowns, continued contact was made with PPS to combat these issues. It was also necessary to keep PPS informed of such breakdown so that the project did not incur costs for downtime from faulty equipment.

5.4.2 Fuel storage and Delivery

It was necessary to obtain drums/tanks for fuel storage and for a bunded area to be constructed to meet health and safety regulations. Clean 205 L drums were obtained through the Chemistry department via the help of Mr Jeff Davis and the construction of a fuel storage bund was organized through the UWA maintenance department. In the second phase of testing the generators used did not have sufficient storage capacity for continual operation and thus external fuel tanks were required. The supply and delivery of this equipment was arranged by PPS on request and Pirtek were contracted to supply and install the necessary fuel piping and adaptations.

Health and safety regulations prevented at the required fuel from being supplied in one or two batches and thus organisation of fuel delivery was required frequently. Mini Tankers were originally contracted to supply the fuel. The estimated required volume of fuel had to be ordered at least 24hrs before delivery and arrangements were made to meet the driver on site for each delivery. Throughout the project the cost of the fuel supplied continued to rise even when the diesel price started to reduce and thus in an effort to reduce costs another company, Cooper & Dysart Pty. Ltd were contracted to supply the fuel at a more competitive rate. However, this was only possible after the installation of bulk storage tanks.

5.4.3 Servicing of equipment

The generators were required to be serviced every 250hrs, however for continuity they could not be serviced in the middle of an additive test. Therefore, servicing of the generators had to be carefully planned and EPS (the generator suppliers had to be notified two to three days in advance). PPS were generally contacted and they then arranged the service for the time specified with EPS. There were also a number of breakdowns that required the immediate attention of EPS.[*]

5.4.4 Accounts

It was necessary to record all project expenditure (and keep receipts). A spreadsheet was created to record and itemise all expenditures (see Appendix D). All project expenditures were conducted through the mechanical engineering department and hence original receipts were provided to accounts and copies taken for records. As mentioned many of the services of required contractors were ordered through PPS, which greatly simplified accounting and organisation. PPS also waived procurement fees.

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[*] Westac were contracted by EPS to conduct servicing and repair, however direct contact was also made with Westrac to make sure the correct information was relayed to them.

5.5 Time management and delays incurred

The initial project timeline was planned using a Gantt chart. This Gantt chart was updated at intervals throughout the project. The original start date for the testing was around the middle of May 2005 and testing was scheduled to be finished by middle of June 2005. However, many delays, breakdowns and additions to the scope of the project delayed this start date and greatly delayed the finish date.

5.6 Budget

The budgeting for the project was conducted in the project cost proposal. All aspects of equipment hire and oil sampling was taken into consideration. However, a number of unforeseeable occurrences meant the budget needed extending. The major changes to the budget pertained to diesel and equipment hire. Failure of equipment, the need for two generators per test and noise complaints increased the required hire period and fuel consumed. The testing could have been terminated after the new generators to keep within budget. However, Pilbara Iron conveyed the importance of the tests and thus the testing was continued as planned in spite of additional costs. The increased fuel and equipment costs are briefly discussed below (a more in-depth account is given in another document for Pilbara Iron).

5.6.1 Hire Costs

5.6.1.1 Breakdowns

As the majority of the equipment was hired through PPS the additional hire time was not charged to the project. Therefore, the downtime of approximately 30days due to faulty flow meters did not result in a great deal of additional hire costs. However, problems with flow meters resulted in large volume of fuel being consumed while results could not be used. Some additional hire costs were incurred from the hire of the exhaust monitoring unit. The use of Generator ‘A’ as a control variable in each test did not double the hire period however did add some addition hire to the budget (this additional hire was pre-approved by Pilbara Iron). PPS charged only for the time that tests required and thus not including any breakdowns or additional running due to breakdowns corrupting data.

5.6.1.2 Additional hire from noise complaints

In an effort to keep hire costs as low as possible tests were conducted 24 hours a day where possible. Unfortunately, noise complaints from local residences were encountered. Noise levels were measured at the Shenton Park laboratories and extrapolated to the distance of the nearest residences soon after equipment installation. The results found the noise levels to be within acceptable limits however, the margin of error was small. The development of temperature inversion layers could have caused noise levels to rise. After discussions with the local council it was agreed to turn the generators off between the hours of 10pm and 7am. This was done to prevent stricter regulations being enforced if levels were too high. The increased testing period due to the restricted run hours considerably increased hire costs. After completion of the first set of tests, noise mitigation strategies were employed to allow continuous running. Noise complaints continued, however the noise production was deemed to be within limits thus testing continued. Testing was conducted as quickly as possible to minimise resident concerns.

5.6.2 **Fuel Costs**

The required funding for diesel increased significantly from the original proposal for a number of reasons:

1. The cost of diesel increased around 30 c/L between the original budget and testing (the possibility of fuel price increases was remarked in the proposal)
2. The project was not eligible for the off-road diesel rebate as previously budgeted for (however this possibility was also noted in the funding proposal)
3. Breakdowns due to the flow meters, overheating problems and engine warming alarms resulted in tests having to be repeated.
4. 60kVA generators could not be sourced of an identical make and model thus 75kVA and 100kVA units had to be used and thus increased the fuel consumption
5. A decision was made in agreement with mentors and supervisors to run the project with four generators rather than two.

6 Results

The following results detail the effects of the two diesel fuel additives and diesel filtering on fuel consumption. Secondary data such as emissions, exhaust temperatures, fuel and oil samples can be found in Appendix A. The data presented consists of frequency histograms and time history data for each test, followed by a summary table and chart of fuel consumption results. All values of fuel consumption are expressed as brake specific fuel consumption (BSFC, kg/kWh).

6.1 Near new condition generators

6.1.1 **Nemo**

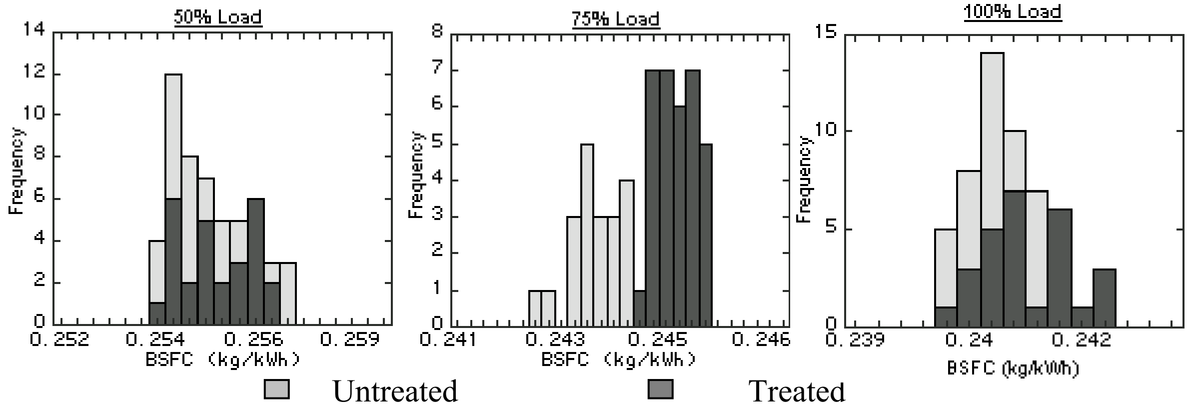

Figure 6-1 Effect of treating with Nemo on a near new engine

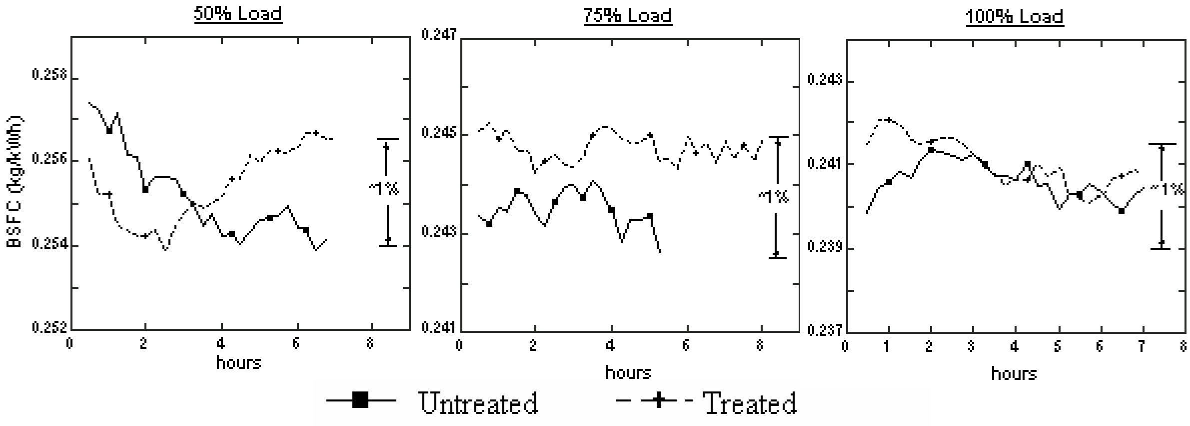

Figure 6-2 Effect of treating with Nemo on a near new engine (time history data)

6.1.2 FTC

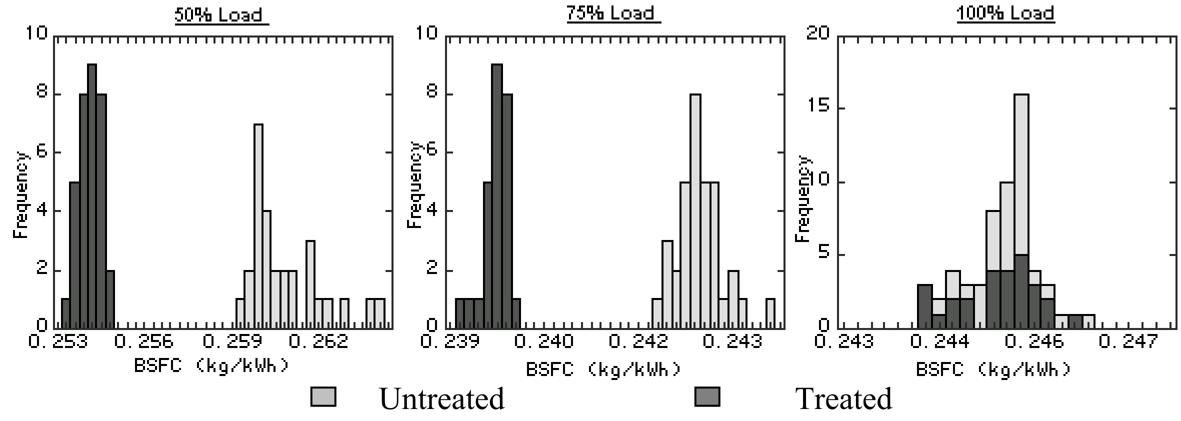

Figure 6-3 Effect of treating with FTC on a near new engine (Frequency Histograms)

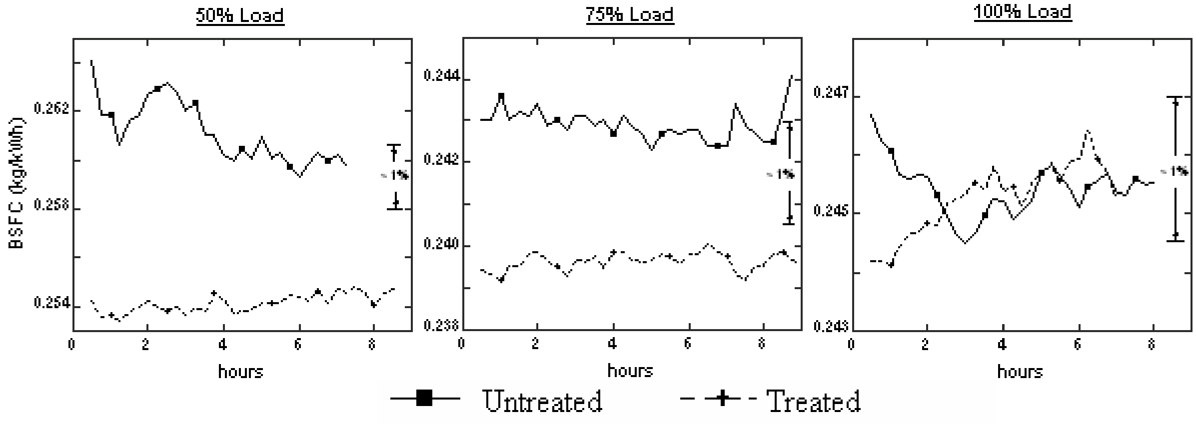

Figure 6-4 Effect of treating with FTC on a near new engine (Time history data)

6.1.3

Filtered Diesel

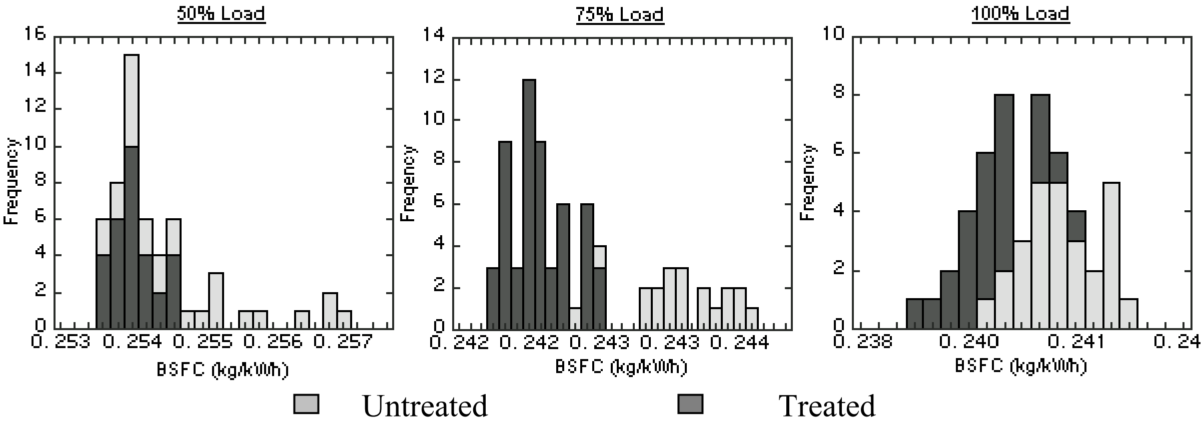

Figure 6-5 Effect of treating filtering standard diesel to 1micron

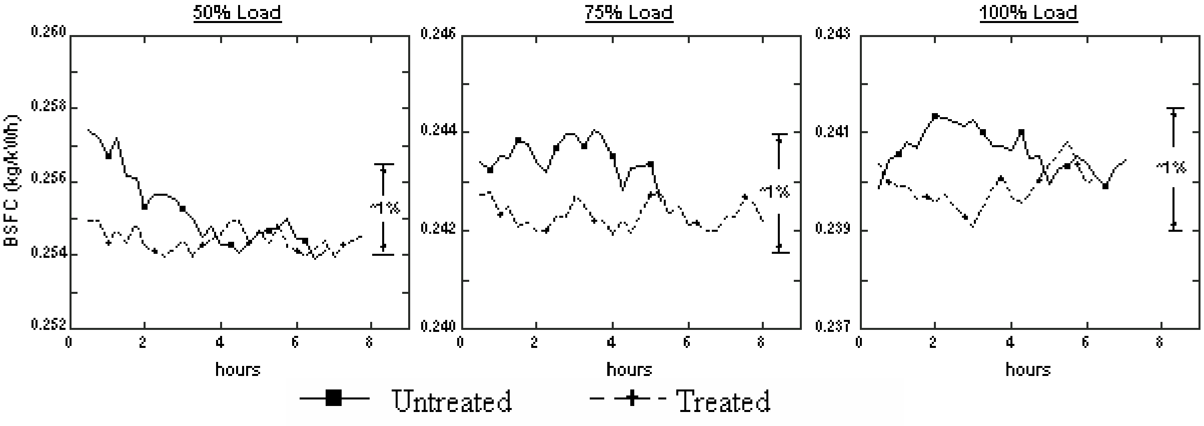

Figure 6-6 Effect of treating filtering standard diesel to 1micron (time history data)

6.2 Older Generators

The fuel consumption of the older generators appeared more erratic than that of the new generators. Moreover, both generators did not respond to ambient conditions in same manner as the new engines. For these reasons, the accuracy of the data can not be considered as high as that of the new engines. The following data is for Nemo and FTC on the older engines. The data was generally analysed in the same fashion however less processing was conducted to reduce propagation of errors in already noisy data (see Appendix B). Following the Nemo tests, Generator ‘A’, acting as the control variable for the FTC tests appeared to change it’s behaviour with regards to ambient conditions. Thus, the control variable had to be calibrated for temperature. This adds further inaccuracy to the data and thus the FTC results should only be taken as a guide to additive performance and should not be used for claims of exact percentage savings.

6.2.1 Nemo

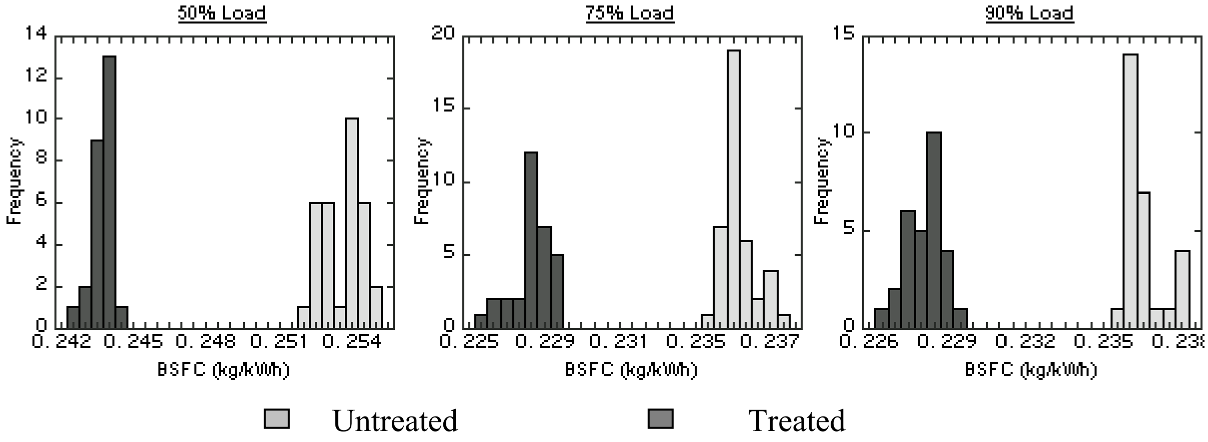

Figure 6-7 Effect of treating with Nemo on an older engine (in excess of 7000hrs)

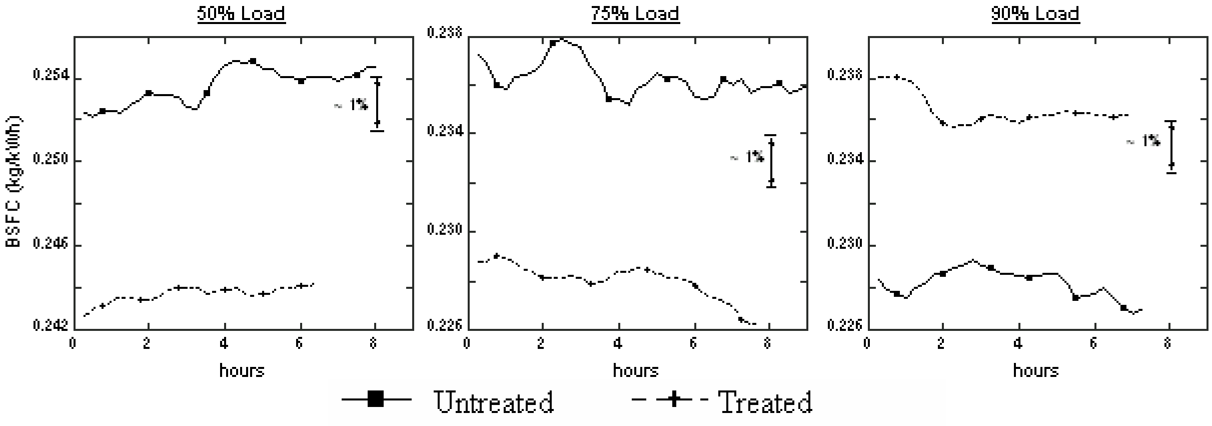

Figure 6-8 Effect of treating with Nemo2001 on an older engine Time history data

6.2.2 FTC

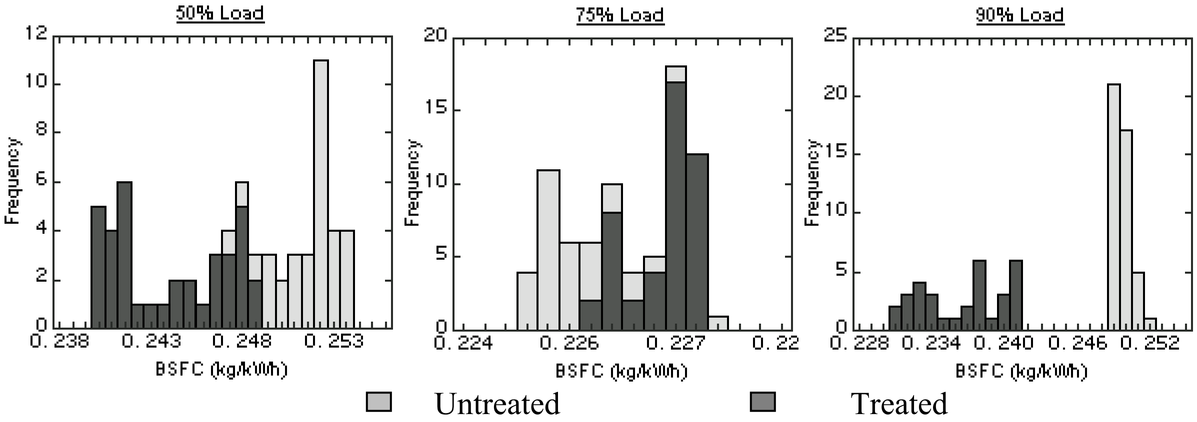

Figure 6-9 Effect of treating with FTC on an older engine (in excess of 5500hrs)

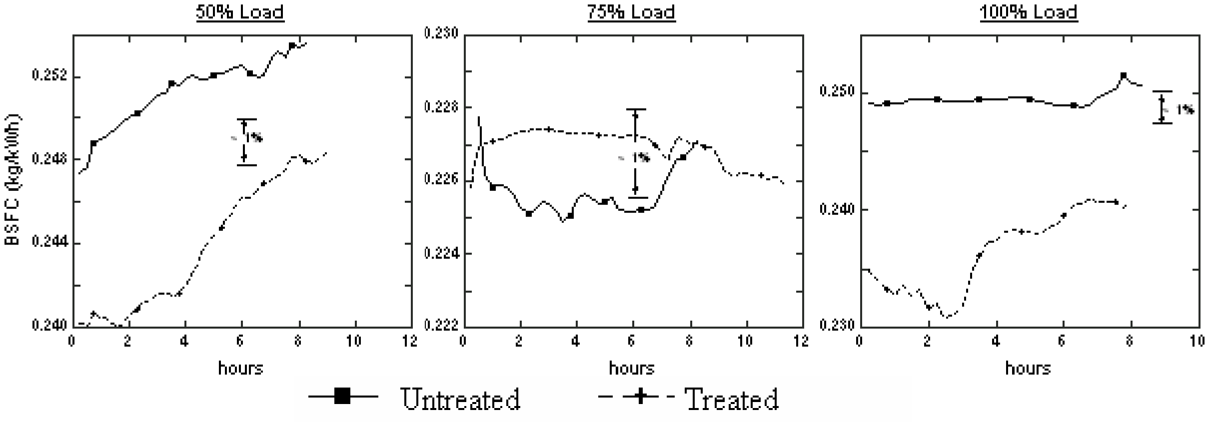

Figure 6-10 Effect of treating with FTC on an older engine (in excess of 5500hrs) Time history data

6.3 Summary of fuel consumption results

Table 6-1 Summary of BSFC results[*]

		BSFC (kg/kWh)				
	Load	Untreated		Treated		**% Change**
		Mean	*Std Dev*	Mean	*Std Dev*	
New Generators FTC-III	50%	0.2609	0.0009	0.2543	0.0003	**-2.6**
	75%	0.2429	0.0003	0.2397	0.0001	**-1.3**
	100%	0.2454	0.0003	0.2453	0.0005	**0.0**
New Generators Nemo 2001	50%	0.2552	0.001	0.2554	0.0009	**0.1**
	75%	0.2435	0.0004	0.2448	0.0003	**0.5**
	100%	0.2406	0.0004	0.2411	0.0006	**0.2**
New Generators Filtered Diesel	50%	0.2552	0.001	0.2544	0.0003	**-0.3**
	75%	0.2435	0.0004	0.2423	0.0003	**-0.5**
	100%	0.2406	0.0004	0.2399	0.0004	**-0.3**
Older Generators FTC-III	50%	0.2519	0.0016	0.2436	0.0030	**-3.4**
	75%	0.2257	0.0007	0.2269	0.0005	**0.5**
	90%	0.2497	0.0006	0.2366	0.0034	**-5.5**
Older Generators Nemo 2001	50%	0.2536	0.0008	0.2437	0.0004	**-4.1**
	75%	0.2363	0.0007	0.228	0.0007	**-3.6**
	90%	0.2362	0.0007	0.2284	0.0007	**-3.4**

Tentative Results

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[*] Note the stated accuracy of the results for the new and old generators is ±1/2 % and ±1% respectively. However, due to additionally required data manipulation for the FTC results on the old generators the results can't be stated to this accuracy (refer to Appendix B for errors in data analysis)

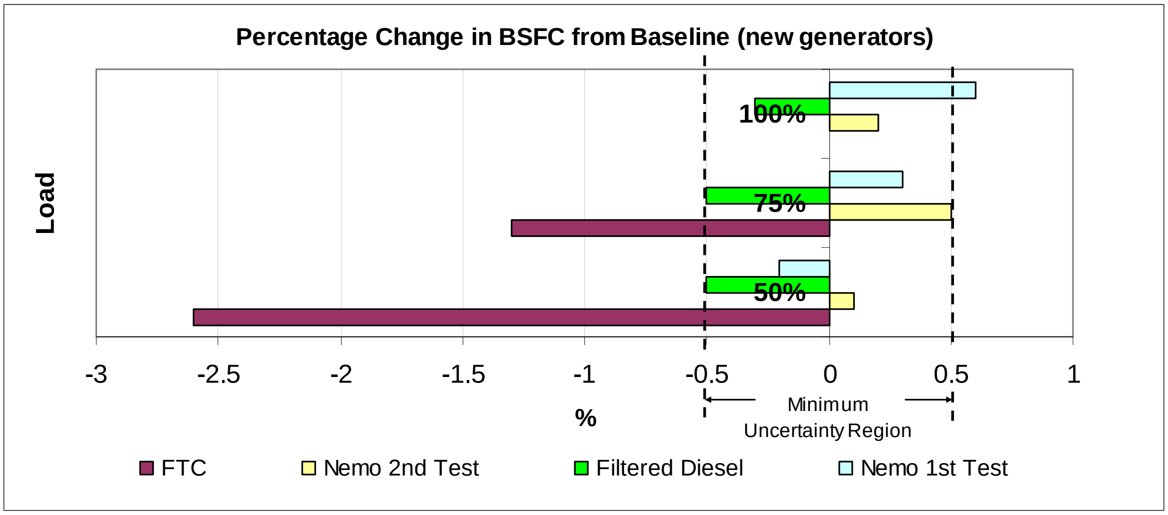

Figure 6-11 Summary of BSFC results (new generators)[†]

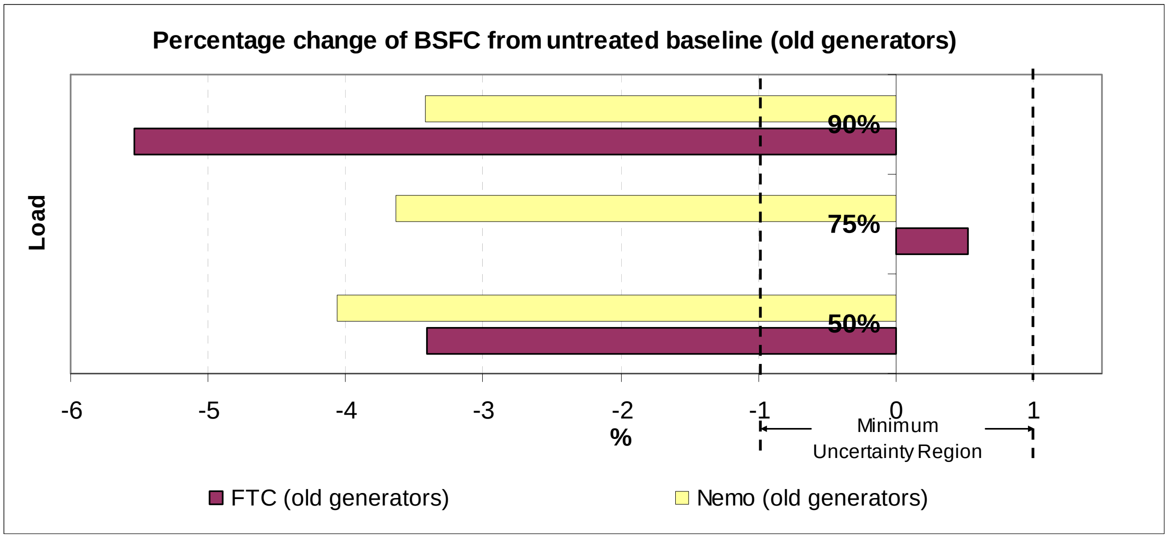

Figure 6-12 Summary of BSFC results (old generators)

[†] The 2nd Nemo test is presented in the results, the 1st test that was repeated due to concerns of engine over-heating is shown for completeness.

7 Discussion

7.1 Fuel Consumption

7.1.1 Additives

The before and after-treatment fuel consumption results with the two additives are shown in section 6. The results on the near new generators show a significant improvement at 50% and 75% loads by treating with FTC combustion catalyst. The recorded improvement in BSFC at 75% was similar to that found by Markworth (2002) on a locomotive engine at a similar loading. There was no apparent change in fuel consumption at 100% load. However overheating problems started to occur with one of the generators, which may have masked any possible improvement. The savings in BSFC via a FTC treatment appeared to decrease with increasing load. A possible explanation for this observation may be higher cylinder temperatures and reduced ignition timing which improve combustion properties at higher loads[*].

Nemo did not show any significant change in the BSFC at any load on the new generator which agrees with the findings of Vipac Engineers and Scientists. Two tests were conducted with Nemo, as there were concerns that the first might have been corrupted by radiator problems; however both tests produced similar results.[†] From these results, it can be inferred that either increasing the cetane number of the fuel had had little effect on the BSFC or the addition of Nemo did not change the cetane number. The latter is unlikely as much of the major content of Nemo (EHN) is a well-known cetane improver. White (2005) claimed that the natural cetane number of the fuel supplied in Perth is generally considerably higher than that of the fuel supplied to the Pilbara (which is supplied from Singapore). Thus, the natural cetane number may play a role in changing the affect of Nemo as the ignition delay may be already optimal for the fuel used in the study, which may not be the case for fuel sourced from other areas.

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[*] The ignition delay has been shown to decrease with increasing load (Judge (1967).

[†] The second test is presented in the results section (the extra test is shown in Figure 6-11).

Further information in regards to the BSFC performance of the additives can be inferred from the conditioning and ramp down periods given in Figure A 1 and Table A 1 respectively. A gradual improvement in BSFC fuel consumption was found by treating with FTC, while no improvement in BSFC was apparent with Nemo. This information re-enforces the results on the new generators. The conditioning period of FTC showed a gradual improvement in fuel consumption over time with FTC treatment, in agreement with Markworth (2002), Guld (1985) and Parsons and Germane (1989). After the additives were removed there was no residual effect, this indicated that the performance gains of FTC were derived from improved combustion efficiency rather than any purported cleaning effects.

The results of the older generators generally showed a higher reduction in BSFC from that of the newer models. This outcome was predicted by additive claims, as part of the performance improvements were derived from cleaning effects. It should be noted, that the reliability of the results for the older generators was poorer than that of the new generators. The reason for this was essentially the inherent variability of older engines. The results of FTC showed a considerable decrease in BSFC (3.4% at 50% load and 5.5% at 90% load) for two out of the three loads. This improvement was greater than that of the new generators and furthermore there appeared to be a sustained decrease in fuel consumption (see Table A 1), which indicated a combination of cleaning effects along with an increase in combustion efficiency. There was no significant change in fuel consumption observed at 75% load. A second test run at this load produced very similar results and thus it was unlikely the FTC BSFC at 75% load was measurement incorrectly.[‡] It might be possible that the baseline fuel consumption of the control variable was exceptionally low. Furthermore, generator ‘B’ (test generator for FTC) produced unusually high fuel consumption results at 75% load in comparison with other loads and that of Generator ‘A’ throughout testing (see Figure A 3). However, no definite reasons could be given for this result and it would appear that tests on old engines incur a high degree of variability in performance.[§] Overall, the BSFC results of FTC compounded with the reduction in fuel

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[‡] The initial 75% tests was preformed after the 90% tests and before the 50% test with the second 75% test being conducted after the 50% test.

[§] This is an example of how results produced by non-independent parties can be dangerous, as such a result could be left out of the final results if one wished consumption during the conditioning phase and the fact that part of the BSFC returned to normal after the additive was removed, indicated that FTC had a positive effect on the BSFC. It also seems that the additive provides some residual benefits on fuel consumption via cleaning or removal of hard carbon as suggested by Parsons and Germane (1989). However, the engines were not dismantled to examine the effects of FTC on carbon deposits directly, due to warranty issues.

The results of treating with Nemo showed an average decrease in BSFC in the range of 3.5% to 4%. Furthermore, a sustained reduction in fuel consumption was found, as shown in Table A 1. The improvement in BSFC after Nemo was removed, was similar to that of the savings realised during the testing phase, with the measurement error taken into consideration. From the results of Nemo on the new and older engines it appears that most of the reduction in BSFC is due to cleaning effects. The magnitude of BSFC improvement measured during these tests agrees with that of Garling et al. (1995).

7.1.2 Filtered Diesel

The effect of filtering the diesel to 1-mircon is shown in Figure 6-5 and Figure 6-6. There appears to be a small improvement in BSFC after treatment at all loads, however this change is within the experimental error. It therefore cannot be concluded whether or not filtering improves fuel consumption directly by removing suspended particles. It should be noted, in personal communication with filter suppliers, that no such performance claims were made. The claims of improved fuel consumption are based on reduced fuel system wear and thus the effect should be long term (Croft, 2005).

7.2 Emissions

The exhaust emissions of an engine can provide a measure of combustion quality. From the results obtained, variation in emissions between the engines and loadings can be clearly seen. However, the accuracy of the emission data was not sufficient to draw any confident conclusions in regards to additive performance. A summary of the emissions results is shown in Table A 3.

7.2.1 **Comparison between generators**

By comparing the emissions of the pairs of generators, trends are discernible from the emissions data. Table A 4 shows a comparison for the two generators during the first baseline and thus no additive had impacted the results. For the new generators, A had a consistently smaller BSFC than B (as shown in Figure A 3) and there were noticeable differences between the emissions of A and B. Generator 'A' showed in general more CO_2, and less CO, PM, UHC and O_2 emissions. This indicates improved combustion with better and more complete oxidation of carbon. However, NO_x emissions were higher with Generator 'A' and thus it could be inferred that the pre-combustion heat release was greater for engine A, as these conditions are favourable for fuel consumption (and CO,PM, UHC). Similar results were observed for the older generators[**] as B had a lower BSFC, CO, PM and UHC emissions while the NOx emissions were greater than that of Generator 'A'.

7.2.2 **Additives and Filtered Diesel**

As mentioned the error in the emissions results was quite high, however a few observations can be highlighted from the emissions results. There seems to be a correlation between fuel savings from Nemo with the older engines and a reduction in CO emissions. The FTC results show an increase in CO and a decrease in CO_2 with treatment. The PM emissions for both additives appear to reduce in the older engines. However, these results are speculative. The changes in emissions with filtered diesel were too small to make any statements about the effect of filtering diesel to 1-micron on emissions. Emissions would need to be monitored continuously with gas analysers capable of a higher degree of accuracy.[††]

7.3 Exhaust Temperature

The exhaust temperatures presented, are an average over a fifteen-minute period and thus do not provide a representation of peak cylinder temperatures. However, they do give some indication of combustion temperatures. Guld (1985) stated that an increase in exhaust temperature indicated more complete combustion. However, those findings disagreed with claims of others such as Garling et al. (1995) who stated that combustion temperatures

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[**] The BSFC of B increased and the emissions trends deviated slightly at 75% load on the older engines.
[††] A number of dedicated gas analysers would be more accurate than a multiple gas analyser

should decrease with improved combustion efficiency due to a reduction in fuel consumption. It was more likely that exhaust temperature was directly proportional to percentage of complete combustion and inversely proportional to thermal efficiency and the mass of fuel induced. Table A 3 provides the percentage change in combustion temperature with treated fuel compared to untreated fuel. The results confirm that there is no significant change to the overall exhaust temperatures with addition of the additives. This means that the additives should not cause increased thermal wear. Furthermore, it appears that the exhaust temperatures if compared to BSFC do increase and thus a thermal efficiency gain may be realised from additive treatment. Although this is hard to quantify as the error in exhaust temperature is similar to that of BSFC and is thus quite high compared with the percentage changes. There was no appreciable change to the exhaust temperature using filtered diesel.

7.4 Fuel samples

The main purpose of the fuel samples taken was to determine the effect, if any, of filtering the diesel supply with a 1-micron filter. The results shown in Table A 6, Figure A 4 Particle contamination of filtered and unfiltered diesel and Figure A 5 show that there was a small reduction in particle contamination, however no effect on water content (Karl Fischer Test) was found. The particle contamination results of the fuel supplied, shown in Table A 7, were generally lower than those collected for the filter tests. This indicates that most suspended particles in the supply diesel were low to start with and additional contamination probably came from the fuel system itself. Unfortunately, the tests, which were organised by others, only tested for particle sizes greater than 5-micron and 15-micron. The three scale ISO 4406 test that also tests for particles greater than 2 micron, would have been more useful for examining the efficiency of the 1-micron filter. A sample of diesel was taken from the outlet (not drain) of one of the large storage tanks hired with the old generators. The results found greatly increased levels of particle contamination at all scales compared with that of the diesel supplied, including the 2-micron scale.[‡‡] The PQ index, a measure of iron particles greater than 15-micron, also was found to be higher. If these values are typical of storage tanks on site, the case finer pore diesel filtration is evident.

[‡‡] This test was done after the others and thus Komatsu CMS were asked to conduct a 3-scale ISO-4406 test

Particle contamination, density and calorific value were tested for various samples of supplied diesel. The particle contamination and density results showed no measurable changes with the addition of the additives. This is to be expected, however important, because it indicates that the additives should not be removed by diesel filtration.

Figure A 6 shows the variation in density of fuel samples taken over the testing period (approximately three months). The variation in the density of the fuel is in the order of the effects of the additives that the tests are attempting to measure. A control engine was used to remove such effects. As the fuel density directly effects fuel consumption, (Chevron, 1998) the variation in density would need to be taken into account in any field testing. This could be achieved either through the use of control variable or continual fuel measurement.

7.5 Oil Analysis

Oil samples were taken for spectral analysis to determine if any immediate negative effects of the additives on engine life existed. The duration between of each sample was roughly 72 hours and thus is not sufficient for determining long-term effects. Further research would be required if one wished to check for the longer-term effects of the additives on wear metals, oil viscosity, acidity etc. It would probably be best to conduct such tests in the field where a good oil service history has been established. The results of the oil sample tests, shown in Figure A 8, do not show any major concerns in relation to the oil condition. There appears to be a slight accelerated increase in Lead, Molybdenum and oil viscosity, while a decrease in some other trace elements was evident with treatment of Nemo. However, the changes are only small and Westrac condition monitoring services did not raise any major concerns about the concentration of the various wear elements. To make full use of oil sample analysis, oil sample history at regular intervals and monitoring over many oil change periods with a selected additive is necessary. This will provide information about the rate of change of compounds over time, so that the positive effects of the additives on engine life can be proven or disproved. The results from the oil sampling in this investigation indicate, that no immediate damage to the engines will result from the addition of FTC or Nemo at the suggested treatment rate.

7.6 Experimental Errors

The testing was designed to isolate many of the errors realised in the field environment, while conducting tests on equipment similar to that on site. Thus, the size of the equipment did not allow the experiments to be conducted in an environmentally controlled laboratory or with the one homogeneous batch of fuel. This nature of testing inevitably introduced errors into the results however, provided comparable outcomes for mining equipment, where as a small single cylinder laboratory engine may not have.

There were a number of different measurement errors present in the testing, however the major experimental errors could be attributed to the generators response to ambient conditions. By comparing each generator set-up to itself and simply using the other Generator ‘A’s a control variable the repeatability of the flow meter measurements became important rather than the absolute accuracy. The repeatability error of the flow meter was far less than that of the measurement accuracy (±0.03%). It was difficult to ascertain the existence and magnitude of all the specific errors associated with the trials. Thus, repeatability of time history data was used to estimate the error present in the measurement of fuel consumption.[§§] As explained in Appendix B the error in measurement of BSFC for the new engines was in the order of ±1/2 %, while the variation in BSFC of the older engines was greater, around ±1%. These findings are quite important as they show that even when the engines are running with a quasi steady state load, the fuel consumption is not steady state. These errors highlight the difficulty of measuring additive performance accurately especially in the field and thus the effect of an additive needs to be averaged over a number of vehicles over as long time as feasible.

[§§] Note BSFC was quoted as it provides a measure of fuel consumption irrespective of load fluctuations. Thus is Assuming that the fuel efficiency of the generators did not differ greatly with a small change in load (1 to 2%)

8 Conclusions and Recommendations

The results of this investigation demonstrate considerable savings, in cost to Pilbara Iron, and CO_2 emissions[*], can be obtained via the treatment with either additive on 4-stroke DI diesel engines. It is also evident that accurate quantitative assessment of additive performance even on stationary equipment is quite difficult especially on older engines. Thus it could be assumed that determining the additive performance on mobile equipment would be even more difficult. The effects of additives and filtered diesel were assessed at different loading conditions so that links between the results and equipment operating conditions on site could be established. Large-scale field tests could be another way of establishing the actual effect on on-site equipment. However, the results of such tests will only provide an indication of efficiency gains as many more errors would exist compared with the methods of testing used herein.

The aim of the investigation was to evaluate the performance of both additives as fairly and accurately as possible with industrial equipment. All feasible steps were taken to maintain the integrity of the results, however inherent difficulties in obtaining such results were observed. The general variation of engine performance, response to changing ambient conditions and fuel quality and air entering the fuel system were among some of the difficulties encountered. Continuous monitoring, the use of control variables, and repetition of corrupted tests were used to mitigate such problems. However the tests indicate that one needs to be scrupulous with the results to remove such inaccuracies and that results presented by others may have been affected by a number of factors other than the fuel additive.

8.1 Fuel Additives

The results of the fuel additive testing showed savings in the order of 3 to 5% could be achieved by treatment on the older engines. Performance gains were also observed on the new engines with FTC. However no improvement in the BSFC was observed with Nemo. Thus it appears that significant BSFC reductions can be obtained by treating equipment with either additive, however the efficiency gains of Nemo appear to be linked to that of

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[*] The savings in CO_2 emissions are drawn from a reduction in fuel consumption

cleaning effects.[†] The results indicate some cleaning effects of FTC, however, these are hard to quantify. Research by others (Parsons and Germane, 1989) found that the FTC removes hard carbon deposits within the engine cylinder although whether or not FTC acts to clean injector deposits is yet to be established. It may be possible that an additive such as FTC combined with the injector cleaning properties of Nemo[‡], or continual treatment with FTC and occasional treatment with Nemo could produce further benefits[§]. Additional testing using the additives in tandem was considered but this was ruled out due to time constraints. It should be noted however, that increasing the CN of diesel has been shown to reduce injector fouling (Judge, 1967) and therefore a continual treatment with Nemo will have benefits over intermittent treatments.

No definite conclusions can be made about the effect of the additives on exhaust emissions however; the test highlights the need for continuous monitoring of emissions. This variation in emission results emphasizes the inaccuracy of intermittent measurement of emissions with a multiple gas analyser. The exhaust temperatures and oil samples results do not indicate any negative effects of the additive on engine life. Longer oil sampling periods would be required to fully understand the long-term effects of the additives on engine wear. However, these results should reinforce the case for further additive testing in mobile equipment as the risk of additive damage appears low.

8.2 Filtered Diesel

It is difficult to provide reliable conclusions from the filtered diesel tests. The results indicate fuel savings are possible through the use of finer diesel filtration which reduces particle contamination. However, the change in BSFC is too small to be measured reliably and the fuel samples appear to contain contaminants from the engine fuel lines. The results of the BSFC from filtered diesel do prove that filtering does not have any negative effects on BSFC. High levels of particle contamination were found from a bulk storage tank even at the 2-micron scale and Hunt (2005) reported similar results obtained from a Pilbara Iron

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[†] Octel, the producer of Nemo, have developed additives based on detergent packages without cetane improving chemicals (Octimise D3026).

[‡] Such additives can be obtained through Octel, White (2005)

§ Note: both additives should not be used at the same time as this may affect product liability insurance site. Furthermore, a study conducted by Das (2005) with iron ore from Tom Price found considerable volumes of particles less than 8-microns were produced from the engagement of bucket material on the ore. Thus it would appear that diesel filtration is a good idea as the fuel received by machinery on site is likely to have high contamination levels less than 8-micron.[**]

8.3 Recommendations and Future Research

8.3.1 Additives

The results of the tests presented in this report, past tests conducted and available literature, indicate possible fuel savings can be achieved from treating with using FTC and Nemo. The results show that both additives warrant further investigation and should prove useful for reducing the fuel consumption of equipment on site. Tests on smaller engines in a highly controlled environment may provide more information about the mechanisms of each additive and the effect on the combustion process. However, such investigations alone would probably not greatly enhance the results for Pilbara Iron and thus field trials would be the next useful step for the introduction of additives. These field trials would have to be carefully planned to remove as many field variable as possible and average over many similar vehicles. Any field trials should include frequent oil sampling to determine the effects of the additive on engine life.

Injector-cleaning chemicals may remove deposits from injectors. However, they cannot restore injector spray patterns if the injectors have sustained too much wear. Therefore, the condition of injectors and injection pumps should be considered in any attempt to improve the fuel efficiency of equipment. This is also true for improved diesel filtration, as filtering to 2-micron is worthless if the injectors have been worn out to 10-micron.

** The most damaging particle sizes have been reported to be 6 to 7 microns, with most diesel filters having a pore size of 10-micron (Chevron 1998). Austen and Goodridge, (1951) found the most damaging particle to be close to clearance dimensions which are now approximately 2 to 3 microns for injectors (Taylor, 2005)

8.3.1.1 Possible framework of field trials

Baselines should also be established over a period of months and the tests conducted at a period of similar environmental conditions. The length of the trials would have to be offset by the need for similar fuel quality and the same group of trucks conducting similar haul runs, or at least the tests trucks conducting the same runs as control trucks. Fuel samples should be taken at regular intervals to check changes that may corrupt results however, control variables should be used in a similar manner to this investigation to remove such problems. An example of a testing schematic for field trials is shown in Figure 8-1.

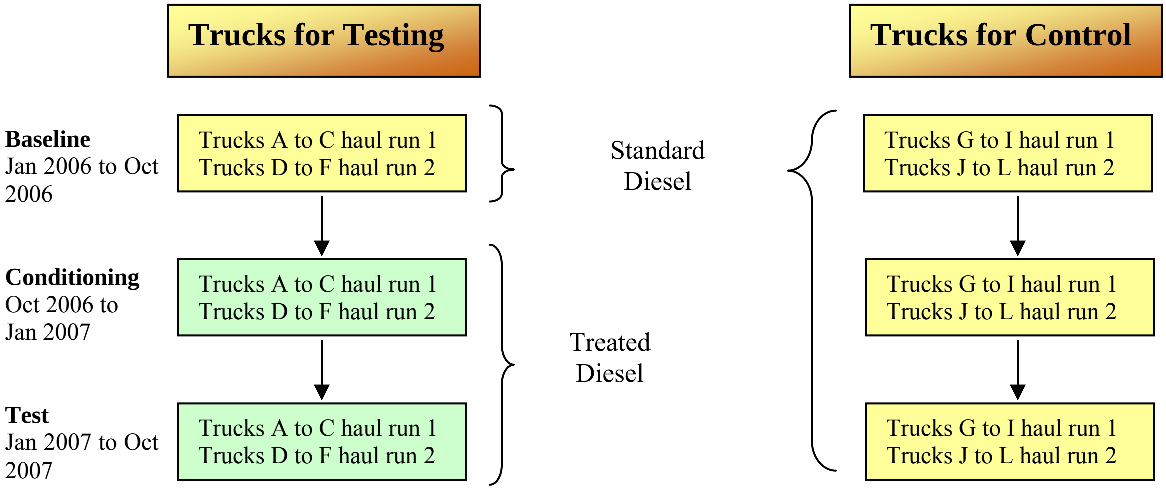

Figure 8-1 Possible testing schematic for field trials

One haul run would be ideal, however is unlikely with 12 trucks. The same set of haul runs throughout the trial would be sufficient, but if this was not possible and an additional haul run was introduced in later stages then both control and test trucks would have to conduct the same run to remove this change.

8.3.2 <u>Filtering</u>

The cost of retrofitting 1 to 3-micron filters on all mobile equipment may be quite high. Thus, the new range of 2-mircon spin-on/off fuel filters recently released by Catapillar® may prove to be a more appropriate alternative. As a further measure to reduce the amount of contaminants introduced into the fuel of mobile equipment, a filter could be connected to the outlet of storage tanks on site. This could help extend fuel filter life, increase the time between services and thereby reduce maintenance costs. With fuel injection pressures on new engines becoming increasingly higher, the need for finer diesel filtration is becoming more important (Caterpillar®, 2003). Thus, the need to supply cleaner diesel to mobile equipment will become more important as finer filtration is used by manufacturers on their fuel systems, otherwise early filter plugging may become a problem.

Filtering at the outlet of storage tank should also be conducted if fuel is treated with Nemo, as the additive is a surfactant and may clean scale from the tanks and fuel lines (Cole, 2005).

8.3.3 Possible future research

As with most scientific research, when one question is investigated more present themselves. Thus, this research has identified a number of areas for further investigation, that maybe beneficial to improved fuel efficiency of equipment and longer service life.

- Field Trials to confirm additive performance on mining equipment in the field
- Medium-term (10 to 20 weeks) effects of additives on combustion chamber and injector deposits (May be included in field trials but would require engine head block removal, which may be a problem for production).
- Long-term effects of additives on engine wear through oil analyses (should be included in field trials).
- The tests of sub 10-micron iron ore particles on injector and injection pump wear (may be done externally to an engine by methods similar to that of Austen and Goodridge (1951)
- A study of the injector condition of mining equipment at different run hours to determine optimum replacement intervals (this could be conducted by examining the injector spray patterns when injectors are replaced, although the frequency of injector replacement would most probably need to be increased).
- Further research pertaining to engine oil additives and filtering could be considered for reducing friction, wear and service intervals.

This investigation was limited by time, budget and facilities constraints and therefore not every avenue of investigation could be conducted. However, the results show that both additives are beneficial and savings will vary depending on engine condition. The research also highlights the difficulty of measuring BSFC, emissions and engine temperatures to a high degree of accuracy.

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Appendix A Additional results

A.1Additional results

A.1.1Conditioning Periods

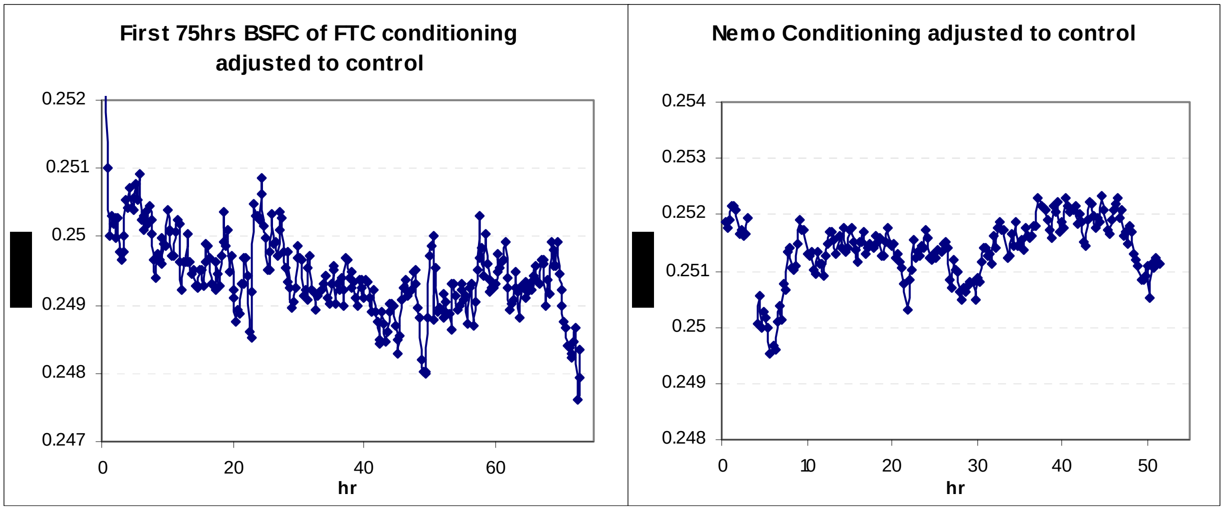


Figure A 1 FTC (left) and Nemo (right) conditioning periods new generators

Note air leaks corrupted the later data of FTC and hence is not shown however the decreasing trend continued after leaks were removed.

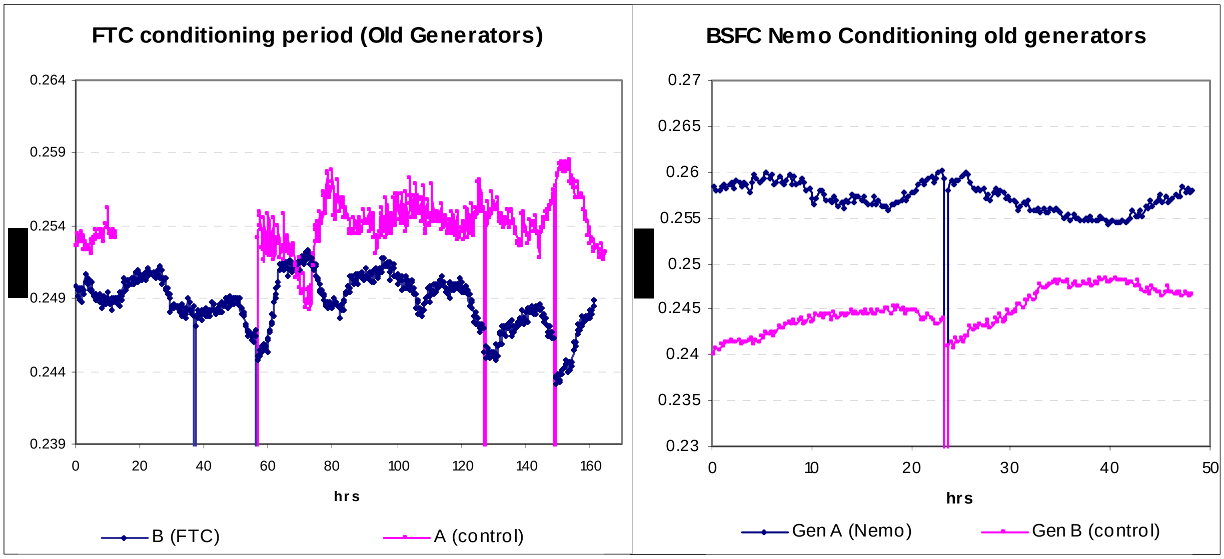


Figure A 2 FTC (left) and Nemo (right) conditioning periods old generators

The BSFC of both generators are shown for comparison as noise was higher the measurements on the older generators

A.1.2 After removal of additive

Table A 1 Average change in fuel consumption after removal of additive

% Change of Fuel Consumption after additive was removed		
	Immediate	> 30hrs
FTC New Generator	Insignificant	Insignificant
Nemo New Generator	Insignificant	Insignificant
FTC Old Generator	-2.50%	-1.5% *
Nemo Old Generator	----------------	-2.5%

* The value was taken 8hrs after the additive was removed, not 30hrs

A.1.3 Emissions

Table A 2 gives the percentage change from the respective untreated baselines, of the average measured emissions for each test. Note, the emission data has been adjusted to the control generator in each case and thus a total error combined error from all sets of measurements is given.

Table A 2 Tail pipe emissions

Summary of emissions (% change from untreated baseline)												
		New Generators							Old Generators			
		FTC	*error*	Nemo	*error*	Filtered	*error*		FTC	*error*	Nemo	*error*
CO	50%	2.1	*6.6*	6.6	*6.7*	-5.0	*6.3*	50%	8.5	*9.4*	-6.1	*4.0*
	75%	13.9	*10.5*	-1.0	*15.0*	1.2	*18.6*	75%	-14.4	*10.5*	-8.6	*8.1*
	100%	9.7	*5.1*	-4.2	*6.4*	6.7	*12.1*	90%	24.8	*6.5*	-27.0	*11.6*
O2	50%	-0.5	*1.9*	-10.3	*3.8*	1.2	*3.1*	50%	-0.5	*0.8*	-0.2	*1.2*
	75%	12.7	*6.9*	3.8	*8.4*	4.2	*10.2*	75%	1.7	*0.5*	-5.2	*4.2*
	100%	-0.5	*8.5*	-20.4	*14.4*	-7.1	*16.7*	90%	-2.2	*1.1*	-2.8	*9.0*
CxHx	50%	8.9	*6.7*	110.3	*15.0*	-3.2	*13.2*	50%	-5.9	*8.8*	-20.6	*6.8*
	75%	12.3	*6.9*	7.5	*9.7*	10.7	*7.3*	75%	-4.6	*6.0*	8.4	*5.1*
	100%	7.1	*2.8*	2.5	*3.4*	10.8	*7.8*	90%	-5.4	*17.8*	-24.1	*53.2*
CO2	50%	-4.8	*2.7*	15.9	*3.1*	3.3	*2.3*	50%	-1.9	*5.0*	7.1	*2.3*
	75%	-17.1	*7.2*	0.3	*9.3*	-4.1	*10.8*	75%	-0.3	*4.0*	0.1	*7.3*
	100%	-0.2	*5.2*	10.8	*10.1*	2.2	*11.0*	90%	1.0	*2.1*	-3.2	*8.1*
NOx	50%	6.2	*3.4*	19.5	*5.5*	-0.9	*4.2*	50%	12.4	*8.8*	3.9	*1.7*
	75%	-29.9	*7.5*	-8.2	*9.9*	-9.8	*10.9*	75%	-2.0	*1.1*	17.7	*22.6*
	100%	-2.5	*22.0*	7.7	*16.8*	7.6	*28.0*	90%	-37.4	*63.0*	3.2	*20.5*
PM	50%	112.4	*8.4*	31.3	*4.3*	26.2	*14.5*	50%	-19.5	*15.19*	-24.9	*24.5*
	75%	6.8	*9.1*	8.6	*3.2*	-6.4	*6.7*	75%	-10.1	*10.34*	-6.9	*10.4*
	100%	0.7	*6.5*	3.9	*0.0*	8.8	*2.6*	90%	-6.8	*7.079*	-34.7	*12.8*

The percentage change of the treated vs untreated has been adjusted for the percentage change in the control generator

Standard deviation was used to represent the error moreover, error propergation techniques were used to combine errors correctly

A.1.4 Exhaust temperatures

Table A 3 Summary of changes in exhaust temperature with treatment from untreated baseline

Percentage Change of Exhaust Temperature from untreated baseline (in kelvin scale)					
		% change			*% change*
New Generators FTC-III	50% 75% 100%	0.8 1.1 1.9	Older Generators FTC-III	50% 75% 90%	-0.5 -0.1 -0.6
New Generators Nemo 2001	50% 75% 100%	-0.1 -0.2 -0.9	Older Generators Nemo 2001	50% 75% 90%	-0.6 -0.6 -1.3
New Generators Filtered Diesel	50% 75% 100%	0.4 -0.1 0.0			

Note; % changes within ~ ± 0.5% are insignificant due to measurement and environmental errors

A.1.5 Comparison between the two generators (fuel consumption and emissions)

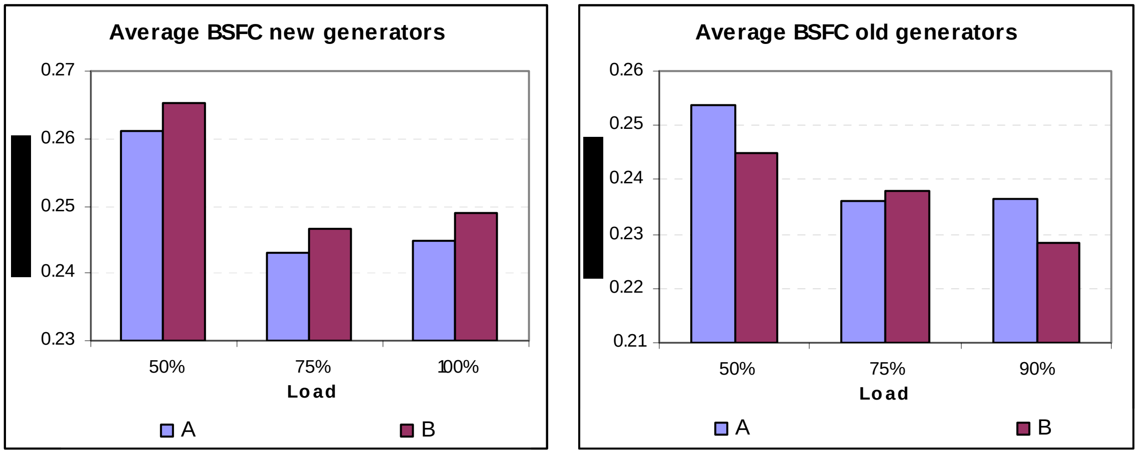


Figure A 3 average fuel consumption of generators before treatment of additives

Table A 4 Emission comparison of new generators

New Generators difference between Generator A and Generator B

		A	B			A	B
CO	50%	82.67	116.0	**CO_2**	50%	7.98	7.76
(ppm)	75%	138.3	181.3	(%)	75%	10.57	8.19
	90%	1445.3	1435.7		90%	13.08	11.59
O_2	50%	12.36	12.3	**NOx**	50%	1022.67	857
(%)	75%	9.54	12.2	(ppm)	75%	1933.67	1294
	90%	6.78	8.1		90%	2924	2271
CxHx	50%	385.67	446.0	**PM**	50%	1	1.55
(ppm)	75%	380.67	422.0	(Bosch #)	75%	2.05	2.50
	90%	819.67	856.0		90%	2.6	3.15

Table A 5 Emission comparison of old generators

Old Generators difference between Generator A and Generator B

		A	B			A	B
CO	50%	345	83.6	**CO_2**	50%	8.62	8.65
(ppm)	75%	792	265.0	(%)	75%	11.5	10.70
	90%	605	547.3		90%	13.1	12.20
O_2	50%	11.8	12.3	**NOx**	50%	655	1074
(%)	75%	9.67	9.7	(ppm)	75%	1287	2122
	90%	7.8	8.3		90%	2079	2620
CxHx	50%	628	376.0	**PM**	50%	2.75	0.65
(ppm)	75%	659	532.0	(Bosch #)	75%	3.5	1.40
	90%	426	390.0		90%	3.5	1.60

Note: the condition of A was noticably poorer as indicated by PM and a considerable drop in RPM with applied load

A.1.5.1Filtered Diesel

Table A 6 contamination and water content tests for diesel filtering

Filtered Diesel Test Results					
	ISO 4406 particle index		PQ index	Karl Fischer Water	
	> 5µ	> 15µ			
50% Unfiltered 1	15	12	11	35	U/F 1
50% Unfiltered 2	18	16	11	34	
75% Unfiltered	16	15	11	34	
100% Unfiltered	16	14	11	34	
100% Unfiltered Generator B	*18*	*15*	*11*	*33*	U/F 2
2nd Test Unfiltered	17	16	11	33	U/F 3
50% Test Filtered	14	11	11	36	F 1
75% Test Filtered	18	17	11	35	
100% Test Filtered	*16*	*12*	*11*	*34*	F 2
2nd Test Filtered	16	13	11	35	F 3

** The fuel used changed by~20% for the 100% test and thus a baseline was taken from the unfiltered fuel in Generator B*

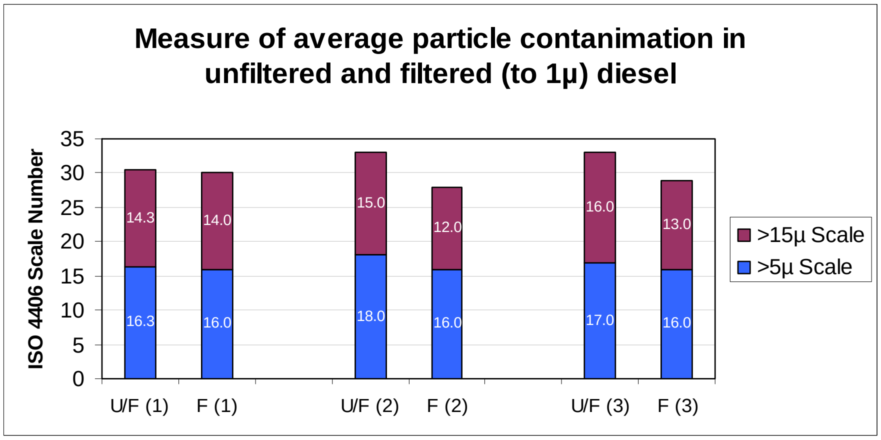


Figure A 4 Particle contamination of filtered and unfiltered diesel

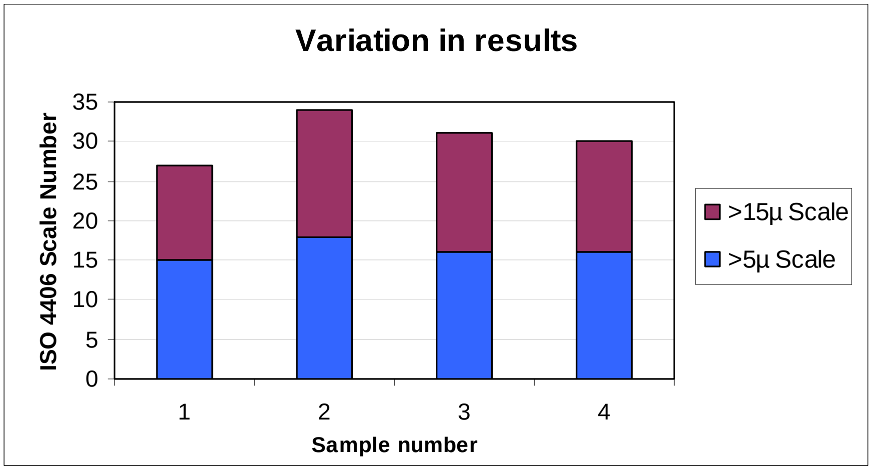


Figure A 5 Variation in particle numbers for the one sample of diesel

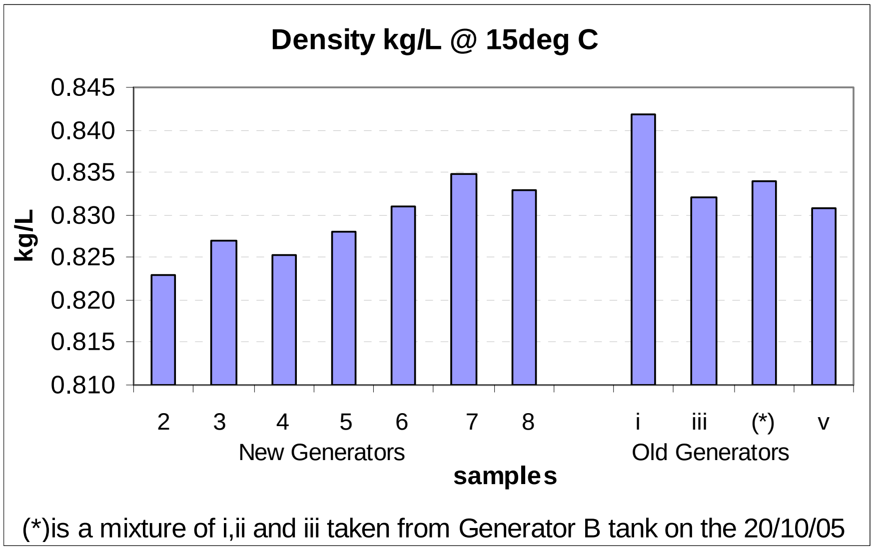
A.1.5.2Contaminate results of fuel samples

Table A 7 Particle contamination results of diesel fuel supply samples NEED EXTRA SAMPLE ADDED

Diesel Sample Tests (No Filtering)					If <1ppm ignored										
	ISO		PQ index	Karl Fischer (water content)	Fe	Pb	Cu	Al	Cr	Si	Na	Mo	Mg	Zn	Ca
	> 5µ	> 15µ													
Diesel Sample # 2	17	14	11								1				
Diesel Sample #4	13	10	11								2				
Diesel Sample # 6	13	11	11								1				
Diesel Sample # 8	14	11	11								2				
Diesel Sample # 2 +FTC	14	11	11	38							2				
Diesel Sample #2 + FTC from bottom of tank (unusual brown colour)	14	11	11	39							1				
Diesel Sample # 8 +Nemo	14	11	11								1			1	
Sample from Bulk Tank*	20	19	13	44											2

* The bulk fuel sample also had a ISO scale number of 21 for the <2µ scale

A.1.5.3Density Variation



(*)is a mixture of i,ii and iii taken from Generator B tank on the 20/10/05

Figure A 6 The measured density corrected to 15deg of numerous fuel samples throughout testing.

Note, that not all the fuel was sampled and the control variable was used to negate this variation. However, this gives an indication how the density can change. Assuming all other fuel qualities remain constant, the density of a fuel directly relates to fuel consumption (Chevron, 1998)

A.1.5.4Calorific Value

	Filtered diesel baseline (25/8/05)	Old gen #3
Density in air at 15°C (kg/l), IP 190/ASTM D1250	0.8306	0.8332
Specific gravity at 15°/15°C, calculated	0.8313	0.8340
Gross calorific value (MJ/kg), AS 1038.5	46.01	46.03
Net calorific value (MJ/kg)	43.25	43.27

Figure A 7 Calorific value and density measurement conducted on two different diesel samples, measured by Komatsu CMS.

Note the Old gen #3 sample is the same as sample (*) from the density measurements.

A.1.6 Oil Samples

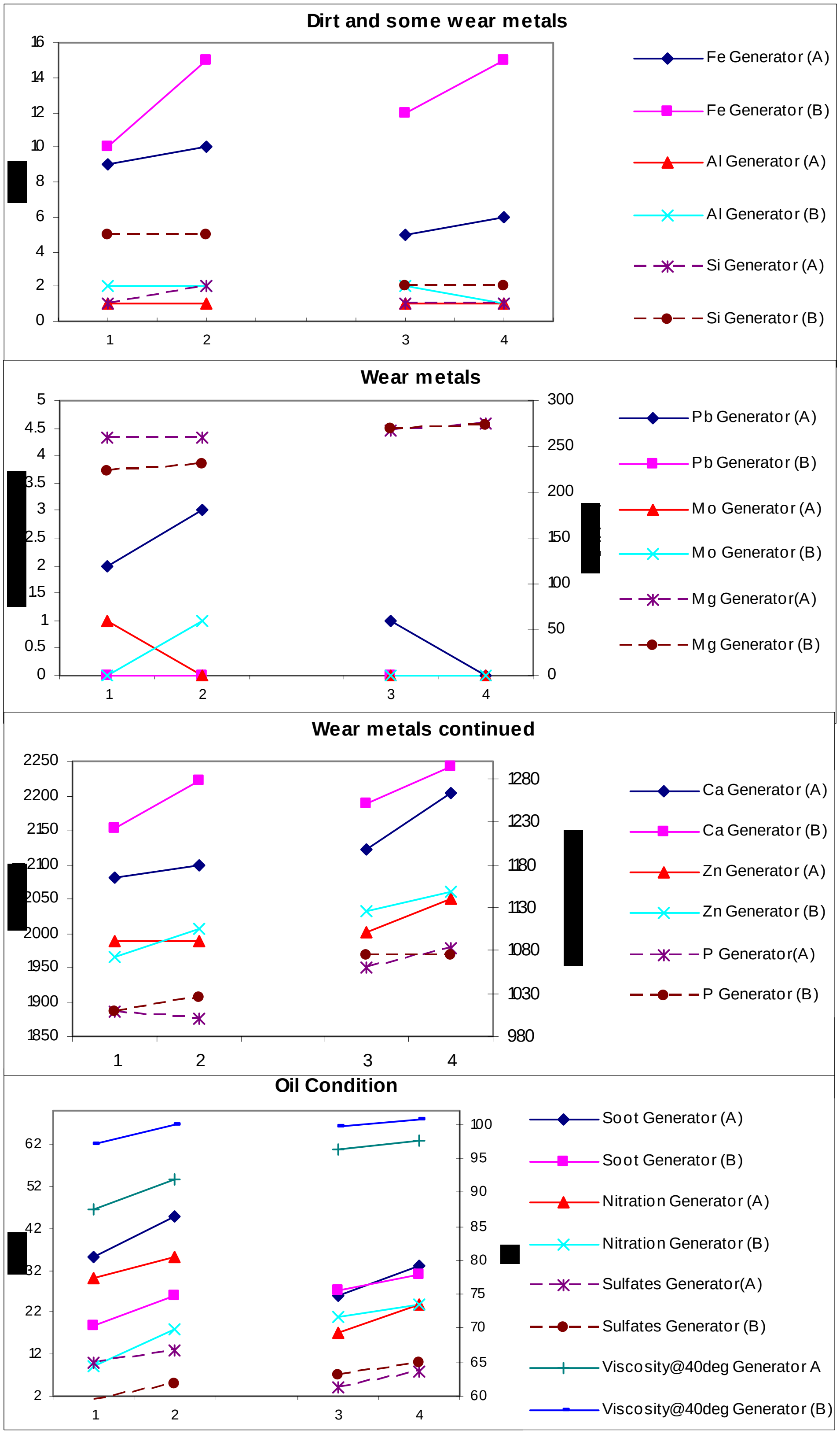


Figure A 8 Oil sample results from the older generators

1-2 Nemo in A standard diesel in B, 3-4 standard diesel in A, FTC in B, gap represents an oil change

Appendix B Environmental effects on fuel consumption and data analysis

B.1Environmental effects on fuel consumption

B.1.1<u>Variation of Load with Temperature</u>

Resistive load banks, supplied by Power Proving Services, provided electrical load on the generators. These load banks were designed to provide a constant specified load in increments of 1kW. There was a small variation of the applied load with temperature as shown by Figure B 1.

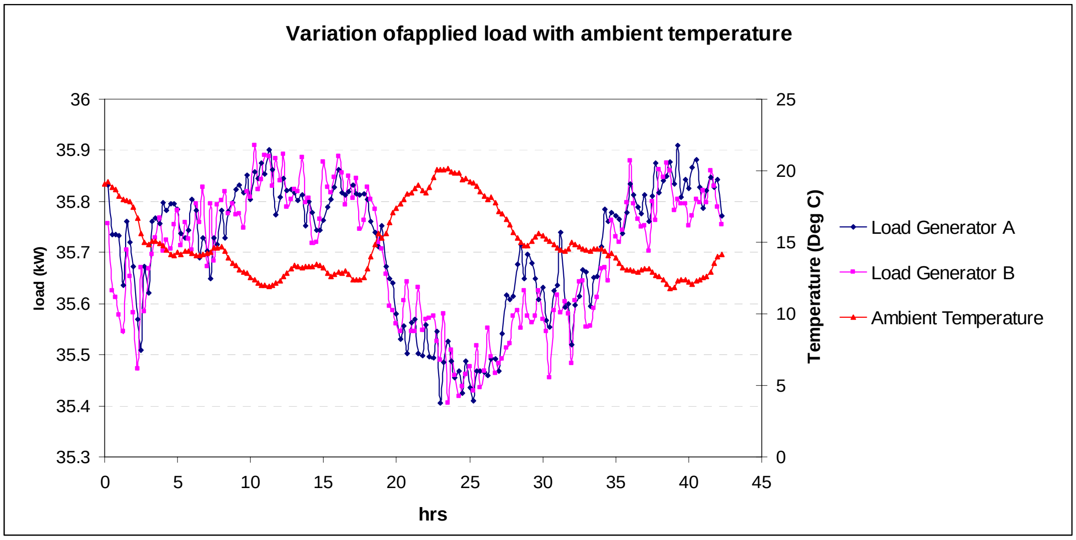


Figure B 1 Effect of Applied load on ambient temperature

The plot is for a 60% untreated test with the new generators, however a similar trend is found for all loads and with the old generators. The plot represents the load demanded by the load banks and is not the power output of the generators.

B.1.2<u>Variation of fuel consumption with temperature</u>

The major environmental factors effecting compression ignition engines are ambient temperature and pressure as explained by as Judge (1967) and Heywood (1988). However in the case of the fuel additive research conducted in the report not only were the effects of ambient conditions on engine performance a concern, but also the effects of ambient conditions on the applied load. As shown in Figure B 1.The applied load of the resistive load banks tends were affected by the ambient temperature. A plot of the theoretical effect of temperature shown in Figure B 2 indicates that fuel consumption is directly proportional to temperature. However the measured fuel consumption (Figure B 3) appears to follow, all be it weakly, an opposite trend to that of temperature. This indicates that the effect of varying load is more influential than temperature alone on engine performance. The overall effect of ambient conditions is of vast important in order to determine the performance of the additives. This problem has been mitigated by two methods.

1. Calculating the fuel consumption in terms of the power produced, that is break specific fuel consumption (BSFC). By dividing by power produced the changes of load with temperature are removed as shown in Figure B 4, where the BSFC is in phase with ambient temperature similarly to theory.
2. Using one Generator 'A's a control variable to remove such effects as accurately as possible.

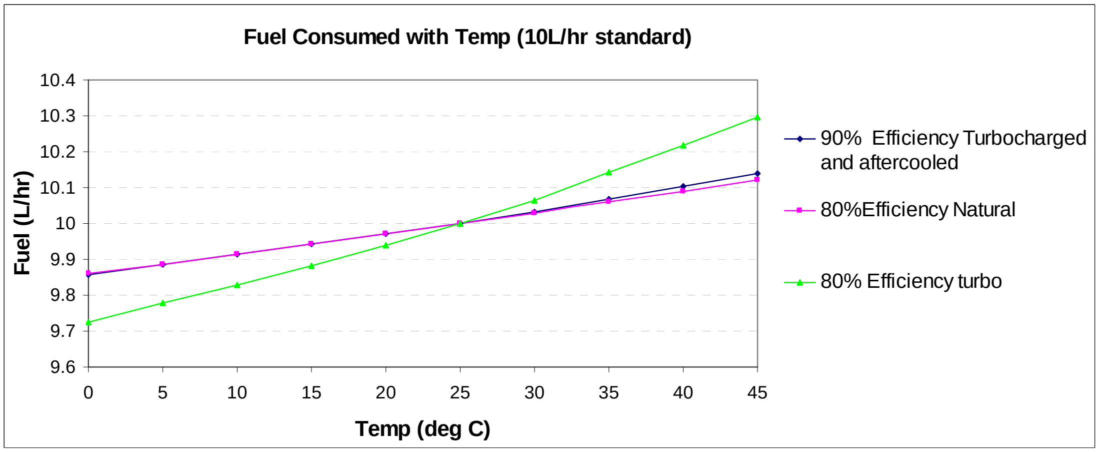


Figure B 2 Theoretical effect of fuel consumption of a CI engine with a rated fuel consumption of 10L/hr at 25 deg C using formulae and table from AS4594

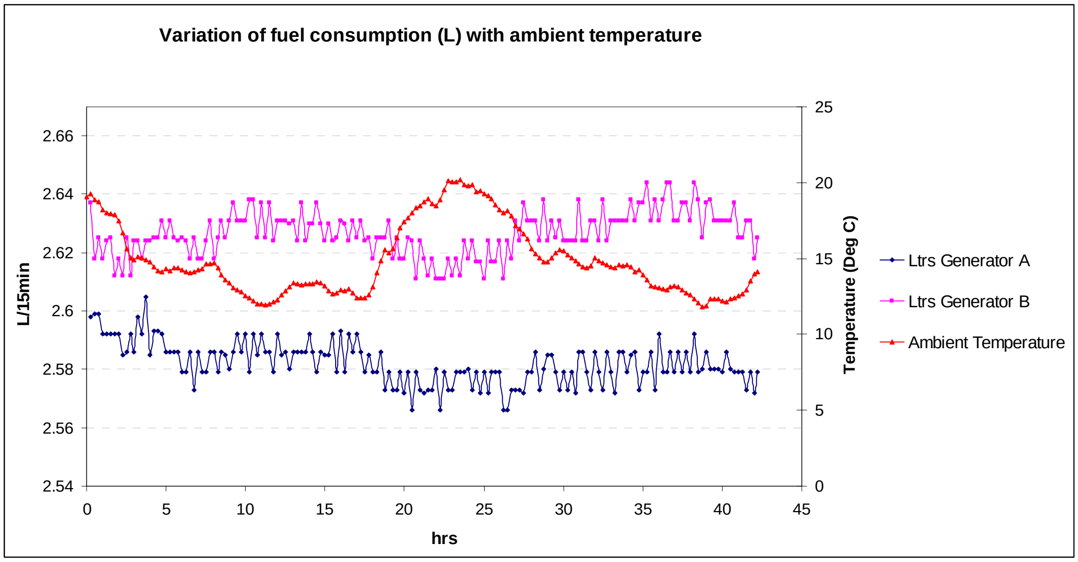


Figure B 3 Variation of fuel consumption with ambient temperature

60% load on new generators

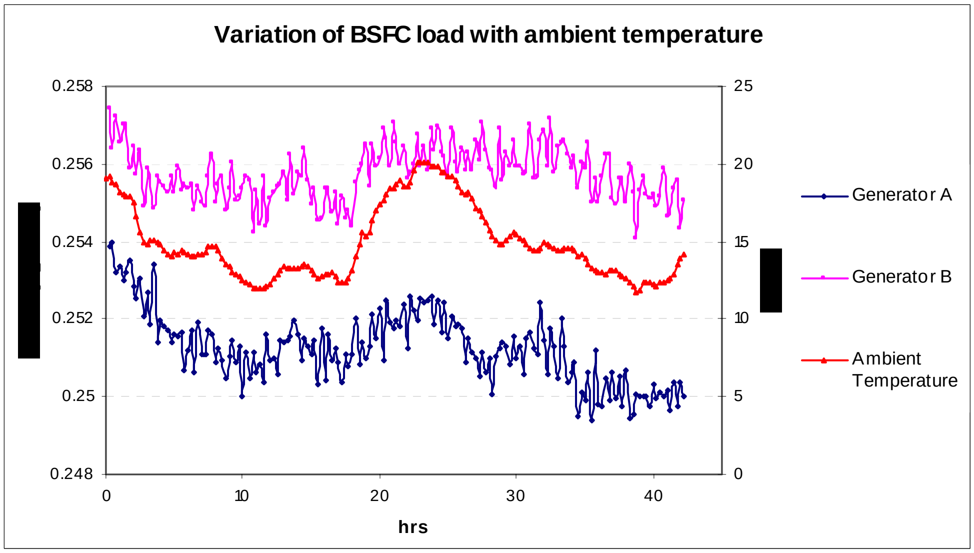


Figure B 4 Variation of BSFC with ambient temperature

60% Load on new generators

B.1.3<u>Behaviour of the new generators to environmental effects</u>

Figure B 4 shows the response of the generators to environmental effects. The BSFC of the generators appeared to follow that of ambient temperature. More importantly however, the BSFC of the two generators was in phases and thus one generator can be used as a control variable to subtract these effects.

B.1.4 Behaviour of the old generators to environmental effects

The older generators did not response to ambient effects quite as in-phase with each other as that of the new generators. Even though, both generators were of the same make and model with similar hours. This highlights the difficulty of measuring repeatable results on older engines. The more out of phase the generators, the harder (and more inaccurate) it was to subtract the effects of ambient conditions and changing fuel quality. The response to the two generators to ambient conditions appeared to diverge as testing progressed.

B.1.4.1 During the Nemo Testing

The Nemo testing was the first phase of testing on the older generators. There is a noticeable difference in response of one generator to the other, although the difference is only small. Generator 'A' appears to be invariant of temperature, while generator exhibits a weak opposite trend to temperature.

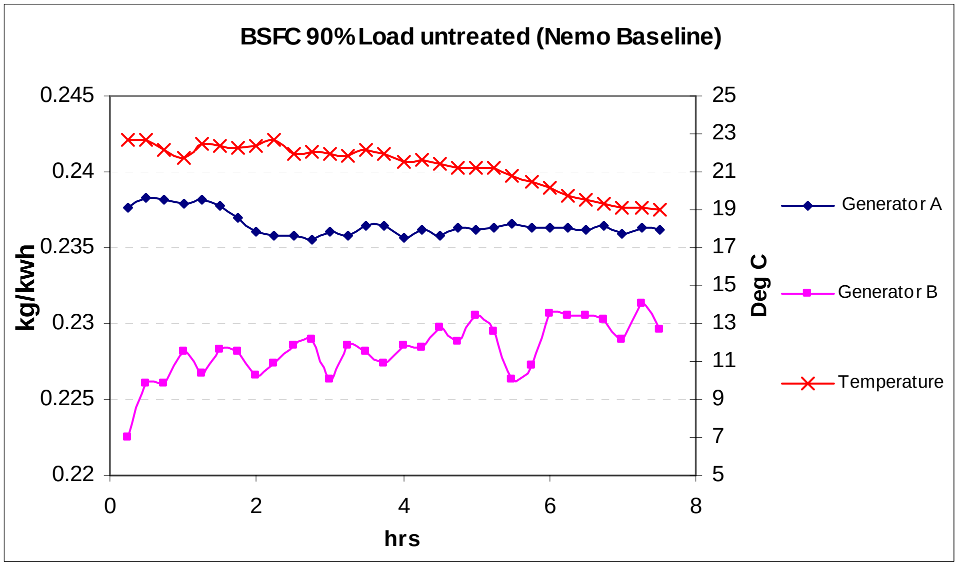


Figure B 5 Response of the old generators to temperature during Nemo testing

B.1.4.2 During the FTC testing

The FTC tests were conducted following the Nemo tests. Generator 'B' used as the untreated control variable throughout the Nemo tests appeared to continue the same trend with respect to temperature. The fuel consumption generator 'B' on the conversely increased it's sensitivity to temperature. The behaviour of the generators thus became out of phase. This provided complication for the data analysis and therefore the data from the FTC tests is somewhat speculative.

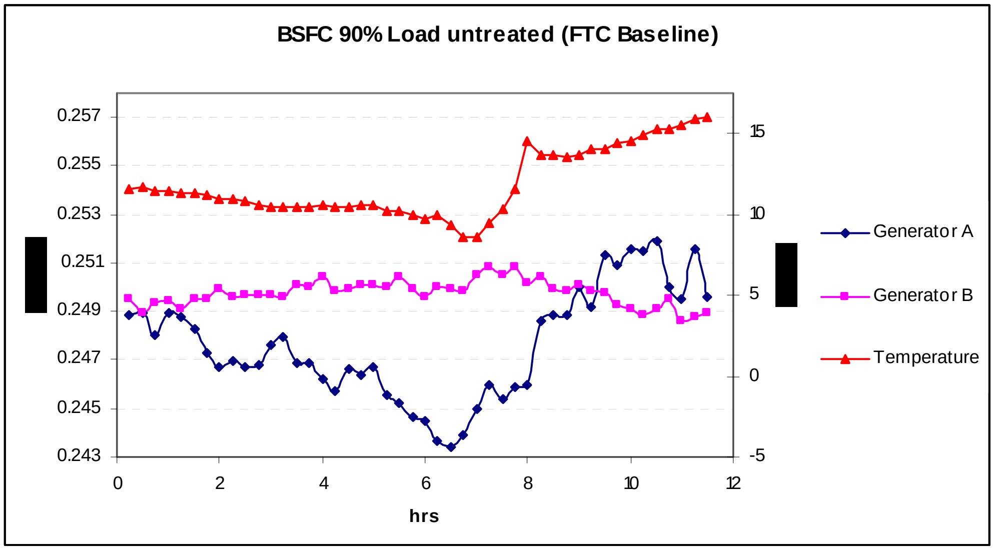


Figure B 6 Response of the older generators to temperature during the FTC testing

B.2Data analysis

The data analysis techniques used were developed to minimise data manipulation while removing environmental fuel quality influences. The quality of the fuel was not identical throughout the tests however, the experiment was conducted such that both generators contained the same fuel at any one time (within 10%). Furthermore, the generators used for the testing were of the same make and model with similar run hours to ensure a similar response to changes in fuel quality and ambient conditions.

B.2.1<u>Compiling of data</u>

The data from the testing was transferred into spreadsheet template developed for compilation of the data. The fuel flows readings, temperatures, and power output data were all imported into the spread sheet with date stamps. The inlet and outlet fuel flows in liters were converted to kilograms via a the adjusted density for the fuel temperature (using a formula relating to ASTM table 53B). The overall mass flow of fuel was then divided by the power produced during that period to provide a break specific fuel consumption (BSFC). This BSFC was then adjusted to with respect to the control variable as explained in the following section.

B.2.2<u>Adjustment of data</u>

The data was adjusted in the following manner to remove the effects of changing fuel quality and ambient conditions. One Generator ‘A’cted as a control variable and thus was run on untreated fuel throughout the testing. All results were adjusted to this generator so that the fuel consumption of the of the control variable during the baseline test and additive test was almost identical. The data was adjusted in the following steps:

1. A 3 point moving average (3PMA) was applied to the BSFC of both generators
2. The 3PMA BSFC of generator 'B' (control) was subtracted from the 3PMA BSFC of A and then the total average of B added to the final result.
3. The difference between the average of the control variable from the baseline to test was the subtracted from the treated result of Generator 'A'.

This process resulted essentially in the change in the difference between the test Generator 'A' and control generator measuring additive performance. Such manipulation of data induces more error into the final BSFC. However, the error associated with each data point from the flow measurement is quite small in comparison to the effects of ambient conditions and engine governing operation. Thus, the error associated from the fuel measurements was taken from observing the repeatability of time history data rather than applied error propagation techniques to the associated error of each data point.

The following example (Figure B 7 and Figure B 8) demonstrates the effect of the data adjustment. Figure B 7 clearly shows this improvement in the BSFC by treating with FTC however, without adjusting this data with respect to the control the percentage gain is over stated.

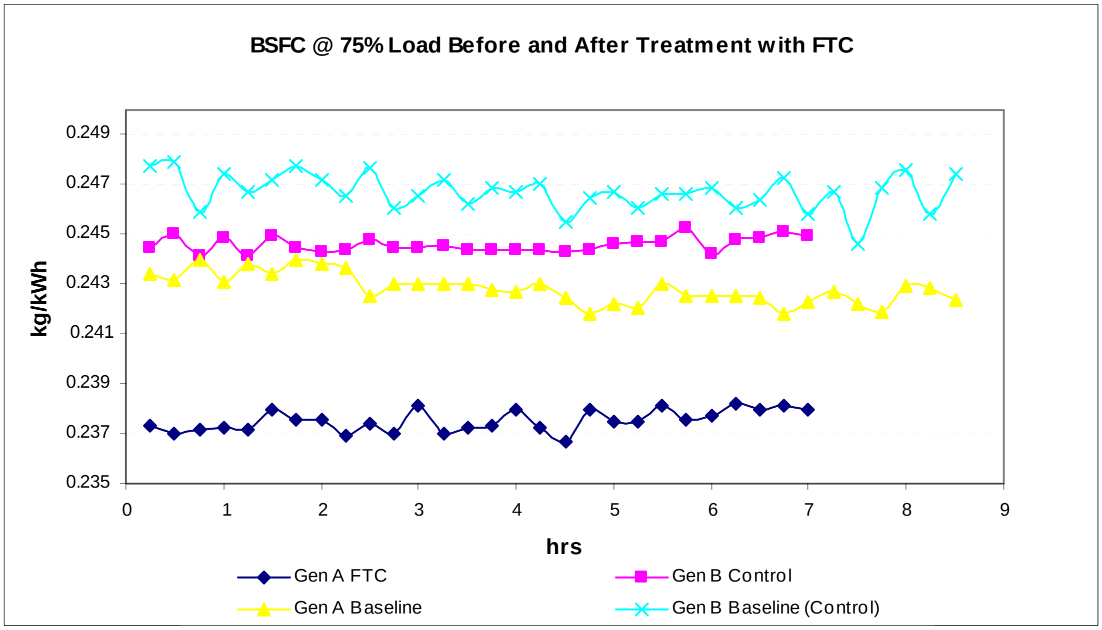


Figure B 7 BSFC before and after treatment with FTC without averaging or adjustment

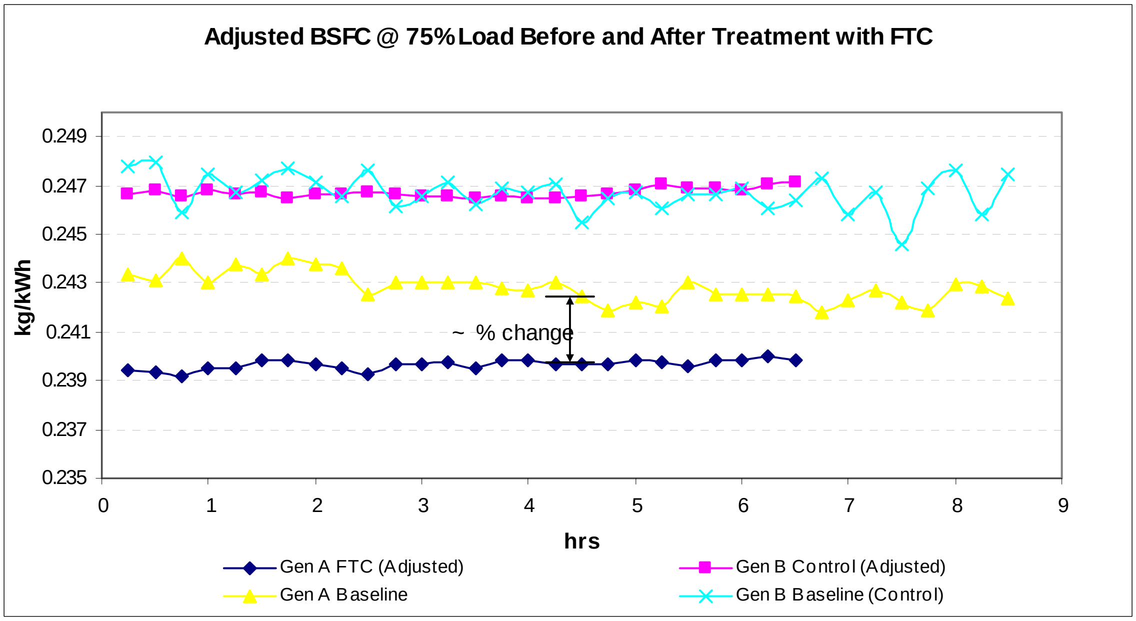


Figure B 8 BSFC before and after treatment with FTC Adjusted

The same data adjustment approach was undertaken for exhaust temperatures and emissions. In the case of exhaust emissions a quantitative error for each point was established from multiple readings of the same quantity. Error propagation techniques were then applied for the data adjustment of emissions.

B.2.2.1Alterations for the old generators

The response of the older generated was not as predictable as the new generators and thus the data exhibited a higher degree of noise. For this reason the data manipulation was kept to a minium to reduce error propagation. The same method was employed as the new generator expect step 2 was removed. This meant the data produced was just a 3-point moving average of the raw data with adjusted to the control generator.

During the FTC fuel consumption tests, the control variable started to move with fuel consumption as explained previously. This put the control variable approximately 180deg out of phase with that of the testing generator. A calibration factor based on the untreated measurements at each load was applied to the data (see Figure B 9 for an example). The same data adjustment of the Nemo test for the old generators was then applied. This method of data manipulation obviously reduces the accuracy of the data and for this reason the FTC results for the old engines have a high degree of error compared to all other tests conducted.

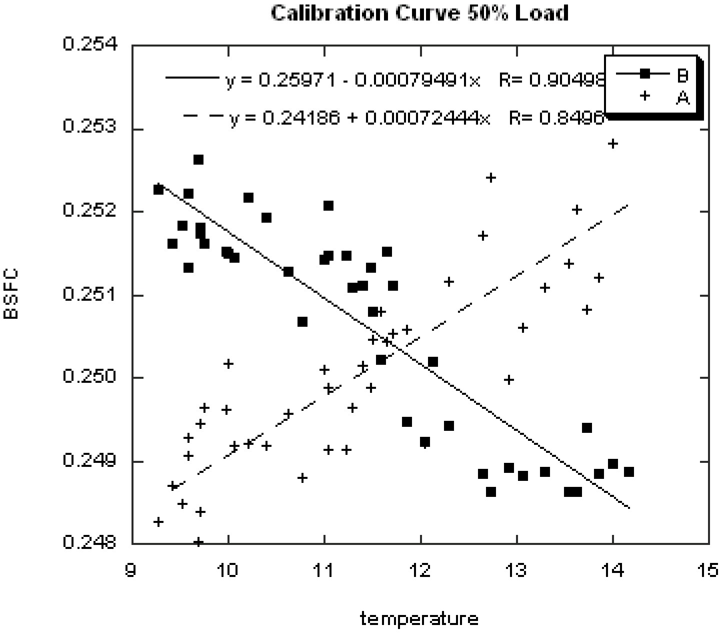


Figure B 9 Calibration curves for both generators 50% load

B.3 Repeatability of Data

The degree of repeatability of the data is important as it indicates how accurately the results can be stated. The following plots show examples of the repeatability of the data for the new and old engines. From the time history data the reliability of the data is around ± ½% and ± ¾% to ±1% for the older engines.

B.3.1 <u>New Generators</u>

Three tests were conducted with generator 'B' on the new engines at similar periods of the day (Figure B 10). Failures in the flow meters on Generator 'A' were present during these tests and thus that data cannot be presented. The plots show a high repeatability of data, such that the test lie within ± 1 percent.

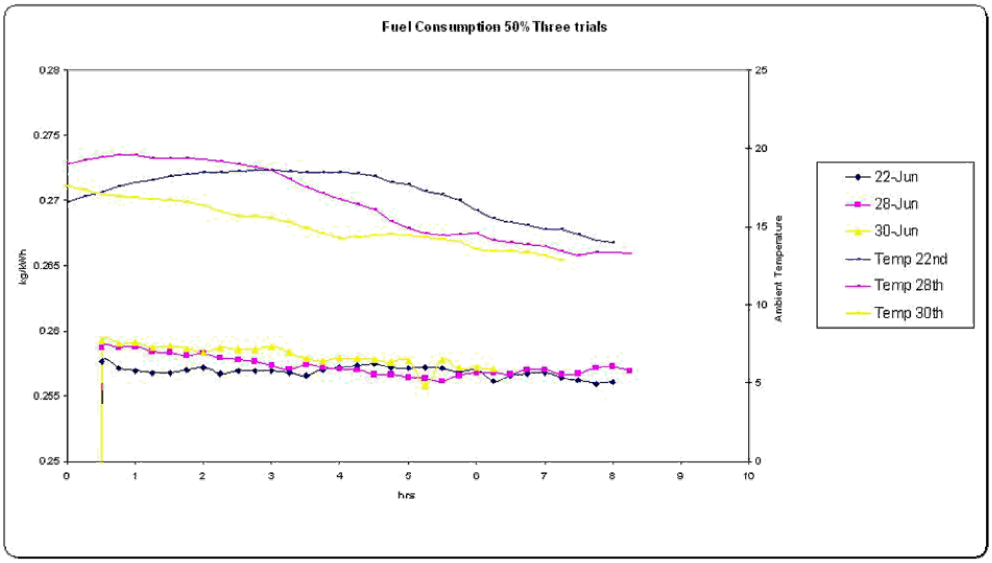


Figure B 10 Repeatability of data on the new generators

B.3.2 <u>Old Generators</u>

As explained each of the older generators did not respond to temperature in phase with each other as the new generators did. Figure B 11 shows the raw fuel consumption of the two generators under similar operating conditions. The same fuel and loading was applied the generators were run during a similar period of the night. However, there is some change in ambient conditions. If the control variable (Generator 'A') was adjusted to coincide for the two runs the error in the BSFC of generator 'B' is about 0.7%. . Figure B 11 highlights to difference in response to temperature that the two older generators were exhibiting during the FTC testing.

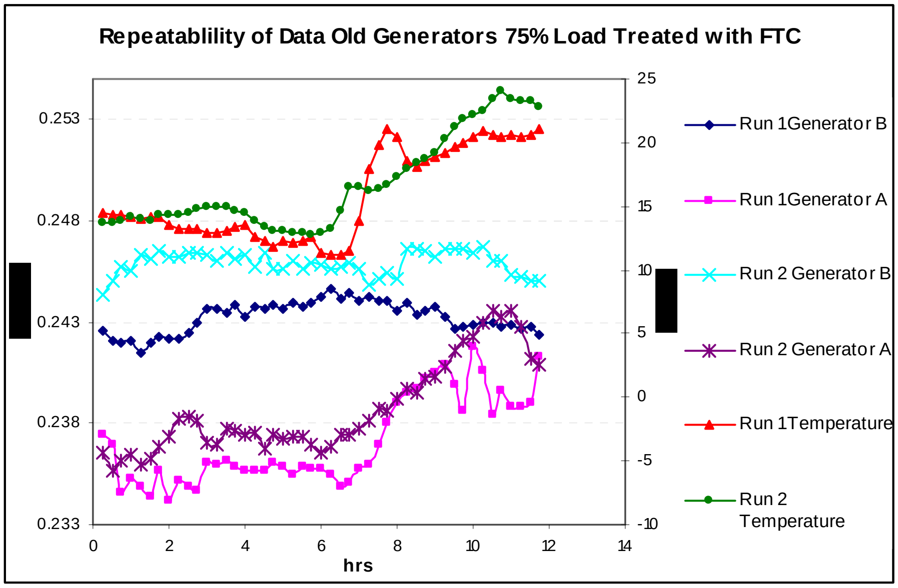


Figure B 11 Variation of fuel consumption for the old generators

Both tests were conducted at 75% load treated with FTC on two successive days.

Appendix C Additional Changes to testing and Considerations for fuel consumption testing

C.1Additional Testing and Changes to Testing

The quality of the data produced from the tests is the utmost concern of this investigation. Therefore any tests conducted that may have been influenced by component failure or degradation had to be re-run wherever possible. Thus, there were some additional tests run from those indicated by Figure 4-3. The following is this list of deviations from those described in section 4.1.1:

- The conditioning period of FTC was closer to 250 hours. This resulted from air entering the fuel system. The cause of this problem had to be isolated and proved significant to gain technical support. Thus a longer runtime occurred.
- The Nemo baseline had to be re-run due faulty radiators. An exhaust leak in Generator ‘A’ caused the clogging of the radiator and a pinhole leak developed in the radiator of engine B.
- Air entering the fuel system became a problem during the Nemo test and thus the test had to be re-run. After inspection of the data there appeared no residual effects of the additive. Thus to save time and money it was decided to run the Nemo baseline after with additive. Furthermore, this allowed the Nemo baseline to be used for the filtered baseline as filtered diesel tests followed this.
- The air entering the fuel system that compromised the first Nemo test also affect the first filtered diesel test. The air effects the fuel measurement through the flow meters however should not effect actual engine performance. Through personal communication with mechanics from Westrac it has been suggested that air bubbles in the fuel system should be removed at the fuel injector pump. Thus, the results of the fuel tests for the filtered diesel should not be affected, however additional tests were also taken on the second filtered diesel test for completeness.

The following section covers some important considerations for the measurement of fuel consumption. This information may also point to further methods of reducing fuel consumption in without major engine modification.

Considerations for fuel consumption testing

There are numerous variables that can effect the fuel consumption of a given engine and thus make the assessment of fuel additives difficult if not isolated. A comprehensive account of the effects is given in Judge (1967), however here is a brief list for future investigations to consider:

- The fuel consumption of engines even of the same model will vary
- The effect of an additive may vary from one engine to another depending on design and condition
- Engine efficiency varies with load and engine speed
- Base fuel properties can effect engine performance
- Ambient temperature and pressure effect fuel consumption and ID
- Fuel temperature and cooling water temperature effect engine performance

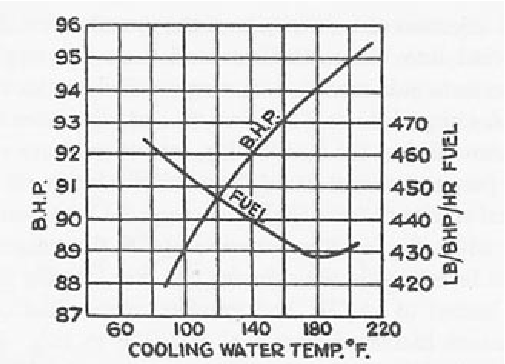


Figure C 1 Effect of fuel consumption and brake power with cooling water temperature Adapted from Judge (1967)

C.2Oil Sampling

Oil sampling is a common way of assessing the condition of an engine. Thus this can be a valuable tool for checking for damaging side effects of fuel additives. The oil sampling in this investigation was only intended to check for dramatic effects of the additives. If the oil sample history of an engine is available oil sampling during treatment with additives can be used to determine the long-term effects of engine life.

C.3Flow meter measurement and location

Positive displacement flow meters were used in this investigation to measure fuel flow rates. Two major issue effect the accuracy of flow measurements:

1. Air bubbles in the fuel lines, generally entering through primary fuel filter on the suction side of the lift fuel pump, or any other fuel line connection not well sealed on the suction side.
2. Fuel lift pumps on diesel engines can cause pulsation of the fuel flow on the pressure side of the pump. This is a problem with bi-directional flow meters and can cause fuel flow readings higher than the actual flow rate. This can generally be removed with a calibration, however is undesirable.

Appendix D Additional Project Management and Expenditure

The following spreadsheet details the project expenditure and the Gantt chart shows the final timeline of the project. Refer to the Microsoft Project® files for the initially planned project timeline. Note a separate report will be submitted showing the costing in more detail and the costs associated with breakdowns.

D.1Project Expenditure

Fuel Additives Project Expendature

	Diesel				Category				
Date	**Unit (L)**	**Cost per Unit**	**Item**	**Cost (Excluding GST)**	**Hire**	**Diesel**	**Fuel Pumping**	**Sundries**	**Other**
27/05/2005			Gloves for FTC and safety glasses	$ 17.16				x	
1/06/2005			Construction of Fuel Bund	$ 650.00					x
2/06/2005			Attapulgite	$ 13.50				x	
3/06/2005	2083.4	1.222	2083.4L of diesel from Min-Tankers	$ 2,545.91		x			
20/06/2005			20m of fuel hose and fitting	$ 217.91			x		
15/06/2005			Stationary for data records	$ 8.18				x	
25/06/2005	1044.5	1.298	1044.5L of diesel from Mini Tankers	$ 1,355.76		x			
27/06/2005			USB Thumb drive	$ 27.90					
15/07/2005	1499.0	1.318	1499L of Diesel from Mini-Tankers	$ 1,976.08		x			
19/07/2005	1619.9	1.318	1619.9L of Diesel from Mini-Tankers	$ 2,135.23		x			
26/07/2005	1754.6	1.313	1754.6L of Diesel From Min-Tankers	$ 2,303.79		x			
2/08/2005	1023.7	1.283	1023.7 Lof Diesel From Mini-Tankers	$ 1,313.41		x			
5/08/2005			Glassware	$ 36.50				x	
6/09/2005	2143.5	1.283	2143.5 L of Diesel from Mini-Tankers	$ 2,750.11		x			
13/08/2005	1607.2	1.299	1607.2L of Diesel from Mini-Tankers	$ 2,087.75		x			
			Extra Funding by Fuel Technology	-$ 2,160.00		x			
			Initial Equipment Hire and Services from PPS	$29,735.00	x				
20/08/2005	1423.3		1423.3L of Diesel from Mini-Tankers	$ 1,884.45		x			
26/08/2005	944.8	1.324	944L of Diesel from Mini Tankers	$ 1,250.92		x			
2/09/2005	2204.7	1.359	2205L of Diesel from Mini-Tankers	$ 2,996.19		x			
22/09/2005	2112.6	1.366	2123L of Diesel from Mini-Tankers	$ 2,885.81		x			
3/10/2005	1161.1	1.402	1161L of Diesel from Min-Tankers						
5/07/2005			Repair of Exhaust probe	$ 210.00					x
11/10/2005	1829.2	1.416	1829L Diesel From Mini-Tankers	$ 2,590.15		x			
5/10/2005	1580.0	1.402	1580L of Diesel from Mini-Tankers	$ 2,215.16		x			
8/10/2005	2228.5	1.416	22228L of Diesel from Mini-Tankers	$ 3,155.56		x			
14/10/2005	2000.0	1.249	2000L of Diesel from Cooper & Dysart	$ 2,497.14		x			
20/10/2005	1237.0	1.242	1237L of Diesel from Cooper & Dysart	$ 1,536.91		x			
18/10/2005	1200.0	1.249	1200L of Diesel from Cooper & Dysart	$ 1,498.28		x			
21/10/2005	1600.0	1.242	1600L of Diesel from Cooper & Dysart	$ 1,987.92		x			
			Extra Funding by Fuel Technology	-$ 2,606.90		x			
			Additional hire costs from PPS	$ 20,000.00	x				
			Additional fuel tanks and labour	$ 3,000.00	x				
				Totals	$ 52,735	$ 36,200	$ 217.91	$ 75	$ 860
Total Cost of Project									**$ 90,088**

Cost shown in yellow are estimated as totals were not finalised at the date of thesis commencement

Project Costs Vs Additional cost incured

Total Project Cost	$ 90,088	$ 90,291	Average fuel cost	1.31586

Acutal Testing Costs

		Cost
Hire (PPS) and Emmisions (4)		
New Generators	20days	$ 19,720
Filtered Diesel Test	4 days	$ 3,944
Old Generators	20days	$ 19,720
Additional fuel tanks and connection		$ 3,000
Fuel (1)		
New Generators	7650L	$ 10,066
FTC extra cond contribution	1600L	-$ 2,160
Filtered Diesel	1030L	$ 1,355
Old Generators (3)	10230L	$ 13,461
FTC extra cond contribution	1990L	-$ 2,607
Other		$ 210
Fuel Bund		$ 650
Sundries		$ 75
Total Testing Costs		$ 67,435

Additional Costs Estimated

Event	Time Lost	Hire Cost	Fuel Cost (2)
Flow meter failure	30days	$ -	$ 3,290
Air leak in primary fuel filter Gen A	7days	$ -	$ 2,632
Failure of radiator cap Gen A	1.5 days	$ -	$ 263
Clogged radiator Gen A	2days	$ -	$ 263
Hole in radiator Gen B	4days	$ 2,000	$ 882
Air leak in primary fuel filter Gen A again (after replacement)	7days	$ 4,000	$ 882
Restricte Running due to Noise complaints	12 days	$ 6,000	$ -
Temp sensor faulure Gen A (Old)	1.5 days	$ -	$ 158
Recording Temperature failure	1 day	$ -	$ 316
Over temperature sensor breakdown	0.5 days		$ 197
Fuel left over due to termination prior to expected completion(Noise complants)	0	0	$ 1,974
Totals		**$ 12,000**	**$ 10,856**
Total Additonal Costs			**$ 22,856**

Notes:

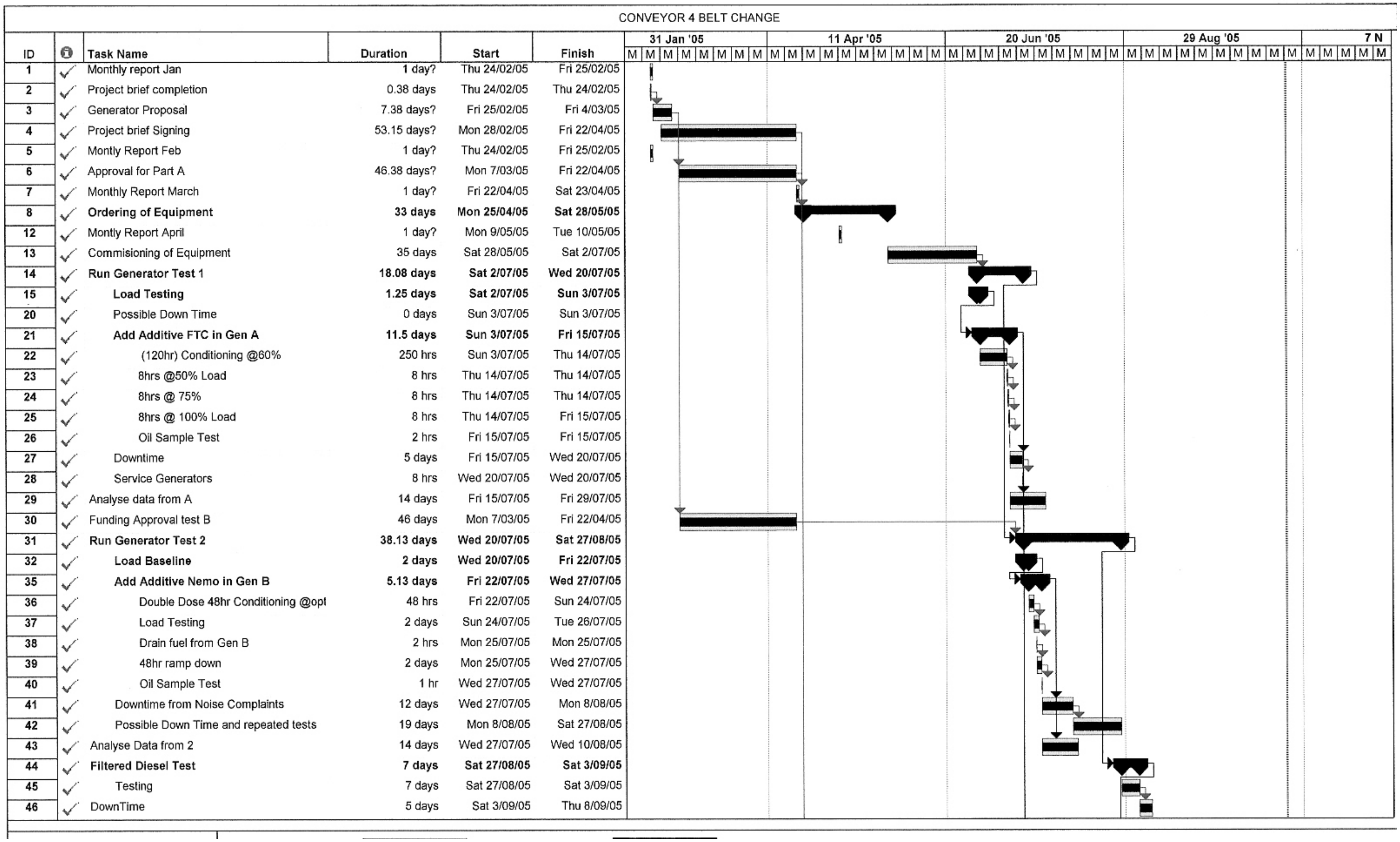
(1) The generator fuel usage was higher than initally budgeted for due to comercial avavliability of generators

(2) fuel costs are priced on the average fuel cost for simplicity

(3)the Older generators were larger and FTC required longer conditioning thus cost were higher

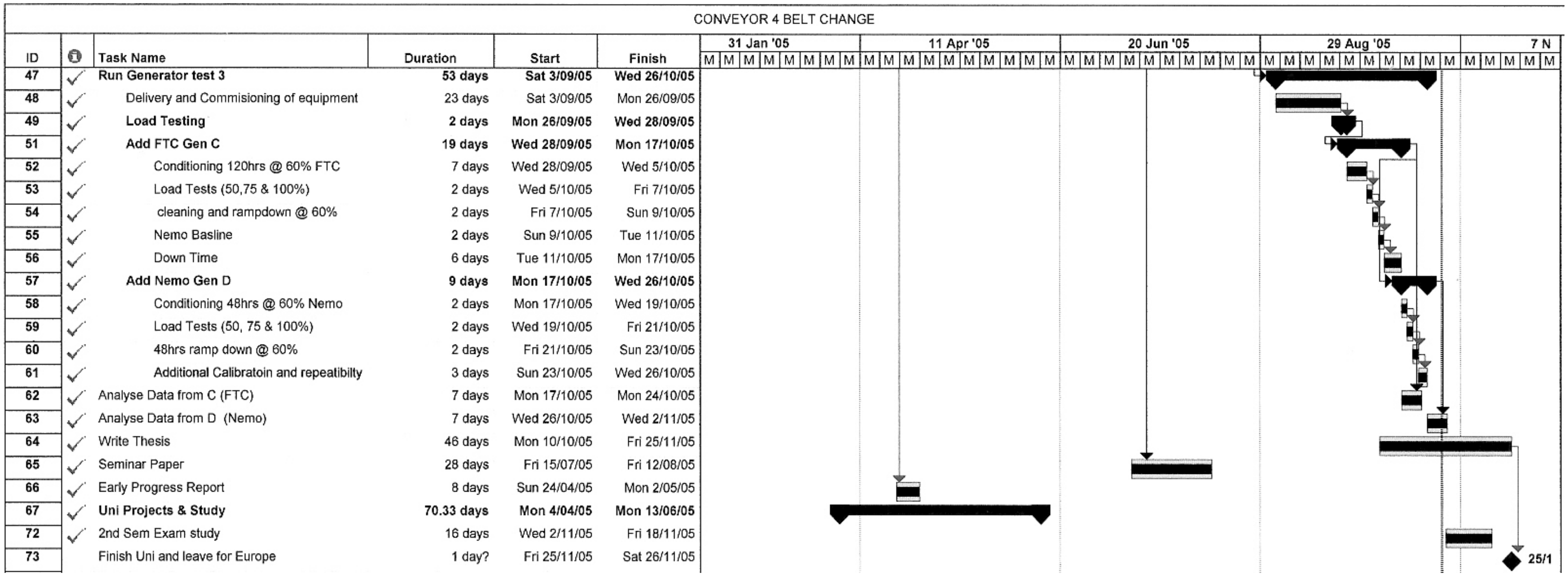
(4) Hire costs include oil samples and servicing

D.2Project Time Allocation



CONVEYOR 4 BELT CHANGE

ID	ⓘ	Task Name	Duration	Start	Finish
1	✓	Monthly report Jan	1 day?	Thu 24/02/05	Fri 25/02/05
2	✓	Project brief completion	0.38 days	Thu 24/02/05	Thu 24/02/05
3	✓	Generator Proposal	7.38 days?	Fri 25/02/05	Fri 4/03/05
4	✓	Project brief Signing	53.15 days?	Mon 28/02/05	Fri 22/04/05
5	✓	Montly Report Feb	1 day?	Thu 24/02/05	Fri 25/02/05
6	✓	Approval for Part A	46.38 days?	Mon 7/03/05	Fri 22/04/05
7	✓	Monthly Report March	1 day?	Fri 22/04/05	Sat 23/04/05
8	✓	**Ordering of Equipment**	**33 days**	**Mon 25/04/05**	**Sat 28/05/05**
12	✓	Montly Report April	1 day?	Mon 9/05/05	Tue 10/05/05
13	✓	Commisioning of Equipment	35 days	Sat 28/05/05	Sat 2/07/05
14	✓	**Run Generator Test 1**	**18.08 days**	**Sat 2/07/05**	**Wed 20/07/05**
15	✓	**Load Testing**	**1.25 days**	**Sat 2/07/05**	**Sun 3/07/05**
20	✓	Possible Down Time	0 days	Sun 3/07/05	Sun 3/07/05
21	✓	**Add Additive FTC in Gen A**	**11.5 days**	**Sun 3/07/05**	**Fri 15/07/05**
22	✓	(120hr) Conditioning @60%	250 hrs	Sun 3/07/05	Thu 14/07/05
23	✓	8hrs @50% Load	8 hrs	Thu 14/07/05	Thu 14/07/05
24	✓	8hrs @ 75%	8 hrs	Thu 14/07/05	Thu 14/07/05
25	✓	8hrs @ 100% Load	8 hrs	Thu 14/07/05	Fri 15/07/05
26	✓	Oil Sample Test	2 hrs	Fri 15/07/05	Fri 15/07/05
27	✓	Downtime	5 days	Fri 15/07/05	Wed 20/07/05
28	✓	Service Generators	8 hrs	Wed 20/07/05	Wed 20/07/05
29	✓	Analyse data from A	14 days	Fri 15/07/05	Fri 29/07/05
30	✓	Funding Approval test B	46 days	Mon 7/03/05	Fri 22/04/05
31	✓	**Run Generator Test 2**	**38.13 days**	**Wed 20/07/05**	**Sat 27/08/05**
32	✓	**Load Baseline**	**2 days**	**Wed 20/07/05**	**Fri 22/07/05**
35	✓	**Add Additive Nemo in Gen B**	**5.13 days**	**Fri 22/07/05**	**Wed 27/07/05**
36	✓	Double Dose 48hr Conditioning @opl	48 hrs	Fri 22/07/05	Sun 24/07/05
37	✓	Load Testing	2 days	Sun 24/07/05	Tue 26/07/05
38	✓	Drain fuel from Gen B	2 hrs	Mon 25/07/05	Mon 25/07/05
39	✓	48hr ramp down	2 days	Mon 25/07/05	Wed 27/07/05
40	✓	Oil Sample Test	1 hr	Wed 27/07/05	Wed 27/07/05
41	✓	Downtime from Noise Complaints	12 days	Wed 27/07/05	Mon 8/08/05
42	✓	Possible Down Time and repeated tests	19 days	Mon 8/08/05	Sat 27/08/05
43	✓	Analyse Data from 2	14 days	Wed 27/07/05	Wed 10/08/05
44	✓	**Filtered Diesel Test**	**7 days**	**Sat 27/08/05**	**Sat 3/09/05**
45	✓	Testing	7 days	Sat 27/08/05	Sat 3/09/05
46	✓	DownTime	5 days	Sat 3/09/05	Thu 8/09/05



CONVEYOR 4 BELT CHANGE

ID	ⓘ	Task Name	Duration	Start	Finish
47	✓	**Run Generator test 3**	**53 days**	**Sat 3/09/05**	**Wed 26/10/05**
48	✓	Delivery and Commisioning of equipment	23 days	Sat 3/09/05	Mon 26/09/05
49	✓	**Load Testing**	**2 days**	**Mon 26/09/05**	**Wed 28/09/05**
51	✓	**Add FTC Gen C**	**19 days**	**Wed 28/09/05**	**Mon 17/10/05**
52	✓	Conditioning 120hrs @ 60% FTC	7 days	Wed 28/09/05	Wed 5/10/05
53	✓	Load Tests (50,75 & 100%)	2 days	Wed 5/10/05	Fri 7/10/05
54	✓	cleaning and rampdown @ 60%	2 days	Fri 7/10/05	Sun 9/10/05
55	✓	Nemo Basline	2 days	Sun 9/10/05	Tue 11/10/05
56	✓	Down Time	6 days	Tue 11/10/05	Mon 17/10/05
57	✓	**Add Nemo Gen D**	**9 days**	**Mon 17/10/05**	**Wed 26/10/05**
58	✓	Conditioning 48hrs @ 60% Nemo	2 days	Mon 17/10/05	Wed 19/10/05
59	✓	Load Tests (50, 75 & 100%)	2 days	Wed 19/10/05	Fri 21/10/05
60	✓	48hrs ramp down @ 60%	2 days	Fri 21/10/05	Sun 23/10/05
61	✓	Additional Calibratoin and repeatibilty	3 days	Sun 23/10/05	Wed 26/10/05
62	✓	Analyse Data from C (FTC)	7 days	Mon 17/10/05	Mon 24/10/05
63	✓	Analyse Data from D (Nemo)	7 days	Wed 26/10/05	Wed 2/11/05
64	✓	Write Thesis	46 days	Mon 10/10/05	Fri 25/11/05
65	✓	Seminar Paper	28 days	Fri 15/07/05	Fri 12/08/05
66	✓	Early Progress Report	8 days	Sun 24/04/05	Mon 2/05/05
67	✓	**Uni Projects & Study**	**70.33 days**	**Mon 4/04/05**	**Mon 13/06/05**
72	✓	2nd Sem Exam study	16 days	Wed 2/11/05	Fri 18/11/05
73		Finish Uni and leave for Europe	1 day?	Fri 25/11/05	Sat 26/11/05

Appendix E Equipment Specifications

E.1Filter used for filtered diesel tests

Supplier: Pall

Model: ULTIPOR III β_1>= 200

Model #: HC74005 KZAN

E.2Flow Meters

MacNaught M05 positive displacement flow meters

Hall effect sensor model (after repeated failure of the reed switch model)

Accuracy ±1%

Repeatability ± 0.03%

E.3Generators

Generators supplied by Energy Power Systems (hired through PPS)

New set of generators

- A (1300hrs on delivery) 75kVA Olympian generator; engine Perkins 4 cylinder 1000 series, turbocharged, not after-cooled
- B (600hrs on delivery) 75kVA Olympian generator; engine Perkins 4 cylinder 1000 series, turbocharged, not after-cooled

Old set of Generators

- A (7000 hrs on delivery) 100kVA Cat Generator; engine Perkins 6 cylinder 1000 series, turbocharged, not after-cooled
- B (5500 hrs on delivery) 100kVA Cat Generator; engine Perkins 6 cylinder 1000 series, turbocharged, not after-cooled

E.4Load Banks

Resistive 600kW load banks constructed by PPS, with load increments of 1kW

E.5Data Recorder

Specially designed unit built by PPS running ION Enterprise software

Appendix F Additive Information

TECHNICAL BULLETIN

No. **TB101-97**

FTC-3 COMBUSTION CATALYST

PRODUCT BENEFITS **DIESEL ENGINES**

- *REDUCES FUEL CONSUMPTION*
- *REDUCES AIR POLLUTION*
- *LOWERS MAINTENANCE COSTS*
- *INCREASES ENGINE EFFICIENCY*
- *ACTS AS A BIOCIDE IN FUEL*

PRINCIPAL USES

FTC-3 is used to reduce fuel consumption, provide cleaner engine combustion spaces and lower maintenance costs.

GENERAL DESCRIPTION

FTC-3 is a complex organo-metallic (ferrous picrate) combustion catalyst which when added to liquid petroleum fuels at the correct ratio effectively improves the combustion reaction.

Density @ 15°C	0.89
Flash Point (Closed Cup) °C	40
Boiling Point°C	140
Colour	Dark Green
Odour	Aromatic

DOSAGE

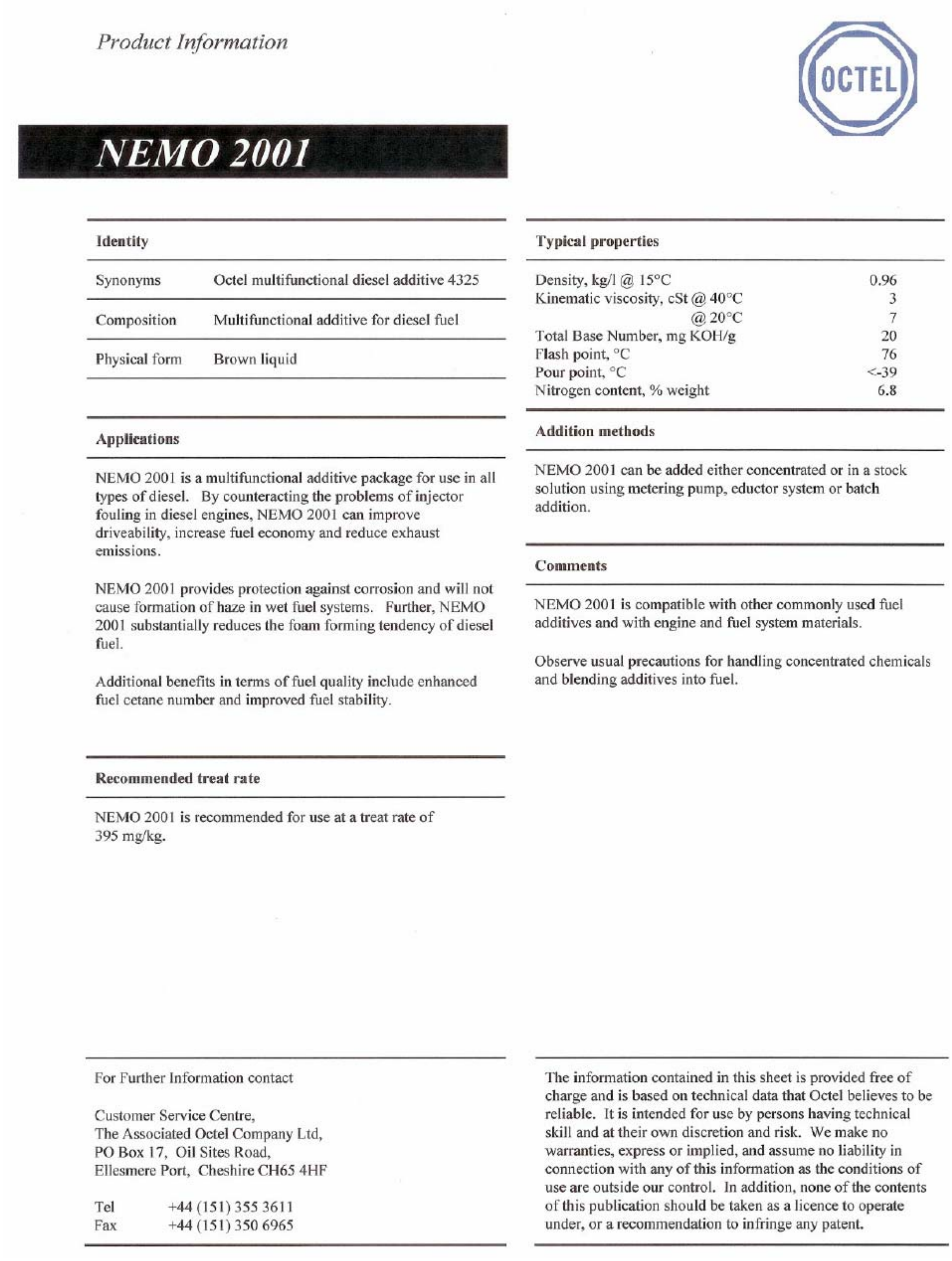
FTC-3 should be added to the fuel storage tank before fuel is added to ensure good mixing, or alternatively be injected by mechanical dosing pump. Dosing rate is one litre **FTC-3** to 3200 litres of fuel.

HANDLING & SAFETY

FTC-3 contains Solvent 150 as a carrier and the same precautions should be taken as when working with any hydrocarbon liquids. Do not get into eyes. Wear goggles or face shield and protective gloves when handling. Avoid contact with skin and clothing. Avoid breathing vapour. Do not take internally. Keep away from open flame. Keep container closed when not in use. Store under shade. For more detail refer Material Safety Data Sheet.

FEATURES	***BENEFITS***
IMPROVES COMBUSTION REACTION	*Helps reduce fuel consumption* *Helps reduce air pollution* *Helps reduce maintenance costs.*
SOLVENT ACTION HELPS CONTROL SLUDGE AND GUM FORMATION IN STORAGE TANKS	*Helps maintain cleaner filters and injectors*
BIOCIDAL ACTION	*Helps maintain freedom from fungal growths in fuel.*

Fuel Technology Pty Ltd warrants that **FTC-3** will not, when used according to the directions, damage in any way or shorten the life of internal combustion engines.



Product Information

NEMO 2001

Identity

Synonyms	Octel multifunctional diesel additive 4325
Composition	Multifunctional additive for diesel fuel
Physical form	Brown liquid

Applications

NEMO 2001 is a multifunctional additive package for use in all types of diesel. By counteracting the problems of injector fouling in diesel engines, NEMO 2001 can improve driveability, increase fuel economy and reduce exhaust emissions.

NEMO 2001 provides protection against corrosion and will not cause formation of haze in wet fuel systems. Further, NEMO 2001 substantially reduces the foam forming tendency of diesel fuel.

Additional benefits in terms of fuel quality include enhanced fuel cetane number and improved fuel stability.

Recommended treat rate

NEMO 2001 is recommended for use at a treat rate of 395 mg/kg.

Typical properties

Density, kg/l @ 15°C	0.96
Kinematic viscosity, cSt @ 40°C	3
@ 20°C	7
Total Base Number, mg KOH/g	20
Flash point, °C	76
Pour point, °C	<-39
Nitrogen content, % weight	6.8

Addition methods

NEMO 2001 can be added either concentrated or in a stock solution using metering pump, eductor system or batch addition.

Comments

NEMO 2001 is compatible with other commonly used fuel additives and with engine and fuel system materials.

Observe usual precautions for handling concentrated chemicals and blending additives into fuel.

For Further Information contact

Customer Service Centre,
The Associated Octel Company Ltd,
PO Box 17, Oil Sites Road,
Ellesmere Port, Cheshire CH65 4HF

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