Bio-Fuels for the Fishing Industry

prepared for:

The Sea Fish Industry Authority

with support from:

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Executive Summary

This report details work carried out to investigate the performance of biofuels in marine diesel engines, relative to the use of fossil petrodiesel. The scope of work ultimately included:

1) The installation of a dynamometer test facility, equipped to run diagnostic and simulated operational duty cycles on marine diesel engines.
2) The leasing of a ~30 feet long fishing vessel, Ma Gandole, equipped for shell fish operations, to provide a dedicated platform for the testing of biodiesel under real operating conditions at sea, based from Newlyn.
3) The fabrication of a 400 litre biodiesel batch production plant to produce self-manufactured biodiesel for testing in the dynamometer test facility and the project fishing vessel.
4) Use of the dynamometer test facility to test a range of diesel additives, proposed for adoption by the UK fishing fleet to reduce diesel fuel consumption and reduce costs.

The dynamometer test facility was successfully installed, commissioned and brought into an operational state. It featured a Perkins marine diesel engine that had already seen operational service rather than a new engine as this was considered to provide a better analogue for actual in service engines of the UK sub-10m fleet. The project suffered setbacks though major engine failures, one of which was attributed to the age of the engine that occurred shortly after the commissioning phase was thought to be complete, and another right at the end of the testing programme supported. Despite these setbacks, the report demonstrates that repeatable and reliable results were obtained from the dynamometer test facility.

This document reports sea trials of Ma Gandole using bio-diesel meeting the BS EN 14214 biodiesel standard and self-manufactured biodiesel that did not, as well as sea trials with the engine running on BS590 fossil diesel. No operational problems were encountered with Ma Gandole's engine when operating on biodiesel. The vessel did encounter operational problems over the project but these are not attributable to the fuel (for example, gearbox malfunction). No significant change in fuel consumption between fossil diesel and biodiesel was observable from the test run data.

This document reports the results of tests on red diesel fuel additives, benchmarking these against identical test cycles with fossil diesel alone. The test cycle used simulated a trawler operating a 20 hour 40 minute excursion from Newlyn and within this involved 3, 4 hour long trawl stages. Seven additives were subjected to the trials.

The results of this phase of the work indicate that there is no significant effect of any of the additives tested on the fuel consumption of the test engine through the test cycle used. If the results from the tests are considered typical of real duty cycles, then use of additives would increase operating costs for fisherman as they would have to pay for the additive as well as for the fuel.

The test cycles adopted for this work ultimately were found to be very demanding on the test engine, especially for the biodiesels tested. As was consistent with the project rationale of minimal intervention when switching fuels, no engine modifications were made to the test engine between comparative trials between different fuels, other than those required as part of normal engine maintenance, e.g. top up of engine oil. Fuel consumption expressed in terms of litres / kWh of useful work provided indicated 14.5% higher fuel consumption than fossil diesel for the BS 14214 biodiesel and 19.3% higher fuel consumption for the self-manufactured fuel. With these figures and if the price of biodiesel is taken to be pegged to the price of fossil diesel for which it is a competing substitute (which is likely as it is dominated by the automotive fuel market as well as Government regulation), there would be no cost benefit to fisherman in switching to biodiesel. The exception to this observation is if biodiesel is self-manufactured by fishermen with control over local feedstocks at a much lower cost. This is why a self-manufacturing facility ultimately featured in the project scope.

Under a maximum power test involving a full throttle setting and set points spanning the range of engine speeds, the engine produced less torque across the range with the biodiesels than with fossil diesel, as expected due to the lower calorific value of biodiesel in comparison to fossil diesel.

In testing with the day trawler cycle initially used for the additives testing, approximately 2.2% of the disparity between fossil diesel and BS 14214 biodiesel fuel consumption could not be explained by the reduced calorific value of the biodiesel; for the self-manufactured biodiesel this figure was 4.3%. In the case of the BS 14214 biodiesel, this is attributed to engine timing settings that while being optimal for fossil diesel are sub-optimal for the biodiesel with its slightly different fuel ignition characteristics. Under the very demanding testing regime specifically imposed by the trawl stages of the day trawler cycle, the differences in fuel characteristics emerge in increased fuel consumption figures or equivalently slightly lower engine efficiency figures. During the test cycle stages with more moderate engine loading, the test engine had higher efficiency when running on biodiesel. This is attributed to the distinctions in ignition characteristics being overwhelmed by the superior lubricity of biodiesel fuels, widely reported in the biodiesel literature.

With either of the biodiesels tested, the engine was able to support an identical fishing operational performance.

Under the prolonged extremely high duty of the trawl stages of the day trawler test cycle, the test engine exhibited progressive deterioration in performance when run with the self-manufactured biodiesel. However the testing was completed successfully and the engine delivered the required performance using the fuel – but not without problems.

After the test had completed, the engine was stripped down and had been found to have suffered a piston ring fracture in one cylinder and piston rings seized in their grooves in two other cylinders. This outcome is attributed to the fuel's different ignition characteristics in comparison to fossil diesel. This difference is not great, but its significance and consequences are much more pronounced when the engine is operating at very close to full load at the specified engine speed. In an engine optimally timed for fossil diesel, the ignition characteristics of the self manufactured fuel lead to irregular combustion pressures. Irregular combustion pressures are the frequently cited reason for piston ring fractures. A piston ring fracture allows combustion gas by-pass into the crankcase. The evidence recorded in the data logged during the testing and the remaining problems identified upon strip down are corollaries of this event. It is worth noting that even after the phase of engine deterioration experienced (it is identifiable in the data recorded), the self-manufactured biodiesel still recorded the highest engine efficiency figure for the simulated return trip to port.

In the context of the project objective of examining the efficacy of biofuels for use in the fishing industry, the testing on the self manufactured biodiesel ultimately provided extremely useful information. In terms of engine performance, self-manufactured biodiesel should provide a competent fuel for skippers of fishing vessels, but even in a very well maintained engine, skippers must not expect that they can push their engines quite as hard as they could, over the durations that they do using fossil diesel, without relatively minor engine modifications to take account for specific variances in fuel properties that become more apparent when the engines are run at high loads for long durations, the engine timing being an obvious example. Unfortunately, these findings still require confirmation through continued testing.

Increased fuel consumption or engine performance problems with this fuel observed in the especially demanding tests on the test rig were not observed in trials at sea, where fuel consumption figures were highly variable and no engine problems were encountered. This confirms that environmental conditions and typical operating duties are significant determinants of fuel consumption at sea, as was recognised at the outset of the project. It is particularly unfortunate and frustrating for the project team that equipment installed on Ma Gandole to measure the *in-situ* engine performance did not survive the wet environment below deck long enough to provide any reliable data. However, it is clear that actual duty cycles <u>must</u> be measured. It is only with this information that a definitive picture of the relative fuel performance will emerge. The facilities at Holman's Test Mine created to support this project remain operational and the project staff now have permanent employment within the University. Therefore the capacity exists to undertake further work relating to marine fuels, and the priority research objective is engine performance testing following actual boat duty cycles, not test cycles that are so close to the maximum power curves that they push the engine toward destruction.

It is hoped that with the continuing support of the Sea Fish Industry Authority for this work, reliable *in-situ* engine performance curves for trawling and potting boats in the ~10m class will be obtained and permit conclusive results on the relative performance of these fuels to emerge, that support the central finding of the work thus far:

This project has successfully demonstrated the technical viability of bio-diesel as a fuel for fishing vessels. The practical issues surrounding relatively small scale production of bio-diesel from low cost sources have been explored such that effective practical support can be provided to any elements of the fishing industry that wish to consider this option.

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Introduction

Project Scope

The project was conceived as an investigation into the use of bio-diesel in the fishing industry. Seafish administered this project in parallel with another study by a third party into the use of straight vegetable oil (SVO) as an alternative to red diesel. Collectively these 2 studies were called "Biofuels for the Fishing Industry" by Seafish. Given that the 2 studies were fundamentally different, there was relatively little contact between them.

The principle source of data was to be an onshore test cell, constructed at Holman's Test Mine. The test cell was to be based around a marine diesel engine, chosen to be typical of those used by inshore fishing vessels. As originally conceived the engine was to be of 40hp to 80hp to represent the size of engine most commonly used in the small inshore vessels that make up most of the Cornish fishing fleet. During pre-project discussions with Seafish, the project was re-focussed on the 120hp bracket to make the findings more applicable to vessels on a national scale.

The test cell was to be fully instrumented to allow test cycles to be programmed and a wide range of performance parameters to be logged. The objective was to establish the suitability of bio-diesel as an alternative to red diesel in the context of a fishing vessel engine.

The testing at the mine was to be supplemented by trials at sea in a real fishing vessel with an engine of similar size. The trials at sea were intended to establish whether the fuel would function adequately under real conditions as well as under standardised test conditions. The sea trials were also intended to raise the profile of the project, making it visible to the local fishing community.

During the project it was agreed with Seafish that the scope would be amended to include the construction of a bio-diesel production facility and a suitable supplier was identified in March 2006. The rationale behind this was that bio-diesel would probably not be economically attractive for fishing if it had to be sourced from producers supplying the road transport market. Having bio-diesel production capacity also facilitated the processing of low grade feedstock to derive a low cost fuel. No additional resources were deployed to implement this broadening of the scope. Although the fuel production plant diverted resources from other areas of the project, it was a very worthwhile element of the work that has greatly enhanced our understanding of the practical issues surrounding fuel production. Bio-diesel was produced from feedstock that was obtained free of charge.

During the course of 2006 assistance was given to Seafish to produce a scope of work for trialling fuel additives using the onshore test cell. In March 2007 this developed into an order to carry out testing, with the additive testing to take priority over bio-diesel testing. The results of the additive testing are reported herein but will also be reported separately.

Rationale

The rationale behind the project was that with rising red diesel prices not being matched by rises in the market prices of fish, the fishing industry was inevitably becoming less viable. Camborne School of Mines, a department of the University of Exeter, is located in west Cornwall where the inshore fishing industry remains an important element in the local economy.

The intention was to evaluate bio-diesel as a realistic alternative to red diesel. It was recognised that fuel substitution would only occur when it was economically attractive, but that there was a need to have an alternative to red diesel available to deploy at relatively short notice in case red diesel prices continued to rise.

It was evident that any requirement to modify a vessel would constitute a barrier to the take up of an alternative fuel. It was also highly desirable that reversion to the use of red diesel should also be readily achieved. Vegetable oil was considered as an option but was thought to be somewhat impractical for most local vessels due to the volume and expense of the equipment needed to pre-heat the fuel. Bio-diesel was identified as the alternative fuel most likely to be interchangeable with red diesel without significant modifications to a vessel.

In order to produce scientifically valid data it was necessary to construct an instrumented test rig that could operate repeatable tests under standardised conditions. The engine was essentially a standardised component within the rig, with the fuel becoming the variable factor. A used engine was selected on the basis that few fishing vessels have new engines so a used engine would be more representative of the operating conditions that the project aimed to simulate. A pair of normally aspirated 120hp Perkins 6 cylinder engines in good working order was procured from a large workboat (Portree II) that was being fitted with larger engines. Having two engines from the same vessel provided a source of spare parts (or a complete spare engine) with a near identical operating history to that which was selected for the rig.

When scoping the project it was felt that whilst standardised testing in an onshore test cell would provide valuable data, it was out of sight from the fishing community. Given that we wanted to raise awareness of bio-diesel amongst fishermen and anticipating that an obvious question from fishermen would be *"does it work at sea?"* it was decided that once confidence in the fuel had been gained through onshore testing, it should then be demonstrated in trials at sea. The issues surrounding dealing with the consequences of potential failures in a working fishing vessel resulted in the conclusion that the sea trials should be performed in a dedicated vessel where access would be unrestricted and no fisherman's livelihood would be jeopardised in the event of technical failures.

Project Objectives

During the course of the project, the scope of work evolved, with changes being based on discussions between the University and Seafish. The basic project objectives have all been met:

1 – to *demonstrate that fishing vessels can be operated using existing fuels from renewable sources without major engine modifications.*

The data obtained from the test plant has demonstrate bio-diesel to EN14214 to be a satisfactory fuel, capable of achieving engine output comparable to that achieved using red diesel but at the cost of increased fuel consumption.

2 – *to develop a renewable fuel suitable for use on fishing vessels that is optimised for cost, thereby offering cost neutrality or better compared with conventional diesel.*

Bio-diesel was successfully manufactured from locally sourced feedstock that was obtained at zero cost. The test results from this fuel were inferior to those obtained from bio-diesel meeting EN14214. The production costs of this fuel were below the cost of red diesel and below the market price for commercially available bio-diesel

3 – *To apply these developments firstly to the Newlyn fishing fleet and then to make the technology available for application through the fishing industry.*

Locally produced bio-diesel not certified to EN14214 has been demonstrated in a fishing vessel based in Newlyn. There has been much interest from other Newlyn fishermen as well as from further afield, including from a group of fishermen visiting from Northern Ireland. There has been favourable publicity in the fishing press, the local press, local and national radio, and on regional television. The project has been monitored by Seafish and all project outputs are being made available to Seafish to disseminate throughout the fishing industry.

As with any development project, the execution posed a number of challenges that could not easily have been foreseen. The construction and commissioning of the onshore test facility took far longer than anticipated, due largely to the complexities of producing an integrated system with failsafe characteristics, capable of running extended tests unattended. Following on from these stages, testing conducted to determine a stable set of benchmark operating characteristics suffered various set backs that prolonged the time to the main testing phase. As well as technical issues, there were a number of health and safety issues that had to be addressed. However, the test cell that emerged has demonstrated its ability to produce highly repeatable data and has been acknowledged as one of the best in the country by visiting specialists in fuel additives. The consistency of the test cell underpins a very high level of confidence in the quality of the data obtained.

During the course of the project, the work being undertaken was overseen by 'Gus' Caslake of Seafish. The project team appreciated the support, encouragement and cajoling that Gus provided. This constructive and professional relationship was of great assistance in ensuring that the project developed along lines that were satisfactory to Seafish.

Report Outline

This report is intended to summarise the knowledge that was acquired during the course of the project. The nature of a development project is such that whilst there may be a defined goal, the route taken to achieve it cannot be accurately mapped in advance and much of what is learned will be from negative experiences. Where problems were encountered or mistakes were made, these are documented in order that other parties taking action on the basis of this report can benefit fully from our work. It should not be construed that this report has a negative tone, but that we have understood the issues surrounding what is still an under-developed technology.

Considerable attention has been paid to reporting system configurations and methodologies. Attention to these details proved to be a critical factor in the project. For instance, the process of producing bio-diesel is conceptually very straightforward, but producing a satisfactory product efficiently requires a considerable amount of effort to be put into process optimisation.

The conclusion to be drawn from the project is that in technical terms, bio-diesel represents a realistic alternative to red diesel in fishing applications. Drawing firm conclusions on economics is rarely advisable as the controlling factors are highly dynamic. However, it has been demonstrated that bio-diesel can be produced at a competitive cost at the current time.

It would be fair to say that however detailed a report, it can never fully capture the experience of those that undertook the work. The project team remain with the University and are committed to continue facilitating the development of bio-diesel as a marine fuel.

Bio-fuel engine test cell facility

Background

The test cell was identified as the core feature of the project from the outset. Cells of this nature are generally configured to test various engines, whereas for this project, the engine needed to be a constant with the fuel being the variable.

Accurate measurements of power and fuel consumption were essential pre-requisites of the design. Other parameters of interest would include engine oil temperatures and pressures, cooling water temperature, exhaust gas temperature and exhaust emissions.

Proprietary instrumentation and data processing systems are available for engine testing applications. However, the interface between the system and the rig hardware would have to be engineered on site.

Overview

Holman's Test Mine was selected as the logical site for the test cell. It offered a suitably sized underground chamber with level access from the mine entrance. Being underground meant that there would be little disturbance from noise, even if the engine was running overnight, and offered good security. Access to utilities was also good. Temperature and humidity underground are much less variable than for similar surface installations and meant that the power correction factors applied to data taken from the operating test rig were always close to unity. In turn this lead to high repeatability and good confidence in the results obtained.

The proprietary instrumentation system chosen was Cadet Light. This offered a high degree of functionality from a PC based system that included the basic SCADA hardware and firmware as well as the software package. The system allowed the operator to program test runs and log a wide range of parameters as well as giving a real-time display.

Power measurement was a major feature of the test cell so much of the design was based around the dynamometer. These are expensive items of equipment so budget constraints dictated that a second hand unit was procured. External specialist advice was sought to identify the most appropriate form of dynamometer leading to the selection of the Schenk unit.

A high precision fuel weighing system was selected for fuel consumption measurement. Although delicate in operation, this system was capable of high precision and interfaced directly with the SCADA system.

Environmental conditions were monitored and logged in order to provide the power correction factors. Exhaust gas monitoring was not integrated with the SCADA system.

Initially the fuel was gravity fed from an elevated header tank. Later an additional pump was added to speed fuel flow to the fuel weigher. An IBC of fuel was located just outside the test chamber and was pumped to the header tank. This system made fuel changes relatively straightforward, by swapping out the IBC and draining down the header tank system.

Exhaust gases were exhausted to the open air via a large diameter duct with the assistance of an extractor fan. The system was unsealed to avoid any influence of pressure on engine performance. Although the air intake was initially alongside the engine, this arrangement was modified to take in air from outside the test chamber. This modification meant that the air fed to the engine from the mine air space was of consistent temperature and quality even though conditions inside the test chamber varied considerably during the course of an extended test.

Cooling the engine was a major issue. In the test cell all of the energy from the fuel, other than that lost through the exhaust and through radiated heat, had to be removed by water cooling. Some of this was removed via the cooling circuit in the engine and the remainder via the cooling water circuit in the dynamometer. After many iterations, an open circuit design was adopted for the cooling water using the mine's sump water tank as a heat sink.

In order to achieve extended test runs it was essential that the test cell was capable of unmanned operation overnight. This required a number of failsafe features to be incorporated to satisfy the demands of the University's insurers as well as those of the mine management. These features ensured that the system would shut down in the event of any parameter going beyond a pre-set range, and that in the event of fire the fuel supply would be shut off. In addition, the cell was equipped with automatic fire extinguishing and gas detectors.

An elevated control room was constructed to house the computer equipment in an air conditioned environment, and to provide a location from which the operator could have a good view of the cell whilst having some isolation from it.

The stringent health and safety regime of a mine ultimately helped to ensure that the test cell was designed and constructed to provide a high degree of safety for both the operators and the equipment itself.

Equipment specification

Engine specification

The engine selected is representative of the type of engine that is employed by the vessels targeted by the research, therefore limiting dimensional differences.

The target group is the 10m day trip fishing vessels generally powered by approximately 90kW marinised diesel engines. The Perkins marine diesel engine employed for this work is detailed below.

Parameter:	**Specification:**
Manufacturer:	Perkins
Type:	6.3544M
Cylinders	6
Cubic capacity	5.8 litres
Compression ratio:	16:1
Bore:	98.4mm
Stroke:	127mm
Firing order:	1-5-3-6-2-4
Combustion system:	Direct injection
Cycle:	4 stroke
Output power:	89.5kW
@ Rotational speed	2800rpm

Dynamometer specification

The selection criteria for the dynamometer consist of:

- Speed capacity
- Torque capacity across the full range of rotational speed
- Variable and precise resistive load control
- Accurate torque measurement
- Accurate speed measurement
- Base mountable

The dynamometer required excess capacity for torque / power across the full range of rotational speeds and needed to be rated for the highest rotational speed to be tested. This was achieved by overlaying the engine's maximum power and torque output curves on the dynamometer's maximum power and torque capacity curves.

The German manufactured Schenk W230 had ample capacity across the range and also allowed for an increase in capacity, if required, in the future. The W230 can be crudely interpreted as having a maximum mechanical power of 230kW.

A summary of the dynamometer's features are stated below.

Parameter:	**Specification:**
Manufacturer:	Schenk
Type:	W230
Serial number:	LWH 0994
Date of manufacture:	1986
Resistance:	Eddy current
Torque transducer:	Load cell
Speed transducer:	60 tooth wheel / inductive cell
Calibration:	Dead weight arm

The Schenk W230 contains a rotor which is attached to the engine under test by a drive shaft. The rotor is a radial disc-shaped component that spins within the field of a stator. The stator is fixed to the body of the machine and consists of an electromagnetic coil. Varying the excitation on the coil varies the amount of resistance the rotor is subject to, which is a function of the excitation current and the rate of flux cutting, i.e. the rotational speed.

The rotor is held within the stator by variable tension bearings and the stator is fixed to the dynamometer frame by flexure strips. These are thin strips of metal which present sufficient rigidity to host the stator vertically but also deform (well within the elastic limit) when torque is applied to the shaft. This movement is registered by a strain gauge (bridge) load cell mounted on an arm connecting the stator to the frame.

Connected to the non-drive-end of the rotor is a 60 tooth wheel. There is an inductive speed pick up mounted to the frame which registers the rotational speed via a Hall Effect sensor.

Incorporated in the stator housing is a heat exchanger that allows cooling water to pass around the rotor disc and stator coil assembly to remove the output power of the engine which has been converted to heat by the dynamometer. The tappings are 1 ½” BSP with both flow and return paths being split two ways to cool each side of the machine.

Supervisory Control and Data Acquisition (SCADA) System

The Supervisory Control and Data Acquisition system is employed to perform data collection and control. It occupies a tier on top of the connected PC to log and control external processes, i.e. logging shaft torque and controlling dynamometer excitation current. The Human Machine Interface is a typical Graphical User Interface with a winged keyboard for control.

All communication is by proprietary protocol and not disclosed by the manufacturer, therefore the unit is autonomous and limited to the expansion permitted by the current configuration. The SCADA system is limited in distribution to the test cell but could be linked by a web server to the internet and be controlled through remote access software as with any PC.

Hardware safety level

The In-Cell Transducer box receives two power sources. The primary source is 240 VAC which is transformed, rectified and regulated for instrumentation applications. The secondary source is a 24 VDC supply from the engine battery. The instrumentation and control package has been installed in parallel with the engine’s existing hardware control suite to enable local operation from the test cell for engine debugging and PC control.

The software safety system constantly monitors and controls the engine and will shut the engine down in the event of a parameter going out of range or other operational fault. However a serious safety concern was how the test unit would respond if the software stopped functioning due to a power outage or a computer hang.

The hardware level protection exists to effectively manage the engine in the event of a software crash, loss of power (240 VAC) or a fault. A set of reset contacts is held high (+10 V) when all safety conditions are met. The contacts feed into a normally closed relay and if the potential is lost across the contacts, the relay is de-energised and closes. In this event a timer in ‘Delay On’ mode pulses a 24 V supply to the stop solenoid on the engine for a predefined period. In this case 5 seconds is long enough to stop the engine. Therefore the system was set up such that any event that caused the loss of potential on the reset contacts resulted in engine shut down.

Input and Control Functionality

The data logging and control hardware is built into a 19” sub-rack. The backplane is fitted with a three row 64 way power supply connector and twelve two row 64 way sockets each of which is associated with a card slot identified as 2 through 13. On the rear of the backplane 10 of the 64 ways are linked to rearward facing 10 way connectors. All signals from the external system are connected to the cards via these 10 way connectors. In a CadetLite system the 13 backplane slots are used as follows:

Slot 1 Power supply card DL-PSU-04 Generates +5, +12 and –12V supplies for the rack of cards.

Slot 2 Speed measurement and over speed protection DLT-SST-01 Measures engine speed from a speed pick-up.

Slot 3 Fast Analogue Input Card DL-VAD-09 Measures dyno current, throttle position, torque, throttle current

Slot 4 Analogue input card with trips DLT-VAD-01 Provides INST1 and INST2, typically engine coolant and oil temperature. Provides over temperature trips to the EPP (equipment protection panel).

Slot 5 Encoder and digital inputs. DL-ED-01 Interfaces to the encoders on the user interface used for manual input card control of the dynamometer and throttle. Accepts 4 digital

Slot 6 Digital input card DL-DI-01 Accepts 8 digital inputs.

Slot 7 Analogue input card DL-VAD-04 Provides analogue inputs INST3 through INST6.

Slot 8 Analogue input card DL-VAD-04 Provides analogue inputs INST7 through INST10.

Slot 9 Analogue input card DL-VAD-04 Provides analogue inputs INST11 through INST14.

Slot 10 Provision for 2 channel DL-FMS-02 For use with an FMS 400, 1000 or 9000 fuel weigher fuel weigher card

Slot 11 Analogue output card DLC-DVI-01 Sets dyno current, throttle position, coolant valve position and oil valve position.

Slot 12 Digital output card DLC-RO-02 Provides 8 digital outputs.

Slot 13 Interface card DL-INT-03 Provides the serial interface to the control PC.

Cadet Lite Cards

DL-DI-01/X 8 channel digital Input

X = ( ) Inputs need to be pulled low.

X = 24 Inputs need to be pulled high (5 -> 24 V)

DL-ED-01 2 channel encoder input and 4 digital inputs (STATUS)

DL-FMS-02 2 channel 16 bit isolated voltage input each with a 16 bit time counter. Primarily used with FMS400,1000 and FMS9000 fuel measurement systems.

DL-INT-03/X Serial Interface

X = 1 (mode) Stand alone CP128 communications board interfacing only with a PC over a RS232C comms. link.

X = 2 Master communications board interfacing with a PC over a RS232C comms. link and other CP128 slave comms. boards over a 20mA current loop link providing the 20mA current source for the CP128 TX loop.

X = 3 Slave and current loop source comms. board acting as a 20mA slave to the master board but providing the 20mA current source for the CP128 RX loop.

X = 4 Slave comms. board acting as a 20mA slave to the master board.

DL-PSU-04 ±12V DC, +5V DC Supply, 1A per rail

DL-VAD-04 4 channel isolated voltage input

Input voltage range selectable on a per channel basis in the ranges:

-0.25V -> 10.25V to -1.25mV -> 51.25mV (unipolar)

-5.25V -> 5.25V to -25.625mV -> 25.625mV (bipolar)

Hence there may be 4 ranges identified within the bracket following DL-VAD-04.

Update rate and resolution is selectable on a per channel basis in the range:

2.5Hz (16 bit) -> 320Hz (9 bit)

DL-VAD-06 4 channel isolated voltage input.

Input voltage range selectable on a per channel basis in the ranges:

0 -> 20V to 0 -> 50mV (unipolar)

-10V -> 10V to -25mV -> 25mV (bipolar)

Hence there may be 4 ranges identified within the bracket following DL-VAD-06.

Update rate and resolution is selectable on a per channel basis in the range:

Up to 40Hz (16 bit) -> 1280Hz (11 bit).

Linearity to best straight line better than 0.025 % of full scale.

DL-VAD-09 4 channel isolated voltage input

Input voltage range selectable on a per channel basis in the ranges:

0 -> 10V to 0 -> 125mV (unipolar)

-10V -> 10V to -62.5mV -> 62.5mV (bipolar)

Hence there may be 4 ranges identified within the bracket following DL-VAD-09.

Update rate and resolution is selectable on a per channel basis in the range:

Up to 20Hz (16 bit) -> 320Hz (12 bit).

Linearity to best straight line better than 0.025 % of full scale.

DLC-DVI-01 4 channel 16 bit analog output

Output type (voltage or current) and range are link selectable on a per channel basis.

The output voltage ranges available are:

0 -> 5V and 0 -> 10V (unipolar) and

-2.5V -> 2.5V, -5V -> 5V, and -10V ->10V (bipolar)

The output current ranges available are:

0 -> 20mA and 4 -> 20mA

DLC-RO-02/X/MODY 8 channel relay output (contacts are connected to one of two commons.)

X = 1	digout 1 only connected to com1, the rest to com2
X = 2	digout 1 & 2 connected to com1, the rest to com2
: :	
X = 8	digouts 1 through 8 connected to com1
Y = 1	Link to provide watchdog contact For use with single DL-INT-03 systems

DLT-SST-01	2 channel frequency input card with relay contacts tripped at pre-set high or low threshold. Counter offers 16 or 24 bit resolution. (Used for bed protection)
DLT-VAD-01	2 channel voltage input card (spec as DL-VAD-04) with relay contacts tripped at pre-set high or low threshold. (Used for bed protection)

FMS (Fuel Measurement System)1000

The FMS system employed is relatively simple in concept and operation. The system functions by dosing approximately 1 kg of fuel into a vessel that is in the fuel delivery line between the header tank and the engine. Return fuel from the engine is also delivered to this weighing vessel. When the predefined fill level is achieved the fuel delivery from the header tank to this vessel is suspended. The vessel sits upon a load cell and the mass of the vessel is logged at predefined time intervals to derive the fuel consumption in terms of mass. When a predefined lower level of fuel is achieved, data logging is suspended and the vessel is re-filled. The operation of the FMS is controlled by the dynamometer software and has hardware settings that intervene when appropriate.

Software

The Cadet software is a large and complex package. To assist the description of its capability it can be split into a number of areas although the flexibility of the software inevitably blurs the boundaries between the different areas:

1. System configuration software
2. Test configuration
3. Test operation
4. Display and report configuration

The params file links the hardware to the software. The backplane addresses and resolution of the hardware input and output channels are defined the params file. channels

The Cadet.ini file is used to link software components to the core Cadet software. Typically the only component that will be used with a Cadet Lite system is the Fuel Weigher component that works with the gravimetric fuel meter (FMS 1000).

The software offers 256 input channels, 64 output channels and 26 PID controllers. Each mode of each control output requires a dedicated output channel and set point output. Hence in engine test applications 6 PID controllers are used for throttle by speed, throttle by load, throttle direct, dynamometer by speed, dynamometer by load and dynamometer direct leaving 20 PID controllers for other control functions e.g. coolant temperature, oil temperature, fuel temperature, inlet air pressure, inlet air humidity etc.

Cadet Lite was configured for use when it arrived however, some options are available such as alternative correction factors for power and torque, and also some units conversions. These options were selected by displaying various pseudo variables on the main screen layout, but first, the system needed to know what transducers were connected to the system. The transducer configuration was undertaken from page 2 of the test report sheet (the first screen displayed when you run a test).

Cadet Lite provides some standard calculations commonly used in the engine test. They can be configured anywhere on the main display layout using the Test Editor. The calculations provided are listed below. Pseudo variables are normally used for calculations, User variables are normally used for configuration but do also contain some calculations.

Variable Number	**Description**
1	Torque in Nm
2	Torque in LbfFt
3	BMEP
4	Saturated Vapour Pressure
5	Air In Temperature
6	Observed Power in KW
7	Observed Power in BHP
8	Vapor Pressure
9	Dry corrected Baro in KPa
10	DIN70020 Gasoline correction factor
11	ISO1585 Gasoline correction factor
13	Atmospheric correction factor, Fa (ISO1585 Diesel)
14	Engine correction factor, Fm (ISO1585 Diesel)

Variable Number	Description
15	Specific Fuel Consumption, SFC
16	Boost Ratio
17	Swept Volume
18	ISO1585 Diesel correction Factor
20	DIN70020 Gasoline corrected power, KW
21	DIN70020 Gasoline corrected power, BHP
22	DIN70020 Gasoline corrected torque, Nm
23	DIN70020 Gasoline corrected torque, kNm
24	DIN70020 Gasoline corrected torque, lbfFt
25	ISO1585 corrected power, KW
26	ISO1585 corrected power, BHP
27	ISO1585 Gasoline corrected torque, Nm
28	ISO1585 Gasoline corrected torque, KNm
29	ISO1585 Gasoline corrected torque, lbfFt
30	ISO1585 Diesel corrected power, KW
31	ISO1585 Diesel corrected power, BHP
32	ISO1585 Diesel corrected torque, Nm
33	ISO1585 Diesel corrected torque, KNm
34	ISO1585 Diesel corrected torque, lbfFt
35	Fuel Delivery, mm3 per stroke

User Variables

User Variable Number	Description
1	Averaged Torque
2	Averaged Speed
150	SST01 ResultA
151	SST01 ClockDividerA
152	SST01 InputPreDividerA
153	SST01 TripLevelA
154	SST01 MinimumReadingA
155	SST01 CalculatedTripLevelA
156	SST01 TripTimeA
157	SST01 ResultB
158	SST01 ClockDividerB

User Variable Number	Description
159	SST01 InputPreDividerB
160	SST01 TripLevelB
161	SST01 MinimumReadingB
162	SST01 CalculatedTripLevelB
163	SST01 TripTimeB
164	FMS Corrected Mass
165	FMS Measured SFC
166	FMS Measured Flow
167	FMS Instantaneous SFC
168	FMS Instantaneous Flow
169	FMS Measure Period
170	FMS Time left to measure
171	FMS Status
172	FMS Calibration State
173	FMS Calibration Result
179	Manual Air Intake Temperature, Deg C
180	Manual Air Intake Humidity, %RH
181	Fuel Instrument No
182	Fuel Specific Gravity
183	Bore Diameter
184	Stroke Length
185	Number of cylinders
186	Boost Pressure Instrument Number
187	Engine type (0=normally aspirated, 1=turbo)
188	Use FMS (0=no, 1=yes)
189	Thermocouple Type (1=K-Type, 2=J-Type, 3=T-Type)
193	Thermocouple units (0=Deg C, 1=Deg F)
194	Air In Temperature instrument number
195	RH instrument number
196	Baro pressure transducer instrument number
197	Manual Baro entry
198	Torque Units (0=Nm, 1=lbf.ft, 2=kNm)
199	Fuel Type (0=gasoline, 1=diesel)

Construction

Site selection

After a careful selection process a large underground chamber within a mine was selected to site the engine test facility, considerations included:

- **Space**; significant space is required to install the main frame, instrumentation, fuel bunkering and control suite, and provide access to vehicles.
- **Noise**; the installation has to be tolerable to the operatives and have the capability of 24 hour running.
- **Ambient conditions**; to limit the effect of changes in humidity and temperature of the engine intake air.
- **Infrastructure**; medium current power supply, compressed air and large volumes of water.
- **Exhaust system**; a suitable distance to run the exhaust to a place it can be safely discharged.

Electrical supply subsystem

The mine electricity supply enters via an underground armoured cable to the sub-station which is 15m from the engine test cell. A spare breaker was assigned to the test cell with an armoured cable installed to feed a distribution board in the control suite. Three phase, 400V is available at the sub-station but only a single phase 220V supply has been transferred to the test cell as currently all equipment is single phase.

The distribution board is split way, where only the power circuits are protected against leakage via an RCD, and all circuits are protected against over current via MCB's. The supplies are distributed via single core cables in a trunking and conduit system; this is to adhere to the strict regulations regarding the use of electricity underground.

The electrical supply system provides an adequate level of redundancy making future expansion of the facility possible.

Engine aspiration

The natural climate in underground workings and mines is reasonably constant all year round. The atmosphere is relatively unaffected by seasonal changes and weather patterns. The temperature remains constant at around 13.5° C +/- 1° C depending on the time of year due to the thermal mass of the rock. The humidity is high at around 80% due to the temperature, still air, presence of water and the absence of solar radiation. However the atmospheric pressure tracks the surface pressure as the mine is not a sealed environment.

When the results of engine tests are normalised according to ISO1585 the measured power is multiplied by a correction factor to derive a corrected power that is predicted to have occurred under standard temperature, humidity and pressure conditions. These corrections are particularly important when testing under widely variable ambient conditions.

The extent to which the results of this work depend upon the ISO1585 power correction factor were reduced by utilising the stability of the underground environment. The air intake has been routed outside of the engine test cell chamber to a drive in the mine where the temperature is unaffected by the engine (*see schematic diagram – figure 01*). The air intake duct contains a cleanable K&N air filter as well as the atmospheric temperature and humidity instrumentation.

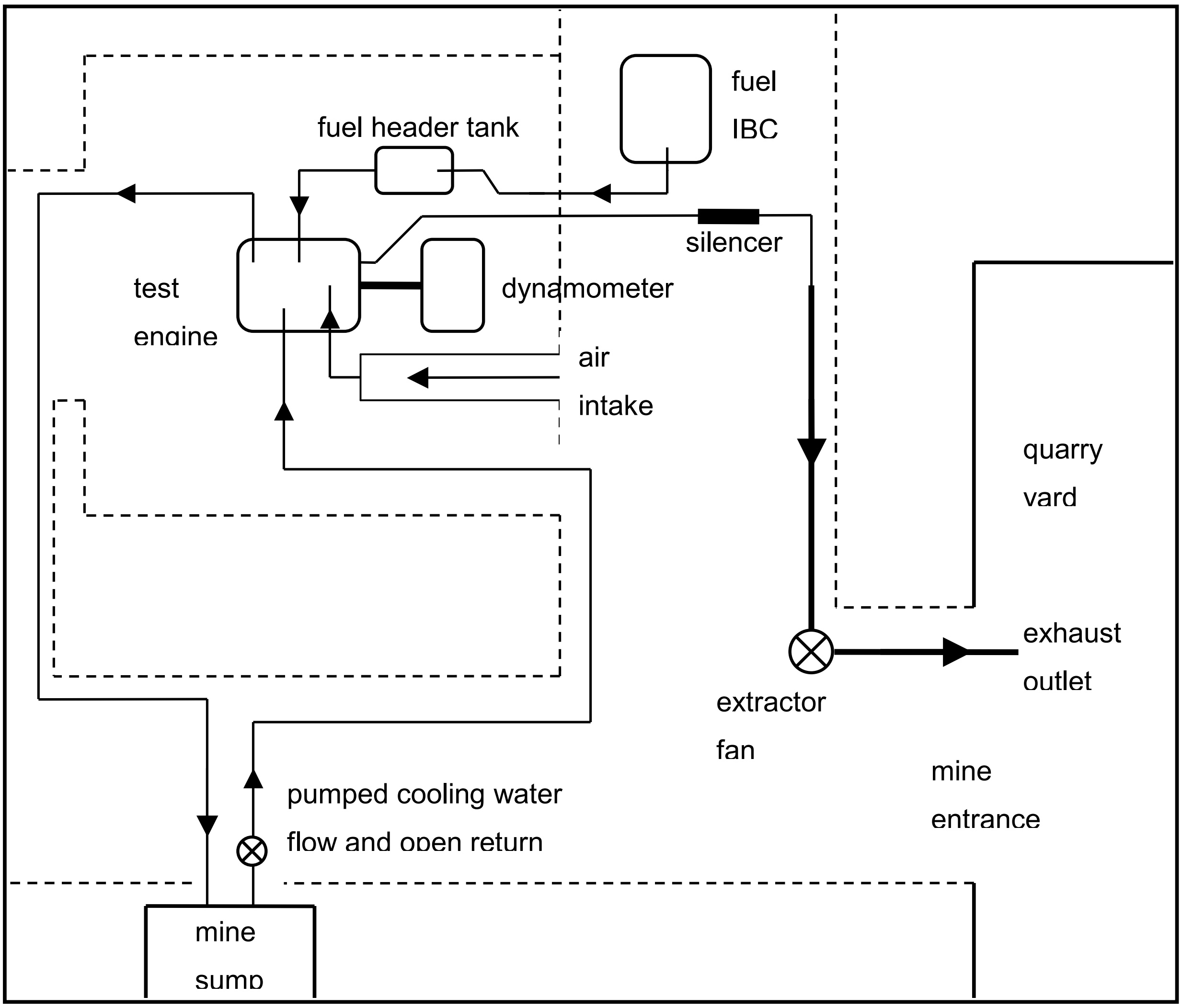


Figure 01: Schematic diagram of test infrastructure within the mine.

Cooling system design

The dynamometer cooling load, which amounts to the engine's mechanical output power, will be the maximum power delivered by the engine. For a new engine this is 90kW. For the cooling system design, the engine was assumed to be 33% efficient under optimum conditions with the result that the engine losses manifested as heat will be 180kW. As the engine has been marinised the exhaust is also cooled, therefore the majority of the 180kW actually passes into the secondary cooling system. The design total cooling requirement was thus taken to be 270kW peak.

The engine has a primary cooling system that is a closed loop. The water / anti freeze mixture is pumped through the engine block and cylinder head and passes through a counter current heat exchanger where it is cooled by the secondary cooling system. In normal marine installations this secondary cooling is provided by a separately pumped seawater system. The flow is regulated in the primary system by two thermostats, rated to begin opening at 85° C and be fully open at 92° C. The secondary cooling system on the engine is equipped with a Jabsco quasi positive displacement pump and is designed to be robust to the quality of fluid passing through.

The dynamometer is cooled by passing the circulating fluid through a network surrounding the stator forming a heat exchanger. This effectively removes the engine output power. The dynamometer heat exchanger consists of corrodible components and is difficult and expensive to strip down and replace; therefore it is advisable to run a closed system utilising an inhibitor. The maximum operating temperature is set at 60° C by the manufacturer.

The cooling system for the engine and dynamometer evolved as described below.

Cooling system 1 consisted of two automotive radiators taken from trucks with rated powers of 160HP (120kW). These were placed in a closed loop cooling system running in a series circuit through the dynamometer, then the engine. The Jabsco pump was used to circulate the fluid and two 400W axial fans were sealed over the radiators to provide the airflow. The system did not work well and the engine could only attain around 25% of full power. Conclusions reached included:

- The flow rate from the Jabsco pump was not high enough
- The surface area of the radiators was insufficient
- The mass flow rate of air across the radiators was insufficient

Cooling system 2 consisted of placing the two radiators below water in the mine sump and continuing with the closed loop system, a buffer tank was also placed in series with the radiators which consisted of a 205 litre metal barrel and a larger circulating pump was installed. The mine sump is a body of water approximately 25m^3 in volume, underground and at the ambient temperature of the mine. This system increased the possible operating power of the engine to 60% but still not full load. The conclusion was that employing a closed loop system meant that the return temperature of the fluid was at some temperature above ambient, therefore not maximising the temperature differential.

Cooling system 3 consisted of an open loop circuit from the mine sump. The pump was up-rated to a 7kW, low specific speed, centrifugal pump, the delivery pipe was increased from 25mm to 50mm (a four-fold increase in area) and the Jabsco pump was removed from the system. All pipe work connecting the dynamometer and engine was increased from 25mm to 40mm. Using this system a much greater flow rate was achieved because of the larger pump and lower system resistance and the return temperature of the water was at the temperature of the sump. The disadvantage of this technique is that the circuit is open loop and a corrosion inhibitor cannot be used. The longer-term effects of this move are unknown at this stage.

The flow rate through the system is approximately 2.5l/s, injecting energy to this system at a rate of 270kW means that the increase in temperature of the cooling water is 26°C. Therefore if the ambient temperature of the sump is 13° C the exit temperature of the dynamometer will be 22° C and the exit temperature from the engine will be 39°C. This satisfies the condition for the dynamometer not to exceed 60° C. Because the dynamometer and engine are in series the exit temperature of the dynamometer must not exceed the permissible intake temperature for the engine so the heat exchanger on the engine still functions effectively. The heat exchanger will have been sized such that it will transfer the appropriate amount of energy per unit time based upon a minimum differential temperature of the two fluids. In its natural environment, the lowest differential temperature will be observed when the boat is operating in the warmest waters in the World. This is not likely to exceed 30°C. Therefore an upper limit of 30° C was placed on the dynamometer exit temperature, i.e. the engine intake temperature that ensures the engine does not overheat.

Certain practical problems have been observed with this technique for cooling. To minimise system resistance the water exits the engine and gravitates back to the mine sump via the open channel drain. On occasions vapour from the warm fluid caused a mist in the drive. As these conditions were ideal for the proliferation of legionella bacteria that are hazardous to health, the mine management instructed a suspension to testing. This suspension was short lived; samples of the water were taken which were tested and revealed no presence of legionella. Measures aimed at mitigating this concern included improving ventilation, water treatment and containment.

Exhaust systems

As the engine test cell is located in an underground chamber, the exhaust by-products produced by the engine have to be safely removed. It is important not to provide the exhaust exit stream with excessive resistance due to the pipe work system. The distance to the quarry from the chamber is approximately 50m and there is a further 10m vertical section to clear the quarry wall. This is too long to rely on the engine expel stroke to successfully empty the cylinders of combustion products. The exhaust was therefore terminated 6m from the engine and a 150mm duct placed around the last 0.5m of the exhaust without sealing on to it. The duct runs along the mine tunnel to the quarry. A fan is located in the duct at the quarry entrance. This fan provides negative pressure in the duct drawing the exhaust gases and some air from the mine tunnel and expelling the mixture in the quarry. Because the duct is not sealed on the exhaust pipe then the two systems are separate and the long duct does not affect the engines operating characteristics.

The exhaust was originally connected to the engine by a 1m section of flexible pipe. This decoupled the engine from the exhaust to protect against vibration. However, flexible exhaust pipes are designed to be used in external applications such as lorries and are not entirely sealed. Under high load conditions small amounts of gas escaped and this section had to be replaced with a rigid, welded section.

The first commissioning tests showed that under high load conditions an unacceptable amount of noise was issuing from the exhaust duct running up the quarry face. The level was not out of place for an agricultural daytime application but was considered unacceptable for 24 hour operations. A section of exhaust pipe was cut out and a large lorry silencer was placed in the system. This reduced the noise significantly to an acceptable level.

Due to the confined nature of the location of the test cell, carbon monoxide sensors were installed in the cell and in the approach to the cell, and both were connected so that if the safe limit for carbon monoxide is exceeded both sensors will sound an audible alarm.

Fuelling system

Fuel is transferred to a position in the mine tunnel adjacent to the test chamber. The fuel is carried in an Intermediate Bulk Container (IBC) within a bunded road trailer. The IBC is coupled to a flexible line which interfaces to the fuel system. A fuel transfer pump supplies the 50 litre day tank in the test cell. The pump is controlled by a float switch in the day tank which actuates a normally open relay. The relay circuit also contains a timer to avoid the pump cutting in and out too frequently. The timer is set to ‘delay on close’ mode with a time interval of 9 minutes. This represents the time taken for the engine to use a significant amount but not all of the fuel in the day tank. After 9 minutes the relay circuit will check the status of the float switch and actuate again if necessary.

The day tank is coupled to the FMS 1000 fuel weigher (fuel flow meter device) by 10mm steel pipe. A positive displacement fuel lift pump is in line between the day tank and the FMS 1000, so that the FMS 1000 refills quickly when its solenoid control valve opens. The pump is connected to the ignition switch on the engine and is therefore powered up when the ignition is turned on (by the PC or the local control). The pump is regulated by pressure; as the downstream valve closes the pressure builds up and the pump cuts out.

This system ensures that the fuel monitoring system always has a swift supply of fuel regardless of how long the test is. With a full IBC of fuel, the test cell can operate for approximately 100 hours of continuous use on a day trawler cycle.

Control centre

The data acquisition equipment required for this scale of facility is expensive and sensitive, and so required a housing that is lockable and climate controlled. The electrical infrastructure also required a dry and safe location to be distributed from. Other drivers included space to work and operate the test equipment free from excessive temperature and noise.
The equipment consists of a 3U enclosed 19” rack of cards, two personal computers and emissions monitoring equipment.

Considerations included the high humidity, constant drips and seasonal condensation. A block and timber construction was favoured due to cost, durability and versatility. This provided 12m^2 of first floor office space, 9m^2 of undercover parts storage and first floor tank storage space.

The office was constructed with 100mm of insulation and double glazed window and door to help reduce noise, with toughened glass in the window overlooking the test cell for safety. The roof has a 1:50 slope and is plastic covered to be watertight. The walls and floors are painted with protective coatings to stop moisture ingress and aid longevity.

Construction work underground was very difficult due to the limitations of light and power, and due to the health and safety requirements.

Equipment mounting system

Due to the uneven shape of the test cell and the irregular walls a framing system was employed to assemble the test cell infrastructure. Unistrut 40mm was used with uprights spaced at 2m and horizontal members spaced at 1m. This system was plugged to the floor and horizontally tied back to the wall, and proved to be extremely valuable by allowing a tidy and sturdy installation.

The electrical trunking ran all around the chamber meeting the control room at each end which enabled the power and instrumentation circuits to tie up. The In Cell Transducer Box was mounted next to the engine with the FMS 1000. The day tank was mounted on top of the framing system, sockets were safely and conveniently located around the cell and the emissions monitoring pipe work is effectively routed.

The system provides scope for any additions or improvements required.

Fire protection

Although diesel is not excessively flammable, fire is certainly not desired from the perspective of personal safety and damage to expensive instrumentation surrounding the engine. During commissioning the engineer was always present and 2 fire extinguishers were located in the cell.

For 24 hour operation an automatic fire suppression and warning system was installed.

The two essential ingredients for fire are the fuel (here diesel) and oxygen. A 2kg powder fire extinguisher was suspended 300mm above the engine with a heat sensitive bulb. If the temperature exceeds 59° C the extinguisher will activate, stifling the fire and depriving it of oxygen. To remove the source of fuel, two valves were installed on the fuel feed and return lines which are sprung closed. A nylon mesh is arranged in a network 100mm above the engine and fastened to each valve, holding each valve open. Under normal conditions the valves are held open and fuel is able flow to and from the engine. In the event of a fire, the string is quickly burnt through and the valves spring closed stopping the source of fuel to the fire. These two measures will act to successfully extinguish a fire by removing the fuel source and depriving the fire of oxygen.

For 24 hour operation a warning system has been installed to alert the operator if a fire has occurred in the night and that it is not safe to enter due to the possible presence of hazardous gasses. The system consists of a smoke sensor and a heat sensor above the engine linked to another smoke sensor in the approach to the test cell. Therefore if smoke is detected or the temperature exceeds 60° C all sensors will actuate audible alarms. The sensors are mains powered but have battery back ups if the power supply is affected.

Commissioning

Engine characterisation

Obtaining a stable characterisation of the engine, such that it could be taken as a ‘constant’ proved a difficult and prolonged task. However, it was ultimately achieved and is detailed later in the section dealing with fuel testing.

Before any testing, the engine was stripped down and all the critical elements examined. The purpose was to record a bench mark to make comparisons against if a change or failure occurred. Cylinder number 3 was examined in detail and the results are as follows;

Ring Gaps

- Top ring gap (No 1) 1.04mm (0.041")
- Second ring gap (No 2) 0.64mm (0.025")
- Third ring gap (No 3) 0.64mm (0.025")
- Oil ring gap (No 4 / scraper ring) 0.94mm (0.037")

The ring gap is the distance between the two ends of the ring when it is located in the piston and the piston is inserted into the cylinder. The distance is measured with feeler gauges. The 'as-new' distance is the same for all rings at 0.41-0.86mm (0.016-0.034"). Therefore a degree of wear exists even before testing commenced due to the previous operating hours on the engine.

Ring Groove Clearance

- Top ring groove clearance (No 1) 0.13mm (0.005")
- Second ring groove clearance (No 2) 0.13mm (0.005")
- Third ring groove clearance (No 3) 0.13mm (0.005")
- Oil ring groove clearance (No 4 / scraper ring) N/A

The ring groove clearance is the remaining width of the groove in the piston that houses each piston ring, when the piston ring is located in the groove. The distance is measured with feeler gauges by inserting them in between the ring and the edge of the groove. The 'as-new' distance for the No 1, 2 and 3 ring groove clearance is 0.05-0.10mm (0.019-0.039"). Therefore a degree of wear exists even before testing commenced due to the previous operating hours on the engine.

Cylinder Bore Diameter

- Cylinder Bore Diameter 98.48mm (3.877")
- Maximum wear 0.08mm (0.003")
- Roundness wear 0.05mm (0.002")

The bore of cylinder 3 shows a degree of uneven wear as the cylinder is slightly oval, as characterised by the roundness wear. The 'as-new' diameter for the cylinder is 98.4mm (3.875").

Principle Bearings

- Big End Journal / Crank Pin ('as-new' 63.47-63.49mm) 63.47mm (2.499")
- Connecting rod bearing clearance ('as-new' 0.03-0.08mm) 0.08mm (0.003")
- Main bearing running clearance ('as-new' 0.05-0.11mm) 0.10mm (0.004")

The Big End Journal is measured with a micrometer screw gauge and the bearing clearances are measured with a proprietary putty strip which is clamped between the bearing shell and the journal. The width of putty strip is then compared to a calibrated chart which indicates the bearing clearance. The bearing running clearances shows that the engine is still within operating tolerances but at the upper limits indicating the engine is in a worn but serviceable state.

Injectors

All 12 injectors from both engines were assessed on a test rig by Cowick Fuel Injection Services, Marsh Barton, Exeter, to characterise their condition. The results were as follows;-

Engine 1:-

Injector Cylinder (No #)	Nozzle Opening Pressure (Atmospheres)	Spray Pattern Description
1	195	Firing
2	190	Firing
3	190	Firing
4	180	Hosing
5	185	Firing
6	190	Needle Sticking

Engine 2:-

Injector Cylinder (No #)	Nozzle Opening Pressure (Atmospheres)	Spray Pattern Description
1	180	Firing
2	185	Firing
3	190	Firing
4	175	Firing Weak
5	180	Firing
6	185	Firing

It was concluded that although selecting the best 6 injectors for the test engine may prove acceptable if problems were encountered during the test programme any change to this element could have significant changes to the engine performance. Therefore it was decided to have new nozzles installed in the worst 6 injectors and have the opening pressure reset to the manufacturers specification.

Seals

During the strip down all principle gaskets like the head, rocker cover, sump, exhaust manifold, inlet manifold, etc, were renewed. All seals were visually inspected and none were found to be in an unacceptable condition.

Valves

An inspection of the valve mating faces and the valve seats showed a degree of deposition and pitting but only in keeping with the age and running hours of the engine. As a control the inlet and exhaust valves were reconditioned by having the valve reground and then lapped into the valve seat. This meant that this element of the engine was maintained in its original condition but that the inlet and outlet valve ports of cylinder 3 were in an 'as-new' condition and could provide the control bench mark if this element was affected due to using a different fuel in the future.

Calibration

Calibration is the process used here to ensure that all transducers accurately convert the physical signal they are measuring into a format suitable for digital manipulation within the SCADA system. This includes signal conditioning and analogue to digital conversion, as required. Where possible a varying physical signal has been applied to the transducer being calibrated and the ADC count monitored. Where necessary in troubleshooting calibration procedures, the (intermediate) analogue signals have been measured.

In the case of the thermocouples that monitor exhaust gas temperature, the temperature monitored is of the order of 750°C, and was not able to be replicated *in-situ*. In this instance a simulator was used to generate a mV signal that was passed to the electronics, and the manufacturers output characteristics for the sensor were used. The sensor employed is the K type thermocouple with an accuracy of ±1.5° C. Thermocouples of this type are also used to measure the dynamometer outlet temperature.

The FMS 1000 is calibrated by automatically applying a built in weight to the load cell. The weight is exactly 100g and this gives two relative points to generate a value for Gain. The Offset is not important as it is the change in weight that is of interest. The manufacturer has assessed the accuracy of this process resulting in a flow rate reading within 0.1%. This is likely to be in ideal conditions and does not take into account many of the practical factors like pulsing of the return line. After assessment of the standard deviation of a large data set a pessimistic estimate would therefore be 0.5%.

The Platinum Resistance Thermometers are used to measure the engine primary cooling jacket temperature and the engine oil sump temperature. These fluids can reach 95° C and so it was not practical to calibrate the physical source, and again, a simulator was used. The sensors are PT100 1/10th DIN Class B with an accuracy of 0.033° C.

The load cell to measure torque on the dynamometer was calibrated by fabricating an arm which could suspend weights exactly one metre from the centre of the device. The arm has a counter balance and is loaded with weights between 0kg and 40kg, which represents a torque range of 0 - 392.3 Nm. Using this set up, an error in mass of 100g and an error in distance of 5mm would result in a torque error of 2.1Nm or 0.5%. The error of 2.1 Nm will be considered to apply across the whole range. The dynamometer was calibrated with the cooling water flowing through it as there is a significant tangential reaction to the impulse of water entering and leaving the dynamometer.

Rotational speed of the engine is determined by a Hall effect transducer on the dynamometer. A 60 tooth wheel rotates in the vicinity of the sensor and if operational, returns the number of inductive pulses which when divided by 60 yields the rotational speed. The sensor does not need calibrating but fails to work at speeds below 300rpm. In all practical testing, the minimum engine speed was well above this at approximately 1000rpm.

Atmospheric temperature and humidity sensors were supplied certified to the following accuracy:

- Temperature – within 0.3° C at 0° C
- Relative humidity - +/- 2.5%

The barometric pressure sensor was supplied with a calibration certificate providing the zero output and specifying the non-linearity as +/- 0.1% full scale deflection.

Control configuration

Set up of the main control elements included:-

Throttle Control

Throttle control is provided by the AT12 throttle actuator which is driven by the OM22 power module, which is controlled by a set point from the control enclosure.

Dynamometer Control

Dynamometer control is provided by an OM12 power module which is controlled by a set point from the control enclosure.

Oil and Coolant Control

Analogue set points are wired to the in-cell enclosure via the Z1 loom and connectors. These set points could be wired to control valves controlling the bed water flow the engine coolant heat exchanger and the engine oil heat exchanger if required. If a pneumatically driven valve actuator with 2 wire 4-20mA control is used the Cadet system set point output may be used to control the valve directly. For this cell the option selected was to use the on-board thermostatic controls of the engine and to supply the maximum flow rate of secondary coolant to the oil and water heat exchangers.

Ignition, Fuel, Cranking and Spare Control

A 24V DC 100A supply has been wired to the heavy current posts on the in-cell enclosure. This supply can then be switched to achieve:-

- Ignition on / off
- Pre-heat on/off
- Starter motor crank

Each switched output is rated and fuse protected at 25A. The manufacturer intended that the engine ignition, fuel pump and starter solenoid (not the starter direct) should be wired to these posts and suggested wiring glow plugs to these posts may overload the circuit. However all this functionality has been achieved by actuating a secondary circuit which operates the primary, high current, circuit.

Spare channels

The Cadet Lite system offers 14 unassigned analogue inputs. These can be utilised in the future if additional parameters are required, subject to installation of the appropriate signal conditioning.

System integration

The Supervisory Control and Data Acquisition system integrates the hardware to acquire data, software to process, monitor and action requests, and hardware to implement actions. The information stream has also been joined with the use of PID controls to form a closed loop system. The hardware is split into three sub systems:

- Data acquisition and Human-Machine Interface
- Control
- Transducers

Integrated by the following kit list:-

1. A 3U control enclosure containing a rack of control cards, nominally 520w x 500d x 166h.
2. A 600 x 600 x 200mm in-cell enclosure
3. A control PC system box preloaded with Windows 2000 and Cadet Lite software. Mouse, monitor with resolution of 1024 x 768.
4. A user interface comprising a keyboard tray with throttle and dynamometer control encoders and keyboard
5. A total of 8 looms:
    a. A Z1 loom to connect the in-cell enclosure to the control enclosure
    b. A Z2 loom to connect the in-cell enclosure to the control enclosure
    c. A Z3 loom to connect the in-cell enclosure to the control enclosure
    d. A 25 way D lead to connect the keyboard tray to the control enclosure
    e. A loom with a total of three 9 way d connectors to connect the control PC to the control enclosure
    f. A mains lead for the control computer
    g. A mains lead for the control rack

Troubleshooting

FMS 1000 intermittent fault

The FMS 1000 caused the greatest number of problems in the entire construction and commissioning of the test cell. Problems with this equipment delayed commissioning and extended into the testing phase. Ultimately they were overcome.

The symptoms of the fault were that the software occasionally displayed fuel consumption values that were obviously erroneous. The fault was intermittent and despite several occurrences under observation, no pattern in circumstances could be observed to provide a clue to the cause. Under certain operating conditions the value would be much lower than expected by the operator. In addition to this problem, occasionally when the fuel weigher performed an automatic cycle, it would fail to close the fill solenoid valve and overfill the weighing vessel causing fuel to spill back to the day tank. When this occurred, it prevented the FMS from providing data for the remainder of the engine test run. Both problems were intermittent and did not occur at defined points or events.

A program of intensive checking took place and many items that were thought to be the cause of the fault (such as the solenoid control valve) were replaced. The software conversion and control logic was examined in detail and minor changes made but without success. Many hours of testing were invalidated because the FMS would fail part way through the test.

The problem turned out to be two intermittent faults.

The internal vessel in the FMS is connected to the supply, flow and return ports by flexible, concertina style bellows, made of stainless steel. After a period of a few months the bellows had started to relax slightly and extend. This change had pushed the vessel towards the side of the enclosure and under certain conditions would touch. This acted to bind the vessel and enclosure, and cause low readings. The problem was discovered when two engineers were investigating the fault. A jump in the voltage output of the load cell was observed when a third party vigorously climbed the staircase to the control centre. It was recognised that the vibration had been carried by the Unistrut to the FMS housing. Close inspection of the mechanics of the FMS revealed the binding fault. The bellows were gently recompressed and the FMS recalibrated. Regular inspection of this equipment for this condition was subsequently undertaken to prevent reoccurrence.

The second intermittent fault was causing the FMS to overfill. After repeated consultations with the manufacturer, they supplied replacement components for the FMS control board. The faulty element was eventually found to be a relay on the control board that is normally open. When energised the relay refills the vessel but occasionally the relay, when de-energised was sticking closed.

Torque measurement

The torque measurement system failed during the early testing period and a constant value appeared at the HMI and did not change even when torque was applied. After investigation it was found that the regulated voltage source applied to the top and bottom of the bridge had failed. The board was removed and returned to the manufacturer who supplied a replacement. No torque reading failures have occurred since.

Dynamometer safety switch

In the cooling water supply line to the dynamometer there is a safety switch. It closes when the pressure exceeds 2 bar and is connected to the hardware protection system of the In Cell Transducer Box. The switch has never functioned properly and does not actuate when the cooling water is turned on. The switch was removed and placed on a regulated compressed air supply and found to actuate when 2 bar was reached. The conclusion was that there is less than 2 bar at the tapping and thus the switch rated inappropriately. The switch is not variable and so a new one will have to be purchased with a lower actuating pressure.

At present the switch is linked out and its protection function is forfeited. It is important to gain this option as it will provide a much quicker shutdown response in the event of a loss of cooling water.

The current mechanism is that the engine will trip on jacket over temperature, which is reactive rather than proactive.

Secondary cooling circuit

As previously detailed, the secondary cooling circuit achieves a flow rate of approximately 2.5 litres per second through the heat exchangers. This is a significantly greater flow rate than the design flow rate reflecting the lower temperature differential available utilising the ‘captive’ mine water. Accordingly the heat exchangers and fittings are subjected to a greater pressure than would be experienced by a standard installation at sea. This increased pressure resulted in a failure of the rubber boot fitting joining the main heat exchanger exit port to return pipework. The failure was recognised early allowing the engine to be shut down with the test being aborted. However, in the period before shut down was achieved a jet of water of considerable power wreaked havoc within the test cell. The entry and exit port boot fittings were replaced with new items and the 10 metre length of return pipework was replaced by a 5 metre length having a larger bore. These actions reduced the likelihood of any re-occurrence of this event.

PRT and Thermocouple

One thermocouple on the dynamometer failed after the above cooling circuit failure; this was attributed to ‘water ingress’.

The oil PRT failed for no determinable reason and was replaced. When sensors fail in this manner the engine is automatically shut down causing the test to be aborted.

Engine-dynamometer couplings

The dynamometer rotor is connected to the engine flywheel by a drive shaft having a Hardy Spicer universal joint at each end and a sliding splined male and female joint between the universal joints. The universal joints are those fitted to Land Rover vehicles with similar engine power to the test engine.

The universal joints have unexpectedly failed during the test regime requiring replacement. It is likely that these failures have occurred due to the high torque that the units are subjected to and the shock loading that has occurred occasionally during automatic emergency shut down.

A contributory factor is probably the lack of significant compliance between the engine crankshaft and the dynamometer rotor. In conventional applications such compliance is provided by slack in the gearbox, slip in the clutch and dedicated ‘cush drive’ units. These all act to reduce the shock loading and to attenuate torsional vibration. Modification was made at an early stage to address the rigidity of the drive connection when Metalastic bushes were incorporated into the drive shaft connection to the rotor. However, this action has proved to be insufficient and further modifications are required to reduce the need for frequent replacements of these components.

Reduced engine power

The strategy of accruing baseline engine performance data and periodically testing the engine condition against this data is defined elsewhere within this report. On occasions such periodic testing revealed a small but significant reduction in engine performance which had to be corrected prior to any further fuel testing. Three conditions were found to contribute to these apparent performance changes and are detailed below:

1. The condition of the air filter was found to be crucial to maintaining a stable engine performance and this is why a cleanable K&N filter element was installed. On two occasions the element was removed, cleaned with a purpose supplied detergent and re-oiled.
2. The valve clearances were found to be incorrect on one occasion, presumably having self adjusted under the extreme duty cycle imposed by some of the initial test work.
3. The failure of the Hardy Spicer universal joints detailed previously caused added losses in the power transmission to the dynamometer giving an inaccurate reading of engine power.

Although it never manifested itself as a problem, there is always a risk that a chocked fuel filter can cause a drop in engine performance. For this reason the fuel filter was changed at the mid point in the test regime.

Engine maintenance, failure and repair

Routine maintenance

Maintenance of the engine was performed according to normal good practice and with reference to the engine manual with further advice from a locally based marine engineer. The engine oil was changed together with the filter at the beginning of the commissioning trials and again immediately prior to the commencement of baseline data testing. The level of engine oil was checked before each test run together with the level of coolant in the primary cooling circuit. Both were topped up as required. Universal joints were regularly greased between test runs and the play in the driveshaft closely monitored. The tension of the alternator / water pump drive belt was also checked between each test run and adjusted as required.

Engine failure 1: 27th September 2007

When sufficient baseline power tests had been conducted and the project was about to move on to make fuel tests the engine suffered a major failure. This failure manifested itself as high pressure within the crankcase that expelled the engine oil from the manual oil pump provided to aid oil changing. Compression from the cylinders was gaining access to the crankcase by leaking past the piston ring seals. The engine was stripped down and it was found that the cylinder liners were badly worn in all cases and that two pistons had broken compression rings with a further piston having compression rings that were seized within their grooves *(see figure 02).*

Six new cylinder liners were fitted together with new pistons and piston rings *(see figure 03).* The opportunity was also taken to replace the connecting rod big end bearings but these appeared to be sound in any case. The engine rebuild then necessitated a period of running in which is required to allow the close fitting components to wear themselves to a working fit without overheating due to the added friction created by new and tight surfaces. Advice received from the marine engineer affiliated to the project suggested 20 hours of running commencing with approximately 25% output power ramping up to around 80% at the end of the period. These 20 hours of running in were performed over 7 days whilst the FMS fill valve problem was being investigated. At the end of the running in period the engine oil was changed together with the filter and the fuel filter. The valve clearances were checked and required only minor re-adjustment suggesting that the cylinder head had settled only very slightly.

Figure 02: Broken and seized piston rings

Figure 03: New cylinder liners and pistons

The failure of the engine in this manner was considered to be due to a combination of the following factors:

1. The engine was an old and well worn unit at the time of commissioning (refer to previous section *Engine characterisation)*. This was deliberate in order to replicate the units in use within the 10 metre class of fishing boat.
2. The baseline test being used until the 19th September was very harsh and far exceeded the duty cycle that engines of this age would be subjected to in boats. This test, Baseline 002 had been replaced by Baseline 003 on this date as it was feared that the severity of the test was placing the engine in jeopardy.

Baseline 002 used the full operating window from 1000 rpm to 2700 rpm to produce torque and power curves for the engine. The decision had been made to reduce the severity of the baseline tests by limiting the engine speed to 2500 rpm. Even so the test is still very harsh as the engine is producing maximum torque at each engine speed between 1000 rpm and 2500 rpm for 1 hour 40 minutes.

The impact of the engine failure on the project schedule was great. With a reconditioned engine the baseline archive already established was no longer valid and a new baseline archive had to be collected.

Engine failure 2: 6th December 2007

After around 400 hours of running since the engine rebuild, comprising 20 baseline tests and 13 day trawl tests, the engine failed with similar symptoms as reported above.

The engine was taken out of service and stripped down for inspection. In this case there was no excessive wear to the cylinder liners or the pistons but one piston compression ring was broken and the rings on two pistons had seized within the grooves. This prevented the rings from exerting pressure on the cylinder walls, a condition that is aggravated by minimal wear that then allows a gas path past the piston into the crankcase.

Investigations if the engine failure on this 2nd occasion appeared to show the following:

- There were no obvious signs of severe localised overheating of the components that would have led to this type of failure.
- There appeared to be no visual evidence of a localised lubrication problem that would have caused excessive wear of the bore and piston skirt.

Engine oil consumption

The addition of engine lubricating oil was entered into the engine log so that oil consumption could be monitored. The additions are shown below in Table A alongside the cumulative engine hours commencing at Baseline 003 001 of the 19th September 2007.

Figure 04 below shows this oil consumption in graphical form and whilst there is no representation of the loading of the engine, merely running hours, the plot clearly demonstrates the reduction in consumption at around 45 hours corresponding to the engine rebuild. The plot also appears to show a gradual reduction of oil consumption since the rebuild which suggests a continuing improvement in engine condition due to bedding in.

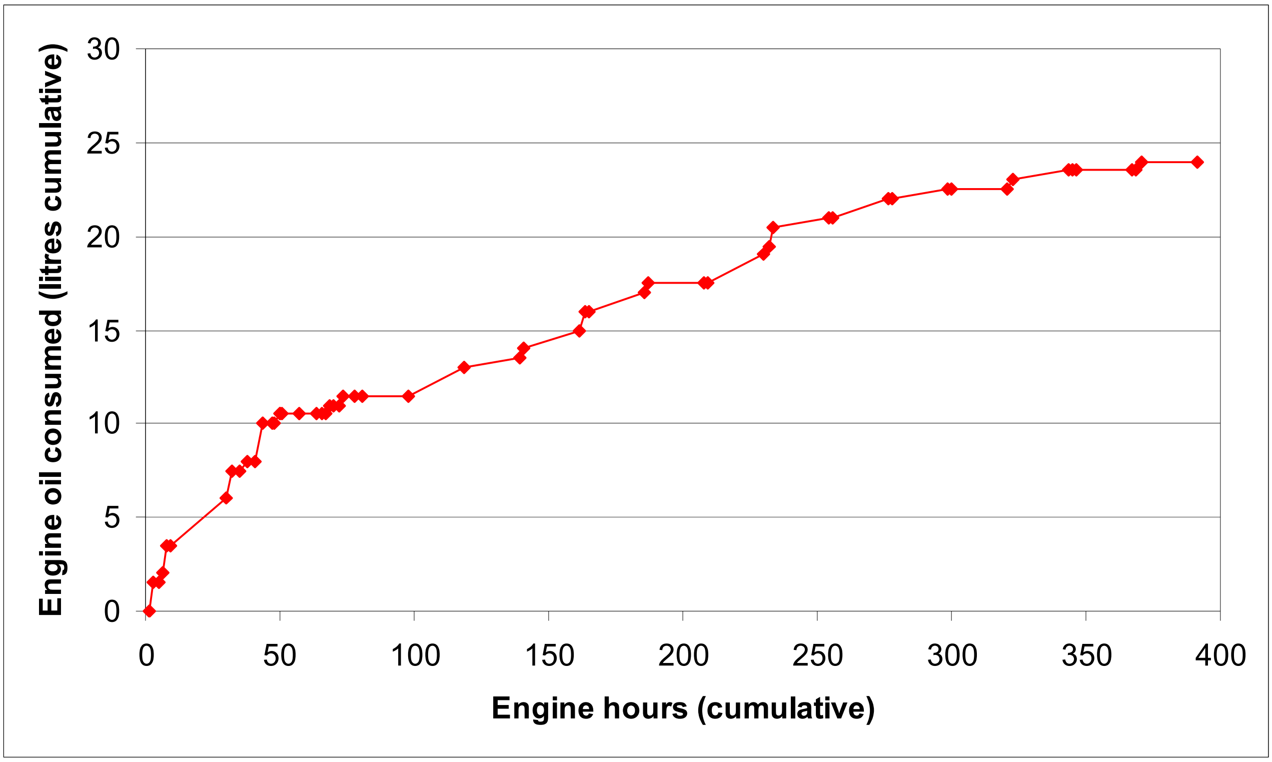


Figure 04: Graphical representation of oil consumption.

Table A: Oil consumption data

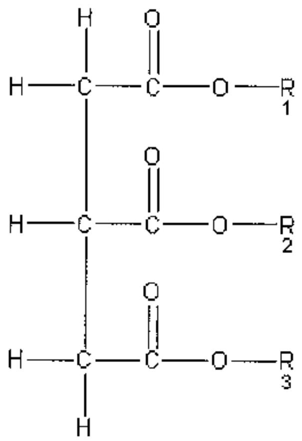
Test I.D.	Fuel base	Additive	Duration (hours)	Cumulative engine hours	Oil added after (litres)	Cumulative Oil added (litres)
BL003-001	red diesel	no	1.6	1.6	0	0
BL003-002	red diesel	no	1.6	3.2	1.5	1.5
BL003-003	red diesel	no	1.6	4.8	0	1.5
BL003-004	red diesel	no	1.6	6.4	0.5	2
BL003-005	red diesel	no	1.6	8	1.5	3.5
BL003-006	red diesel	no	1.6	9.6	0	3.5
DT002-001	red diesel	no	20.7	30.3	2.5	6
BL003-007	red diesel	no	1.6	31.9	1.5	7.5
EM-001	red diesel	no	3	34.9	0	7.5
EM-002	red diesel	no	3	37.9	0.5	8
EM-003	red diesel	no	3	40.9	0	8
EM-004	red diesel	no	3	43.9	2	10
Running in	red diesel	no	3	46.9	0	10
Running in	red diesel	no	1	47.9	0	10
Running in	red diesel	no	2	49.9	0.5	10.5
Running in	red diesel	no	0	49.9	0	10.5
Running in	red diesel	no	1	50.9	0	10.5
Running in	red diesel	no	6	56.9	0	10.5
Running in	red diesel	no	7	63.9	0	10.5
BL003-101	red diesel	no	1.6	65.5	0	10.5
BL003-102	red diesel	no	1.6	67.1	0	10.5
BL003-103	red diesel	no	1.6	68.7	0.5	11
BL003-104	red diesel	no	1.6	70.3	0	11
BL003-105	red diesel	no	1.6	71.9	0	11
BL003-106	red diesel	no	1.6	73.5	0.5	11.5
Manual run	red diesel	no	4.5	78	0	11.5
Manual run	red diesel	no	3	81	0	11.5
Aborted DT	red diesel	no	17	98	0	11.5
DT002-101	red diesel	no	20.7	118.7	1.5	13
DT002-102	red diesel	yes	20.7	139.4	0.5	13.5
BL003-107	red diesel	no	1.6	141	0.5	14
DT002-103	red diesel	no	20.7	161.7	1	15
BL003-108	red diesel	no	1.6	163.3	1	16
BL003-109	red diesel	no	1.6	164.9	0	16
DT002-104	red diesel	yes	20.7	185.6	1	17
BL003-110	red diesel	no	1.6	187.2	0.5	17.5
DT002-105	red diesel	yes	20.7	207.9	0	17.5
BL003-111	red diesel	no	1.6	209.5	0	17.5
DT002-106	red diesel	yes	20.7	230.2	1.5	19
BL003-112	red diesel	no	1.6	231.8	0.5	19.5
BL003-113	red diesel	no	1.6	233.4	1	20.5
DT002-107	red diesel	no	20.7	254.1	0.5	21
BL003-114	red diesel	no	1.6	255.7	0	21
DT002-108	red diesel	yes	20.7	276.4	1	22
BL003-115	red diesel	no	1.6	278	0	22
DT002-109	red diesel	yes	20.7	298.7	0.5	22.5
BL003-116	red diesel	no	1.6	300.3	0	22.5
DT002-110	red diesel	yes	20.7	321	0	22.5
BL003-117	red diesel	no	1.6	322.6	0.5	23
DT002-111	red diesel	no	20.7	343.3	0.5	23.5
BL003-118	red diesel	no	1.6	344.9	0	23.5
BL003-119	methyl ester	no	1.6	346.5	0	23.5
DT002-112	methyl ester	no	20.7	367.2	0	23.5
BL003-120	methyl ester	no	1.6	368.8	0	23.5
BL003-121	methyl ester	no	1.6	370.4	0.5	24
DT002-113	methyl ester	no	20.7	391.1	0	24

Containerised bio-diesel batch production plant

Process description

Reaction chemistry

The reaction employed in this scale of biodiesel production is termed a transesterification reaction. Consider new vegetable oil which is comprised of triglyceride molecules.



A triglyceride molecule is shown to the left. It consists of three hydrocarbon chains, shown as R_1 R_2 R_3. These chains might be of different lengths, saturated, mono-unsaturated and poly-unsaturated which is why the shorthand notation is used.

The triglyceride molecule is a triester because there are three esters in the molecule. An ester is a molecule that has a hydrocarbon chain attached to the single bonded oxygen atom of the functional group.

As the term transesterification suggests, the reaction used to make biodiesel from vegetable oil changes the esters in the oil (glyceryl esters) into alternative esters (methyl esters). In so doing the triesters become esters and by splitting the three chains apart in this manner, the viscosity of the biodiesel fuel is markedly less than that of the original oil.

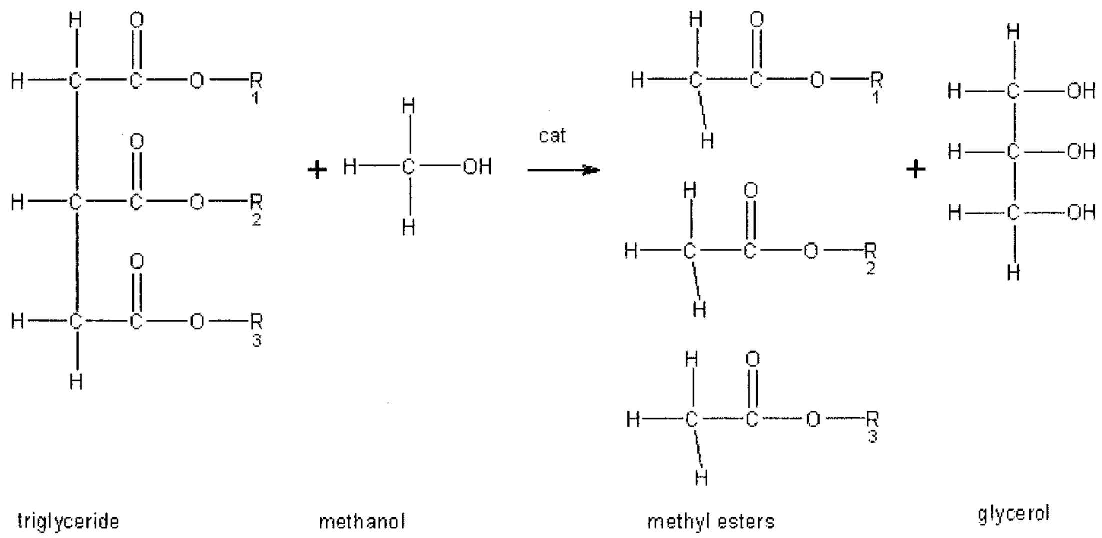


Figure 05: The transesterification of vegetable oil using methanol.

In the reaction shown above in *Figure 05*, it is evident that the methanol has replaced the glycerol "backbone" creating the three separate methyl esters and releasing the glycerol.

The transesterification reaction is reversible and as the triglycerides are separating, releasing glycerol and forming methyl esters, so the methyl esters are forming triglycerides and releasing methanol. The way in which we bias the equilibrium position well to the right (in small scale production) is to ensure the presence of a great excess of methanol.

An alternative transesterification of vegetable oil can be performed with ethanol rather than methanol hence producing ethyl esters rather than methyl esters. This is favoured by some because although the calorific value of the fuel is less than for fatty acid methyl ester fuel, the ethanol is more readily available as a carbon neutral reagent, unlike the methanol which is almost exclusively produced from petroleum.

In use as cooking oil, the triglycerides of the vegetable oil can break down and form fatty acids. Being unattached these are known as free fatty acids. These free fatty acids are undesirable in fuel due to their acidity and will not take part in the transesterification as they are not esters. One way to deal with the free fatty acids is to esterify them prior to the transesterification. However, this adds a chemical process to the production of the fuel and for small scale production the free fatty acids are simply neutralised with sodium hydroxide (or potassium hydroxide) to form soaps which are then removed.

The level of free fatty acids present in used cooking oil will depend on how much use the oil has had and what temperatures it was heated to; the more severe the use of the oil, the greater the concentration of free fatty acids. A titration is performed to assess the acidity of the oil and hence to determine how much alkali to add to neutralise it.

The Production Process

This section gives a brief outline of the production process with the batch reactor installed at Holmans Test Mine. The process is detailed in a stage by stage manner in the operating procedures given as *Appendix 2*. A schematic diagram of the production process is given as *Figure 06.*

There are five key stages to the production process, these are:

Stage 1	Vegetable oil conditioning and preheating.
Stage 2	The transesterification reaction.
Stage 3	Separation of the waste by-product (glycerine).
Stage 4	The Magnesol wash.
Stage 5	Final filtration.

The techniques and equipment employed for stage 1 will vary depending on the type and quality of the feedstock oil being used. The requirement is to deliver oil to the reactor at 55 – 60° C and for this oil to be free of water, free of solids and of known free fatty acid content. Water if present in too high a proportion, will affect the reaction by reducing the action of the catalyst and hence the reaction will not achieve the same degree of completion. Also water will form an emulsion with the soaps that are formed and this will cause difficulties in the subsequent washing and filtering operations.

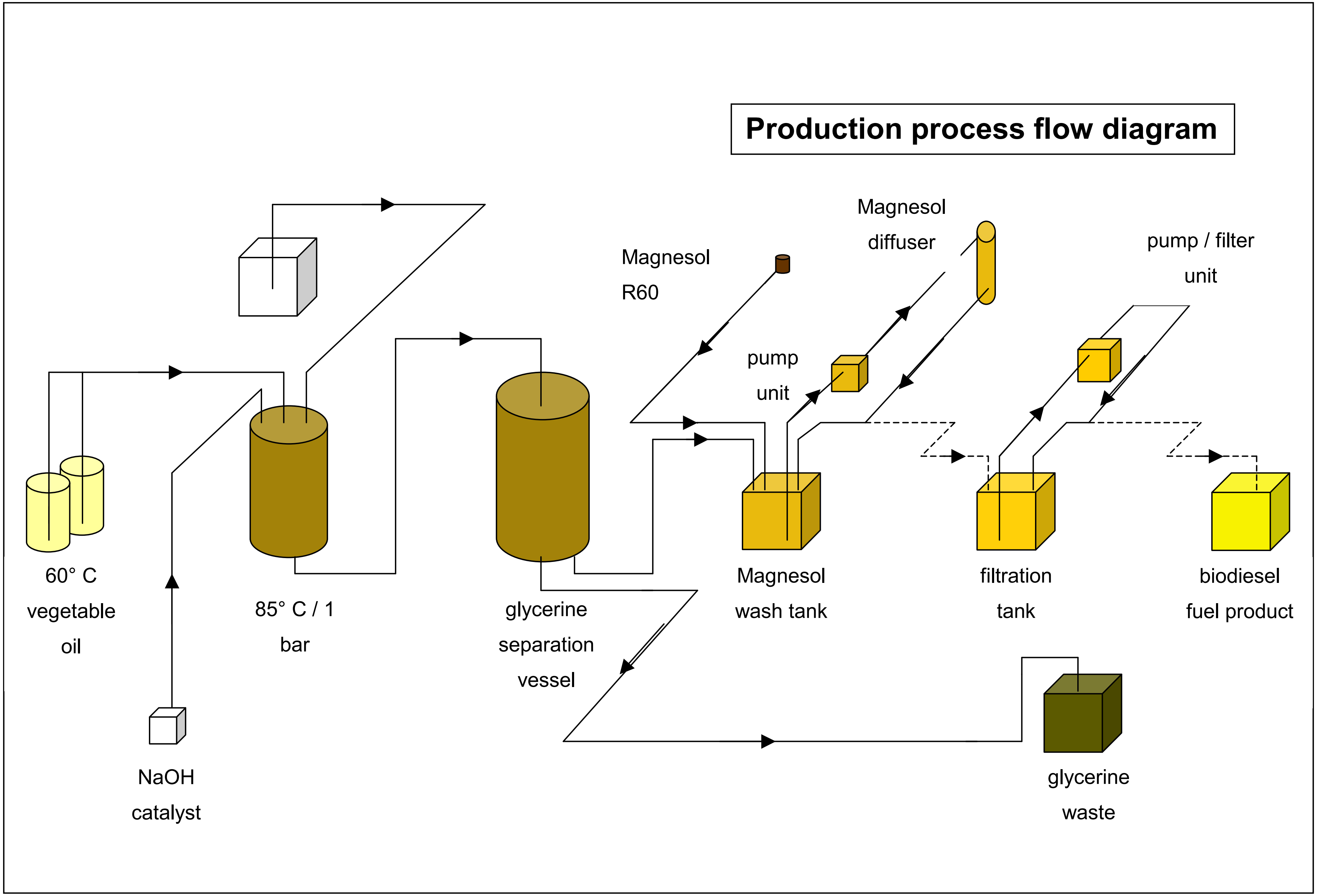
The free fatty acid content must be assessed so that the correct amount of sodium hydroxide can be determined. The sodium hydroxide performs two functions, firstly that of a catalyst for the transesterification reaction and secondly as a neutralizing agent for the free fatty acids.

In stage 2 the methanol is pumped by hand into the reactor followed by the sodium hydroxide and then the oil. A circulating pump mixes and agitates the reagents and electric elements raise the temperature resulting in a rise in pressure within the sealed vessel. Once 85° C is reached the reaction completes within 25 minutes after which the pressure is released and the products are pumped immediately to the separation vessel. Significant separation occurs quite soon after the transfer is complete and an initial drain off of the glycerine is performed after 1 hour. The final drain off of glycerine can be performed 6 – 8 hours later if 2 or 3 separation vessel batches are required per 24 hour day but overnight separation yields a higher grade of product and reduces the consumption of subsequent filter elements. When the glycerine is removed, the biodiesel is pumped to the Magnesol ‘wash’ tank.

Magnesol R60 powder is mixed into the biodiesel and mechanically agitated for 15 – 20 minutes. The Magnesol powder is described by its manufacturers, The Dallas Group of America inc., as a synthetic, amorphous, hydrous form of magnesium silicate with a porous internal structure and an enormous activated surface. It adsorbs the water, soaps, and residual methanol present in the biodiesel allowing them to be filtered out. The pump unit is used to circulate the colloidal mixture through the diffuser which removes solids above 1 micron in diameter. Periodic agitation is necessary during this time to prevent the Magnesol from settling out on to the bottom of the tank. When sufficient washing has been achieved, the biodiesel returning to the tank from the diffuser is diverted into the filtration tank. This method of transfer eliminates the risk of some unfiltered fluid being picked up by a separate suction hose in the Magnesol wash tank.

Final filtration employs a simple multi–pass pumped filtration circuit through 1 micron filters. Four or five passes through the filters are recommended which will take approximately 5 hours for a full batch of around 700 litres. When the filtration is complete the filter return line is diverted to send the finished biodiesel into a clean IBC for storage and use.

Figure 6: Production process flow diagram (overleaf)

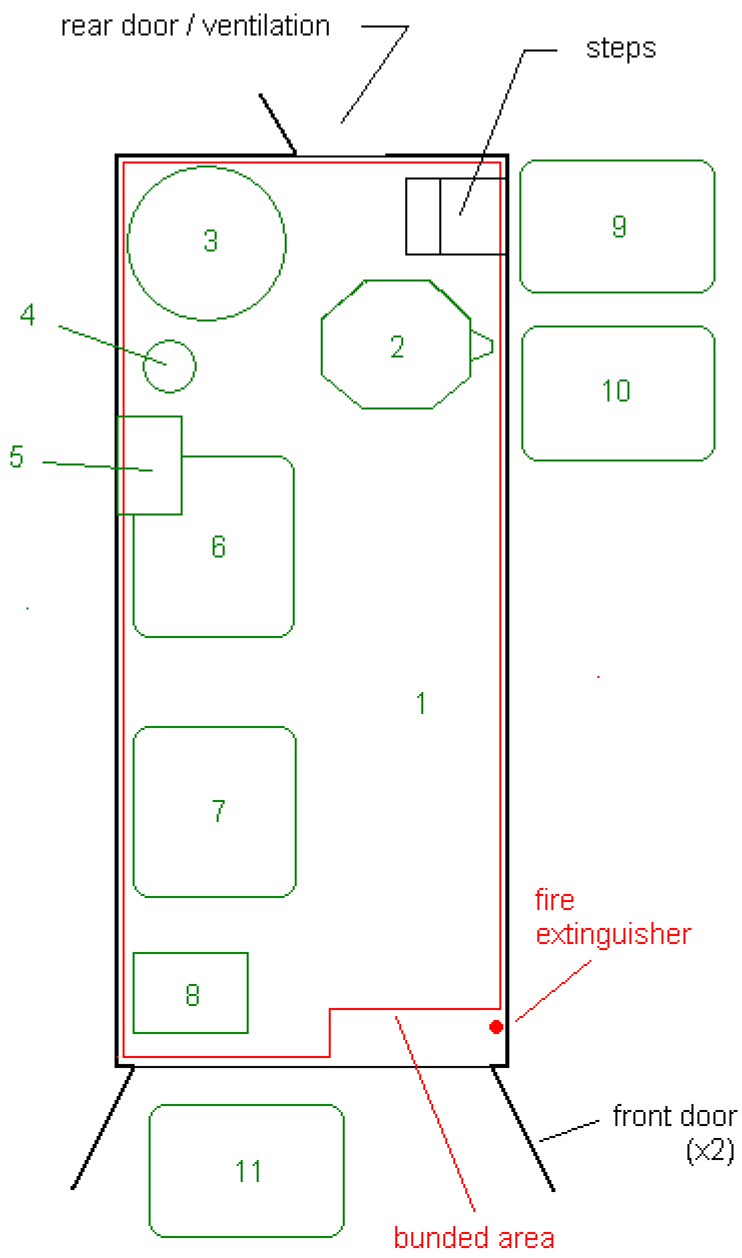

Production process flow diagram
Magnesol diffuser
Magnesol R60
pump / filter unit
pump unit
60° C vegetable oil
85° C / 1 bar
glycerine separation vessel
Magnesol wash tank
filtration tank
biodiesel fuel product
glycerine waste
NaOH catalyst

Plant specification

Containerised Plant Layout

The production unit comprises the equipment required for the 5 stages of the process, pumps and pipework to effect the fluid transfer from stage to stage, an electrical distribution system and suitable lighting. This equipment is rigidly assembled into a specially modified steel shipping container providing a secure, safe and bunded operating environment that can be relocated to any suitable site.

Figure 07 below shows the layout of the process equipment within the container and the positioning of methanol, glycerine and the fuel product outside of the container.



1	Area for feedstock oil preparation	7	Filtration tank
2	Transesterification reactor	8	Filtration unit
3	Glycerine separation vessel	9	IBC containing methanol
4	Magnesol wash diffuser	10	IBC receiving waste glycerine
5	Magnesol wash pump unit	11	IBC receiving final fuel product
6	Magnesol wash tank		

Figure 07: Plan view of process equipment layout

Plant Specifications

Production unit	
External dimensions:	6.0 m x 2.4 m x 2.5 m high
Internal dimensions:	5.5 m x 2.25 m x 2.3 m high
Gross dry weight:	~ 3.75 tonnes
Electricity supply requirement:	3 phase (32 amp) + neutral + earth
Electricity supply connection:	Armoured cable terminating in a 32 amp 5 pin socket
Maximum daily fuel output:	~ 700 litres (overnight separation phase). Up to ~ 1400 litres (7 hour separation phase with 24 hour working).
Feedstock oil conditioning	
Vessel:	Dependant on oil supply
Heating:	2 x 3 kW submersible barrel elements
Reactor vessel	
Manufacturer:	UK Fueltech Ltd
Model:	BD 400
Minimum batch size:	200 litres of vegetable oil + 34 litres of methanol (17%)
Maximum batch size:	400 litres of vegetable oil + 80 litres of methanol (20%)
Operating temperature:	85° C
Operating pressure:	1 bar
Instrumentation:	Digital temperature display Bordon tube pressure gauge Fluid input volume meter
Settling vessel	
Manufacturer:	Camborne School of Mines
Material:	Steel
Capacity:	1000 litres
Instrumentation:	Fluid level sight tube
Washing equipment	
Manufacturer:	Hydrotechnik Ltd
Model:	Magnesol wash diffuser
Washing agent:	Magnesol R60 powder (magnesium silicate – 60 micron)
Diffuser filter grade:	1 micron
Diffuser maximum pressure:	3.5 bar
Working temperature:	20° C – 120° C

Washing tank	
Type:	Modified IBC
Capacity:	800 litres
Filtration equipment	
Manufacturer:	Hydrotechnik Ltd
Model:	BD 6000
Pre-filter grade:	10 – 50 micron
Final filter grade:	1 micron
Final filter capacity:	Up to 4 kg of particulate matter
	Up to 1.6 litres of water
Rate of filtration flow:	600 litres / hour
Filtration tank	
Type:	Modified IBC
Capacity:	800 litres
Methanol delivery pump	
Manufacturer:	Arco Ltd
Model:	950 plastic hand pump
Stage to stage transfer pumps (4)	
Manufacturer:	Clarke
Model:	Diesel delivery pump
Hot reaction products transfer hose	
Supplier:	Pirtek
Type:	10 bar petroleum resistant hose
All other fluid transfer hose	
Supplier:	Pirtek
Type:	Ribbed PVC hose
Thread sealants	
In contact with methanol:	Araldite 2012 epoxy resin
All others:	PTFE thread tape
Ball Valves	
Materials:	Chrome plated brass / PTFE

Suitability for quayside operation

The containerised production plant could feasibly be located on the quayside at a fishing port. The bunding provided within the unit serves well to contain the inevitable spillages that occur whilst processing the fuel. However, it is envisaged that a second container would be required in an adjacent position providing safe and secure storage for the feedstock oils, methanol, sodium hydroxide, Magnesol, waste products, consumable items and the fuel product itself.

The exact location of such a processing plant would need to allow for the following factors:

- Safe provision of a 32 amp, 3 phase power supply
- Adequate exclusion of unauthorised personnel
- Adequate movement areas for materials handling
- Provision of suitable mechanised handling equipment (fork lift truck).

Additionally it would be necessary to comply with the relevant pollution control regulations and this is likely to require the provision of equipment suitable for containing a spillage into the harbour.

Reagent storage and handling

Waste vegetable oil has been procured in two distinct forms, liquid waste vegetable oil purchased from dealers and solid waste palm oil freely available for collection.

The liquid waste oil is generally received in a 1000 litre IBC and contains high levels of free fatty acids which densely populate the ‘whites’ that settle out at the bottom of the container with time. Whilst the IBC serves well as a delivery and storage container for the oil, it is important that the ‘whites’ are allowed to settle and that the oil is pumped from the top of the IBC rather than the outlet port provided at the bottom.

The solid waste palm oil has been poured (warm) into 50 litre plastic drums having barrel shaped sides. It is found that the re-entrant form of the containers has made it difficult to remove the solid oil from these containers once the oil has set firm. The original plan to upturn the containers above a heat source has not been successful due to the very poor thermal conductivity of the solid fat.

Methanol has been procured in both 1000 litre IBCs and 205 litre barrels. The latter option is preferable due to the lower risks associated with smaller volume containers. It is important that any pump used for transferring methanol is intrinsically safe. In this instance there is no spark risk as the specified unit is hand operated.

Both reagents should be stored within a bunded area to avoid accidental contamination to the surrounding environment. The methanol should be stored with the container sealed to prevent evaporation to the atmosphere but this necessitates shielding the container from heat sources such as sunlight. The liquid vegetable oil should be stored in such a manner as to prevent the ingress of moisture which will be absorbed by the oil.

Processing Plant operations

Required infrastructure

The infrastructure requirements for the processing plant operation are based on the safety of personnel and the public and protection of the environment as well as the practical needs of the plant. The requirements are:

1. Electrical power supply – 415 V, 3 phase + neutral +earth, rated at 32 amp maximum.
2. Mechanical handling equipment suited to the safe lifting and movement of the chosen bulk liquid containers (IBC or 205 litre barrel etc).
3. Bunding dedicated to the safe storage of the liquid reagents and products (vegetable oil, methanol, methyl ester fuel and glycerol by-product).
4. Equipment, materials and a written plan providing emergency measures in the case of accidental fluid spillages.
5. Adequate fire prevention and control measures.
6. Appropriate waste disposal streams for the glycerol by-product, the process filters and the filter cake.
7. Adequate space suited to the safe storage of the reagents, products and wastes.

Health and safety issues

The production process, equipment and the materials involved present a variety of hazards to personnel operating the plant. These hazards and the resulting risks must be recognised and understood in order that they can be controlled and reduced to acceptable levels. For this reason a full risk assessment study has been carried out. The risk assessment study is continuously reviewed and updated in the light of experience gained and to this end a member of the production team has taken 'ownership' of this document.

The measures to control risks determined by the study translate into procedures that are detailed within the *Operational Procedures* (reported here as Appendix 1) and the *Maintenance* (reported here as Appendix 2) sections of the plant operating manual. All safety instructions contained within the *Operational Procedures* and *Maintenance* sections appear in red.

Material safety data sheets (sometimes referred to as CoSHH sheets) are made available on site for all substances involved in the process. Suppliers are required to provide such information under the Control of Substances Hazardous to Health legislation. The substances involved in the fuel processing that require CoSHH sheets are listed below.

1. Sodium Hydroxide
2. Methanol
3. Phenolphthalein solution

4. Isopropanol
5. Magnesol R

Pressure vessel regulations

Under the current UK legislation any vessel subjected to more than 0.5 bar is regarded as a pressure vessel. Further, if the product of the maximum pressure and the internal volume is greater than 250 bar litres, the pressure vessel is subject to the regulations. In the case of the reactor vessel the maximum pressure is 1 bar and the product is around 600 - 1000 bar litres (the precise volume of the reactor is not specified). Therefore the reactor vessel is classified as a pressure vessel under the regulations and must be inspected and insured accordingly.

Feedstock collection and provenance

Recovered vegetable oil was sourced locally from several fish and chip shops, although the vast majority was acquired from The Galley Fish and Chip Shop, in Camborne. It was found that most chip shops were willing to provide their waste oil free of charge, as long as suitable barrels were supplied. Only one chip shop asked any questions about the waste transport licence. Local chip shops were found to produce between 25 litres and 100 litres of waste oil per week. The quality of oil varied between establishments and oil that had been used to fry chicken was found to be of particularly poor quality, with a high free fatty acid content.

It was found that in the local area only about half of the fish and chip shops used vegetable oil, the remainder using animal fats. Although animal fats can be converted into bio-diesel, none was collected as this requires an acid esterification process rather than the transesterification process established.

Plant operation

Successful operation of the fuel processing plant is achieved by close adherence to the operating procedures. In addition to these specific instructions the following points are made:

1. It is important that the feedstock waste vegetable oil is of adequate quality. Particular attention must be given to the exclusion of water from the oil and to the settling out of the 'whites' containing high levels of free fatty acids.
2. It is important that the catalyst is kept in an air tight container to prevent moisture ingress. If the granular sodium hydroxide absorbs moisture it loses effect as a catalyst for the transesterification reaction.
3. Good housekeeping within the processing plant is vital to maintain a safe working environment and to prevent unnecessary errors from being made.

Waste products

The waste products from the fuel processing include the glycerol by-product, wet catalyst retrieved from the settling vessel, magnesol filter cake, magnesol filter sock, final filter elements and the 'whites' from the feedstock waste oil. Options for disposal / use of these materials are detailed below:

The glycerol by-product can be combusted but this combustion must be achieved at high temperatures to prevent the release of acrolein, a very hazardous gas. (Carter et al, 2005). Dedicated glycerine burners are commercially available for this purpose and these burners typically rely on the methanol remnants in the glycerine and an addition of 10 – 15% methyl ester fuel to achieve the temperature required. However, consideration should be given to whether this disposal method risks contravening waste incineration regulations.

An alternative to combustion is to compost the waste glycerine. This must be performed together with compostable solid matter so that the liquid waste is absorbed into a larger solid mass rather than simply running off into the water course. The wet catalyst can be added to this compost as the sodium hydroxide is recognised as a fertiliser.

A third option for disposal of the glycerine might be to use it as a simple soap, perhaps for washing down fishing boat decks. In their book, How to make biodiesel, the Low Impact Living Initiative recommend warming and filtering the glycerine and then leaving it to stand for at least a week in an open top container. This time period is required to allow any methanol remnants to evaporate.

For larger scale operations it has been financially attractive to refine the waste glycerine into its pure form however this may not be as attractive now due to the large surplus of glycerine on the market.

The whites of the waste vegetable oil can be composted in a similar manner to that described above and the magnesol filter cake can also be composted although the magnesol itself will not undergo any change and will simply add bulk to the compost. The filter cartridges from the final filtration are made from paper and can therefore be composted.
In the event that the volume of waste product exceeds that which can be dealt with as described above, commercial waste disposal will be required.

One potential disposal route worthy of further assessment but not discussed above is that of anaerobic digestion (AD). It is possible that all of the wastes suitable for composting can be processed in an 'energy from waste' anaerobic digester. Low grade glycerine is currently being used as part of the feedstock for the Holsworthy anerobic digestion power plant. Its high calorific value relative to cattle slurry and other similar components of the feedstock means that its addition to the AD process must be strictly regulated. Consequently, it is not thought that even a burgeoning AD market would provide sufficient demand for by-product glycerine from biodiesel plants.

Experience of bio-diesel production

Cold weather problems

Operation of the processing plant is made considerably more difficult by cold weather. As the plant is located within a steel container the ambient temperature within the plant closely follows the outside air temperature. The effect of the lower temperature is to increase the viscosity of the liquids involved in the process and to promote solid plugging of fluid transfer ports and pumps making transfer impossible. The problem is eased somewhat by heating the environment within the processing plant or by continuous operation which achieves the same end without additional energy input.

Pumping problems

On occasions the pump employed to lift the feedstock oil into the pre-heating vessels has been inadequate due to the viscosity of the oil and the suction head required. In such instances oil has been dosed from the bottom tapping of an IBC and consequently fuel washing and filtering operations have been severely hampered by the level of emulsified soaps present.

Fluid transfer from the settling vessel

By definition the catalyst passes through the reaction unchanged although it is dissolved in the products. As the products cool in the settling vessel, the catalyst crystallises in the bottom of the vessel and eventually blocks the outlet ports used to transfer the waste glycerine and the methyl ester from the vessel. This has necessitated the removal of hoses and rodding of the ports to clear the obstruction on several occasions.

Washing and Filtering

The pumped circuits that take the fuel through the Magnesol filter sock and the final filters have maximum pressure limits of 3.5 bar. This pressure limit is soon exceeded in cold conditions when the fuel is more viscous and this has necessitated external heating of the filter units and more recently a re-heat of the fuel itself to around 40° C. Even with this action these filtering operations have been problematic and have not been sufficiently controllable. On at least one occasion Magnesol powder has been found in the final fuel product despite multiple passes through filters that should prevent passage of this particle size. Additionally the success of the Magnesol wash in removing emulsified soaps is unpredictable. It is recognised that this problem is closely related to the issues concerning feedstock handling and ambient conditions and it is apparent that at times all factors have acted together to undermine the process.

Bio-diesel production costs

Costing basis

The costs listed below are all given excluding VAT and represent the costs that applied to the last batch of fuel processed during November 2007.

Feedstock costs

The cost of feedstock vegetable oil procured for fuel processing has varied between zero as described previously and £0.60 per litre for virgin rapeseed oil purchased direct from a local farmer. Perhaps the most representative cost to consider is the general market value of waste vegetable oil which can be purchased in a 1000 litre IBC. During the summer of 2006 this cost was £0.20 per litre but with the increasing demand this cost has risen to £0.27 per litre in September 2007. With the current transesterification only process, a quantity of this feedstock oil (the whites) is unusable and this can be as much as 10%.

Methanol and Catalyst costs

In September 2007 the cost of methanol purchased from a chemicals supplier in 200 litre barrels was £95.58 giving a cost per litre of £0.48 / litre.

The current cost of pearl granular sodium hydroxide is £16.00 per 25 Kg bag or £0.64 per Kg.

Costs of consumables

The pre-filter elements that screen larger particulates from the reactor and the final filters currently cost £5.78 each for disposable elements or £46.00 for cleanable elements. For costing purposes it is assumed that disposable elements are used.

The final filtration / polishing filter elements currently cost £15.00 each and are used in pairs.

The Magnesol filter sock currently costs £8.95 and Magnesol powder costs £2.00 per Kg.

Electrical power consumption

The fuel processing plant is connected to the test site's electrical sub-system via a dedicated three phase power / energy meter which has facilitated easy measurement of electrical energy consumption. Splitting the process into three parts, the measured energy consumed for a 400 litre batch of feedstock oil is as follows:

1. Pre-heating feedstock, pumping, reacting and pumping to the settling vessel consumed 25 kWh.
2. The Magnesol wash stage consumed ~ 2 kWh.
3. The Final filtration stage consumed ~ 3 kWh.

This gives a total energy consumption of 30 kWh for a 400 litre batch of oil producing approximately 380 litres of fuel. These figures do not take into account any additional heating of the working environment that might be required in cold weather.

Assuming a cost per kWh for electricity of £0.12 this gives a cost of £3.60 to produce 380 litres of fuel.

Labour costs

The labour cost to process a single 400 litre batch of feedstock oil is not representative of economic operation because of the large amount of 'idle time'. It is therefore sensible to consider the labour cost content for a 400 litre batch assuming that the previous batch is being washed/filtered and the following batch is being prepared. Also the assumption is made here that cold weather difficulties do not apply. In this manner the following approximates to the labour input to the current production facility.

1. Stages 1, 2 and 3 combined – 2 man hours
2. Stages 4 and 5 combined – 3 man hours

Assuming a labour value of £10 per man hour gives a labour value of £50.00 to produce 380 litres of fuel.

Costs of bio-diesel production

In summary, the observed costs of bio-diesel produced for this project were as follows:

Recovered vegetable oil was obtained at a cost of 0p to 30 per useable litre (after allowing for discarded whites), which, after allowing for losses during the production process gave a feedstock cost per litre of 0p to 32p.

With the process consuming just over 1 litre of methanol for every 4 litres of bio-diesel produced, the cost of methanol per litre of product was 12.5p. It should be noted that this cost could be reduced if methanol recovery was included within the process.

The cost of the sodium hydroxide catalyst added a further 0.75p per litre to the production cost.

The magnesium silicate dry washing process employed adds up to 2p per litre to the production cost. Alternative systems would also have similar costs: water washing has a low input cost but a more significant effluent disposal cost, whilst ion exchange systems have an initial resin cost plus the cost of periodic recharging.

In order to improve the cold weather properties of the bio-diesel, a cold weather additive is required, just as it is in fossil diesel. The cost of this additive will vary upon the concentration used, which is in itself a function of the nature of the feedstock and the ambient temperature at which the fuel is to be used. A conservative cost would be 2p per litre.

The marginal cost of materials to produce 1 litre of bio-diesel was therefore either 18p or 48p depending upon whether the feedstock oil had been obtained free of charge or was purchased on the open market. However, these are not the only costs associated with bio-diesel production. Power, consumables and maintenance add a significant overhead cost. The observed power costs as outlined earlier, amount to around 1p per litre of product. The costs arising from consumables, maintenance and local collection of feedstock were highly variable from batch to batch. However, it is unlikely that these overheads would amount to less than 5p per litre. When filtration problems or other breakdowns were encountered, the costs were far higher.

Therefore, before taking into account the value of labour, the production cost per litre of bio-diesel produced was at least 23 pence per litre when feedstock was locally obtained free of charge, and at least 53 pence per litre when commercially sourced recovered vegetable oil was used.

Recommendations

Process improvements

Recommendations for improvements to the methyl ester production process are as follows:

1. Utilise an esterification reaction prior to transesterification to reduce the problematic production of soaps in the fuel product. This measure will also eliminate the requirement for a suitable waste stream for the 'whites' from the waste oil and produce only a small amount of filtered solids which can be composted.
2. Implement methanol recovery by condensing the methanol vapours that are expelled from the reactor at the completion of the reaction stage. This stage can be extended to allow sufficient time for significant methanol recovery.
3. Replace the Magnesol wash with a process that does not compromise the intrinsic safety of the fuel product by the addition of particulate matter.

Plant improvements

Recommendations for the improvement of plant to suit the current process are as follows:

1. The provision of a robust diaphragm type pump capable of achieving a minimum suction head of 3 metres and being unaffected by large particulate matter and tolerant of viscous

fluids. This pump will be used to transfer waste vegetable oil into the processing plant and to transfer fuel and glycerol from the settling vessel.

2. The reduction in height (and thus capacity) of the settling vessel allowing for easier periodic removal of wet catalyst and other particulate matter.
3. The addition of insulation material to the steel container, perhaps on the outside. This would allow a favourable working temperature to be maintained within the processing plant. A better solution would be to locate the processing plant container within a heated environment such as a large industrial building. Better still might be to install the process equipment freely in an industrial building. If this were possible advantages would be realised by adopting a multi level process where gravity is used to transfer fluids from stage to stage.

Engine Test Cell Operation

Preliminaries

Insurers & health & safety protocols

Day trawl test schedules took over 20 hours meaning that there were significant periods of time when the test cell would operate unattended. Initially, the University's insurers took a dim view of these circumstances and imposed a ban on unattended testing. A risk assessment for 24 hour operations, provided in Appendix 3, was prepared for the insurers that summarised the safety measures in place for the test cell. The insurers requested that the first 20 hour test be undertaken while an engineer was in attendance which was done. For the most part, the trial passed uneventfully, however at around 5.30am a power outage on the local Western Power Distribution 11kV network occurred momentarily. This caused the engine test cell to shut down completely – as designed. The engineer in attendance restarted the cooling water system with highest priority to minimise the chances of the engine overheating, having been stopped rapidly from around 60% full load. At the time, this clearly raised concerns about how frequently such outages occurred, but subsequently no similar outage during 24 hour testing was experienced.

Quality assurance

All data gathered from the engine test cell are stored on the SCADA computer in the operator's cabin within the test cell chamber. These are time stamped and are recovered via the data export facility of the CP Engineering CADET V12 Lite software. Data exported from the CADET V12 Lite software are structured in date-sorted directories. Data are exported in 3 distinct file formats to ensure that they are recoverable in the event of corruption of all copies of the primary format adopted. These formats are: i) comma separated variable (.CSV) files, ii) tab delimited text (.TXT) files, iii) Quattro Pro (.WK1) files. In two of these file formats, the data files contain time and date stamps for each record of logged data (every 10 seconds, 1 minute, etc). The text files contain general information regarding the conduct of the test, for example, Engineer's name, engine details, fuel density, sensor channel numbers, etc.

Data removed from the test cell computer is archived on project engineers' PCs as well as on portable storage devices, and conforms to the same directory structure and file naming conventions as found on the test cell computer.

Calibration certificates or results of in-house calibration procedures, as appropriate, are held within the project engineer's records.

A test log book has been maintained for all testing undertaken. Data file root names are recorded here as well as details or observations of each test that are not recorded by the SCADA software, for example, state of exhaust, fan or pump shut downs, oil and coolant levels before and after testing, notes of routine or other maintenance undertaken, etc. This log has been reproduced for inclusion in this report and is presented in Appendix 4. It will provide the reader valuable assistance when interpreting the test sequence.

Initial testing prior to main commissioning

In the Spring of 2007, very shortly after the engine test cell became operable (but in no way commissioned), a series of trial tests on petrodiesel (46.20 MJ/kg), palm oil methyl ester (38.73 MJ/kg) and Biopower 100 (a straight vegetable oil fuel with a propriety additive, 39.32 MJ/kg) were undertaken to determine where effort needed to be focussed during the commissioning phase. Due to the engine and dynamometer cooling problems detailed earlier, it was not possible at this time to operate the engine at full power. Results from these tests were not designed to be as accurate as those post-commissioning and after the engine had been fully characterised, but simply were to highlight problem areas. In particular, they subsequently assisted in development of procedures for handling different and blended fuels in and around the test cell. However, in addition to proving the basic set-up, these tests also provided useful data which informed the design of subsequent testing.

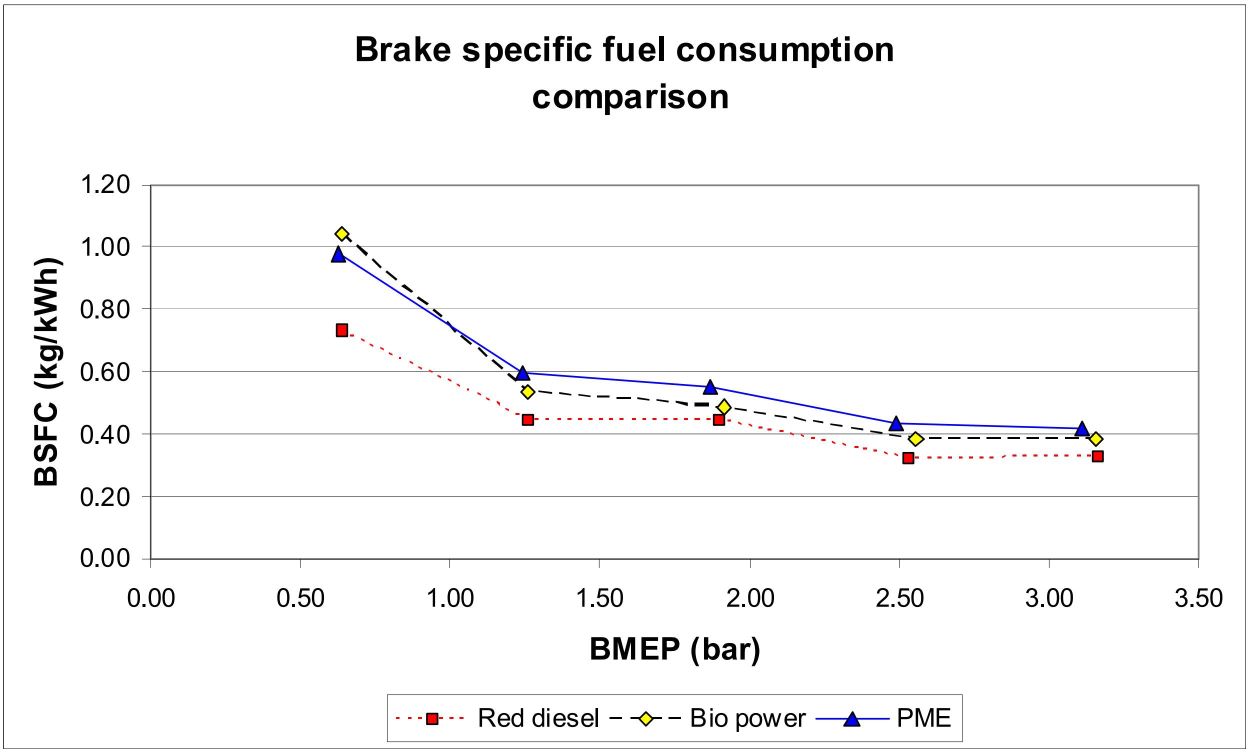


Figure 08: Preliminary fuel consumption tests from the test cell, with petrodiesel, palm methyl ester and 'Biopower V100' (sunflower oil with a propriety additive).

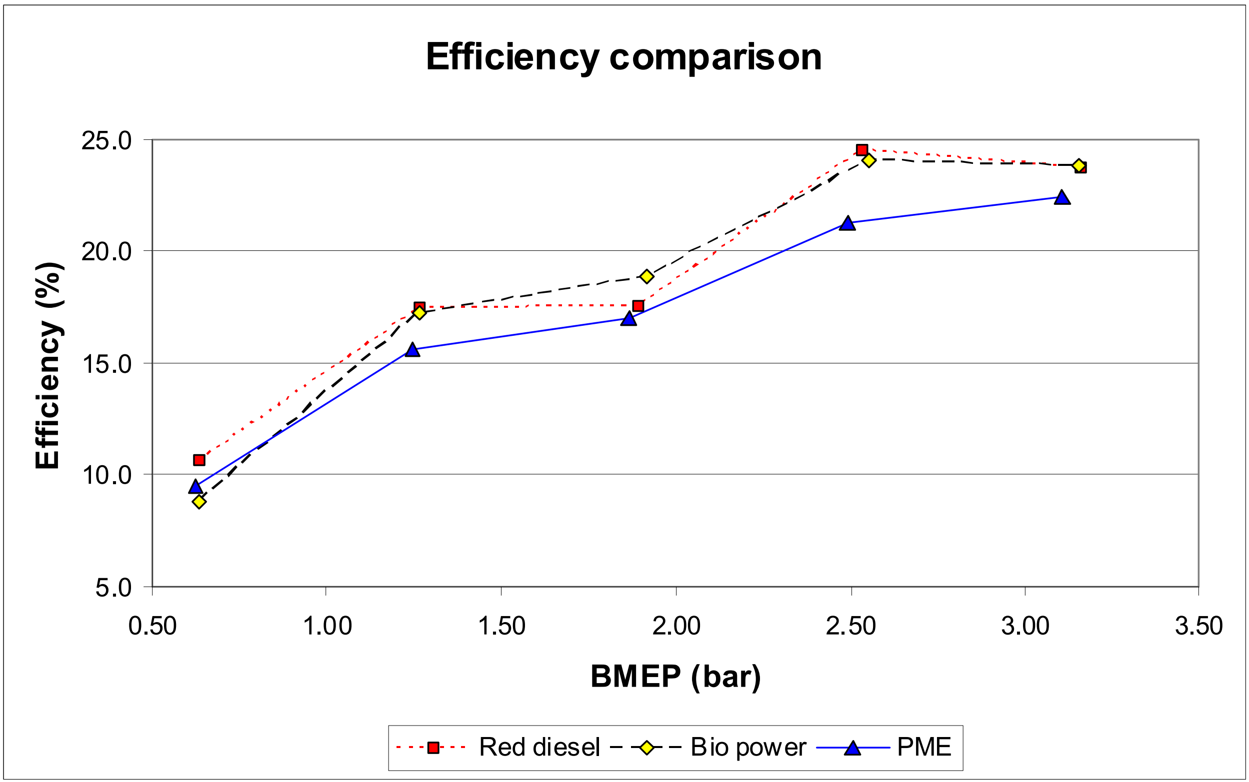


Figure 09: Preliminary efficiency tests from the test cell, with petrodiesel, palm methyl ester and 'Biopower V100' (sunflower oil with a propriety additive).

As far as the relative performance of the fuels were concerned, the conclusions of this short study were as follows:

1. Red diesel consistently has the lowest specific fuel consumption across the range, by virtue of its high calorific value.
2. Red diesel and Biopower V100 provide more efficient operation of the engine than palm methyl ester.
3. On the basis of the tests conducted, the Biopower V100 leads to the most carbon savings (@70.2% of the carbon that would be emitted in use of petrodiesel.
4. Vegetable oils with additives can be tested in the test cell engine but impose additional problems in starting the engine.

Engine Correction Factor

The standard adopted for applying corrections to engine torque and power to account for atmospheric conditions was ISO1585. The implementation of this standard with the engine test cell set up is as follows.

The saturated vapour pressure of intake air, p_{vs} is found from:

$$p_{vs} = 0.009806 \exp\left(58.739 - \frac{6852.5}{(273.15 + t_d} - 5.262 \ln(273.15 + t_d)\right)$$

where t_d is the dry bulb temperature of the engine intake air expressed in °C. The partial vapour pressure, p_v, of the air is then calculated with knowledge of the relative humidity, h, of the engine intake air:

$$p_v = h \cdot p_{vs}.$$

Factor Fa is then calculated thus:

$$Fa = \left(\frac{273.14 + t_d}{298}\right)^{0.7}\left(\frac{p_0 - p_{v0}}{p - p_v}\right)$$

where p_0 is a standard atmospheric pressure given as 100 kPa, p_{v0} is a standard partial vapour pressure defined as 1 kPa (equivalent to a relative humidity of ~32.5%), and p is the measured atmospheric pressure.

The next step in the calculation is to determine the factor q, thus:

$$q = \frac{c \cdot s}{\mathrm{rpm} \cdot V}$$

where c is a constant equal to 120,000 for diesel engines, s is the specific fuel consumption in g/s, rpm is the engine rotational speed, and V is the engine swept volume. The factor q is high and low thresholded at 65 and 40 respectively and then used to determine factor Fn:

$$Fn = 0.036 \cdot q - 1.14$$

from which the power correction factor, CF ,is finally obtained:

$$CF = Fa^{Fn}.$$

Note that for convenience in the calculations to correct power and torque, this formulation is actually the reciprocal of the power correction factor as defined in many standards. Another standard, DIN70020 was initially adopted for the study, due to its, relative, simplicity:

$$CF = \left(\frac{273 + t_d}{293}\right)^{0.5}\left(\frac{101.3}{p}\right)$$

with p in kPa. However DIN70020 does not take air humidity into account and it was found that as testing progressed, the most consistent results were obtained when air humidity was taken into account, as with ISO1585; adopting DIN70020 introduced more variance between our baseline tests when the engine operating condition had finally stabilised.

Maximum power test description and test schedule

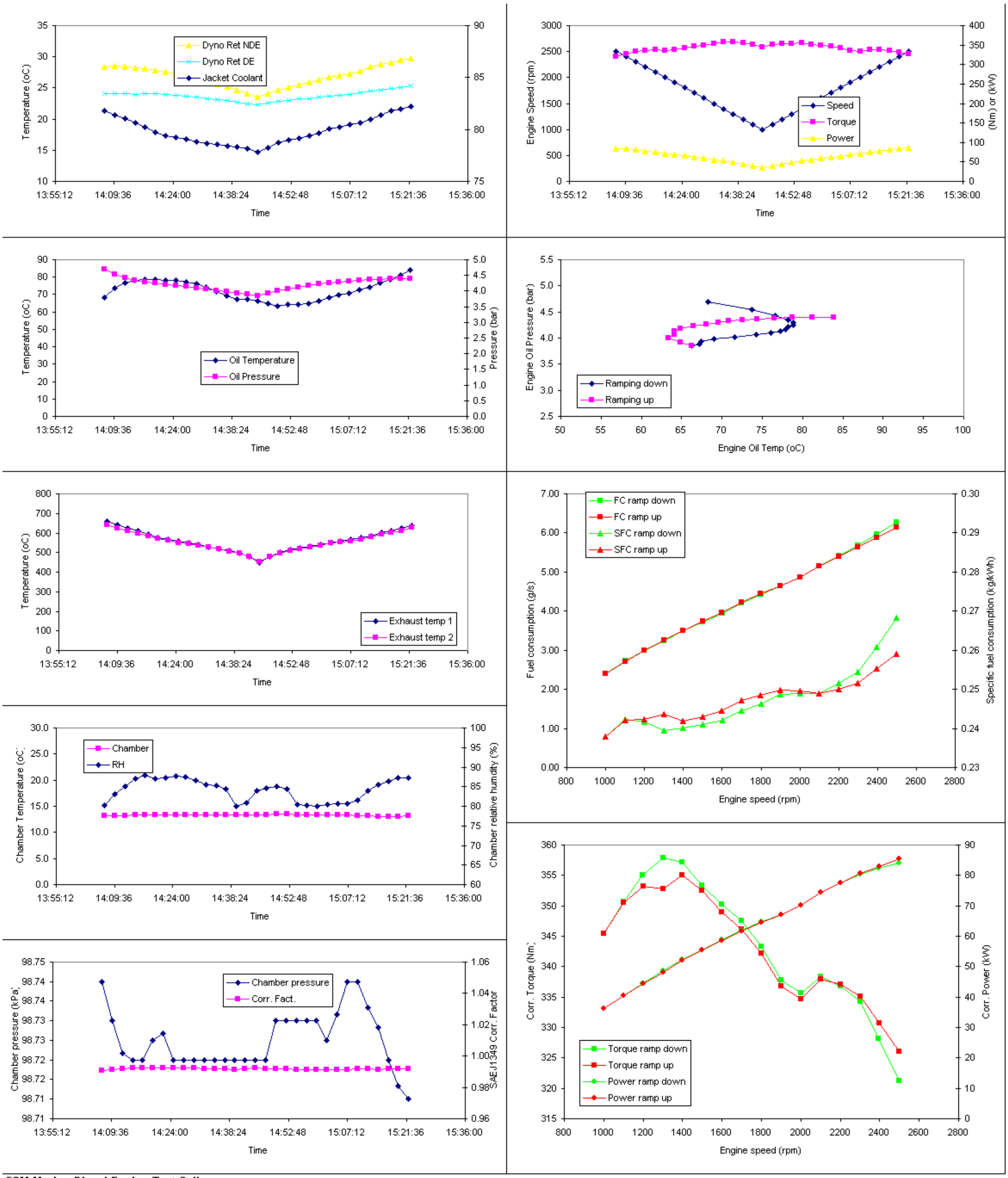
The maximum power test schedule was designed as a demanding, detailed diagnostic and benchmarking test. These tests are referred to as Baseline tests as they were also the means through which the repeatability of fuel tests with the engine test cell was established.

In this test schedule, after cranking the engine, it is first allowed to warm up under moderate load. During this preliminary phase, the engine is held at constant torque and constant rotational speed until the engine jacket temperature reaches predefined values of i) 30ºC, ii) 60ºC and iii) 75ºC. When 75ºC jacket temperature is reached, the engine power is ramped up in steps, to maximum power, by controlling rotational speed and throttle setting, increasing both simultaneously.

Once maximum power is reached, the system is allowed to settle for one minute, then the control system holds the engine in this state for 2 minutes to ensure that any and all FMS refill instructions have cleared. After this the first test point begins and data logging proceeds at 10 second intervals. For each test set point 5, 10 second long averaging periods are recorded. The test proceeds by maintaining 100% throttle, but using the control system to adjust the dynamometer load on the engine such that the rotational speed falls by 100 rpm to the next set point. Settling and refill stages are then applied to the new operating condition, and after stabilisation, the performance of the engine is logged as above. The first half of a complete test comprises a series of similar steps, each one separated by 100 rpm, until the operating condition of minimum rotational speed at 100% throttle is attained. In this operating condition, the minimum engine speed of 1000 rpm is below the engine idling rotational speed of around 1100 – 1050 rpm. After the minimum rotational speed test point is completed, the engine performance is then ramped back up in 100 rpm increments (all at maximum throttle setting) to investigate any hysteresis in engine performance in the second half of the test.

For reasons discussed earlier, a decision was taken to remove the two highest engine speed set points from the original Baseline test schedule as they were deemed too demanding, and possibly damaging to the engine. The result was the development of two Baseline test schedules: Baseline 002 and Baseline 003 (Baseline 001 was used to refer to earlier, cruder testing to establish the operational state of the engine). Full listings of both schedules, as programmed into the SCADA system, are presented in Appendix 5.

Baseline 002 and Baseline 003 tests take around 1 ½ hours to run and put the engine through a punishing series of performance stages that are quite remote from typical operating conditions of the engine within a fishing vessel. The rationale for these Baseline tests was that they would be run before and after any alternative fuel testing to establish whether or not the engine returned to similar physical conditions at the end of the test, as applied at the start. Without these baseline tests, it would be possible to misinterpret the results of a test on a alternative fuel, as any change of engine performance relative to diesel could be due to an engine malfunction or more simply, a need for service, rather than be due to the use of the alternative fuel.



CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 29/10/07

Figure 10: Example output from a Baseline 003 test on the engine test cell.

Guide to graphically presented results of a Baseline test cycle

Typical results from these tests are presented in *Figure 10*. All Baseline test results are presented in Appendix 6. Graphs on the left hand side mainly reflect the record of the environmental parameters prevailing during the test as well as variables characterising the dynamometer and engine cooling / lubrication system. The graphs on the right hand side present the test schedule, oil temp versus oil pressure during the test, fuel consumption (g/s), and power and torque curves (from top to bottom). In each plot, the data are presented as ramping down and ramping up separately, reflecting the first half of the test and the second half of the test respectively. Torque and power data are corrected to standard atmospheric conditions according to ISO1585 using chamber pressure, intake air temperature, relative humidity, engine speed and fuel consumption data. Hysteresis effects are discernable in the oil temperature versus oil pressure curves and the torque and power curves.

Seafish day trawl test description and test schedule

This section details a schedule of set point stages for simulation of a fishing trawler operating a day boat duty. This engine test schedule was used to test a series of additives to diesel for use in fishing vessels and to test the relative performance of biodiesels and red, fossil, diesel. The purpose of this test schedule is to determine the extent by which fuel consumption, and other engine performance measures, change with the use of additives or with a switch to biodiesel. In contrast to the Baseline test cycle of the previous section which was simply a demanding diagnostic test, this Daytrawl test cycle simulates a realistic, practical operating cycle.

The engine duty cycle established aims to simulate a vessel of 8 tons (7.23 metric tonnes) with a hull length at the waterline of 30 feet (9.14m) equipped with a diesel engine of nominal rating 80kW and maximum engine speed of 2700 rpm. The maximum hull speed of such a vessel will be 7.34 knots. The proposed cycle allows for the vessel to spend ~2 ½ hours steaming to the trawl site and to carry out 3 x 4 hour long trawl cruises, and then return to port. The proposed schedule has been informed by experience gained in establishing duty cycles for the CSM potting boat, conversations with skippers from the Newlyn sub 10 metre fleet, and Richard Caslake of SeaFISH.

The cycle comprises 15 Phases in total, from engine start before departure from port to engine stop on return to port.

Zero load set points

Various zero load set point phases feature in the cycle. Phase 0, tick over following engine start; Phases 5 and 9, tickover during net handling and unload; and Phase 15, tick over and warm down following the vessel's return to port.

Phases 1 and 14: Gentle cruising from port & Phases 6 and 10: Gentle cruising while shooting

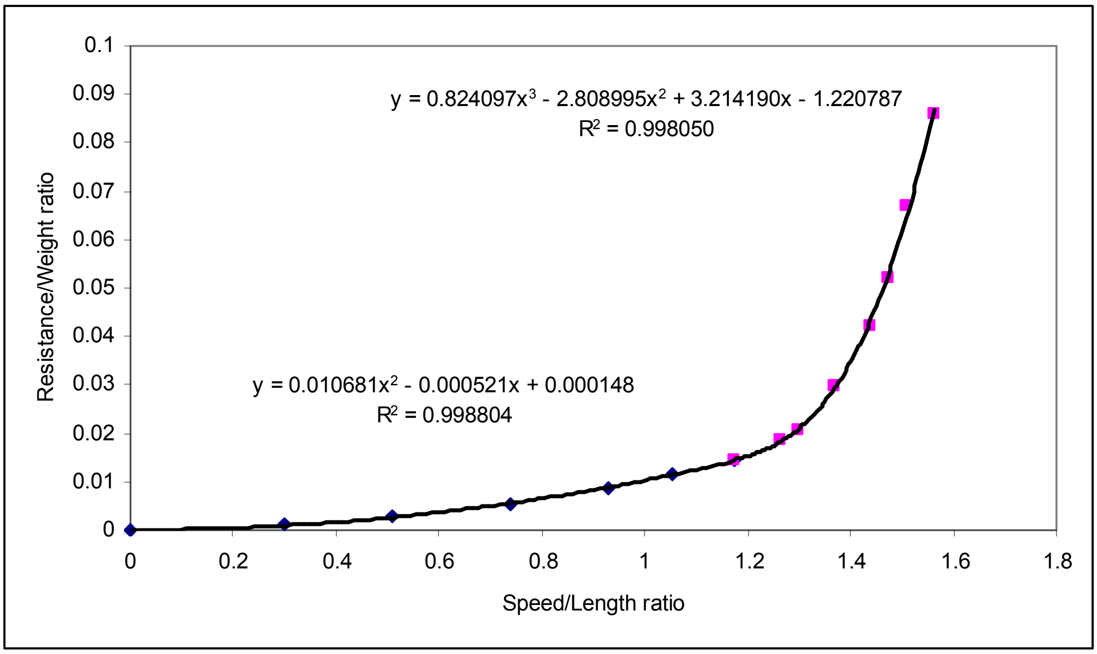


Figure 11: Resistance curve for a generic displacement hull (based on formulation presented by Savitsky, 2003).

Newlyn skippers will make around 3.5 knots for a period of around 15 minutes until they reach a certain marker buoy at the entrance to the Newlyn Harbour channel. Engine speed will be maintained at 1300 rpm during this period. At this speed for a boat of this size, the speed / length ratio is 0.639. This speed to length ratio defines a total resistance to weight ratio of 0.004176 (corresponding to 4.2 kg/tonne) and a total resistance on the hull of 30.3 kg (or 297.3 N). The power developed by the engine during this gentle cruising is then calculated as 1.07kW (2 x speed (m/s) x resistance (N) / 1000). With an assumed engine efficiency of 25%, the fuel consumed during this stage of the duty cycle would be around 0.5 litres. These values are used to inform those defined for the engine set point for these 'gentle cruising' phases which was finalised at 5 kW. At 1300 rpm, the torque developed by the engine would have to be 36.7 Nm.

Total resistance (skin friction, wave & drag) to weight ratios for varying speed / length ratio are determined from the curve shown in *Figure 11*.

Phases 2 and 14: Steaming to/from the trawl site from/to port

The time taken to steam from the navigation channel marker buoy to the trawl area has been assumed to be 2 ½ hours (for a boat operating a day duty). During this time, the engine throttle setting is taken to be such that engine speed of 2000 rpm and vessel speed of 7 knots (close to maximum speed for this hull) are maintained. Using the same approach as for Phases 1 and 14, maintaining this speed implies the engine developing 9.85 kW power and 47 Nm of torque. Under this load the back calculated fuel consumption for a 25% efficient engine is around 4 litres per hour.

Phases 3, 7 and 11: Main trawl

The main trawl is taken to have a 4 hour duration while the vessel maintains a trawl speed of 2.5 knots and engine revolutions of 1750 rpm. The engine covers the power requirements to overcome hull resistance and additional duty due to drag of the trawl gear. The trawl gear has been assumed to offer a resistance equivalent to 4 tonnes while deployed for trawling. Under these conditions, the engine would be expected to deliver an output of around 51kW, equivalent to 278 Nm torque at 1750 rpm (The CSM Test Cell dynamometer calibration holds until 400 Nm).

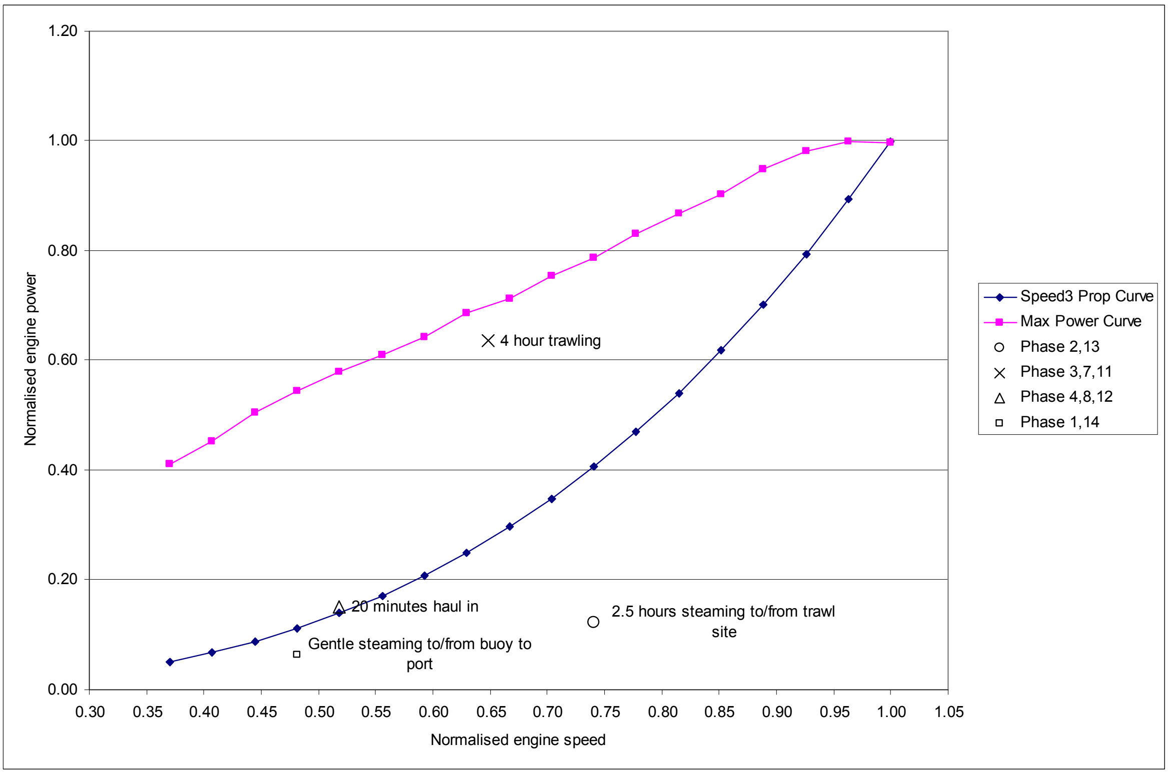


Figure 12: Normalised maximum power curve for 6 cylinder Perkins 6.3544M engine in CSM Test Cell together with phase set points for proposed day boat trawler cycle and cubic propeller law relating engine speed to power (as in EPA, 1998).

Phases 4, 8 and 12: Net haul in

After the main trawl, the nets are wound in. For the purposes of estimating engine duty during this time, the vessel is assumed to maintain position while winding in 300m warp over a 20 minute period. The velocity of the trawl gear relative to the seawater (assuming no currents) is around 0.25 m/s and the loading on the winding drum is assumed equivalent to 4 tonnes. The trawl gear is assumed to be deployed in waters around 70 metres deep, thus the engine must also provide sufficient power to raise the potential energy of the gear as it is brought to surface with its catch. Under these conditions, the engine is expected to develop 12.1 kW power.

Table 1: Day boat trawler duty (DayTrawl) cycle test schedule

Proposed Day Boat Trawler Duty Cycle for fuel additives tests (discussed with Gus Caslake on Sunday 21/08/2007)

		Set point duration	Boat speed (knots)	(m/s)	Engine Revs (rpm)	(rads/sec)	Trawl Load (tonnes)	(N)	Engine Power (kW)	Engine Torque (Nm)	Normalised Engine Speed	Normalised Engine Power
Phase 0	15 minute tick over under zero load	00:15:00	0	0.00	1000	104.7			0	0.0	0.37	0.00
Phase 1	15 minute gentle cruise out to marker buoy	00:15:00	3.5	1.80	1300	136.1			5	36.7	0.48	0.06
Phase 2	2.5 hr steaming to trawl site	02:30:00	7	3.60	2000	209.4			9.85	47.0	0.74	0.12
Phase 3	5 min gentle cruise while shooting	00:05:00	3.5	1.80	1500	157.1			6	38.2	0.56	0.08
Phase 4	4 hour trawl	04:00:00	2.5	1.29	1750	183.3	4	39240	51.0	278.1	0.65	0.64
Phase 5	20 min haul in of nets	00:20:00	0	0.00	1400	146.6	4	39240	12.1	82.5	0.52	0.15
Phase 6	20 min tickover during net handling & unload	00:20:00	0	0.00	1000	104.7			0	0.0	0.37	0.00
Phase 7	5 min gentle cruise while shooting	00:05:00	3.5	1.80	1500	157.1			6	38.2	0.56	0.08
Phase 8	4 hour trawl	04:00:00	2.5	1.29	1750	183.3	4	39240	51.0	278.1	0.65	0.64
Phase 9	20 min haul in of nets	00:20:00	0	0.00	1400	146.6	4	39240	12.1	82.5	0.52	0.15
Phase 10	20 min tickover during net handling & unload	00:20:00	0	0.00	1000	104.7			0	0.0	0.37	0.00
Phase 11	5 min gentle cruise while shooting	00:05:00	3.5	1.80	1500	157.1			6	38.2	0.56	0.08
Phase 12	4 hour trawl	04:00:00	2.5	1.29	1750	183.3	4	39240	51.0	278.1	0.65	0.64
Phase 13	20 min haul in of nets	00:20:00	0	0.00	1400	146.6	4	39240	12.1	82.5	0.52	0.15
Phase 14	2.5 hr steaming to trawl site	02:30:00	7	3.60	2000	209.4			9.85	47.0	0.74	0.12
Phase 15	15 minute gentle cruise to port from marker buoy	00:15:00	3.5	1.80	1300	136.1			5	36.7	0.48	0.06
Phase 16	Tick over for 1 hour	01:00:00	0	0.00	1000	104.7			0	0.0	0.37	0.00

Total test duration **20:40:00**

Rev 2: Increased engine power while shooting compared with gentle cruising alone
Inserted additional shooting stage after 2.5 hr steaming to trawl site

Newlyn skippers reported that typically their engine speeds would be around 1400 rpm while the hydraulic motor was engaged to power the winding drum. Torque developed by the engine during this phase is calculated as 82.5 Nm.

Guide to graphically presented results of a DayTrawl test cycle

This engine duty cycle to simulate the trawler duty is summarised in *Table 01*. The overall test duration is 20 hours and 40 minutes. Prior to the testing it was anticipated that this would involve the consumption of around 300 litres of fuel in the test cell engine. In practice, the fuel consumed was rather less, at around 200 litres / cycle for petrodiesel.

Typical results for a Daytrawl test using red petrodiesel are presented in *Figure 13*. The curves shown in the top two diagrams specify the state of the control variables, engine speed and torque, for each set point comprising the test cycle. The SCADA system ensures that the engine speed and torque have values as specified, by adjusting the load on the dynamometer to match. The control system operates by monitoring the non-atmospheric corrected torque, while the values for torque and power reported are those that have been corrected for atmospheric conditions according to ISO1585. The atmospheric pressure in the test cell chamber and inlet air temperature are shown in the second plot of *Figure 13*. The third plot shows how the relative humidity of the intake air varies over the test duration This plot also presents the power correction factor, which uses the values of humidity, pressure, temperature, engine speed and fuel consumption in its calculation. Data for the latter of these quantities are presented in the lowest plot of *Figure 13*.

The fourth plot of *Figure 13* reports temperature information for the engine cooling jacket, the engine oil and the dyno return cooling water temperatures (x2). This plot also hosts the time series of engine oil pressure. These give an indication of whether the engine operating condition was at steady state or not during different stages of the test. Finally, the fifth plot of *Figure 13* reports the exhaust gas temperatures of the engine in the exhaust manifold. These two plots provide the best indication of the well-being of engine condition.

The temperature time series indicate that for the trawling elements of the test cycle which were four hours long, steady state operating conditions are achieved around 15-20 minutes after the beginning of the stage, with the oil temperature being the variable taking the longest period of time to respond to new conditions. As expected, jacket temperatures respond the most rapidly when changing from one set point to another.

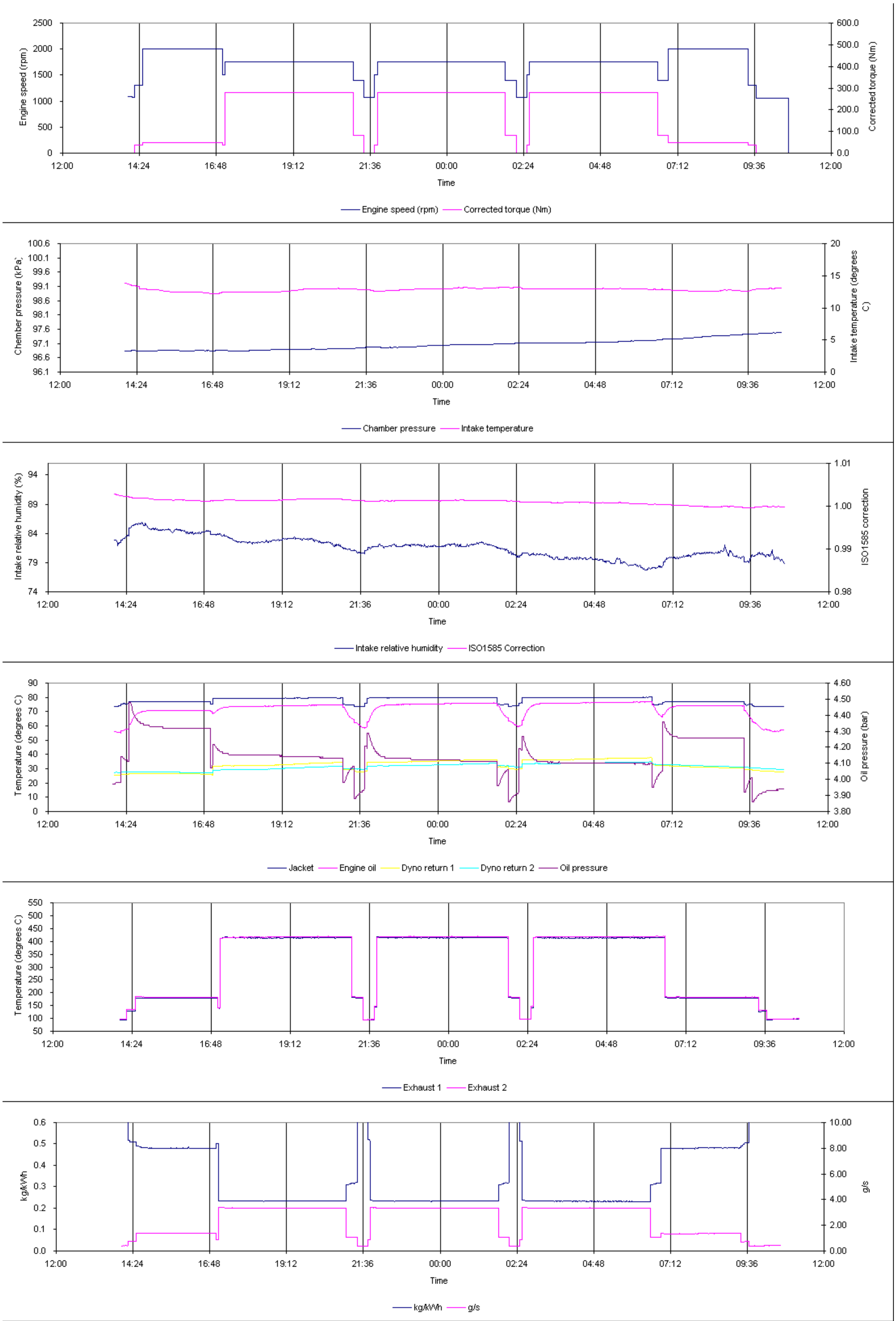


Figure 13: Typical time series traces produced from a DayTrawl test cycle.

Fuel used

Values of engine performance variables, average of 1 min average over the stage.

Fuel consumption results, 1 minute SFC averages, integrated over the whole stage, presented cumulatively.

Engine efficiency, average of ~1 min averages, over the stage

Salient fuel properties

Day trawl test cycle results

Description: M&W Batch 1 BS590 diesel only	Warm-up duration: 00:01:59	Specific gravity	0.86 kg/litre
	Test duration: 20:40:00	Calorific value	44.73 MJ/kg
	Test date (start): 24/10/2007		

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consumed (Start of stage) Mass	Cum. fuel consumed (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	14:16:41	14:31:41	00:15:00	1092.79	6.74	1.28	0.13	10.294	0.900	10.239	0.00	0.00	0.79	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	14:31:41	14:46:41	00:15:00	1299.93	0.27	38.08	0.00	0.523	0.003	0.520	0.37	0.43	15.39	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	14:46:41	17:16:41	02:30:00	1999.95	0.27	48.40	0.01	0.494	0.001	0.491	1.05	1.22	16.29	1.33	1.34
Stage Start TP03	5 min gentle cruise while shooting	17:16:41	17:21:41	00:05:00	1500.25	0.50	39.57	0.00	0.515	0.000	0.512	13.57	15.71	15.62	26.68	26.83
Stage Start TP04	4 hour trawl	17:21:41	21:21:41	04:00:00	1750.00	0.00	279.87	0.11	0.236	0.001	0.234	13.84	16.02	34.13	27.20	27.35
Stage Start TP05	20 min haul in of nets	21:21:41	21:41:41	00:20:00	1400.00	0.00	83.87	0.00	0.321	0.003	0.319	62.21	72.00	25.07	232.35	233.84
Stage Start TP06	20 min tickover: net handling & unload	21:41:41	22:01:41	00:20:00	1066.16	2.48	1.67	0.00	7.797	0.158	7.741	63.53	73.53	1.03	236.45	237.97
Stage Start TP07	5 min gentle cruise while shooting	22:01:41	22:06:41	00:05:00	1500.50	0.58	39.51	0.00	0.526	0.003	0.522	64.01	74.09	15.29	236.51	238.03
Stage Start TP08	4 hour trawl	22:06:41	02:06:41	04:00:00	1750.00	0.00	279.86	0.09	0.235	0.001	0.233	64.28	74.40	34.27	237.03	238.56
Stage Start TP09	20 min haul in of nets	02:06:41	02:26:41	00:20:00	1400.00	0.00	83.96	0.00	0.319	0.003	0.317	112.46	130.16	25.21	442.18	445.06
Stage Start TP10	20 min tickover: net handling & unload	02:26:41	02:46:41	00:20:00	1058.53	2.14	1.67	0.00	7.690	0.113	7.644	113.77	131.68	1.05	446.28	449.18
Stage Start TP11	5 min gentle cruise while shooting	02:46:41	02:51:41	00:05:00	1500.25	0.50	39.56	0.00	0.524	0.003	0.521	114.24	132.23	15.35	446.34	449.25
Stage Start TP12	4 hour trawl	02:51:41	06:51:41	04:00:00	1750.00	0.00	280.10	0.04	0.234	0.001	0.233	114.51	132.54	34.38	446.86	449.77
Stage Start TP13	20 min haul in of nets	06:51:41	07:11:41	00:20:00	1400.05	0.23	84.00	0.00	0.318	0.003	0.317	162.58	188.17	25.27	652.19	656.27
Stage Start TP14	2.5 hr steaming to trawl site	07:11:41	09:41:41	02:30:00	1999.98	0.30	48.39	0.00	0.487	0.002	0.484	163.89	189.69	16.54	656.29	660.39
Stage Start TP15	15 minute gentle cruise to port	09:41:41	09:56:41	00:15:00	1299.86	0.36	38.07	0.00	0.513	0.004	0.510	176.22	203.95	15.70	681.63	685.88
Stage Start TP16	Tick over for 1 hour	09:56:41	10:56:41	01:00:00	1046.74	0.97	1.85	0.04	7.164	0.238	7.125	176.88	204.72	1.12	682.92	687.18
Stage End TP16	End of test	10:56:41										178.33	206.40		683.13	687.38

	Mass (kg)	Volume (litres)	es/kW
Fuel consumed over steam out stages	13.57	15.71	
Fuel consumed over first trawl stages	50.44	58.38	
Fuel consumed over second trawl stages	50.23	58.14	
Fuel consumed over third trawl stages	49.65	57.46	
Fuel consumed over steam in stages	14.44	16.72	
Fuel consumed over whole test cycle	178.33	206.40	0.2998
Fuel consumed over census stages (TP12 - TP15)	**62.37**	**72.18**	**0.3058**

Total fuel consumed in cycle

Fuel consumed in census stages

Litres of fuel/ kWh of useful work produced

Work done, 1 minute power averages x (1/60) hr, integrated over each stage, presented cumulatively.

Figure 14 : Guide to tabular results format for DayTrawl test results

Guide to tabular presented results of a DayTrawl test cycle

The tabular format of results for the DayTrawl test cycle *(Figure 14)* summarises performance values against the individual cycle stages. For engine speed, torque and power, the figures reported are averages of the one minute averages logged by the SCADA system for each stage in the test cycle. The average specific fuel consumption figures also apply of each stage of the cycle. Corrected torque, engine speed and fuel consumed in each one minute period are used to determine the SFC applying for that minute, and the average over all minutes in the stage is reported in the table *(Figure 14).* The mass of fuel consumed figures are integrated over each cycle but are presented cumulatively, and apply at the start of each stage of the cycle; the measured specific gravity of the fuel has been used to convert these mass consumption figures to volume consumption figures as fisherman pay for their fuel on a volume basis rather than a mass basis. The engine efficiency figures are averages over each minute of each stage of the cycle. The underlying figures from which the averages are found, are determined from the useful shaft work done in the one minute period divided by the energy contained in the fuel consumed in that same one minute period. The denominator of this ratio is found by multiplying the mass of fuel by the measured calorific value of the fuel.

From test to test, the length of warm up time may vary depending on whether the engine has been operated immediately before the test or not (for example by running a pre-DayTrawl Baseline test), but in all cases, the SCADA system ensures that the engine jacket temperature has been raised to 75°C before the first logging stage begins.

Beneath the main table are summary fuel consumption performance indicators, expressed in terms of kilogrammes and litres of fuel consumed during each stage. The most important of these are the last two listed: fuel consumed over the whole test and fuel consumed over the census stages. The former is self-explanatory however the latter requires some explanation. Reports from suppliers of fuel additives suggest that there may be some kind of cumulative effect of additives on the engine. Thus, as well as reporting the consumption figure for the test as a whole, the 'census stages' figure includes fuel consumed only for the last trawl cycle, the last haul in of nets, steaming to return to port and cruising to jetty. The rationale for this is that if there is any effect of the additive, it should be most pronounced during these latter stages of the test cycle.

Narrative on establishing engine characterisation

Table 2: Abbreviated test Baseline test log

Test Date	FileRef	Schedule	Comments
13/08/2007 13:40	BASELINE_002_001_c	Baseline 002	
13/08/2007 13:40	BASELINE_002_001_c	Baseline 002	First ever test of engine
15/08/2007 11:22	BASELINE_002_003D_c	Baseline 002	
15/08/2007 13:16	BASELINE_002_004_c	Baseline 002	
15/08/2007 15:13	BASELINE_002_005_c	Baseline 002	
15/08/2007 17:07	BASELINE_002_006_c	Baseline 002	
22/08/2007 14:25	BASELINE_002_007_c	Baseline 002	
05/09/2007 12:57	BASELINE_002_008_c	Baseline 002	After recalibration of dynomometer torque sensor
05/09/2007 15:02	BASELINE_002_009_c	Baseline 002	
06/09/2007 09:45	BASELINE_002_010_c	Baseline 002	
06/09/2007 12:38	BASELINE_002_011_c	Baseline 002	
06/09/2007 14:28	BASELINE_002_012_c	Baseline 002	
07/09/2007 09:20	BASELINE_002_013_c	Baseline 002	
07/09/2007 14:09	BASELINE_002_014_c	Baseline 002	Probable fall of torque at 2000 rpm - but not noticed until next test
10/09/2007 11:02	BASELINE_002_015_c	Baseline 002	Noticed significant fall of torque at 2000 rpm on ramp up
10/09/2007 14:45	BASELINE_002_016_c	Baseline 002	Repeat to confirm the above
11/09/2007 08:32	BASELINE_002_017_c	Baseline 002	Repeat to confirm the above
11/09/2007 15:01	BASELINE_002_018_c	Baseline 002	Repeat to confirm the above
12/09/2007 15:02	BASELINE_002_019_c	Baseline 002	Repeat to debug the above
14/09/2007 09:06	BASELINE_002_020_c	Baseline 002	After replacement of universal joint in engine dyno coupling shaft
14/09/2007 11:33	BASELINE_002_021_c	Baseline 002	Repeat of the above
18/09/2007 11:56	BASELINE_002_022_c	Baseline 002	After resetting valve clearances and tightening stud on cam shaft
19/09/2007 11:32	BASELINE_003_001_c	Baseline 003	After cleaning out air manifold and replacing air filter
19/09/2007 13:26	BASELINE_003_002_c	Baseline 003	
20/09/2007 10:13	BASELINE_003_003_c	Baseline 003	
20/09/2007 12:56	BASELINE_003_004_c	Baseline 003	
20/09/2007 14:32	BASELINE_003_005_c	Baseline 003	
21/09/2007 09:22	BASELINE_003_006_c	Baseline 003	Last baseline test before 21 hour daytrawl test
24/09/2007 15:22	BASELINE_003_007_c	Baseline 003	Conducted after 21 hour Daytrawl test on 20/09/07
16/10/2007 10:55	BASELINE_003_101_c	Baseline 003	Did Enersol testing - discovered broken rings & excessive bore wear - new pistons, liners, rings, big end bearings,gaskets. First test after 20 hour run in
16/10/2007 13:36	BASELINE_003_102_c	Baseline 003	2nd test after run in - establishing new baseline performance
16/10/2007 15:20	BASELINE_003_103_c	Baseline 003	Decoupled seawater pump from engine
17/10/2007 10:40	BASELINE_003_104_c	Baseline 003	Repeat to establish new baseline archive after run in
17/10/2007 12:30	BASELINE_003_105_c	Baseline 003	Repeat to establish new baseline archive after run in
17/10/2007 14:56	BASELINE_003_106_c	Baseline 003	Repeat to establish new baseline archive after run in
29/10/2007 14:03	BASELINE_003_107_c	Baseline 003	Baseline test after additive A daytrawl
01/11/2007 11:40	BASELINE_003_108_c	Baseline 003	After fossil daytrawl
02/11/2007 10:38	BASELINE_003_109_c	Baseline 003	Cleaned air filter and retested baseline before next additive
05/11/2007 13:30	BASELINE_003_110_c	Baseline 003	Baseline test after additive B daytrawl
09/11/2007 13:55	BASELINE_003_111_c	Baseline 003	Baseline test after additive C daytrawl
12/11/2007 16:05	BASELINE_003_112_c	Baseline 003	Baseline test after additive D daytrawl
13/11/2007 14:47	BASELINE_003_113_c	Baseline 003	Baseline test after mini-service
15/11/2007 10:56	BASELINE_003_114_c	Baseline 003	After daytrawl on red for new batch of fuel
16/11/2007 15:23	BASELINE_003_115_c	Baseline 003	Baseline test after additive E daytrawl
21/11/2007 10:27	BASELINE_003_116_c	Baseline 003	Baseline test after additive F daytrawl
22/11/2007 11:28	BASELINE_003_117_c	Baseline 003	Baseline test after additive G daytrawl
26/11/2007 09:55	BASELINE_003_118_c	Baseline 003	Closing baseline on red, after daytrawl on red
26/11/2007 12:28	BASELINE_003_119_ME_c	Baseline 003	Opening baseline on methyl ester
30/11/2007 11:34	BASELINE_003_120_ME_c	Baseline 003	Closing baseline on methyl ester
03/12/2007 13:05	BASELINE_003_121_WO_c	Baseline 003	Opening baseline on waste oil methyl ester

The success or failure of the proposed testing methodology relied on establishing a set of Baseline performance test results that demonstrated mutual consistency and low variance of engine operating performance. This section provides a narrative on how that set was established. While it is rather lengthy, it is important in order that an appreciation of the precision of the testing undertaken is gained.

Baseline 002_001 to Baseline 002_007

Firstly all processed Baseline test files were imported into a Baseline test archive file, where the results from each individual test could be compared with another or a group of other Baseline tests contained within the archive. *Table 02* summarises all the Baseline tests undertaken in the study. The table is colour coded to indicate the 'like' Baseline tests, or clusters of Baseline tests.

Stage 1: The first grouping comprises Baseline tests Baseline 002_001 to Baseline 002_007 inclusive. Performance curves obtained from the test cell for these tests are presented in *Figures 15* and *16*.

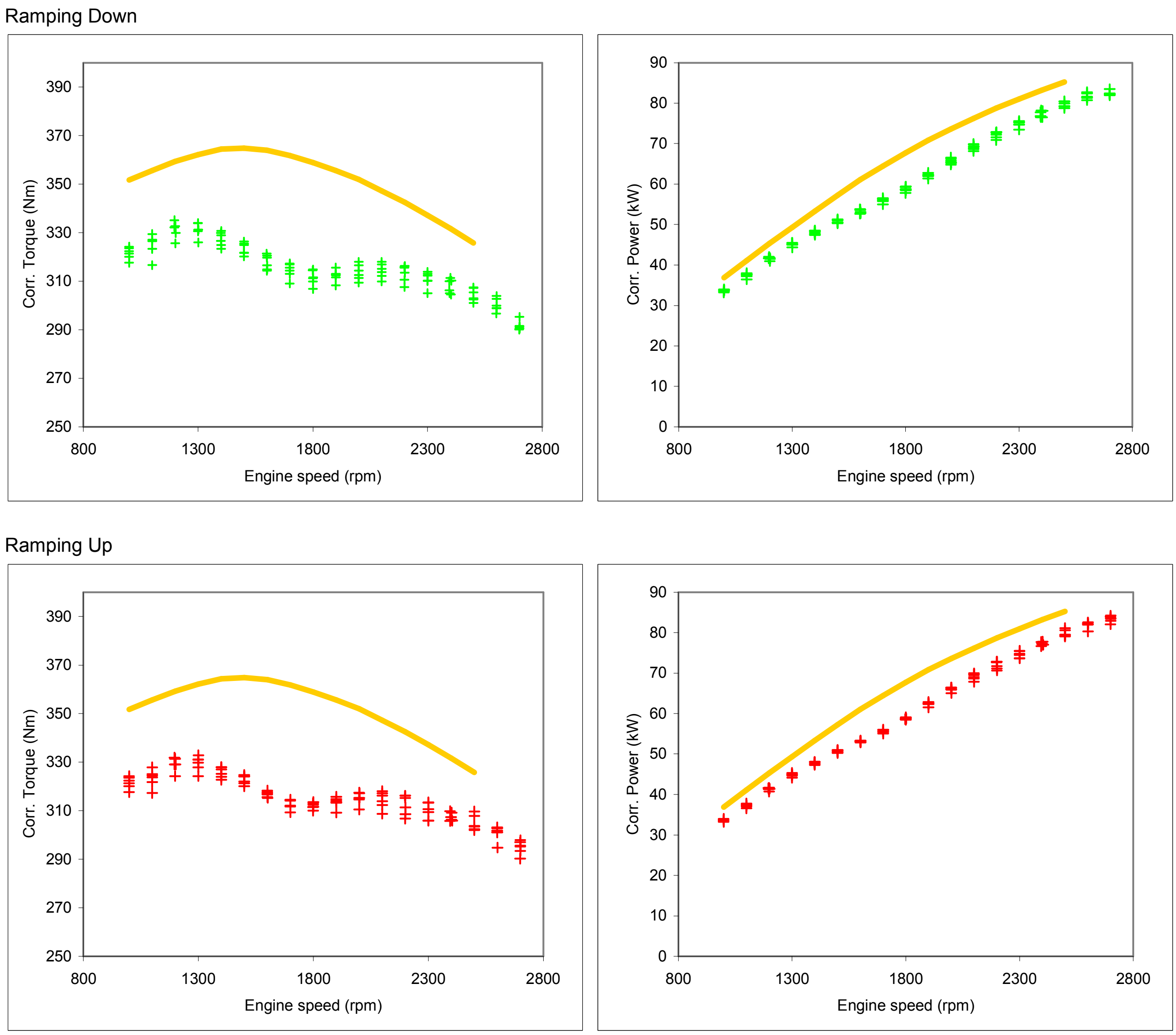


Figure 15: Baseline archive plot of tests Baseline_002_001 to Baseline_002_007 inclusive

Figure 15 shows four plots:

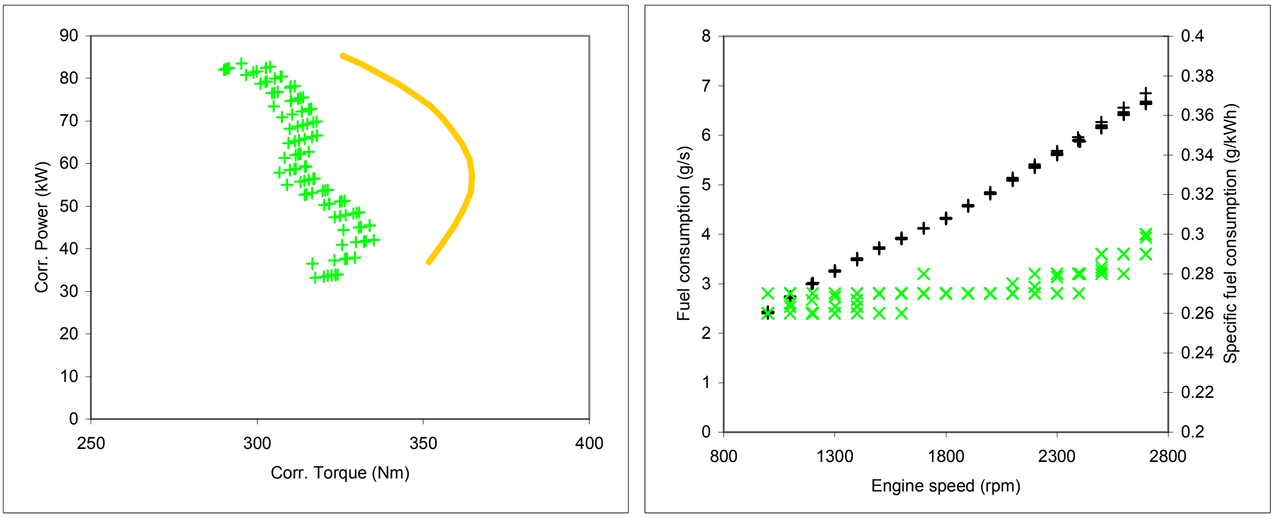
- Top LHS – corrected torque against engine speed while ramping down from maximum power at 2700 rpm to minimum power at 1000 rpm.
- Top RHS – corrected power against engine speed while ramping down from maximum power to minimum power.

- Bottom LHS corrected torque against engine speed while ramping up from minimum power at 1000 rpm to maximum power at 2700 rpm.
- Bottom RHS - corrected power against engine speed while ramping down from maximum power to minimum power

The yellow lines in each plot show the ‘as new’ performance of this engine model. *Figure 16* also shows four plots:

- Top LHS – corrected power against corrected torque while ramping down from maximum power at 2700 rpm to minimum power at 1000 rpm.
- Top RHS – fuel consumption and specific fuel consumption against engine speed while ramping down from maximum power to minimum power.
- Bottom LHS - corrected power against corrected torque while ramping up from minimum power at 1000 rpm to maximum power at 2700 rpm.
- Bottom RHS - fuel consumption and specific fuel consumption against engine speed while ramping down from maximum power to minimum power

Ramping Down



Ramping Up

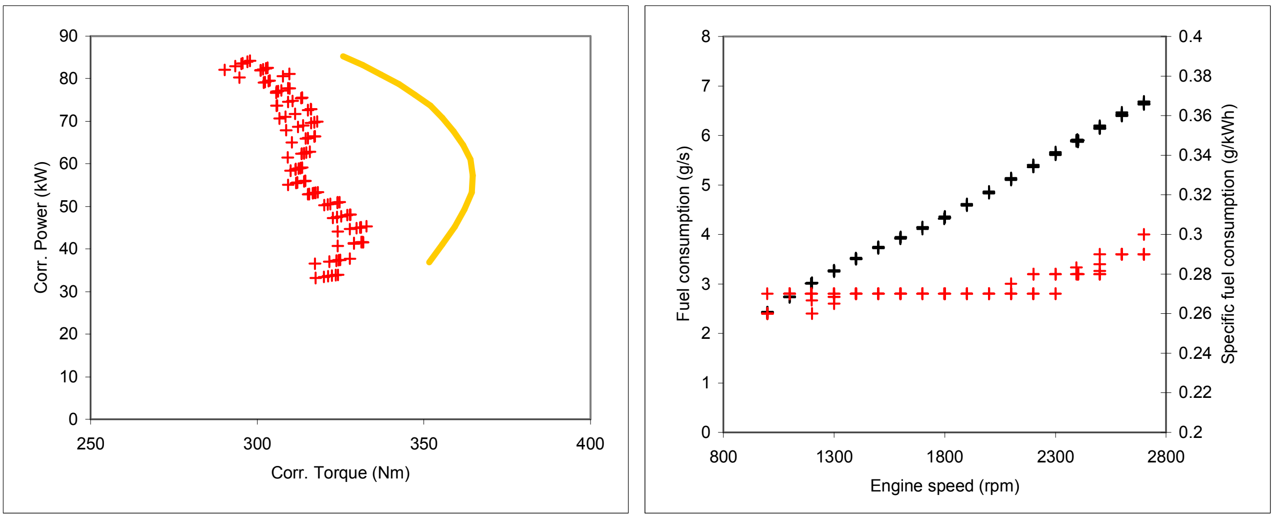


Figure 16: Baseline archive plot of tests Baseline_002_001 to Baseline_002_007 inclusive

The main conclusions drawn at this stage of commissioning tests was that a fairly consistent, relatively low variance set of Baseline tests had been established and testing could proceed. These tests were summarised through the establishment of an engine performance envelope against which future Baselines could be compared. These curves are illustrated in *Figure 17*.

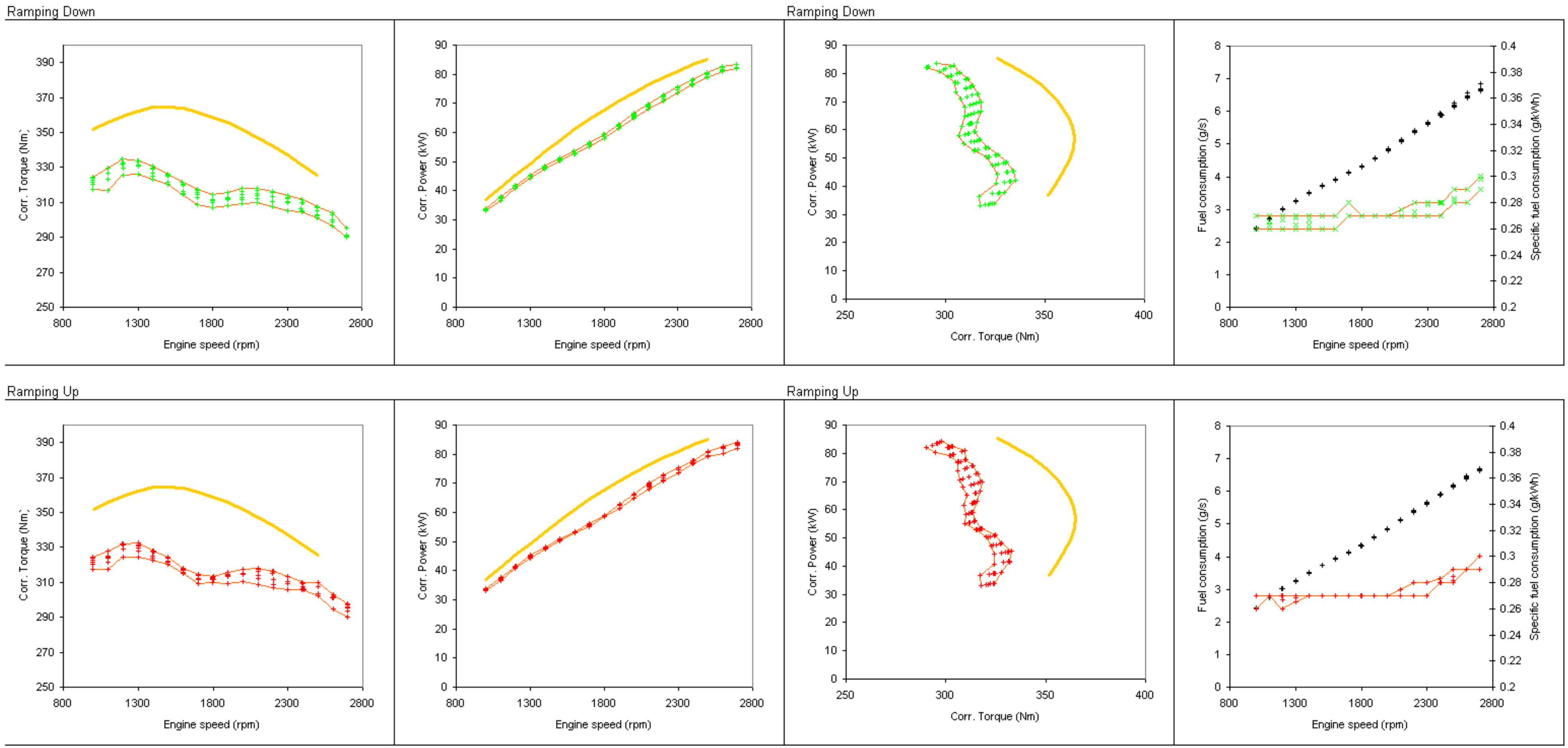


Figure 17: Baseline archive plot of tests Baseline_002_001 to Baseline_002_007 inclusive, showing engine performance envelope defined by these tests.

Figure 17 is a comprehensive view of the performance of a series of Baseline tests, that allows the interpretation of a large amount of data simultaneously. However, it is not ideally suited to presentation in a report such as this. Thus in subsequent parts of the discussion, only the two extreme LHS plots will be presented. The complete corresponding sequence is presented in Appendix 7.

Baseline 002_008 to Baseline 002_013

At this stage in the test work a fault with the dynamometer necessitated that its calibration be checked. After the calibrating exercise subsequent baselines were undertaken to determine whether or not the characteristic curves had changed substantially or not. *Figure 18* below suggests that indeed there had been a change. A new performance envelope was compiled from tests Baseline_002_008 to Baseline_002_013. The results from Baseline_002_001 to Baseline_002_007 had to be ignored, in terms of defining a suitable benchmark for engine diagnostics and performance comparisons. However, they were useful in establishing, at least initially the degree of variance between similar tests that may be expected.

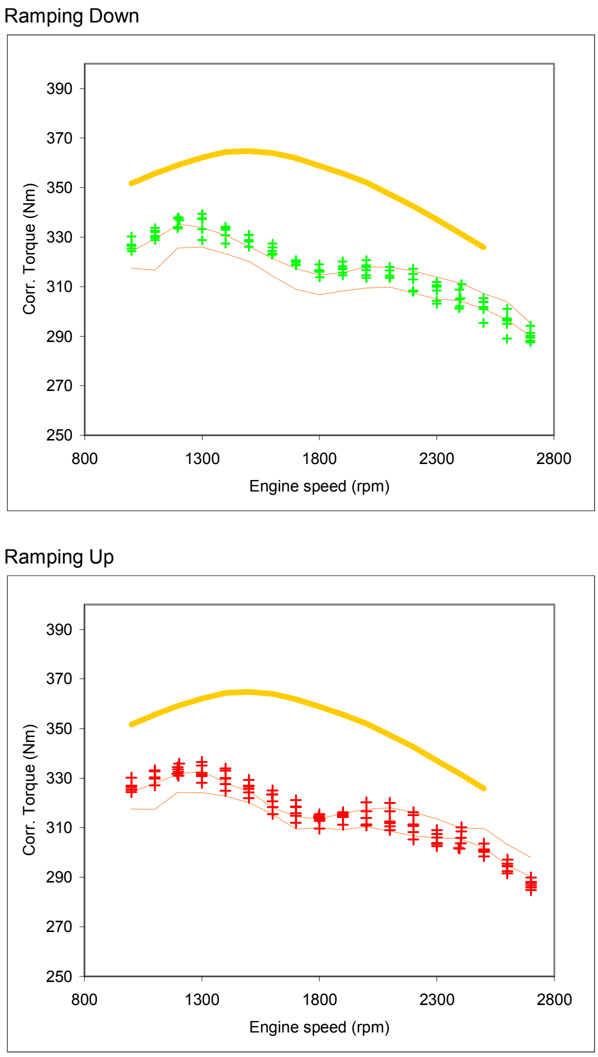


Figure 18: Baseline archive plot of tests Baseline_002_008 to Baseline_002_013 inclusive, showing engine performance envelope defined by Baseline_002_001 to Baseline_002_007.

Baseline 002_014 to Baseline 019

Two more Baseline tests were conducted to confirm engine stability, Baseline 002_014 and Baseline 002_015. When the second of these was completed, it was noticed that there was an appreciable drop of torque in the ramping up set points of the tests, notably in the range 2000 to 2100 rpm (Baseline 002_015 is black continuous line in *Figure 19*). The cause of this dip in torque was puzzling and unknown at the time that test was completed. As, at that stage, it was quite possible that these individual test points were simply outliers further, and subsequent Baseline tests were undertaken with the aim of tracking down the problem. The result was that the torque 'dip' at 2000 rpm became worse with continued testing. Various causes were postulated and acted upon including i) replacing the universal joint from the drive shaft to the dynamometer, ii) adjusting valve clearances and iii) tightening a stud that appeared to be loose in a cam shaft retainer and Baseline tests were repeated after each 'correction' to see if the problem persisted – which it did. Finally, the air filter was removed and found to be heavily soiled and the inlet manifold was found to contain debris.

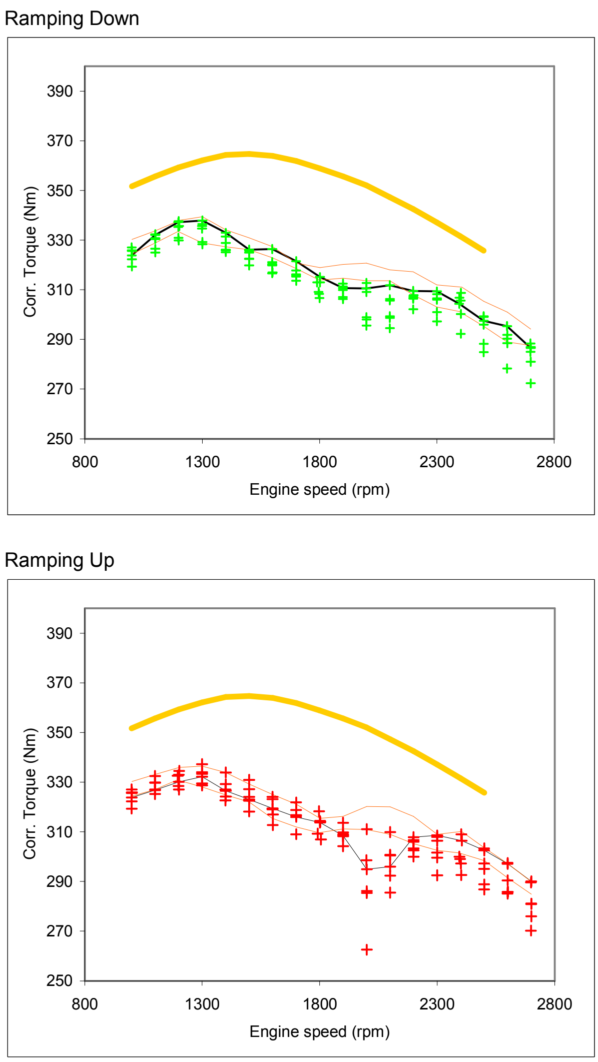


Figure 19: Baseline archive plot of tests Baseline_002_014 to Baseline_002_019 inclusive, showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013. Solid, black line – Baseline 002_015 performance. With progressive testing, problem became worse.

Baseline 003_001 to Baseline 003_006

After the manifold was cleaned, and the air filter renewed, further Baseline testing was undertaken with the results indicated in *Figure 20*, below. As the plot shows the engine performance envelope previously established and the points plotted are from Baseline tests conducted after these troubleshooting measures were undertaken, the results indicate that the project engineers had returned the state of the engine to its state earlier in the sequence, before the problems occurred. This highlighted inspection of the air intake filter as a new routine inspection task. It will be appreciated from *Figure 20*, that the new six Baseline tests "push down" the torque curves around the 1900 rpm level, in both ramping up and ramping down datasets. As a result, a revised performance envelope was compiled from Baseline 002_008 to Baseline 0002_013 and Baseline 003_001 to Baseline 003_006. This return to the nominal performance envelope in response to an identified problem gave the project team a higher confidence in the repeatability of fuel test work on the test cell.

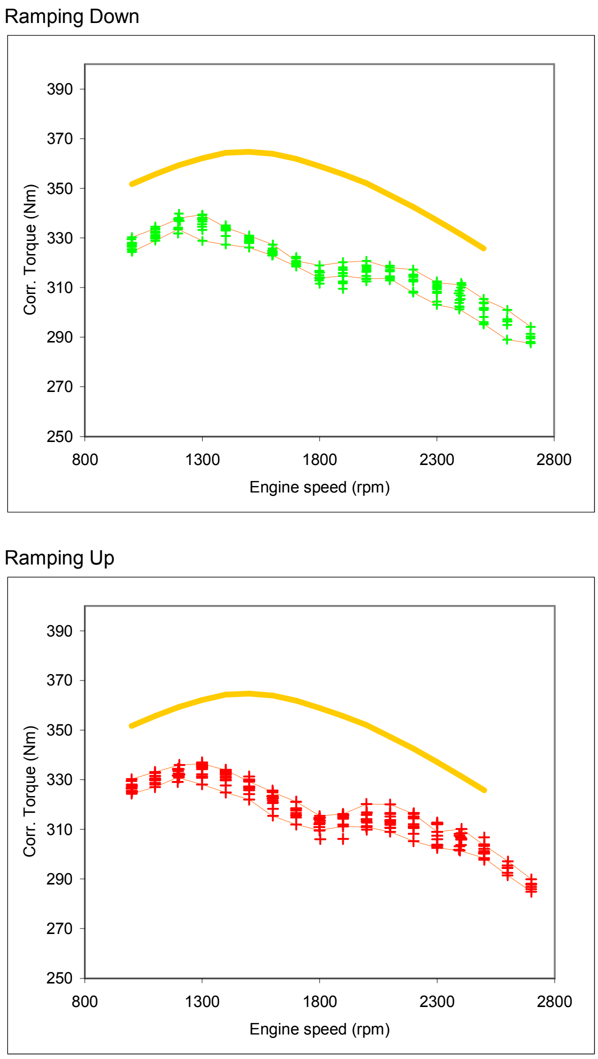


Figure 20: Baseline archive plot of Baseline 003_001 to Baseline 003_006 showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013

Baseline 003_007

The first 20 hour DayTrawl test on red diesel was subsequently undertaken, and Baseline 003_007 completed following this. The optimism of the project team was short lived when the results from Baseline 003_007 were plotted against the currently defined performance envelope *(Figure 21).* In both the ramping down and ramping up set points of the test, the engine performance exceeded the established performance envelope between 1000 rpm and 1700 rpm and was lower than the established performance envelope at 2000 rpm on ramping down and up stages and at 2500 rpm for ramping down stages. It appeared that the engine performance was not going to be as stable as hoped that the outset of commissioning. In fact, after a further ~5 hours running during tests of an electromagnetic calorific value enhancer system, the engine would not start and suffered its first serious mechanical breakdown.

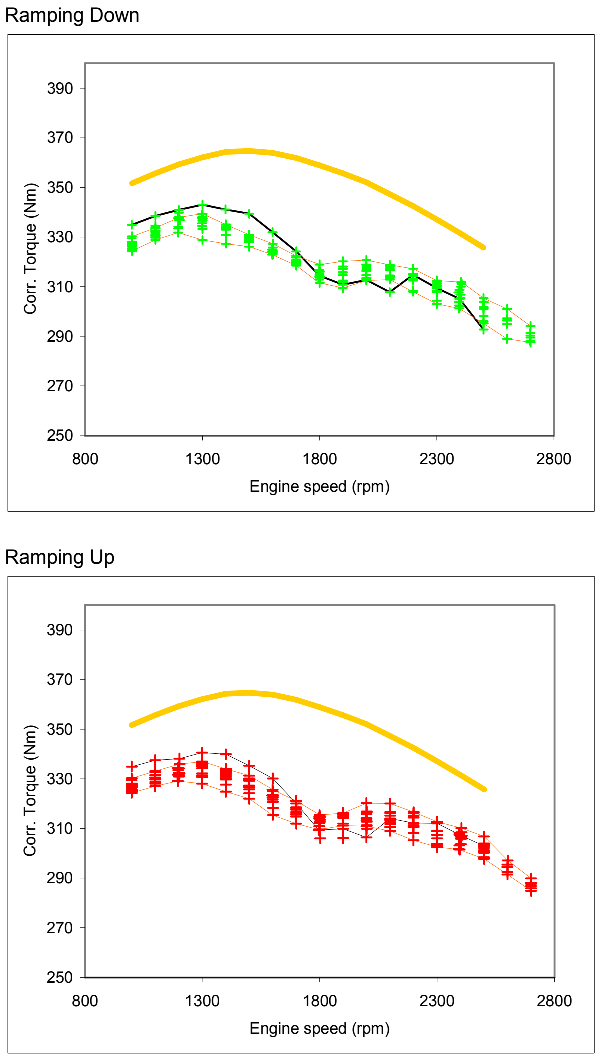
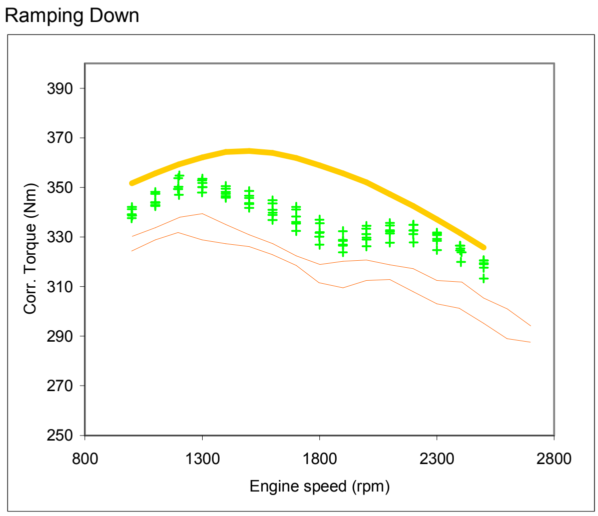


Figure 21: Showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013 and Baseline 003_001 to Baseline 003_006 with Baseline 003_007 performance curve superimposed (solid black line).

Baseline 003_101 to Baseline 003_106

After overhaul and repair of the engine, to progress the project, the team had no choice but to re-establish a new engine performance envelope by undertaking another round of Baseline testing. This was done after ~20 hours run in of the engine as reported earlier. It was expected that the engine performance would be quite different than that observed before the engine failure and hopefully better. *Figure 22* shows the results of these new Baseline 003 tests, together with the engine performance envelope developed prior to the engine failure. It is quite evident from *Figure 22* that the performance of the engine was much improved in comparison to the situation previously.



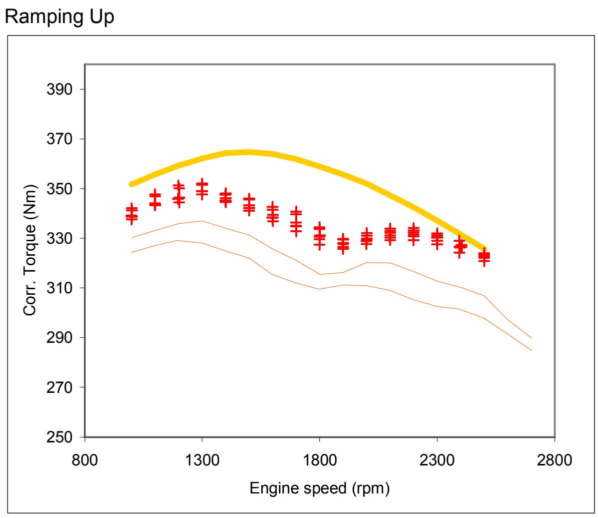


Figure 22: Showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013 and Baseline 003_001 to Baseline 003_006 with Baseline 003_101 to Baseline 003_107 performance data shown as discrete points.

The delay due to the engine failure began to put the project team under severe time pressure. A decision was taken to proceed with DayTrawl testing on the basis of the six Baseline tests completed post failure. A further 7.5 running hours at medium duty running was given over to engine cooling tests and a DayTrawl was then started but aborted after 17 hours due to an FMS failure (the project team was still encountering an intermittent fault with this unit at this stage). Then, with the engine considered 'fully run in' testing could start, however a decision was taken not to conduct any further testing until the FMS fault had been rectified.

Baseline 003_107 to 003_118

These tests took place within the fuel additives testing programme. They were used to determine whether or not the engine performance / condition had returned to its pre-additive state. Baseline 003_107 was undertaken after a DayTrawl test using red diesel with Additive A. *Figure 23* shows Baseline 003_107 (solid line) together with the engine performance envelope established from Baseline 003_101 to Baseline 003_107 and results from 4 subsequent Baseline tests each of which was conducted after a 20 hour DayTrawl test on fossil only (so that no remnant of additive is assumed to remain). It is evident that the performance curve for Baseline 003_107 lies within the defined performance envelope only in one small part, at low engine speed. Baseline 003_107 lies much closer to the cluster of Baseline tests conducted immediately following a DayTrawl on red diesel only.

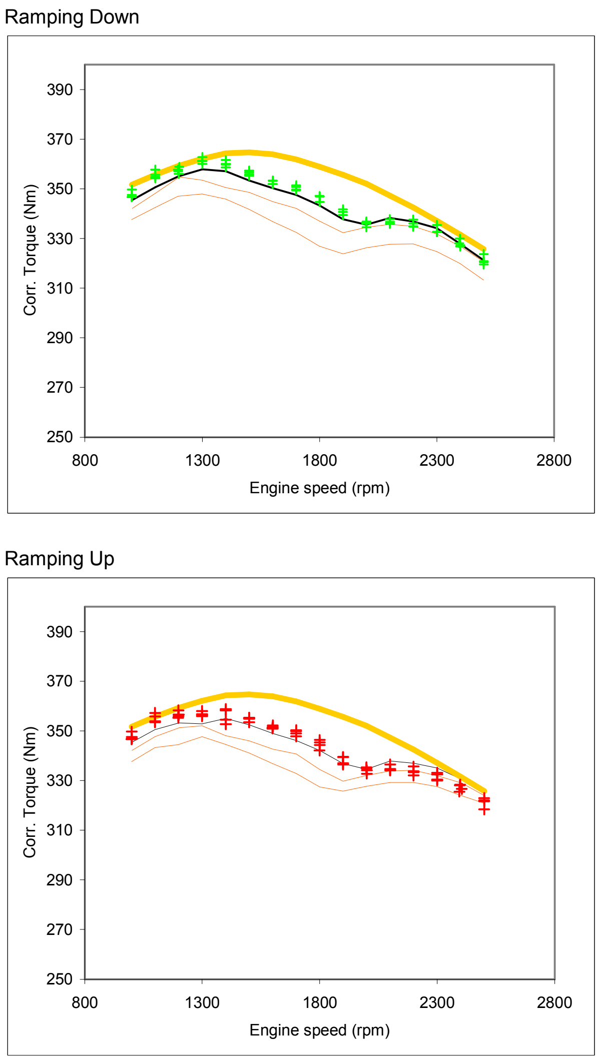


Figure 23: Baseline 003_107 (solid line) together with the engine performance envelope established from Baseline 003_101 to Baseline 003_107 and results from Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118 (clusters)

There is other data that will be reported subsequently that gives support to the idea that the engine had possibly not been fully run in at the time that the Baseline tests that defined the ‘reference’ performance envelope were undertaken. It is considered that the cluster representing Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118 defines the reference performance envelope, and unfortunately, the performance envelope defined by Baseline 003_101 to Baseline 003_106 must be disregarded.

Fuel Additives Testing

Assessment with Baseline tests

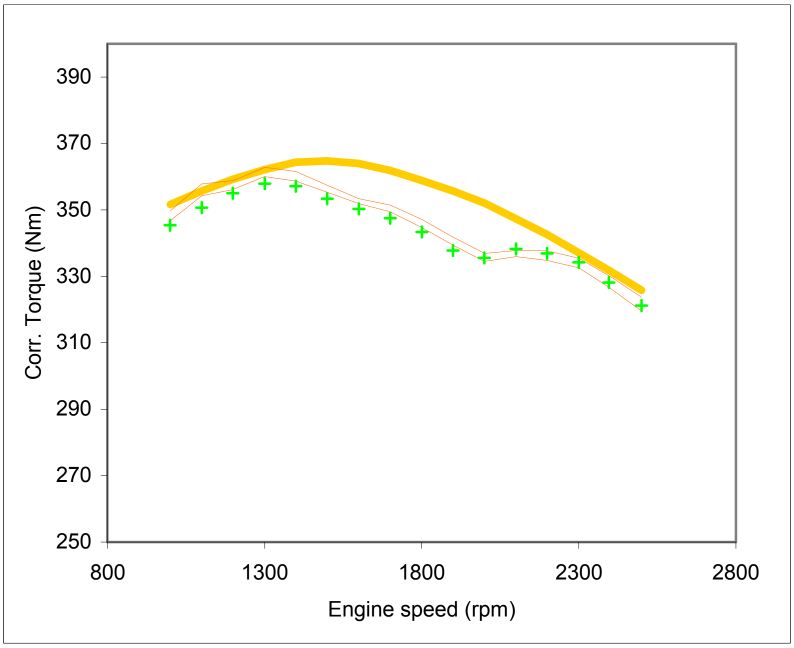
The primary means of assessing the effectiveness of fuel additives to red petrodiesel for fishing vessels was the DayTrawl test schedule. However, before reviewing the DayTrawl results, the performance of the engine under the Baseline test regime, using red petrodiesel only, but immediately following DayTrawl tests undertaken with additives is considered. These considerations are one way of assessing whether there is any prolonged ‘after effect’ on the engine, of the use of any one of the additives. It also confirms whether or not any engine failure or malfunction occurred during the intervening DayTrawl test, which may have a bearing on the interpretation of results from that test. The data are presented in the following 14 graphs *(Figures 24 to 30)*; the summary conclusions based on examination of the data are as presented below:

Table 3: Summary interpretation of Baseline test response to an immediately prior DayTrawl test fuelled by petroldiesel and additive.

Additive	Indication of possible engine failure or other system malfunction during preceeding DayTrawl (diesel with additive) cycle	Evidence of any after effect of the additive on performance with diesel only Baseline test
A	NO	NO
B	NO	Possible minor improvement between 1600 and 2000 rpm
C	NO	Possible very minor improvement between 1600 and 2000 rpm
D	NO	Possible minor improvement between 1600 and 2000 rpm
E	NO	NO
F	NO	Possible minor improvement between 2000 and 2500 rpm
G	NO	Possible very minor improvement between 2000 and 2500 rpm

There is no indication from Baseline testing that any engine or system malfunction or significant deterioration of engine performance occurred during the fuel additives tests conducted with the DayTrawl schedule

Ramping Down



Ramping Up

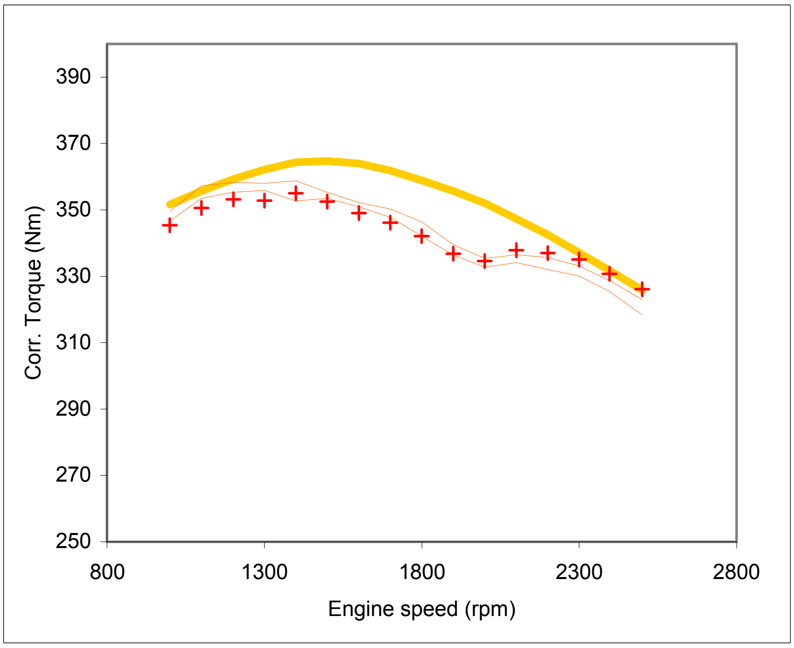
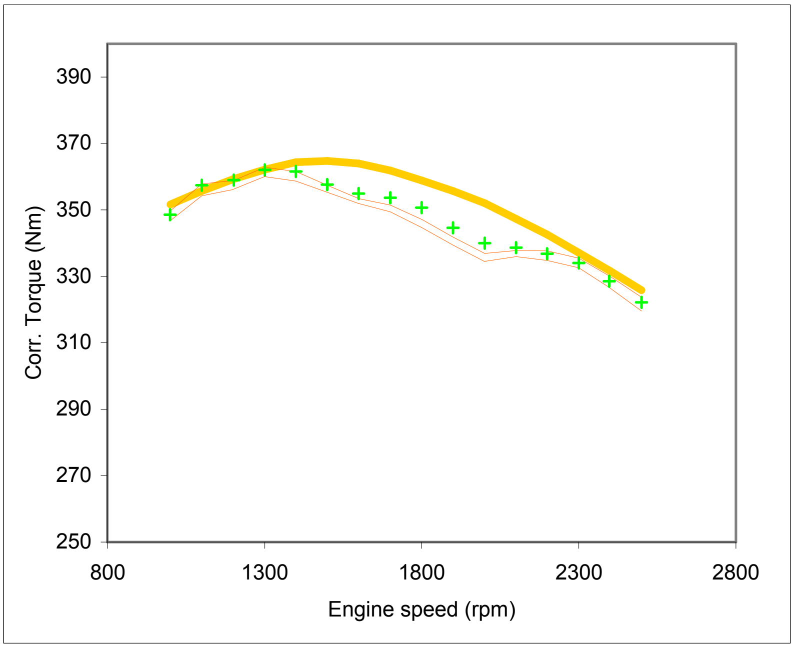


Figure 24: Post additive A Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Ramping Down



Ramping Up

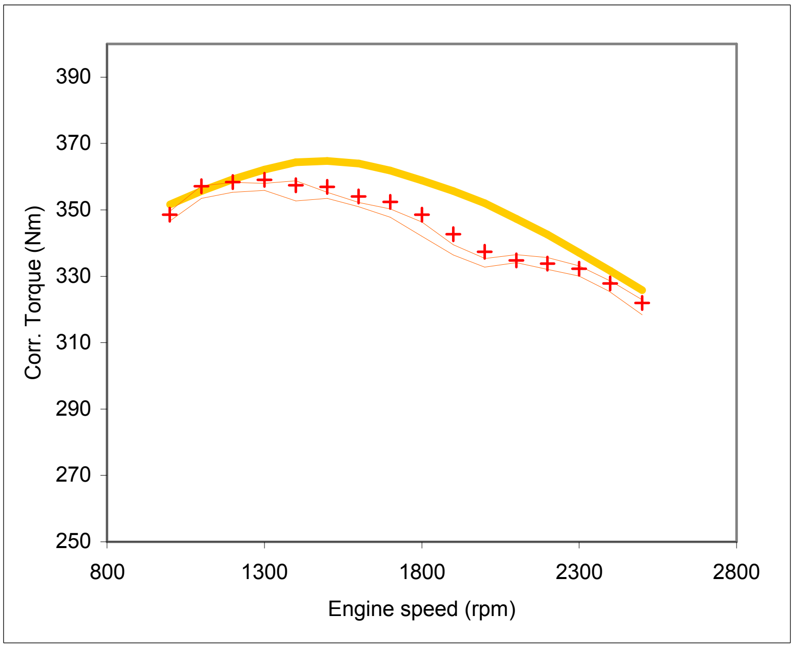
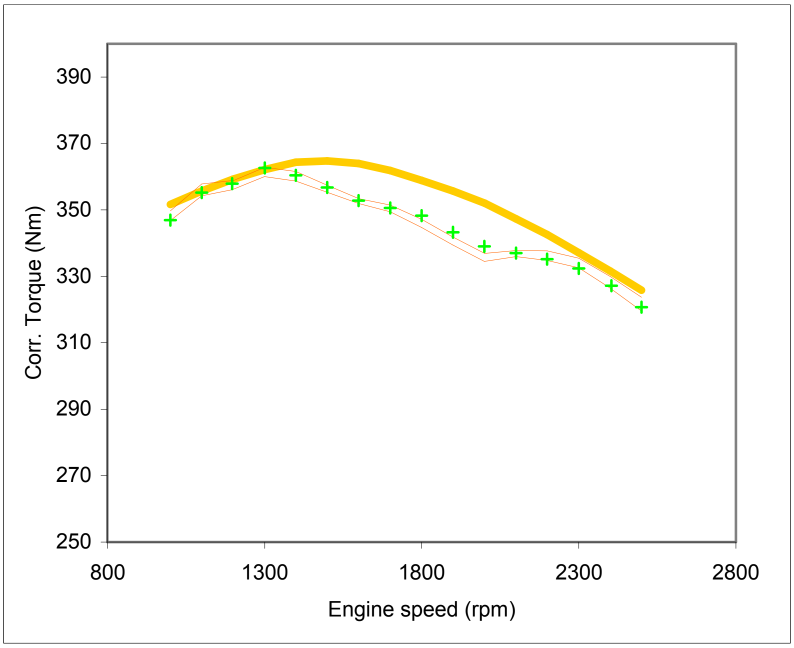


Figure 25: Post additive B Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Ramping Down



Ramping Up

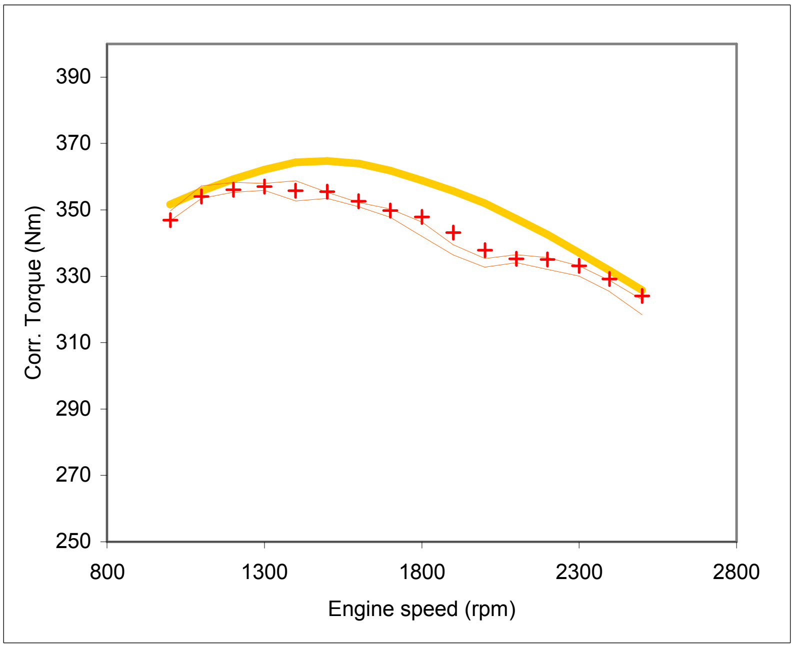
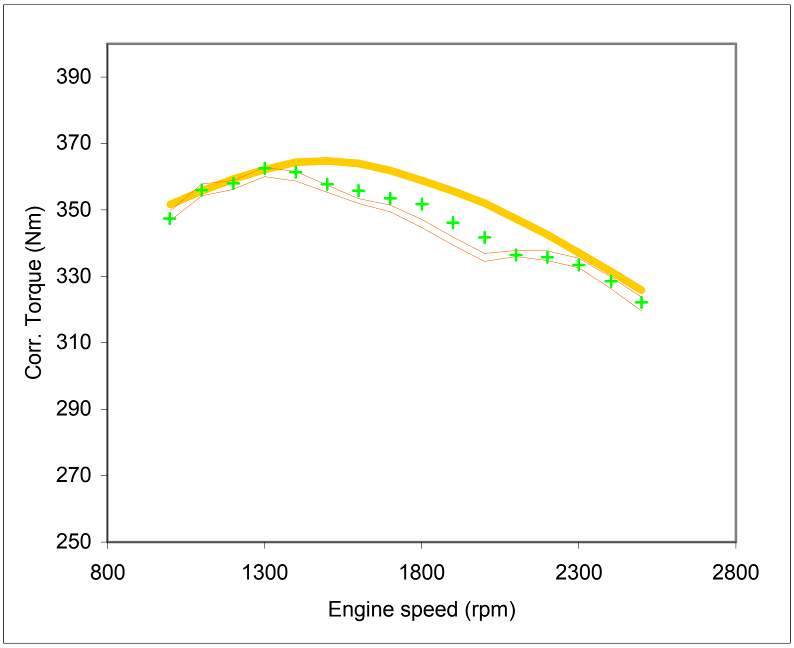


Figure 26: Post additive C Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Ramping Down



Ramping Up

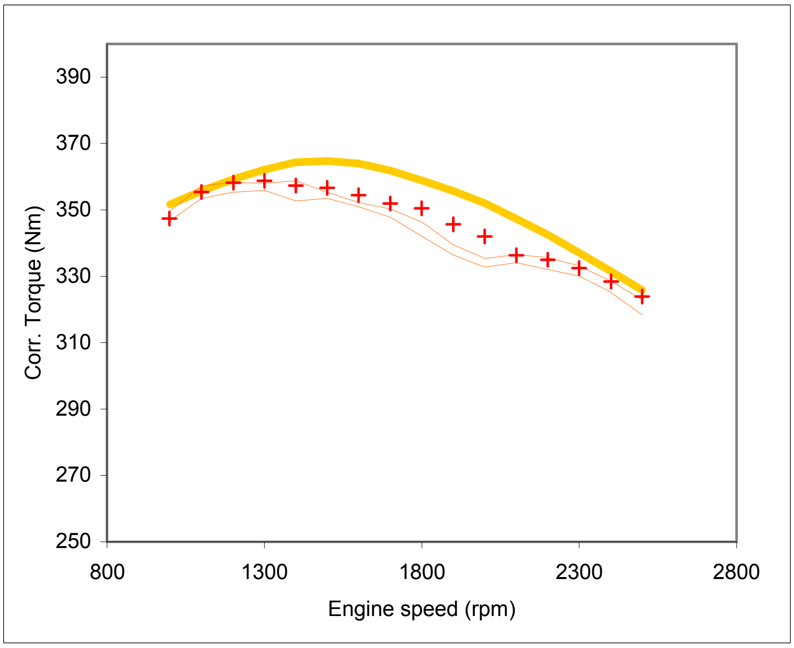
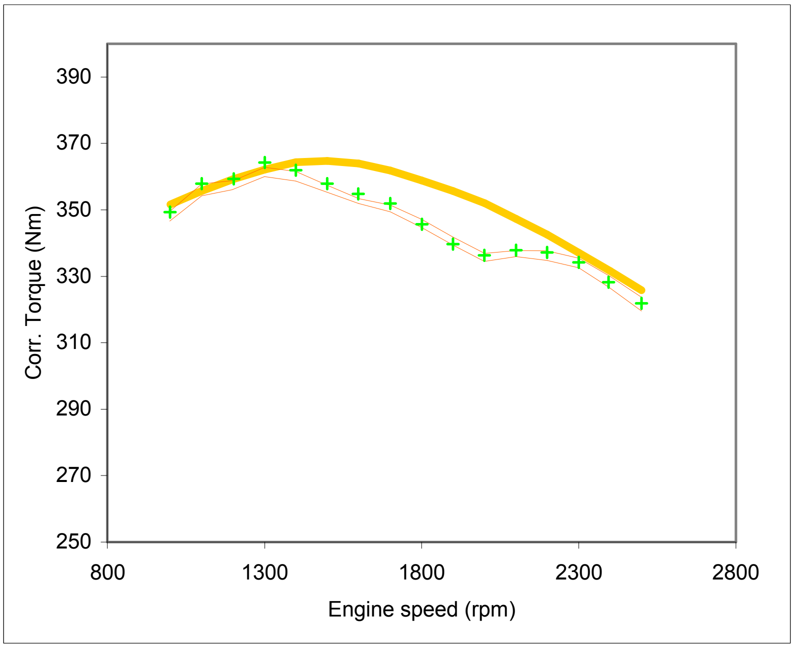


Figure 27: Post additive D Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Ramping Down



Ramping Up

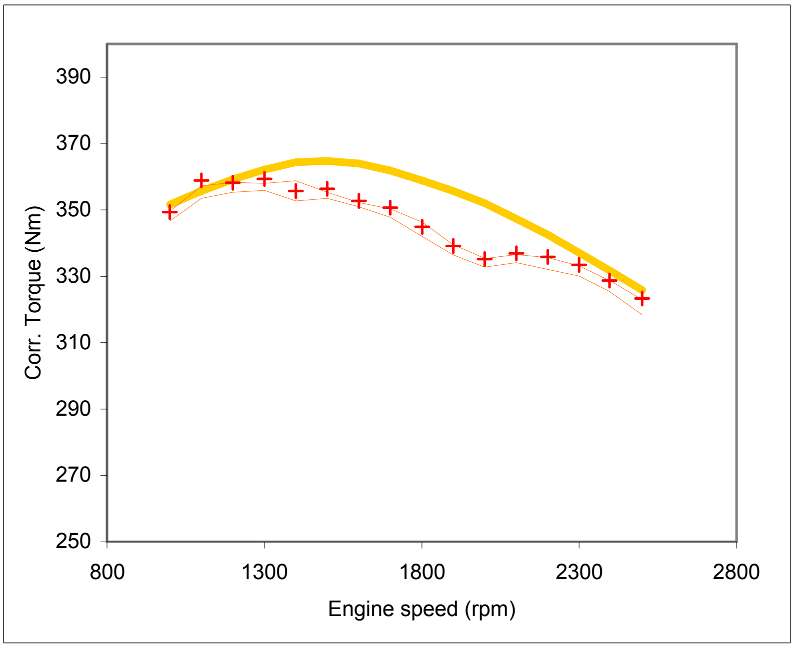
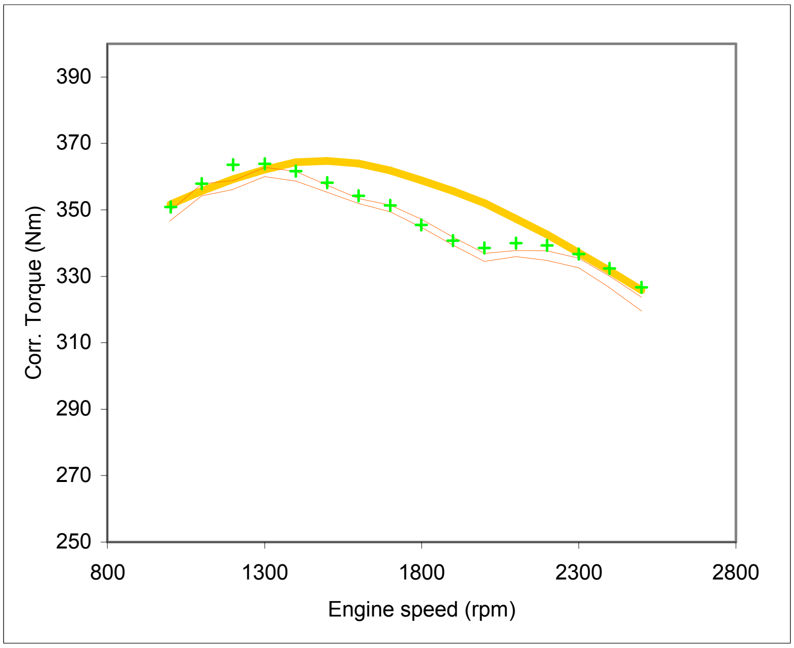


Figure 28: Post additive E Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Ramping Down



Ramping Up

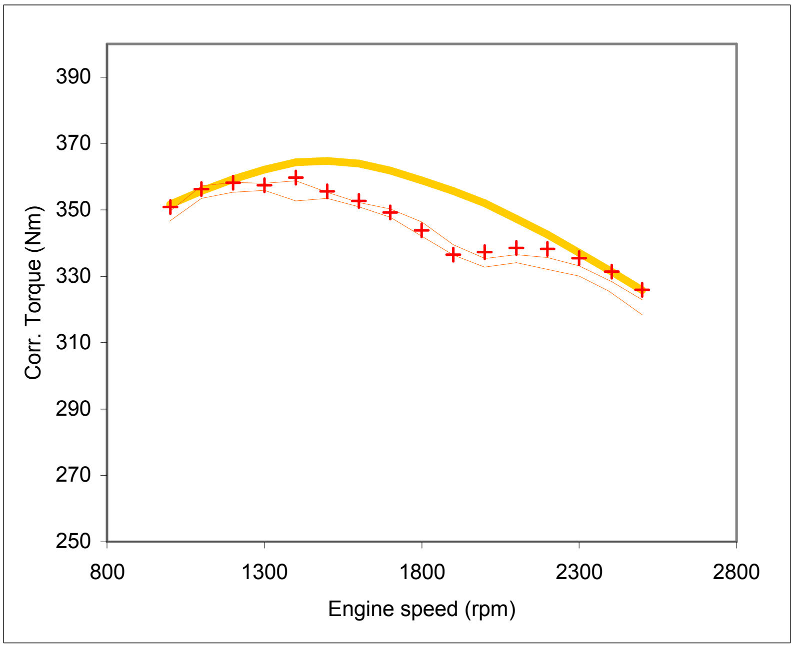
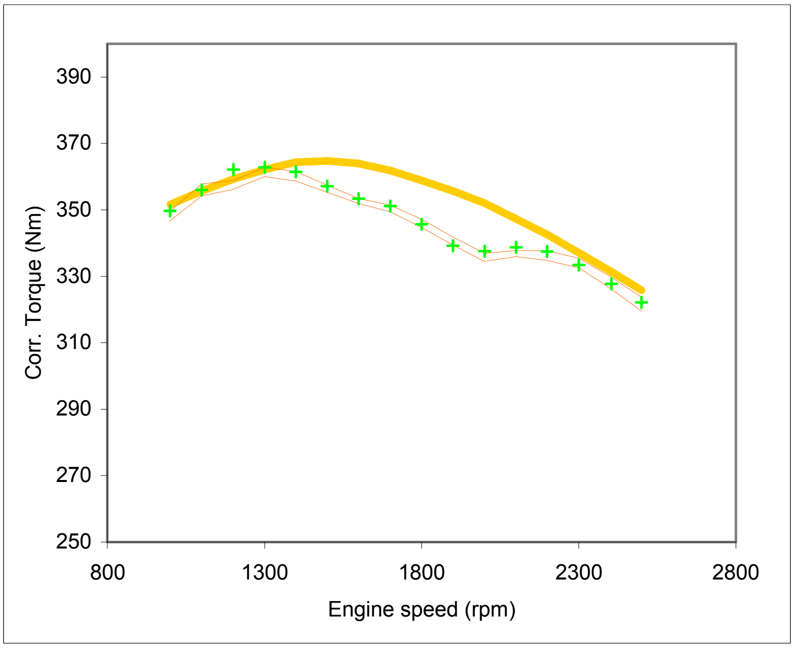


Figure 29: Post additive F Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Ramping Down



Ramping Up

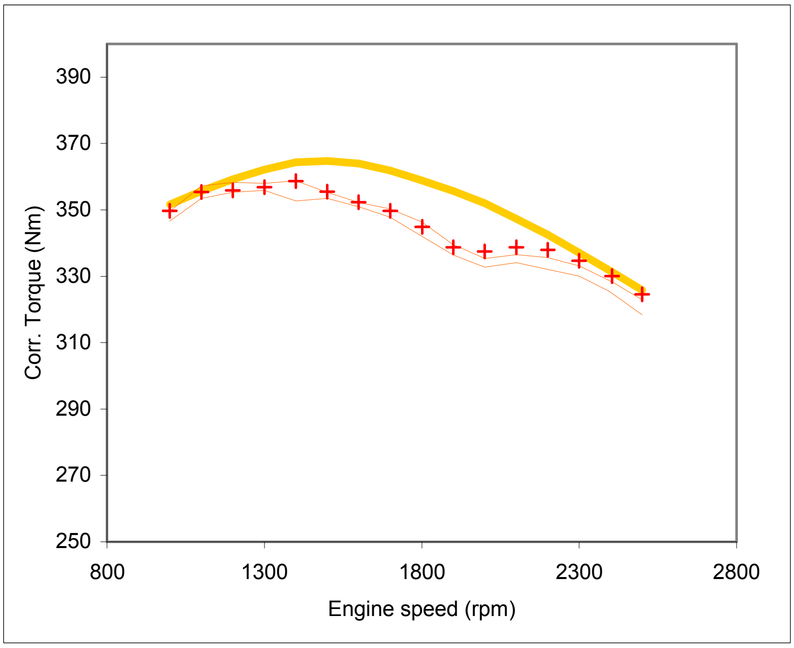


Figure 30: Post additive G Baseline test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Assessment of additive performance using the DayTrawl test schedule.

The next 11 tables presented summarise the results of 11, 20 ½ hour long, DayTrawl cycle fuel consumption tests. During these tests, the fuel used varied, either by using an additive to red diesel or running the test on red diesel alone for comparison purposes. Detailed results of all DayTrawl tests discussed herein are presented in graphical form in Appendix 8.

Table 4: DayTrawl_101 test cycle results

Day trawl test cycle results

Description: M&W Batch 1 BS590 diesel only	Warm-up duration: 00:01:59	Specific gravity	0.86 kg/litre
	Test duration: 20:40:00	Calorific value	44.73 MJ/kg
	Test date (start): 24/10/2007		

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	14:16:41	14:31:41	00:15:00	1092.79	6.74	1.28	0.13	10.294	0.900	10.239	0.00	0.00	0.79	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	14:31:41	14:46:41	00:15:00	1299.93	0.27	38.08	0.00	0.523	0.003	0.520	0.37	0.43	15.39	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	14:46:41	17:16:41	02:30:00	1999.95	0.27	48.40	0.01	0.494	0.001	0.491	1.05	1.22	16.29	1.33	1.34
Stage Start TP03	5 min gentle cruise while shooting	17:16:41	17:21:41	00:05:00	1500.25	0.50	39.57	0.00	0.515	0.000	0.512	13.57	15.71	15.62	26.68	26.83
Stage Start TP04	4 hour trawl	17:21:41	21:21:41	04:00:00	1750.00	0.00	279.87	0.11	0.236	0.001	0.234	13.84	16.02	34.13	27.20	27.35
Stage Start TP05	20 min haul in of nets	21:21:41	21:41:41	00:20:00	1400.00	0.00	83.87	0.00	0.321	0.003	0.319	62.21	72.00	25.07	232.35	233.84
Stage Start TP06	20 min tickover: net handling & unloa	21:41:41	22:01:41	00:20:00	1066.16	2.48	1.67	0.00	7.797	0.158	7.741	63.53	73.53	1.03	236.45	237.97
Stage Start TP07	5 min gentle cruise while shooting	22:01:41	22:06:41	00:05:00	1500.50	0.58	39.51	0.00	0.526	0.003	0.522	64.01	74.09	15.29	236.51	238.03
Stage Start TP08	4 hour trawl	22:06:41	02:06:41	04:00:00	1750.00	0.00	279.86	0.09	0.235	0.001	0.233	64.28	74.40	34.27	237.03	238.56
Stage Start TP09	20 min haul in of nets	02:06:41	02:26:41	00:20:00	1400.00	0.00	83.96	0.00	0.319	0.003	0.317	112.46	130.16	25.21	442.18	445.06
Stage Start TP10	20 min tickover: net handling & unloa	02:26:41	02:46:41	00:20:00	1058.53	2.14	1.67	0.00	7.690	0.113	7.644	113.77	131.68	1.05	446.28	449.18
Stage Start TP11	5 min gentle cruise while shooting	02:46:41	02:51:41	00:05:00	1500.25	0.50	39.56	0.00	0.524	0.003	0.521	114.24	132.23	15.35	446.34	449.25
Stage Start TP12	4 hour trawl	02:51:41	06:51:41	04:00:00	1750.00	0.00	280.10	0.04	0.234	0.001	0.233	114.51	132.54	34.38	446.86	449.77
Stage Start TP13	20 min haul in of nets	06:51:41	07:11:41	00:20:00	1400.05	0.23	84.00	0.00	0.318	0.003	0.317	162.58	188.17	25.27	652.19	656.27
Stage Start TP14	2.5 hr steaming to trawl site	07:11:41	09:41:41	02:30:00	1999.98	0.30	48.39	0.00	0.487	0.002	0.484	163.89	189.69	16.54	656.29	660.39
Stage Start TP15	15 minute gentle cruise to port	09:41:41	09:56:41	00:15:00	1299.86	0.36	38.07	0.00	0.513	0.004	0.510	176.22	203.95	15.70	681.63	685.88
Stage Start TP16	Tick over for 1 hour	09:56:41	10:56:41	01:00:00	1046.74	0.97	1.85	0.04	7.164	0.238	7.125	176.88	204.72	1.12	682.92	687.18
Stage End TP16	End of test	10:56:41										178.33	206.40		683.13	687.38

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.57	15.71	
Fuel consumed over first trawl stages	50.44	58.38	
Fuel consumed over second trawl stages	50.23	58.14	
Fuel consumed over third trawl stages	49.65	57.46	
Fuel consumed over steam in stages	14.44	16.72	
Fuel consumed over whole test cycle	178.33	206.40	0.2998
Fuel consumed over census stages (TP12 - TP15)	**62.37**	**72.18**	**0.3058**

Table 5: DayTrawl_102 test cycle results

Day trawl test cycle results

Description					
M&W Batch 1 BS590 diesel + Additive A	Warm-up duration	00:06:06	Specific gravity	0.86	kg/litre
	Test duration	20:40:00	Calorific value	44.73	MJ/kg
	Test date (start)	25/10/2007			

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consumed (Start of stage) Mass	Cum. fuel consumed (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	16:33:05	16:48:05	00:15:00	1083.36	5.49	1.39	0.05	9.581	0.285	9.549	0.00	0.00	0.84	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	16:48:05	17:03:05	00:15:00	1300.00	0.55	38.14	0.00	0.528	0.002	0.526	0.30	0.35	15.24	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	17:03:05	19:33:05	02:30:00	2000.03	0.38	48.46	0.01	0.492	0.003	0.490	0.99	1.14	16.34	1.34	1.34
Stage Start TP03	5 min gentle cruise while shooting	19:33:05	19:38:05	00:05:00	1500.00	0.82	39.62	0.00	0.512	0.003	0.510	13.48	15.60	15.72	26.71	26.82
Stage Start TP04	4 hour trawl	19:38:05	23:38:05	04:00:00	1750.00	0.00	280.56	0.03	0.235	0.001	0.234	13.75	15.91	34.31	27.23	27.34
Stage Start TP05	20 min haul in of nets	23:38:05	23:58:05	00:20:00	1400.00	0.00	84.14	0.00	0.319	0.003	0.317	61.99	71.75	25.26	232.89	233.85
Stage Start TP06	20 min tickover: net handling & unloa	23:58:05	00:18:05	00:20:00	1068.26	2.40	1.96	0.00	6.538	0.059	6.512	63.30	73.26	1.23	237.00	237.98
Stage Start TP07	5 min gentle cruise while shooting	00:18:05	00:23:05	00:05:00	1500.00	0.00	39.63	0.00	0.520	0.000	0.518	63.78	73.82	15.46	237.08	238.05
Stage Start TP08	4 hour trawl	00:23:05	04:23:05	04:00:00	1750.00	0.00	280.80	0.10	0.234	0.001	0.233	64.05	74.13	34.41	237.60	238.57
Stage Start TP09	20 min haul in of nets	04:23:05	04:43:05	00:20:00	1400.00	0.00	84.20	0.01	0.317	0.003	0.316	112.20	129.86	25.36	443.43	445.08
Stage Start TP10	20 min tickover: net handling & unloa	04:43:05	05:03:05	00:20:00	1069.68	2.24	1.94	0.05	6.606	0.126	6.586	113.50	131.37	1.22	447.54	449.21
Stage Start TP11	5 min gentle cruise while shooting	05:03:05	05:08:05	00:05:00	1500.00	0.00	39.66	0.00	0.520	0.000	0.518	113.98	131.92	15.47	447.62	449.28
Stage Start TP12	4 hour trawl	05:08:05	09:08:05	04:00:00	1750.00	0.00	280.87	0.07	0.233	0.001	0.233	114.25	132.23	34.47	448.14	449.80
Stage Start TP13	20 min haul in of nets	09:08:05	09:28:05	00:20:00	1400.00	0.00	84.26	0.00	0.316	0.003	0.316	162.32	187.87	25.44	654.02	656.31
Stage Start TP14	2.5 hr steaming to trawl site	09:28:05	11:58:05	02:30:00	1999.97	0.40	48.52	0.01	0.482	0.001	0.480	163.62	189.37	16.70	658.14	660.44
Stage Start TP15	15 minute gentle cruise to port	11:58:05	12:13:05	00:15:00	1300.00	0.39	38.17	0.00	0.506	0.005	0.505	175.86	203.54	15.90	683.54	685.92
Stage Start TP16	Tick over for 1 hour	12:13:05	13:13:05	01:00:00	1045.75	1.67	2.16	0.02	6.044	0.082	6.027	176.52	204.30	1.33	684.84	687.22
Stage End TP16	End of test	13:13:05										177.95	205.96		685.08	687.46

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.48	15.60	
Fuel consumed over first trawl stages	50.30	58.21	
Fuel consumed over second trawl stages	50.20	58.10	
Fuel consumed over third trawl stages	49.64	57.46	
Fuel consumed over steam in stages	14.33	16.59	
Fuel consumed over whole test cycle	177.95	205.96	0.2983
Fuel consumed over census stages (TP12 - TP15)	**62.27**	**72.07**	**0.3045**

Table 6: DayTrawl_103 test cycle results

Day trawl test cycle results

Description					
M&W Batch 1 BS590 diesel only	Warm-up duration	00:06:16	Specific gravity	0.86	kg/litre
	Test duration	20:40:00	Calorific value	44.73	MJ/kg
	Test date (start)	31/10/2007			

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consumed (Start of stage) Mass	Cum. fuel consumed (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	13:42:09	13:57:09	00:15:00	1073.64	3.34	1.22	0.08	11.307	0.694	11.233	0.00	0.00	0.71	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	13:57:09	14:12:09	00:15:00	1300.00	0.39	38.01	0.00	0.539	0.004	0.536	0.39	0.45	14.93	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	14:12:09	16:42:09	02:30:00	1999.97	0.34	48.32	0.00	0.498	0.003	0.494	1.08	1.26	16.17	1.33	1.34
Stage Start TP03	5 min gentle cruise while shooting	16:42:09	16:47:09	00:05:00	1500.00	0.00	39.51	0.00	0.519	0.003	0.516	13.68	15.83	15.50	26.63	26.82
Stage Start TP04	4 hour trawl	16:47:09	20:47:09	04:00:00	1750.00	0.00	279.88	0.02	0.233	0.001	0.232	13.95	16.14	34.47	27.15	27.34
Stage Start TP05	20 min haul in of nets	20:47:09	21:07:09	00:20:00	1400.00	0.00	83.91	0.00	0.320	0.003	0.318	61.85	71.59	25.15	232.31	233.85
Stage Start TP06	20 min tickover: net handling & unload	21:07:09	21:27:09	00:20:00	1044.79	3.31	2.02	0.05	6.413	0.233	6.371	63.16	73.10	1.26	236.41	237.98
Stage Start TP07	5 min gentle cruise while shooting	21:27:09	21:32:09	00:05:00	1499.75	0.50	39.52	0.00	0.528	0.000	0.524	63.63	73.65	15.25	236.48	238.06
Stage Start TP08	4 hour trawl	21:32:09	01:32:09	04:00:00	1750.00	0.00	279.92	0.04	0.233	0.001	0.231	63.91	73.97	34.55	237.00	238.58
Stage Start TP09	20 min haul in of nets	01:32:09	01:52:09	00:20:00	1400.00	0.00	83.93	0.00	0.319	0.003	0.317	111.71	129.29	25.22	442.19	445.09
Stage Start TP10	20 min tickover: net handling & unload	01:52:09	02:12:09	00:20:00	1045.26	3.00	2.05	0.00	6.244	0.076	6.205	113.01	130.80	1.29	446.29	449.22
Stage Start TP11	5 min gentle cruise while shooting	02:12:09	02:17:09	00:05:00	1500.00	0.00	39.53	0.00	0.525	0.003	0.521	113.48	131.34	15.34	446.37	449.30
Stage Start TP12	4 hour trawl	02:17:09	06:17:09	04:00:00	1750.00	0.00	279.97	0.02	0.233	0.001	0.231	113.75	131.66	34.61	446.89	449.82
Stage Start TP13	20 min haul in of nets	06:17:09	06:37:09	00:20:00	1400.00	0.00	83.93	0.00	0.318	0.003	0.316	161.47	186.89	25.30	652.12	656.33
Stage Start TP14	2.5 hr steaming to trawl site	06:37:09	09:07:09	02:30:00	2000.01	0.37	48.32	0.01	0.487	0.001	0.484	162.77	188.40	16.52	656.22	660.46
Stage Start TP15	15 minute gentle cruise to port	09:07:09	09:22:09	00:15:00	1300.00	0.39	38.00	0.00	0.511	0.005	0.507	175.10	202.66	15.75	681.52	685.94
Stage Start TP16	Tick over for 1 hour	09:22:09	10:22:09	01:00:00	1034.60	0.94	2.34	0.02	5.678	0.082	5.640	175.76	203.43	1.42	682.81	687.24
Stage End TP16	End of test	10:22:09										177.20	205.09		683.07	687.50

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.68	15.83	
Fuel consumed over first trawl stages	49.96	57.82	
Fuel consumed over second trawl stages	49.84	57.69	
Fuel consumed over third trawl stages	49.30	57.06	
Fuel consumed over steam in stages	14.43	16.70	
Fuel consumed over whole test cycle	177.20	205.09	0.2979
Fuel consumed over census stages (TP12 - TP15)	**62.01**	**71.77**	**0.3042**

Table 7: DayTrawl_104 test cycle results

Day trawl test cycle results

Description			
M&W Batch 1 BS590 diesel + Additive B			
Warm-up duration	00:06:24	Specific gravity	0.86 kg/litre
Test duration	20:40:00	Calorific value	44.73 MJ/kg
Test date (start)	02/11/2007		

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	14:15:51	14:30:51	00:15:00	1081.00	2.42	1.72	0.11	7.784	0.489	7.729	0.00	0.00	1.04	0.01	0.01
Stage Start TP01	15 minute gentle cruise from port	14:30:51	14:45:51	00:15:00	1300.00	0.39	37.97	0.00	0.524	0.003	0.520	0.38	0.44	15.36	0.05	0.06
Stage Start TP02	2.5 hr steaming to trawl site	14:45:51	17:15:51	02:30:00	1999.99	0.37	48.28	0.00	0.492	0.002	0.488	1.06	1.22	16.36	1.35	1.36
Stage Start TP03	5 min gentle cruise while shooting	17:15:51	17:20:51	00:05:00	1500.50	0.58	39.47	0.00	0.512	0.003	0.508	13.49	15.62	15.71	26.63	26.83
Stage Start TP04	4 hour trawl	17:20:51	21:20:51	04:00:00	1750.00	0.00	279.74	0.04	0.233	0.001	0.232	13.76	15.92	34.47	27.14	27.35
Stage Start TP05	20 min haul in of nets	21:20:51	21:40:51	00:20:00	1400.05	0.23	83.86	0.00	0.321	0.004	0.319	61.64	71.34	25.09	232.20	233.87
Stage Start TP06	20 min tickover: net handling & unloa	21:40:51	22:00:51	00:20:00	1061.53	3.42	2.34	0.02	5.554	0.068	5.515	62.95	72.86	1.45	236.30	238.00
Stage Start TP07	5 min gentle cruise while shooting	22:00:51	22:05:51	00:05:00	1500.00	0.00	39.49	0.00	0.527	0.003	0.523	63.43	73.42	15.28	236.39	238.09
Stage Start TP08	4 hour trawl	22:05:51	02:05:51	04:00:00	1750.00	0.00	279.84	0.08	0.233	0.001	0.231	63.70	73.73	34.53	236.90	238.61
Stage Start TP09	20 min haul in of nets	02:05:51	02:25:51	00:20:00	1400.00	0.00	83.92	0.00	0.320	0.003	0.318	111.51	129.07	25.19	442.04	445.13
Stage Start TP10	20 min tickover: net handling & unloa	02:25:51	02:45:51	00:20:00	1060.11	3.65	2.35	0.04	5.497	0.099	5.462	112.82	130.58	1.46	446.14	449.26
Stage Start TP11	5 min gentle cruise while shooting	02:45:51	02:50:51	00:05:00	1500.25	0.50	39.52	0.00	0.525	0.003	0.521	113.30	131.13	15.34	446.22	449.35
Stage Start TP12	4 hour trawl	02:50:51	06:50:51	04:00:00	1750.00	0.00	280.03	0.04	0.233	0.001	0.231	113.57	131.45	34.60	446.74	449.87
Stage Start TP13	20 min haul in of nets	06:50:51	07:10:51	00:20:00	1400.00	0.00	83.95	0.00	0.319	0.003	0.317	161.31	186.71	25.26	652.02	656.40
Stage Start TP14	2.5 hr steaming to trawl site	07:10:51	09:40:51	02:30:00	1999.99	0.30	48.34	0.00	0.487	0.002	0.484	162.62	188.22	16.53	656.12	660.52
Stage Start TP15	15 minute gentle cruise to port	09:40:51	09:55:51	00:15:00	1300.07	0.27	38.01	0.00	0.512	0.005	0.509	174.94	202.48	15.71	681.43	685.99
Stage Start TP16	Tick over for 1 hour	09:55:51	10:55:51	01:00:00	1048.84	0.91	2.53	0.06	5.303	0.191	5.270	175.61	203.25	1.52	682.72	687.30
Stage End TP16	End of test	10:55:51										177.08	204.95		683.00	687.58

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.49	15.62	
Fuel consumed over first trawl stages	49.94	57.80	
Fuel consumed over second trawl stages	49.87	57.72	
Fuel consumed over third trawl stages	49.32	57.08	
Fuel consumed over steam in stages	14.46	16.73	
Fuel consumed over whole test cycle	177.08	204.95	0.2977
Fuel consumed over census stages (TP12 - TP15)	**62.03**	**71.80**	**0.3043**

Table 8: DayTrawl_105 test cycle results

Day trawl test cycle results

Description					
M&W Batch 1 BS590 diesel + Additive C	Warm-up duration	00:05:02	Specific gravity	0.86	kg/litre
	Test duration	20:39:59	Calorific value	44.73	MJ/kg
	Test date (start)	06/11/2007			

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	15:27:58	15:42:58	00:15:00	1077.00	3.06	1.71	0.03	7.915	0.146	7.845	0.00	0.00	1.02	0.01	0.01
Stage Start TP01	15 minute gentle cruise from port	15:42:58	15:57:58	00:15:00	1299.79	0.43	37.89	0.00	0.532	0.003	0.528	0.38	0.44	15.11	0.06	0.06
Stage Start TP02	2.5 hr steaming to trawl site	15:57:58	18:27:58	02:30:00	2000.01	0.31	48.18	0.01	0.497	0.003	0.492	1.07	1.24	16.19	1.34	1.36
Stage Start TP03	5 min gentle cruise while shooting	18:27:58	18:32:58	00:05:00	1500.00	0.00	39.37	0.00	0.515	0.003	0.510	13.61	15.75	15.62	26.57	26.82
Stage Start TP04	4 hour trawl	18:32:58	22:32:58	04:00:00	1750.00	0.00	279.10	0.07	0.234	0.001	0.231	13.87	16.06	34.45	27.09	27.34
Stage Start TP05	20 min haul in of nets	22:32:58	22:52:58	00:20:00	1400.00	0.00	83.67	0.01	0.320	0.003	0.317	61.66	71.37	25.14	231.68	233.88
Stage Start TP06	20 min tickover: net handling & unloa	22:52:58	23:12:58	00:20:00	1052.47	2.89	2.38	0.05	5.469	0.114	5.419	62.97	72.88	1.47	235.76	238.00
Stage Start TP07	5 min gentle cruise while shooting	23:12:58	23:17:58	00:05:00	1500.00	0.00	39.40	0.00	0.529	0.000	0.525	63.45	73.44	15.20	235.85	238.09
Stage Start TP08	4 hour trawl	23:17:58	03:17:57	03:59:59	1750.00	0.00	279.37	0.13	0.233	0.001	0.231	63.72	73.75	34.51	236.37	238.61
Stage Start TP09	20 min haul in of nets	03:17:57	03:37:57	00:20:00	1400.00	0.00	83.79	0.01	0.320	0.003	0.317	111.48	129.03	25.18	441.14	445.13
Stage Start TP10	20 min tickover: net handling & unloa	03:37:57	03:57:57	00:20:00	1056.16	4.63	2.40	0.03	5.358	0.089	5.317	112.79	130.54	1.50	445.23	449.26
Stage Start TP11	5 min gentle cruise while shooting	03:57:57	04:02:57	00:05:00	1500.00	0.00	39.45	0.00	0.526	0.003	0.522	113.26	131.09	15.31	445.32	449.35
Stage Start TP12	4 hour trawl	04:02:57	08:02:57	04:00:00	1750.00	0.00	279.62	0.04	0.232	0.001	0.231	113.53	131.41	34.62	445.84	449.87
Stage Start TP13	20 min haul in of nets	08:02:57	08:22:57	00:20:00	1400.00	0.00	83.81	0.00	0.319	0.003	0.316	161.18	186.56	25.25	650.81	656.41
Stage Start TP14	2.5 hr steaming to trawl site	08:22:57	10:52:57	02:30:00	2000.01	0.38	48.28	0.01	0.487	0.001	0.484	162.49	188.06	16.51	654.91	660.53
Stage Start TP15	15 minute gentle cruise to port	10:52:57	11:07:57	00:15:00	1300.00	0.00	37.99	0.00	0.511	0.005	0.508	174.81	202.33	15.75	680.19	686.00
Stage Start TP16	Tick over for 1 hour	11:07:57	12:07:57	01:00:00	1047.48	1.51	2.54	0.04	5.213	0.131	5.180	175.47	203.09	1.54	681.48	687.30
Stage End TP16	End of test	12:07:57										176.92	204.77		681.76	687.58

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.61	15.75	
Fuel consumed over first trawl stages	49.84	57.69	
Fuel consumed over second trawl stages	49.81	57.65	
Fuel consumed over third trawl stages	49.23	56.97	
Fuel consumed over steam in stages	14.43	16.70	
Fuel consumed over whole test cycle	176.92	204.77	0.2980
Fuel consumed over census stages (TP12 - TP15)	**61.93**	**71.68**	**0.3042**

Table 9: DayTrawl_106 test cycle results

Day trawl test cycle results

Description			
M&W Batch 1 BS590 diesel + Additive D	Warm-up duration	00:01:21	Specific gravity 0.86 kg/litre
	Test duration	20:40:00	Calorific value 44.73 MJ/kg
	Test date (start)	09/11/2007	

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	16:27:13	16:42:13	00:15:00	1061.00	5.72	2.02	0.08	6.454	0.219	6.400	0.00	0.00	1.25	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	16:42:13	16:57:13	00:15:00	1299.93	0.47	37.91	0.00	0.523	0.000	0.519	0.29	0.33	15.38	0.06	0.06
Stage Start TP02	2.5 hr steaming to trawl site	16:57:13	19:27:13	02:30:00	1999.93	0.36	48.19	0.01	0.495	0.002	0.491	0.96	1.12	16.24	1.35	1.36
Stage Start TP03	5 min gentle cruise while shooting	19:27:13	19:32:13	00:05:00	1500.00	0.00	39.38	0.00	0.515	0.003	0.510	13.47	15.59	15.63	26.58	26.82
Stage Start TP04	4 hour trawl	19:32:13	23:32:13	04:00:00	1750.00	0.00	279.41	0.09	0.234	0.001	0.232	13.73	15.89	34.46	27.09	27.34
Stage Start TP05	20 min haul in of nets	23:32:13	23:52:13	00:20:00	1399.95	0.23	83.76	0.00	0.321	0.003	0.319	61.56	71.25	25.06	231.91	233.88
Stage Start TP06	20 min tickover: net handling & unloa	23:52:13	00:12:13	00:20:00	1049.58	2.39	2.41	0.03	5.419	0.107	5.375	62.88	72.77	1.49	236.00	238.01
Stage Start TP07	5 min gentle cruise while shooting	00:12:13	00:17:13	00:05:00	1499.75	0.50	39.43	0.00	0.529	0.000	0.525	63.35	73.33	15.21	236.09	238.10
Stage Start TP08	4 hour trawl	00:17:13	04:17:13	04:00:00	1750.00	0.00	279.58	0.06	0.233	0.001	0.231	63.63	73.64	34.52	236.61	238.62
Stage Start TP09	20 min haul in of nets	04:17:13	04:37:13	00:20:00	1400.00	0.00	83.81	0.01	0.319	0.003	0.317	111.41	128.95	25.23	441.55	445.16
Stage Start TP10	20 min tickover: net handling & unloa	04:37:13	04:57:13	00:20:00	1050.11	3.00	2.45	0.05	5.291	0.142	5.251	112.72	130.46	1.52	445.65	449.29
Stage Start TP11	5 min gentle cruise while shooting	04:57:13	05:02:13	00:05:00	1500.50	0.58	39.45	0.00	0.526	0.003	0.522	113.19	131.01	15.31	445.74	449.38
Stage Start TP12	4 hour trawl	05:02:13	09:02:13	04:00:00	1750.00	0.00	279.81	0.10	0.233	0.001	0.231	113.46	131.32	34.58	446.25	449.90
Stage Start TP13	20 min haul in of nets	09:02:13	09:22:13	00:20:00	1400.05	0.23	83.90	0.00	0.319	0.003	0.317	161.20	186.58	25.24	651.37	656.44
Stage Start TP14	2.5 hr steaming to trawl site	09:22:13	11:52:13	02:30:00	2000.01	0.31	48.30	0.00	0.488	0.002	0.485	162.51	188.09	16.47	655.47	660.57
Stage Start TP15	15 minute gentle cruise to port	11:52:13	12:07:13	00:15:00	1299.93	0.27	37.99	0.00	0.516	0.003	0.512	174.86	202.39	15.61	680.76	686.03
Stage Start TP16	Tick over for 1 hour	12:07:13	13:07:13	01:00:00	1038.19	1.28	2.52	0.03	5.321	0.125	5.288	175.53	203.16	1.51	682.05	687.33
Stage End TP16	End of test	13:07:13										176.98	204.84		682.33	687.61

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.47	15.59	
Fuel consumed over first trawl stages	49.89	57.74	
Fuel consumed over second trawl stages	49.84	57.68	
Fuel consumed over third trawl stages	49.31	57.08	
Fuel consumed over steam in stages	14.48	16.75	
Fuel consumed over whole test cycle	176.98	204.84	0.2979
Fuel consumed over census stages (TP12 - TP15)	**62.06**	**71.83**	**0.3046**

Table 10: DayTrawl_107 test cycle results

Day trawl test cycle results

Description					Warm-up duration			00:10:51				Specific gravity		0.86 kg/litre		
	M&W Batch 2 BS590 diesel				Test duration			20:40:00				Calorific value		45.20 MJ/kg		
					Test date (start)			14/11/2007								
Stage	Description	Start time	End time	Duration	Engine Speed		Torque		Specific Fuel Consumption			Cum. fuel consume (Start of stage)		Engine Eff.	Cum. Work Done (Start of stage)	
					Ave.	Stdev.	Ave. Corr.	Stdev. Corr.	Ave. Corr.	Stdev. Corr.	Ave. Uncorr.	Mass	Volume		Corr.	Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	10:54:54	11:09:54	00:15:00	1071.14	6.56	1.38	0.09	9.940	0.676	9.889	0.00	0.00	0.80	0.01	0.01
Stage Start TP01	15 minute gentle cruise from port	11:09:54	11:24:54	00:15:00	1300.00	0.39	38.02	0.00	0.532	0.004	0.529	0.38	0.44	14.98	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	11:24:54	13:54:54	02:30:00	2000.01	0.36	48.36	0.00	0.494	0.003	0.492	1.07	1.24	16.12	1.34	1.35
Stage Start TP03	5 min gentle cruise while shooting	13:54:54	13:59:54	00:05:00	1500.25	0.50	39.54	0.00	0.511	0.003	0.509	13.59	15.80	15.57	26.66	26.80
Stage Start TP04	4 hour trawl	13:59:54	17:59:54	04:00:00	1750.00	0.00	280.61	0.15	0.233	0.001	0.232	13.85	16.10	34.21	27.18	27.32
Stage Start TP05	20 min haul in of nets	17:59:54	18:19:54	00:20:00	1400.00	0.00	84.17	0.00	0.318	0.003	0.317	61.74	71.79	25.06	232.87	233.87
Stage Start TP06	20 min tickover: net handling & unloa	18:19:54	18:39:54	00:20:00	1051.16	2.91	2.31	0.07	5.579	0.237	5.562	63.04	73.31	1.43	236.99	238.00
Stage Start TP07	5 min gentle cruise while shooting	18:39:54	18:44:54	00:05:00	1500.00	0.00	39.61	0.00	0.524	0.003	0.522	63.52	73.86	15.21	237.07	238.09
Stage Start TP08	4 hour trawl	18:44:54	22:44:54	04:00:00	1750.00	0.00	280.87	0.03	0.232	0.001	0.232	63.79	74.17	34.29	237.59	238.61
Stage Start TP09	20 min haul in of nets	22:44:54	23:04:54	00:20:00	1399.95	0.23	84.15	0.00	0.318	0.003	0.317	111.61	129.78	25.08	443.48	445.16
Stage Start TP10	20 min tickover: net handling & unloa	23:04:54	23:24:54	00:20:00	1047.21	4.04	2.38	0.04	5.340	0.060	5.322	112.92	131.30	1.49	447.59	449.29
Stage Start TP11	5 min gentle cruise while shooting	23:24:54	23:29:54	00:05:00	1500.00	0.00	39.60	0.00	0.521	0.000	0.519	113.38	131.84	15.29	447.68	449.37
Stage Start TP12	4 hour trawl	23:29:54	03:29:54	04:00:00	1750.00	0.00	280.56	0.14	0.232	0.001	0.231	113.65	132.15	34.37	448.20	449.89
Stage Start TP13	20 min haul in of nets	03:29:54	03:49:54	00:20:00	1400.00	0.00	83.99	0.00	0.317	0.003	0.315	161.31	187.57	25.14	653.86	656.45
Stage Start TP14	2.5 hr steaming to trawl site	03:49:54	06:19:54	02:30:00	1999.99	0.35	48.33	0.01	0.485	0.002	0.483	162.61	189.08	16.41	657.96	660.58
Stage Start TP15	15 minute gentle cruise to port	06:19:54	06:34:54	00:15:00	1300.14	0.53	37.98	0.00	0.509	0.006	0.505	174.89	203.36	15.66	683.27	686.03
Stage Start TP16	Tick over for 1 hour	06:34:54	07:34:54	01:00:00	1040.52	1.06	2.52	0.05	5.248	0.151	5.215	175.55	204.13	1.52	684.56	687.33
Stage End TP16	End of test	07:34:54										176.99	205.80		684.84	687.61

Fuel consumed over steam out stages	13.59	15.80	
Fuel consumed over first trawl stages	49.93	58.06	
Fuel consumed over second trawl stages	49.86	57.98	
Fuel consumed over third trawl stages	49.23	57.24	
Fuel consumed over steam in stages	14.38	16.72	litres/kWh
Fuel consumed over whole test cycle	176.99	205.80	0.2982
Fuel consumed over census stages (TP12 - TP15)	**61.90**	**71.97**	**0.3045**

Table 11: DayTrawl_108 test cycle results

Day trawl test cycle results

Description: M&W Batch 2 BS590 diesel + Additive E

Warm-up duration 00:05:25
Test duration 20:40:00
Test date (start) 15/11/2007

Specific gravity 0.86 kg/litre
Calorific value 45.20 MJ/kg

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consumed (Start of stage) Mass	Cum. fuel consumed (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	14:09:00	14:24:00	00:15:00	1082.43	2.79	1.84	0.05	7.120	0.221	7.090	0.00	0.00	1.12	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	14:24:00	14:39:00	00:15:00	1299.93	0.27	38.03	0.00	0.516	0.002	0.513	0.30	0.35	15.45	0.05	0.05
Stage Start TP02	2.5 hr steaming to trawl site	14:39:00	17:09:00	02:30:00	1999.99	0.44	48.34	0.02	0.487	0.002	0.484	0.96	1.12	16.35	1.35	1.35
Stage Start TP03	5 min gentle cruise while shooting	17:09:00	17:14:00	00:05:00	1500.00	0.00	39.49	0.00	0.508	0.003	0.505	13.29	15.46	15.68	26.66	26.80
Stage Start TP04	4 hour trawl	17:14:00	21:14:00	04:00:00	1750.00	0.00	280.17	0.09	0.233	0.001	0.232	13.56	15.76	34.16	27.17	27.32
Stage Start TP05	20 min haul in of nets	21:14:00	21:34:00	00:20:00	1400.00	0.00	84.00	0.01	0.319	0.003	0.317	61.45	71.45	24.99	232.55	233.89
Stage Start TP06	20 min tickover: net handling & unloa	21:34:00	21:54:00	00:20:00	1067.32	2.98	2.37	0.03	5.375	0.129	5.347	62.75	72.97	1.48	236.65	238.01
Stage Start TP07	5 min gentle cruise while shooting	21:54:00	21:59:00	00:05:00	1500.00	0.00	39.52	0.00	0.520	0.003	0.518	63.23	73.52	15.30	236.74	238.10
Stage Start TP08	4 hour trawl	21:59:00	01:59:00	04:00:00	1750.00	0.00	280.13	0.08	0.232	0.001	0.231	63.50	73.83	34.26	237.26	238.62
Stage Start TP09	20 min haul in of nets	01:59:00	02:19:00	00:20:00	1400.00	0.00	83.88	0.01	0.317	0.004	0.315	111.23	129.34	25.11	442.60	445.18
Stage Start TP10	20 min tickover: net handling & unloa	02:19:00	02:39:00	00:20:00	1063.42	3.36	2.38	0.00	5.362	0.093	5.327	112.53	130.85	1.49	446.70	449.31
Stage Start TP11	5 min gentle cruise while shooting	02:39:00	02:44:00	00:05:00	1500.25	0.50	39.46	0.00	0.521	0.003	0.518	113.00	131.40	15.28	446.79	449.40
Stage Start TP12	4 hour trawl	02:44:00	06:44:00	04:00:00	1750.00	0.00	279.98	0.07	0.232	0.001	0.231	113.27	131.71	34.29	447.31	449.92
Stage Start TP13	20 min haul in of nets	06:44:00	07:04:00	00:20:00	1400.00	0.00	83.92	0.00	0.317	0.003	0.315	160.95	187.15	25.11	652.54	656.48
Stage Start TP14	2.5 hr steaming to trawl site	07:04:00	09:34:00	02:30:00	2000.01	0.37	48.30	0.01	0.484	0.002	0.481	162.25	188.66	16.44	656.64	660.61
Stage Start TP15	15 minute gentle cruise to port	09:34:00	09:49:00	00:15:00	1300.07	0.27	37.97	0.00	0.509	0.005	0.506	174.50	202.91	15.65	681.93	686.06
Stage Start TP16	Tick over for 1 hour	09:49:00	10:49:00	01:00:00	1051.80	1.80	2.46	0.03	5.310	0.138	5.279	175.16	203.67	1.50	683.22	687.36
Stage End TP16	End of test	10:49:00										176.60	205.35		683.49	687.63

	Mass	Volume	litres/kWh
Fuel consumed over steam out stages	13.29	15.46	
Fuel consumed over first trawl stages	49.93	58.06	
Fuel consumed over second trawl stages	49.78	57.88	
Fuel consumed over third trawl stages	49.25	57.26	
Fuel consumed over steam in stages	14.35	16.68	
Fuel consumed over whole test cycle	176.60	205.35	0.2981
Fuel consumed over census stages (TP12 - TP15)	**61.89**	**71.96**	**0.3050**

Table 12: DayTrawl_109 test cycle results

Day trawl test cycle results

Description			
M&W Batch 2 BS590 diesel + Additive F		Specific gravity	0.86 kg/litre
Warm-up duration	00:18:07	Calorific value	45.20 MJ/kg
Test duration	20:40:00		
Test date (start)	20/11/2007		

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	12:06:24	12:21:24	00:15:00	1063.93	7.35	0.81	0.10	16.626	2.053	16.655	0.00	0.00	0.49	0.01	0.01
Stage Start TP01	15 minute gentle cruise from port	12:21:24	12:36:24	00:15:00	1300.21	0.58	38.28	0.00	0.527	0.003	0.528	0.37	0.43	15.11	0.03	0.03
Stage Start TP02	2.5 hr steaming to trawl site	12:36:24	15:06:24	02:30:00	2000.02	0.32	48.68	0.00	0.491	0.003	0.492	1.06	1.23	16.22	1.34	1.33
Stage Start TP03	5 min gentle cruise while shooting	15:06:24	15:11:24	00:05:00	1500.25	0.50	39.79	0.00	0.513	0.000	0.513	13.57	15.78	15.54	26.83	26.78
Stage Start TP04	4 hour trawl	15:11:24	19:11:24	04:00:00	1750.00	0.00	282.34	0.03	0.233	0.001	0.234	13.84	16.09	34.13	27.35	27.30
Stage Start TP05	20 min haul in of nets	19:11:24	19:31:24	00:20:00	1400.00	0.00	84.58	0.00	0.317	0.003	0.317	62.14	72.25	25.15	234.32	233.87
Stage Start TP06	20 min tickover: net handling & unloa	19:31:24	19:51:24	00:20:00	1049.84	2.03	2.10	0.04	6.056	0.126	6.068	63.45	73.77	1.32	238.45	238.00
Stage Start TP07	5 min gentle cruise while shooting	19:51:24	19:56:24	00:05:00	1500.00	0.00	39.79	0.00	0.521	0.003	0.522	63.91	74.32	15.28	238.53	238.07
Stage Start TP08	4 hour trawl	19:56:24	23:56:24	04:00:00	1750.00	0.00	282.35	0.05	0.232	0.001	0.233	64.18	74.63	34.30	239.05	238.59
Stage Start TP09	20 min haul in of nets	23:56:24	00:16:24	00:20:00	1400.00	0.00	84.60	0.00	0.315	0.003	0.316	112.25	130.52	25.29	446.02	445.17
Stage Start TP10	20 min tickover: net handling & unloa	00:16:24	00:36:24	00:20:00	1047.89	3.94	2.15	0.05	5.906	0.042	5.918	113.55	132.03	1.35	450.15	449.29
Stage Start TP11	5 min gentle cruise while shooting	00:36:24	00:41:24	00:05:00	1500.25	0.50	39.80	0.00	0.517	0.003	0.518	114.01	132.57	15.41	450.23	449.37
Stage Start TP12	4 hour trawl	00:41:24	04:41:24	04:00:00	1750.00	0.00	282.43	0.03	0.232	0.001	0.232	114.28	132.89	34.36	450.75	449.89
Stage Start TP13	20 min haul in of nets	04:41:24	05:01:24	00:20:00	1400.00	0.00	84.59	0.01	0.315	0.003	0.316	162.27	188.69	25.27	657.78	656.46
Stage Start TP14	2.5 hr steaming to trawl site	05:01:24	07:31:24	02:30:00	1999.93	0.40	48.68	0.01	0.481	0.002	0.482	163.58	190.21	16.56	661.92	660.59
Stage Start TP15	15 minute gentle cruise to port	07:31:24	07:46:24	00:15:00	1299.93	0.27	38.25	0.00	0.507	0.005	0.508	175.84	204.46	15.71	687.41	686.03
Stage Start TP16	Tick over for 1 hour	07:46:24	08:46:24	01:00:00	1038.93	1.12	2.32	0.05	5.680	0.155	5.686	176.50	205.23	1.40	688.71	687.33
Stage End TP16	End of test	08:46:24										177.93	206.89		688.96	687.59

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.57	15.78	
Fuel consumed over first trawl stages	50.34	58.53	
Fuel consumed over second trawl stages	50.10	58.26	
Fuel consumed over third trawl stages	49.56	57.63	
Fuel consumed over steam in stages	14.35	16.69	
Fuel consumed over whole test cycle	177.93	206.89	0.2980
Fuel consumed over census stages (TP12 - TP15)	**62.21**	**72.34**	**0.3040**

Table 13: DayTrawl_110 test cycle results

Day trawl test cycle results

Description		Warm-up duration	00:10:27	Specific gravity 0.86 kg/litre
	M&W Batch 2 BS590 diesel + Additive G	Test duration	20:40:00	Calorific value 45.20 MJ/kg
		Test date (start)	21/11/2007	

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	13:59:21	14:14:21	00:15:00	1081.14	4.38	1.75	0.10	7.410	0.376	7.429	0.00	0.00	1.08	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	14:14:21	14:29:21	00:15:00	1300.21	0.43	38.28	0.00	0.512	0.003	0.513	0.29	0.34	15.55	0.05	0.05
Stage Start TP02	2.5 hr steaming to trawl site	14:29:21	16:59:21	02:30:00	1999.91	0.50	48.66	0.01	0.481	0.002	0.482	0.96	1.12	16.54	1.35	1.35
Stage Start TP03	5 min gentle cruise while shooting	16:59:21	17:04:21	00:05:00	1500.00	0.00	39.76	0.00	0.502	0.000	0.502	13.23	15.38	15.88	26.83	26.79
Stage Start TP04	4 hour trawl	17:04:21	21:04:21	04:00:00	1750.00	0.00	282.24	0.05	0.233	0.000	0.234	13.49	15.68	34.15	27.35	27.31
Stage Start TP05	20 min haul in of nets	21:04:21	21:24:21	00:20:00	1399.95	0.23	84.54	0.01	0.316	0.003	0.316	61.74	71.79	25.24	234.24	233.89
Stage Start TP06	20 min tickover: net handling & unloa	21:24:21	21:44:21	00:20:00	1069.05	3.91	2.37	0.00	5.397	0.079	5.403	63.04	73.30	1.48	238.37	238.01
Stage Start TP07	5 min gentle cruise while shooting	21:44:21	21:49:21	00:05:00	1500.00	0.00	39.75	0.00	0.516	0.003	0.517	63.52	73.86	15.44	238.46	238.10
Stage Start TP08	4 hour trawl	21:49:21	01:49:21	04:00:00	1750.00	0.00	282.18	0.02	0.233	0.001	0.233	63.79	74.17	34.21	238.98	238.62
Stage Start TP09	20 min haul in of nets	01:49:21	02:09:21	00:20:00	1400.00	0.00	84.52	0.01	0.315	0.003	0.315	111.94	130.17	25.30	445.83	445.20
Stage Start TP10	20 min tickover: net handling & unloa	02:09:21	02:29:21	00:20:00	1067.21	2.59	2.37	0.00	5.392	0.079	5.398	113.24	131.68	1.48	449.96	449.33
Stage Start TP11	5 min gentle cruise while shooting	02:29:21	02:34:21	00:05:00	1500.25	0.50	39.74	0.00	0.513	0.000	0.514	113.72	132.23	15.52	450.05	449.42
Stage Start TP12	4 hour trawl	02:34:21	06:34:21	04:00:00	1750.00	0.00	282.04	0.04	0.233	0.001	0.233	113.98	132.54	34.25	450.57	449.94
Stage Start TP13	20 min haul in of nets	06:34:21	06:54:21	00:20:00	1400.00	0.00	84.45	0.00	0.315	0.003	0.315	162.06	188.45	25.31	657.31	656.52
Stage Start TP14	2.5 hr steaming to trawl site	06:54:21	09:24:21	02:30:00	1999.98	0.36	48.59	0.01	0.480	0.002	0.480	163.36	189.96	16.61	661.44	660.64
Stage Start TP15	15 minute gentle cruise to port	09:24:21	09:39:21	00:15:00	1300.00	0.00	38.18	0.00	0.502	0.005	0.502	175.56	204.14	15.86	686.88	686.08
Stage Start TP16	Tick over for 1 hour	09:39:21	10:39:21	01:00:00	1056.10	1.30	2.48	0.04	5.306	0.130	5.305	176.22	204.90	1.50	688.18	687.38
Stage End TP16	End of test	10:39:21										177.67	206.59		688.45	687.66

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.23	15.38	
Fuel consumed over first trawl stages	50.29	58.48	
Fuel consumed over second trawl stages	50.20	58.37	
Fuel consumed over third trawl stages	49.64	57.73	
Fuel consumed over steam in stages	14.31	16.64	
Fuel consumed over whole test cycle	177.67	206.59	0.2977
Fuel consumed over census stages (TP12 - TP15)	**62.23**	**72.36**	**0.3045**

Table 14: DayTrawl_111 test cycle results

Day trawl test cycle results

Description			
Red diesel only (M & W - Batch 2)	Warm-up duration	00:10:50	Specific gravity 0.86 kg/litre
	Test duration	20:40:00	Calorific value 45.20 MJ/kg
	Test date (start)	23/11/2007	

Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consume (Start of stage) Mass	Cum. fuel consume (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	10:13:01	10:28:01	00:15:00	1068.64	7.27	1.31	0.10	10.325	0.762	10.252	0.00	0.00	0.78	0.01	0.01
Stage Start TP01	15 minute gentle cruise from port	10:28:01	10:43:01	00:15:00	1299.79	0.58	37.90	0.00	0.532	0.003	0.528	0.38	0.44	14.96	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	10:43:01	13:13:01	02:30:00	1999.99	0.36	48.20	0.00	0.495	0.003	0.491	1.06	1.24	16.09	1.33	1.34
Stage Start TP03	5 min gentle cruise while shooting	13:13:01	13:18:01	00:05:00	1500.25	0.50	39.39	0.00	0.515	0.003	0.511	13.56	15.77	15.47	26.57	26.78
Stage Start TP04	4 hour trawl	13:18:01	17:18:01	04:00:00	1750.00	0.00	279.57	0.18	0.232	0.001	0.231	13.82	16.08	34.27	27.09	27.30
Stage Start TP05	20 min haul in of nets	17:18:01	17:38:01	00:20:00	1400.05	0.23	83.61	0.00	0.320	0.003	0.317	61.45	71.46	24.89	232.02	233.89
Stage Start TP06	20 min tickover: net handling & unloa	17:38:01	17:58:01	00:20:00	1050.47	2.72	2.60	0.05	4.988	0.050	4.941	62.76	72.98	1.60	236.11	238.01
Stage Start TP07	5 min gentle cruise while shooting	17:58:01	18:03:01	00:05:00	1500.00	0.00	39.31	0.00	0.528	0.003	0.523	63.23	73.53	15.10	236.20	238.11
Stage Start TP08	4 hour trawl	18:03:01	22:03:01	04:00:00	1750.00	0.00	279.00	0.04	0.232	0.001	0.230	63.51	73.84	34.30	236.72	238.63
Stage Start TP09	20 min haul in of nets	22:03:01	22:23:01	00:20:00	1400.05	0.23	83.55	0.00	0.320	0.003	0.317	111.00	129.07	24.88	441.23	445.22
Stage Start TP10	20 min tickover: net handling & unloa	22:23:01	22:43:01	00:20:00	1047.47	2.82	2.63	0.00	4.929	0.073	4.882	112.31	130.59	1.62	445.32	449.35
Stage Start TP11	5 min gentle cruise while shooting	22:43:01	22:48:01	00:05:00	1500.00	0.00	39.34	0.00	0.527	0.003	0.523	112.78	131.14	15.11	445.41	449.44
Stage Start TP12	4 hour trawl	22:48:01	02:48:01	04:00:00	1750.00	0.00	279.10	0.08	0.232	0.001	0.229	113.05	131.46	34.37	445.93	449.96
Stage Start TP13	20 min haul in of nets	02:48:01	03:08:01	00:20:00	1400.00	0.00	83.58	0.00	0.320	0.003	0.317	160.47	186.59	24.90	650.52	656.55
Stage Start TP14	2.5 hr steaming to trawl site	03:08:01	05:38:01	02:30:00	2000.01	0.31	48.09	0.00	0.489	0.001	0.484	161.77	188.11	16.28	654.61	660.68
Stage Start TP15	15 minute gentle cruise to port	05:38:01	05:53:01	00:15:00	1300.07	0.27	37.80	0.00	0.514	0.005	0.509	174.10	202.44	15.51	679.79	686.11
Stage Start TP16	Tick over for 1 hour	05:53:01	06:53:01	01:00:00	1033.10	2.45	2.83	0.00	4.673	0.057	4.627	174.76	203.20	1.70	681.07	687.41
Stage End TP16	End of test	06:53:01										176.18	204.87		681.38	687.72

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	13.56	15.77	
Fuel consumed over first trawl stages	49.67	57.76	
Fuel consumed over second trawl stages	49.55	57.62	
Fuel consumed over third trawl stages	48.99	56.97	
Fuel consumed over steam in stages	14.41	16.75	
Fuel consumed over whole test cycle	176.18	204.87	0.2984
Fuel consumed over census stages (TP12 - TP15)	**61.70**	**71.75**	**0.3051**

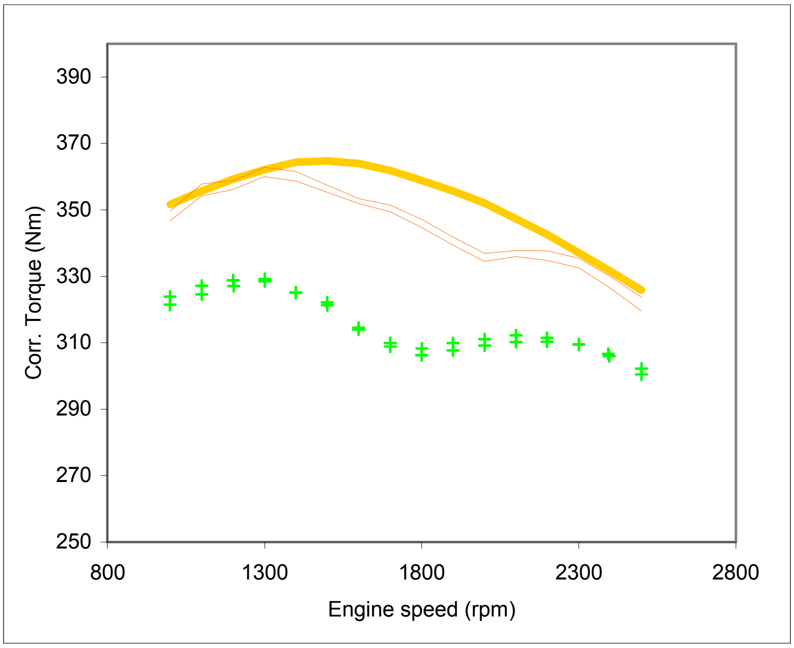
Bio-diesel testing

BS14214 bio-diesel – Baseline Tests

The data for Baseline 003_120_ME lies close to, but consistently higher then the data for Baseline 003_119_ME (both of which used BS14214 specification biodiesel). Thus it is possible prolonged use of this fuel improves the engine performance. However the main result is that Baseline test results for these tests are tightly clustered and consistent with each other. This indicates that no malfunction or significant deterioration of engine performance occurred during the intervening DayTrawl test fuelled with methyl ester.

Figure 31 also indicates that the torque delivered by the engine is substantially lower than that delivered when the engine is fuelled with petroldiesel.

Ramping Down



Ramping Up

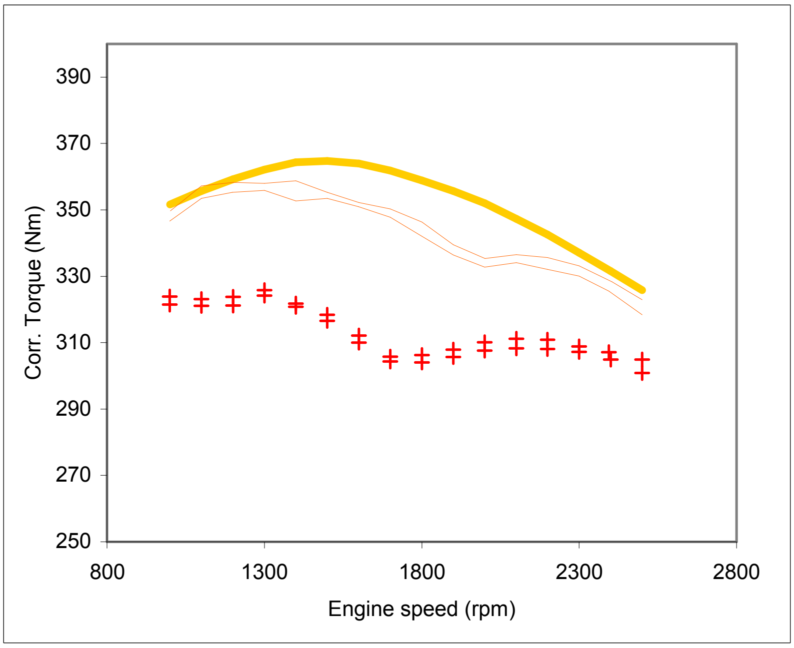


Figure 31 : Baseline 003_119_ME and Baseline 003_120_ME test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

BS14214 bio-diesel – day trawl test

Table 15: DayTrawl_112 test cycle results

Day trawl test cycle results

Description		Warm-up duration	00:03:06
BS 14214 Standard Methyl Ester		Test duration	20:40:00
		Test date (start)	26/11/2007
Specific gravity	0.879 kg/litre	Calorific value	39.27 MJ/kg

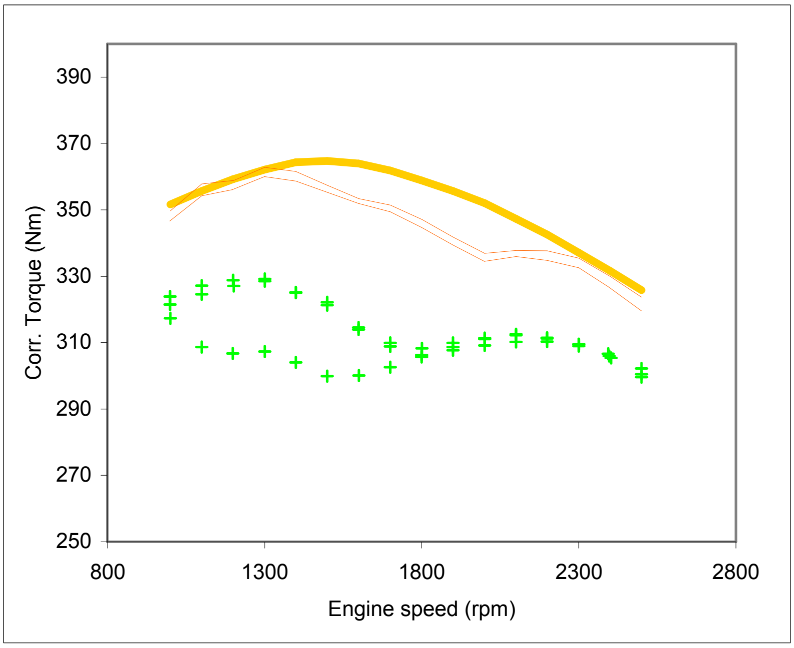
Stage	Description	Start time	End time	Duration	Engine Speed Ave.	Engine Speed Stdev.	Torque Ave. Corr.	Torque Stdev. Corr.	Specific Fuel Consumption Ave. Corr.	Specific Fuel Consumption Stdev. Corr.	Specific Fuel Consumption Ave. Uncorr.	Cum. fuel consumed (Start of stage) Mass	Cum. fuel consumed (Start of stage) Volume	Engine Eff.	Cum. Work Done (Start of stage) Corr.	Cum. Work Done (Start of stage) Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	14:28:50	14:43:50	00:15:00	1087.71	2.64	2.57	0.05	5.829	0.194	5.789	0.00	0.00	1.57	0.00	0.00
Stage Start TP01	15 minute gentle cruise from port	14:43:50	14:58:50	00:15:00	1300.07	0.27	37.90	0.00	0.593	0.000	0.589	0.34	0.39	15.46	0.07	0.07
Stage Start TP02	2.5 hr steaming to trawl site	14:58:50	17:28:50	02:30:00	2000.00	0.28	48.21	0.00	0.552	0.002	0.548	1.11	1.26	16.60	1.36	1.37
Stage Start TP03	5 min gentle cruise while shooting	17:28:50	17:33:50	00:05:00	1500.00	0.00	39.39	0.00	0.579	0.003	0.575	15.05	17.12	15.83	26.60	26.80
Stage Start TP04	4 hour trawl	17:33:50	21:33:50	04:00:00	1750.00	0.00	278.37	0.09	0.275	0.001	0.272	15.35	17.46	33.30	27.12	27.32
Stage Start TP05	20 min haul in of nets	21:33:50	21:53:50	00:20:00	1400.00	0.00	83.83	0.00	0.365	0.003	0.363	71.52	81.37	25.10	231.18	233.92
Stage Start TP06	20 min tickover: net handling & unloa	21:53:50	22:13:50	00:20:00	1072.58	1.61	2.80	0.04	5.337	0.097	5.301	73.02	83.07	1.72	235.27	238.05
Stage Start TP07	5 min gentle cruise while shooting	22:13:50	22:18:50	00:05:00	1500.00	0.00	39.41	0.00	0.596	0.003	0.592	73.57	83.70	15.38	235.38	238.15
Stage Start TP08	4 hour trawl	22:18:50	02:18:50	04:00:00	1750.00	0.00	278.68	0.09	0.274	0.000	0.271	73.88	84.05	33.42	235.89	238.67
Stage Start TP09	20 min haul in of nets	02:18:50	02:38:50	00:20:00	1400.00	0.00	83.88	0.00	0.366	0.003	0.364	129.92	147.80	25.04	440.18	445.27
Stage Start TP10	20 min tickover: net handling & unloa	02:38:50	02:58:50	00:20:00	1076.63	3.06	2.65	0.05	5.567	0.185	5.533	131.42	149.51	1.65	444.28	449.40
Stage Start TP11	5 min gentle cruise while shooting	02:58:50	03:03:50	00:05:00	1500.25	0.50	39.44	0.00	0.593	0.000	0.589	131.97	150.14	15.47	444.38	449.50
Stage Start TP12	4 hour trawl	03:03:50	07:03:50	04:00:00	1750.00	0.00	278.98	0.07	0.274	0.001	0.271	132.28	150.49	33.45	444.89	450.02
Stage Start TP13	20 min haul in of nets	07:03:50	07:23:50	00:20:00	1400.00	0.00	83.90	0.00	0.365	0.003	0.363	188.33	214.25	25.10	649.39	656.62
Stage Start TP14	2.5 hr steaming to trawl site	07:23:50	09:53:50	02:30:00	1999.99	0.23	48.26	0.01	0.545	0.001	0.542	189.83	215.96	16.82	653.49	660.74
Stage Start TP15	15 minute gentle cruise to port	09:53:50	10:08:50	00:15:00	1300.14	0.36	37.93	0.00	0.577	0.004	0.573	203.60	231.62	15.90	678.76	686.17
Stage Start TP16	Tick over for 1 hour	10:08:50	11:08:50	01:00:00	1068.59	1.00	2.83	0.03	5.311	0.078	5.279	204.34	232.47	1.73	680.05	687.47
Stage End TP16	End of test	11:08:50										206.02	234.38		680.37	687.79

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	15.05	17.12	
Fuel consumed over first trawl stages	58.52	66.58	
Fuel consumed over second trawl stages	58.40	66.44	
Fuel consumed over third trawl stages	57.85	65.82	
Fuel consumed over steam in stages	16.20	18.43	
Fuel consumed over whole test cycle	206.02	234.38	0.3418
Fuel consumed over census stages (TP12 - TP15)	**72.06**	**81.98**	**0.3486**

Batch plant bio-diesel – Baseline Test

It was not possible to conduct a Baseline performance test after DayTrawl testing with methyl ester manufactured from recovered vegetable oil, and processed using the project batch reactor. This was because the engine suffered its second critical failure following the DayTrawl test with the manufactured fuel.

Ramping Down



Ramping Up

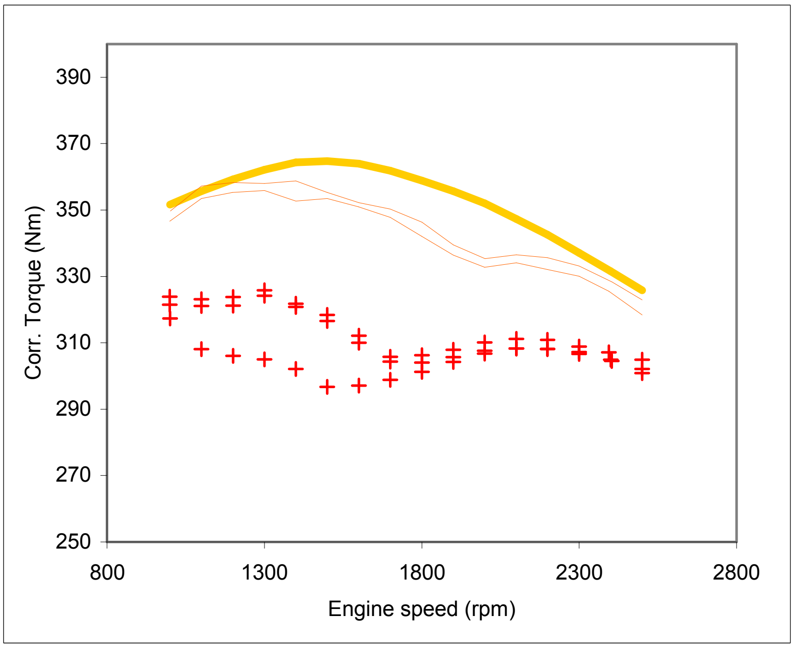


Figure 32 : Baseline 003_119_ME, Baseline 003_120_ME and Baseline 003_121_WO test performance with engine performance envelope defined by Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118.

Figure 32 shows the Baseline results for BS14214 methyl esters and waste oil methyl esters. There is a clear reduction in delivered torque for the waste oil methyl esters in the range 1100 rpm to 1700 rpm. It is postulated that this could be a result of poor spray pattern through the engine injectors at low engine speeds. At higher engine speeds, more of the more viscous fuel is pumped through the injectors and the spray pattern may improve, such that the performance curve for the waste oil methyl ester merges with the performance curve for the more refined BS14214 methyl ester.

Batch plant bio-diesel – day trawl test

Table 16: DayTrawl_113 test cycle results

Day trawl test cycle results

Description			
Waste Oil Methyl Ester from batch reactor	Warm-up duration 00:11:12		Specific gravity 0.899 kg/litre
	Test duration 20:39:59		Calorific value 38.00 MJ/kg
	Test date (start) 04/12/2007		

Stage	Description	Start time	End time	Duration	Engine Speed		Torque		Specific Fuel Consumption			Cum. fuel consumed (Start of stage)		Engine Eff.	Cum. Work Done (Start of stage)	
					Ave.	Stdev.	Ave. Corr.	Stdev. Corr.	Ave. Corr.	Stdev. Corr.	Ave. Uncorr.	Mass	Volume		Corr.	Uncorr.
		hh:mm:ss	hh:mm:ss	hh:mm:ss	(RPM)	(RPM)	(Nm)	(Nm)	(kg/kWh)	(kg/kWh)	(kg/kWh)	(kg)	(litres)	(%)	(kWh)	(kWh)
Stage Start TP00	15 minute tick over under zero load	16:48:52	17:03:52	00:15:00	1050.07	1.94	1.24	0.08	15.001	0.886	14.971	0.00	0.00	0.63	0.01	0.01
Stage Start TP01	15 minute gentle cruise from port	17:03:52	17:18:52	00:15:00	1299.93	0.47	38.08	0.00	0.655	0.003	0.654	0.51	0.57	14.46	0.04	0.04
Stage Start TP02	2.5 hr steaming to trawl site	17:18:52	19:48:52	02:30:00	2000.00	0.31	48.46	0.01	0.576	0.003	0.575	1.36	1.51	16.44	1.34	1.34
Stage Start TP03	5 min gentle cruise while shooting	19:48:52	19:53:52	00:05:00	1500.00	0.00	39.61	0.00	0.613	0.000	0.612	15.99	17.78	15.45	26.71	26.76
Stage Start TP04	4 hour trawl	19:53:52	23:53:52	04:00:00	1750.00	0.00	281.44	0.27	0.292	0.001	0.291	16.30	18.14	32.45	27.23	27.28
Stage Start TP05	20 min haul in of nets	23:53:52	00:13:52	00:20:00	1400.00	0.00	84.40	0.00	0.385	0.002	0.385	76.53	85.12	24.63	233.53	233.89
Stage Start TP06	20 min tickover: net handling & unloa	00:13:52	00:33:52	00:20:00	1054.47	1.02	1.97	0.07	8.859	0.301	8.860	78.11	86.89	1.07	237.66	238.02
Stage Start TP07	5 min gentle cruise while shooting	00:33:52	00:38:52	00:05:00	1500.00	0.00	39.68	0.00	0.627	0.003	0.627	78.75	87.60	15.12	237.73	238.09
Stage Start TP08	4 hour trawl	00:38:52	04:38:51	03:59:59	1750.00	0.00	282.44	0.25	0.291	0.003	0.292	79.08	87.96	32.55	238.25	238.61
Stage Start TP09	20 min haul in of nets	04:38:51	04:58:51	00:20:00	1400.00	0.00	84.53	0.00	0.391	0.003	0.392	139.34	155.00	24.21	445.27	445.20
Stage Start TP10	20 min tickover: net handling & unloa	04:58:51	05:18:51	00:20:00	1045.95	1.75	2.22	0.05	8.082	0.160	8.095	140.96	156.80	1.17	449.40	449.33
Stage Start TP11	5 min gentle cruise while shooting	05:18:51	05:23:51	00:05:00	1500.25	0.50	39.74	0.00	0.634	0.000	0.635	141.62	157.53	14.94	449.49	449.41
Stage Start TP12	4 hour trawl	05:23:51	09:23:51	04:00:00	1750.00	0.06	282.84	0.18	0.297	0.005	0.298	141.95	157.89	31.95	450.01	449.93
Stage Start TP13	20 min haul in of nets	09:23:51	09:43:51	00:20:00	1400.00	0.00	84.49	0.01	0.393	0.003	0.394	203.44	226.30	24.09	657.34	656.54
Stage Start TP14	2.5 hr steaming to trawl site	09:43:51	12:13:51	02:30:00	2000.00	0.33	48.57	0.01	0.568	0.002	0.568	205.07	228.11	16.67	661.46	660.66
Stage Start TP15	15 minute gentle cruise to port	12:13:51	12:28:51	00:15:00	1300.14	0.36	38.16	0.00	0.627	0.005	0.627	219.52	244.18	15.12	686.90	686.09
Stage Start TP16	Tick over for 1 hour	12:28:51	13:28:51	01:00:00	1053.00	0.99	2.63	0.03	6.480	0.083	6.477	220.33	245.09	1.46	688.20	687.39
Stage End TP16	End of test	13:28:51										222.21	247.18		688.49	687.68

	Mass (kg)	Volume (litres)	litres/kWh
Fuel consumed over steam out stages	15.99	17.78	
Fuel consumed over first trawl stages	62.77	69.82	
Fuel consumed over second trawl stages	62.86	69.93	
Fuel consumed over third trawl stages	63.45	70.58	
Fuel consumed over steam in stages	17.15	19.07	
Fuel consumed over whole test cycle	222.21	247.18	0.3561
Fuel consumed over census stages (TP12 - TP15)	**78.39**	**87.19**	**0.3661**

Discussion of results

Fuel Additives Testing

Table 17 : Summary of relative performance between fuel additives on DayTrawl cycle tests

Test Number	Cum Uncorr. Work (kWh)	Cum Correct Work (kWh)	Cenus fuel consumption (litres/kWh)	% different from BS590 average	Whole test fuel consumption (litres/kWh)	% different from BS590 average	Whole test fuel consumption (kg/kWh)	Whole test fuel consumption (kWh/kWh)	Whole test Efficiency (kWh / kWh)	Fuel
102	687.46	685.08	0.3045	-0.14	0.3006	-0.08	0.2598	3.1735	0.315	Batch 1 BS590 diesel only + Additive A
104	687.58	683.00	0.3043	-0.21	0.3001	-0.27	0.2593	3.1675	0.316	Batch 1 BS590 diesel only + Additive B
105	687.58	681.76	0.3042	-0.23	0.3004	-0.18	0.2595	3.1705	0.315	Batch 1 BS590 diesel only + Additive C
106	687.61	682.33	0.3046	-0.08	0.3002	-0.23	0.2594	3.1690	0.316	Batch 1 BS590 diesel only + Additive D
108	687.63	683.49	0.3050	0.04	0.3004	-0.15	0.2584	3.1941	0.313	Batch 2 BS590 diesel only + Additive E
109	687.59	688.96	0.3040	-0.29	0.3003	-0.20	0.2583	3.1926	0.313	Batch 2 BS590 diesel only + Additive F
110	687.66	688.45	0.3045	-0.12	0.3001	-0.27	0.2581	3.1903	0.313	Batch 2 BS590 diesel only + Additive G
Stdev	0.065	2.916	0.00033		0.00020		0.00068	0.01207		
101	687.38	683.13	0.3058	0.29	0.3021	0.42	0.2611	3.1894	0.314	Batch 1 BS590 diesel only
103	687.50	683.07	0.3042	-0.23	0.3003	-0.21	0.2594	3.1695	0.316	Batch 1 BS590 diesel only
107	687.61	684.84	0.3045	-0.13	0.3005	-0.13	0.2584	3.1949	0.313	Batch 2 BS590 diesel only
111	687.72	681.38	0.3051	0.07	0.3007	-0.08	0.2586	3.1965	0.313	Batch 2 BS590 diesel only
Stdev	0.145	1.412	0.00070		0.00085		0.00120	0.01245		
112	687.79	680.37	0.3486	14.34	0.3445	14.49	0.3028	3.2592	0.307	BS 14214 Standard Methyl Ester
113	687.68	688.49	0.3661	20.06	0.3590	19.32	0.3228	3.3243	0.301	Waste Oil Methyl Ester

N.B. (kWh/kWh) refers to kWh of fuel consumed per kWh of corrected work delivered.

The column in Table 17 labelled “Cum Uncorr. Work” gives the total useful work delivered by the test engine over the 20 hour 40 minute DayTrawl test cycle. The control system of the test cell controls engine torque using the non-atmospheric conditions corrected (uncorrected) torque. This means that during every DayTrawl cycle, the same total uncorrected work should be delivered by the engine during the test; the control system ensures that the same programme of torque and engine speed is delivered each time, other variables including fuel consumption and the various engine temperatures adjust to match. Thus the extent of agreement of cumulative uncorrected work from each test is no surprise; the values should all be the same. What variance there is in this quantity arises from minor instrumentation error and it also has its source in the ‘tick over’ phases of the test cycle, when the torque is not controlled, but the throttle rack position is set to minimum. The engine can tick over at slightly different engine speeds from test to test and from tick over set point to tick over set point in a single test cycle (see Tables 4 to 16 for confirmation).

Over all the DayTrawl tests, the standard deviation in cumulative uncorrected work is 0.1087 kWh. Test 101 lies more than 2 standard deviations away from the mean value of all tests, and thus could be considered an outlier. Including 101, the test cycle can be considered to be repeatable to better than 1 in 6300 which is considered good. Excluding 101, the experiment could be considered repeatable to better than 1 in 7480.

The “Cum. Corr. Work” column of Table 17 indicates the work delivered by the test engine over the duty cycle, referred to standard conditions of temperature, pressure and relative humidity. A higher value is generally better, but it is not until the quantity of fuel used is simultaneously taken into consideration, that a proper measure of the relative performance of a fuel or a fuel with additive in the test cell engine is produced. In tables 4 to 17, fuel economy is expressed as litres of fuel consumed per kWh of work delivered. This measure was chosen over a mass based or energy based fuel consumption measure as fishermen pay for their fuel in volume terms. However, for reference, Table 17 gives also provides the corresponding measures in mass and energy terms.

The results of the DayTrawl tests indicate that none of the diesel additives have reduced the fuel consumption over the test cycle by more than 0.29% over the census stages of the cycle or by more than 0.27% over the complete cycle.

The results indicate that there is no significant effect of any of the additives tested on the fuel consumption of the engine through the DayTrawl test cycle.

It would cost the fishermen more to run their vessels on BS590 diesel with additives because as well as paying for the base fuel, they would also have to pay for the additive.

Table 17 also shows the results for the BS14214 methyl ester and results for the Waste Oil methyl ester produced by the batch production plant. The fuel consumption measure for these two fuels is higher than those for the BS590 only or BS590 + Additive cases – as is expected. Part of this disparity is due to the fact that the calorific values of the two biofuels are different from the calorific values of the fossil diesel (11.2% and 12.1% lower on a volume basis, respectively). It is valuable to note that the DayTrawl test cycle has been effective in identifying the differences between fossil diesel and the biofuels, although it is clear that the relative magnitudes of the calorific values of the latter cannot completely explain the disparity in the fuel consumption measures. However at the very least, this result provides increased confidence that there is indeed no difference between fossil diesel only and fossil diesel with additives, as the test cycle has been effective in its discriminating power when it is definitely known that there should be a difference.

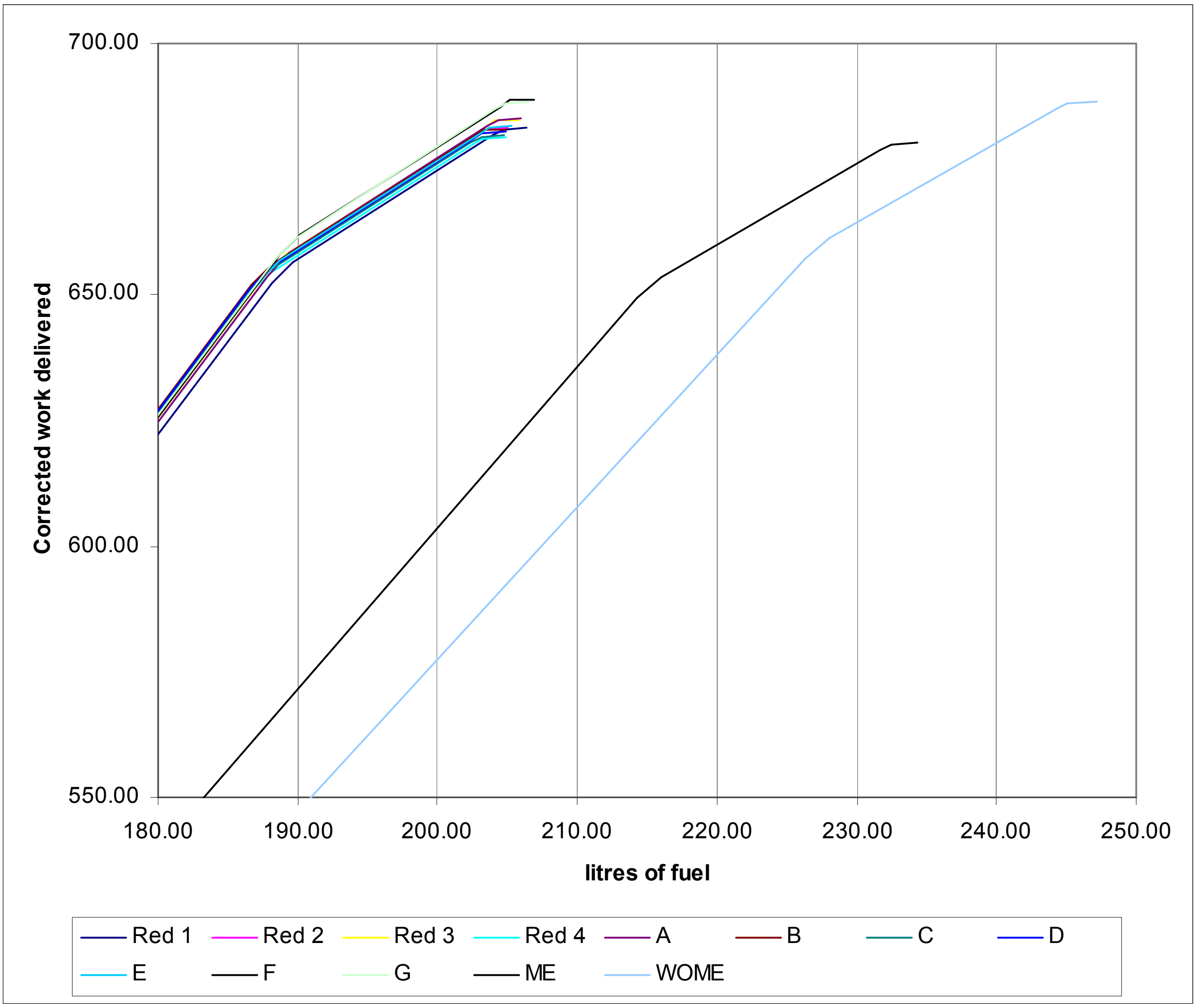


Figure 33: Comparison between fuel / fuel + additive performance over the DayTrawl test cycle.

Fuel consumption and engine efficiency using fossil diesel compared with biodiesels

The key results relating to the testing of BS14214 standard biodiesel and biodiesel manufactured from recovered vegetable oil (RVO) have already been outlined in the previous section. As expected, the use of both of these biofuels in the engine leads to an increase of fuel consumption, expressed in terms of litres/kWh of corrected work done. Fuel consumption was found to be 14.5% higher for the BS14214 methyl ester and 19.3% higher for the biodiesel produced from RVO. If the price of fossil diesel and the price of either of these biodiesels, expressed in (£/litre) were the same, then clearly there would not be any economic advantage for fishermen to switch. Irrespective of the cost of production, in the case of the automotive sector, it seems that commercial biodiesel suppliers sell their product at a price that is the same as, or only slightly lower than, the prevailing price of fossil diesel (with which it competes as a substitute).

The calorific value (expressed in MJ/litre) of the BS14214 biodiesel used in the testing is 11% lower than that of the fossil diesel used. Thus when required (by the SCADA control system) to deliver a given output power, one would expect that the volume fuel consumption of biodiesel would be greater than that of the fossil diesel such that the same amount of fuel energy (expressed in kWh) was supplied.

In fact, the overall results of the experiments (Table 17) show that differences between the biodiesel energy fuel consumption and the fossil diesel energy fuel consumption (kWh of fuel consumed / kWh of corrected work done) cannot be explained by the difference in calorific value alone. Over a full DayTrawl test cycle on BS14214 the engine consumed ~2.2% more chemical energy in fuel than it did when it ran on fossil diesel. In the case of the biodiesel manufactured with waste oil, ~4.3% more chemical fuel energy was required to deliver the same amount of corrected output work. In the latter case, part of this increased variance from expectations can be explained by a progressive deterioration of engine condition (see later). For the BS14214 methyl ester case, the increased variance compared with expectations is attributed to engine set up conditions which are 'tuned' to fossil diesel fuel properties. The fuel properties of methyl ester are known to be slightly different than fossil diesel and these differences emerge most clearly when the fuel is subjected to a demanding trial, such as the DayTrawl test.

Table 18: Engine efficiency (kWh corrected work done / kWh fuel energy supplied) for three fuels tested in the test cell engine using the DayTrawl cycle.

Stage description	Engine Speed (rpm)	Corrected Torque (Nm)	Engine stage efficiency (kWh/kWh)		
			Fossil Diesel (%)	BS14214 Biodiesel (%)	Waste Oil Biodiesel (%)
15 minute tick over under zero load	1050	1.3	0.79	1.60	0.65
15 minute gentle cruise from port	1300	37.9	15.20	15.67	14.82
2.5 hr steaming to trawl site	2000	48.2	16.34	16.82	16.85
5 min gentle cruise while shooting	1500	39.4	15.71	16.05	15.83
4 hour trawl	1750	279.6	34.81	33.75	33.26
20 min haul in of nets	1400	83.6	25.28	25.44	25.24
20 min tickover: net handling & unload	1050	2.6	1.62	1.74	1.10
5 min gentle cruise while shooting	1500	39.3	15.33	15.59	15.49
4 hour trawl	1750	279.0	34.83	33.87	33.35
20 min haul in of nets	1400	83.6	25.27	25.38	24.81
20 min tickover: net handling & unload	1050	2.6	1.64	1.67	1.20
5 min gentle cruise while shooting	1500	39.3	15.34	15.68	15.31
4 hour trawl	1750	279.1	34.91	33.90	32.74
20 min haul in of nets	1400	83.6	25.29	25.44	24.69
2.5 hr steaming to trawl site	2000	48.1	16.53	17.05	17.09
15 minute gentle cruise to port	1300	37.8	15.75	16.11	15.49
Tick over for 1 hour	1053	2.8	1.73	1.75	1.50

Table 18 shows that this picture of inferiority of the biodiesels is not consistent across all the individual component stages of the DayTrawl duty cycle. It tabulates engine efficiency results (the reciprocal of the energy fuel consumption referred to in the previous section), quantified stage-by-stage, and indicates that a BS14214 methyl ester fuel allowed the engine to operate with higher efficiency than fossil diesel in all but the highest duty stages (the 4 hour long trawl stages). On less demanding duty, this biodiesel was better than fossil diesel. As the trawl stages dominate the overall cycle in terms of the energy consumed, the marginally higher efficiency of fossil diesel in these 3 stages of the cycle determines the overall fuel consumption with the result that fossil diesel is determined to be superior. Had the cycle been designed for more moderate overall duty, the finding above may have been reversed; the BS14214 methyl ester fuel may have returned superior energy fuel consumption figures over a light duty cycle.

For the three onerous trawl stages of the test cycle, the efficiency with each fuel increases as the test progresses, with the exception of the test conducted with the waste oil methyl ester. In the latter case, by the 3rd, 4 hour long trawl stage, the efficiency has dropped to 32.7% from 33.4%. As shall be seen, this is not unsurprising as detailed analysis revealed that a piston ring failure occurred mid way through the second trawl stage and became worse as the test progressed.

The Waste Oil methyl ester (hereafter known as WOME) fuel produces inferior engine efficiency in comparison to both BS14214 methyl ester and the fossil diesel fuel in all stages with two exceptions. For the stages simulating steaming to and from the trawl site, the waste oil methyl ester had the highest efficiency. It is interesting to note that for the simulated ‘return trip’ this result is obtained after it is known that the engine had suffered a fracture piston ring in one cylinder and piston rings that were seizing in their grooves in two other cylinders.

Performance of biodiesels under Baseline testing

The performance of the test engine under the Baseline test cycle was predominantly as expected when using BS14214 fuel. Specific fuel consumption (kg/kWh) increased, the torque delivered by the engine reduced and the exhaust gas temperatures were slightly reduced in comparison to Baseline tests run with fossil diesel (Figure 34). The peak torque delivered by the engine was 328 Nm @ 1300 rpm with BS14214 methyl ester, whereas it was 360Nm @ 1300 rpm with the last fossil diesel test undertaken before the biodiesel testing commenced. This is an 8.8% reduction in torque with the biofuel. At minimum torque, the drop in torque with the BS14214 methyl ester was lower at ~6.5%. These drops in torque were anticipated due to the reduction in the calorific value of the fuel. Baseline tests are conducted at maximum throttle throughout. At maximum throttle setting with biodiesel, the chemical fuel energy being fed to the engine is lower than that delivered when fossil diesel is used. Thus, exhaust gas temperatures are expected to be lower with BS14214 biodiesel than fossil diesel during Baseline tests. Also there are variations in the chemistry of the combustion products of the respective fuels. Methyl ester contains an appreciable proportion of oxygen while fossil diesel generally does not. As a result, with the former, more water vapour is present in the combustion products. Compared with other gaseous combustion products, water’s heat capacity is higher with the result that the temperature of the mixture of products will be lower.

The chemistry of the waste oil methyl ester from the batch production plant is not as tightly controlled as is the case with the BS14214 methyl ester. The presence of remnant vegetable oil, methanol and other impurities is thus possible for this fuel. These undesirables raise the exhaust gas temperature higher than for either fossil diesel or BS14214 methyl ester. However, this result should not be over-interpreted because, as will be discussed later, the engine was subject to progressive failure while the WOME was under test.

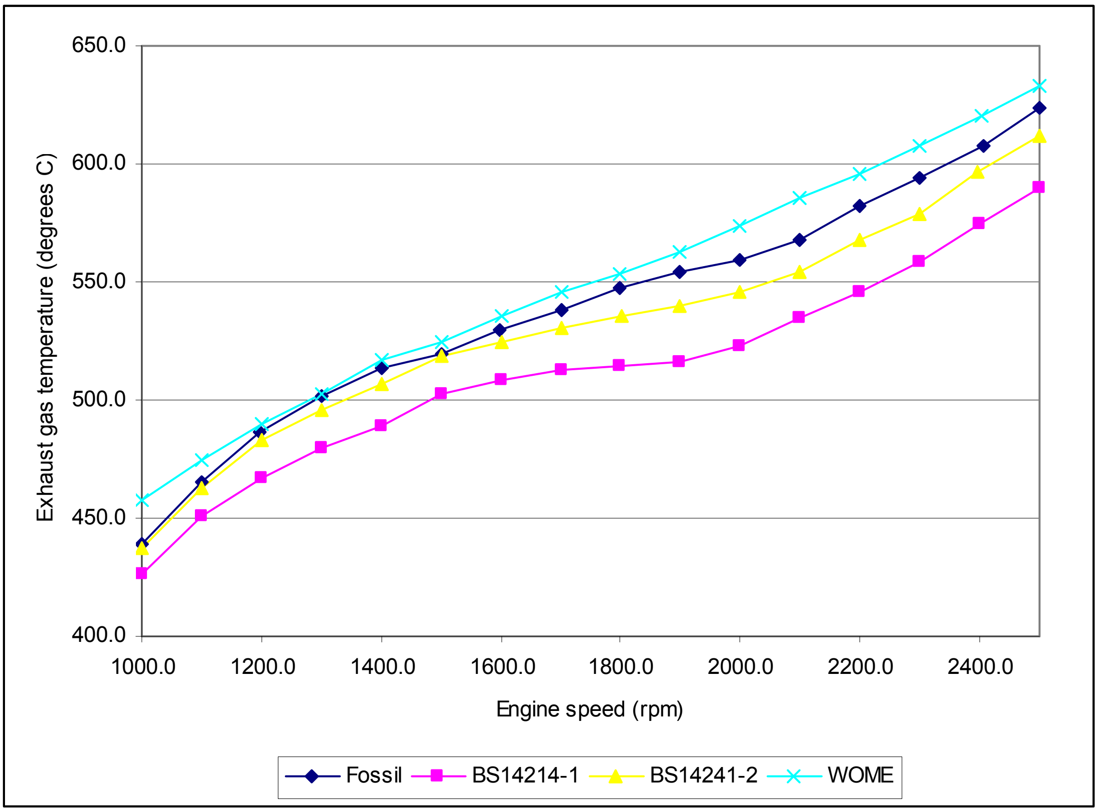


Figure 34: Exhaust gas temperature from the ramping up sections of Baseline tests 118 (Fossil diesel) 119 (BS14214 methyl ester), 120 (BS14214 methyl ester) and 121 (waste oil methyl ester).

Although the torque curves for the BS14214 methyl ester Baseline tests were depressed relative to those obtained for fossil diesel, their general form followed that established to be characteristic of the engine operating without malfunction on fossil diesel; both BS14124 methyl ester tests exhibited a pronounced 'dip' in their torque curves throughout the 1500 – 2000 rpm range. The extent of hysteresis in the torque curves between ramping down and ramping up halves of the Baseline test is greater (in both cases) in comparison to that observed with tests using fossil diesel.

Prior to running the DayTrawl test for the WOME, an 'opening' Baseline test was undertaken as a diagnostic that would be used for comparison with a subsequent Baseline test carried out after the DayTrawl test. The fuel was much more viscous than either the fossil diesel or BS14214 biodiesel tested previously. Although the engine was difficult to start with this fuel, it did start and the test proceeded. The expected increase in specific fuel consumption was realised in the test. However, the torque curves for this test (121) were distinctly different in form, in comparison to those of either the fossil diesel or the biodiesel fuels that preceded them. Peak torque of 317Nm was obtained at minimum revolutions of 1000 rpm, rather than at 1300 rpm with the other fuels. The spread of the 'dip' in torque increased across to lie between 1100 rpm to 1900 rpm. Despite this, the torque was maintained above 295 Nm across the whole engine operating range. There were no previous data with which to compare these torque curves as this was the first time this fuel had been used in the engine. A DayTrawl test followed.

In summary, Baseline testing with the BS14214 methyl ester fuels produced results largely as expected; those for the WOME produced pronounced differences in the torque delivered by the engine across its operating range.

Operations leading up to engine failure.

Figures 35 to 38 show a sequence of engine performance curves over 4 different DayTrawl tests. They are presented to allow a detailed appraisal of the condition of the engine leading up to the engine failure to be made.

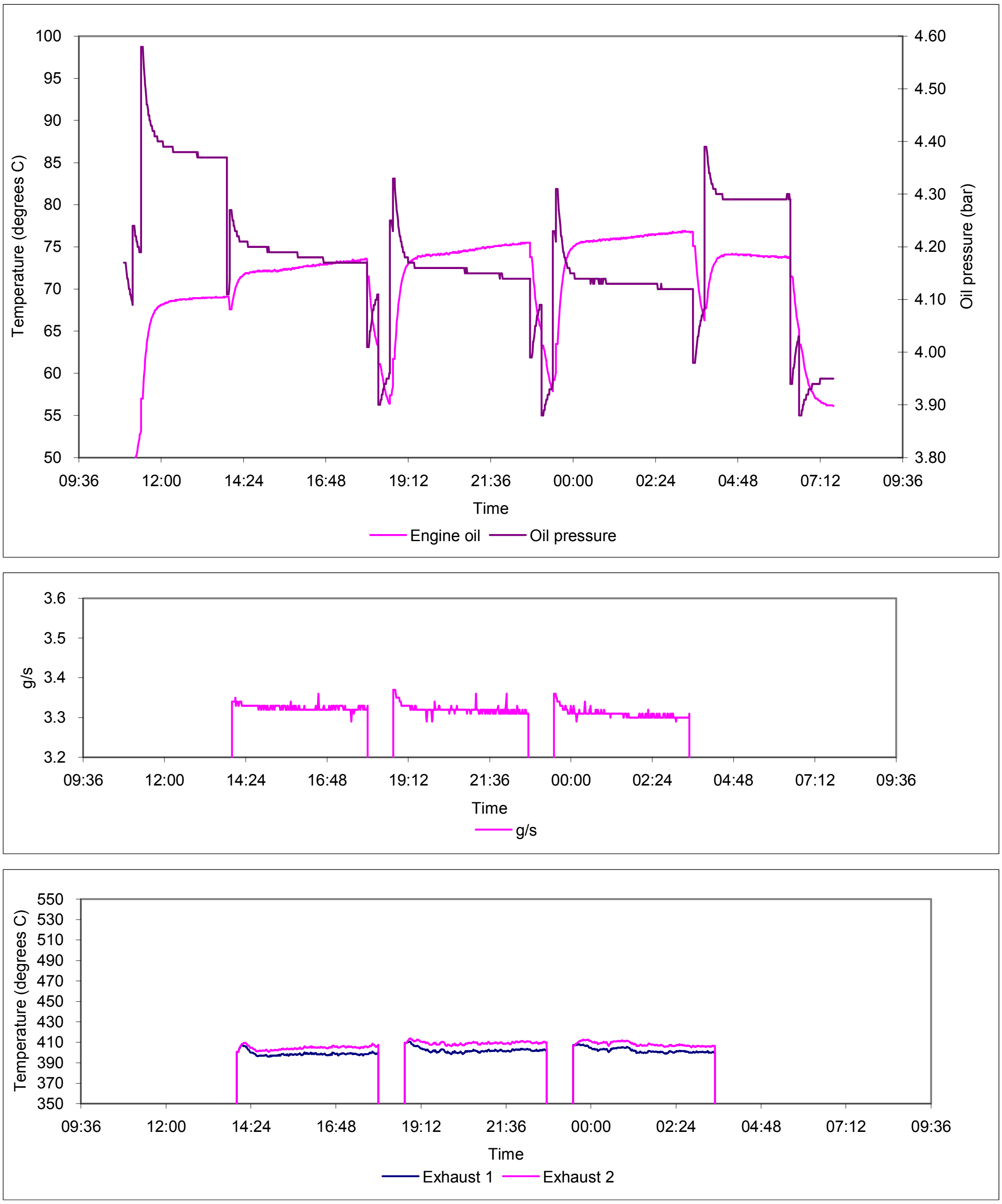


Figure 35: Oil temperature, oil pressure, fuel consumption and exhaust gas temperature for test 107 fuelled using fossil diesel with no additives.

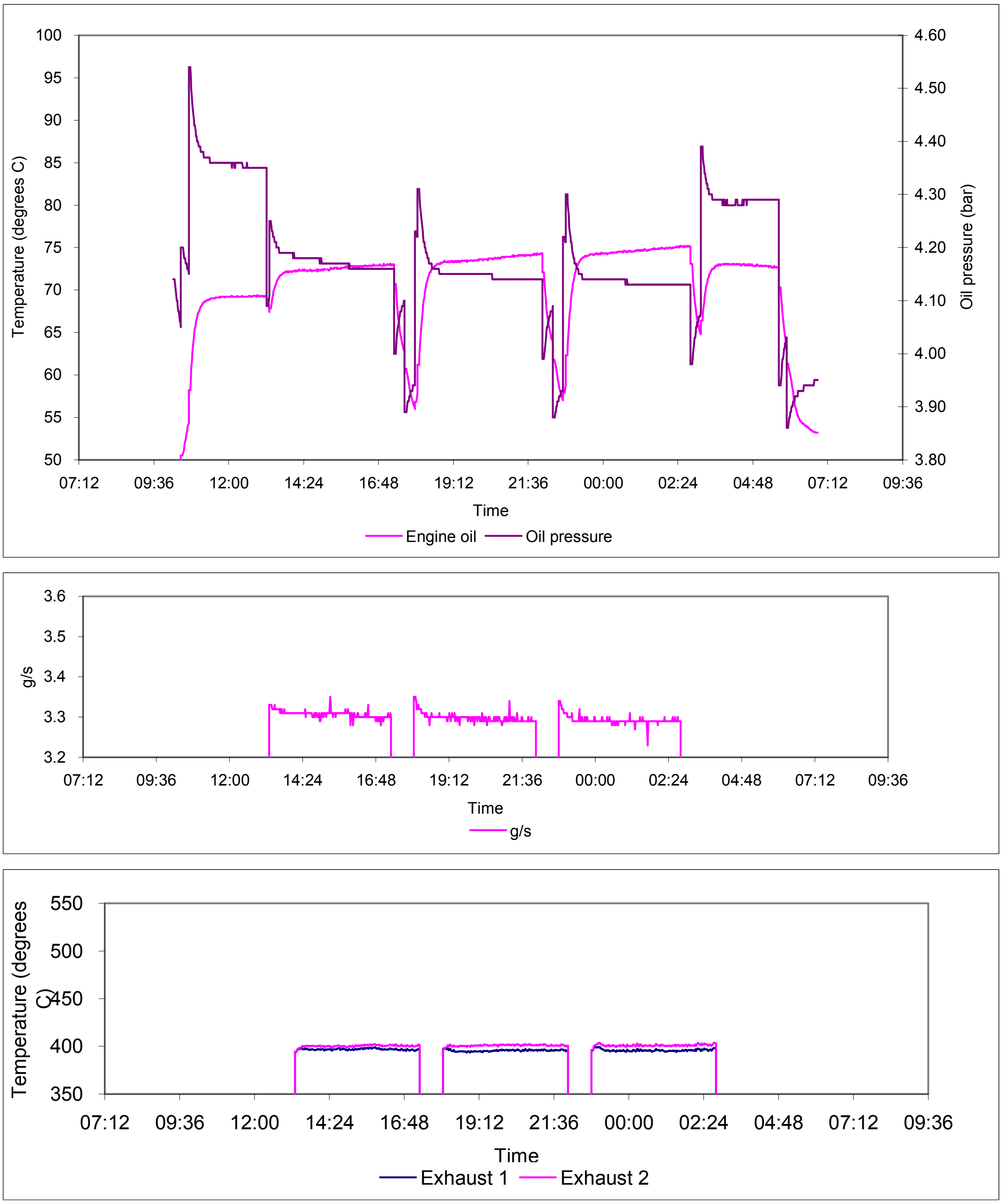


Figure 36: Oil temperature, oil pressure, fuel consumption and exhaust gas temperature for test 111 fuelled using fossil diesel with no additives. This was the last DayTrawl test conducted prior to testing biofuels.

Comparison of the charts in Figure 35 and 36 show that immediately prior to the start of biofuels test work the engine behaved as it did during the additives test work, where the DayTrawl cycle test results and the Baseline test results both confirmed that the engine was operating repeatably.

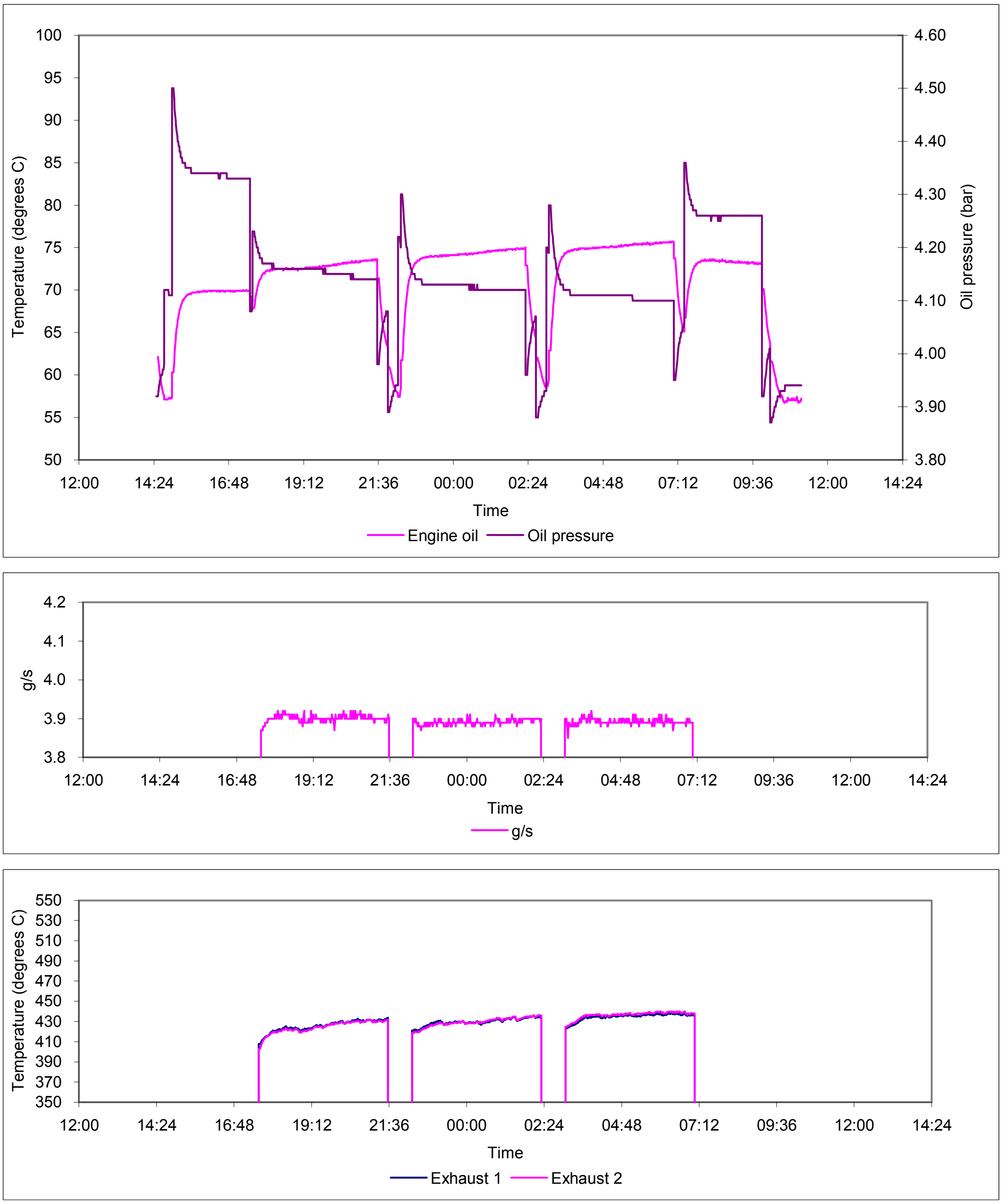


Figure 37: Oil temperature, oil pressure, fuel consumption and exhaust gas temperature for test 112 fuelled using BS14214 methyl ester.

Comparison of the charts in Figure 37 with either Figure 35 or Figure 36 shows that these DayTrawl cycle data from a test using BS14214 methyl ester are in good agreement with those obtained using fossil diesel. Engine oil pressure and temperature profiles match their fossil diesel counterparts. The main differences are firstly that the exhaust gas temperature seems to be in a transient condition for the first and second trawl stages of the test cycle, but it does stabilise under this high load condition during the last 2/3 of the last trawl stage. Secondly, fuel consumption data here indicate a transient upward to a stable operating condition for the first trawl stage whereas those for fossil diesel (Figures 35 or 36) show a transient downward to stable operating conditions.

The latter condition is assumed to correspond to the period during which the engine responds to a new thermal equilibrium with its surroundings.

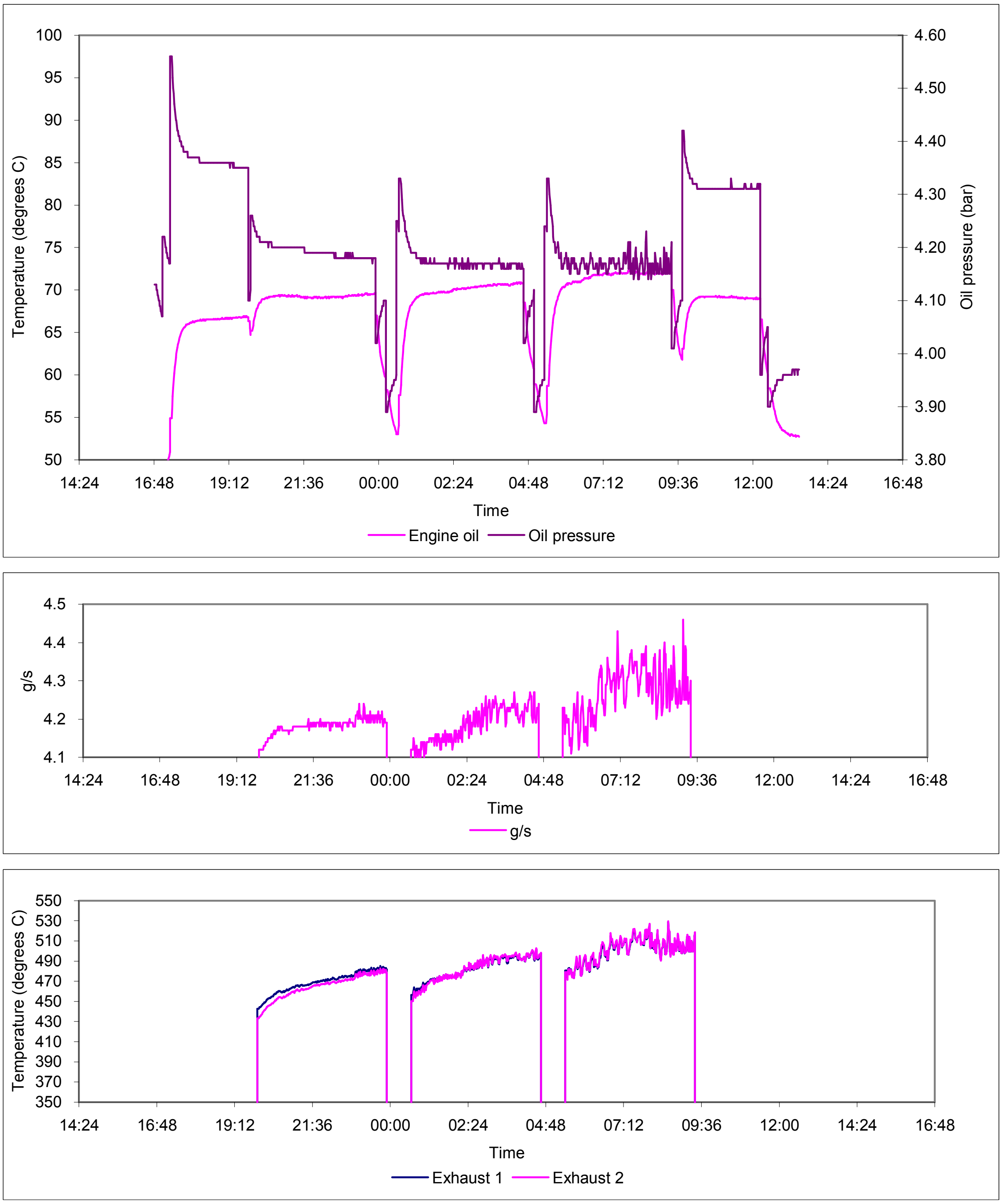


Figure 38: Oil temperature, oil pressure, fuel consumption and exhaust gas temperature for test 113 fuelled using waste oil (RVO) derived biodiesel. This was the last test conducted prior to it being discovered that the engine had suffered a failure.

Comparison of the charts in Figure 38 and those that precede show many important differences. Firstly engine oil pressure fluctuates rapidly from around 2 hours into the second trawl stage of the test cycle. The fuel consumption undergoes a upward transient to a relatively constant consumption rate over the first 1 ½ hours of the first trawl stage of the cycle and after this point, the fuel consumption rate becomes much more variable than previously. During the next 2 trawl stages, the engine fuel consumption becomes progressively less stable until the end of the third trawl stage, when it is clearly erratic. This pattern of engine behaviour recurs in the exhaust gas temperature profiles.

The time at which serious engine failure occurred has thus been identified at 22:54 hrs on the 4th December 2007. The curves for test 113 have been examined in further detail and have revealed very strong correlation between fluctuations in fuel consumption, oil pressure and exhaust gas temperature. What is clear from this monitoring of failure is that combustion gases were able to pass by the side of the pistons and rings. This would increase the crank case pressure and thus the oil pressure and would also increase the volume of hot combustion products vented from the crankcase to the inlet manifold. This mechanism also explains the elevated exhaust gas temperatures as the inlet air becomes pre-heated.

The compression ratio of the engine is reduced if combustion products can pass by pistons, with the result that engine efficiency is reduced (creating more heat, or allowing unburnt fuel to pass through the engine). The engine is set to maintain constant speed and constant torque. If the engine speed or torque fall due to a loss of efficiency, the control system will adjust throttle position to send more fuel. If engine speed or torque increase, the control system will adjust position to send less fuel. This mechanism explains the dramatic swings in fuel consumption.

The data fully support the ultimate observations that were taken of the engine when it was stripped down for inspection that were reported earlier. Piston rings were seized in their grooves on two pistons and the rings on one piston were broken. These circumstances would allow combustion products to pass by pistons.

A failure 'event' or progressive deterioration?

While the analysis of the data supported the observations of the engineers that stripped the engine down, at present neither these observations, nor the available data provide any firm explanation as to what initiated the engine failure, and this is subject to ongoing investigation. At the time of writing, the project team are still waiting for results of fuel and oil analysis.

After detailed analysis of the performance data for the BS14214 methyl ester DayTrawl and Baseline tests and comparison with previously undertaken 'good' tests, no evidence has been found that the initiating cause of the failure occurred during use of this fuel.

A common cause of fractures in piston rings in diesel engines is irregular combustion pressure. Irregular combustion pressure can be caused by, *inter alia*, i) defective or broken injector nozzles ii) the start of fuel delivery too early, iii) the compression ratio being too high iv) fuel cetane value too low causing extreme delay of start of ignition. All injector nozzles on the test cell engine were inspected during the strip down and were found to be in good condition. No change was made to engine timing as this was part of the test rationale, and the compression ratio was constant. These last two issues cannot be eliminated as contributory causes of the problem. If determined to be the core cause, in the context of the test objectives, they would indicate incompatibility of the fuel under the engine loading conditions imposed. Cetane values that were too low or too high would lead to a similar conclusion.

Prolonged presence of a piston ring fracture would be noticed through increased oil consumption, loss of power, enhanced engine noise and higher oil pressures due to blow by. As noted earlier oil consumption of the engine was stable. In testing with the BS14214 methyl ester, there was a reduction of power across the full range at full throttle (maximum power), but this was expected due to the reduced calorific value of this fuel. In the case of the Baseline test with WOME, the torque curve did deviate from the shape or form characteristic of the engine and this was manifest as lower torque (and hence power) at the low revolutions, ‘high torque’ end of engine performance. Baseline tests start the test at high power, ramp down to the highest torque set point and ramp up to high power again. In the case of the WOME, when the engine was returned to the high power range of set points, the engine performance observed then ‘merged’ with that determined with unproblematic, Baseline data obtained during testing with BS14214 methyl ester. In short, the engine performance with WOME, ‘recovered’ at the high power set points. At the time, engineers observing the WOME Baseline test concluded that the altered torque curve was characteristic of the fuel, rather than being indicative of the initiation of an engine failure cause by the fuel.

Common causes of piston rings becoming trapped in their grooves are i) excessive combustion temperatures and ii) oil presence in the combustion chamber. The external symptoms of piston ring seizure are higher oil consumption, and loss of power – as is the case for a piston ring fracture. As mentioned earlier, presence of remnant vegetable oil in the WOME cannot be eliminated as a contributing factor but awaits fuel analysis for confirmation. The exhaust gas temperatures observed in the WOME DayTrawl test were ~70°C higher than seen in DayTrawl tests running with BS14214 methyl ester and ~100°C higher than seen in DayTrawl tests running with fossil diesel. Higher exhaust gas temperatures in the trawl stages of the WOME DayTrawl tests could well be ‘allowed by’ an earlier piston ring fracture allowing blow by of combustion products into the crankcase. This assertion is supported by the fact that the ascent of exhaust gas temperatures in the WOME DayTrawl test is progressive, if increasingly erratic. At no time during the WOME test did the exhaust gas temperature appear that it was asymptotically converging on an equilibrium temperature – as was the case for the BS14214 Baseline test. As the set points for the Baseline tests are of relatively short duration compared to the 4 hour duration set point of the trawl stage in the DayTrawl cycle, it is unsurprising that particularly high or erratic exhaust gas temperatures are not evident in the analysis of the WOME Baseline test results. The fault condition requires time for the feedforward effect of blow by of combustion products to take hold. Once it has taken hold, the fault is progressive and the engine condition deteriorates with ring seizures, intermittent or otherwise.

At this stage, it is worth reiterating just how demanding the Baseline and DayTrawl test cycles are. The Baseline cycle runs the engine in a condition of maximum power at varying engine speed for around 1 ½ hours, clearly quite an exceptional condition in the context of typical duty cycles. For a DayTrawl test using fossil diesel, the trawl stage of a DayTrawl cycle involves running the engine for 4 hours engine at 65kW (nominally 80% of the engine rating). As can be seen in Figure 39 these operating conditions correspond to a demand of 80.4% of the available torque at the required operating speed for the fossil diesel. For the BS14214 methyl ester fuel this figure rises to 90.3% and for the WOME, this figure rises to 92.1% (see also Table 19).

Table 19: Required torque of a DayTrawl stage set points as a proportion of maximum available torque at the set point, for the different fuels tested.

DayTrawl Stage	Engine Speed (rpm)	Torque Demand (Nm)	Maximum available torque (Nm)			Demand torque, as a proportion of maximum available torque (%)		
			Fossil	BS14214	WOME	Fossil	BS14214	WOME
15 minute gentle cruise out to marker b	1300	36.7	356.3	326.4	305.3	10.3	11.3	12.0
2.5 hr steaming to trawl site	2000	47.0	335.2	310.6	308.8	14.0	15.1	15.2
5 min gentle cruise while shooting	1500	38.2	354.7	319.4	299.5	10.8	12.0	12.8
4 hour trawl	1750	278.1	345.8	308.1	301.9	**80.4**	**90.3**	**92.1**
20 min haul in of nets	1400	82.5	356.2	323.6	302.6	23.2	25.5	27.3

Clearly, the DayTrawl cycle duty asked of the engine for the fuel for which the engine is designed is demanding. This was by design, primarily for the purposes of discrimination of fuel consumption performance when testing fossil diesel with additives. A decision was taken after consultation with local fishing vessel skippers at Newlyn and SeaFish not to run the trawl stage set point any higher for fear of damage to the engine.

Subsequently, the project team took the decision to carry over the DayTrawl cycle to the biofuels trials. Part of the project concept was to investigate biofuels from the point of view that very little in the way of engine modification need be undertaken when switching fuels. Thus, for the project team, it was important to ensure that when running the biofuels tests, the engine essentially remained unchanged so that variance in performance arising from different fuels was revealed. No modification in timing of the engine was undertaken in order to account for the known variations in the fuel properties of biodiesels (meeting BS14214 or otherwise) in comparison to BS590 fossil diesel. In following this policy and operating the DayTrawl cycle with the biofuels, the project team took the engine running on BS14214 methyl ester from a demanding trial to a very demanding trial and took the engine running on WOME from a demanding trial to an extreme test.

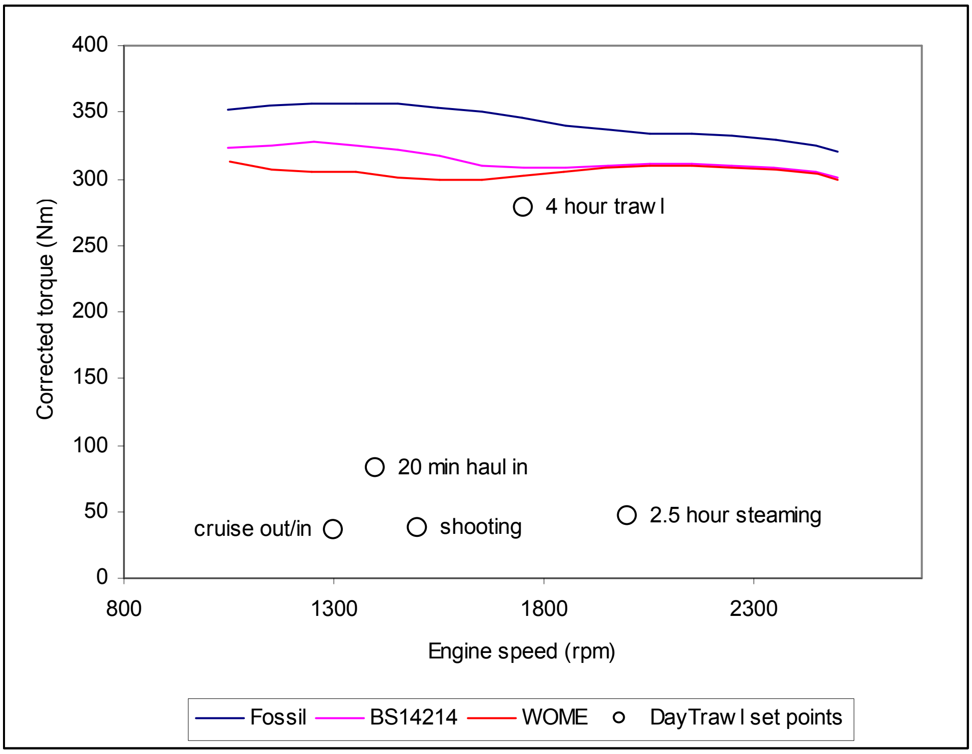


Figure 39: Torque curves (average of ramp down and ramp up) for fossil diesel, BS14214 biodiesel, and waste oil methyl ester (WOME), also showing DayTrawl stage set points.

It is in extreme operating conditions where the differences between the specific properties of fuels become most visible and consequential. In the case of the WOME, that despite its self-manufactured nature was still considered a competent fuel (as evidenced in trials with the diesel engine in Ma Gandole – see later), in not making timing allowances for the likely higher cetane value and viscosity of WOME, the DayTrawl test cycle becomes so extreme that it effectively becomes a test to destruction.

In short, and in retrospect, the project team believe that engine failure under the DayTrawl cycle with WOME was predictable.

The signs of engine distress after the Baseline test on WOME were evident (variation in the form of the torque curve, difficult engine start on the DayTrawl test), however, they were misinterpreted. It is unlikely that there was much wrong with the fuel, (although this still awaits confirmation with fuel analysis results), what was 'wrong' was the demand placed upon the engine by the DayTrawl cycle using fuel known to have good fuel properties, but slightly different from those for which the engine was designed and, importantly, timed.

So, while it was disappointing for the project team to encounter an engine failure with the first demanding trial with self-manufactured fuel, the failure is now understood and hence this test provides particularly valuable information in the context of the project objectives. In terms of engine performance, self-manufactured biodiesel should provide a competent fuel for skippers of fishing vessels, but they must not expect that they can push their engines quite as hard as they could, over the durations that they do using fossil diesel, without relatively minor engine modifications to take account for specific variances in fuel properties, the engine timing being an obvious example.

An important caveat needs to be appended to the statements in the preceding two paragraphs. This is that the observations put forward and the explanations for failure are based on detailed analysis of data arising from one test, albeit prolonged, and observations following engine strip down. Unfortunately, more testing, including further testing to failure, is required before any of the discussion points set out herein can be regarded as conclusive. While the formal project is clearly at the reporting stage, 'the work' is at its outset.

Bio-diesel at sea

Attitudes of Fishermen

The cost of red diesel varies considerably, as with most commodities. Users such as fishermen tend to worry about fuel costs when they are rising and then tend to switch their attention to other matters when they are falling. However, most, if not all, fishermen are aware that fuel costs are critical to their operating margins as the marketing mechanisms for their catch do not allow them to pass on cost increases. Many are also aware that instability in the Middle East could result in a sudden and dramatic impact on both price and availability.

Probably for the reasons outlined above, there has been overwhelming support from fishermen in both Padstow and Newlyn for the bio-diesel trials. Discussions with fishermen have reinforced the view that the potential key selling feature of bio-diesel would be a cost advantage over red diesel. Whilst fishermen generally appreciate that bio-diesel offers environmental advantages over fossil diesel, there has been no indication that fishermen perceive this to be a factor in their potential choice of fuel.

It should be recognised that different forms of fishing follow different economic models, the main distinction being between static fishing and trawling/dredging. As the bulk of the Cornish fleet fall into the under 10m category, which is dominated by boats operating static gear, this was the sector around which the bio-diesel project was conceived.

Public Attitudes

Positive Perceptions

The general public attitude towards renewable energy in general is positive. This seems largely to be driven by general concern about climate change. However, attempting to justify a project of this nature on the grounds that it is part of a strategy to mitigate climate change would be ill-advised. Sceptics could justifiably point out that the scale of the issues affecting climate change are such that only a total change in culture would have any significant impact.

Publicity associated with the project has stimulated considerable positive public interest, principally from people wanting information about their own potential uses of bio-diesel. Several contacts have been received from potential marine users with other contacts from commercial road vehicle users.

The use of recovered vegetable oil seems to be particularly well received, as it fulfils public desires for recycling as well as being seen as an environmentally friendly fuel.

In July 2006 the European Commissioner for Energy visited Cornwall. As a part of this visit he was given a demonstration of a small jet engine running on bio-diesel and was shown around the bio-diesel test vessel, Ma Gandole. He expressed his strong support for the work being done here.

Negative Perceptions

There has been considerable publicity surrounding the destruction of rain forest to make way for palm oil plantations. In the minds of some people, all bio-diesel is produced from palm oil and all palm oil comes from questionable sources. This is clearly untrue, even to the extent that palm oil is far from the best oil to use for bio-diesel destined for use in temperate climates. However, there is a small but well organised group of people determined to undermine the use of bio-diesel on these grounds.

Consequences of Publicity

Publicity connected with the project has resulted in numerous contacts initiated by third parties. The majority of these contacts have come from other marine fuel users interested in the possibility of using bio-diesel. The motivation behind these contacts was invariably a desire to establish “green” credentials for the organisation involved.

The association of this project with the Regenatec project attracted a very large number of identical e-mails calling for a stop to the use of imported oils from sources where de-forestation is an issue.

Approaches to Compatibility and Logistics

When considering alternative fuels there are two basic approaches: to adapt the fuel to suit current engines and fuel systems with little or no modification, or to adapt the engines and/or fuel systems to suit a chosen fuel. The choice of approach is critical to the probability of take-up in the intended application.

Bio-diesel is generally derived from vegetable oil by a process of transesterification. Clearly it would be cheaper to use the unprocessed oil as a fuel without the added cost of processing. However, the main distinction between vegetable oil and bio-diesel in practical terms is that bio-diesel has a viscosity that is likely to be compatible with most diesel engines at ambient temperatures whereas vegetable oil probably would not be. In the context of a small fishing vessel this distinction is significant. Installing the additional fuel tank(s) and heat exchange equipment that would probably be required to run on straight vegetable oil would be difficult or impossible on most under 10m boats due to lack of space.

Irrespective of the practicalities of installation, the primary driving force behind a change of fuel would be economics. Installing a heat exchanger and additional fuel tank(s) represents a significant capital cost. This expenditure could only be justified on the basis of reductions in fuel costs, so the fuel to be used would have to be significantly cheaper than red diesel and used in substantial volumes. These factors mean that vessels fishing static gear would see a much longer payback period from such a conversion than trawlers or scallop dredgers where the fuel cost to catch ratio is much higher.

The more barriers there are to a change in practice, the less likely it is that change will happen. The ability to change fuel type without substantial effort or cost represents a low barrier to change. The fact that a change of fuel could just as easily be reversed (i.e. vessels could readily revert to running on red diesel) eliminates another potential barrier to change.

As well as considering the vessels themselves, bunkering logistics cannot be ignored. A straight replacement for fossil diesel presents few problems for quayside bunkering installations, whereas bunkering for more viscous fuels is likely to require more intensive capital investment, something that would tend to be unattractive to smaller ports.

The combination of installation practicalities and pay-back period suggests that a straight replacement for fossil diesel is likely to be the most attractive option for smaller vessels fishing static gear.

Potential Benefits

Potential Cost Benefits

It is evident that the primary motivation for a change to bio-diesel would be economic benefit. All fishermen are interested in reducing operating costs, and fuel represents a substantial proportion of operating cost for all but the smallest vessels.

If it assumed that a typical 10 metre vessel fishing static gear would run for 1,200 hours per year using an average of 5 litres per hour, the annual fuel usage would be 6,000 litres. At 50 pence per litre, this equates to an annual operating cost of £3,000. Every penny per litre that could be saved through cheaper fuel would reduce annual costs by £60.

For inshore trawlers, the fuel usage and therefore the potential savings are an order of magnitude greater. Thus even a small cost advantage over red diesel would make bio-diesel an attractive option for a trawler, whilst larger savings would probably be required in order to tempt a static gear vessel into making a change.

Marketing and Catch Value Benefits

The general mood in the fishing industry is that there are issues of sustainability to be addressed. In part this is driven by "real" sustainability issues linked to stock levels and environmental damage attributed to the fishing industry. However, it is also driven by the marketing potential of seafood that is in some way branded as sustainable. Several such schemes are already in operation and appear to have been well received. The benefit of "sustainable" branding is twofold: firstly, suitably branded product has been shown to commend premium prices and secondly, the potential market volume may be increased by mollifying the concerns of some consumers that attempt to shop ethically.

There is a clear opportunity for at least elements of the fishing industry to boost its environmental credentials by publicising its use of bio-diesel. Identifying seafood as '*caught using bio-diesel'* has the potential to significantly increase the value of the catch. This potential was explored with a company called Falmouth Bay Oysters. This company supply seafood to premium outlets all over the country, mostly restaurants. They expressed considerable enthusiasm for seafood that could be marketed as *caught using bio-diesel* on the basis that it would provide a competitive advantage. A small quantity of shellfish caught during the trials was provided to Falmouth Bay Oysters to test actual consumer reaction, with strongly positive feedback.

A branding scheme of this nature could be modelled on that currently used in Cornwall to identify line caught bass and pollack, where a tag is attached to the product that not only identifies its nature but allows consumers to look up the fisherman on a website. It would be most appropriately used by static gear vessels landing shellfish or premium quality whitefish. For this category of vessel, the potential increase in the value of the catch could be far more significant than the potential fuel savings. For example, pollack tagged as line caught attract a premium of 30 – 50 pence per kilo whilst bass attract an additional 50 pence to £1 per kilo (source: Cornwall Fisheries Resource Centre). This scale of premium represents an increase of around 10% in gross income. The feedback from Falmouth Bay Oysters suggests that it may be possible to replicate this scale of benefit for shellfish caught using bio-diesel.

If the anticipated marketing benefit of using bio-fuel is realised, then the calculation determining the economically viable cost of bio-diesel versus red diesel would be fundamentally changed. It would no longer be necessary for bio-diesel to be cheaper than red diesel in order to yield a net economic benefit. It is the potters that would be most likely to benefit from this scenario, especially in relation to lobster. This is because lobster is largely destined for the upper end of the restaurant market where the consumer is most likely to be willing to pay premium prices for a premium product.

SWOT Summary

Strengths

Switching between bio-diesel and red diesel is straightforward

Pollution potential is lower relative to red diesel

Flash point is higher than for red diesel

No resistance encountered from insurers

Weaknesses

Poor availability of fuel

Bio-diesel is an efficient solvent for natural rubber

Opportunities

Potential cost saving relative to red diesel

Potential for enhancing value of the catch

Threats

Image of bio-diesel tarnished by threat to rain forests from palm oil plantations

Availability and cost of fuel is influenced by government policy

The Application of Bio-Diesel in Ma Gandole

Preparations

Ma Gandole, the test vessel, is of wooden carvel construction and was built in France in 1976. She is just under 30 feet in length and is registered at 6.3 tonnes. She is decked, and rigged as a crabber with a small wheelhouse aft and a hydraulic hauler mounted forward on the starboard side. The engine, located under the wheelhouse, is a Volvo MD70B approximately 20 years old, coupled to a 3:1 reduction gearbox. The MD70B engine is a normally aspirated, 6 cylinder design rated at 120 hp. It is understood to be based on the Volvo F7 truck engine.

At the outset of the trials, the vessel was fitted with twin steel fuel tanks amidships, mounted on wooden bearers either side of a small hold accessed through a deck hatch. The fuel tanks had originally been further aft, either side of the engine but had been relocated several years previously to provide more space around the engine and to give the vessel better balance.

As originally conceived, the project was to have been based on a smaller vessel. At the request of Seafish, the specification for the test vessel was amended to require a 120hp engine. Ma Gandole was selected on the basis that there were very few vessels available within the project budget.

Ma Gandole was leased to the project. This was important to the trials as it allowed access at any time and there was no conflict between the project and fishing operations. There was also no risk that fishing operations could be hindered in the event of mechanical problems attributable to the project. The absence of potential conflict proved to be extremely helpful.

The vessel was brought to Newlyn for the trials. This was a logical choice given the proximity of Newlyn to the University campus, the good standard of the facilities at Newlyn, and the number of other vessels operating out of Newlyn. The Harbour Master was very supportive and local fishermen were cooperative.

As a test vessel, Ma Gandole had a number of limitations. The bilges were constantly wet. The engine bay was cramped, which combined with the generally wet and dirty conditions made for a challenging working environment. The engine smoked quite heavily, although it ran smoothly. However, the intention was to perform the precision testing on the rig at Holman's Test Mine with the test vessel being used to demonstrate the use of bio-diesel in 'real' conditions.

Since bio-diesel is an efficient solvent for natural rubber, one of the first checks on the vessel was to identify any rubber components. The fuel lines were found to be synthetic hydraulic hose and there were no rubber engine mountings so no areas of concern were identified.

As a precaution, the fuel priming system on the engine was upgraded to a more modern arrangement. This was not done out of concern for potential damage, but was motivated by a desire to improve the efficiency of fuel priming in the event of problems at sea.

When switching from fossil diesel to bio-diesel in road vehicles it is widely advised to change the fuel filters shortly after making the change. This is because bio-diesel tends to dislodge accumulated deposits from the walls of the fuel tank and fuel lines. Once the system has been cleaned out by the action of the bio-diesel there is no further hazard, but it is wise to take precautions in the first instance.

Inspection of the fuel tanks on Ma Gandole was difficult due to poor access, but one of the tanks was emptied so that the fuel line and valve could be removed. This enabled scrapings to be taken from the lower part of the tank. The tank was found to contain a substantial quantity of heavy, oily deposits with some particulate contamination embedded in it. Given that the intention was to evaluate bio-diesel rather than to evaluate the contamination in the fuel tanks, the decision was made to replace the tanks with plastic tanks. The original fuel lines were retained. The plastic tanks eliminated the major potential sources of fuel contamination and also made it easier to make visual checks on the condition of the fuel (colour and clarity) and to record fuel consumption.

Use on Ma Gandole

With 2 fuel tanks available, one was dedicated to red diesel whilst the other was dedicated to bio-diesel. At no time was fuel deliberately mixed in a tank as this would have infringed the regulations laid down by H.M. Customs and Excise. It should be noted that some very small quantities of fuel would have been transferred from one tank to another when the fuel types were switched, this being the volume of fuel trapped in the fuel lines and not consumed by the engine.

By retaining an uncontaminated tank of red diesel at all times, there was an additional level of assurance that the vessel would be able to return to port safely in the event that fuel problems were encountered at sea.

Each fuel tank had a valve at its outlet, feeding into a common fuel line to the engine. Switching fuels was achieved by closing the valve on the tank in use before opening the valve on the other tank. The return line was then moved from one tank to the other and a check was made to ensure that the tank breather was open and clear.

Fuel was brought to the vessel in 25 litre plastic containers. Different colours of container were used to readily distinguish between the types of fuel. A fill level was clearly marked on each tank and the first fill was made to this level. Subsequent re-fuelling was done manually, using a large measuring jug to record the quantities of fuel going into the tank. This gave a simple but reliable measure of fuel consumption.

No special protective measures were taken during re-fuelling. No skin irritations or other ill effects were observed. Both polyurethane boots and PVC oilskins appeared to be unaffected by contact with the bio-diesel. However, spillages needed to be wiped up effectively as they proved to be extremely slippery.

Spare fuel, both red diesel and bio-diesel, was retained on board in the 25 litre plastic containers, often for several weeks at a time. These were stored below deck.

Shortly after the first use of bio-diesel, the engine was serviced including a change of fuel filters. This was purely precautionary, in accordance with good practice. The chances of fuel filter blockage had been greatly reduced by changing the fuel tanks but there was still scope for debris to have been dislodged from within the fuel lines.

An attempt was made to supplement the fuel usage data gathered with instantaneous measurement using in-line turbine flow meters. Simple, low cost turbine flow meters were obtained and tested in the laboratory where their performance was satisfactory. Installation on the vessel was more problematic. They were used to determine the proportion of the fuel flow returning to the tank over a period of several minutes. However, they proved to be unreliable as a source of instantaneous net fuel flow measurement, with highly unstable readings being observed. It is thought that this may have been due to pulsing within the system, with pulses affecting the feed line and the return line differently. Further development effort would be required in order to derive a reliable reading of fuel consumption in real time. It should be noted that the fuel flow measurement system used for the onshore test rig was of a totally different nature but was two orders of magnitude more expensive than the low cost turbine flow meters.

Observations

With the definitive quantitative data coming from the onshore test rig, the first question to be answered at sea was whether it was possible to “feel” any difference between the fuels at sea. In practice, it proved impossible to tell which fuel was being used other than by the smell of the exhaust fumes. Both fuels started the engine equally well, even on cold mornings (although being Newlyn, no severely cold weather was encountered). The vessel was felt to handle and perform equally with either fuel.

An area of potential concern was whether the bio-diesel would degrade in the tank, especially during periods of cold weather. No evidence of fuel deterioration was observed, even after the vessel had not been started for periods of 2 weeks during the winter. With the fuel tanks located below deck and below the waterline, they would have been protected from any extremes of cold that may have caused the larger molecules to crystallise. It is possible that the rocking motion of the boat on its mooring would also provide some movement in the fuel to inhibit crystallisation.

With the engine running, it was observed (using the, rather unreliable, in-line flow meters) that over 90% of the fuel delivered to the engine was returned to the tank. This large volumetric flow would have kept the fuel reasonably well agitated as well as warming it, thus keeping the bio-diesel in good condition.

Several attempts were made to obtain direct torque measurements from the propellor shaft. The nature of the required installation made this an extremely difficult operation. The large diameter of the propeller shaft meant that there was a very substantial mass of stainless steel acting as a heat sink which made soldering of the leads to the strain gauges very difficult. After several trials, the first of which is shown in Figure 40, eventually an installation was achieved and some data was obtained. However, maintaining sufficiently dry conditions for the torque sensor to operate reliably in proved to be extremely challenging, to the point where continued operation of the torque sensor became impossible.

Figure 40: Ma Gandole torque sensor after initial installation on 14th December 2006.

Being an aging vessel, the engine and other mechanical parts were quite high maintenance. Typical faults encountered were a leak of gearbox oil, failure of the engine shut-down solenoid, starter motor problems and corrosion of a hose tail on the intake strainer resulting in a seawater leak. However, no failures were encountered that could reasonably have been attributed to the fuel.

Data

The fuel consumption test runs were preceded by some basic reliability trials. It was realised that whilst the skipper had confidence that bio-diesel would perform adequately as a fuel for a fishing vessel, the fact that it was unproven in these conditions was thought to have an impact on the way in which the vessel was used. The skipper observed that when first using bio-diesel, he instinctively altered hid behaviour. This was particularly noticeable in the use of the throttle where it was observed that speed increases were made more cautiously and that cruising revolutions per minute were reduced. These instinctive alterations in behaviour appeared to make little difference to the performance of the vessel but made fair comparison of fuel consumption impossible until confidence in the fuel was fully developed. As time went on, it was found that the skipper became far less conscious of which fuel was being used and behaviour patterns converged.

During the summer of 2007, fuel consumption runs were carried out on 46 separate days with weather conditions ranging from flat calm to unpleasantly heavy seas. The testing area in and around Mounts Bay is subject to strong tides. Fuel consumption test runs were designed to replicate the activities of a potter, with a run of about half an hour to the fishing area, followed by periods of idling as strings of pots were hauled.

On fuel consumption test runs, 71 hours were logged using red diesel for baseline purposes, during 3 blocks of test runs. During these tests 271 litres of red diesel were consumed giving an average fuel consumption rate of 3.82 litres per hour. However, average fuel consumption for each block of test runs varied from 3.48 to 4.19 litres per hour, suggesting that fuel consumption at sea can be highly variable.

In comparative test runs, 3 blocks of trials were performed using bio-diesel. The total hours logged during these runs was 66 during which time 225 litres of bio-diesel was consumed, giving an average fuel consumption rate of 3.41 litres per hour. However, across the blocks of tests the average fuel consumption ranged from 3.45 to 3.73 litres per hour.

Table 20: Fuel consumption on Ma Gandole when fuelled with red (fossil) diesel

Ma Gandole - Fuel Usage Record

Red Diesel

Date	Hrs End	Hrs Start	Hrs Run	Notes	Fuel	l/hr
15/05/2007	9604	9603	1	moderate swell		
22/05/2007	9609	9604	5	calm - exhaust leak in engine bay		
				Added 25 litres (22 litres to mark + 3 litres)	25	
05/06/2007	9610	9609	1	pontoon run		
06/06/2007	9612	9610	2	potting, moderate swell		
07/06/2007	9613	9612	1	filled with 9 litres	9	
08/06/2007	9617	9613	4	Potting & lining - calm	14	
10/06/2007	9620	9617	3	potting, moderate swell		
12/06/2007	9623	9620	3		9	
14/06/2007	9625	9623	2	heavy swell	9	
15/06/2007	9629	9625	4	moderate swell	12	
03/07/2007	9632	9629	3		23	
			29		**101**	**3.48**
07/08/2007	9668	9665	3	calm	14	
09/08/2007	9671	9668	3	calm	11	
10/08/2007	9674	9671	3	calm	11	
13/08/2007	9677	9674	3	lumpy	11	
16/08/2007	9682	9677	5	calm	15	
17/08/2007	9686	9682	4	moderate	20	
			21		**82**	**3.90**
28/08/2007	9705	9701	4		22	
29/08/2007	9709	9705	4	windy	21	
30/08/2007	9712	9709	3		15	
10/09/2007	9713	9712	1	pontoon run		
11/09/2007	9718	9713	5	calm sea, strong breeze, big tide	18	
12/09/2007	9722	9718	4	flat calm	12	
			21		**88**	**4.19**

Table 21: Fuel consumption on Ma Gandole when fuelled with biodiesel.

Ma Gandole - Fuel Usage Record

Bio-Diesel

Date	Hrs End	Hrs Start	Hrs Run	Notes	Fuel	
13/04/2007	9590	9588	2	Pontoon run, no problems		
20/04/2007	9592	9590	2	easy start after cool weather, cruised Mounts Bay		
22/04/2007	9594	9592	2	easy start, cruised Mounts Bay. 6.5 kts @1400 rpm		
02/05/2007	9595	9594	1	shot pots, rough sea		
03/05/2007	9597	9595	2	potting, fair weather		
04/05/2007	9600	9597	3	potting, fair weather		
05/05/2007	9603	9600	3	potting, calm - filled with 44 litres	56	
			15		**56**	**3.73**
06/07/2007	9634	9632	2	pontoon run		
08/07/2007	9637	9634	3	potting, calm		
10/07/2007	9640	9637	3	breezy, some chop		
16/07/2007	9643	9640	3	potting, lumpy!	25	
17/07/2007	9646	9643	3	very lumpy	20	
24/07/2007	9648	9646	2	slight swell		
25/07/2007	9650	9648	2	lumpy		
26/07/2007	9652	9650	2	horrible sea conditions		
27/07/2007	9655	9652	3	fairly calm		
30/07/2007	9658	9655	3	calm		
31/07/2007	9661	9658	3		40	
03/08/2007	9665	9661	4	heavy seas	29	
			33		**114**	**3.45**
21/08/2007*	9688	9686	2	horrible sea conditions		
22/08/2007*	9692	9688	4	windy & choppy	11	
23/08/2007*	9697	9692	5	wind & swell	44	
24/08/2007*	9701	9697	4	fair		
			15		**55**	**3.67**

* Self manufactured biodiesel from the project batch reactor.

Practical Tips for Skippers

The fact that no fuel related problems were encountered during testing at sea was probably due to the fact that appropriate precautions were taken when switching to bio-diesel. In summary, a sensible checklist of preparations would be as follows:

(i) Survey the vessel to identify components made from natural rubber. Any natural rubber items that may come into contact with bio-diesel should be replaced with a synthetic rubber, or effectively protected. Few modern diesel fuel systems will contain natural rubber components but engine mountings in particular could be vulnerable.

(ii) Check the fuel tank(s) for cleanliness and either replace them or thoroughly clean them before filling with bio-diesel.

(iii) Replace the fuel filters after the first trip using bio-diesel and also carry a spare set of fuel filters, plus a filter wrench.

(iv) Remember that H.M. Customs and Excise do not permit the mixing of bio-diesel with red diesel. If carrying both fuels, it is prudent to clearly identify and separate tanks and to carry spare fuel in colour coded containers.

(v) If the vessel has been left un-started for a long period of time, especially in cold weather, make a visual inspection of the fuel before starting the engine to check that the fuel remains homogenous.

Recommendations for Further Work at Sea

This project has demonstrated that an inshore fishing vessel can be operated using bio-diesel. The remaining issues centre on the long term use of bio-diesel at sea, something that was beyond the scope of this project. A typical fishing boat engine will be expected to give many years of reliable service so it is logical that further work should be conducted to monitor the long term effects, if any, of using bio-diesel in a fishing vessel.

The ideal scenario would be to conduct a trial over several years on a vessel fitted with twin engines, preferably new engines. By running one engine on bio-diesel and the other on red diesel it would be possible to build up a history not only of relative fuel consumption under service conditions, but also of maintenance issues. There are reasonable grounds to believe that an engine running on bio-diesel may consume less oil and suffer less wear than an equivalent engine running on bio-diesel.

These trials have highlighted the fact that fuel consumption at sea is highly dependent upon a number of factors that cannot be standardised, such as wind, sea conditions and tide. By running identical engines under identical conditions these factors can be eliminated as variables to allow true comparison. If both engines are new at the start of the trial then there is a greater degree of certainty that the engines are in identical condition than would be the case with older engines.

Cost / Benefit Analysis

Cost of bio-diesel production (per litre)

Using commercial grade recovered vegetable oil:

Feedstock: 32p
Methanol: 13p
Sodium Hydroxide: 1p
Filtration/washing: 2p
Cold weather additive: 2p

Therefore the total cost before labour and overheads is 50 pence per litre which compares unfavourably with red diesel at around 50 pence per litre. The feedstock input cost per litre of fuel output has been based on the assumption that 10% of the feedstock could not be processed (the whites) and that the process yield is 95% (1 litre feedstock oil processed > 0.95 litres bio-diesel).

Using low grade locally sourced recovered vegetable oil:

Feedstock: 0p
Methanol: 13p
Sodium Hydroxide: 1p
Filtration/washing: 2p
Cold weather additive: 2p

At 18 pence per litre before overheads and labour bio-diesel looks economically attractive. In an optimised plant, it should be possible to produce a batch of bio-diesel with a labour input of about 2 hours, although not continuously. If the assumed batch size is 400 litres and a labour value of £10 per hour is used, then the labour cost per litre of bio-diesel is 5 pence. This will clearly vary greatly according to batch size, plant efficiency and actual labour cost. The labour element of cost when using low grade feedstock may also increase as the feedstock is harder to handle at low temperatures (solid) and may require more pre-treatment. However, when producing fuel for own use there is only a true labour cost if the activity prevents money being earned from elsewhere.

Overheads are difficult to estimate as they will vary greatly from plant to plant. They would include the cost of collecting feedstock, power, maintenance and depreciation. Power costs were found to be just over 1 penny per litre of fuel produced. Collection of feedstock cost about 2p per litre in fuel for the collection vehicle. Maintenance is highly variable but 2p per litre is assumed.

In conclusion, ignoring depreciation costs on plant, the marginal cost of self-produced bio-diesel could be as low as 23p per litre, but in practice is likely to be somewhat higher.

Therefore, if a fisherman manufactures his own bio-diesel from a nil cost feedstock, he is likely to see a cost saving of 25 pence per litre compared with red diesel at 50p per litre. For a static gear vessel using 6,000 litres of red diesel per year at 50 pence per litre, the annual fuel cost would amount to £3,000. Substituting self manufactured bio-diesel and assuming an additional fuel consumption of 12.5%, the volume of bio-diesel used would be 6,750 litres at a cost of £1,687.50 (or £1,350.00 if labour is excluded) giving an annual saving of £1,359.50 (£1,650.00 if labour is excluded). If it is assumed that the realistic total labour input to produce the fuel is 1 hour per 100 litres (double the optimum) then this saving represents a benefit of over £24 per hour spent on fuel production.

If the fisherman also obtains a market premium of 10% on his catch through certifying it as caught using bio-fuel, the benefit of enhanced catch value would be greater than the savings in fuel costs, thereby more than doubling the net economic benefit.

For trawlers, the fuel cost savings would be substantially higher, pro-rata to their fuel usage, but there is less scope to enhance catch value through bio-diesel based marketing.

Discussion, Conclusions and Further Work

There are a number of reasons to consider the use of bio-diesel in fishing vessels. For many members of the public the primary consideration would be the environmental benefits. Whilst it is fair to say that the combustion products of bio-diesel are an improvement on those of red diesel in environmental terms, there can be little doubt that technical and social changes are driven by pragmatism rather than by idealism. For bio-diesel to constitute a realistic alternative to red diesel it has to offer an economic benefit. This economic benefit does have to come solely from savings in fuel costs, but may also be derived from enhanced prices for fish certified as caught using bio-diesel.

This project has demonstrated that bio-diesel is a technically feasible direct substitute for red diesel in engines typical of 10 metre class fishing vessels. The lower calorific value will result in increased fuel consumption relative to red diesel.

The central issues to the potential take-up of bio-diesel in fishing vessels will be those of economics and logistics. Of these, the economic factors will dominate as favourable economics would stimulate solutions to logistical issues. Fishing, or even general marine use of bio-diesel cannot be considered in isolation. The dominant factor in the development of the market for bio-diesel is the level of demand for road transport use, which in turn is driven by government policy. The policy of renewable obligations will artificially stimulate demand for bio-diesel for road use which is likely both to stimulate additional production capacity and to drive up market prices. The inevitable consequence will be that all bio-diesel that is certified as conforming to the requirements of BS 14214 will be sold into the road transport market as that is where the greatest profit margin will be achieved. The superior profitability of bio-diesel in the road transport market will continue for as long as supply does not excessively exceed demand and as long as the duty differential between road transport bio-fuel and fossil fuel remains.

Based upon the probable scenario for demands for bio-diesel by the road transport sector, it is logical to conclude that security of supply for the fishing industry can only be achieved if the industry has control of adequate production capacity. Furthermore, there is no benefit in having available capacity without a sufficiency of feedstock. In order to avoid competition with the road transport fuel industry, the fishing industry will need to utilise less favourable feedstock that would be unlikely to economically yield fuel that complies with BS EN14214. In terms of dynamic performance, fishing operations under marine diesels are less demanding of fuel quality than many road diesel engines. In contrast to automotive applications, marine diesels are operated at high load for prolonged periods and one result from this project is that if this high load setting is too extreme (taking account of revised engine performance curves), engine condition can deteriorate when no engine timing adjustments are made to allow for the new fuel. Under the less onerous, but typical operating conditions experienced on Ma Gandole, no issues arose from the use of fuel produced in-house, that almost certainly did not comply with BS EN14214, or externally sourced BS 14214 specification fuel.

This raises the possibility of producing a “marine grade” of bio-diesel at a lower cost than commercial bio-diesel for road. It was this possibility that stimulated the extension of the project scope to include a practical investigation into small scale commercial production of bio-diesel from low grade recovered vegetable oil. The implication of setting out to produce a grade of bio-diesel that does not conform to EN14214 is that a new, less demanding standard will need to be developed to define the point at which the reliability or suitability of the fuel for fishing vessel use becomes unsatisfactory. Such a standard should be based on parameters that are compatible with low cost, low volume, batch manufacture.

The bio-diesel production plant selected for the project was a 400 litre per batch system produced by UK Fueltech Limited. This system was chosen because it featured a closed system reactor, meaning that the reaction could be driven at temperatures above the boiling point of methanol for a reduced reaction time. It also featured what was then the latest in “washing” technology. This was a dry wash system, whereby instead of removing water and impurities from the bio-diesel by showering it with water, a very fine powder (magnesium silicate) was added to absorb the water and the impurities. The contaminated powder was then filtered out leaving clean fuel and a small amount of solid residue that is much more easily disposed of than the effluent produced through water washing.

In practice, this powder based dry wash replaced one set of problems with another. Since the powder was so fine, filtering it out of the fuel proved to be quite problematic. Any powder left in the fuel was almost impossible to see with the naked eye, but may have been damaging to an engine. The filtration process was found not to be fully reliable, filtration operations became prolonged and the replacement of relatively expensive filter elements became a frequent necessity. Whilst not making the production of satisfactory fuel impossible, it was found that the systems employed were not entirely straightforward to use and that maintenance requirements were relatively high.

The drawbacks of washing using magnesium silicate seem to have been widely recognised by the bio-diesel industry with the result that a new generation of dry-washing systems are being introduced. These are based on ion exchange resins where the fuel is slowly passed through a column containing resin beads. The impurities are absorbed by the resin until it becomes saturated, at which point it can be refreshed by back-flushing with methanol. This system would appear to be far more robust than the magnesium silicate system, although it is likely that excess methanol will need to be removed from the fuel before it reaches the ion exchange column if the resin is to work efficiently. The ion exchange systems available should be evaluated before a potential production plant is considered.

It should also be noted that another variant of ion exchange resin is coming into commercial production. This resin is designed to process free fatty acids directly into esters thus enabling the use of feedstock that is considered as unsuitable for the transesterification process and avoiding the less favoured acid esterification process. It is too early to assess the impact that such resins will have on the market.

The actual processing cost of bio-diesel will depend upon the details of the process used. As yet, there is no reliable data available on costs associated with the ion exchange process but it is likely that the costs will be comparable with those of magnesium silicate (1 – 2 pence per litre). Added to the costs of methanol and sodium hydroxide, the marginal cost of producing bio-diesel would amount to less than 25 pence per litre, plus the cost, if any, of the vegetable oil used as feedstock. Low grade feedstock was obtained for the project free of charge; better quality recovered vegetable oil was also externally sourced at 26 pence per litre. Labour costs per unit of production would vary according to the batch size and the reliability of the plant. The cost of production plant relative the potential production volume is low, so depreciation charges would not add greatly to the cost of production. It can therefore be seen that with red diesel prices above 50 pence per litre, bio-diesel has the potential to offer a cost advantage relative to red diesel.

There is potential for considerable instability in the price of crude oil, to which the cost of red diesel is closely related. The current high spot prices for crude oil on the world markets are partly mitigated by the weakness of the US dollar which is at historically low levels (£1.00 = $2.04). A recovery in the value of the dollar relative to sterling would translate directly into higher red diesel prices. There are also questions over the security of supply of crude oil. Tensions in the Middle East, particularly between the USA and Iran, have the potential to result in a sudden depletion of supply that would not only cause dramatic price rises but could also result in physical fuel shortages. Given these risks, it would be prudent to have a contingency plan to keep the fishing fleet supplied with fuel at a price that does not render the industry uneconomic.

The fragmented supply of feedstock for the bio-diesel process, especially of recovered vegetable oil, lends itself to localised, small-scale production of bio-diesel. The ready availability of suitable production plant means that it is feasible for bio-diesel to be produced by individual vessel owners as well as collectively, providing security of supply that is as good as the availability of the feedstock.

During the course of the project, Seafish organised several group visits to Holman's Test Mine to view the test cell and the production plant. Visiting fishermen expressed considerable interest in, and support for, the project. Visiting technical specialists acknowledged the capabilities of the facilities that have been created as a result of this project.

The central results of the onshore test rig correlate well with previous published work on bio-diesel. The lower effects of the lower calorific value of bio-diesel relative to red diesel are seen in the form of increased fuel consumption, and torque and power at full throttle are reduced. Increased fuel consumption as measured on the test rig was in the range of 12% to 15%. Skippers adopting BS 14214 standard biodiesel at 100% concentrations, or manufacturing and using their own biodiesel should be aware of the need to make allowances in operating their engines with different fuels, particularly if their duty cycle involves prolonged engine running under high load (as with trawling). In any event, adjustment of engine timing to allow for the changed ignition characteristics of the biofuels should be considered.

Increased fuel consumption observed in the especially demanding tests on the test rig was not observed in trials at sea where fuel consumption figures were highly variable. This confirms that environmental conditions and typical operating duties are significant determinants of fuel consumption at sea, as was recognised at the outset of the project. It is particularly unfortunate and frustrating for the project team that equipment installed on Ma Gandole to measure the *in-situ* engine performance did not survive the wet environment below deck long enough to provide any reliable data. However, it is clear that actual duty cycles must be measured. It is only with this information that a definitive picture of the relative fuel performance will emerge. The facilities at Holman's Test Mine created to support this project remain operational and the project staff now have permanent employment within the University. Therefore the capacity exists to undertake further work relating to marine fuels, and the priority research objective is engine performance testing following actual boat duty cycles. It is hoped that with the continuing support of the Sea Fish Industry Authority for this work, reliable *in-situ* engine performance curves for trawling and potting boats in the ~10m class will be obtained and permit conclusive results on the relative performance of these fuels to emerge, that support the central finding of the work thus far:

This project has successfully demonstrated the technical viability of bio-diesel as a fuel for fishing vessels. The practical issues surrounding relatively small scale production of bio-diesel from low cost sources have been explored such that effective practical support can be provided to any elements of the fishing industry that wish to consider this option.

Appendix 1 : Fuel plant operating procedures

Fuel plant operating procedures

General Instructions

1. Personnel operating the production unit must wear a suitable laboratory coat or overalls to protect themselves from hot and harmful chemicals.

2. The front and rear doors are to be open to allow a through draft at all times.

3. The rear door is to be unbolted (x2) immediately upon entering the production unit and only re-secured immediately prior to locking up the front door. The rear door provides both ventilation and a fire escape.

4. Smoking is not permitted anywhere within 10 metres of the production unit.

5. Personnel operating the production unit must be free from the effects of alcohol and drugs.

6. Each process stage procedure starts by listing any loose equipment that is required for that stage. Equipment shown in red is safety equipment and the process is not to be commenced until these items have been located.

7. If at any time the methanol vapour detector alarms to signify excess methanol vapour, leave the unit for fresh air, only returning when safe to do so.

8. As a precaution against skin and eye burns, bottled water and vinegar is to be kept within the production unit along with an eye wash kit. In case of an accidental skin / eye contamination or an accidental ingestion, refer to the appropriate material safety data sheet in the back of this manual.

Figure 3: Emergency water and vinegar

Stage 1 - Vegetable Oil Conditioning and Preheating

Stage 1a – Assembling a Batch of Used Oil for Processing

Loose equipment required:

2 x 205 litre empty barrels	Pump no.1 suction extension hose
Torch or head torch	Pump no.1 alternative delivery hose
Paper towel	Screwdriver for hose clip

1) Allow the used oil to stand for several days so that the “whites” and solids settle to the bottom of the container(s).

2) Causing minimal disturbance bring the container(s) to the open front of the production unit.

3) Fit the suction extension hose to pump no.1 and submerge the suction end approximately 100 mm deep into the oil. If multiple small containers are being emptied, take all of the tops off and rest them over the openings.

4) Fit the alternative delivery hose to pump no.1 and put the delivery end securely into a 205 litre barrel.

5) Switch on the pump and take hold of the suction pipe above the oil. As the oil level drops, lower the suction end so that it remains just below the surface using the torch to look inside at the oil. Just before the hose starts to suck up the “whites” or solids, pull the hose swiftly out of the container and place in into the next container etc.
A colleague should be watching the oil level in the 205 litre barrel and should switch off the pump when it is full, move the delivery hose to the second barrel and switch the pump back on.

6) When the transfer is complete swap the pump hoses back and hang the extension and alternative delivery hoses back above the drip collector.

7) Wipe up any oil that has dribbled onto the floor or down the sides of the barrels.

Stage 1b - Assessing the Moisture Content (not required for new oil)

Loose equipment required:

Small saucepan	Heat source (cooker, bunsen burner)
Thermometer	100 ml measuring cylinder
Thermal insulation	Bung
Safety goggles	Paper towel

Note: Both 205 litre barrels should be assessed as detailed below even when the 400 litres is known to originate from one batch i.e. from a 1000 litre IBC. Settlement within the IBC may have resulted in significant separation of oils resulting in differences between the two barrels after the transfer in stage 1a.

1) Stir the batch of used oil to ensure that it is homogenised and then pour a 100 ml sample of the feedstock oil into a small, clean, dry saucepan. Wipe away any oil on the outside of the pan.

2) Relocate to a work place away from the production unit. Wearing safety goggles heat the sample slowly over a flame to 60°C. Do not bring a flame or other source of heat into or within 20 metres of the production unit.

3) Carefully pour the hot oil into a warm, dry 100 ml measuring cylinder and fit the thermal insulation and the top bung and leave for 2 hours to settle.

4) Taking care not to remix the contents, remove the insulation and assess the proportion of water that has separated out at the bottom of the cylinder. Record the findings in the batch record log for future analysis.

5) Keep the dried sample of oil to use for the PH determination (stage 1d). If 2 x 205 litre drums are to make up a processing batch, the 2 dried samples of oil should be mixed together in equal quantities for use later in stage 1d.

Figure 4: Heating the oil slowly

Stage 1c - Drying the Feedstock Oil (if required after stage 1b)

Loose equipment required:

Thermometer	Stirring stick	Water pump
Safety goggles	Gloves	

1) Insert one oil heating element and thermostat into each of the 205 litre barrels putting the element into the large top hole and the thermostat into the smaller hole on the opposite side.

2) Plug the heating elements into the commando type sockets provided. They are live immediately.

3) Ensure that the thermostats are set to around 60°C and are hence calling for heat. Monitor the temperature closely using the thermometer.
Do not peer into the top of a container without wearing safety goggles.
Do not leave the oil unattended for more than 15 minutes during this period.

4) Put on gloves and safety goggles. When the temperature reaches 65°C at the top of a barrel, unplug the element, remove the heating element and the thermostat from their holes and stir the oil thoroughly to distribute the heat. Replace the heaters, resume heating and repeat this mixing until an even temperature of 60°C is achieved.
Do not allow the temperature of the oil to exceed 65°C at any time.

Note: The mixing is required because the combined action of heat conduction and heat convection is too slow to distribute the heat through the relatively viscous oil. Without mixing, the temperature of the oil at the top soon reaches > 75° whilst the middle portion (carrying the thermostat) remains at < 25°C.

5) Unplug the heating elements and remove them placing them into the drip container. Allow the oil to cool slowly (as slowly as possible) and during this time the water will coalesce and separate to the bottom.
Do not disturb the barrels whilst separation is occurring.

6) Using the manual water pump, remove the water from the bottom of the barrel.

Stage 1d - Determining the Amount of NaOH to use

Loose equipment required:

- Small conical glass flask
- White tile
- I ml calibrated pipette
- 0 – 10 ml burette
- Burette stand
- Measuring cylinder (10 ml)
- Safety goggles

Substances required:

- 0.1 % standard solution NaOH
- (1 gramme NaOH in 1 litre H_2O)
- Phenolphthalein indicator
- Isopropyl alcohol

Note: For new vegetable oil go directly to step 10.

1) Ensure that the receptacles are clean and dry.

2) Using the measuring cylinder, pour approximately 10 ml of isopropyl alcohol into the conical flask.

3) Add 3 drops of phenolphthalein to the flask and mix by swirling it gently.

4) Put on safety goggles.

5) Fill the burette with the NaOH solution. There is no need to meet the zero mark. Drop by drop add the NaOH solution to the flask whilst maintaining a gentle agitation of its contents and observing the colour using the white tile as a background. When equivalence (neutralising) is approaching the flare of pink seen around the entry point of the NaOH will become more persistent until at the exact point of equivalence the indicator turns the colour of the contents to a sustained pink. At this point the acidity of the isopropyl alcohol has been exactly neutralised. No further addition should be made.

Figure 5: The flare of pink nearing the equivalence point

Stage 1d – continued

6) Using the calibrated pipette, add 1 ml of the used oil from the dried sample provided by stage 1b step 5 (now at ambient temperature) to the conical flask. Agitate the flask so that the oil dissolves fully in the alcohol. The free fatty acids present in the oil will turn the contents from pink back to a clear solution.

7) Record the level of NaOH solution in the burette.

8) Recommence the slow and careful addition of NaOH whilst swirling the flask and stop at the equivalence point as above.

9) Record the level of NaOH solution in the burette.

The amount of 0.1 % NaOH standard solution added between steps 7 and 9 is the amount required to neutralise the free fatty acids contained in 1 ml of the used oil. As the 0.1 % solution is 1 gramme of NaOH dissolved in 1 litre of water, the weight of $NaOH_{(s)}$ in grammes required to neutralise 1 litre of the oil is simply the number of mls of standard solution added between steps 7 and 9.

The number of grammes of $NaOH_{(s)}$ required to neutralise 1 litre of the used oil must be added to the number of grammes of $NaOH_{(s)}$ required as a catalyst for each litre of oil. The Low Impact Living Initiative (LILI) give this as 3.5 grammes in their book How to make biodiesel (Carter et al, 2005). The sum of these must then be multiplied by the number of litres of used oil to be processed.

Note: If the sum gives more than 8 grammes / litre, the oil is of very poor quality.

10) For new oil simply use 3.5 grammes of $NaOH_{(s)}$ for every litre of oil to be processed.

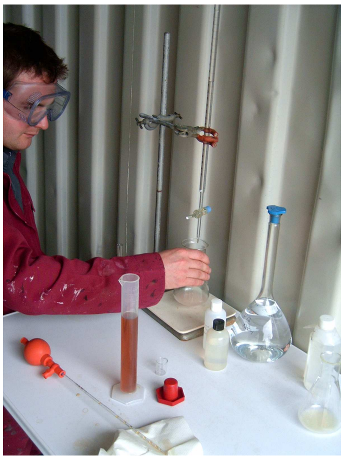


Figure 6: Titration in progress

Stage 1e – Preheating the Feedstock Oil

Loose equipment required:

Thermometer	Stirring stick
Safety goggles	Gloves

1) Insert one oil heating element and thermostat into each of the 205 litre barrels putting the element into the large top hole and the thermocouple into the smaller hole on the opposite side.

2) Plug the heating elements into the commando type sockets provided. They are live immediately.

3) Ensure that the thermostats are set to around 60°C and are hence calling for heat. Monitor the temperature closely using the thermometer.
Do not peer into the top of a container without wearing safety goggles.
Do not leave the oil unattended for more than 15 minutes during this period.

Figure 7: Lifting the thermostat slightly to measure the temperature at the top of the barrel. Note that the red light is lit showing that the thermostat is calling for heat.

Stage 1e - continued

4) Put on gloves and safety goggles. When the temperature reaches 65°C at the top of a barrel, unplug the element, remove the heating element and the thermostat from their holes and stir the oil thoroughly to distribute the heat. Replace the heaters, resume heating and repeat this mixing until an even temperature of 60°C is achieved.
Do not allow the temperature of the oil to exceed 65°C at any time.

Note: The mixing is required because the combined action of heat conduction and heat convection is too slow to distribute the heat through the relatively viscous oil. Without mixing, the temperature of the oil at the top soon reaches > 75° whilst the middle portion (carrying the thermostat) remains at < 25°C.

5) Unplug the elements, remove them placing them into the drip container.

6) Insert the suction pipe for pump no.1 into the hole vacated by the element of barrel no.1.

7) Calculate the volume of oil that is in the barrel. Deduct 5% from this figure as a safety margin and the resulting volume is the target delivery volume from barrel no.1.
Make a note of this.

8) Repeat step 7 for barrel no. 2.

9) Add the two target volumes together to obtain the total target volume which will be used to calculate the amounts of methanol and NaOH to use.

Note: The total target delivery volume must be between 200 and 400 litres of oil.

10) Proceed immediately with stage 2 while the oil is between 55°C and 60°C.

Stage 2 – The Transesterification Reaction

Stage 2a – Preparation

Loose equipment required:

Methanol vapour detector	Dust mask
Safety goggles	Gloves
Plastic bucket	Jug
Scales	

1) Calculate the weight of NaOH required using the figure required per litre of oil (stage 1d, step 9) and the total target oil delivery (stage 1e, step 9).

2) Put on safety goggles, gloves and dust mask.
Ensure that the bucket is clean and thoroughly dry.
Using the jug as a scoop and with the bucket on the scales, put the correct weight of NaOH into the bucket. Cover the bucket and reseal the NaOH.

3) Using the total target oil delivery, calculate the amount of methanol that will be required which is 17% of the volume of oil.

Note: 20% is a safer proportion which guarantees near complete transesterification but leaves a lot of excess methanol in the by-product phase. Unless experience demands for an increase, use 17%.

4) Still wearing safety goggles and gloves, fit the methanol pump into the methanol IBC lid. This is best done by removing the IBC lid and spinning it onto the thread of the pump and then refitting the lid with pump attached. Keep your face away from the opening of the IBC. The vapours are very strong and are harmful. Work upwind of the opening.

Figure 8: Fitting the methanol pump

Stage 2a - continued

5) Take the end of the methanol delivery hose in through the rear door, step onto the elevated platform and connect the quick release coupling to the nearest of the two inputs to the flow meter. Support the female coupling whilst you push the male into it i.e. do not strain the pipework.

6) Still up on the platform, open the valve below the flow meter. This type of valve is open when the handle is parallel to the flow and closed when it is across the flow. Open the valve which will allow methanol to reach the flow meter. Close the valve which will allow oil to reach the flow meter (the other one). Ensure that the large opening (closest to you) has its cap locked in position. This is the NaOH delivery port. Take the cap off and put it back so that you are familiar with it. The two arms lock it down and make the seal.

7) From the front of the reactor, ensure that the vent valve is open. This is the valve next to the pressure gauge.

Figure 9: Methanol delivery hose connected and 4 valves set for methanol delivery.

8) Ensure that the external vent hose is submerged in a bucket of water.

9) Ensure that the large bottom valve of the reactor is closed.

10) Ensure that the reactor isolator switch is off and that the heater and temperature switches are both off (fully anticlockwise).

11) Check again that all doors are open and that there is adequate ventilation.

Stage 2b – Performing the Reaction

Loose equipment required:

Watch or stopwatch	Plastic funnel
Methanol vapour detector	Safety goggles
Gloves	Dust mask

1) Switch on the methanol detector.
Put on safety goggles and gloves (all personnel).

2) Very slowly start pumping the methanol hand pump whilst a colleague watches the flow meter and listens. The first few strokes of the pump may only send air through the flow meter. As soon as liquid is heard falling in the reactor, the flow meter should be reset to zero using the knob on the side. With this the rate of pumping can be increased but a smooth deliberate action is best suited to the flow meter.
When the target methanol delivery is achieved cease pumping.

3) Step onto the elevated platform and close the nearest valve that isolates the methanol quick release coupling from the flow meter. Release the quick release coupling (using two hands) and take the methanol delivery hose outside and coil it up on top of the pump.

4) Turn on the reactor isolator switch. Wait for the temperature display to settle and then turn on the pump. You will hear the methanol circulating.

5) Put on the dust mask (as well as goggles and gloves).
Make certain that the plastic funnel is thoroughly dry (the bucket and funnel must be plastic to eliminate a spark risk whilst adding the NaOH).

6) Step onto the elevated platform and remove the cap from the large port.
Place the funnel in position and slowly pour the NaOH into the reactor. To avoid causing the pump a problem, this must be done slowly so that the NaOH dissolves before it contacts the pump. Around 1 kg per minute is acceptable. When complete, remove the funnel and reseal the port.

Stage 2b – continued

7) Open the vegetable oil inlet valve to allow flow through to the flow meter. The valve below the flow meter should still be open.

8) Zero the flow meter and switch on pump no.1 to deliver the hot vegetable oil from barrel no.1. Check that the level is falling in the barrel and that this roughly matches the flow meter reading. Keep the suction hose in the oil.

Figure 10: The valves set for oil delivery.

9) When the first 100 litres of oil has been delivered turn on the heater and temperature switches (fully clockwise). Two lights will illuminate. Maintain oil delivery.

10) When the target delivery from barrel no.1 is complete switch off the pump, move the hose across to barrel no.2 and switch back on. Check that the level is falling.

11) When the total target oil delivery is complete switch off the pump, close the vegetable oil inlet valve, close the valve below the flow meter and close the vent valve.

12) The temperature is already rising at this point and in a few minutes the pressure within the reactor will begin to rise towards its maximum of almost 1 bar.

13) When the temperature reaches 85°C, note the time and allow a further 25 minutes for the reaction to complete.

Figure 11: The vent valve closed and the pressure nearing 1 bar.

Stage 2b – continued

14) When 25 minutes has passed turn the heater and temperature switches off but leave the pump running. Crack the vent valve open and observe the methanol vapour discharging into the bucket of water. Open the valve in stages to vent the reactor without blowing the water from the bucket.

15) As soon as vapour stops bubbling through the water pull the vent hose out of the water to prevent water being drawn into the reactor when the contents are pumped out. Turn off the pump. Turn the reactor isolator switch off. Open the vent valve fully if not already fully open.

16) Check that the lid is in place on the separation tank and that the delivery hose is also in place. This is locked into the lid.

17) Check that all 3 valves beneath the separation vessel are closed.

18) Put safety goggles on in case of a hose failure.
Open the large valve beneath the reactor and switch on pump no. 2 to transfer the reaction products to the separation vessel.

Figure 12: These 3 valves are closed

19) When the transfer is complete the pump will make excessive noise. Switch off the pump and close the valve beneath the reactor.

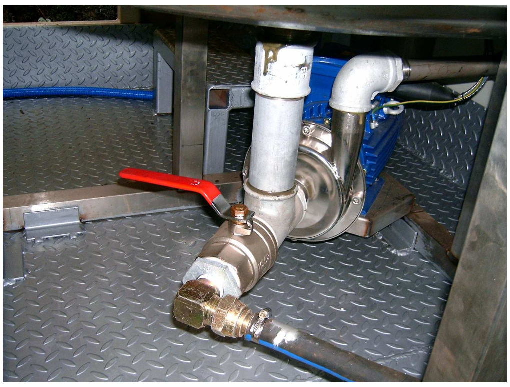


Figure 13: The valve beneath the reactor closed

Stage 3 – Separation of the Waste By-product (glycerine)

Loose equipment required:

Safety Goggles Gloves

Small receptacle (jug)

After 1 hour of separation proceed as follows:

1) Put on safety goggles and gloves. The waste glycerine will contain most of the excess methanol.

2) Locate the glycerine transfer hose which lies across the floor beneath the rear doorway. Take the end of this hose out through the door to the waste glycerine container.

3) Remove the lid of the container, open the valve at the end of the hose and secure the hose within the container.

4) Open the valve that is located centrally beneath the separation vessel. This is the glycerine outlet valve which allows flow to pump no. 3

5) Switch on pump no. 3 and observe the waste glycerine entering the waste container.

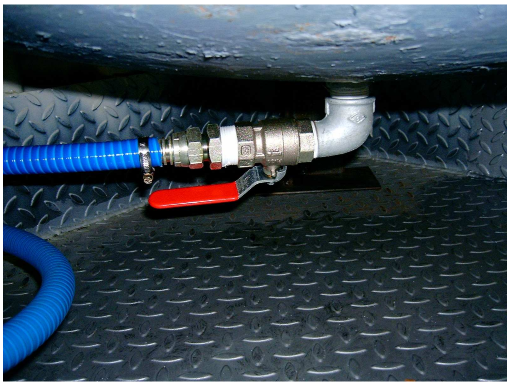


Figure 14: Glycerine outlet valve open

6) Watch the lower surface of the methyl ester in the sight tube. This will slowly fall as the glycerine is pumped away. Just as this separation is exiting the bottom of the sight tube, turn the pump off.

7) Close the valve beneath the separation vessel and the valve at the end of the transfer hose. Reseal the waste container and return the hose to its place inside.

After a further 6 hours minimum of undisturbed settling, continue with step 8.

Stage 3 – continued

8) If further separation has occurred glycerine will once again be visible in the sight tube and steps 1 – 7 above should be repeated.

Note: Methyl ester will be pumped from a slightly higher connection in the separation vessel. This is done to enhance the separation of the glycerine.

9) Place the jug beneath the lower of the two other valves. This valve is positioned to remove a "slug" of glycerine that will have settled in the methyl ester outlet valve (the higher of these two).

10) Crack open the valve very slightly and let the small amount of glycerine into the jug. Close the valve and put the glycerine into the waste container.

11) Open the upper of these two valves, the methyl ester outlet valve. This allows methyl ester to flow to pump no. 4.

12) Switch on pump no. 4 and observe the methyl ester entering the wash tank.

13) The pump will be heard to change tone when the level of fluid in the separation vessel reaches the outlet port. At this point switch off the pump and close the outlet valve.

Note: Be careful not to overfill the wash tank. The methyl ester must be stirred in this tank and sufficient volume of tank must remain empty to ensure that spillage does not occur.

14) Proceed with stage 4 while the methyl ester is still slightly warm.

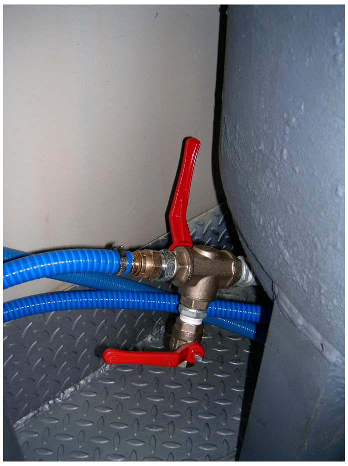


Figure 15: The glycerine slug valve and the methyl ester outlet valve (both closed).

Stage 4 – The Magnesol Wash

Loose equipment required

Safety Goggles	Stirrer / paddle
Dust mask	Bucket
Methanol vapour detector	Scales

Note: The Magnesol wash should be performed on batches of 800 litres or close to this amount i.e. two full reactor batches. The temperature of the methyl ester in the wash tank should be above 20°C for the adsorbent proce ss to work to its full effect.

1) Using the original capacity of the IBC tank (1000 litres), estimate the volume of the batch to be washed. Convert this batch volume to weight using a specific gravity of 0.87

2) Put on safety goggles and dust mask. Using the bucket and scales, weigh out 0.5 % by weight of Magnesol R60 powder.

3) Turn on the methanol vapour detector. Pour the Magnesol powder into the wash tank and start stirring it in with the paddle. The Magnesol needs to be kept in suspension in the wash tank for a duration of 15 minutes so stirring and scraping from the bottom must be maintained for this period.

4) After 15 minutes the Magnesol should have adsorbed much of the soaps, water, and methanol. Check that the return valve (mounted on the wall) has its handle pointing upwards (which directs the return flow back to the wash tank), and that the diffuser unit (the tall silver housing) has a filter in place and that the lid is securely fitted.

Figure 16: The wash return valve

Stage 4 – continued

5) Press the start button to run the pump. The pump should be primed from the last time it was operated but if no flow is achieved within 1 minute switch off and consult the manual dedicated to this equipment.

6) Agitate the suspension further paying particular attention to scraping powder from the bottom and stirring it back into the suspension.

7) Closely monitor the pressure gauge mounted on top of the diffuser. The pressure must not exceed 3.5 bar (approximately 50 psi). If the pressure reaches this limit it is an indication that the diffuser filter cartridge is full and it will need changing. In this case switch off the pump and refer to the manual dedicated to this equipment.

Note: If the pump has been turned on, 2 minutes should be allowed for the fluid pressure within the diffuser to reduce before opening the diffuser lid. Use the gauge to verify that it is safe to remove the clamp.

8) Let the suspension circulate through the diffuser for 1 hour whilst occasionally scraping and mixing. Powder settling on the bottom of the tank can now be pushed towards the suction hose end so that it is sucked up into the diffuser.

9) After 1 hour, observe the cleanliness of the fuel, take a sample if necessary. If it appears to be clean move the handle of the return valve to the horizontal position which diverts the flow to the final filtration tank.

10) Use the suction hose to “hoover” up the powder still remaining on the bottom of the wash tank. Remember to check that the pressure does not exceed 3.5 bar at any time.

11) When the wash tank is empty switch off the pump and move the return valve to its original position.

Stage 5 – The Final Filtration

Loose equipment required

IBC or similar fuel storage vessel

1) Check that the filter cartridges are fitted and are still serviceable. If this is not the case consult the manual dedicated to this equipment and locate new filter cartridges. Secure the filter housing lids.

2) Ensure that the suction hose (with the steel pipe fitted) is located in the bottom corner of the tank and that the return hose is set to return the fuel to the opposite upper corner.

3) Press the start button to run the pump. The pump should be primed from the last time it was operated but if no flow is achieved within 1 minute switch off and consult the manual dedicated to this equipment.

4) Four passes through the filters are required at 600 litres per hour. Calculate the time required for the batch being filtered and make a note of the completion time. Filtration can be suspended (e.g. overnight) and resumed again later if required.

Note: If the pressure reaches 4 bar the filtration pump will automatically stop. This indicates that the filter cartridges or the pre-filter cartridge needs to be changed.

5) Position the storage vessel (IBC or similar) outside the unit but adjacent to the filter pump unit. At the time of completion, switch off the pump and move the return hose from the filtration tank to the storage vessel. Turn the pump back on.

6) The finished fatty acid methyl ester fuel will now be transferred to the storage vessel at a rate of 600 litres per hour. When the pump starts to suck in air, switch it off. Do not try to “hoover” up the dregs left in the bottom. These are best left at the bottom and cleaned out periodically.

7) Seal the storage vessel and move it to a safe place.

Appendix 2 : Fuel plant maintenance procedures

Fuel Plant Maintenance Procedures

As a general rule the working environment within the production unit should be kept clean and tidy, this will make routine inspection of the equipment a quick and easy task to perform.

Daily Tasks

Magnesol Diffuser Filter

Remove the diffuser lid, twist and remove the locking plate and inspect the available volume remaining. Remove filter element, empty out "cake" and refit if there is insufficient volume remaining. Fit a new filter element if required.
Refer to the manual dedicated to this equipment as necessary.

Final Filter Unit

Remove the two filter lids. Inspect the filter elements and replace if sodden with water. Water will not provide the increased backpressure that will stop the pump from operating therefore physical examination for water saturation must be made.
Refer to the manual dedicated to this equipment as necessary.

Reactor Vent

Top up the bucket of water as necessary.

Weekly Tasks

Electrical System

Visually check that the earth ground stake (secondary earth) is in tact.
With the mains supply connected, push the RCD test button on the consumer board to verify that the RCD is functioning correctly.
Visually inspect the power sockets, plugs and power cables supplying the equipment within the unit. Rectify if damaged.

Transfer, Feed and Return Hoses

Make a visual and physical inspection of all hoses. Look for the early signs of decay which will include a softening of the structure of the hose and a softening of the material itself (although this will be on the inside). Seek advice and replace if necessary.

Ball Valves

Make a visual and manual inspection of all ball valves. Look for damage and decay. Operate the valve and assess whether the valve still has a normal action or if it is sticky or sloppy. Seek advice and replace if necessary.

Joints

Make a visual and physical examination of all pipe joints. If leaking seek advice and rectify.

Final Filter Unit

Remove and inspect the pre-filter element (back of the unit) and replace as necessary.

Annual Tasks

Magnesol Diffuser Unit

Remove and inspect the lid seal. Replace if necessary.

Final Filter Unit

Remove and inspect the lid seals. Replace if necessary.

Reactor Vessel

Facilitate pressure vessel inspection by recognised authority.

Fire Extinguisher

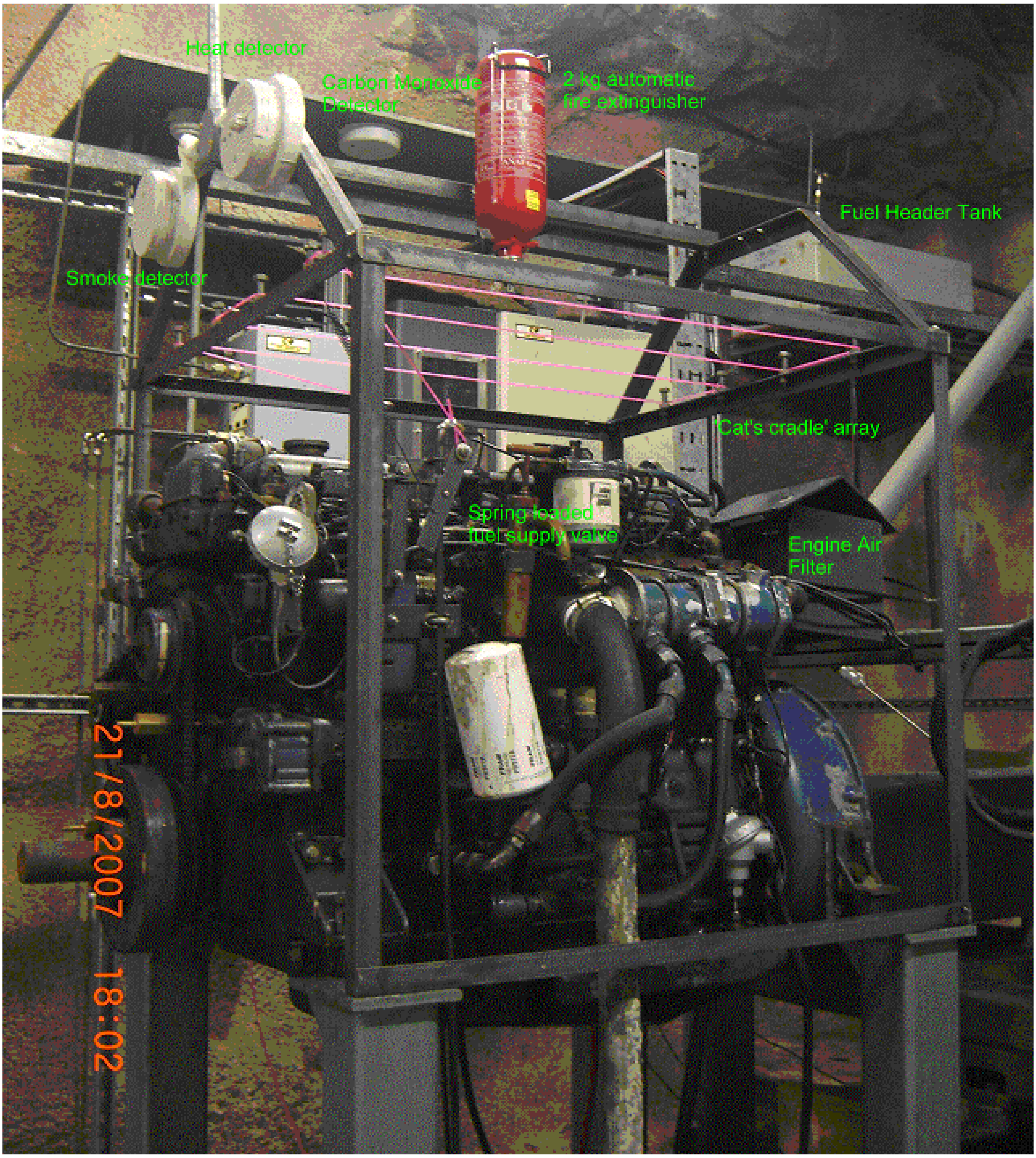
Facilitate inspection by recognised authority.

Doors

Grease door hinges.

Appendix 3 : Risk assessment for 24 hour operations of diesel engine test cell

Risk Assessment for 24 hour operation of diesel engine test cell



Introduction

CSM has developed an diesel engine test cell at Holman's Test Mine as part of biofuels research funded by DEFRA, the European Union, and the Sea Fisheries Authority (SeaFISH). The test cell comprises a Perkins 6 cylinder marine diesel engine that can develop 80kW shaft power output (designed for sub-10m class fishing boats), a dynamometer that applies load to the engine and a computer controlled Supervisory Control And Data Acquisition (SCADA) system.

SeaFISH have commissioned further work for the test cell in order to determine whether fuel additives to diesel would enhance the fuel consumption of similar engines installed in fishing vessels operating a day trawl cycle. A document detailing the duty of the engine under such a cycle is appended. The essential point about the cycle is that its duration is just over 20 hours, meaning that the tests will have to be conducted without the test cell engineers present. This document details additional safety measures that have been installed to the test cell unit to allow safe operations when the engine is unattended.

The SCADA system is specifically designed to allow unattended operations. It monitors the performance of the engine and the environment ensuring that the engine performs as specified according to a predefined schedule of set points.

Various temperature sensors are installed within the engine, but from the point of view of safety, the key probes are those that monitor and record the engine jacket temperature, the exhaust gas temperatures and the cooling water feed temperatures. If any one of these temperatures exceeds predefined threshold limits, the SCADA system will shut the engine down. Similarly, a low oil pressure occurrence will shut the engine down. The system has been additionally designed such that should the SCADA system fail, hardwired control switches intervene with the same effect.

The engine draws air from the test cell chamber and an exhaust line runs directly from the engine exhaust manifold along a duct to a chimney stack outside the portal of the mine (the top of which is around 7 metres higher than the portal roof elevation). The exhaust duct has an exhausting fan / air handler within it which assists the exhaust combustion products to clear the top of the chimney. This fan must be in operation before the engine in the test cell can be started and a screen exists within the SCADA system to check that this is done.

Fresh air is forced into the test cell chamber using a 15 inch fan located outside the portal leading to the underground workings. The air passes along a ventilation duct and into the test cell chamber at high level. In addition, the test cell chamber has 2 entrances / egresses for personnel and equipment. The first is a 3 metre span x 2 metre high roadway entrance, the second is a standard doorway.

The engine is cooled using water that is drawn from the mine sump and pumped to the engine and dynamometer along a 3 inch main pipe. This pump must be in operation before the engine in the test cell can be started.

Test diesel for the engine is temporarily stored in a ~50 litre header tank that is securely fixed to unistrut framework and in turn is securely bolted into the rock walls comprising the test cell chamber. Diesel in this tank is automatically topped up using a specialist fuel delivery pump drawing fuel from an IBC located in a fuel delivery bay located outside the test cell chamber.

In design, construction and operation of the test cell thus far, all applicable health and safety legislation has been adhered to. As the Holmans Test Mine Manager, Dr Patrick Foster, Senior Lecturer in Mining Engineering and an internationally renowned expert in Health, Safety and Risk Assessment has overseen this work.

This document is an Addendum to the basic risk assessment already prepared and approved and is prepared to deal with the circumstances of unattended operations as required by Health and Safety legislation and by the University’s insurers.

Risks Identified

University's Risk category	Risk keywords	Notes
Confined Space	asphyxiant cold hot toxic irritant lone working ventilation	Large working area, well ventilated naturally, assisted by forcing fan and duct. See measures for re-entry of test cell detailed below.
Building Related	CONDAM Regs Ass't scaffolding work at height falling object asbestos containing materials	N/A for this addendum
Display Screen Equip't	DSE Regs Ass't desk chair electricity eye strain eye test posture	N/A for this addendum
Electricity	PAT testing live static induced arc heat burn shock 240V AC 405V AC high voltage	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Environment	temperature humidity light sound space	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Fire	flammable combustible explosion oxygen heat	See detailed mitigation measures explained below. See measures for re-entry of test cell detailed below.
Handling	MHO Regs Ass't abrasive heavy lifting pushing pulling sharp hot cold awkward	N/A for this addendum
Heat / Cold	radiation conduction convection burn scald touch	No exposure to personnel for unattended operations.
Housekeeping	falling tripping slipping storage space cables combustion sources hygiene	No exposure to personnel for unattended operations.
Machinery	MHO Regs Ass't cutting rotating sliding falling entrapment breakage ejection of parts electricity radiation heat cold	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Movement	slip fall trip wet ice steps stairs height	N/A for this addendum
Pressure / Vacuum	burst release lines joints container cylinder explosion leak blockage relief/control failure	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Radiation (Ionising)	radioisotope X-ray alpha beta gamma contamination exposure use storage disposal	N/A for this addendum
Radiation (Non Ionising)	ultra-violet infra-red laser microwave burns welding eye cataract	N/A for this addendum
Transport	road markings road signs dangerous loads minibus fork-lift truck trolley truck commercial vehicle passenger lift goods lift footpath ramp car boat	N/A for this addendum
Water	diving drowning slipping electricity	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Weather	hot cold wet ice wind lone-working frost-bite heat-stroke sunburn skin cancer hypothermia	N/A for this addendum
Physical state	solid dust liquid gas vapour fume hot cold	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Properties	COSHH Ass't toxic corrosive irritant carcinogen allergen flammable unstable explosive	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.
Routes of Entry	inhalation ingestion skin contact	No exposure to personnel for unattended operations. See measures for re-entry of test cell detailed below.

There is no life risk while the test cell operates unattended which is the circumstance covered by this risk assessment addendum. As can be seen from the above, many risks that can be sensibly identified for operations with the test cell engineers in attendance are not present when the unit operates unattended.

The main risk is loss of the asset due to overheating and possibly fire when the cause has not been foreseen and mitigated through the test cell control and protection systems.

In the event of a fire, there is a risk of harm to personnel if they were unaware that a fire had occurred in the test cell chamber; residual combustibles or asphyxiants may be present when they attend the area afterwards.

Mitigation measures in the event of a fire when test cell unattended.

Mitigation measures to protect the asset.

1. A 2kg automatic powder fire extinguisher (CE 0029; P.E.D. 97/23/EC) has been installed above the diesel engine. This is sufficient to cover an area of 2 m^2 around the point of discharge. The extinguisher is activated by a temperature sensitive glass bulb when the temperature around this bulb reaches 79°C. The engine air filter is directly within the line of fire of the powder fire extinguisher and will become clogged very quickly after the extinguisher has actuated. This will starve the engine of air and cause it to shut down. Cooling water is supplied by an independent pump located at the mine sump. The cooling water will continue to flow and will cool the engine down removing heat from the cause of the fire.
2. A ‘cat’s cradle’ array of plastic cord has been installed under tension on a steel frame above the engine. If flame touches the cord, the cord melts quickly and the tension is lost. Under operating conditions, the tension in the cord acts against two loaded springs, one connected to a valve on the fuel supply line and another connected to a valve on the fuel return line. If the cord breaks and tension is lost, the springs are unloaded and turn the valves closed, isolating the engine from its fuel supply.

Mitigation measures to protect personnel entering the test cell chamber after a fire.

3. A Kidde Fynetics mains operated (battery back-up) smoke alarm 123/9HI (BS 5446: Pt 1:2000) has been installed above the diesel engine. Mains leads to this unit are in galvanised metal ducting into the connection box on the engine test frame. From this point, 20 cm long 3 core plus earth flex leading to the sensor is wrapped in heat and fire resistant tape. This unit emits an 85 dB alarm signal when activated by excessive presence of smoke. It is wired so that both a second smoke alarm and the heat alarm are simultaneously activated.
4. A Kidde Fynetics mains operated (battery back-up) heat alarm 323/9HI (BS 5446: Pt 1:2000) has been installed above the diesel engine. Mains leads to this unit are in galvanised metal ducting into the connection box on the engine test frame. From this point, 20 cm long 3 core plus earth flex leading to the sensor is wrapped in heat and fire resistant tape. This unit emits an 85 dB alarm signal when activated by heat in excess of 57°C. It is wired so that two additional smoke alarms are simultaneously activated.
5. A Kidde Fynetics mains operated (battery back-up) smoke alarm 123/9HI (BS 5446: Pt 1:2000) has been installed on the wall <u>outside the test cell chamber</u>. Mains leads to this unit are in galvanised metal ducting. This unit emits an 85 dB alarm signal when activated by excessive presence of smoke in the drive leading from the test cell to the portal or when either the smoke alarm or the heat alarm located above the engine are activated. The alarm signal from this unit can be heard from the mine portal.
6. A Kidde Fynetics battery operated carbon monoxide sensor (EN50291:2001) has been installed adjacent to and above the diesel engine, close to the exhaust manifold and exhaust ducting. This unit emits an 85 dB alarm signal when activated by excessive, prolonged concentrations of carbon monoxide (120 minutes @ 30 ppm, 60-90 minutes @ 50 ppm, 10-40 minutes @ 100 ppm, 3 minutes @ 300 ppm).

7. A forcing fan has been installed at the portal to underground workings. Fresh air is ducted directly to the test cell chamber and enters the chamber at high level. This is used to dilute hazardous gases or vapours that may accumulate for unexpected reasons to low levels of concentration.

Mitigation measures for the event of loss of power

The test cell has a fail-to-safe set up so that it requires mains power at all times including engine start-up and engine operation. In the event of an unexpected loss of electric power, if it is running, the engine will shut down. In the event that the engine is running and needs to be shut down when access to the test cell chamber cannot be secured, switchgear located in the mine workshop can be used to shut the system down in this way. The engine needs manual intervention to start.

Mitigation measures for the event of loss of cooling water

The pump supplying cooling water to the engine and dynamometer may trip out for unexpected reasons. The SCADA system monitors a cooling water pressure sensor. If the pressure recorded by this sensor drops below 2 bar, the SCADA system shuts the engine down to protect it. If this fails, and the engine continues to operate temperatures in engine water jacket will quickly become elevated above 95°C (the engine cooling system has been designed to keep jacket temperatures at or below 90°C under full load) and the SCADA system will shut the engine down. If the SCADA system fails due to a software fault, the hardware-based engine protection system shuts the system down.

Mitigation measures for the event of loss of ventilating air

The engine has already been operated for prolonged, attended periods without the forcing ventilation fan running, as natural ventilation to the test cell chamber is good due to its proximity to the mine portals and the fully ducted exhaust system. Use of the forcing fan is an additional precaution for unattended operations. Its main purpose is additional protection for personnel re-entering the test cell following a fire that has been extinguished when the test cell operated unattended. By continuously forcing fresh air into the chamber it any high concentrations of fumes or dangerous gases are diluted.

Procedure for re-entering the test cell chamber.

With near continuous testing (20 hours of each 24 hour period) with high probability personnel entering the chamber will do so while the engine is still running its test cycle. In instances when the engine has operated for a prolonged period unattended, i.e. overnight or for greater than 1 hour during normal working hours, the inspecting person will carry a battery operated gas detector (KANE CO75 CO Detector) during entry to the test cell chamber. At any time if this portable device sounds, personnel should retreat to the quarry yard and inform the mine captain or project engineer immediately. While entering, the following sequence of checks is carried out:

In the quarry yard

1. Is there smoke from the exhaust stack? This means that the engine is running.
2. Can one hear the engine running? This confirms that the engine is running or not.
3. Examine clip board on hook on the side of the forcing fan in the quarry yard stating expected test completion time. Should the engine be (not) running according to the test schedule? If it is running and should be running then proceed. If it is not running and should have completed then proceed.
4. If it is not running when it should be or if it is running when it should not be, be suspicious, but proceed with check list.

5. Is the forcing fan running? This confirms that fresh air is being supplied to the test cell chamber.

At the portal to underground workings

6. Is the exhaust fan running (removing engine combustion products)? If so then proceed. If not and the engine is running, be suspicious and report immediately to the mine captain or project engineer. Do not enter the mine.
7. Is the cooling water pump running? If so, then proceed. If not and the engine is running, be suspicious and report immediately to the mine captain or project engineer. Do not enter the mine.
8. Have one of the alarms been actuated (85 dB noise on klaxon on smoke alarm in drive from portal to test cell chamber)? If not, then proceed. If so, be suspicious and report immediately to the mine captain or project engineer. Do not enter the mine.

At the entrance to the engine test cell chamber

9. Ensure the motion sensor actuated lamp comes on. This confirms that there is power to the main ring main around the test cell chamber.
10. Check that there is cooling water flowing into the return drain if the engine is running. This can be seen from the door to the test cell chamber.
11. Do a visual check for smoke in the test cell.
12. Do a visual check for discharge of the automatic fire extinguisher.
13. Do a visual check of the cat's cradle above the engine.
14. If 11,12 and 13 are okay, then enter the test cell chamber. If not, then report immediately to the mine captain and the test cell engineers. Do not enter the chamber.
15. If at any time the portable carbon monoxide detector alarm sounds, retreat to the quarry and inform the mine captain or project engineer.

Procedure for the case of a fire.

1. If a fire in the test cell is noticed from the quarry yard. Phone fire brigade. Do not enter.
2. If a fire in the test cell is noticed at the portal. Phone fire brigade. Do not enter.

3a. If a small fire in the test cell is noticed from the door to the chamber (this is highly unlikely due to the fire suppression systems and the various alarms) use the fire extinguisher located outside the test cell to tackle the fire – if appropriate. Then leave immediately. Inform the mine captain or project engineer.

3b. If the engine is still running (which is very unlikely due to the fire protection systems), the project engineer or the mine captain may isolate test cell electrical systems from the underground sub station. Independent access is available to this room and shutting down the power to the test cell chamber will cause the engine to stop. If access underground is not possible, the engine may be stopped by isolating the underground substation using switchgear located in the mine workshop. This will cause the engine to stop running. Electrical power to the underground workings should then be re-established immediately to keep ventilation equipment running to clear smoke and other fumes.

4. If a larger fire in the test cell is noticed from the door to the chamber. Leave the mine immediately. Phone the fire brigade.
5. If the smoke or heat alarms are activated (this will be noticed at the portal) this means there are dangerous concentrations of smoke or carbon monoxide gas present or a source of excessive heat. Do not enter the sub-surface. Ensure the forcing fan is activated and wait for the alarms to stop (which they will when concentrations fall to acceptable levels). Follow the procedure for entry to the test cell following a known fire (immediately below).

Procedure for re-entry to workings following a known fire with alarms not sounding

Alarms could stop sounding if the concentrations of dangerous gases and smoke have reduced to acceptable levels or because all three devices have malfunctioned. If there is no visible indication of fire, smoke or fumes remaining in the test cell chamber assessed from the portal, and the alarms are off and forcing fan on, the mine captain may enter the area equipped with a hand held battery operated carbon monoxide sensor and may only proceed where the sensor indicates carbon monoxide levels are below threshold values. If possible, the mine captain will inspect the test chamber to determine whether it is safe for other personnel to enter.

Appendix 4 : Test engine log / test schedule

Date	Test		Fuel			Duration	Maintenance / comments	
	Type	Identification	Base	Source	Additive	(hours)	Engine oil	
								New K&N air filter fitted Valve clearances reset
19-09-2007	Baseline 003	BL003-001	red diesel	M&W batch 1	-			
19-09-2007	Baseline 003	BL003-002	red diesel	M&W batch 1	-			
							+ 1.5 litre	
20-09-2007	Baseline 003	BL003-003	red diesel	M&W batch 1	-			
								Exhaust re-fitted
20-09-2007	Baseline 003	BL003-004	red diesel	M&W batch 1	-			
							+ 0.5 litre	
20-09-2007	Baseline 003	BL003-005	red diesel	M&W batch 1	-			Fuel measurement failure
							+ 1.5 litre	
21-09-2007	Baseline 003	BL003-006	red diesel	M&W batch 1	-			
								Alternator belt re-tensioned
21-09-2007	Daytrawl 002	DT002-001	red diesel	M&W batch 1	-			Fuel measurement failure
							+ 2.5 litre	
24-09-2007	Baseline 003	BL003-007	red diesel	M&W batch 1	-			Peak power slightly low. Fuel measurement failure
							+ 1.5 litre	Enersol field coil fitted
25-09-2007	Enersol EM	EM-001	red diesel	M&W batch 1	-			300 Hz magnetic field
								Coil placement corrected
25-09-2007	Enersol EM	EM-002	red diesel	M&W batch 1	-			300 Hz magnetic field
							+ 0.5 litre	Coil windings adjusted

26-09-2007	Enersol EM	EM-003	red diesel	M&W batch 1	-			300/1000 Hz magnetic field
26-09-2007	Enersol EM	EM-004	red diesel	M&W batch 1	-			100/50 Hz magnetic field
							+ 2 litre	
27-09-2007	Manual start to check engine		red diesel	M&W batch 1	Major breakdown – compression in crankcase. Engine strip down – new cylinder liners, pistons, piston rings and big end connecting rod bearing shells.			
					New air inlet duct built to aspirate engine from adjacent mine road thus reducing the variation of air inlet temp.			
05-10-2007	Running in		red diesel	M&W batch 1	-			3 hours – 1200 rpm / 38% throttle.
								Dynamometer fault – dyno applying load but load cell not outputting a load value.
08-10-2007	Running in		red diesel	M&W batch 1	-			1 hour – 1300 rpm / 40% throttle.
								Fuel leaking from injector pipe work – stripped and re-fitted.
								Load cell module circuit board replaced – working
09-10-2007	Running in		red diesel	M&W batch 1	-			2 hours – 1350 rpm / 45%
							+ 0.5 litre	
10-10-2007	Running in		red diesel	M&W batch 1	-			

								Prop. Shaft universal joint (engine end) failure. Bearings replaced.
11-10-2007	Running in		red diesel	M&W batch 1	-			1 hour – 1400 rpm / 50%
12-10-2007	Running in		red diesel	M&W batch 1	-			6 hours – varying up to
								45 kW shaft power.
15-10-2007	Running in		red diesel	M&W batch 1	-			7 hours – varying up to
								60 kW at 1900 rpm.
							Engine oil changed	
16-10-2007	Dyno load cell calibration		red diesel	M&W batch 1	-			Calibration accepted
16-10-2007	Baseline 003	BL003-101	red diesel	M&W batch 1	-			Excessive smoke from
								exhaust at peak power.
16-10-2007	Baseline 003	BL003-102	red diesel	M&W batch 1	-			
								Redundant seawater pump
								decoupled from drive shaft.
16-10-2007	Baseline 003	BL003-103	red diesel	M&W batch 1	-			Fuel measurement failure
							+ 0.5 litre	Alternator belt re-tensioned
17-10-2007	Baseline 003	BL003-104	red diesel	M&W batch 1	-			
17-10-2007	Baseline 003	BL003-105	red diesel	M&W batch 1	-			
17-10-2007	Baseline 003	BL003-106	red diesel	M&W batch 1	-			
							+ 0.5 litre	
18-10-2007	Manual running (cooling trials)		red diesel	M&W batch 1	-			4.5 hours running at
								medium duty.
22-10-2007	Manual running (cooling trials)		red diesel	M&W batch 1	-			3 hours running as above.

22-10-2007	Daytrawl 002	-	red diesel	M&W batch 1	-			Fuel measurement failure. Test aborted after 17 hours.
								Fuel measurement system
								refill relay replaced.
24-10-2007	Daytrawl 002	DT002-101	red diesel	M&W batch 1	-			Test completed with full fuel
								consumption data.
							+ 1.5 litre	Alternator belt re-tensioned
25-10-2007	Daytrawl 002	DT002-102	red diesel	M&W batch 1	A			Additive mixed 1:2000
							+ 0.5 litre	
29-10-2007	Baseline 003	BL003-107	red diesel	M&W batch 1	-			
							+ 0.5 litre	Alternator belt re-tensioned.
								Prop. shaft greased. Dynamometer greased.
31-10-2007	Daytrawl 002	DT002-103	red diesel	M&W batch 1	-			
							+ 1 litre	
01-11-2007	Baseline 003	BL003-108	red diesel	M&W batch 1	-			Excessive smoke from
								exhaust at peak power. Peak power marginally lower than normal.
							+ 1 litre	Air filter cleaned
02-11-2007	Baseline 003	BL003-109	red diesel	M&W batch 1	-			
02-11-2007	Daytrawl 002	DT002-104	red diesel	M&W batch 1	B			Additive mixed 1:3000
							+ 1 litre	Alternator belt re-tensioned

05-11-2007	Baseline 003	BL003-110	red diesel	M&W batch 1	-			Excessive smoke from exhaust at peak power.
							+ 0.5 litre	
06-11-2007	Daytrawl 002	DT002-105	red diesel	M&W batch 1	C			Additive mixed 1:4000
								Alternator belt re-tensioned. Prop. shaft greased.
07-11-2007	Baseline 003	-	red diesel	M&W batch 1	-			Auto shut down after 10 minutes – oil temperature. Oil temp. sensor failure.
								Oil temp. sensor replaced
09-11-2007	Baseline 003	BL003-111	red diesel	M&W batch 1	-			
09-11-2007	Daytrawl 002	DT002-106	red diesel	M&W batch 1	D			Additive mixed 1:2000
							+1.5 litre	Broken timing cover bolt
12-11-2007	Baseline 003	BL003-112	red diesel	M&W batch 1	-			Excessive smoke from exhaust at peak power.
							+ 0.5 litre	Timing cover bolt replaced. Valve clearances checked – minor adjustments made. Engine fuel filter replaced. Oil filter replaced. Air filter inspected - OK
13-11-2007	Baseline 003	BL003-113	red diesel	M&W batch 1	-			
							+ 1 litre	Prop. shaft greased
14-11-2007	Daytrawl 002	DT002-107	red diesel	M&W batch 2	-			New red diesel batch

							+ 0.5 litre	
15-11-2007	Baseline 003	BL003-114	red diesel	M&W batch 2	-			
15-11-2007	Daytrawl 002	DT002-108	red diesel	M&W batch 2	E			Additive mixed 1:1000
							+ 1 litre	
16-11-2007	Baseline 003	BL003-115	red diesel	M&W batch 2	-			
20-11-2007	Daytrawl 002	DT002-109	red diesel	M&W batch 2	F			Additive mixed 1:2500
							+ 0.5 litre	Prop. shaft greased
21-11-2007	Baseline 003	BL003-116	red diesel	M&W batch 2	-			
21-11-2007	Daytrawl 002	DT002-110	red diesel	M&W batch 2	G			Additive mixed 1:1000
22-11-2007	Baseline 003	BL003-117	red diesel	M&W batch 2	-			
							+ 0.5 litre	Alternator belt re-tensioned
23-11-2007	Daytrawl 002	DT002-111	red diesel	M&W batch 2	-			
							+ 0.5 litre	Prop. shaft greased
26-11-2007	Baseline 003	BL003-118	red diesel	M&W batch 2	-			
26-11-2007	Baseline 003	BL003-119	methyl ester	M&W to BS 14214				
26-11-2007	Daytrawl 002	DT002-112	methyl ester	M&W to BS 14214				
30-11-2007	Baseline 003	BL003-120	methyl ester	M&W to BS 14214				
								Prop. shaft greased
30-11-2007	Baseline 003	-	methyl ester	made on site – waste oil				Test aborted – fuel feed pump not operating. Signal failure in control unit. Alternative signal wired in.
03-12-2007	Baseline 003	-	methyl ester	made on site – waste oil				Reluctant engine start up.

								Test aborted - Fuel feed too slow.
								In line fuel filter replaced
03-12-2007	Baseline 003	-	methyl ester	made on site – waste oil				Test aborted – fuel feed still too slow.
								In line fuel filter removed
03-12-2007	Baseline 003	BL003-121	methyl ester	made on site – waste oil				
							+ 0.5 litre	
04-12-2007	Daytrawl 002	DT002-113	methyl ester	made on site – waste oil				Reluctant engine start up
								Prop. shaft greased. Engine fuel filter replaced.
06-12-2007	Baseline 003	-	red diesel	M&W batch 2	-			Very reluctant engine start up. Test aborted – compression in crankcase ejecting oil. Significant breakdown.

Note: All mixing ratios are as per manufacturers instructions. Where instructions call for double dose on first batch, this has been done. Mixing ratios presented in the table take account of this.

Appendix 5 : Detailed specification of Baseline test schedules

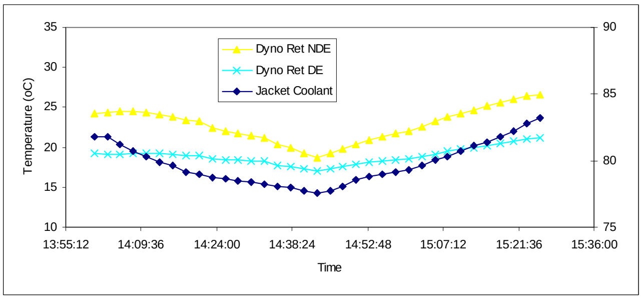
Baseline 002

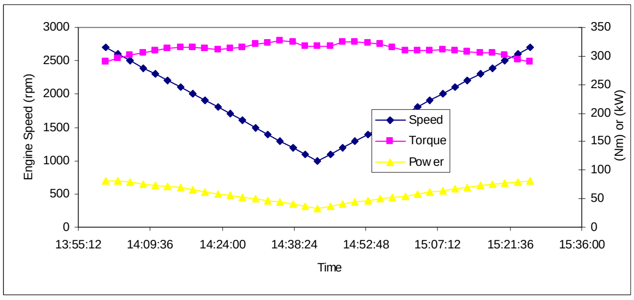
Stage	Description	Interstage Ramp Duration	Interstage Settling Period	Stage Duration	Total Duration	Dyno (Nm)	Speed (rpm)	Throttle (%)
1	Set Up	0	00:00:00	0	0:00:00			
2	Pre-heat	0	00:00:00	00:00:20	0:00:20			
3	Crank	0	00:00:00	00:01:00	0:01:00			
4	Warm Up 30	00:00:05	00:00:00	01:00:00	1:00:05	30	1400	
5	Warm Up 60	00:00:05	00:00:00	01:00:00	1:00:05	60	1600	
6	Warm Up 75	00:00:05	00:00:00	01:00:00	1:00:05	90	1800	
	Total start up time							
7	Ramping 1500/50	00:00:10	00:00:00	00:00:10	0:00:20		1500	50
8	Ramping 1700/57	00:00:10	00:00:00	00:00:10	0:00:20		1700	57
9	Ramping 1900/64	00:00:10	00:00:00	00:00:10	0:00:20		1900	64
10	Ramping 2100/71	00:00:10	00:00:00	00:00:10	0:00:20		2100	71
11	Ramping 2300/78	00:00:10	00:00:00	00:00:10	0:00:20		2300	78
12	Ramping 2500/85	00:00:10	00:00:00	00:00:10	0:00:20		2500	85
13	TP1	00:00:10	00:01:00	00:01:20	0:02:30		2700	100
14	TP2	00:00:10	00:01:00	00:01:20	0:02:30		2600	100
15	TP3	00:00:10	00:01:00	00:01:20	0:02:30		2500	100
16	TP4	00:00:10	00:01:00	00:01:20	0:02:30		2400	100
17	TP5	00:00:10	00:01:00	00:01:20	0:02:30		2300	100
18	TP6	00:00:10	00:01:00	00:01:20	0:02:30		2200	100
19	TP7	00:00:10	00:01:00	00:01:20	0:02:30		2100	100
20	TP8	00:00:10	00:01:00	00:01:20	0:02:30		2000	100
21	TP9	00:00:10	00:01:00	00:01:20	0:02:30		1900	100
22	TP10	00:00:10	00:01:00	00:01:20	0:02:30		1800	100
23	TP11	00:00:10	00:01:00	00:01:20	0:02:30		1700	100
24	TP12	00:00:10	00:01:00	00:01:20	0:02:30		1600	100
25	TP13	00:00:10	00:01:00	00:01:20	0:02:30		1500	100
26	TP14	00:00:10	00:01:00	00:01:20	0:02:30		1400	100
27	TP15	00:00:10	00:01:00	00:01:20	0:02:30		1300	100
28	TP16	00:00:10	00:01:00	00:01:20	0:02:30		1200	100
29	TP17	00:00:10	00:01:00	00:01:20	0:02:30		1100	100
30	TP18	00:00:10	00:01:00	00:01:20	0:02:30		1000	100
31	TP19	00:00:10	00:01:00	00:01:20	0:02:30		1100	100
32	TP20	00:00:10	00:01:00	00:01:20	0:02:30		1200	100
33	TP21	00:00:10	00:01:00	00:01:20	0:02:30		1300	100
34	TP22	00:00:10	00:01:00	00:01:20	0:02:30		1400	100
35	TP23	00:00:10	00:01:00	00:01:20	0:02:30		1500	100
36	TP24	00:00:10	00:01:00	00:01:20	0:02:30		1600	100
37	TP25	00:00:10	00:01:00	00:01:20	0:02:30		1700	100
38	TP26	00:00:10	00:01:00	00:01:20	0:02:30		1800	100
39	TP27	00:00:10	00:01:00	00:01:20	0:02:30		1900	100
40	TP28	00:00:10	00:01:00	00:01:20	0:02:30		2000	100
41	TP29	00:00:10	00:01:00	00:01:20	0:02:30		2100	100
42	TP30	00:00:10	00:01:00	00:01:20	0:02:30		2200	100
43	TP31	00:00:10	00:01:00	00:01:20	0:02:30		2300	100
44	TP32	00:00:10	00:01:00	00:01:20	0:02:30		2400	100
45	TP33	00:00:10	00:01:00	00:01:20	0:02:30		2500	100
46	TP34	00:00:10	00:01:00	00:01:20	0:02:30		2600	100
47	TP35	00:00:10	00:01:00	00:01:20	0:02:30		2700	100
48	Ramping 2700/100	00:00:10	00:00:00	00:00:10	0:00:20		2700	100
49	Ramping 2500/85	00:00:10	00:00:00	00:00:10	0:00:20		2500	85
50	Ramping 2300/78	00:00:10	00:00:00	00:00:10	0:00:20		2300	78
51	Ramping 2100/71	00:00:10	00:00:00	00:00:10	0:00:20		2100	71
52	Ramping 1900/64	00:00:10	00:00:00	00:00:10	0:00:20		1900	64
53	Ramping 1700/57	00:00:10	00:00:00	00:00:10	0:00:20		1700	57
54	Ramping 1500/50	00:00:10	00:00:00	00:00:10	0:00:20		1500	50
55	Cool Down 2	00:00:30	00:00:00	00:01:00	0:01:30	30	2000	
56	Cool Down 1	00:00:10	00:00:00	00:01:00	0:01:10	0	1300	
	Test duration				1:34:30			
57	Set Offline	00:00:10	00:00:00	00:01:00	0:01:10	0%		0%
58	Stop Engine	00:00:10	00:00:00	00:01:00	0:01:10			
59	End Test	00:00:00	00:00:00	00:05:00	0:05:00			

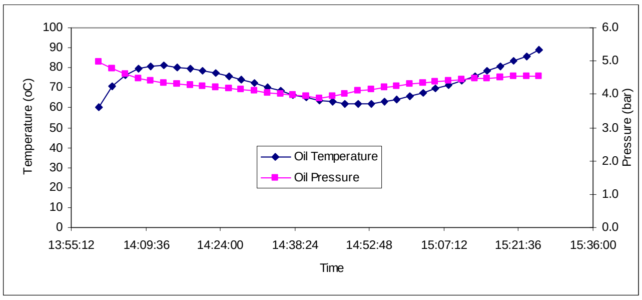
Baseline 003

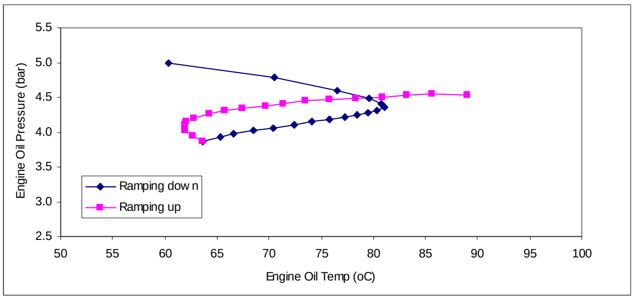
Stage	Description	Interstage Ramp Duration	Interstage Settling Period	Stage Duration	Total Duration	Dyno (Nm)	Speed (rpm)	Throttle (%)
1	Set Up	0	00:00:00	0	0:00:00			
2	Pre-heat	0	00:00:00	00:00:20	0:00:20			
3	Crank	0	00:00:00	00:01:00	0:01:00			
4	Warm Up 30	00:00:05	00:00:00	01:00:00	1:00:05	30	1400	
5	Warm Up 60	00:00:05	00:00:00	01:00:00	1:00:05	60	1600	
6	Warm Up 75	00:00:05	00:00:00	01:00:00	1:00:05	90	1800	
	Total start up time							
7	Ramping 1500/50	00:00:10	00:00:00	00:00:10	0:00:20		1500	50
8	Ramping 1700/57	00:00:10	00:00:00	00:00:10	0:00:20		1700	57
9	Ramping 1900/64	00:00:10	00:00:00	00:00:10	0:00:20		1900	64
10	Ramping 2100/71	00:00:10	00:00:00	00:00:10	0:00:20		2100	71
11	Ramping 2300/78	00:00:10	00:00:00	00:00:10	0:00:20		2300	78
12	Ramping 2500/85	00:00:10	00:00:00	00:00:10	0:00:20		2500	85
	Ramping 2500/100	00:00:10	00:00:00	00:00:10	0:00:20		2500	100
13	TP1	00:00:10	00:01:00	00:01:20	0:02:30		2500	100
14	TP2	00:00:10	00:01:00	00:01:20	0:02:30		2400	100
15	TP3	00:00:10	00:01:00	00:01:20	0:02:30		2300	100
16	TP4	00:00:10	00:01:00	00:01:20	0:02:30		2200	100
17	TP5	00:00:10	00:01:00	00:01:20	0:02:30		2100	100
18	TP6	00:00:10	00:01:00	00:01:20	0:02:30		2000	100
19	TP7	00:00:10	00:01:00	00:01:20	0:02:30		1900	100
20	TP8	00:00:10	00:01:00	00:01:20	0:02:30		1800	100
21	TP9	00:00:10	00:01:00	00:01:20	0:02:30		1700	100
22	TP10	00:00:10	00:01:00	00:01:20	0:02:30		1600	100
23	TP11	00:00:10	00:01:00	00:01:20	0:02:30		1500	100
24	TP12	00:00:10	00:01:00	00:01:20	0:02:30		1400	100
25	TP13	00:00:10	00:01:00	00:01:20	0:02:30		1300	100
26	TP14	00:00:10	00:01:00	00:01:20	0:02:30		1200	100
27	TP15	00:00:10	00:01:00	00:01:20	0:02:30		1100	100
28	TP16	00:00:10	00:01:00	00:01:20	0:02:30		1000	100
29	TP17	00:00:10	00:01:00	00:01:20	0:02:30		1100	100
30	TP18	00:00:10	00:01:00	00:01:20	0:02:30		1200	100
31	TP19	00:00:10	00:01:00	00:01:20	0:02:30		1300	100
32	TP20	00:00:10	00:01:00	00:01:20	0:02:30		1400	100
33	TP21	00:00:10	00:01:00	00:01:20	0:02:30		1500	100
34	TP22	00:00:10	00:01:00	00:01:20	0:02:30		1600	100
35	TP23	00:00:10	00:01:00	00:01:20	0:02:30		1700	100
36	TP24	00:00:10	00:01:00	00:01:20	0:02:30		1800	100
37	TP25	00:00:10	00:01:00	00:01:20	0:02:30		1900	100
38	TP26	00:00:10	00:01:00	00:01:20	0:02:30		2000	100
39	TP27	00:00:10	00:01:00	00:01:20	0:02:30		2100	100
40	TP28	00:00:10	00:01:00	00:01:20	0:02:30		2200	100
41	TP29	00:00:10	00:01:00	00:01:20	0:02:30		2300	100
42	TP30	00:00:10	00:01:00	00:01:20	0:02:30		2400	100
43	TP31	00:00:10	00:01:00	00:01:20	0:02:30		2500	100
44	Ramping 2500/85	00:00:10	00:00:00	00:00:10	0:00:20		2500	85
45	Ramping 2300/78	00:00:10	00:00:00	00:00:10	0:00:20		2300	78
46	Ramping 2100/71	00:00:10	00:00:00	00:00:10	0:00:20		2100	71
47	Ramping 1900/64	00:00:10	00:00:00	00:00:10	0:00:20		1900	64
48	Ramping 1700/57	00:00:10	00:00:00	00:00:10	0:00:20		1700	57
49	Ramping 1500/50	00:00:10	00:00:00	00:00:10	0:00:20		1500	50
50	Cool Down 2	00:00:10	00:00:00	00:00:10	0:00:20		2000	
51	Cool Down 1	00:00:10	00:00:00	00:00:10	0:00:20	30	1300	
52	Test duration	00:00:10	00:00:00	00:00:10	0:00:20	0		
			Total duration		1:22:50			

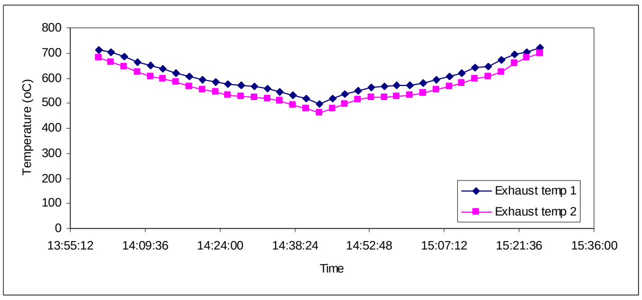
Appendix 6 : Archive of Baseline test results

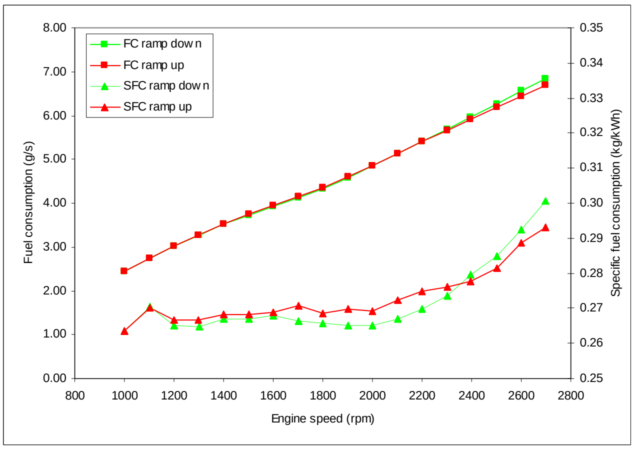


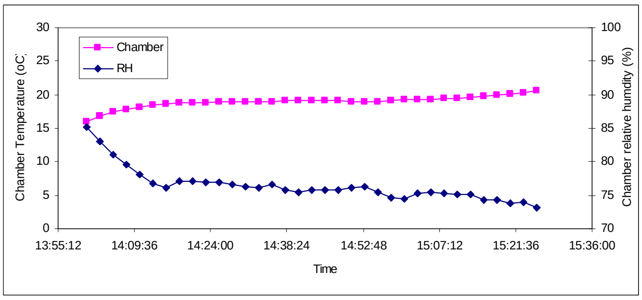


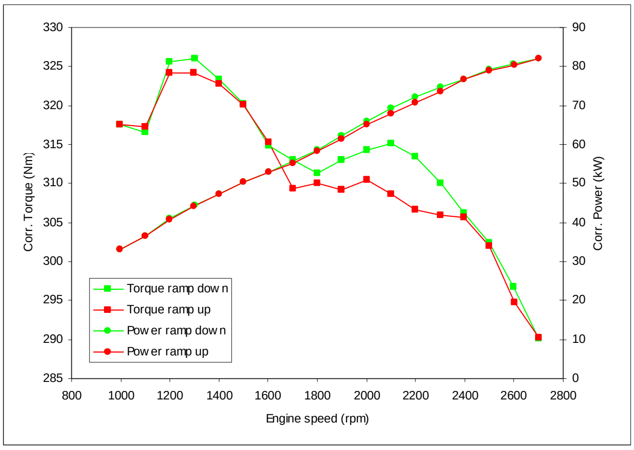


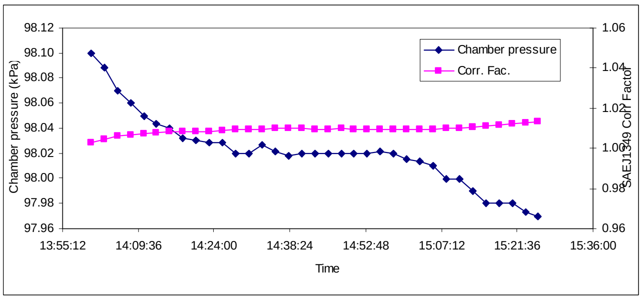






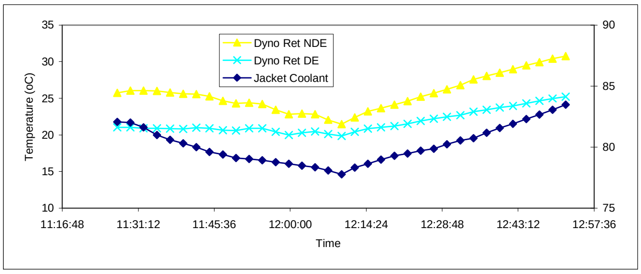


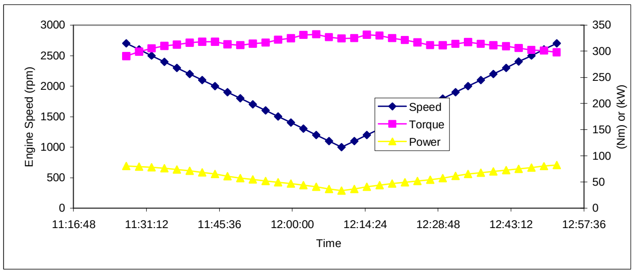


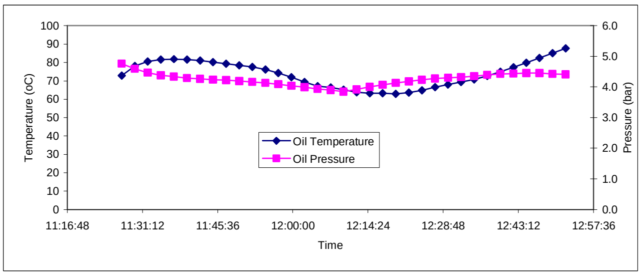


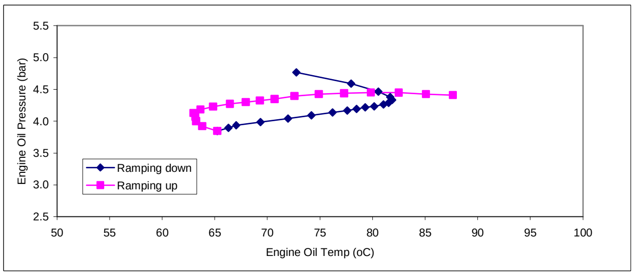
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 13/08/07

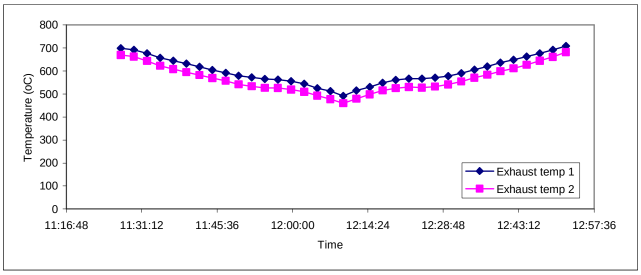
Baseline 002_001

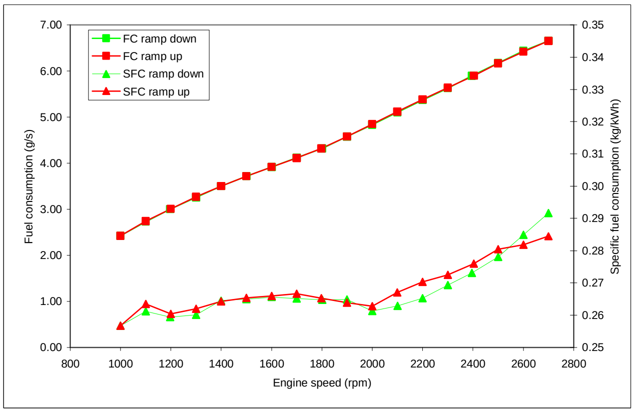


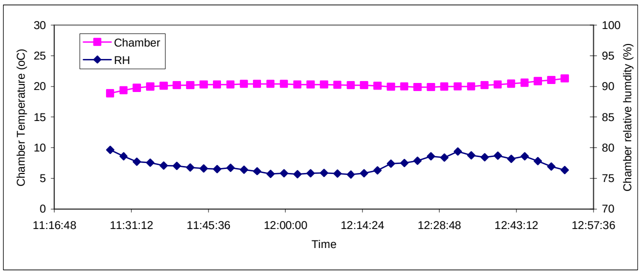


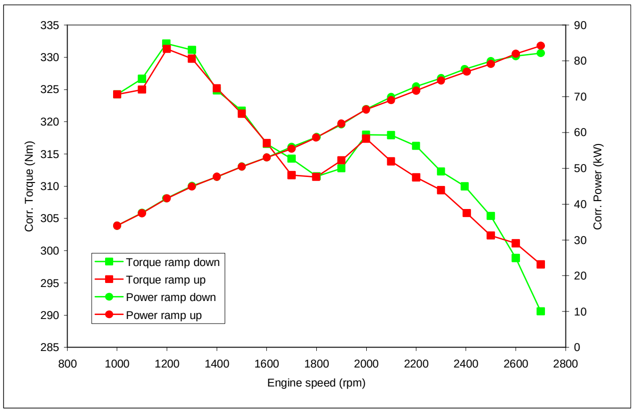


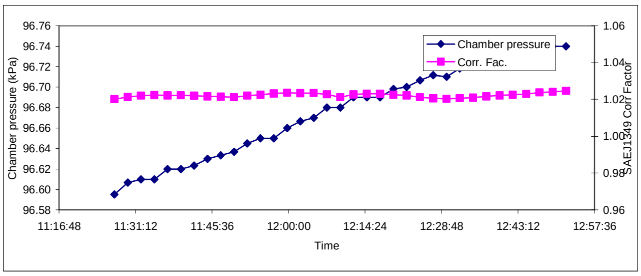






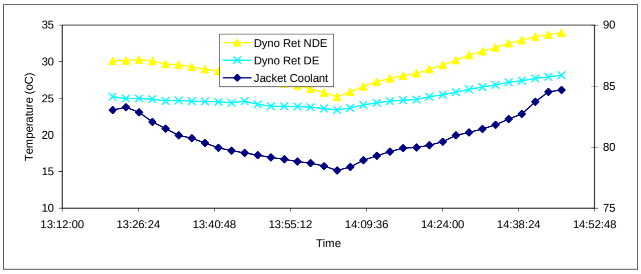


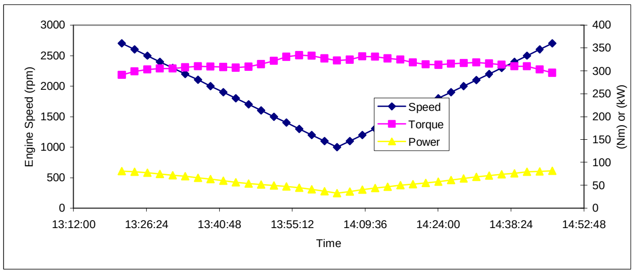


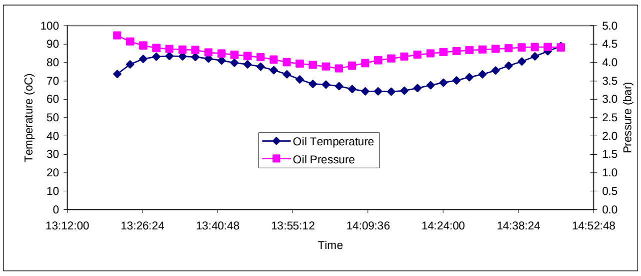


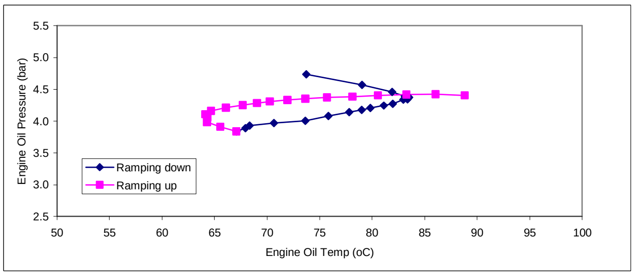
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 15/08/07

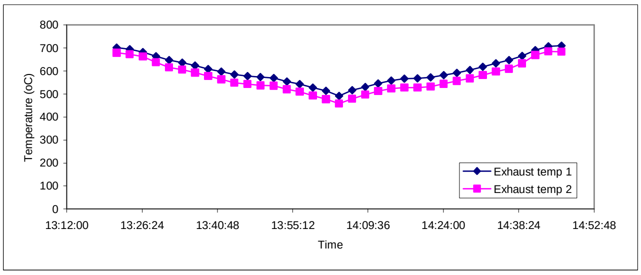
Baseline 002_003D

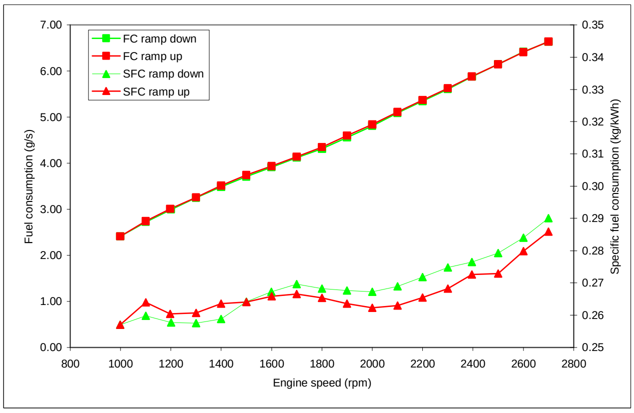


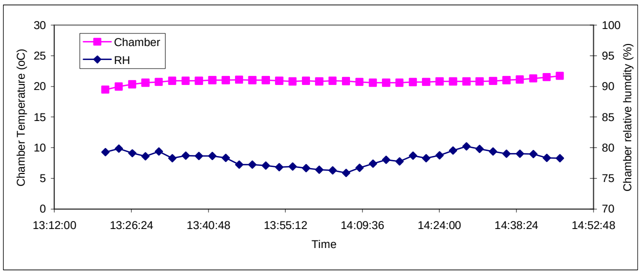


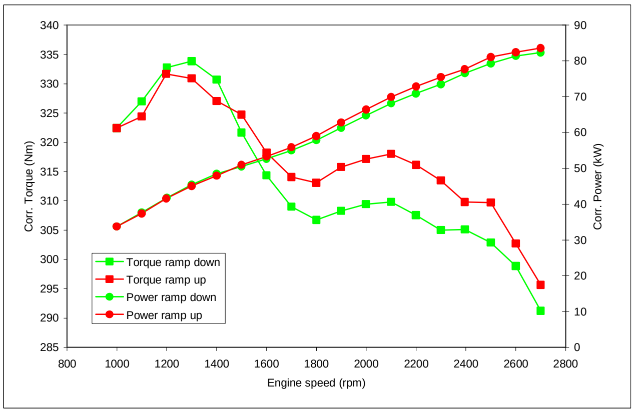


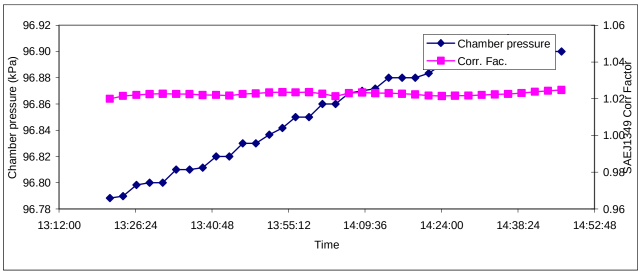






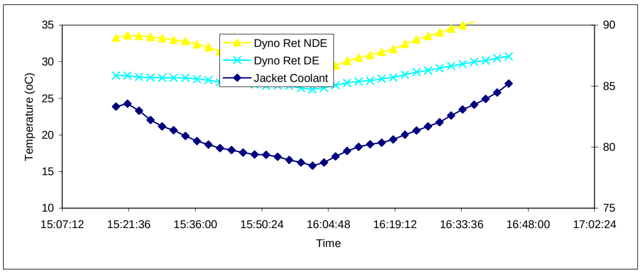


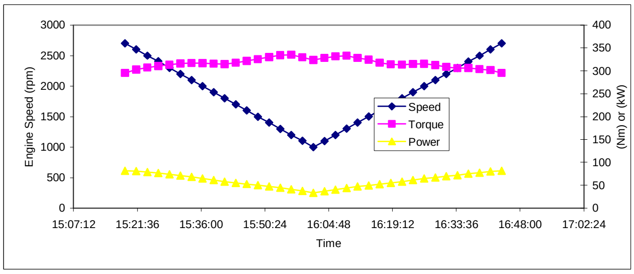


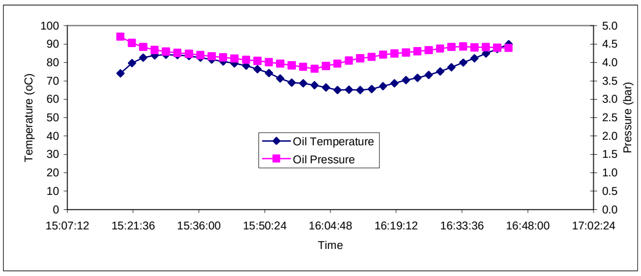


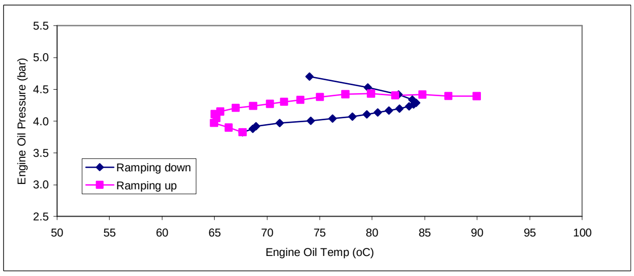
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 15/08/07

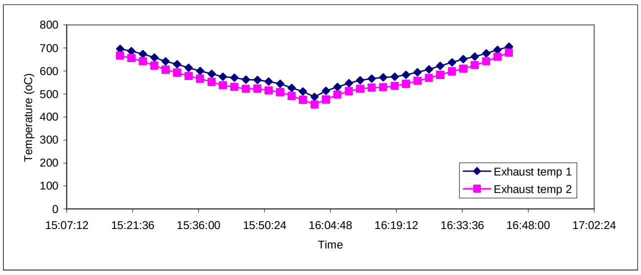
Baseline 002_004

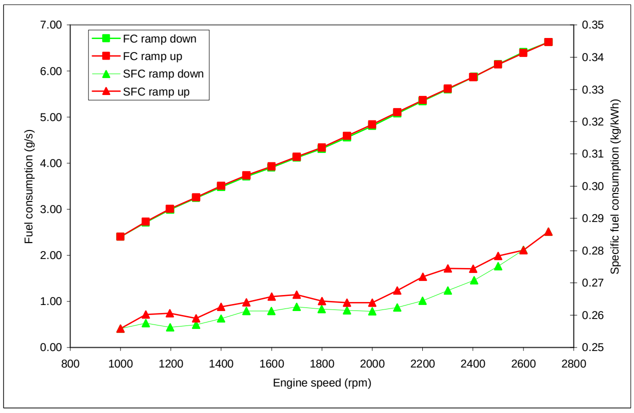


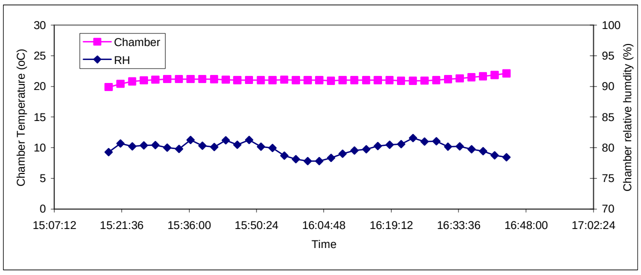


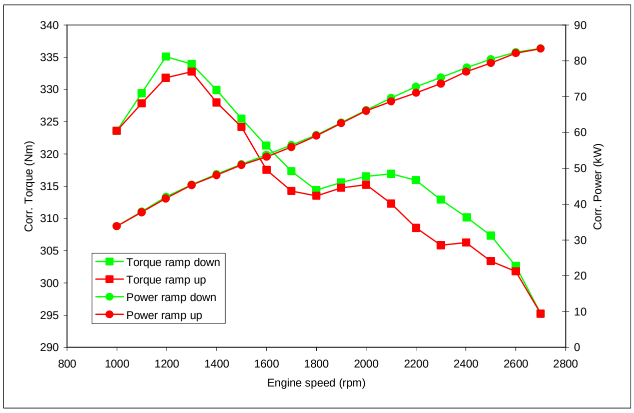


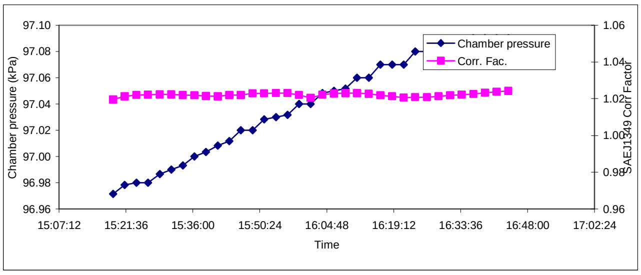






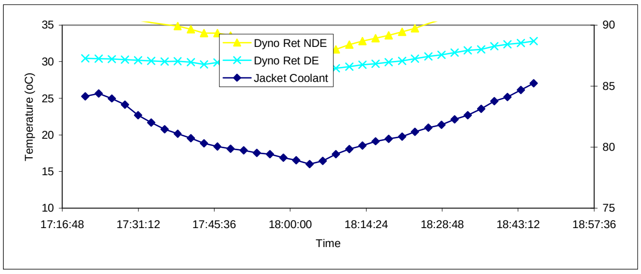


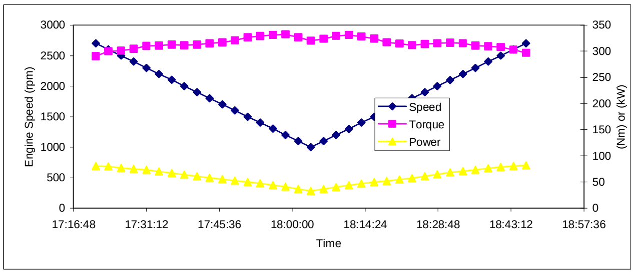


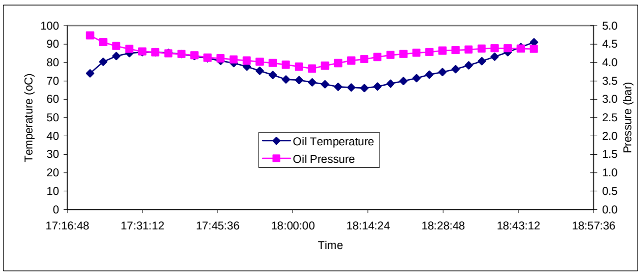


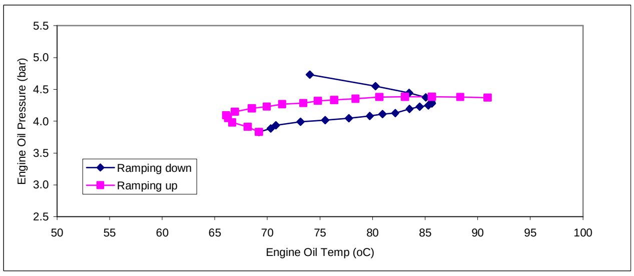
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 15/08/07

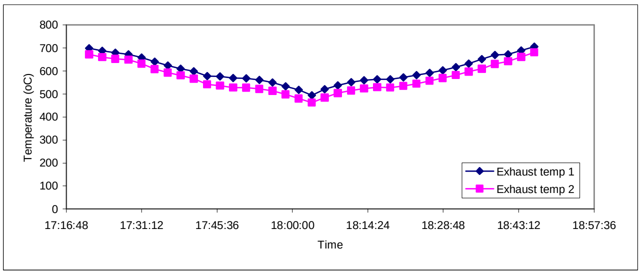
Baseline 002_005

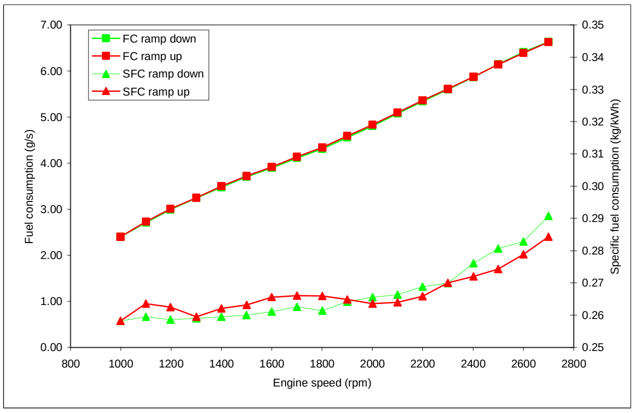


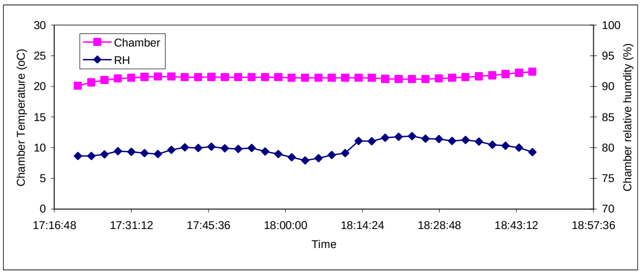


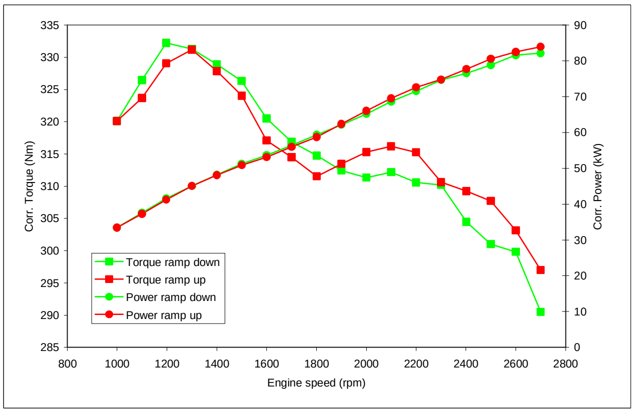


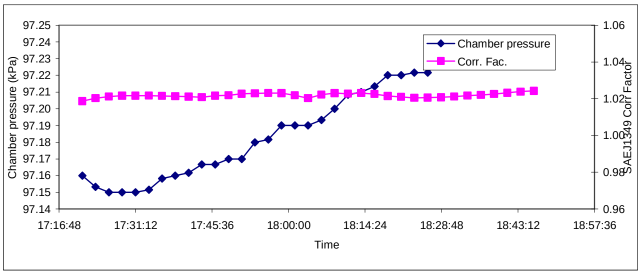






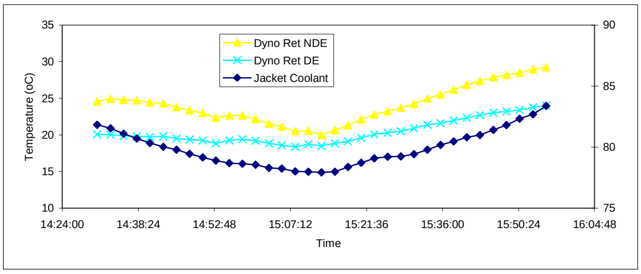


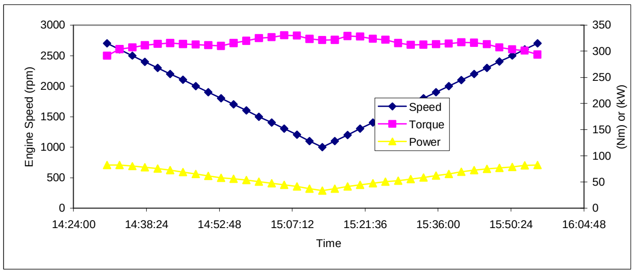


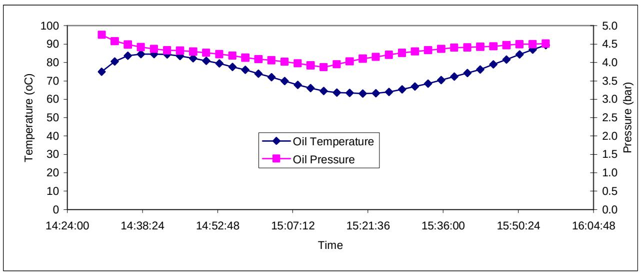


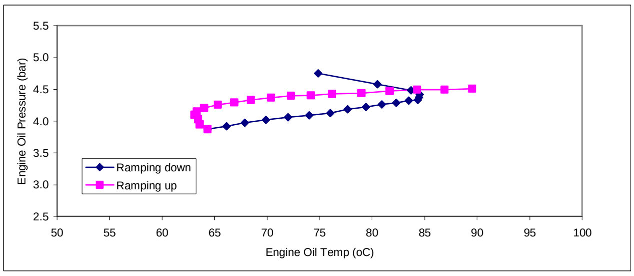
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 15/08/07

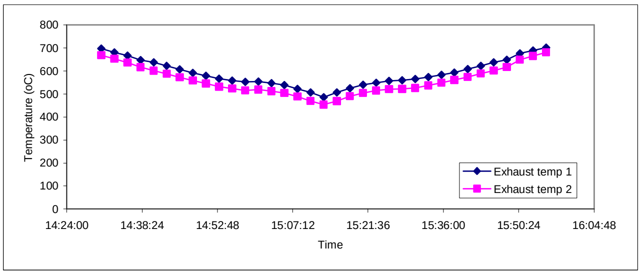
Baseline 002_006

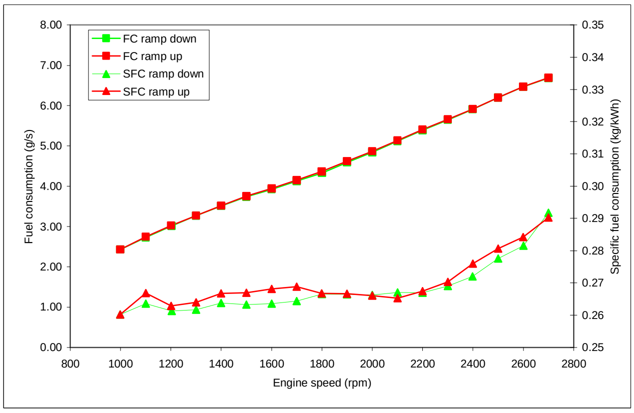


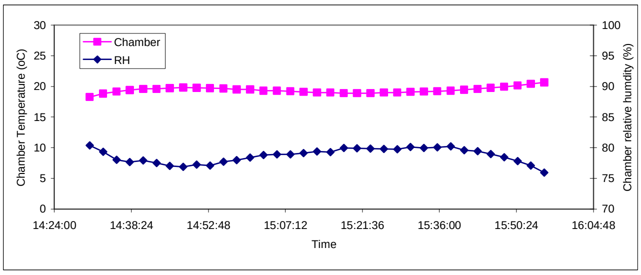


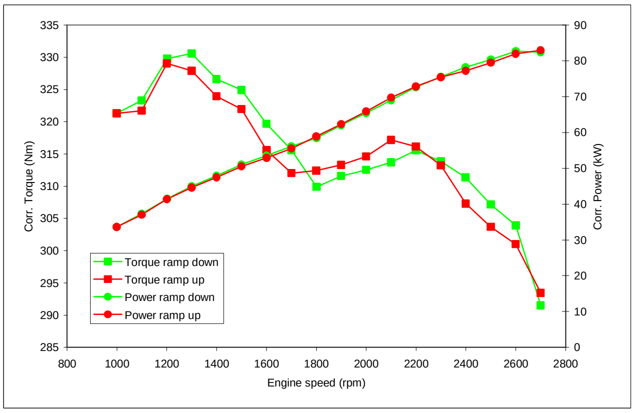


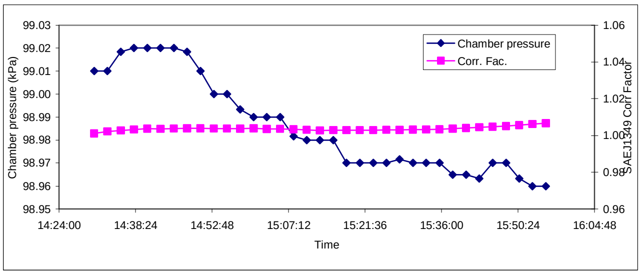






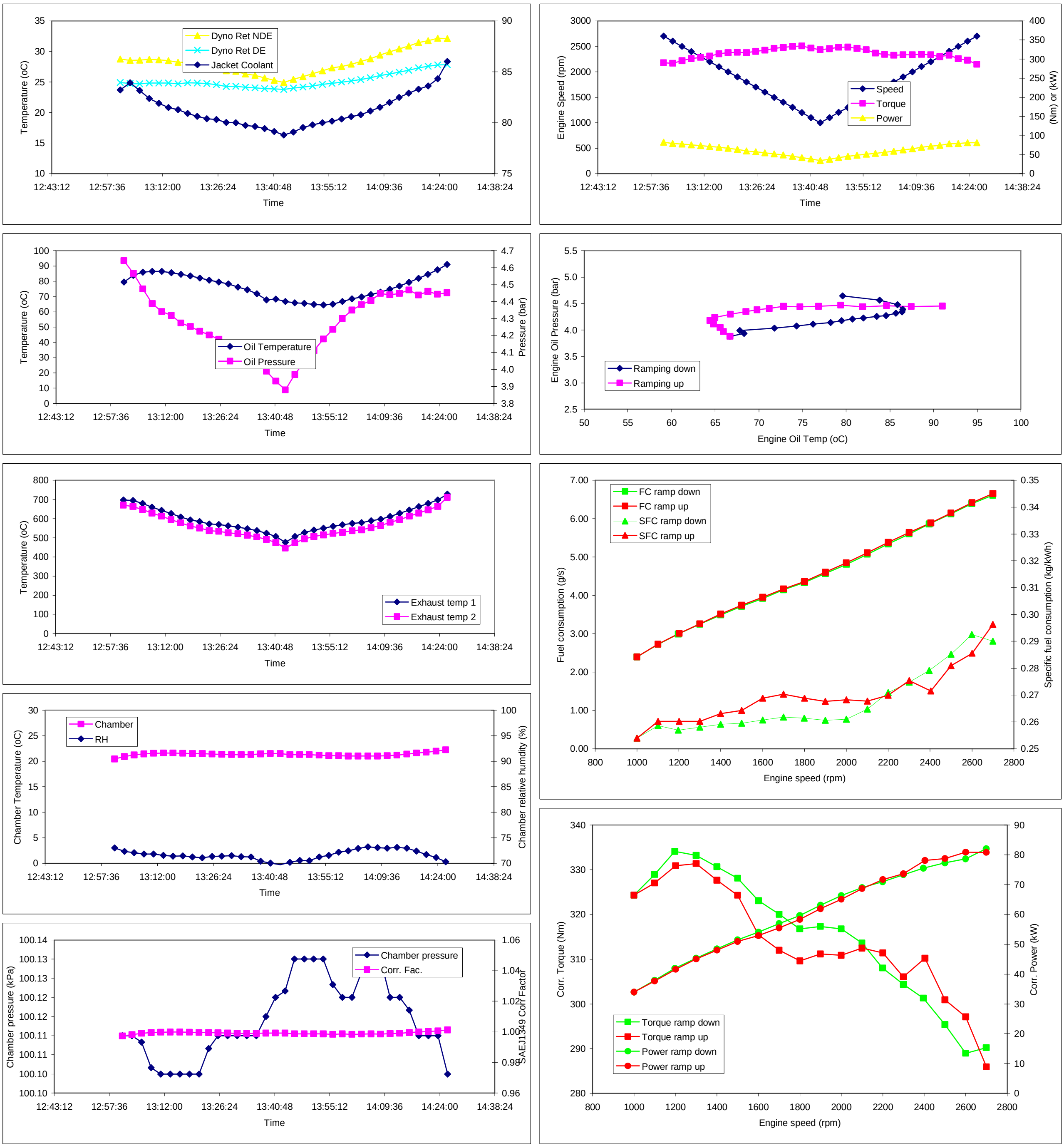






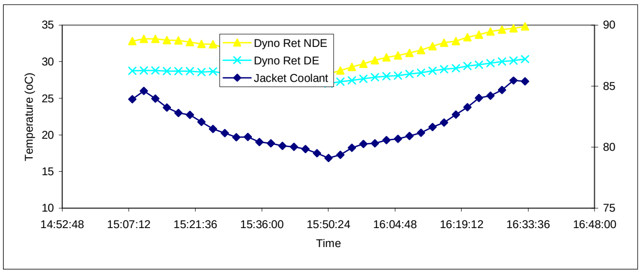
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 22/08/07

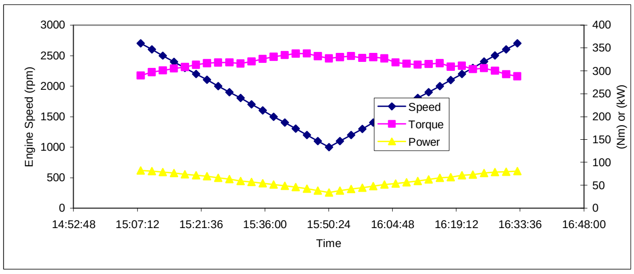
Baseline 002_007

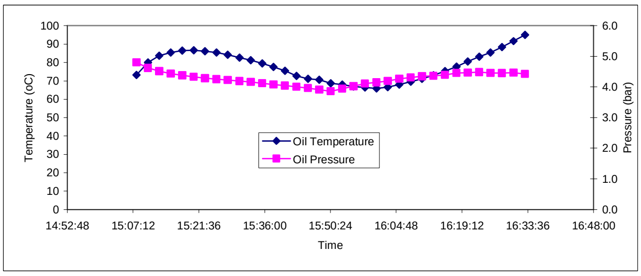


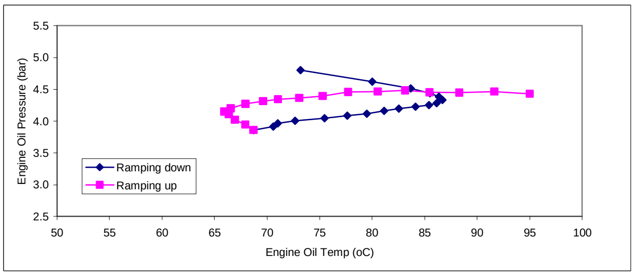
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 05/09/07

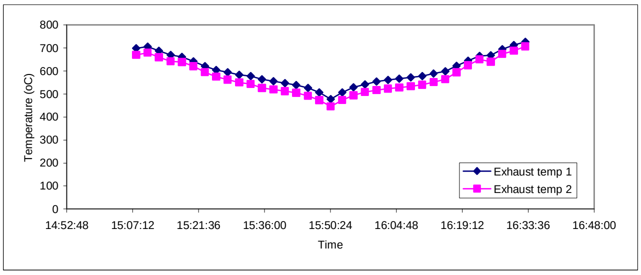
Baseline 002_008

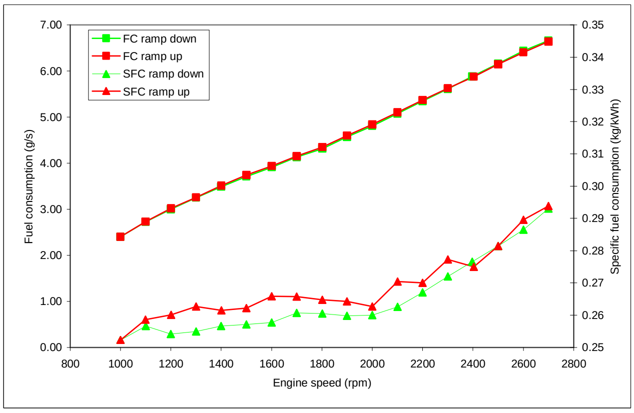


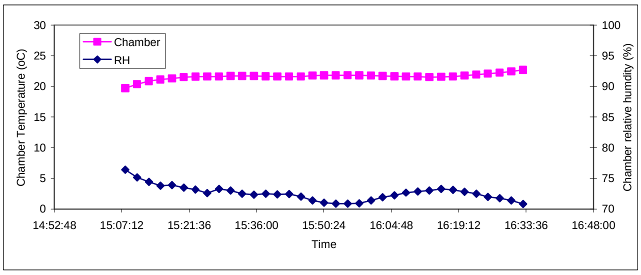


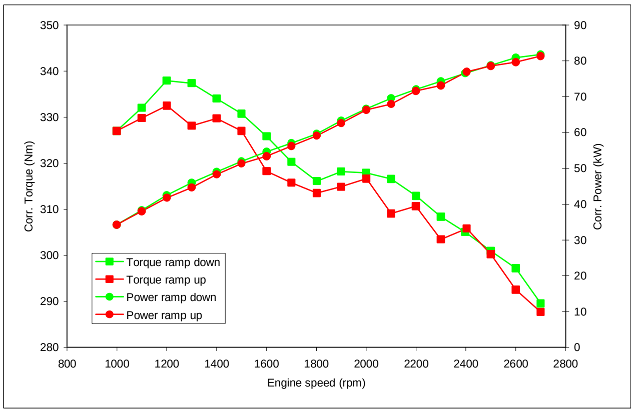


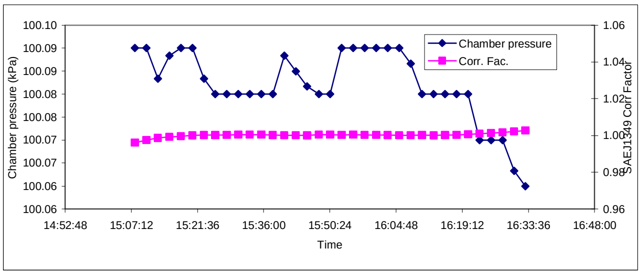






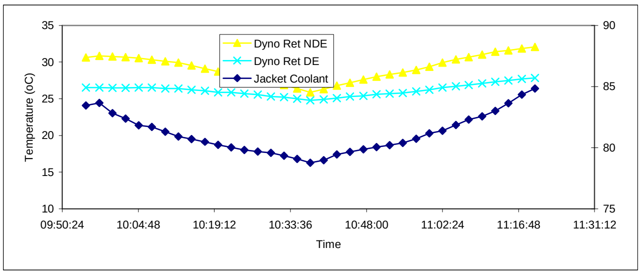


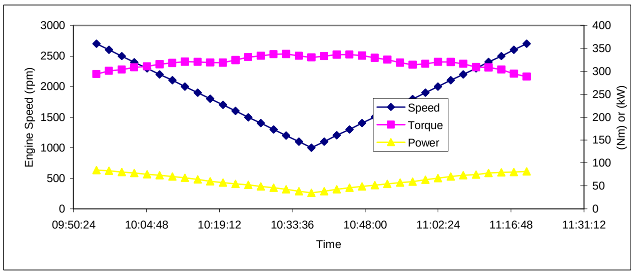


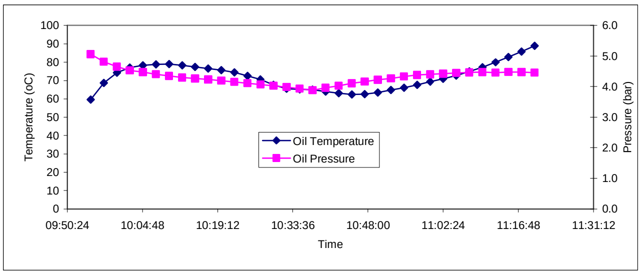


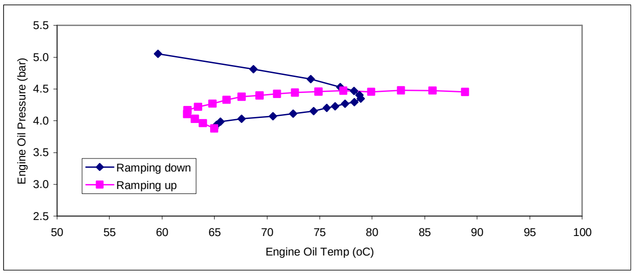
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 05/09/07

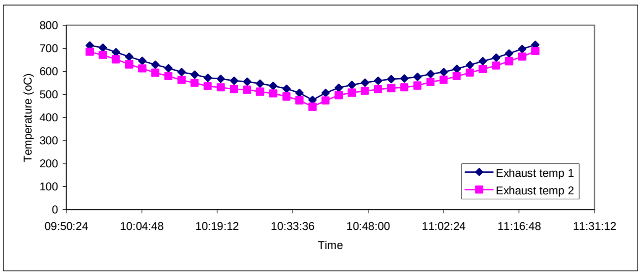
Baseline 002_009

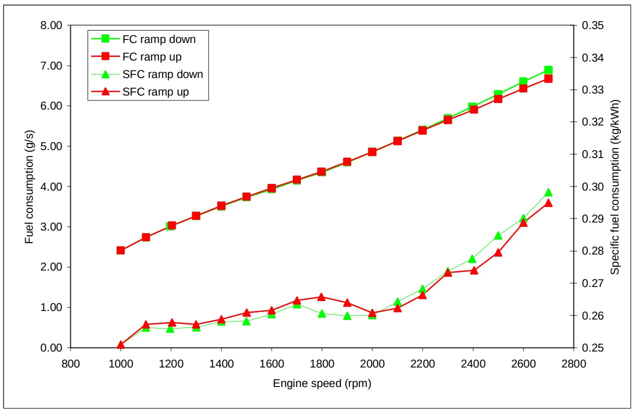


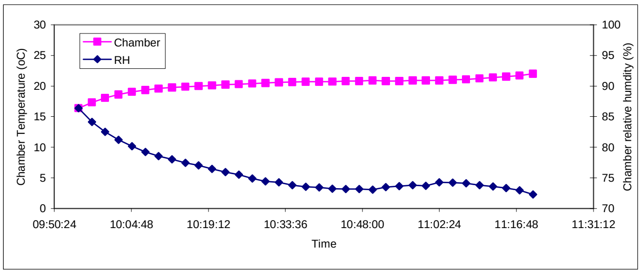


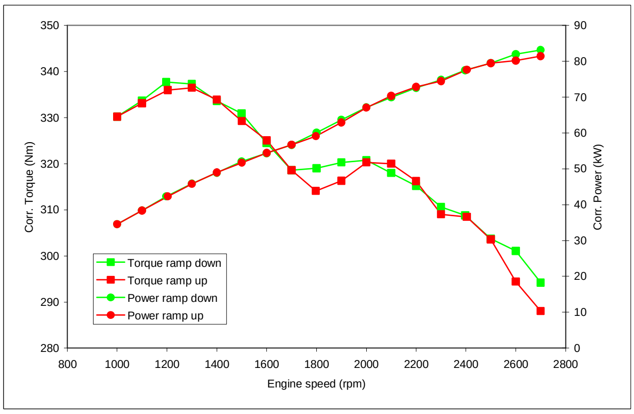


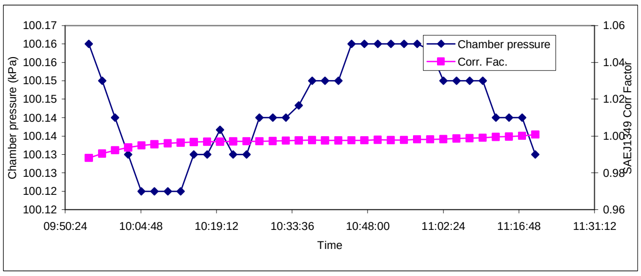






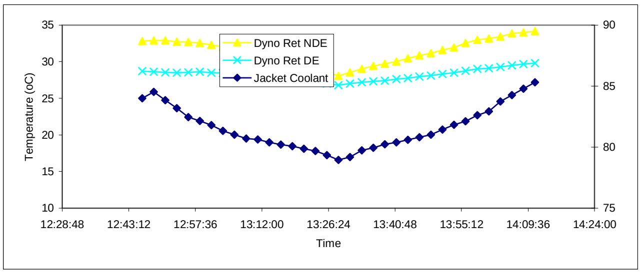


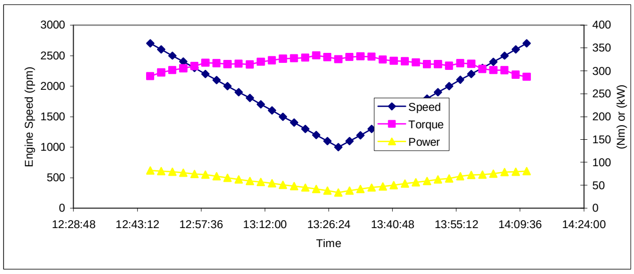


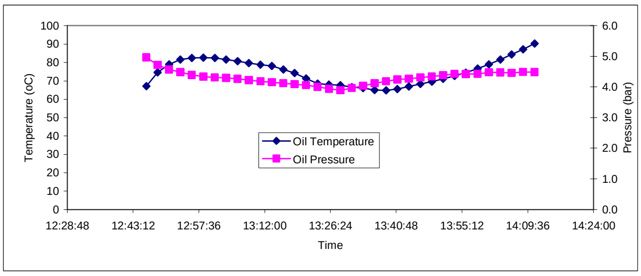


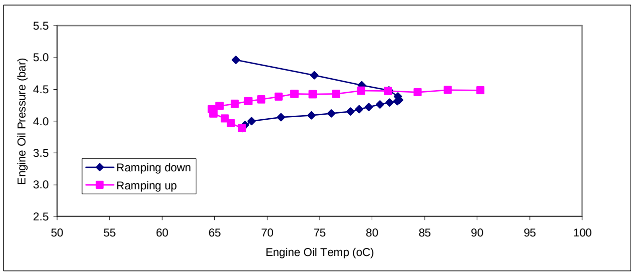
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 06/09/07

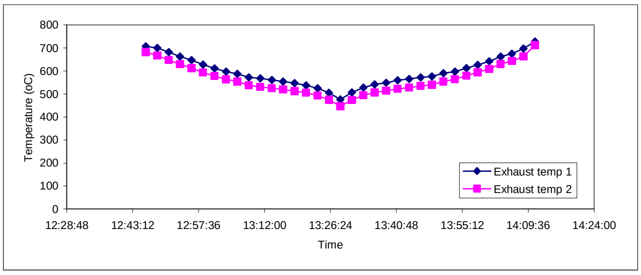
Baseline 002_010

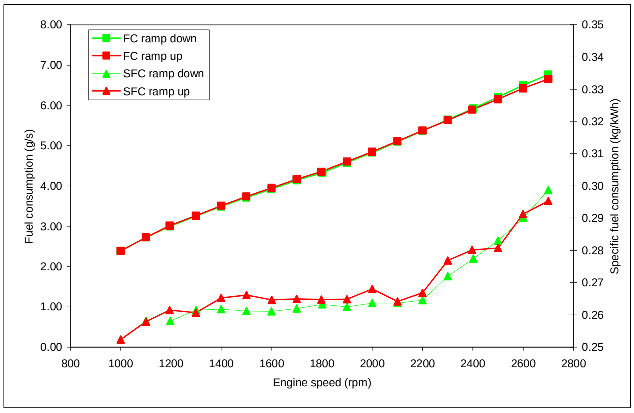


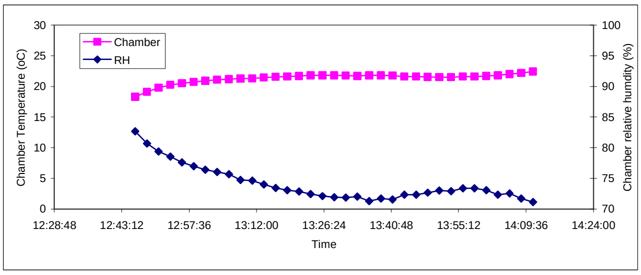


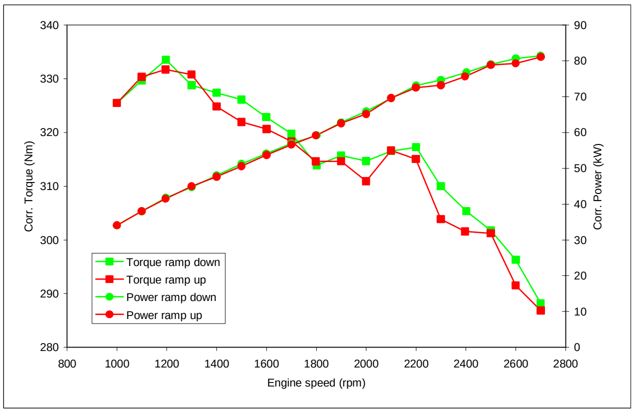


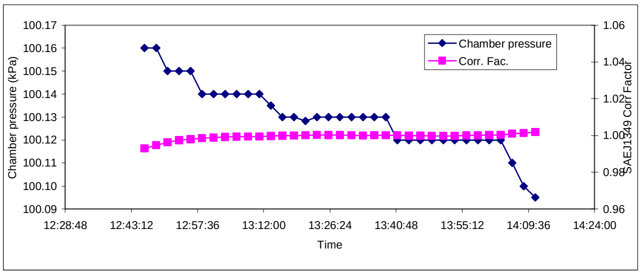






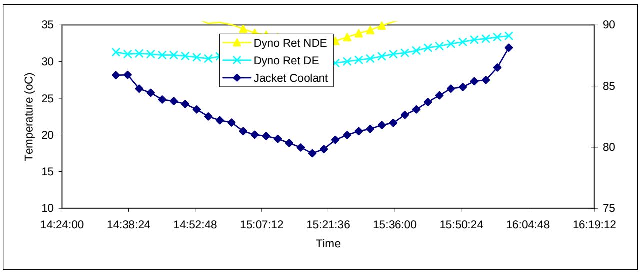


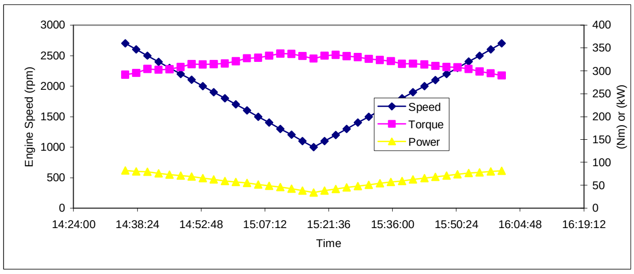


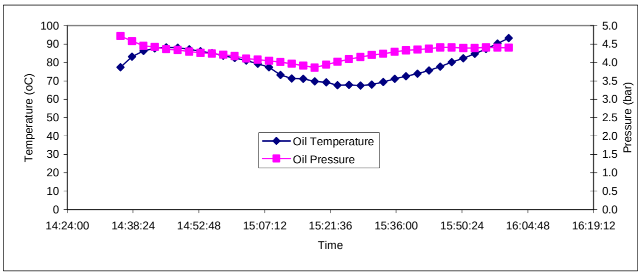


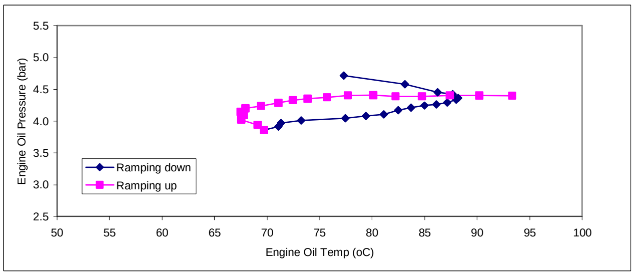
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 06/09/07

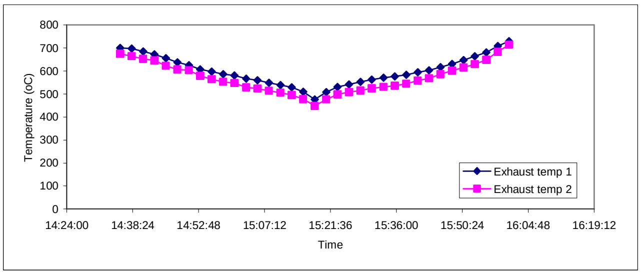
Baseline 002_011

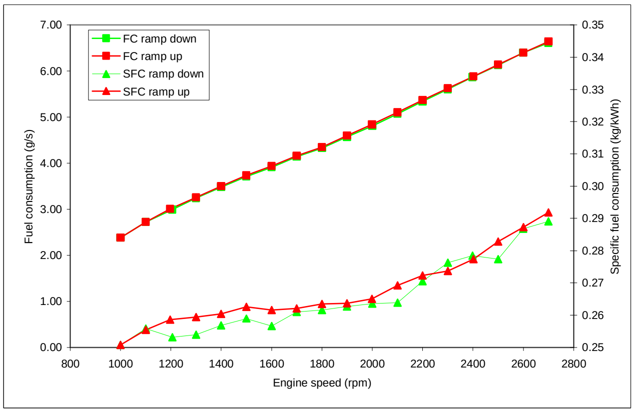


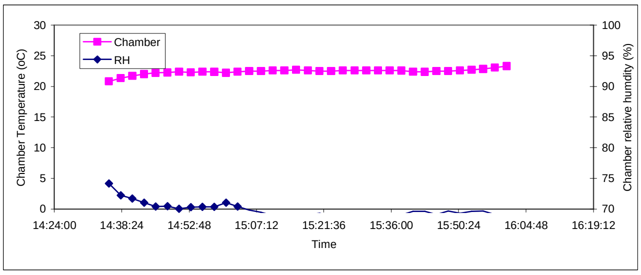


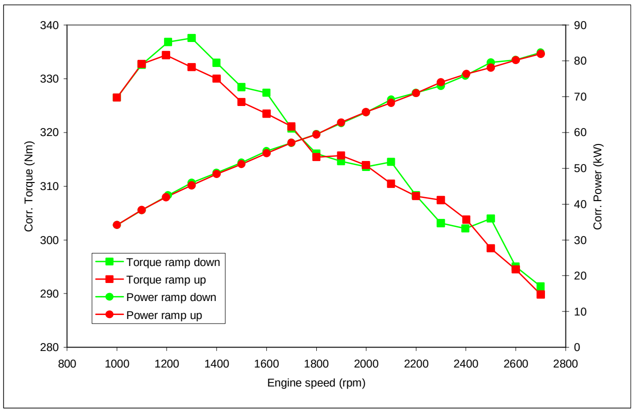


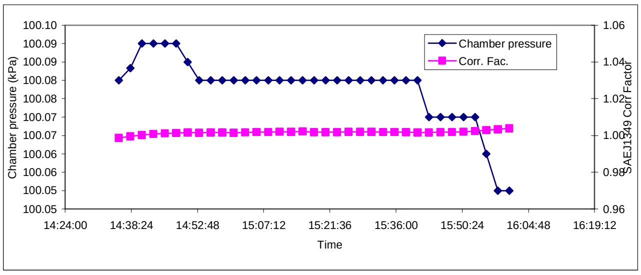






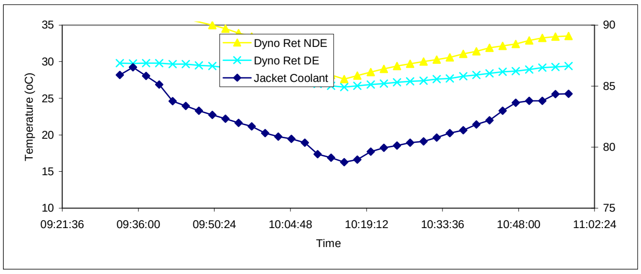


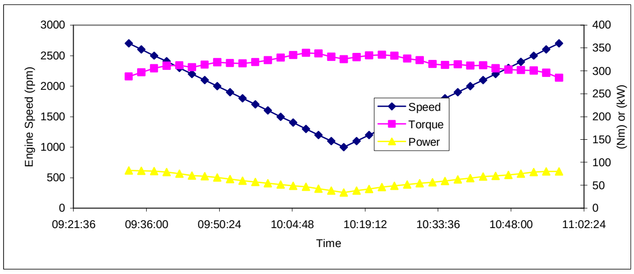


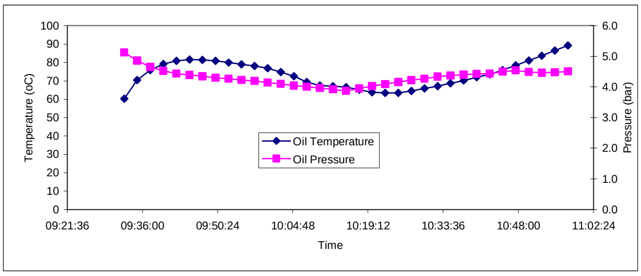


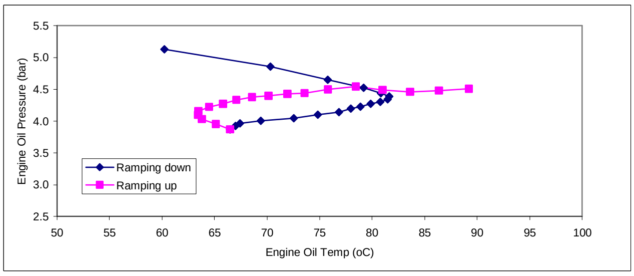
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 06/09/07

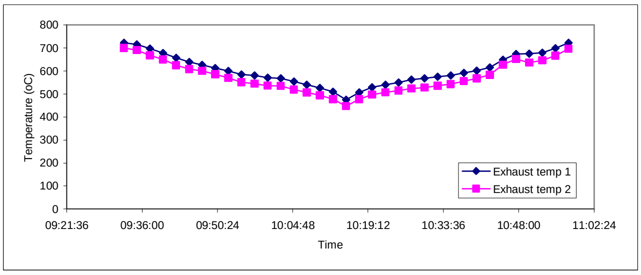
Baseline 002_012

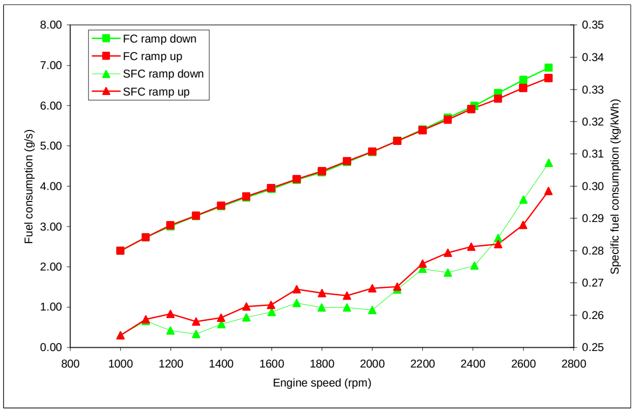


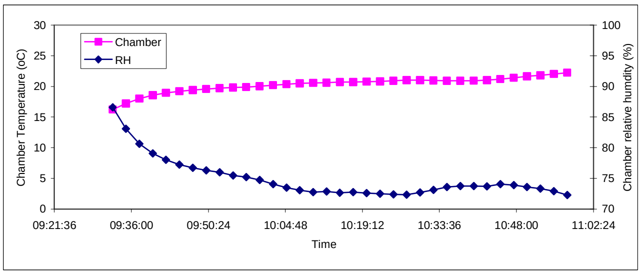


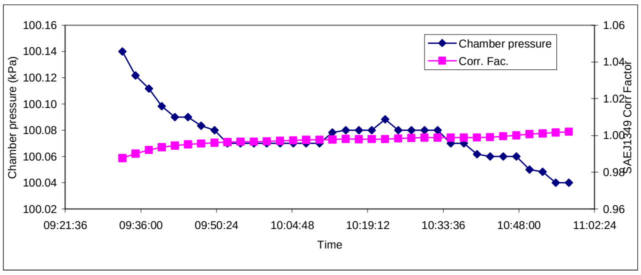


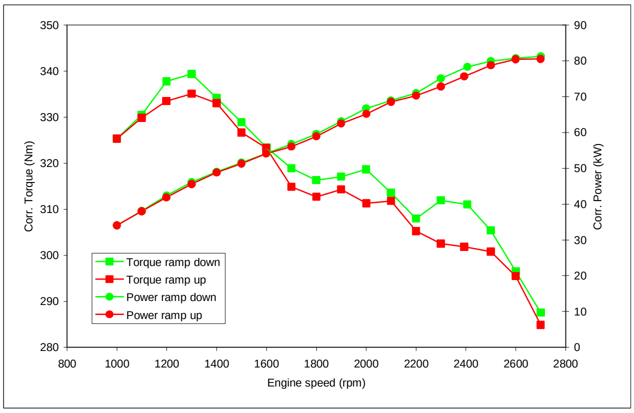






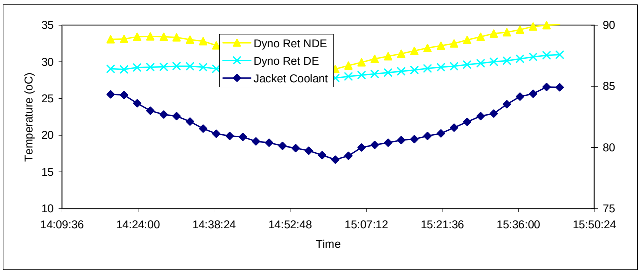


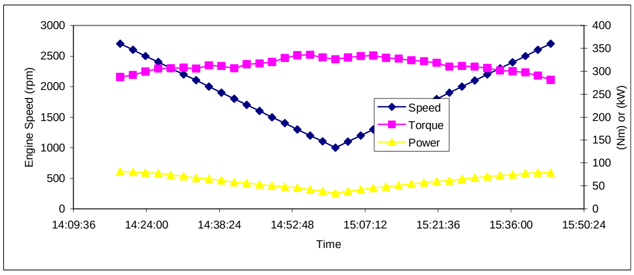


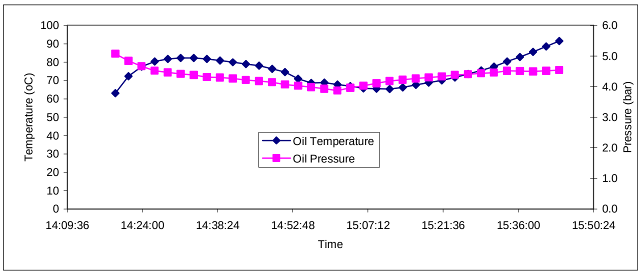


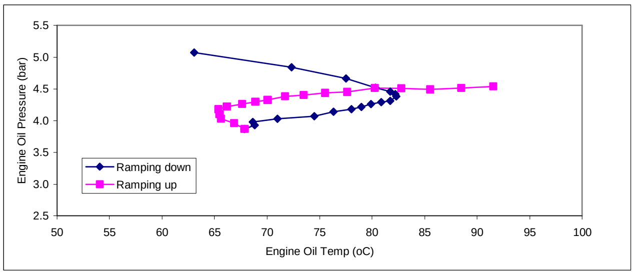
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 07/09/07

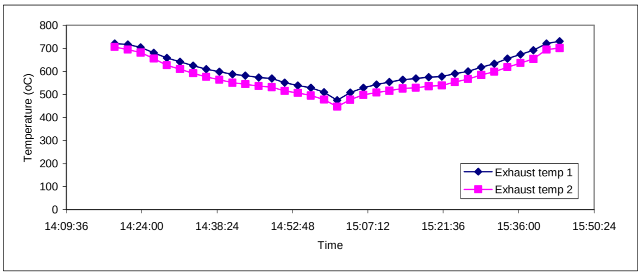
Baseline 002_013

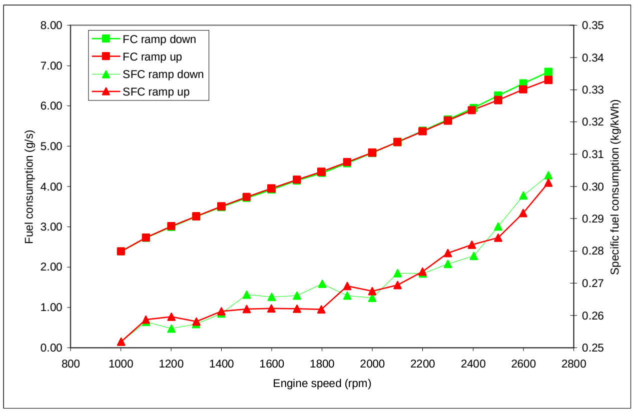


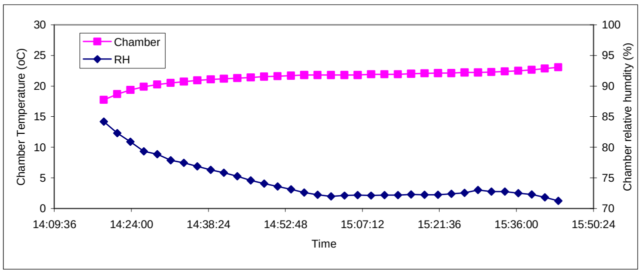


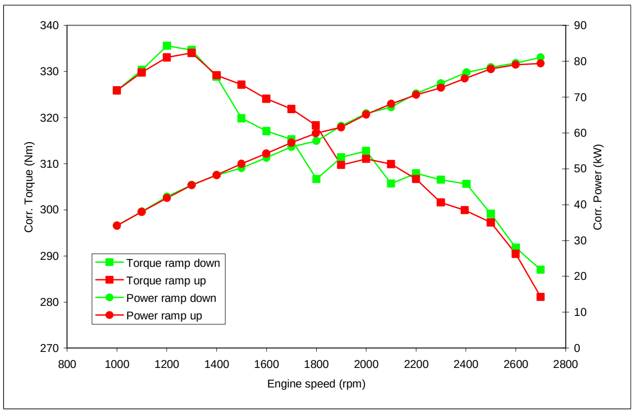


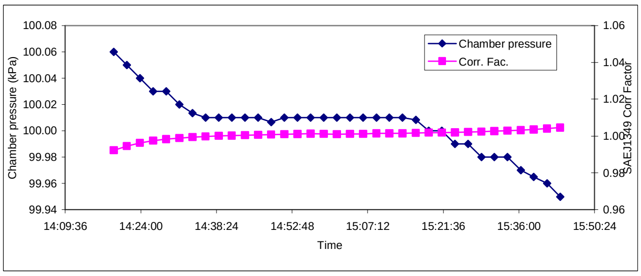






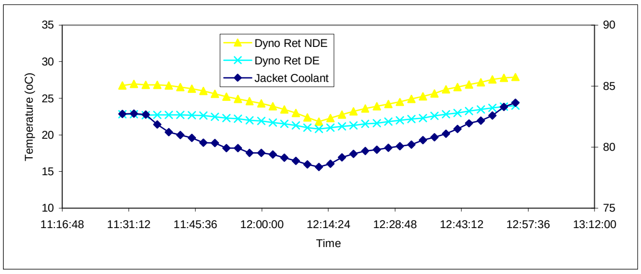


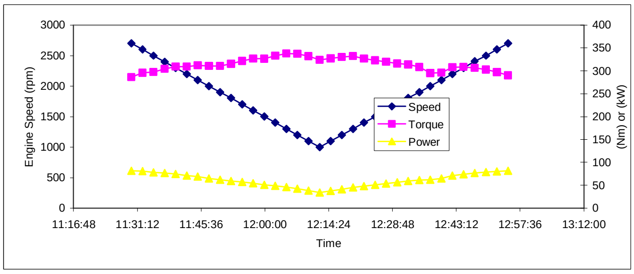


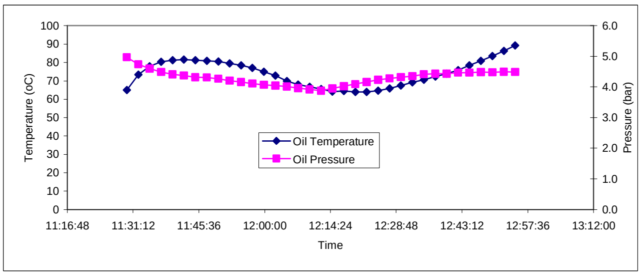


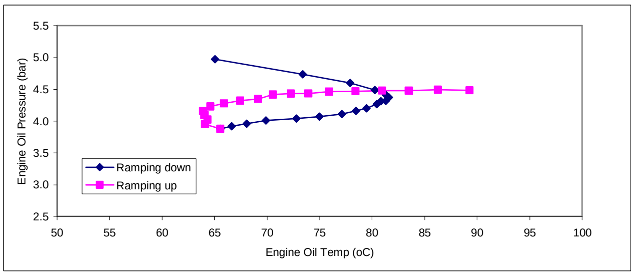
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 07/09/07

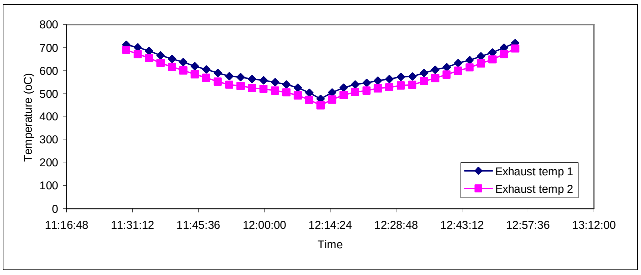
Baseline 002_014

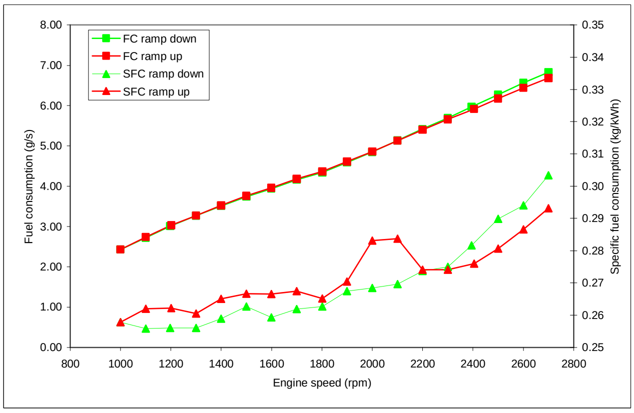


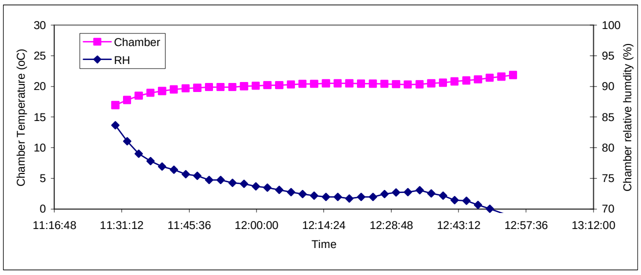


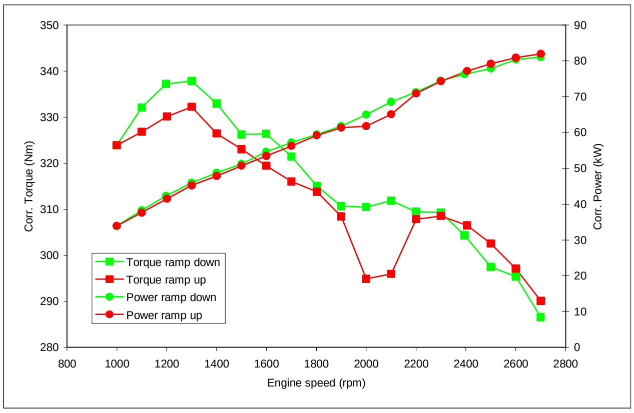


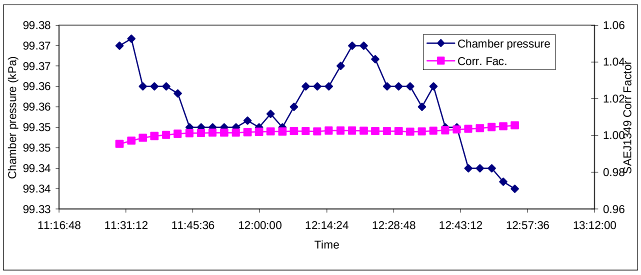






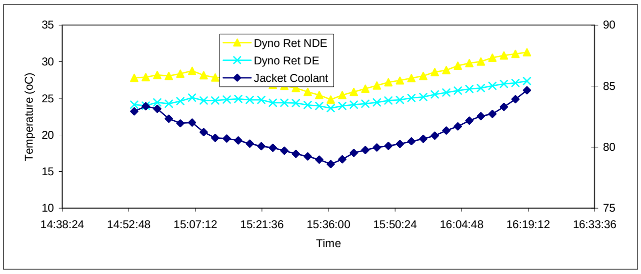


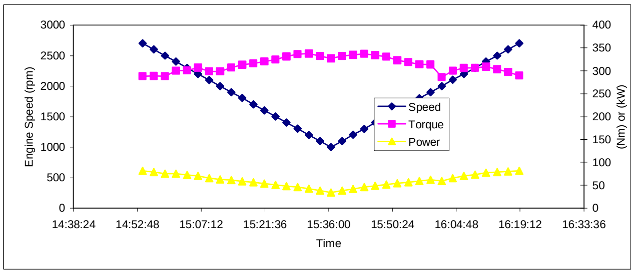


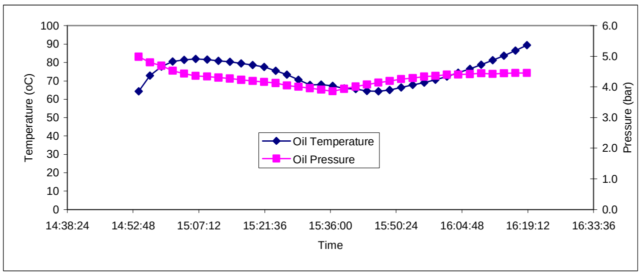


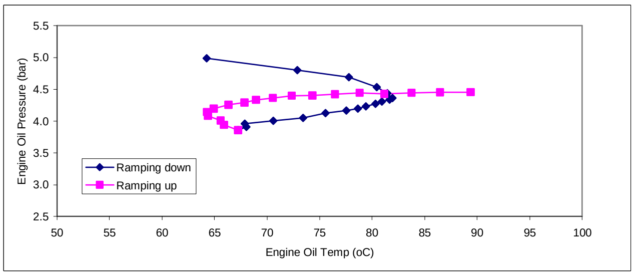
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 10/09/07

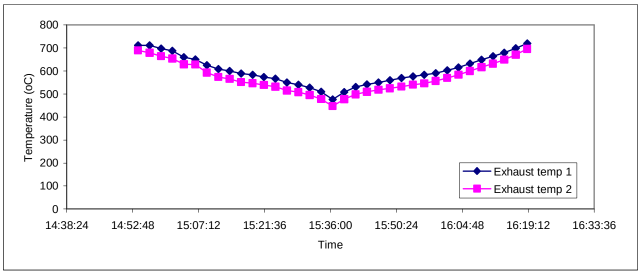
Baseline 002_015

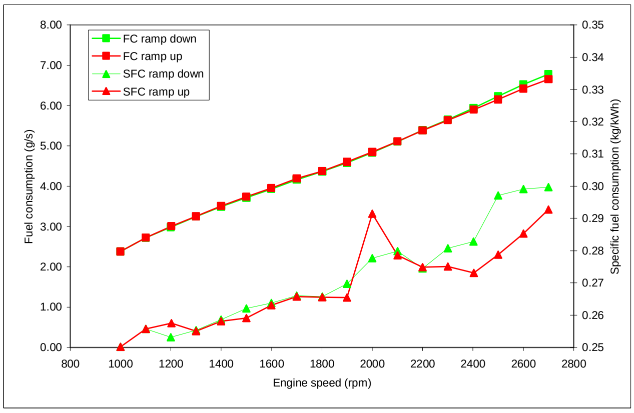


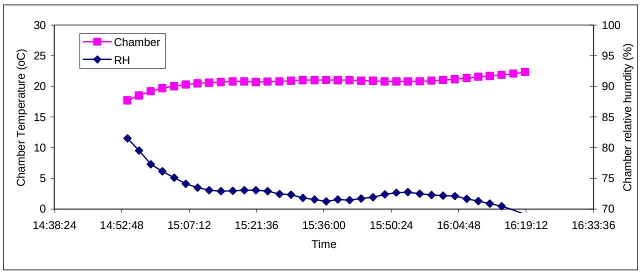


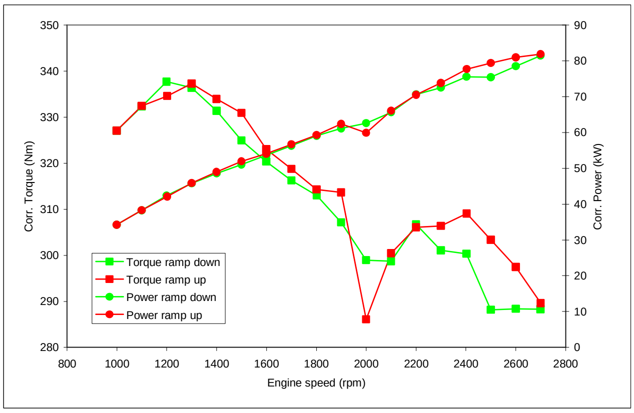


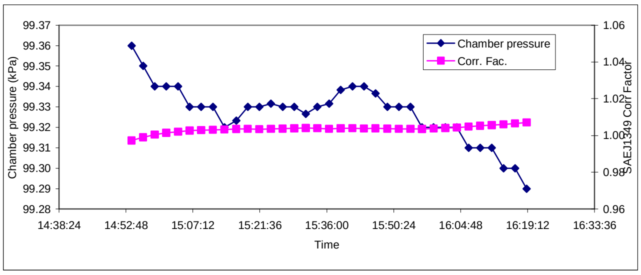






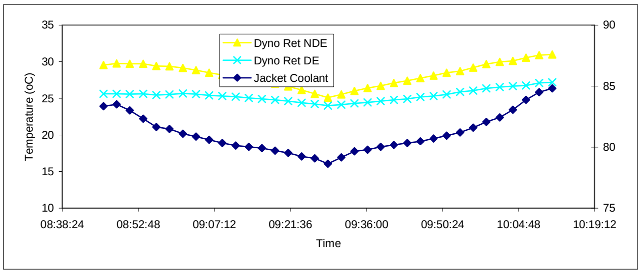


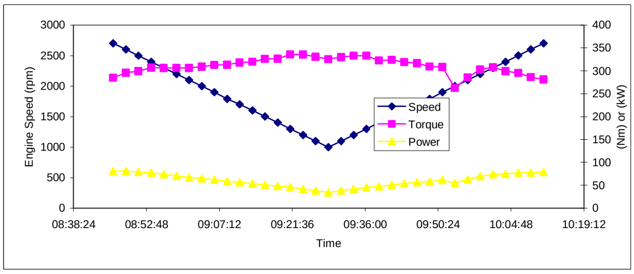


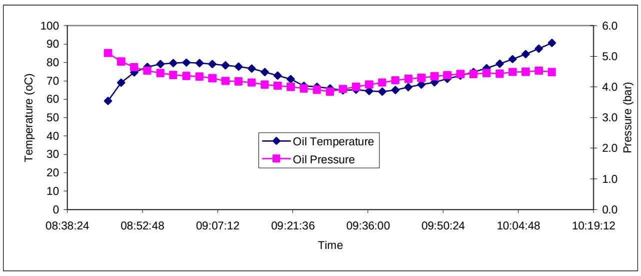


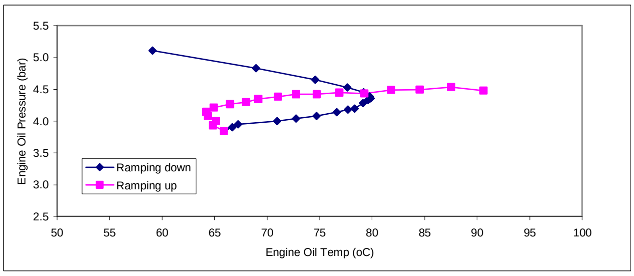
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 10/09/07

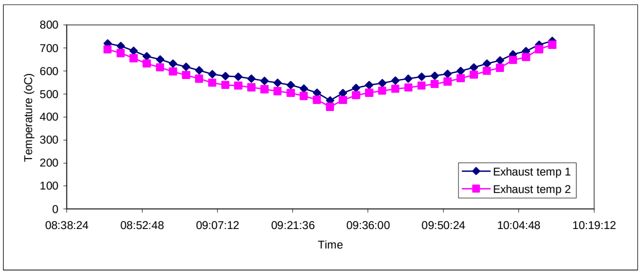
Baseline 002_016

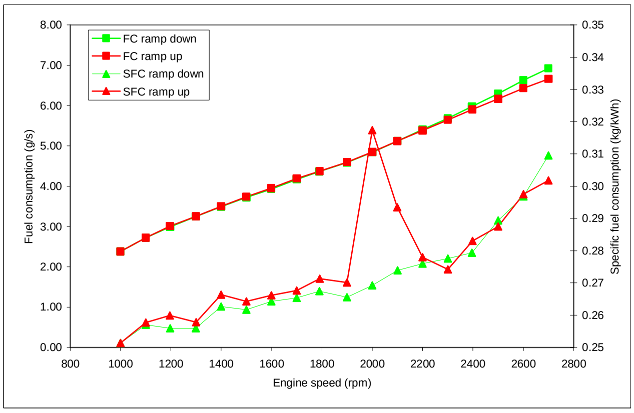


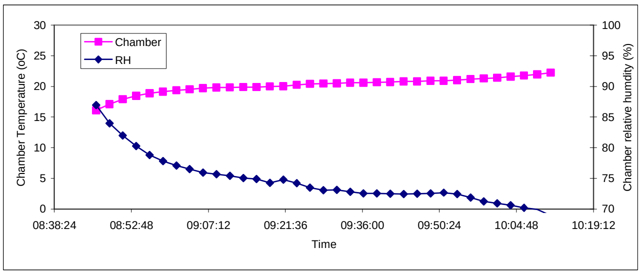


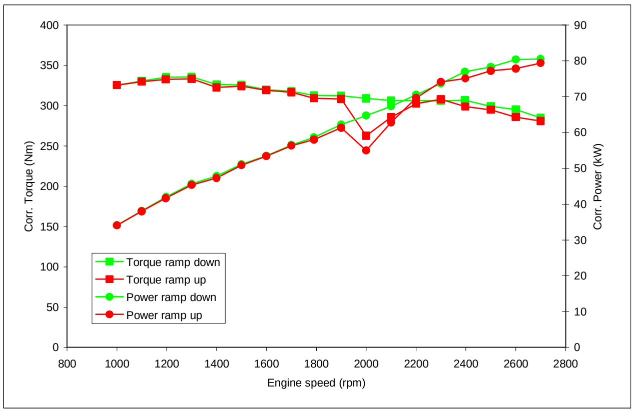


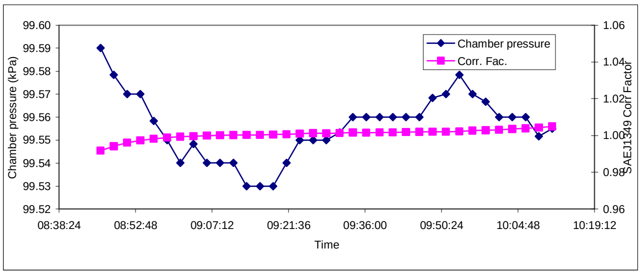






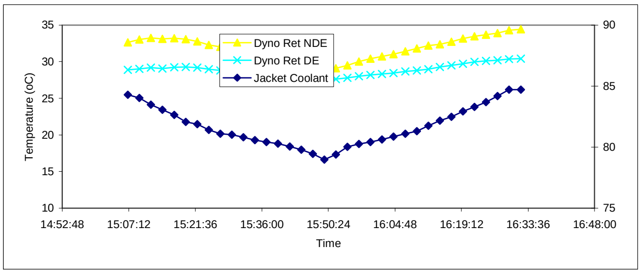


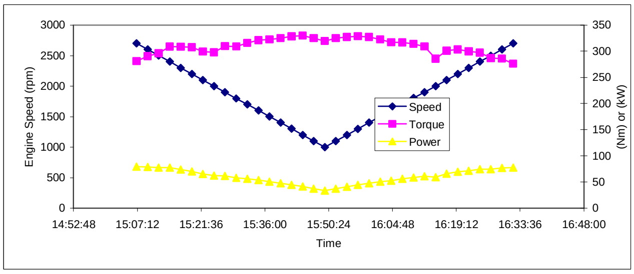


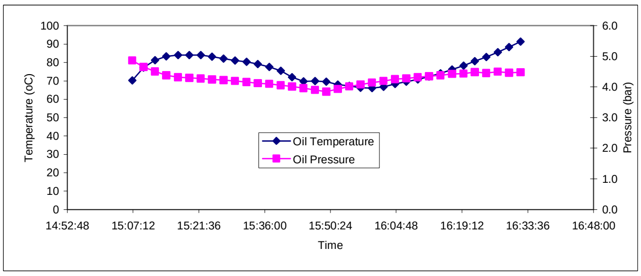


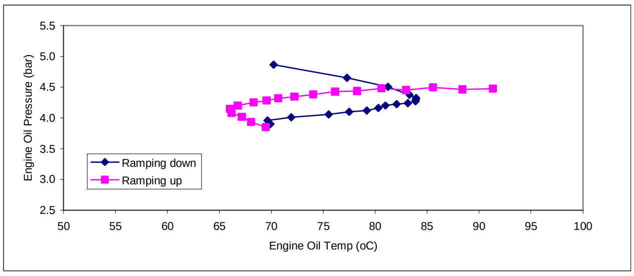
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 11/09/07

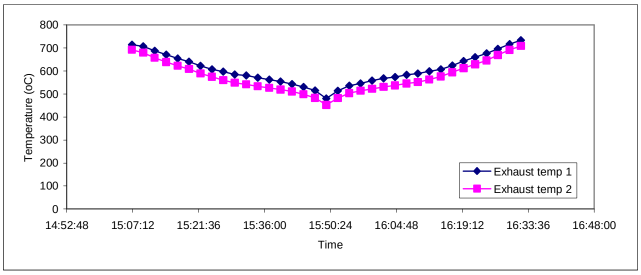
Baseline 002_017

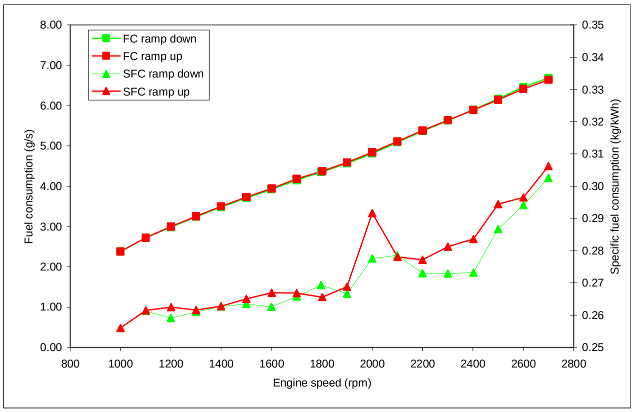


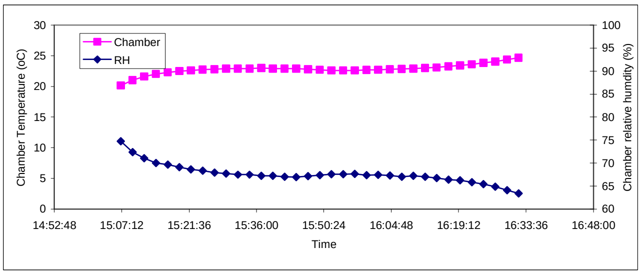


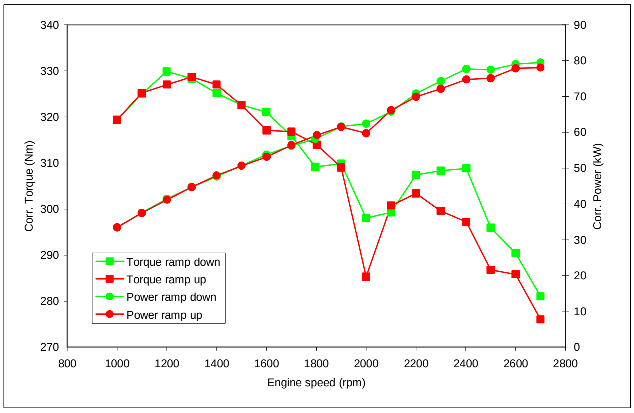


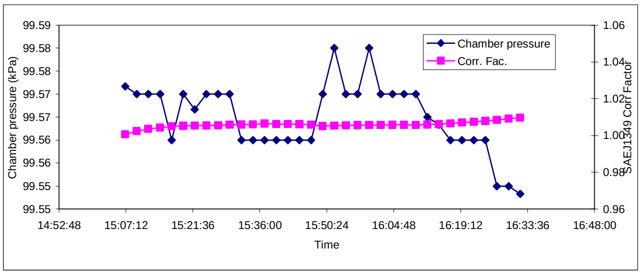






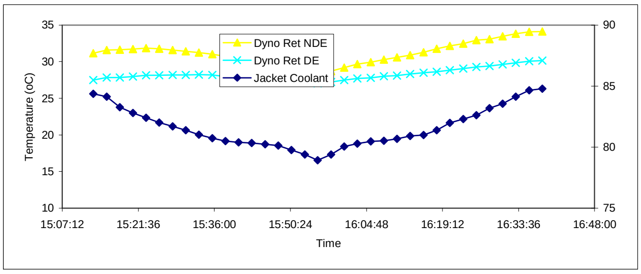


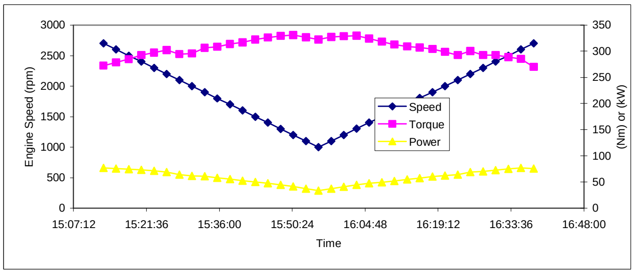


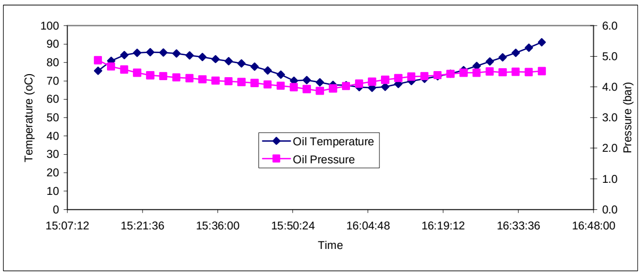


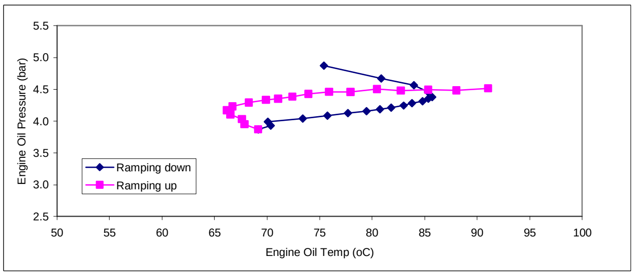
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 11/09/07

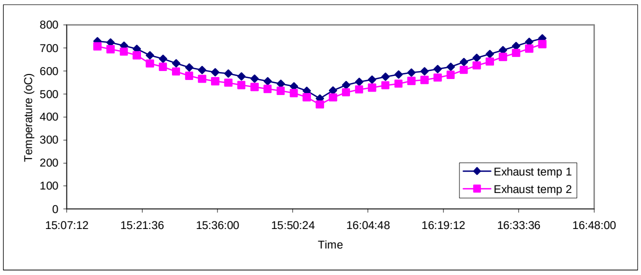
Baseline 002_018

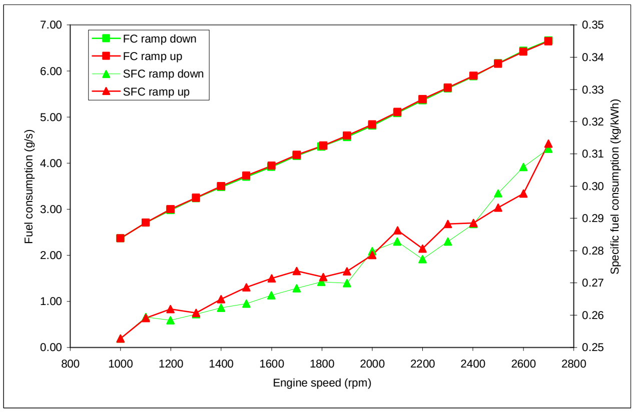


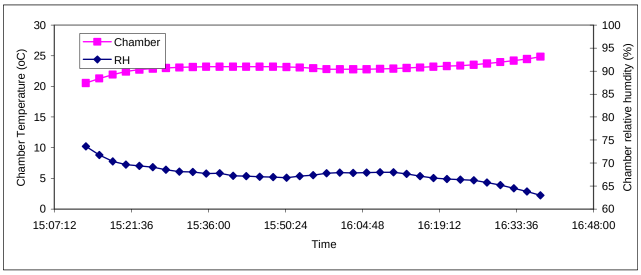


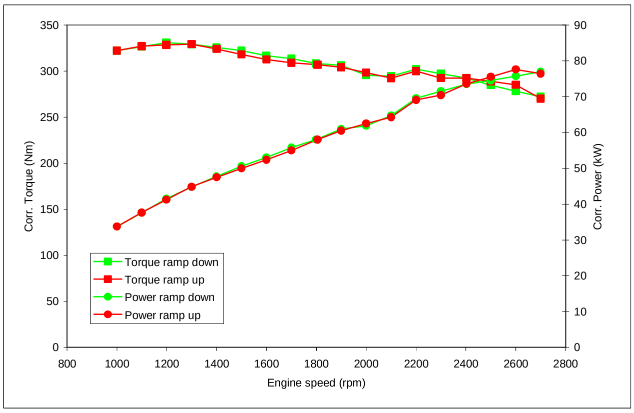


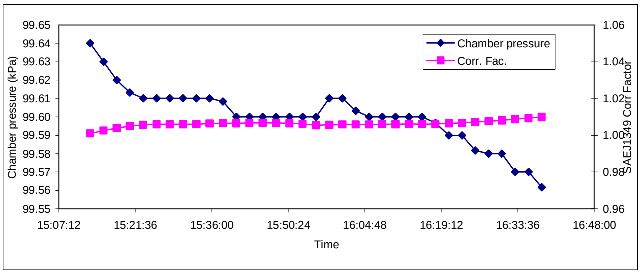






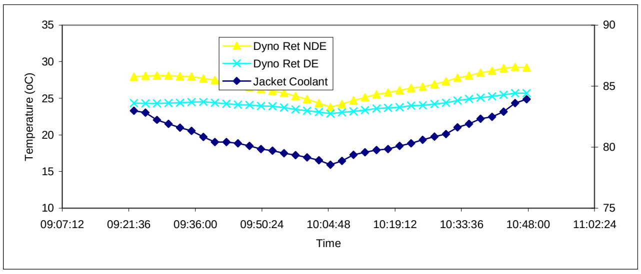


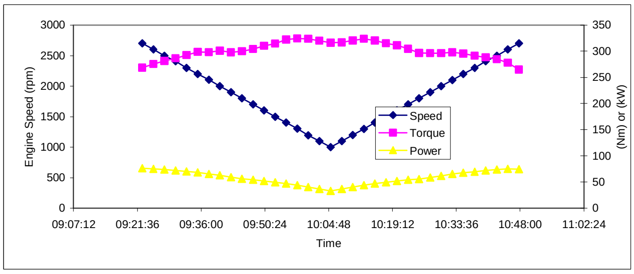


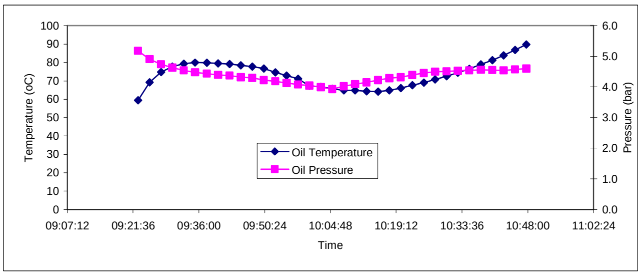


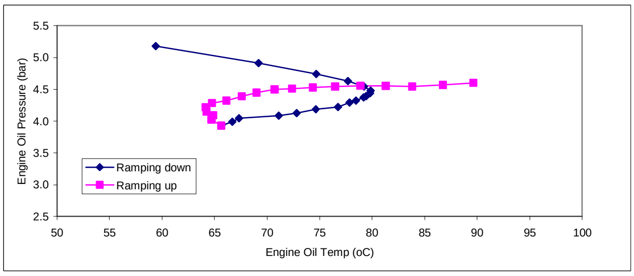
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 12/09/07

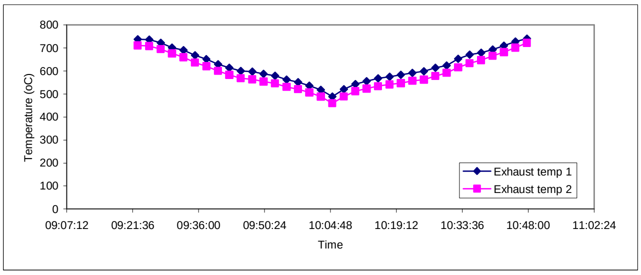
Baseline 002_019

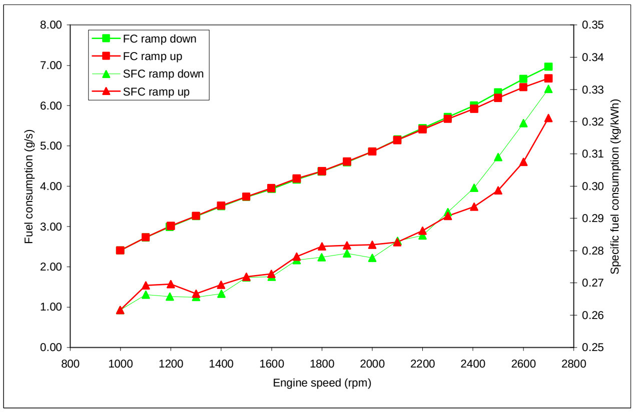


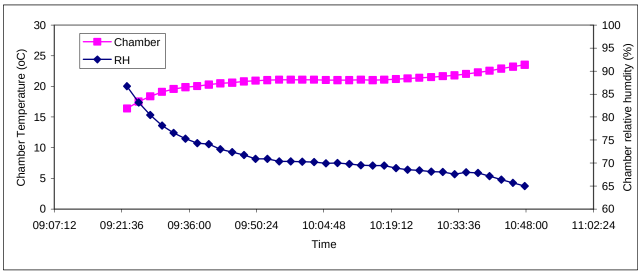


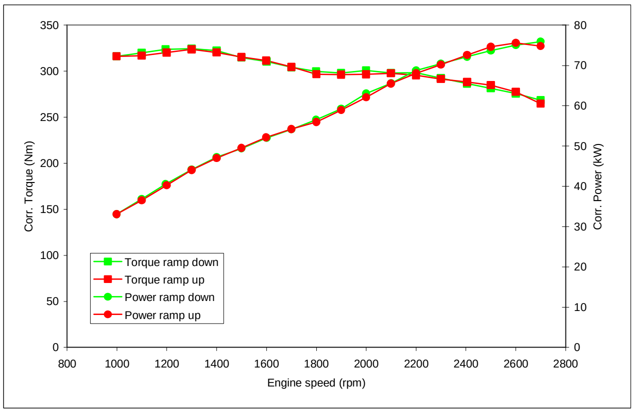


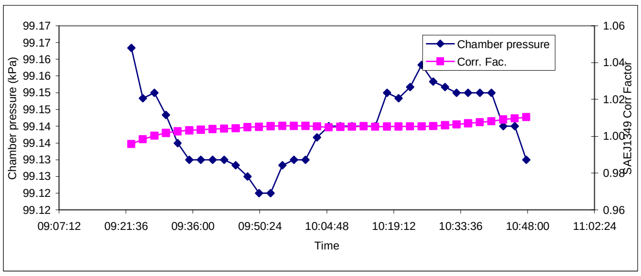






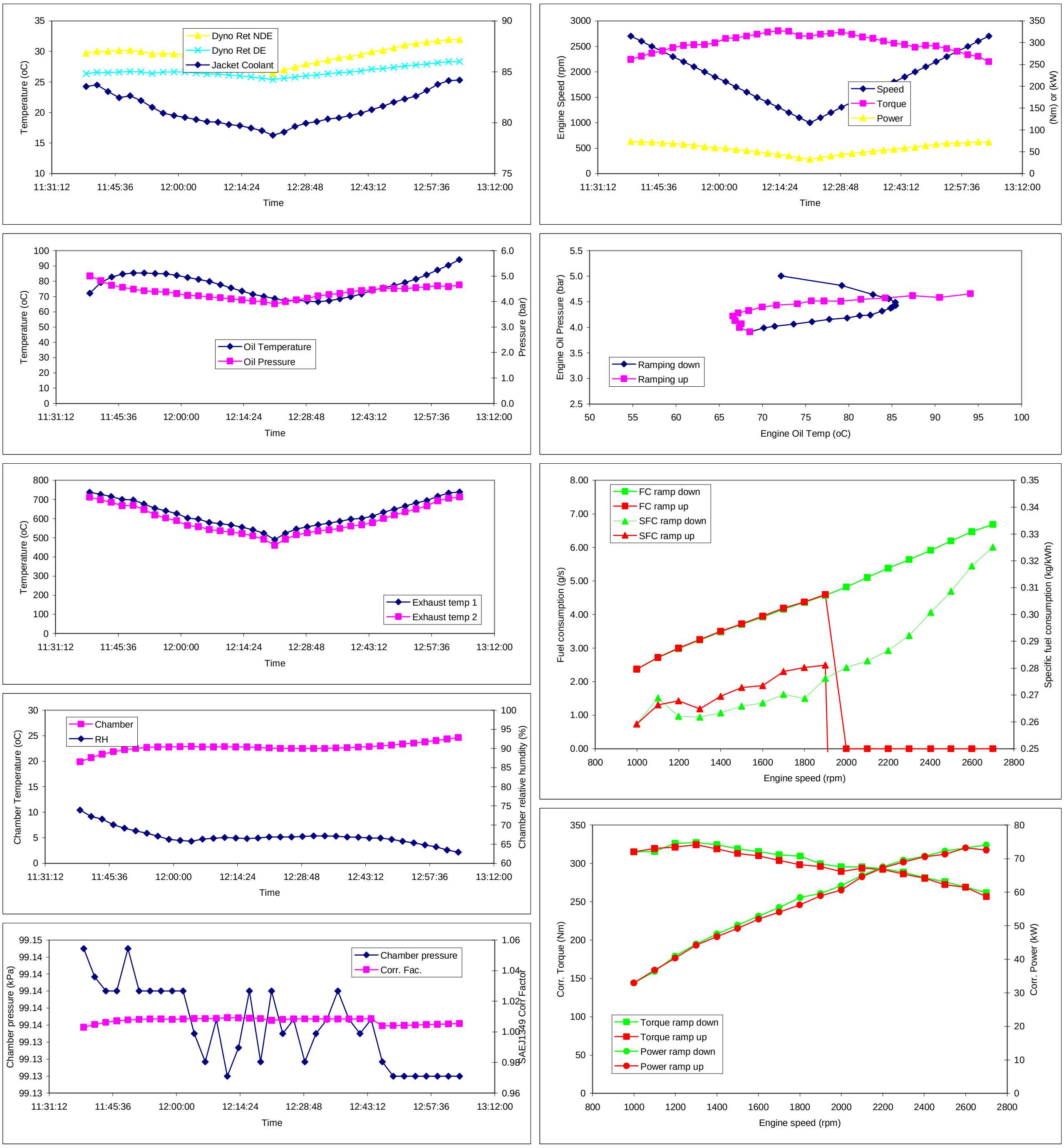






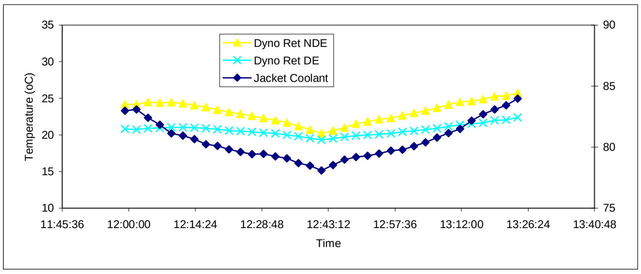
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 14/09/07

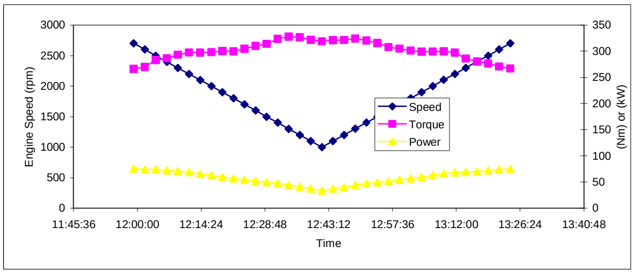
Baseline 002_020

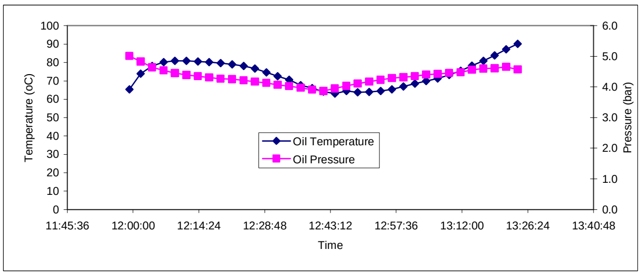


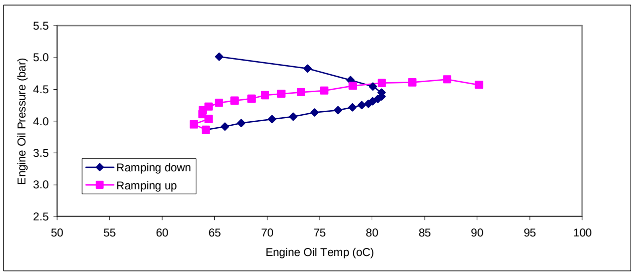
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 14/09/07

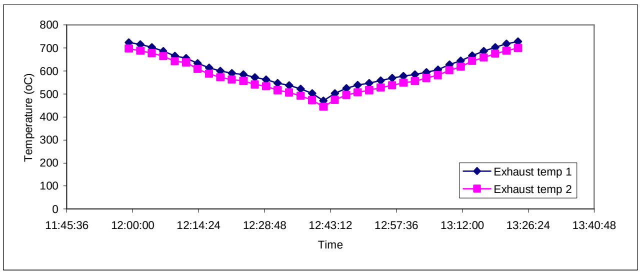
Baseline 002_021

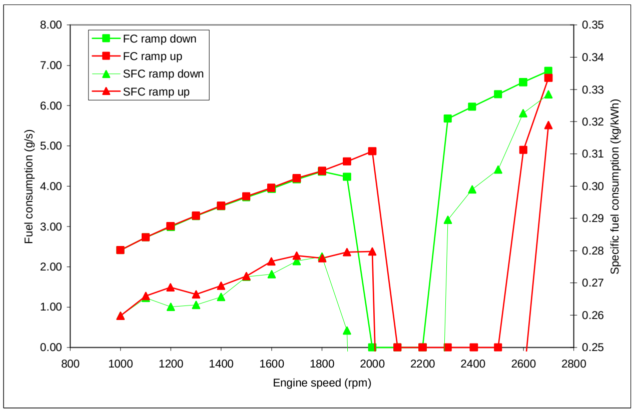


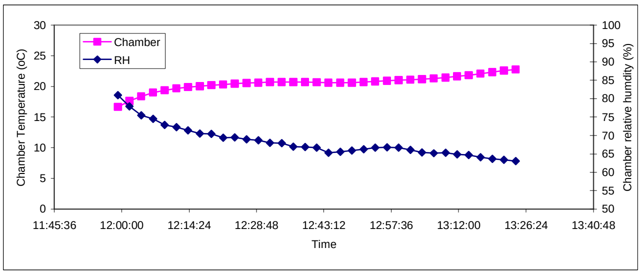


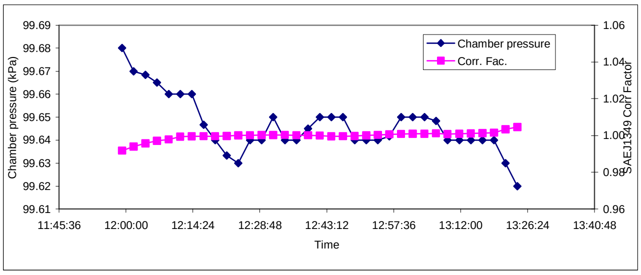


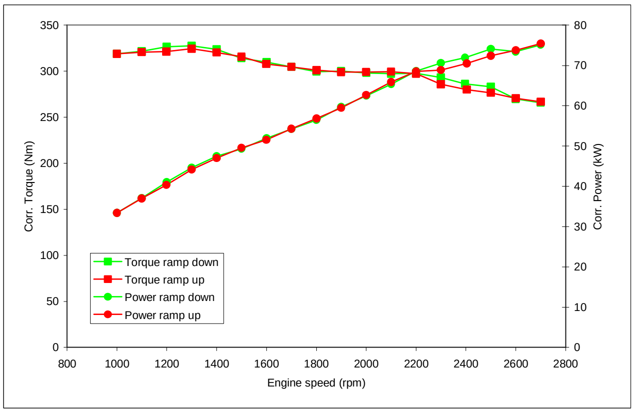






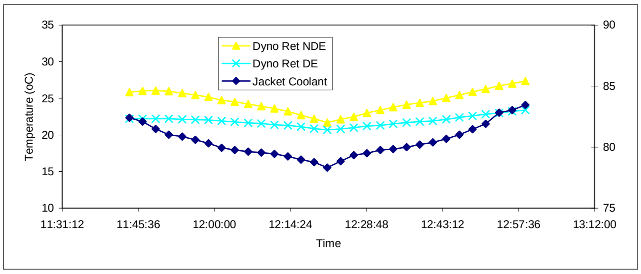


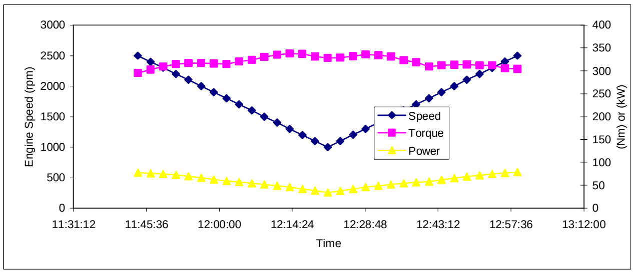


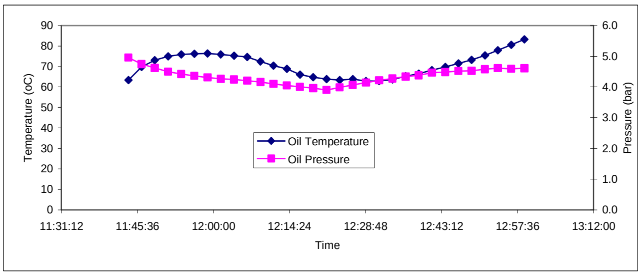


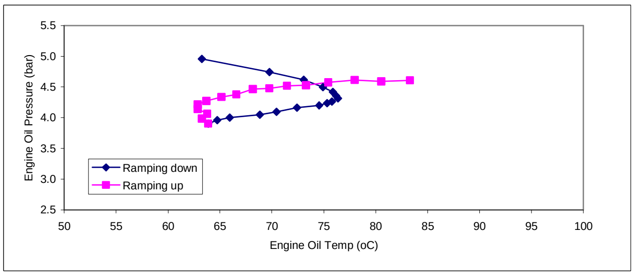
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 18/09/07

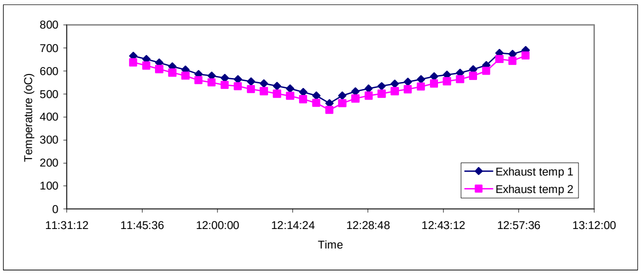
Baseline 002_022

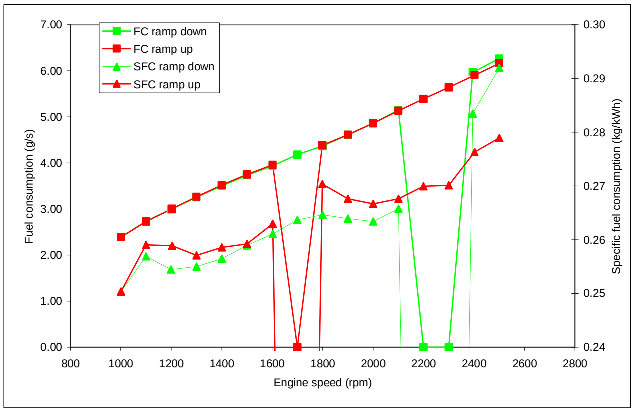


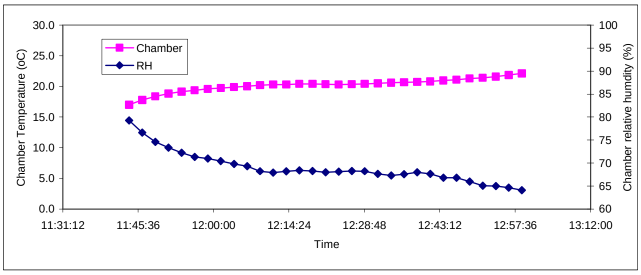


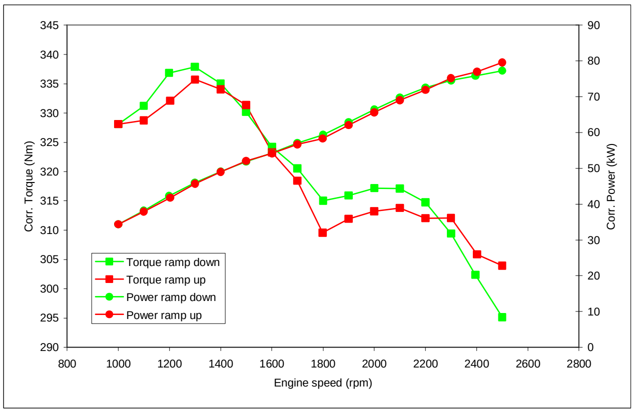


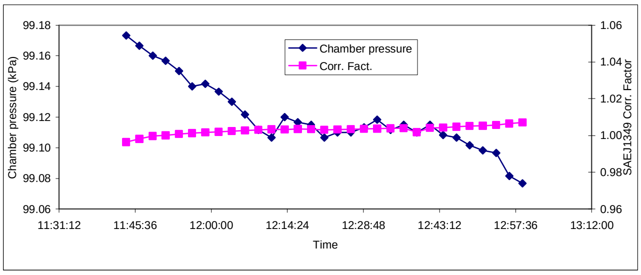






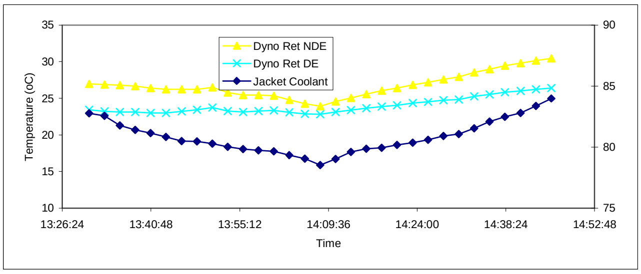


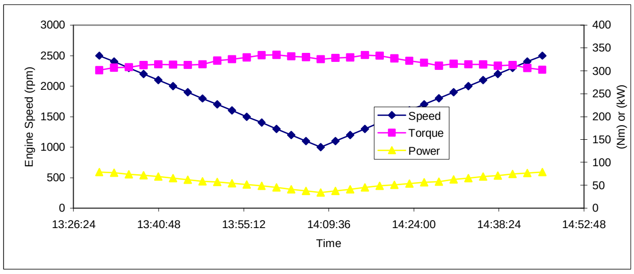


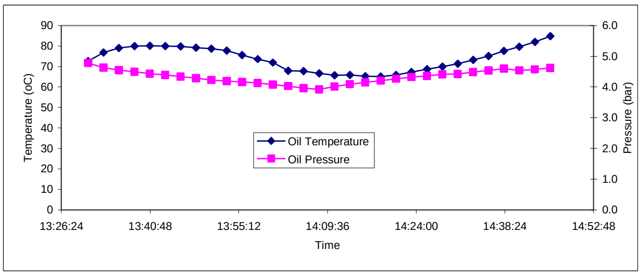


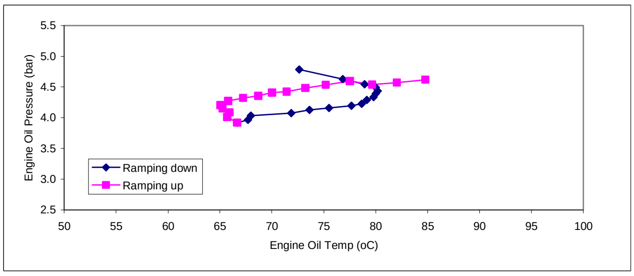
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 19/09/07

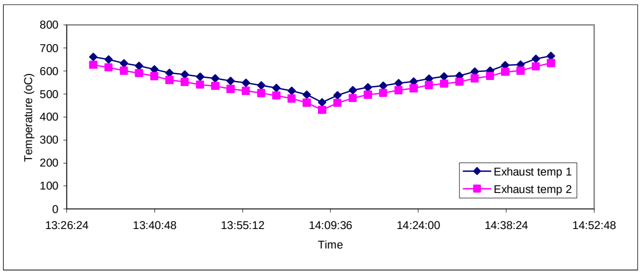
Baseline 003_001

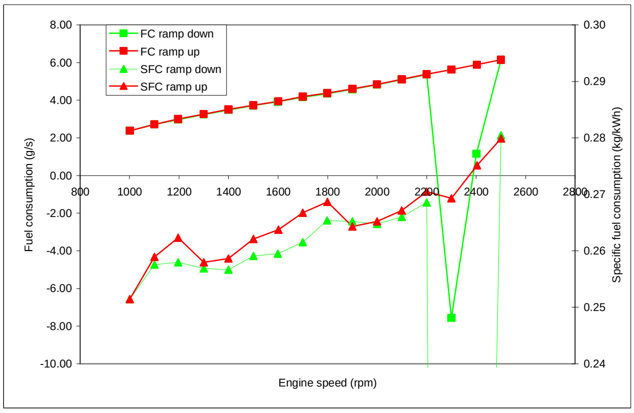


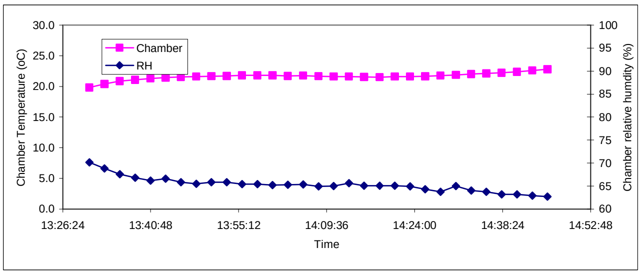


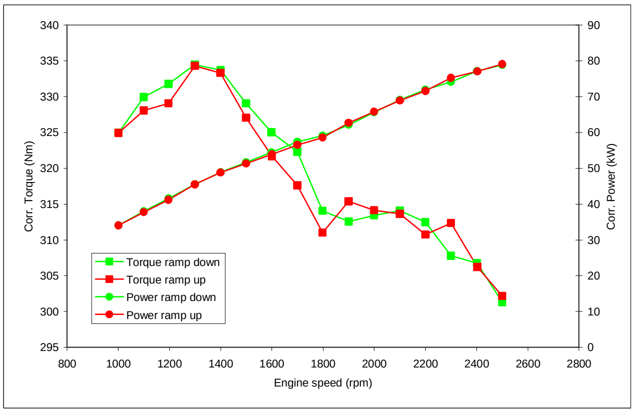


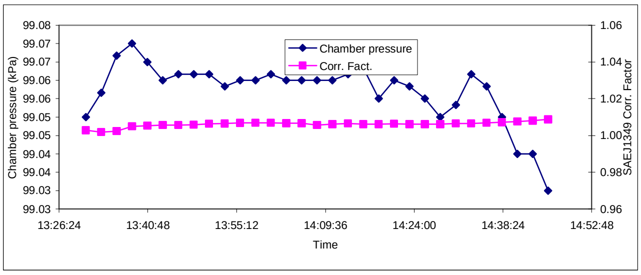






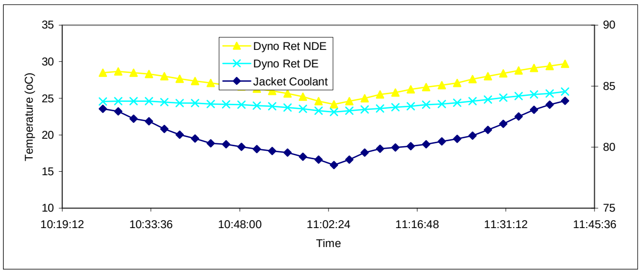


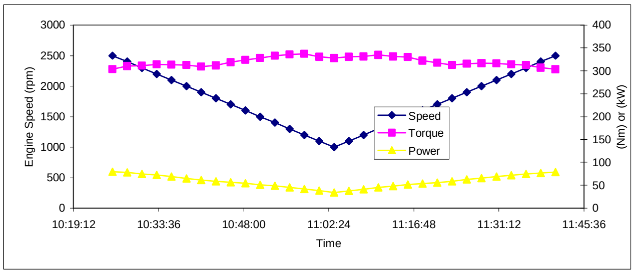


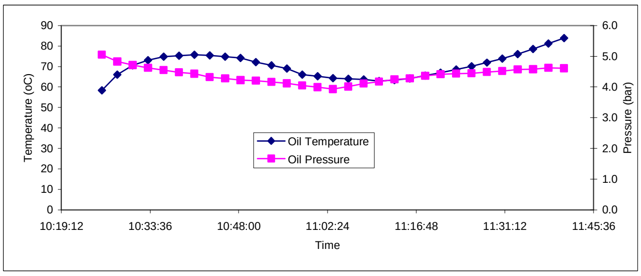


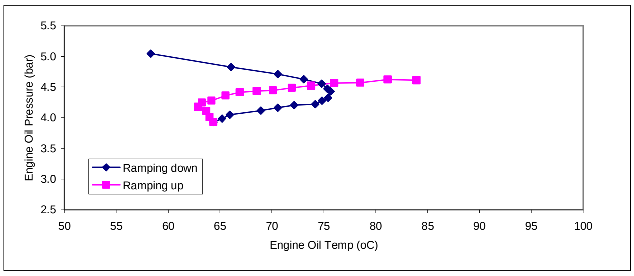
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 19/09/07

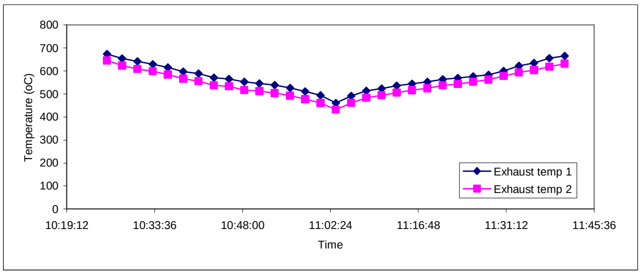
Baseline 003_002

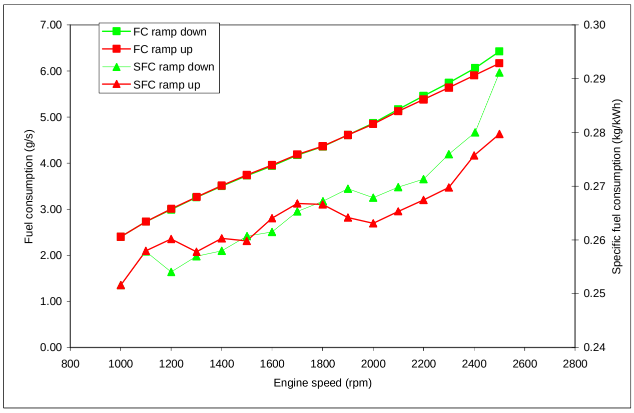


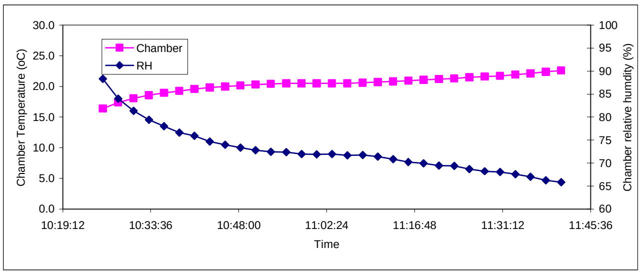


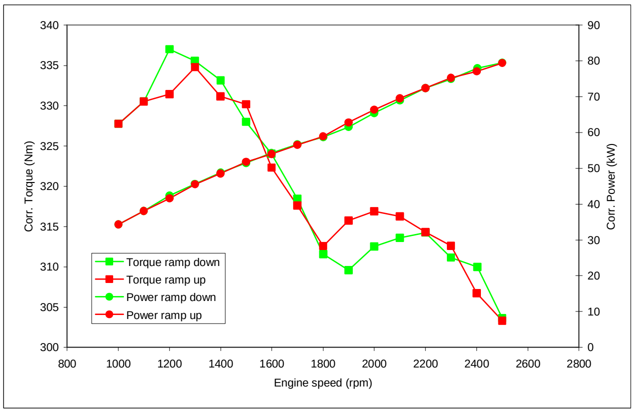


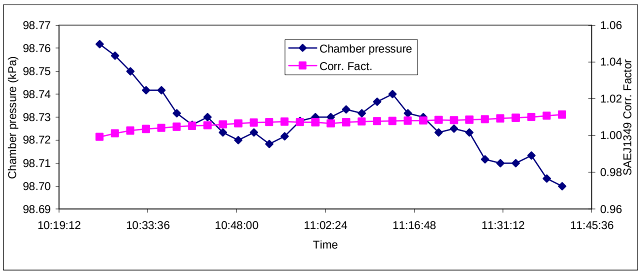






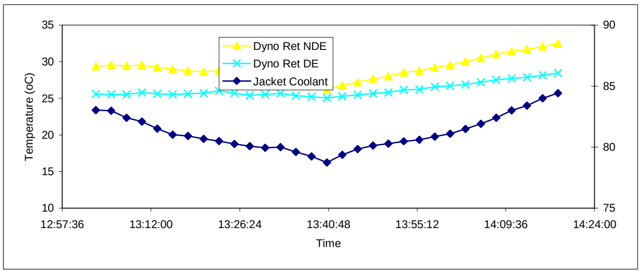


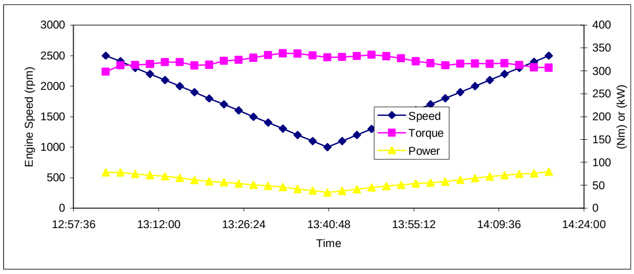


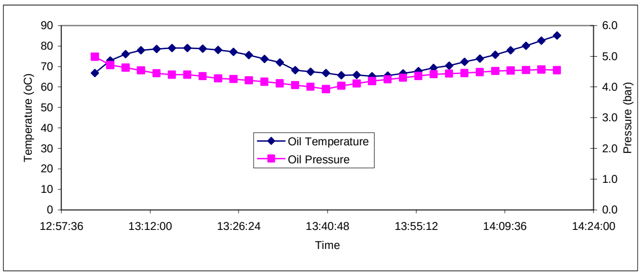


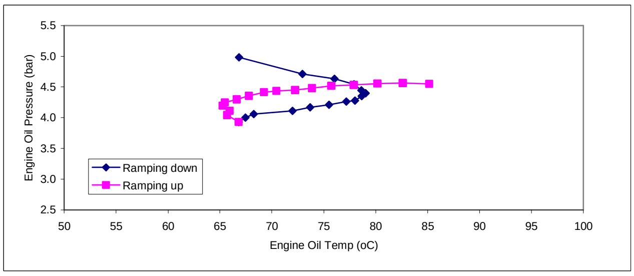
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 20/09/07

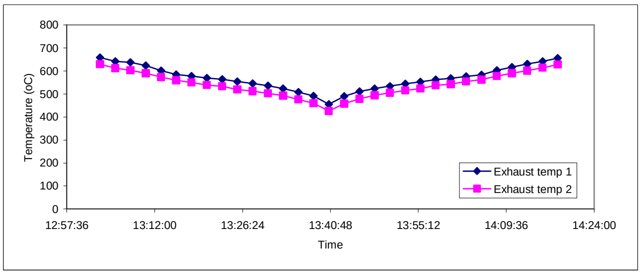
Baseline 003_003

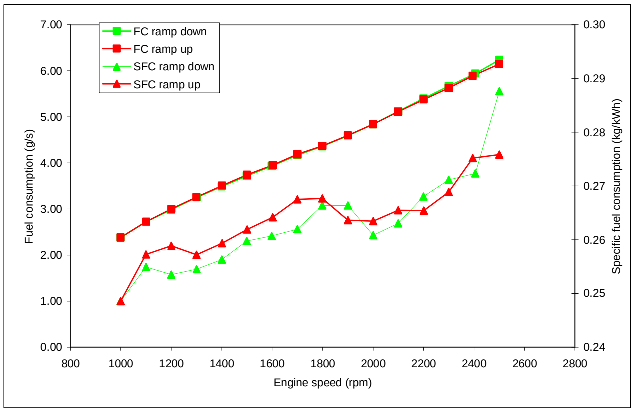


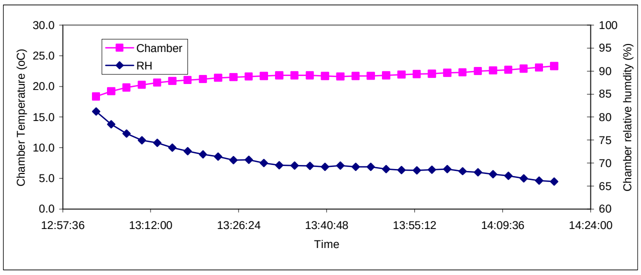


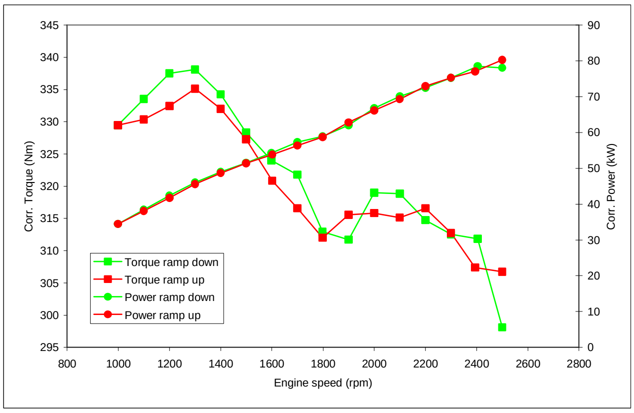


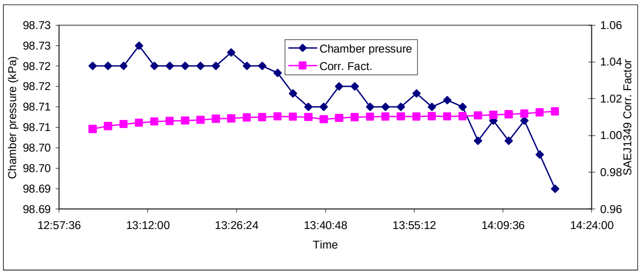






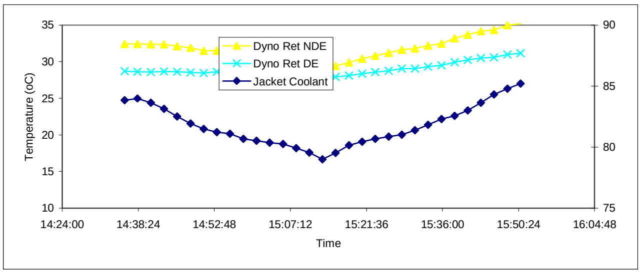


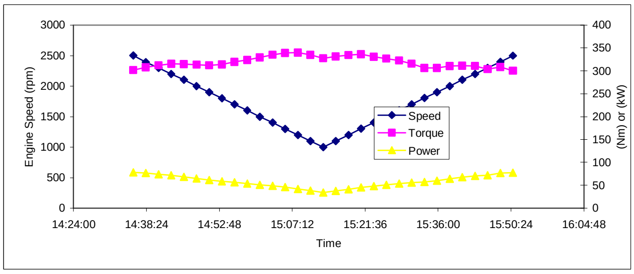


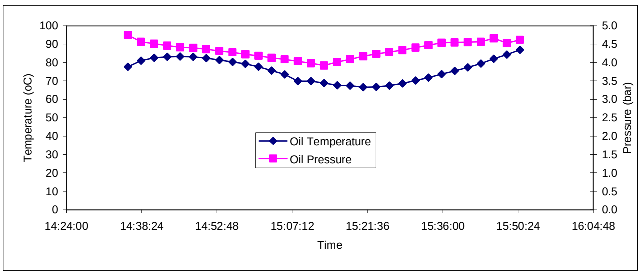


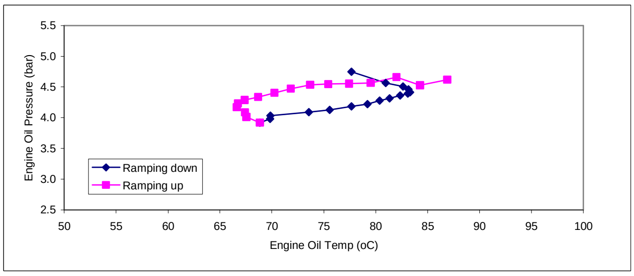
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 20/09/07

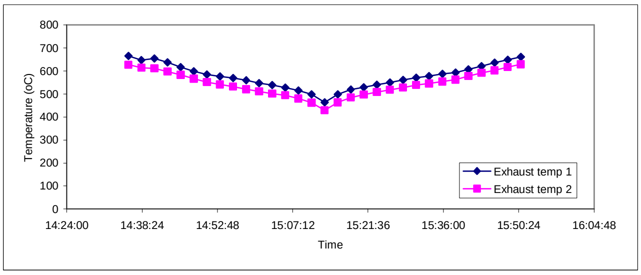
Baseline 003_004

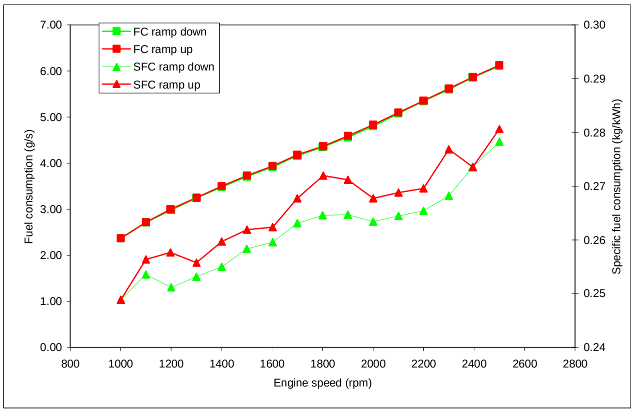


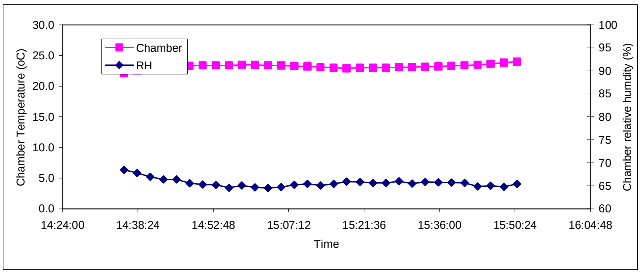


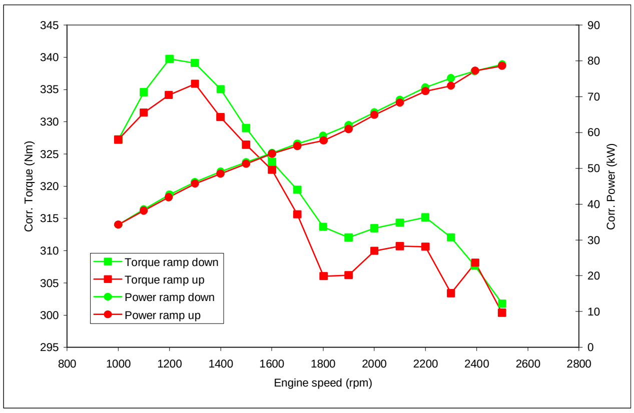


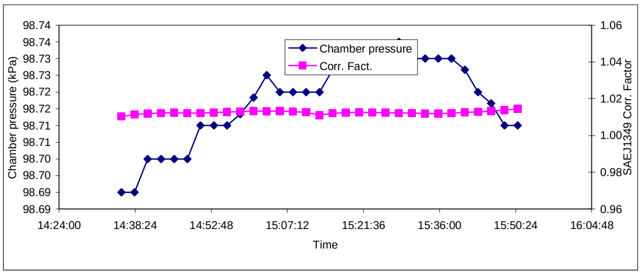






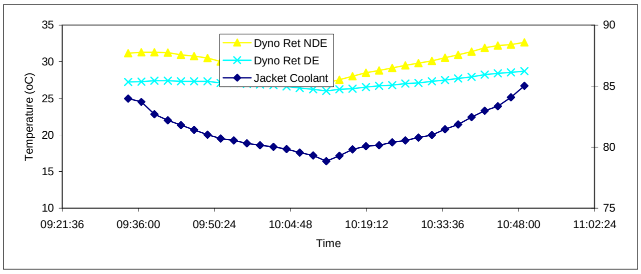


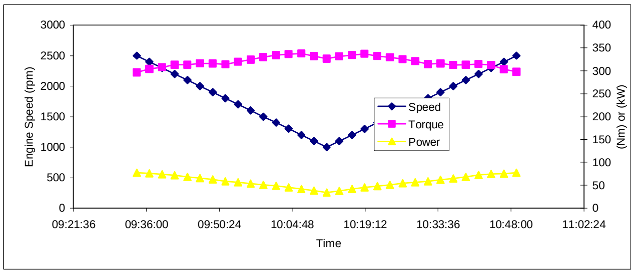


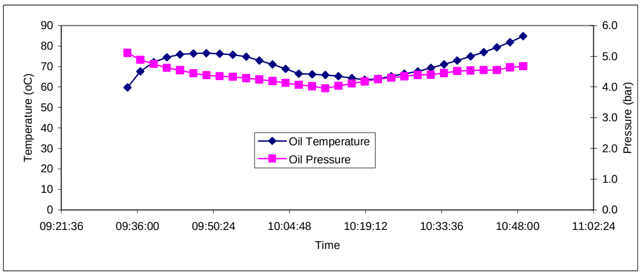


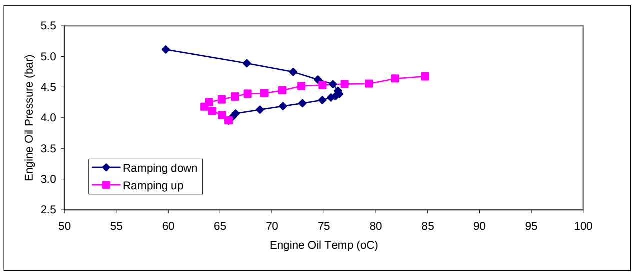
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 20/09/07

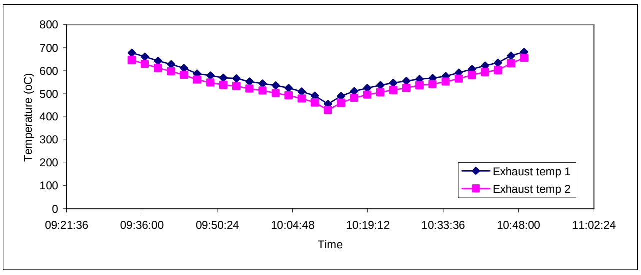
Baseline 003_005

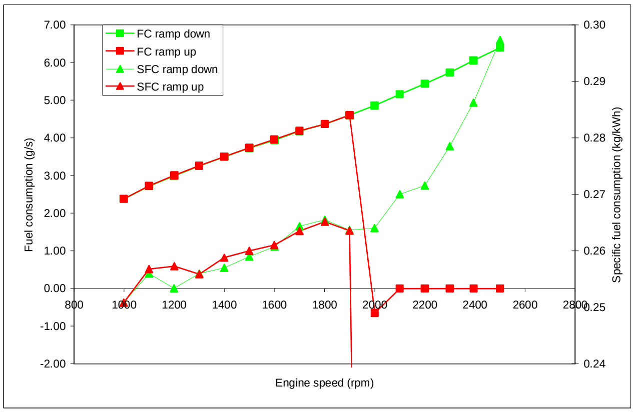


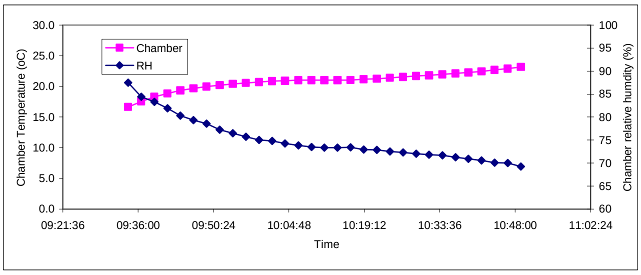


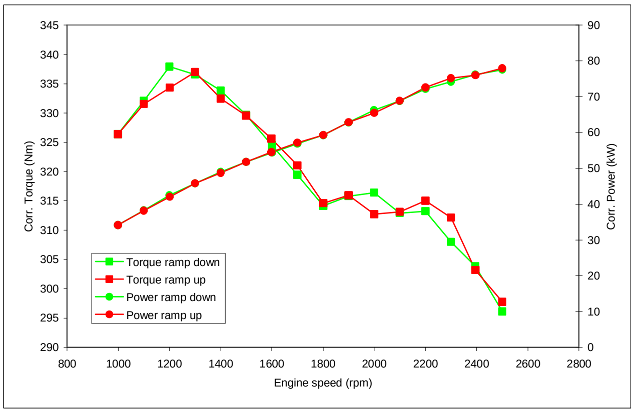


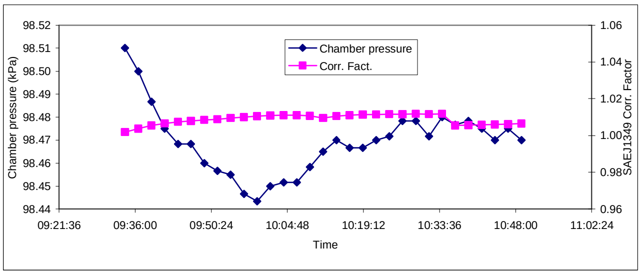






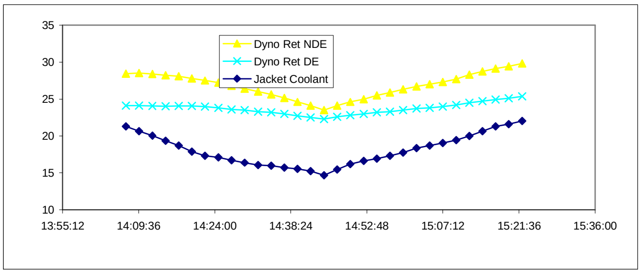


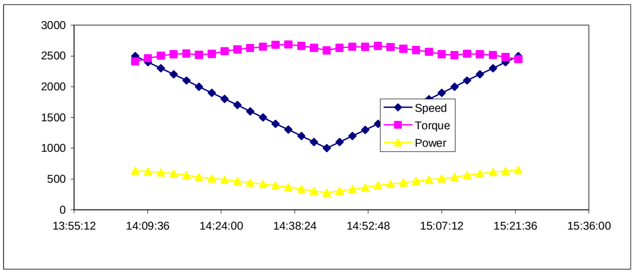


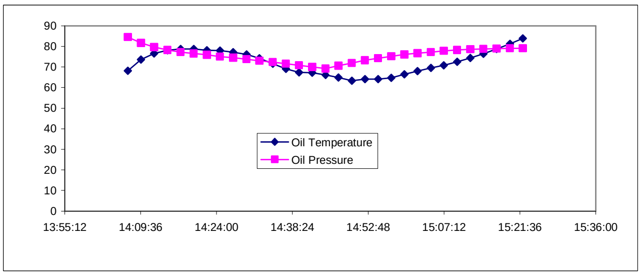


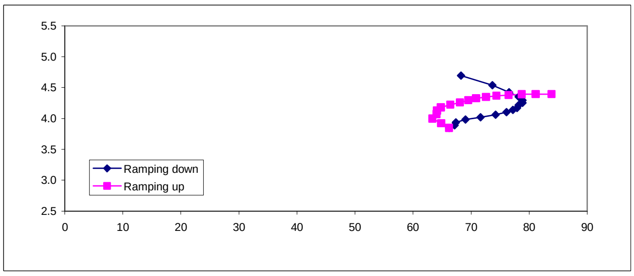
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 21/09/07

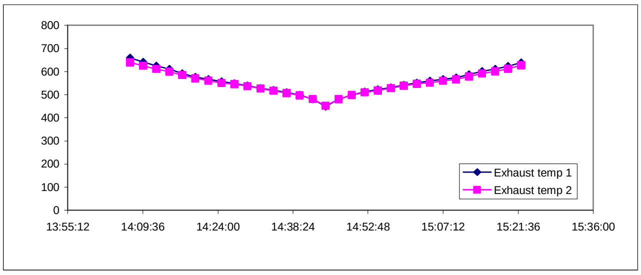
Baseline 003_007

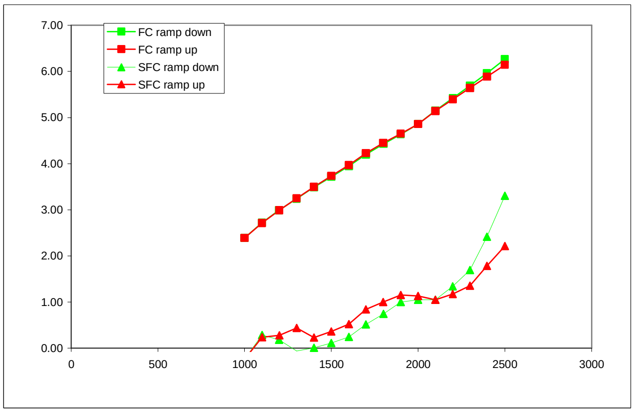


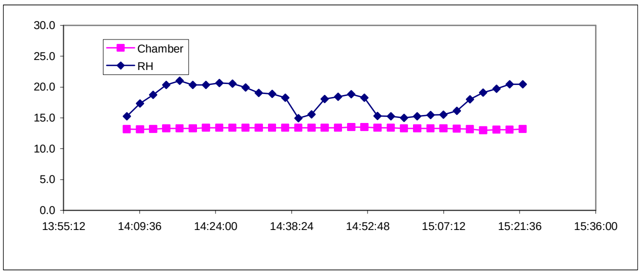


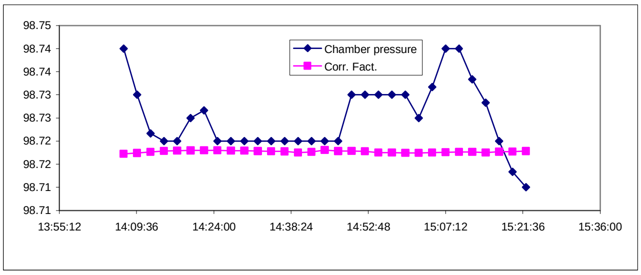


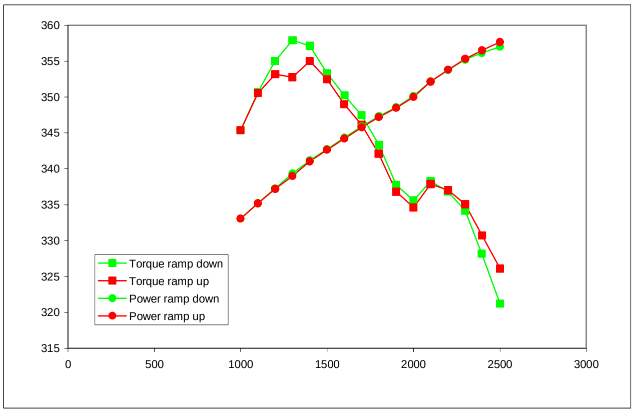






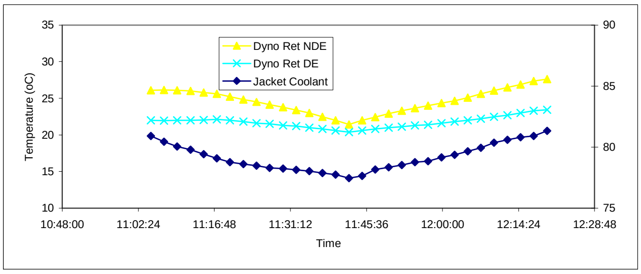


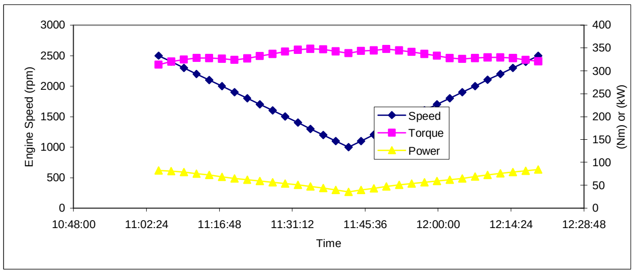


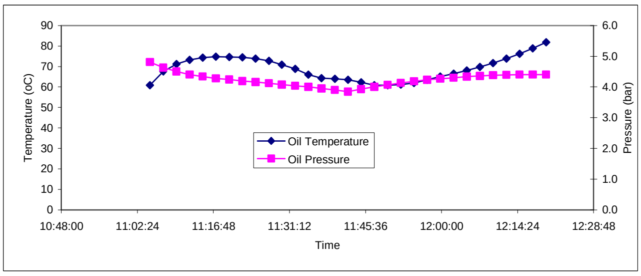


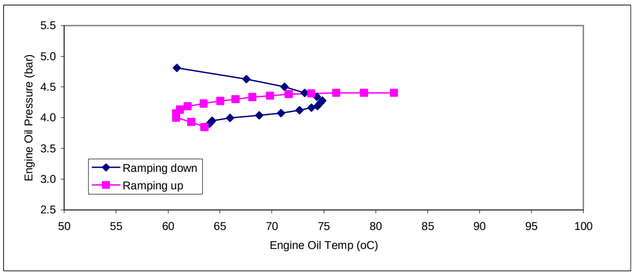
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 29/10/07

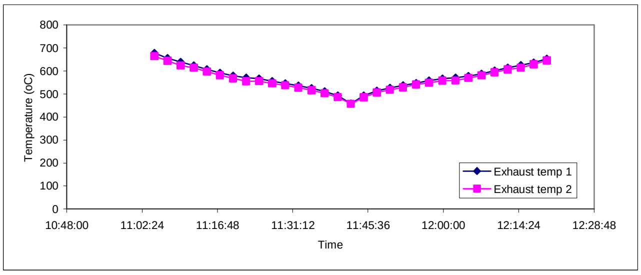
Baseline 003_007

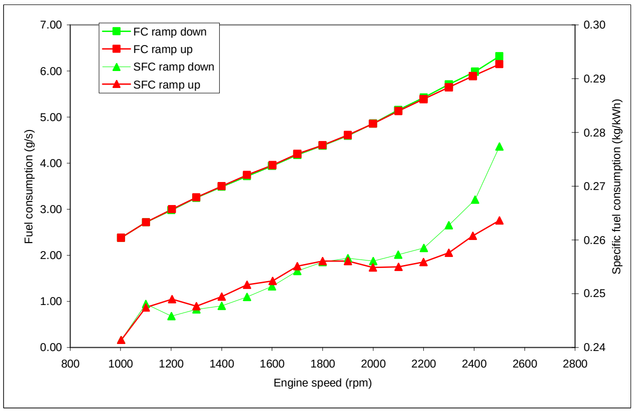


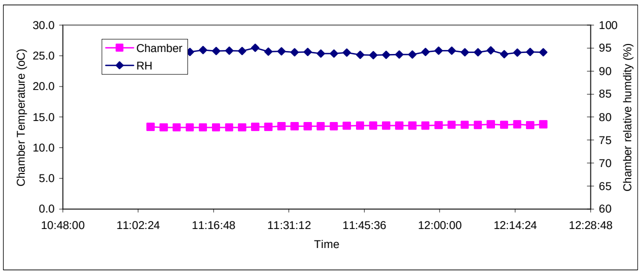


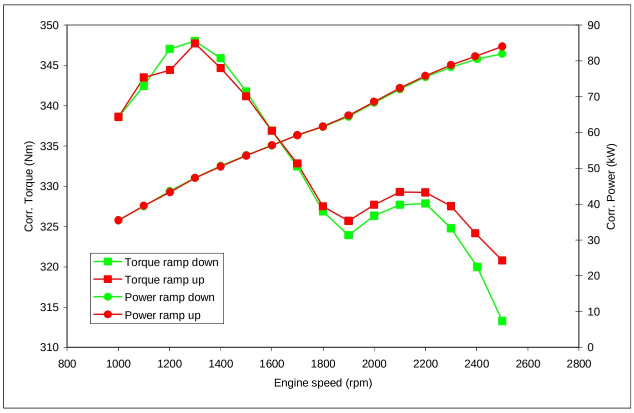


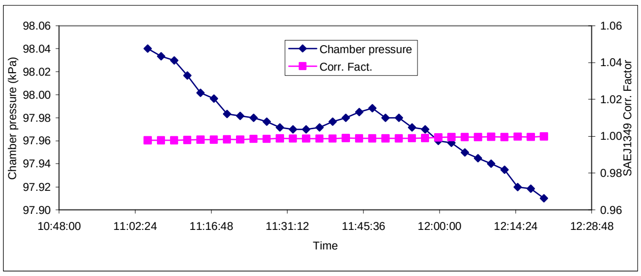






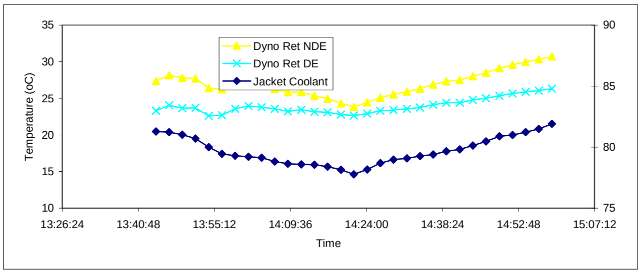


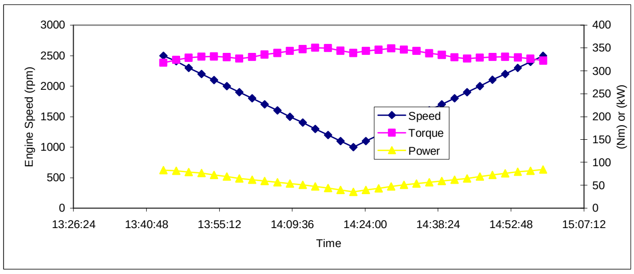


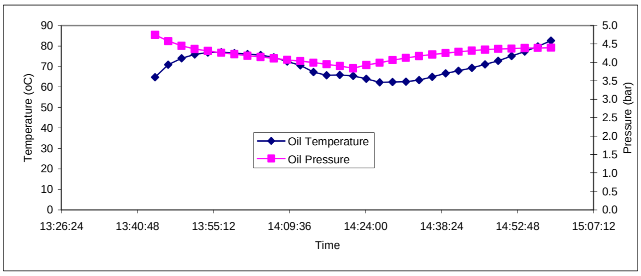


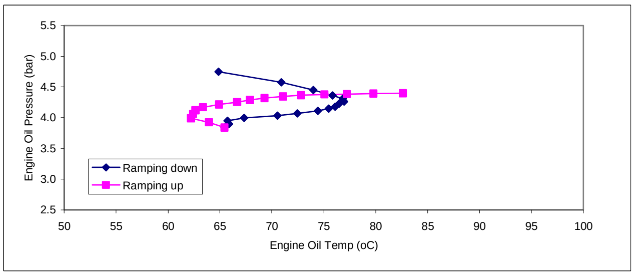
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 16/10/07

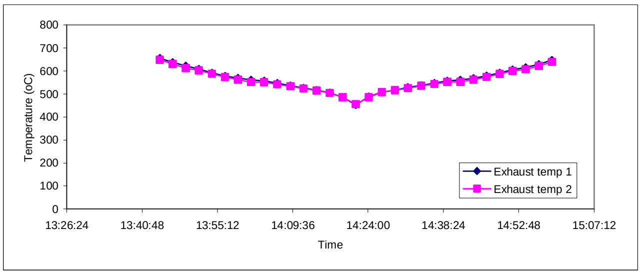
Baseline 003_101

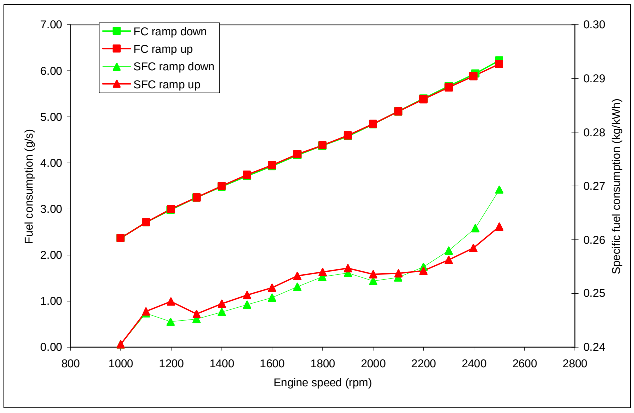


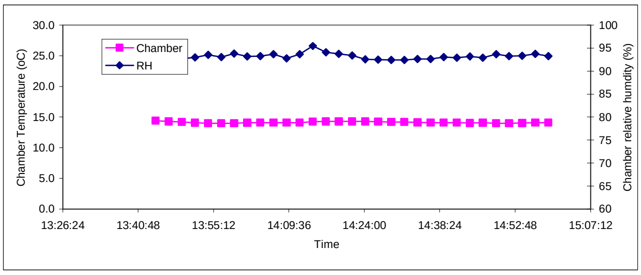


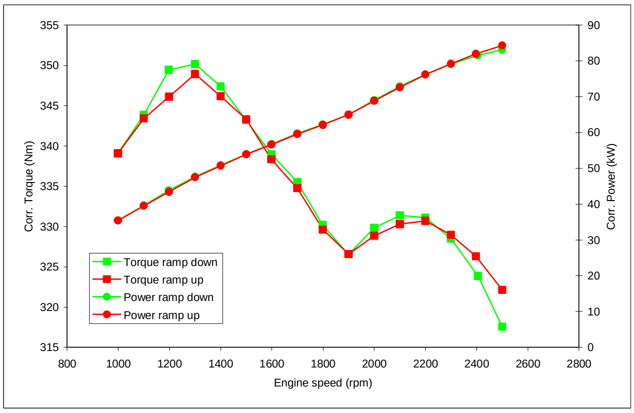


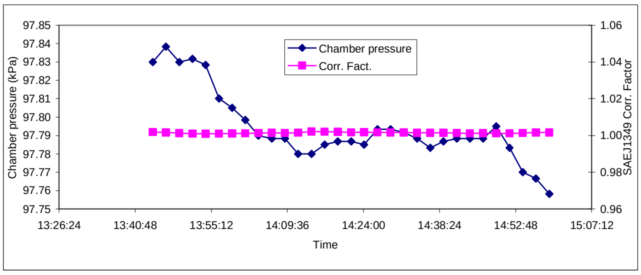






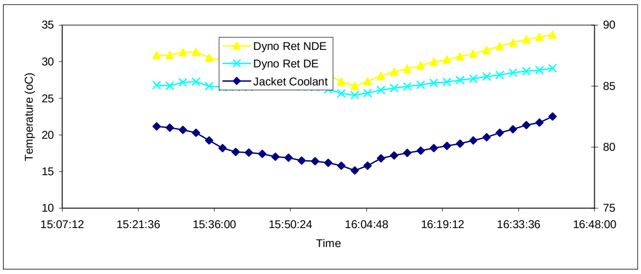


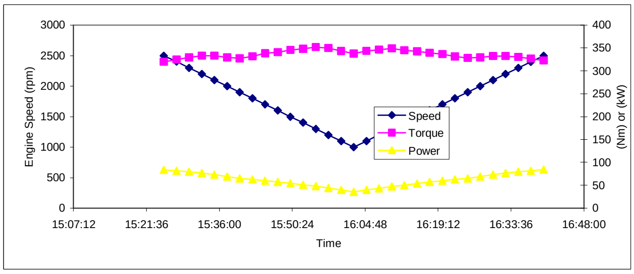


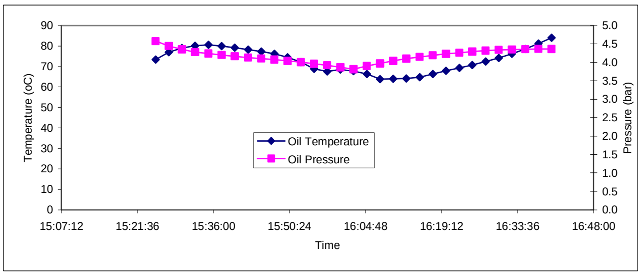


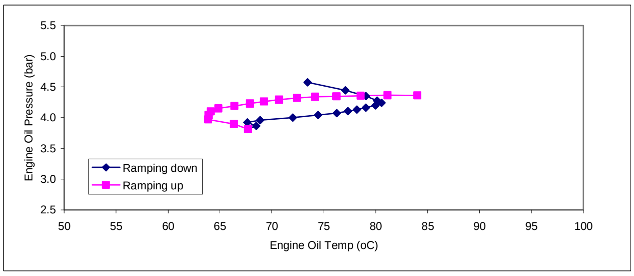
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 16/10/07

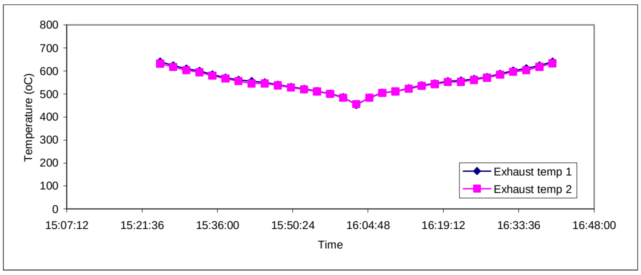
Baseline 003_102

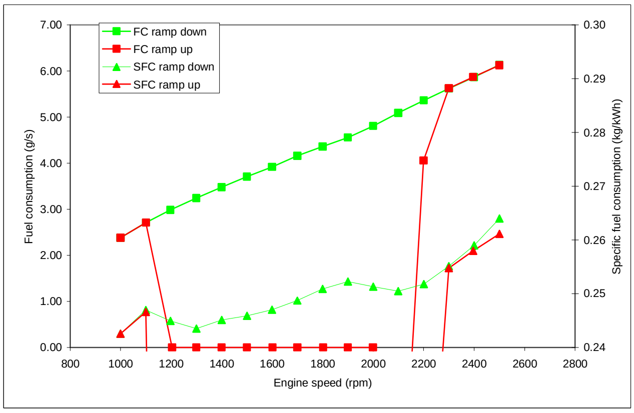


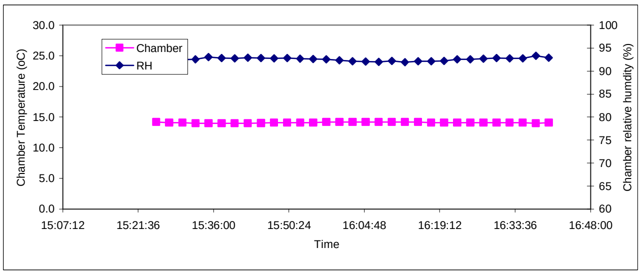


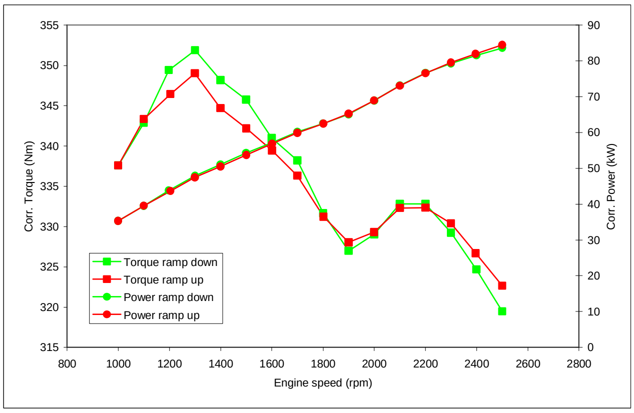


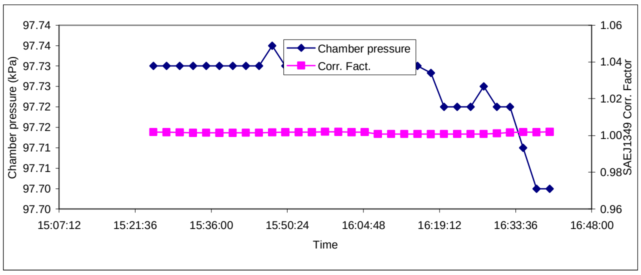






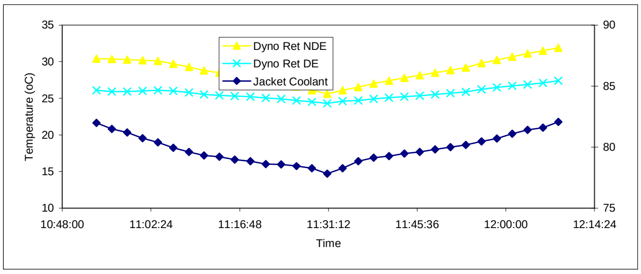


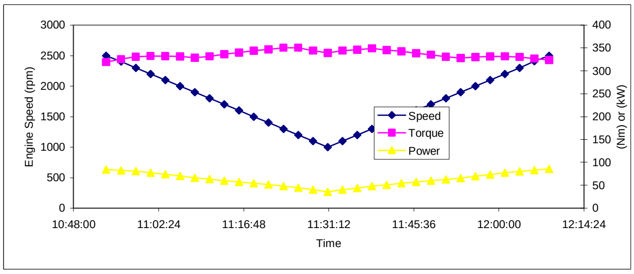


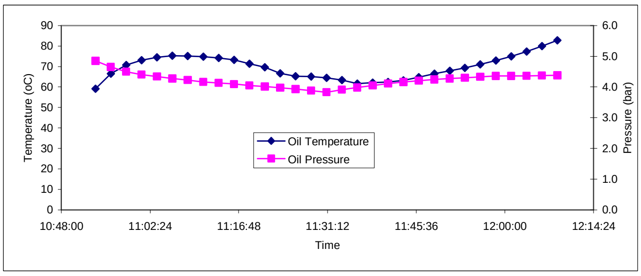


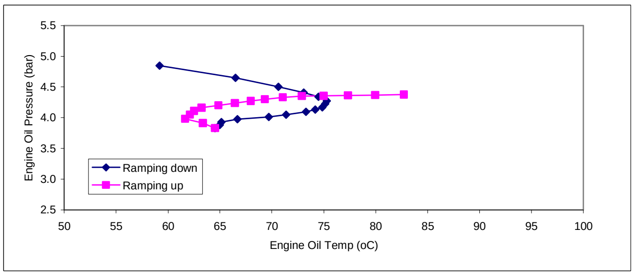
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 16/10/07

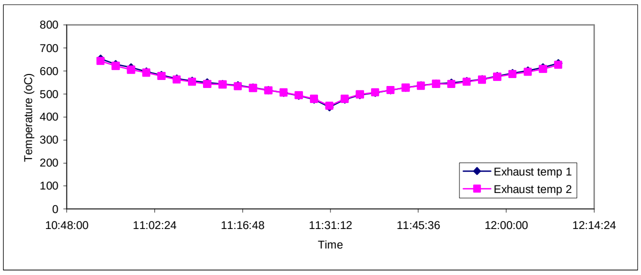
Baseline 003_103

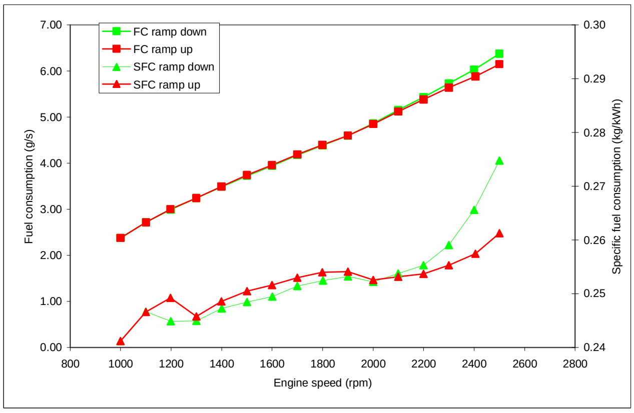


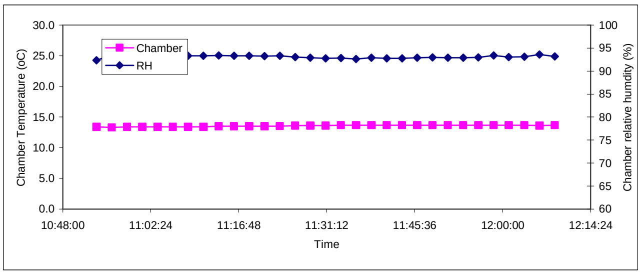


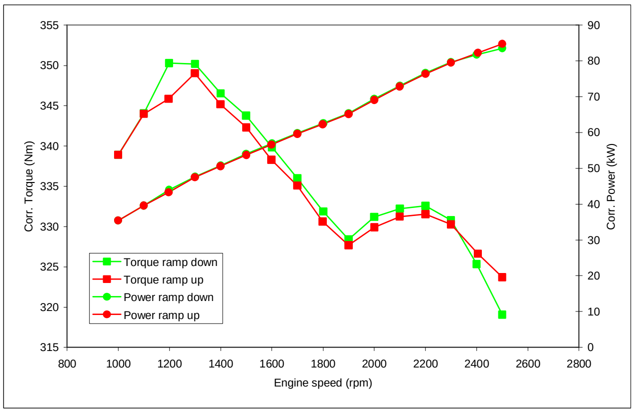


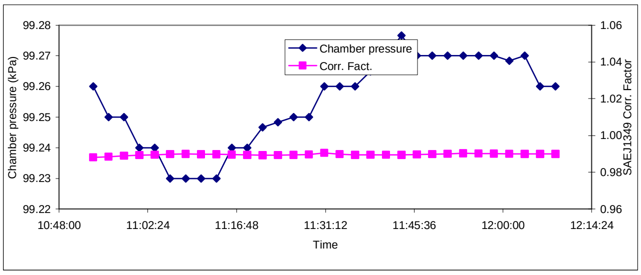






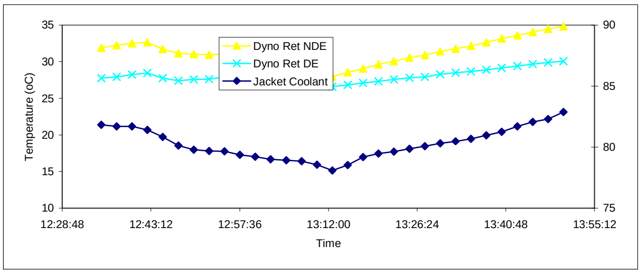


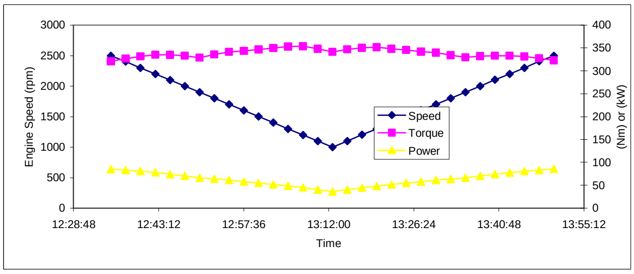


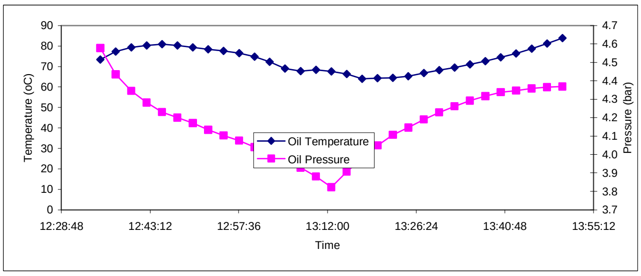


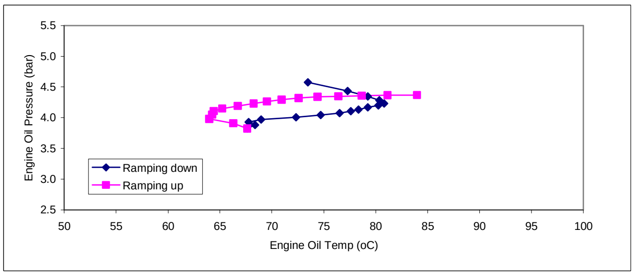
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 17/10/07

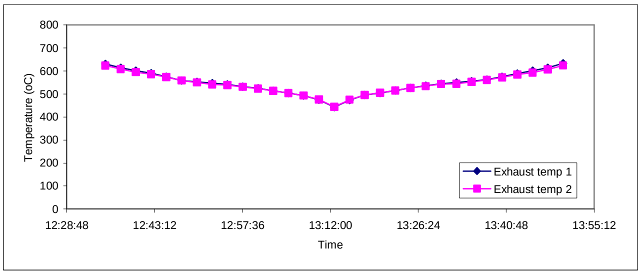
Baseline 003_104

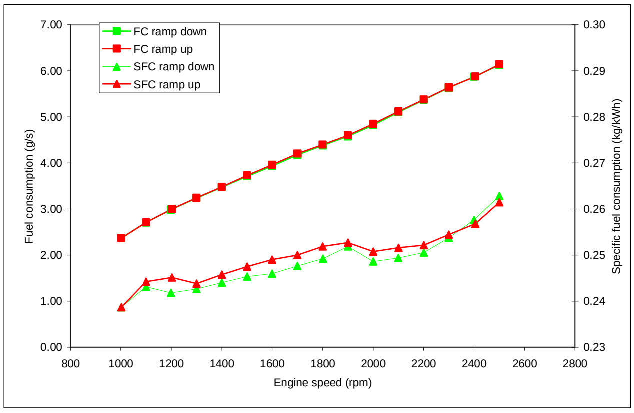


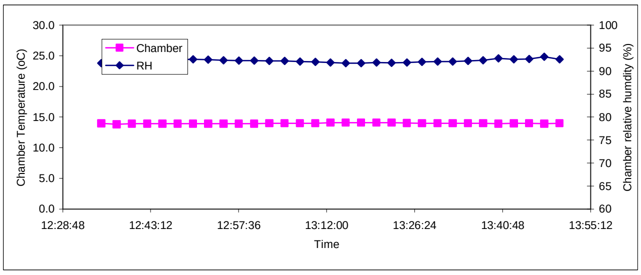


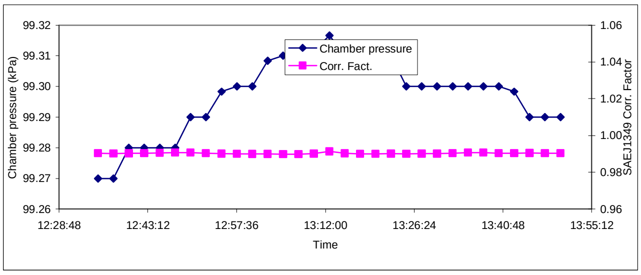


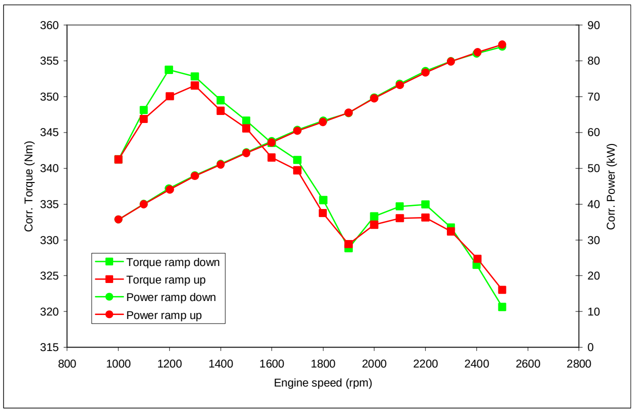






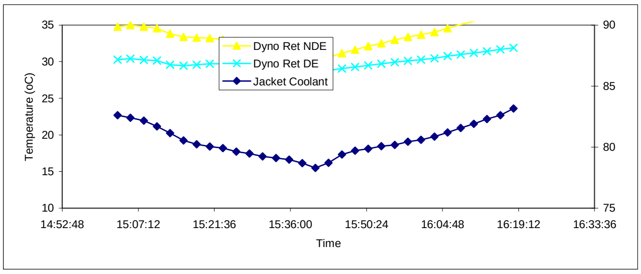


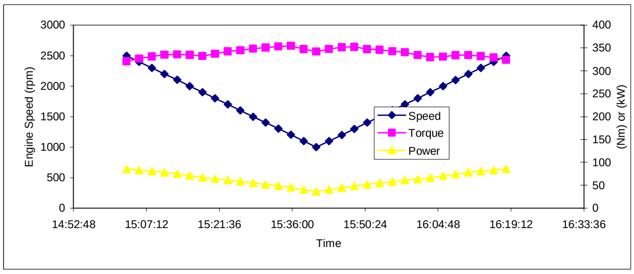


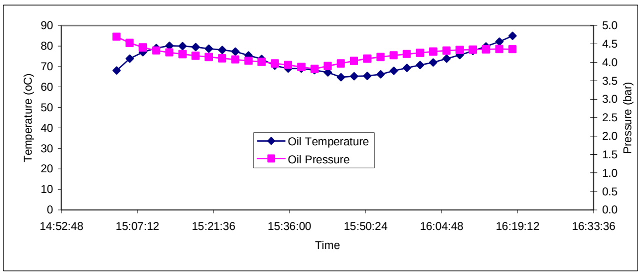


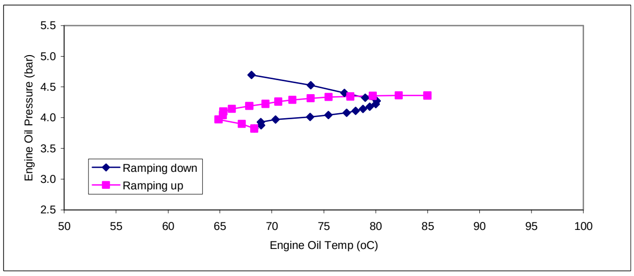
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 17/10/07

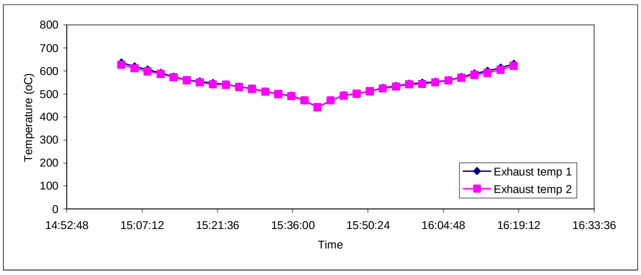
Baseline 003_005

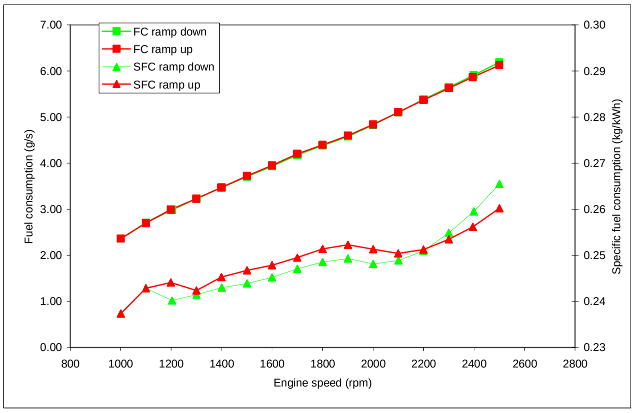


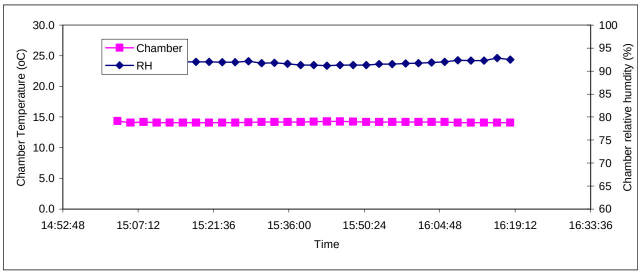


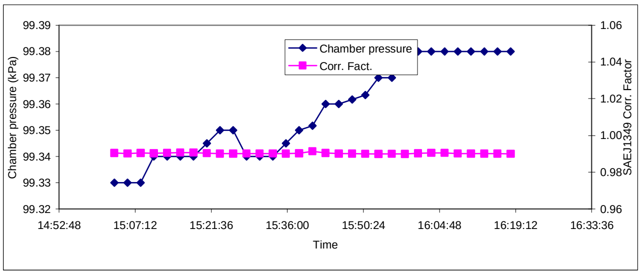


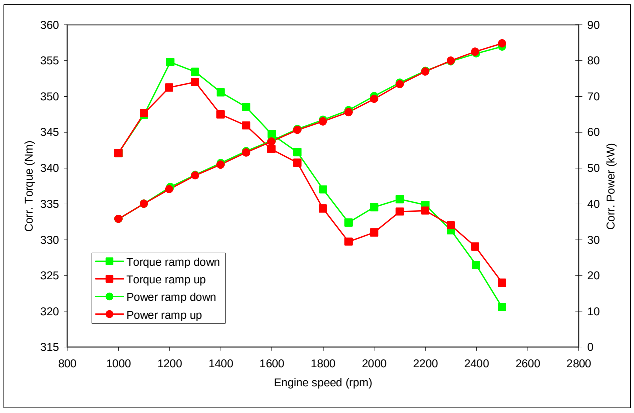






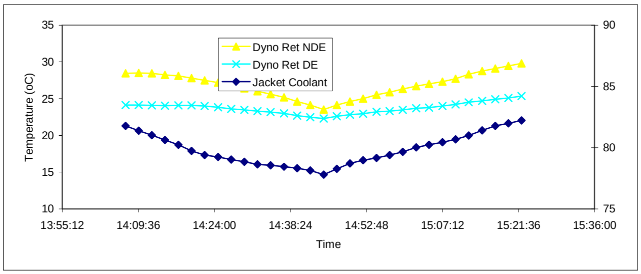


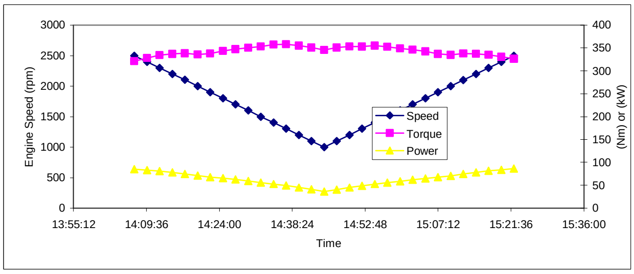


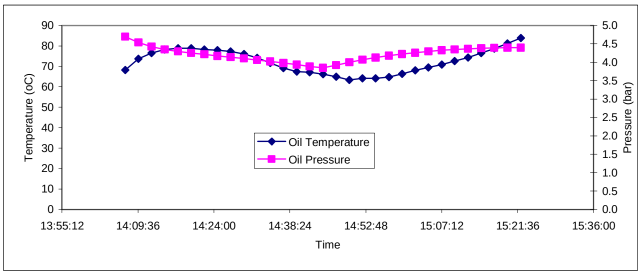


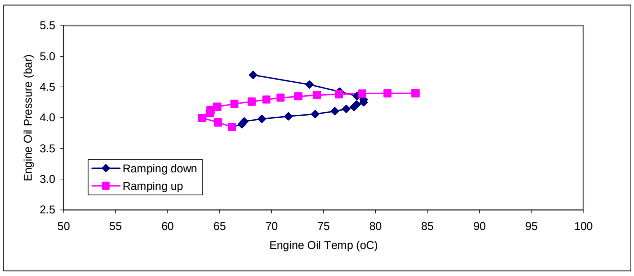
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 17/10/07

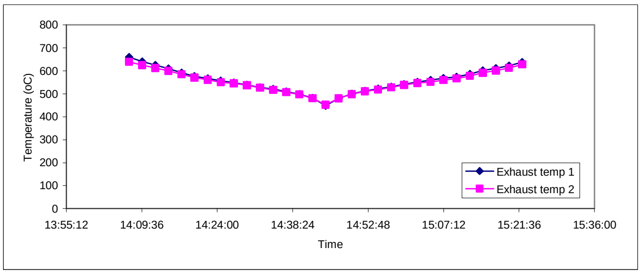
Baseline 003_106

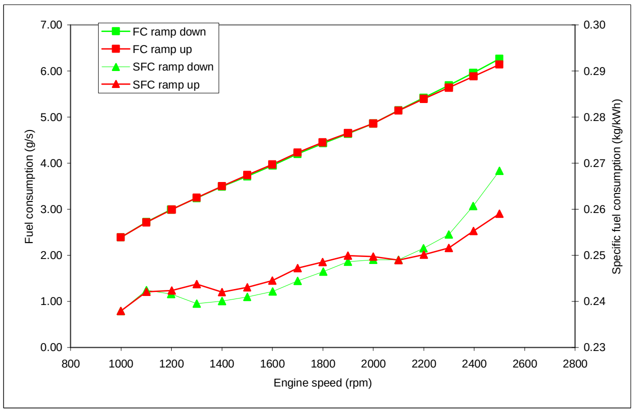


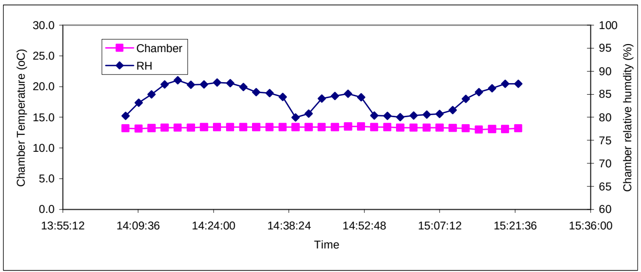


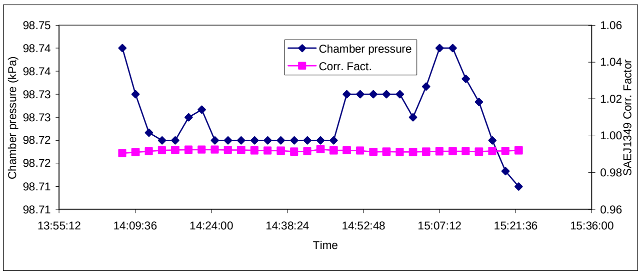


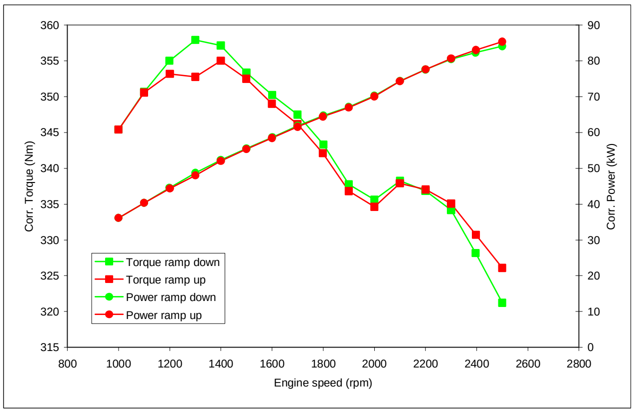






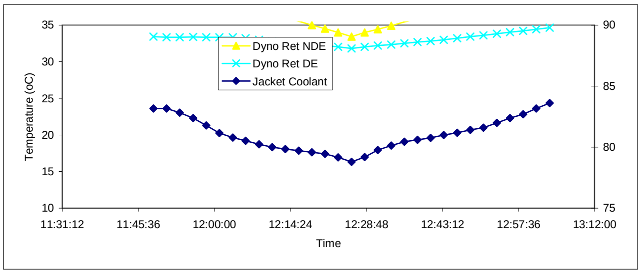


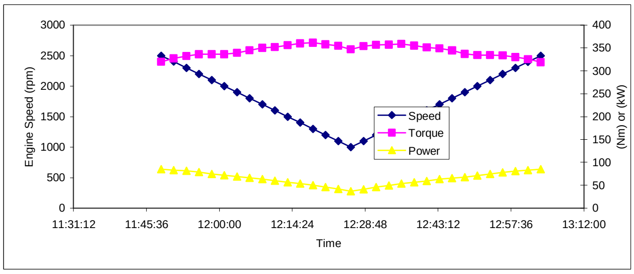


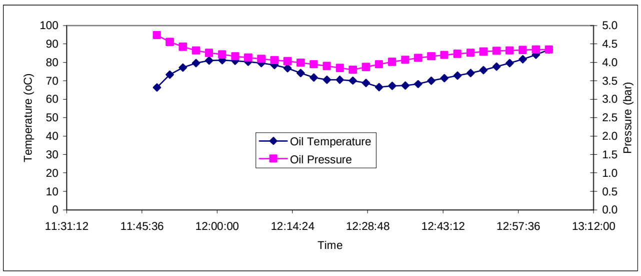


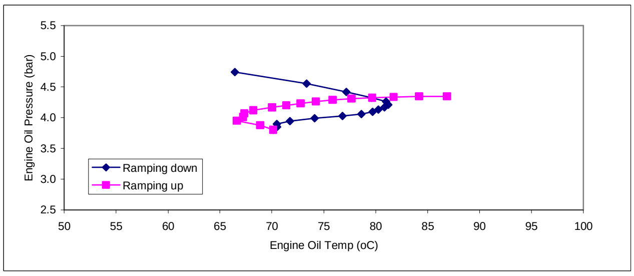
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 29/10/07

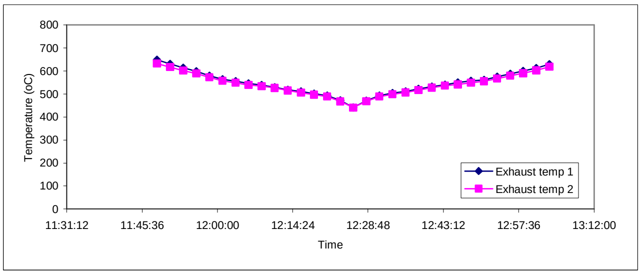
Baseline 003_107

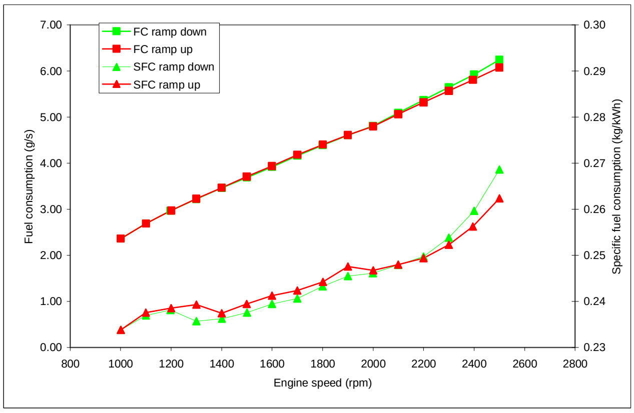


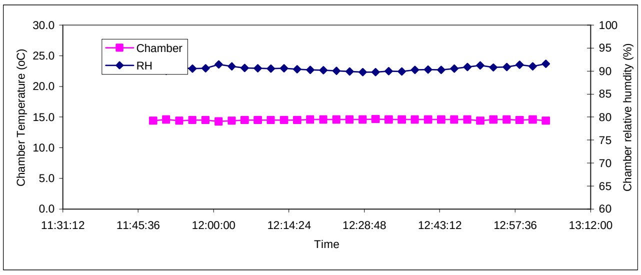


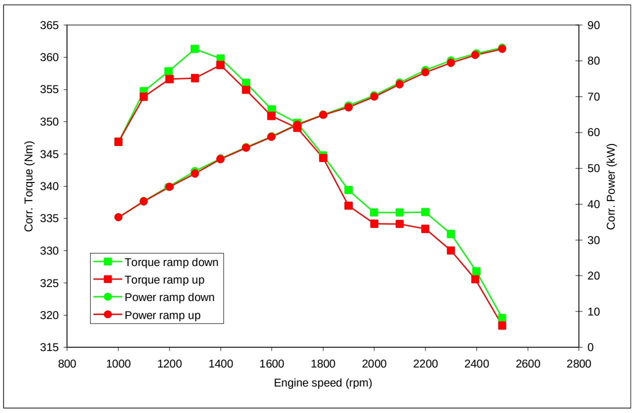


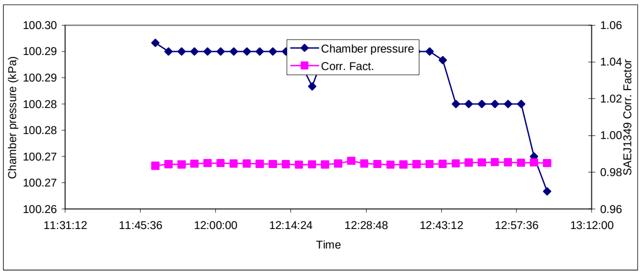






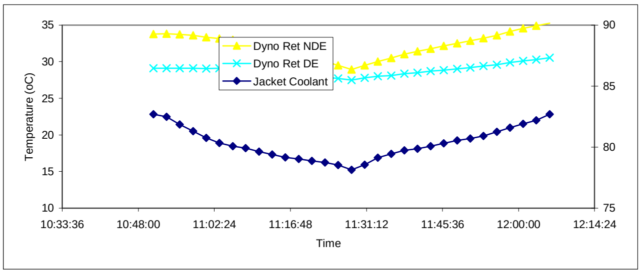


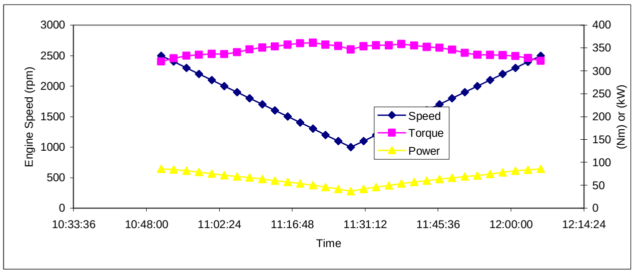


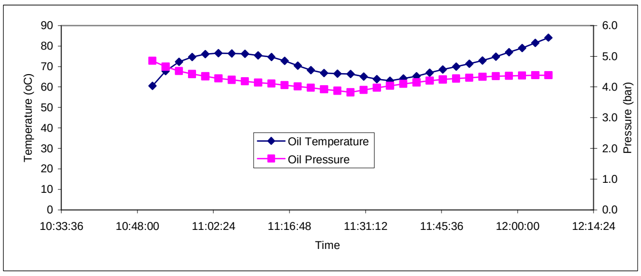


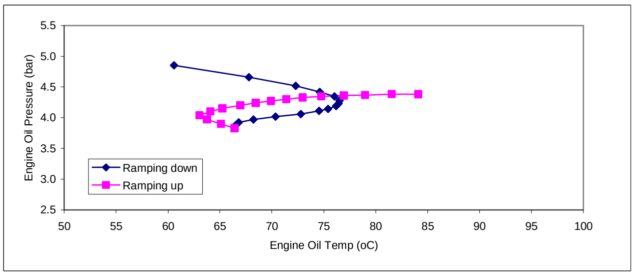
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 01/11/07

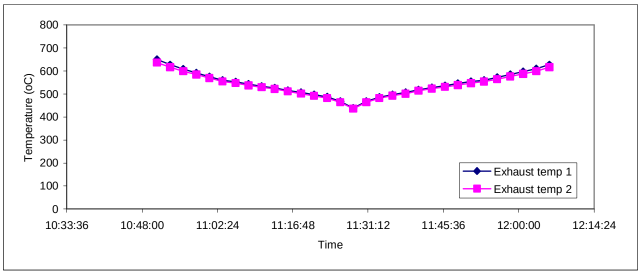
Baseline 003_108

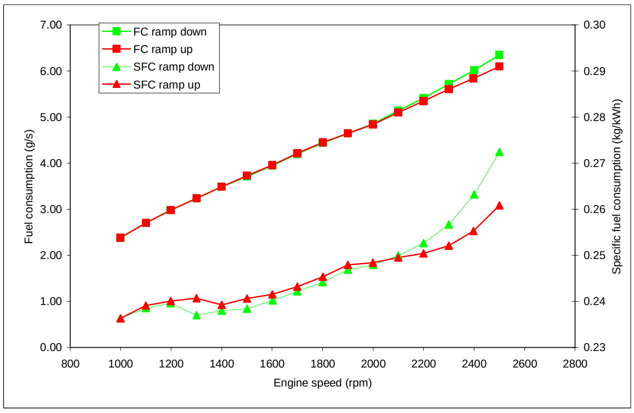


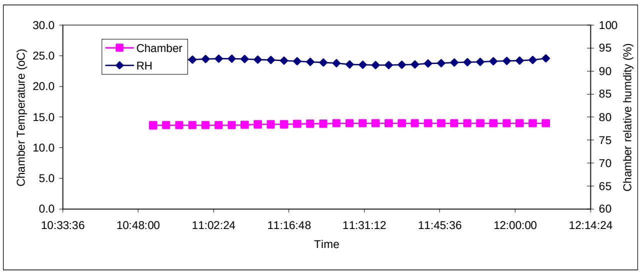


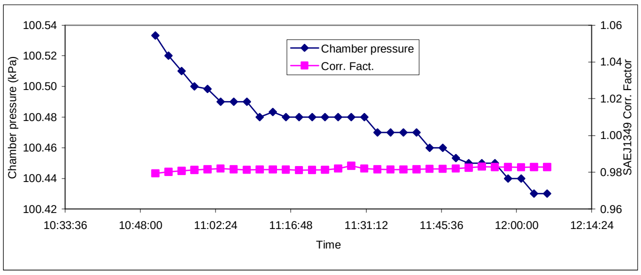


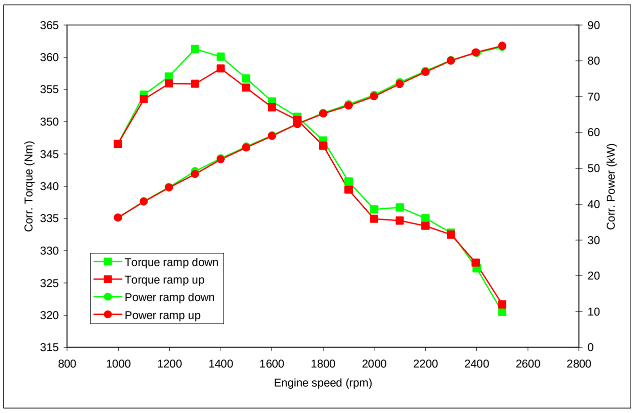






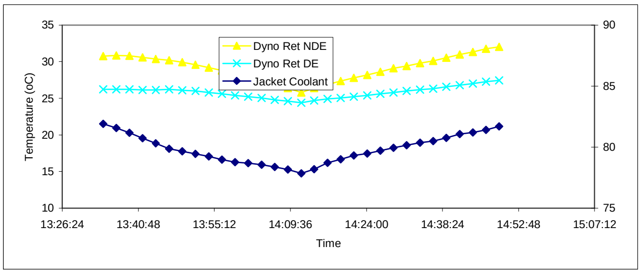


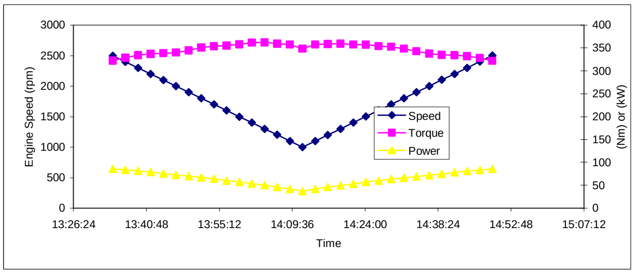


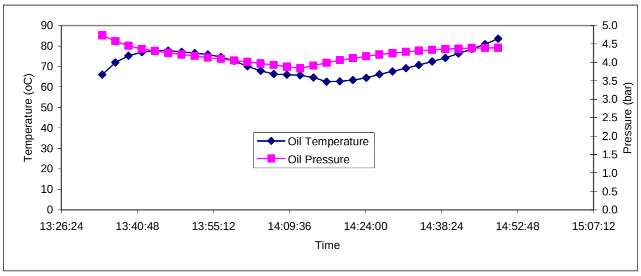


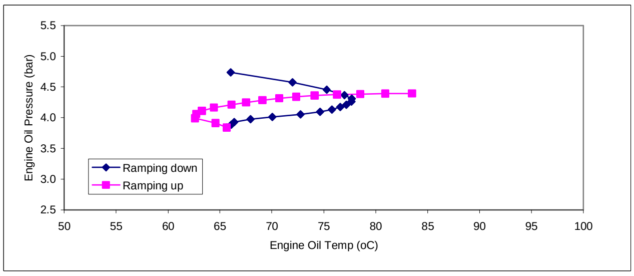
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 02/11/07

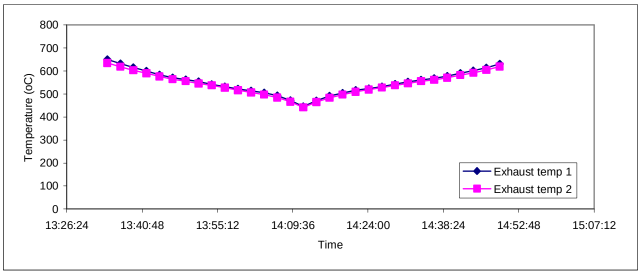
Baseline 003_109

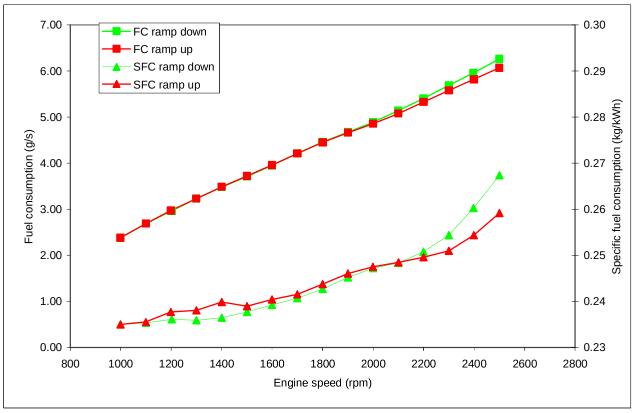


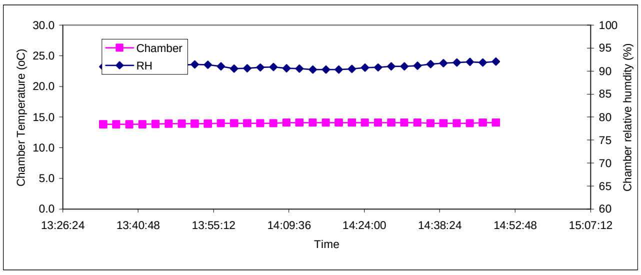


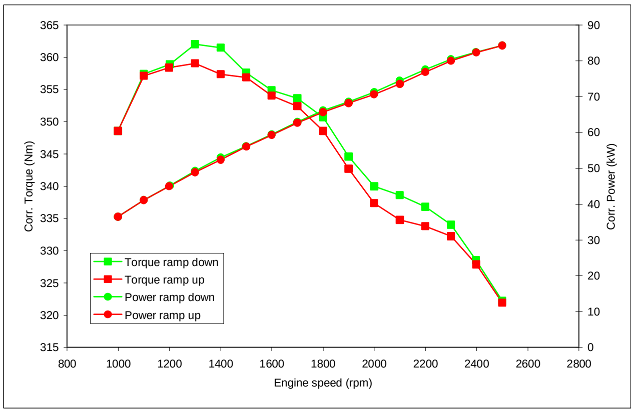


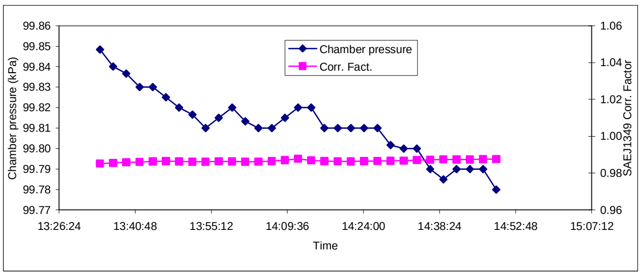






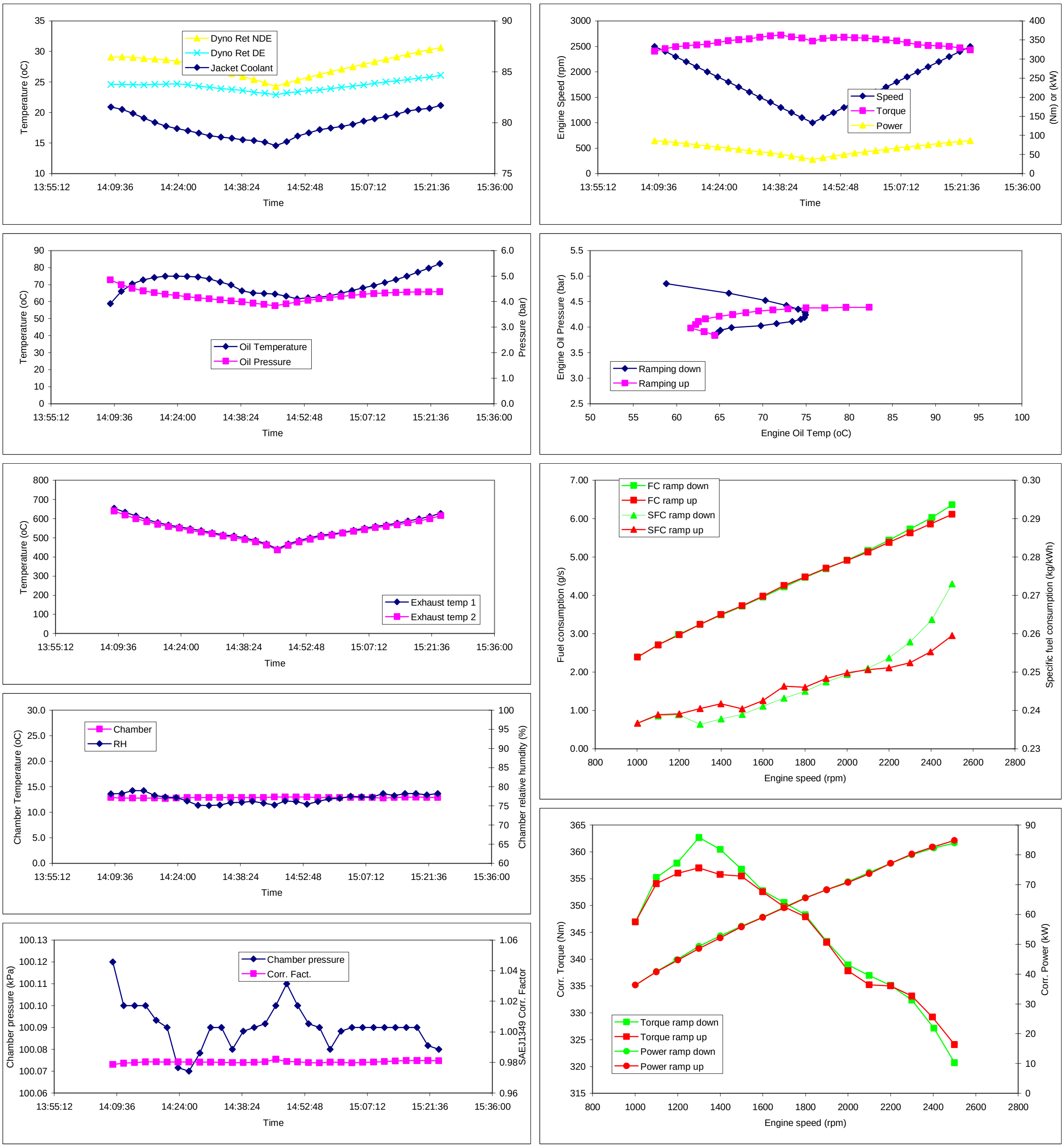






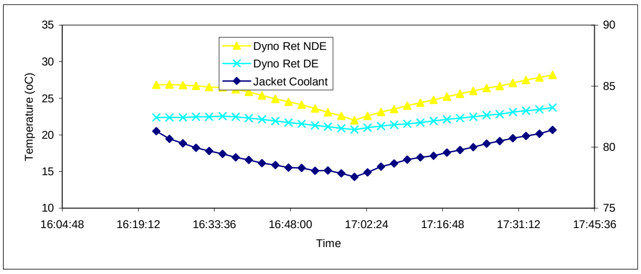
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 05/11/07

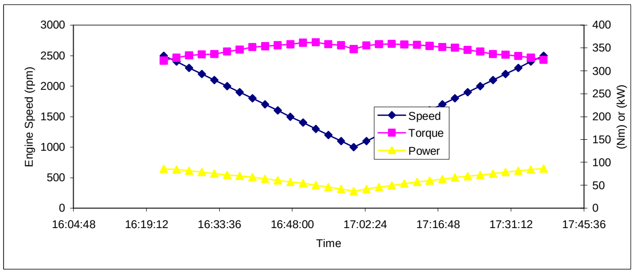
Baseline 003_110

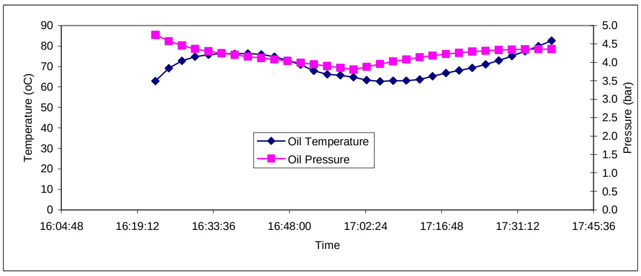


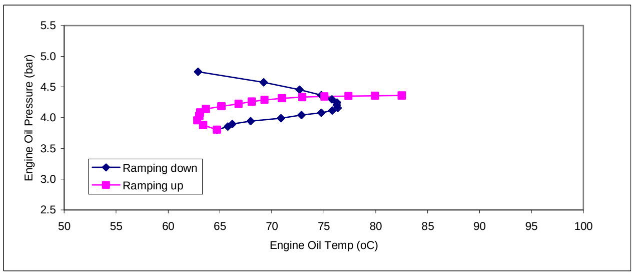
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 09/11/07

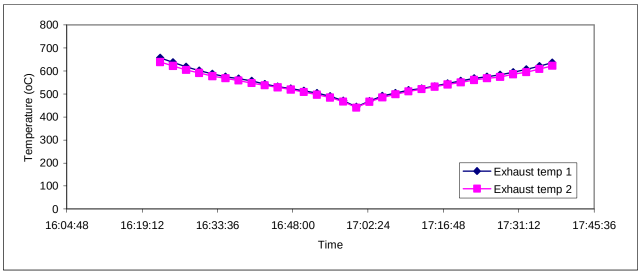
Baseline 003_111

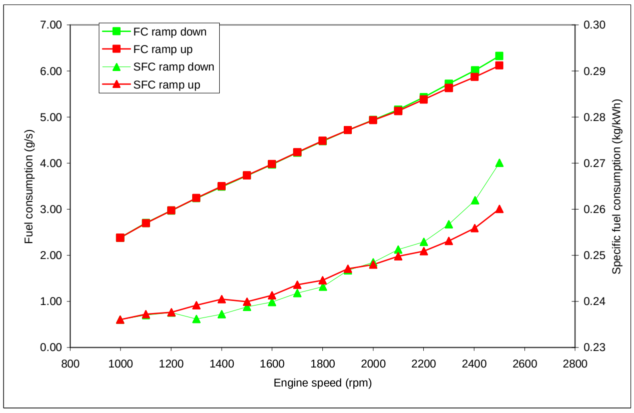


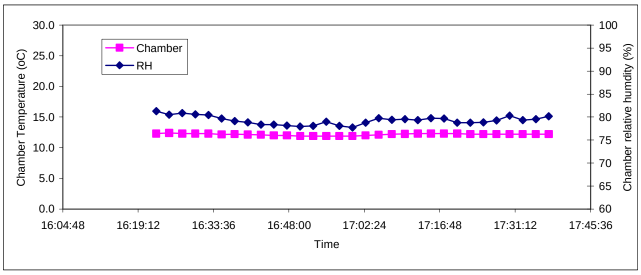


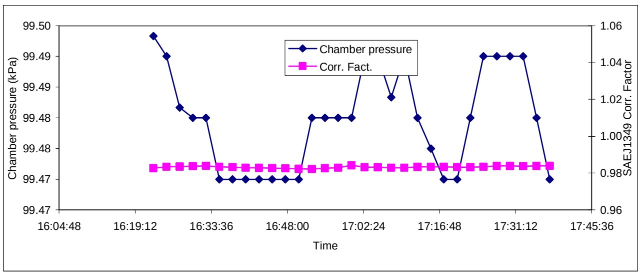


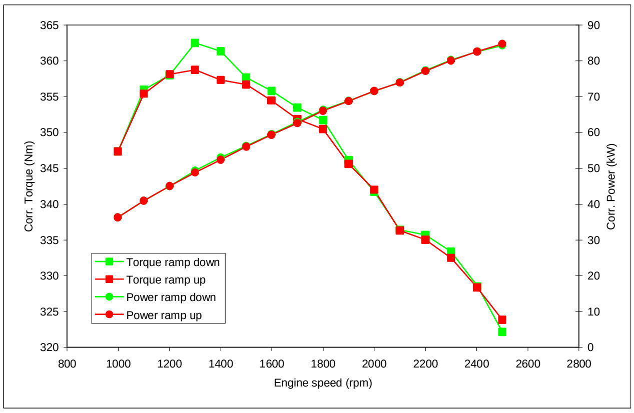






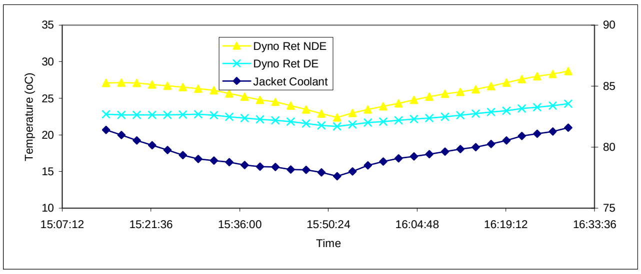


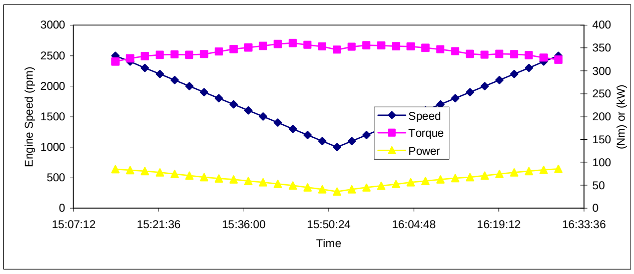


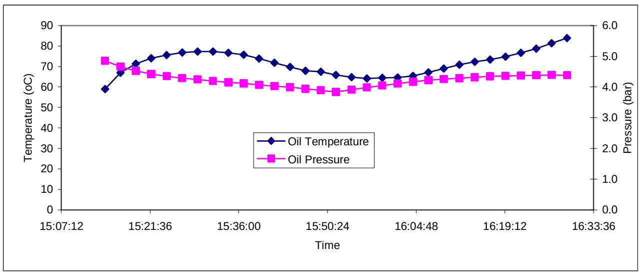


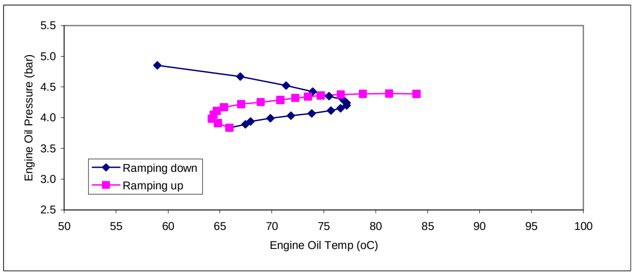
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 12/11/07

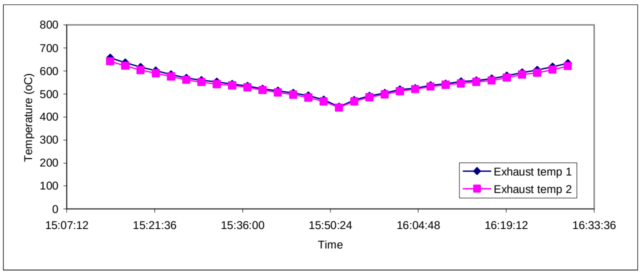
Baseline 003_112

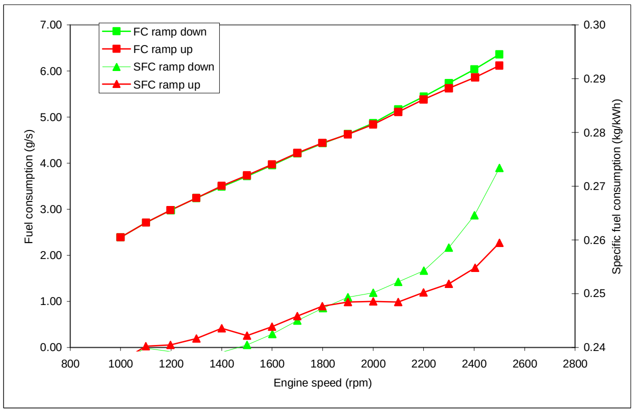


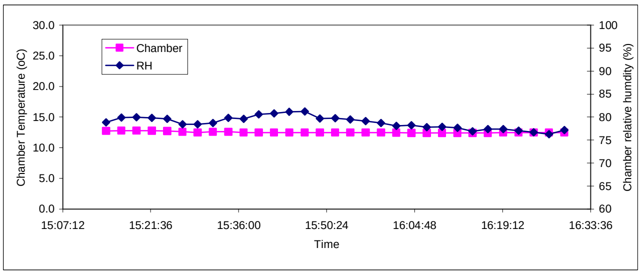


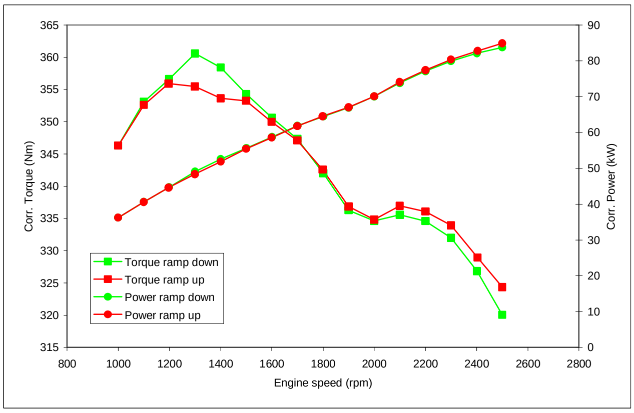


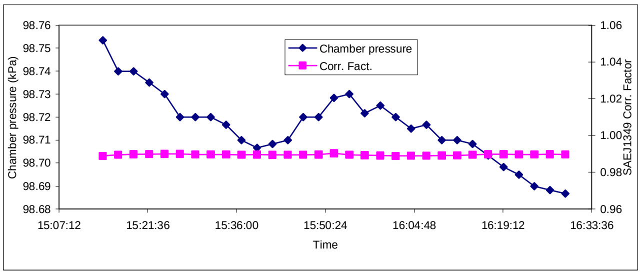






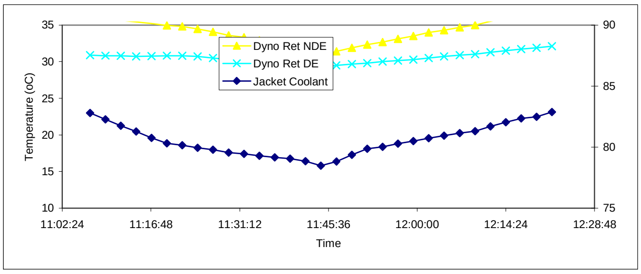


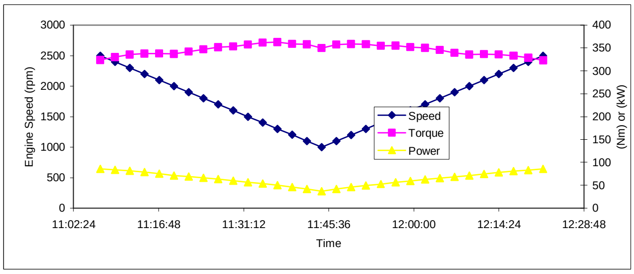


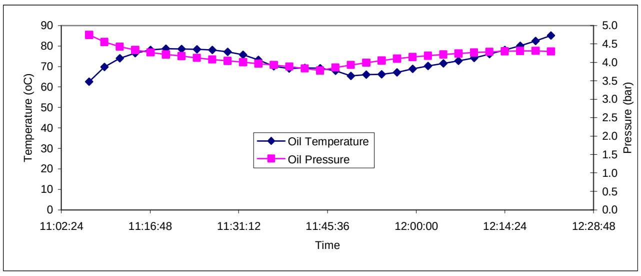


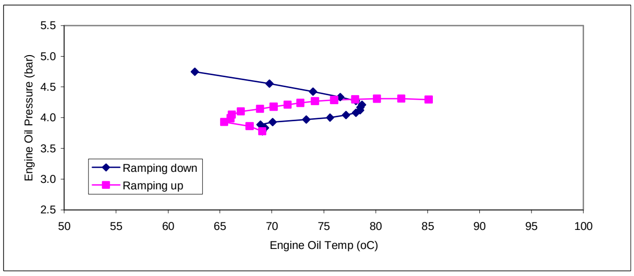
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 13/11/07

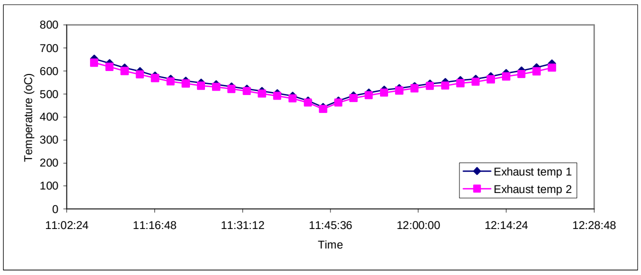
Baseline 003_113

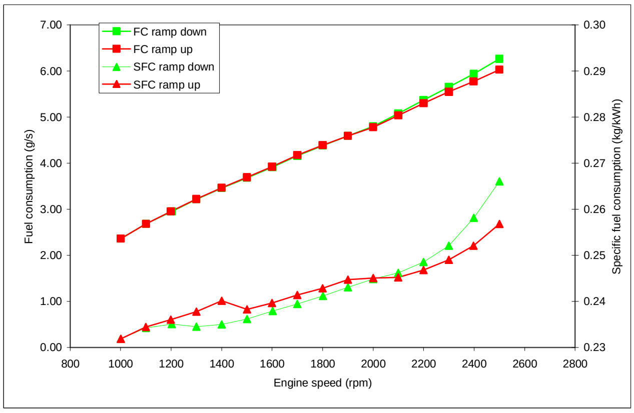


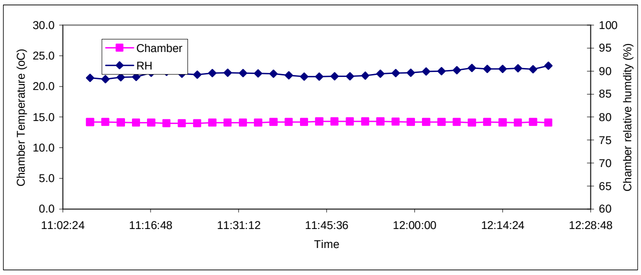


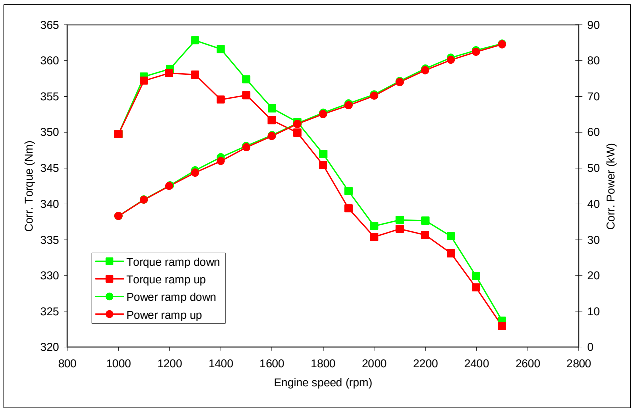


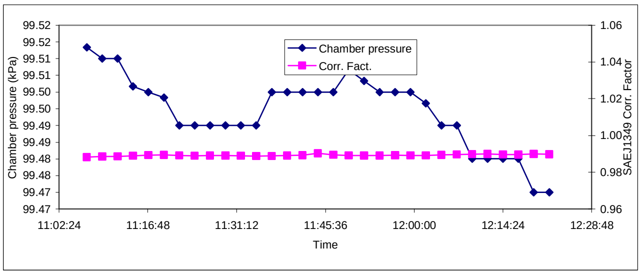






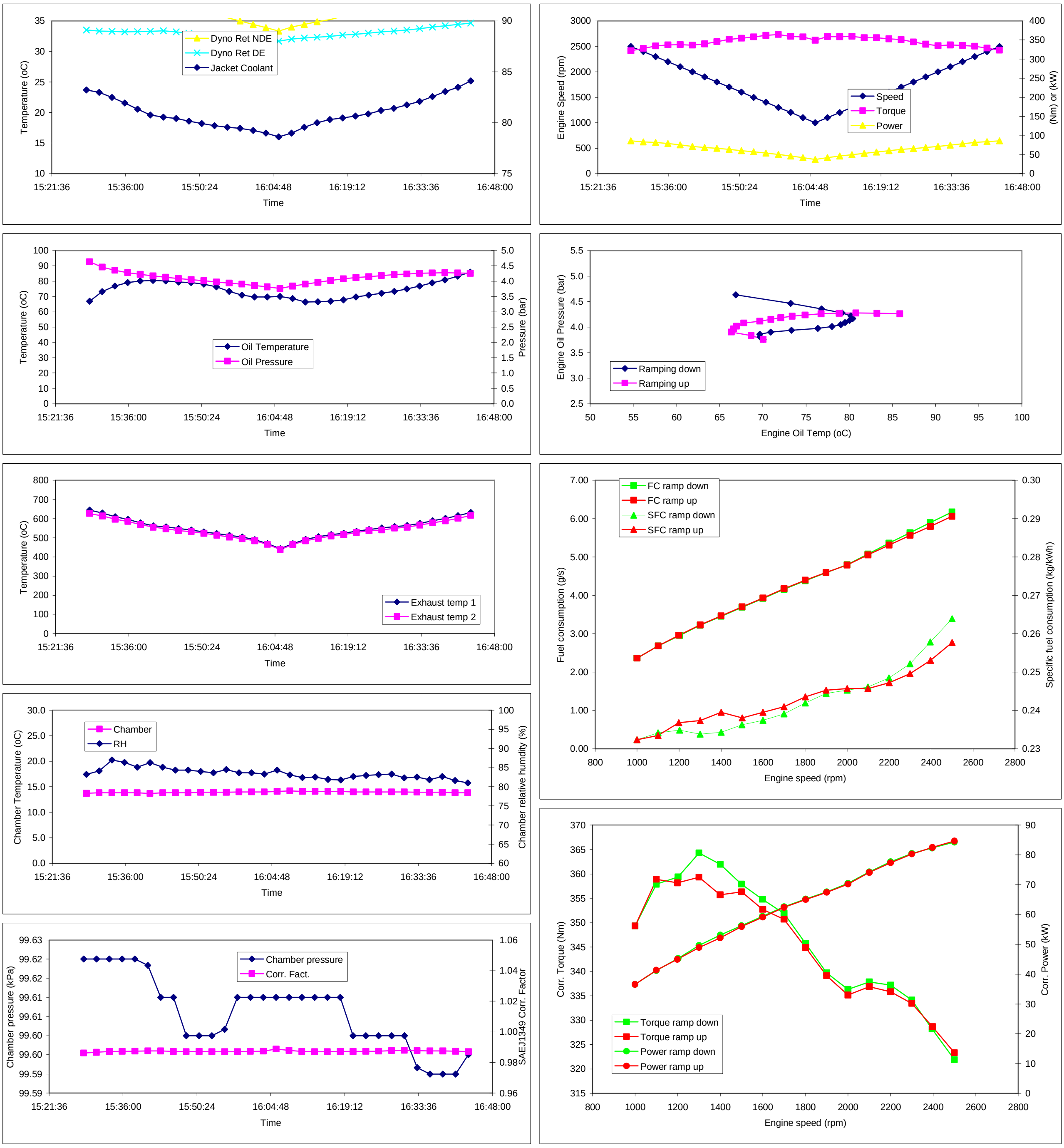






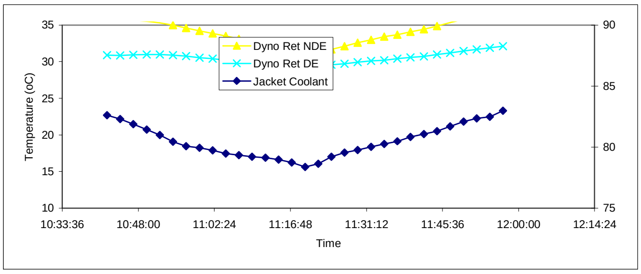
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 15/11/07

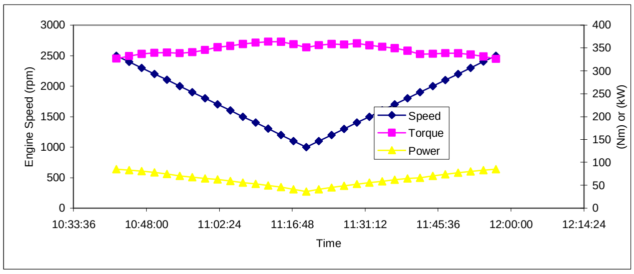
Baseline 003_114

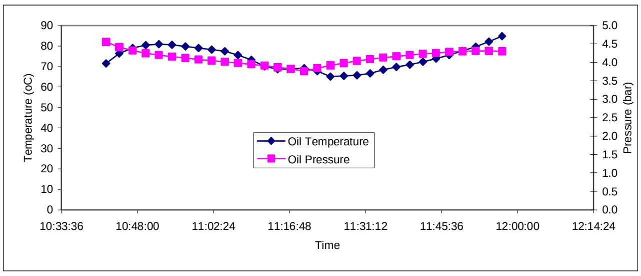


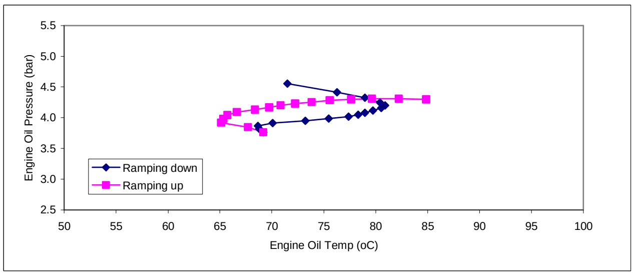
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 16/11/07

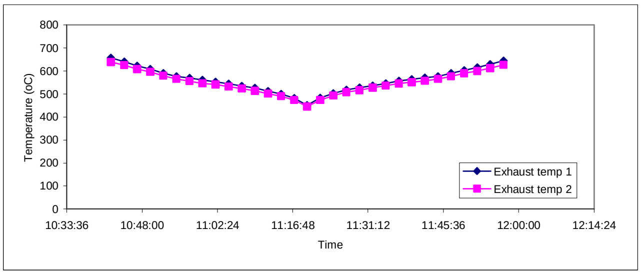
Baseline 003_115

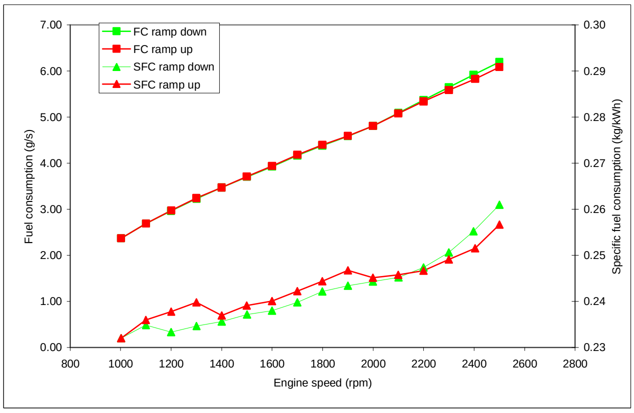


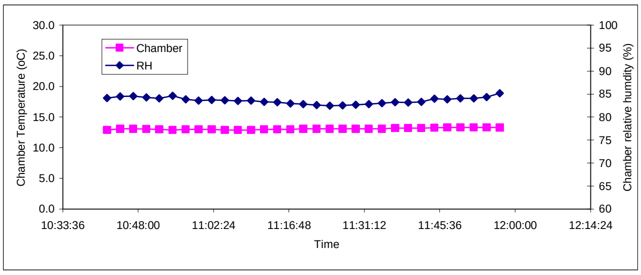


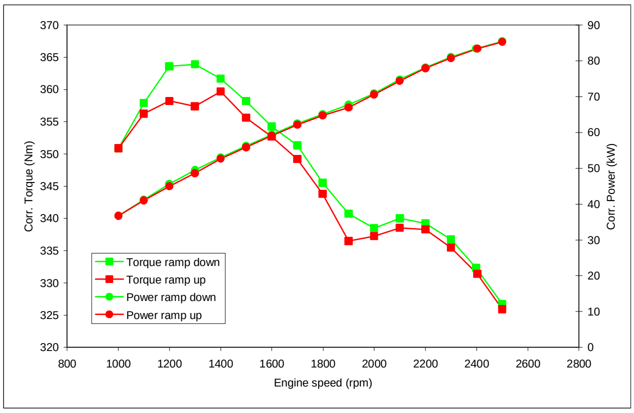


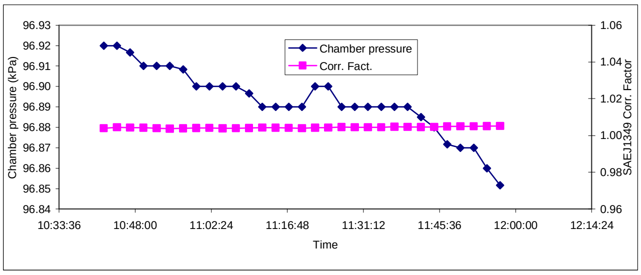






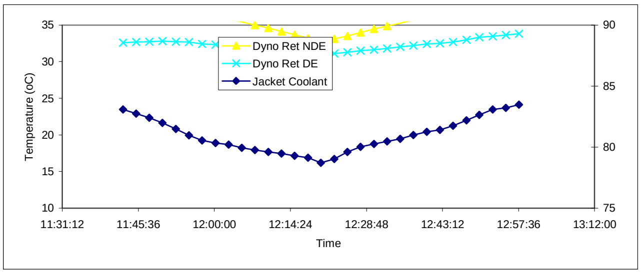


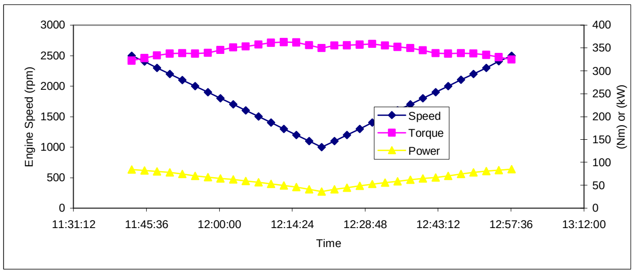


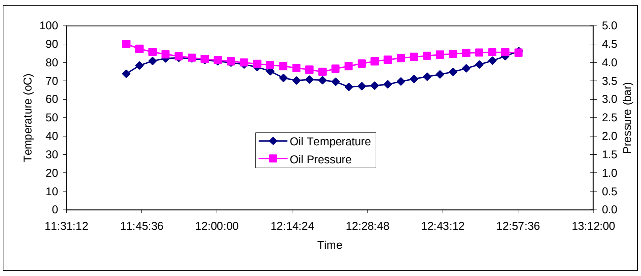


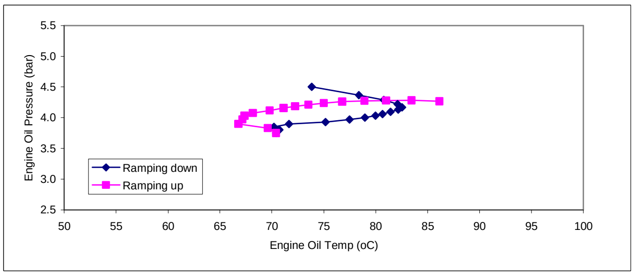
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 21/11/07

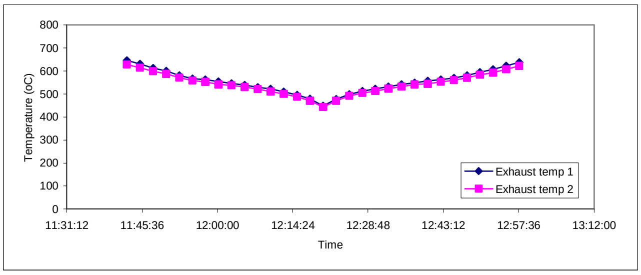
Baseline 003_116

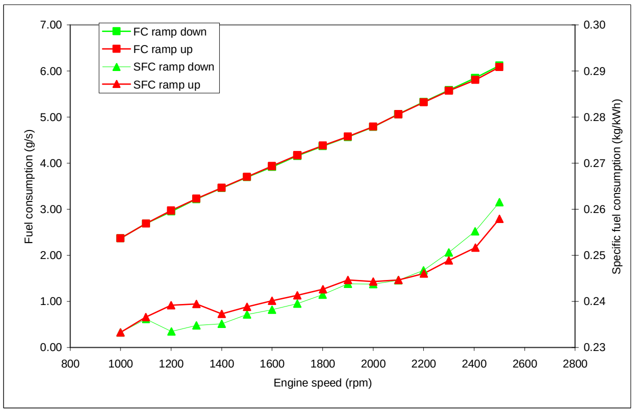


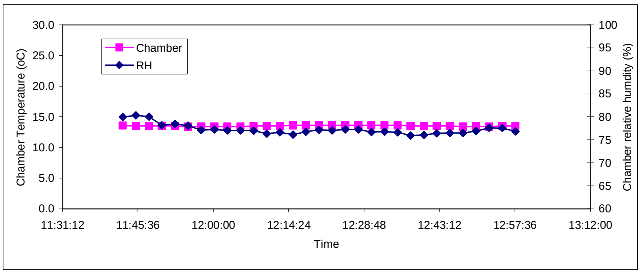


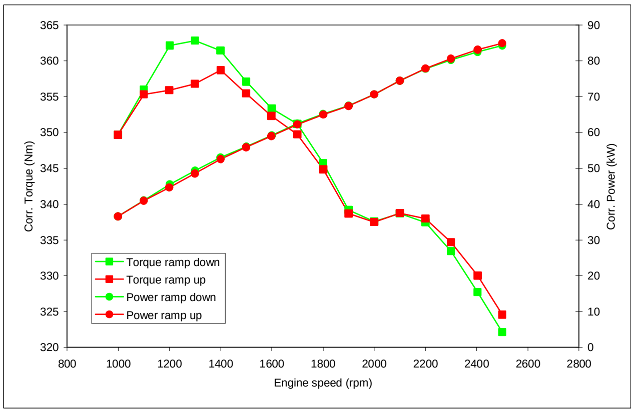


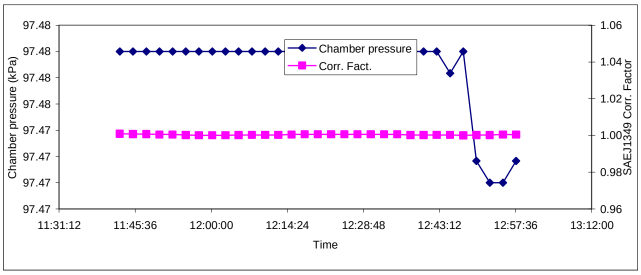






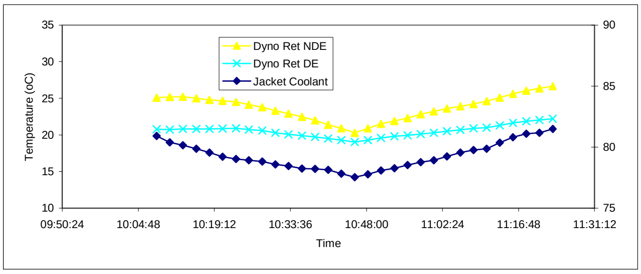


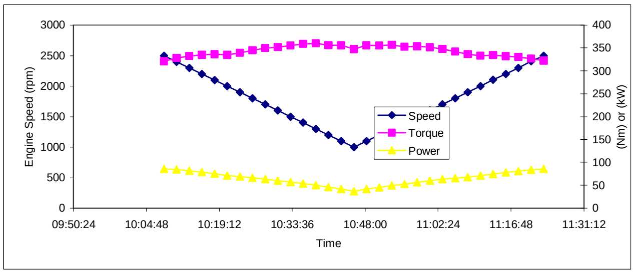


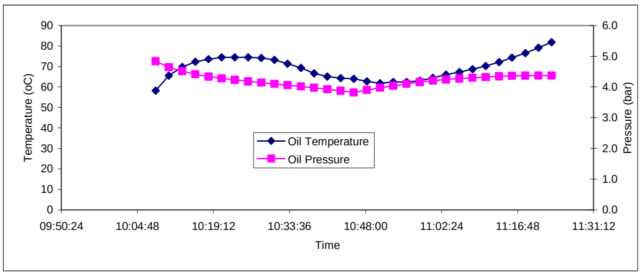


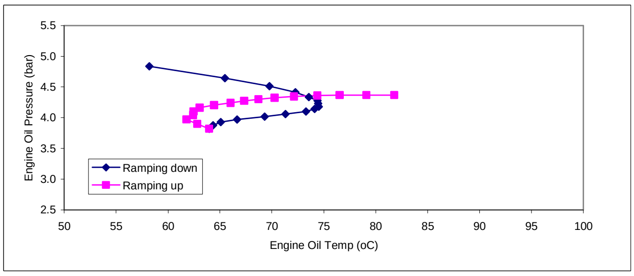
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 22/11/07

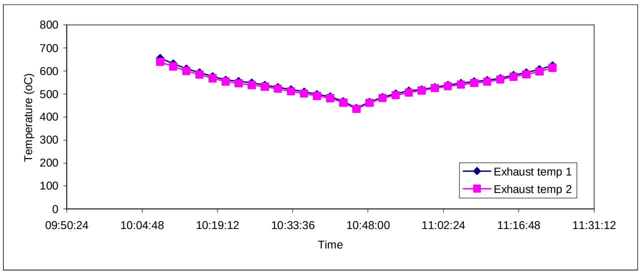
Baseline 003_117

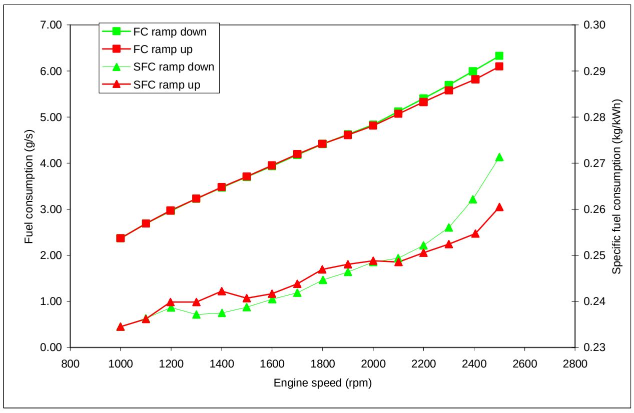


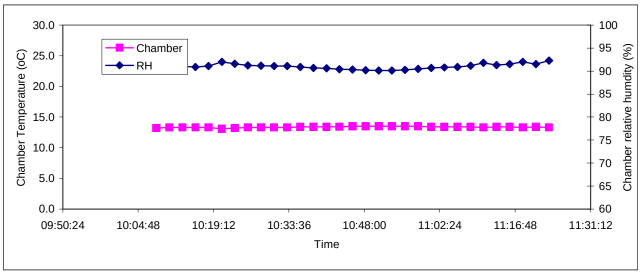


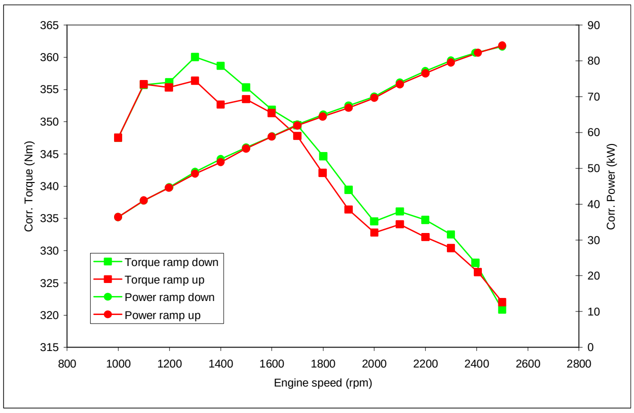


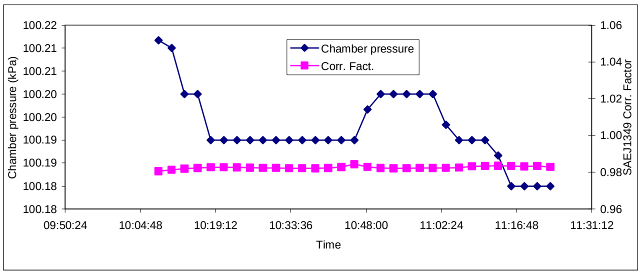






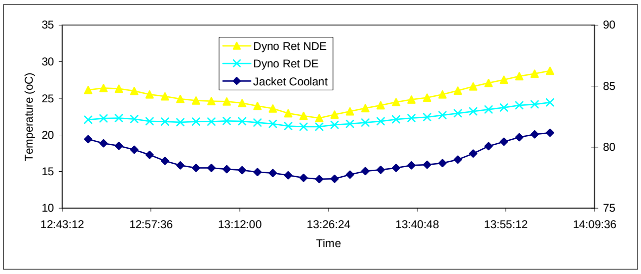


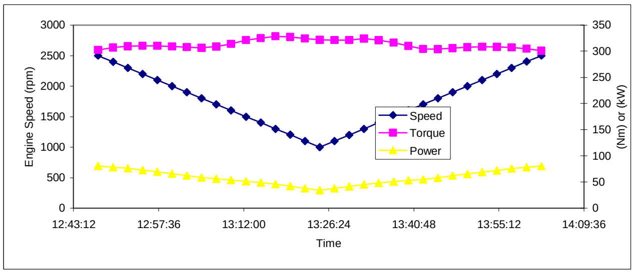


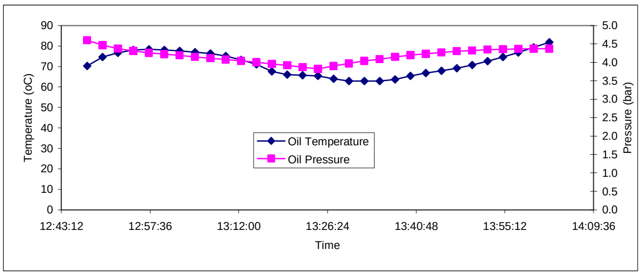


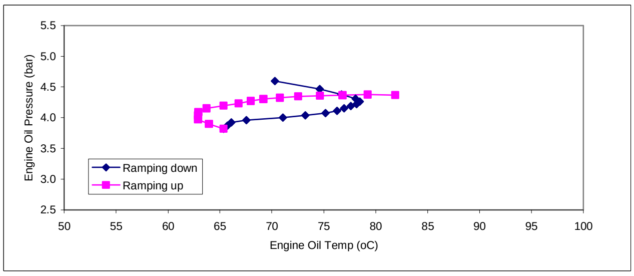
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 26/11/07

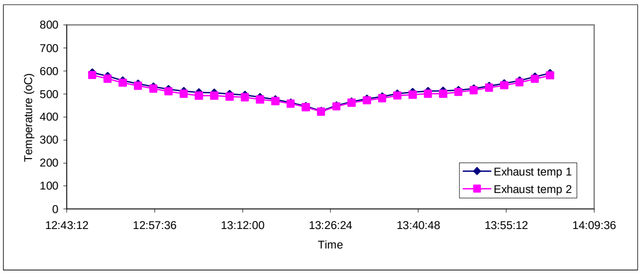
Baseline 003_118

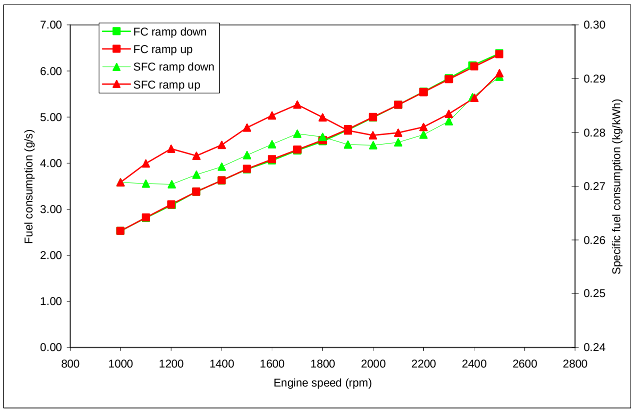


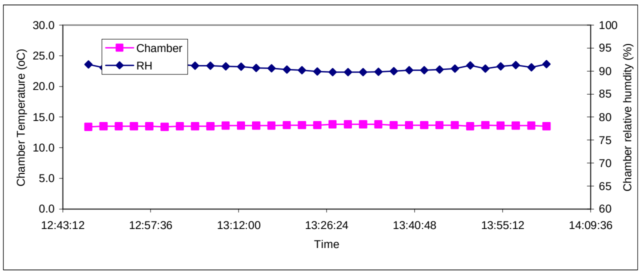


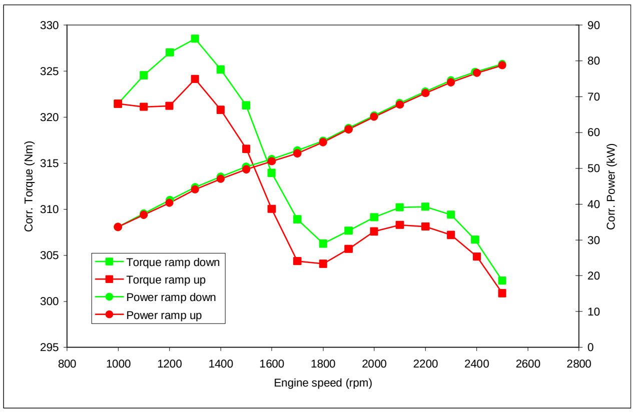


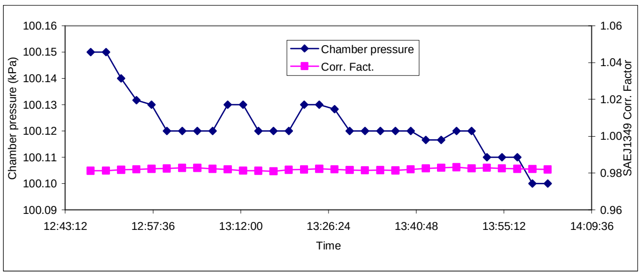






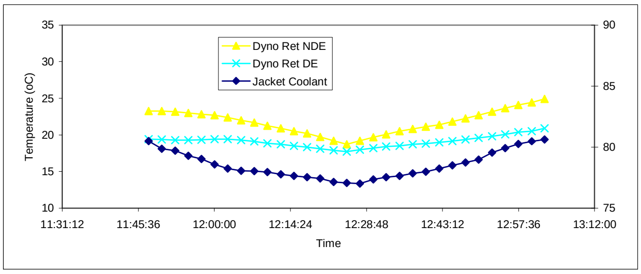


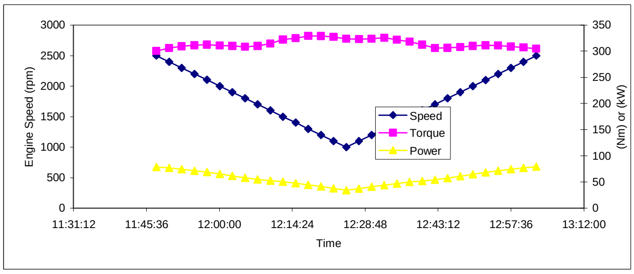


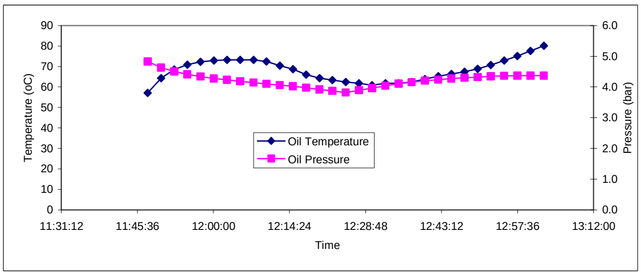


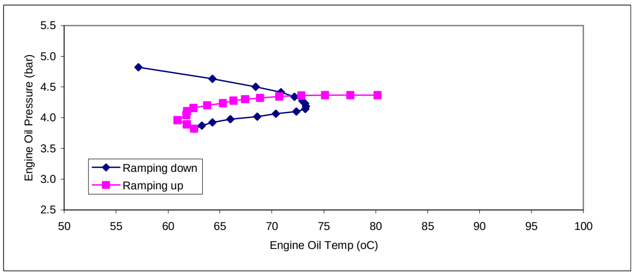
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 26/11/07

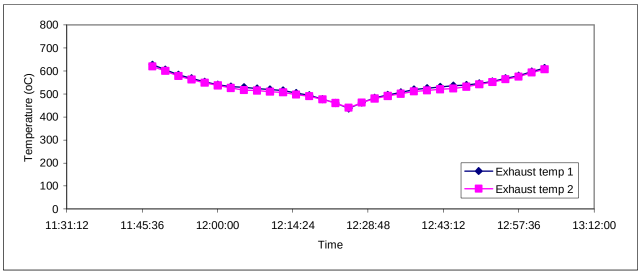
Baseline 003_119_ME

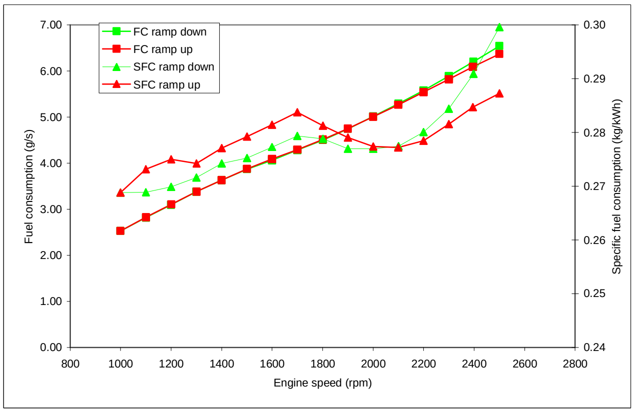


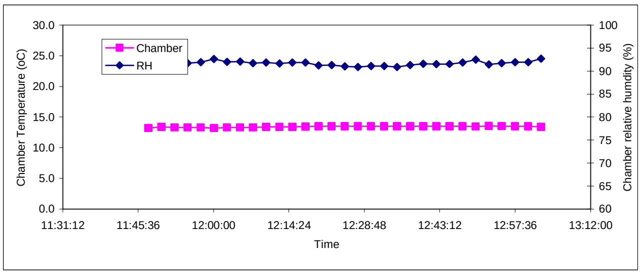


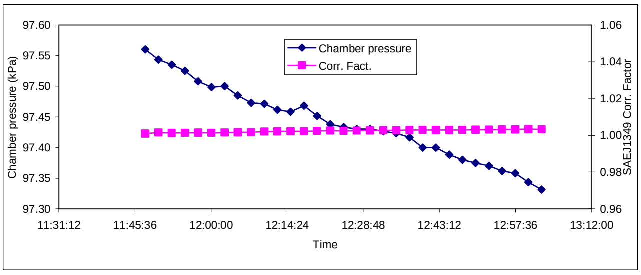


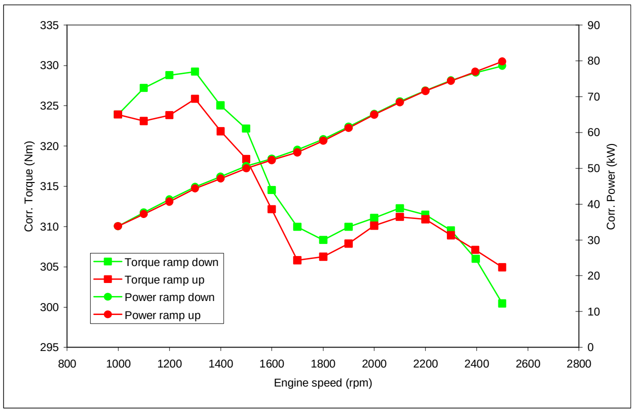






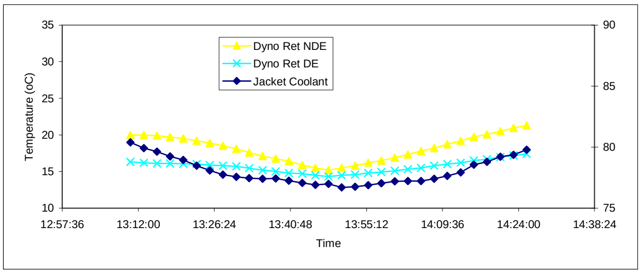


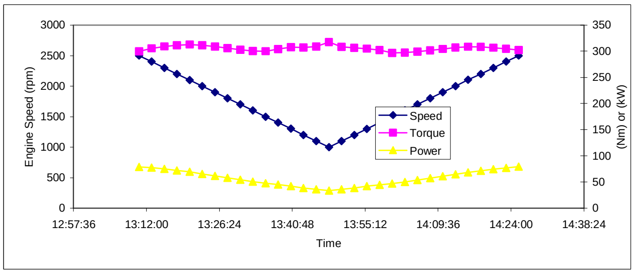


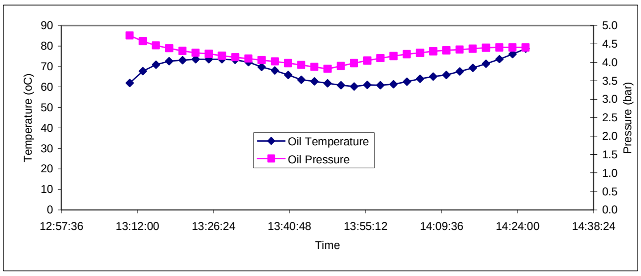


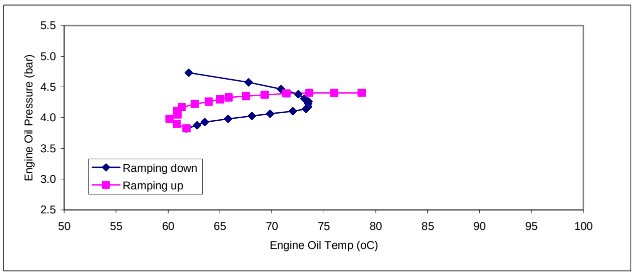
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 30/11/07

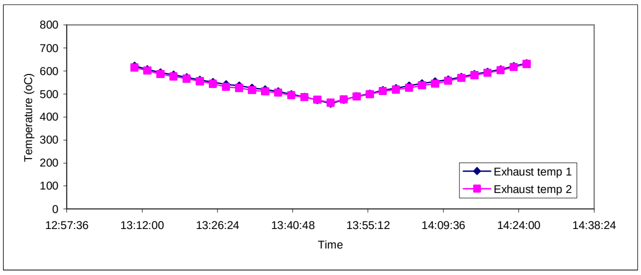
Baseline 003_120 ME

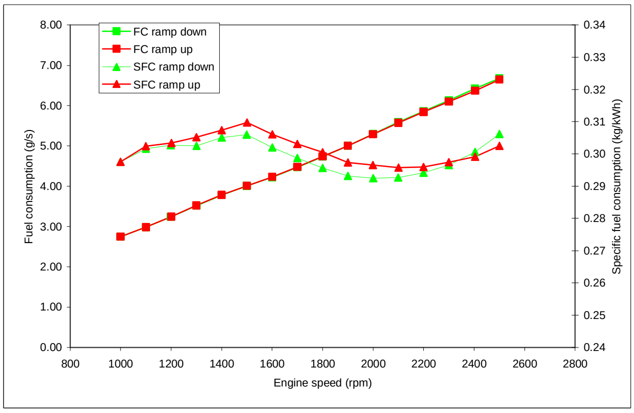


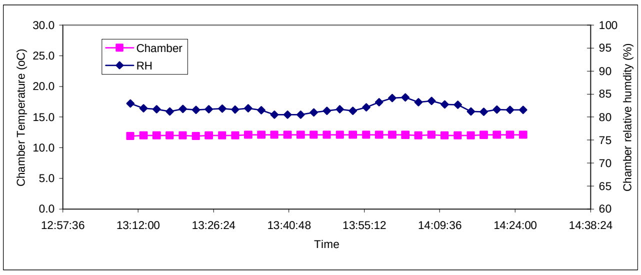


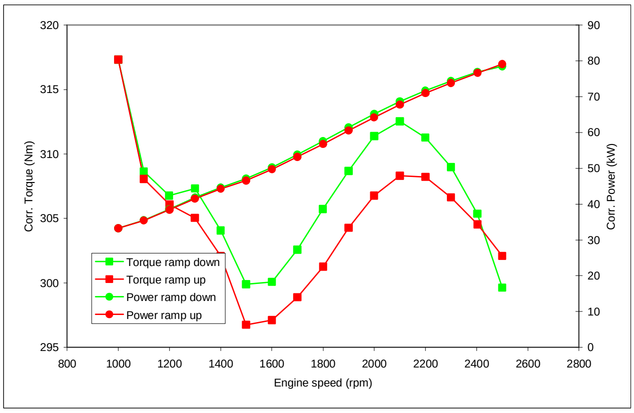


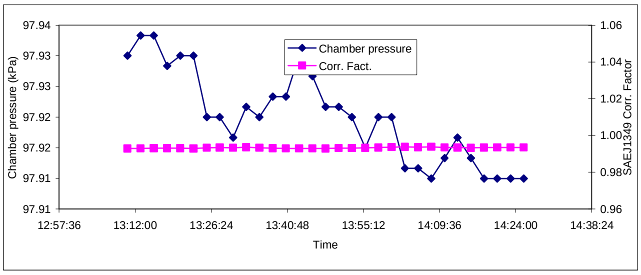








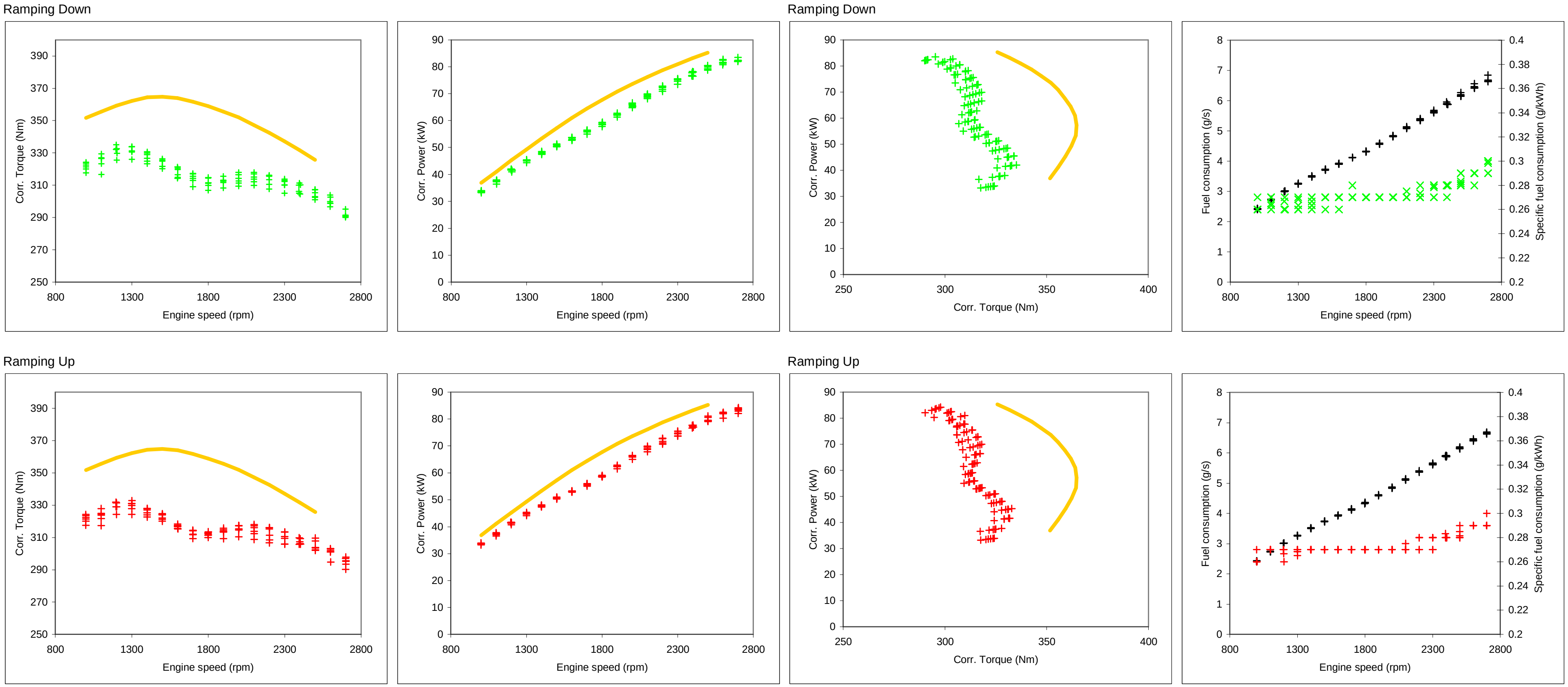




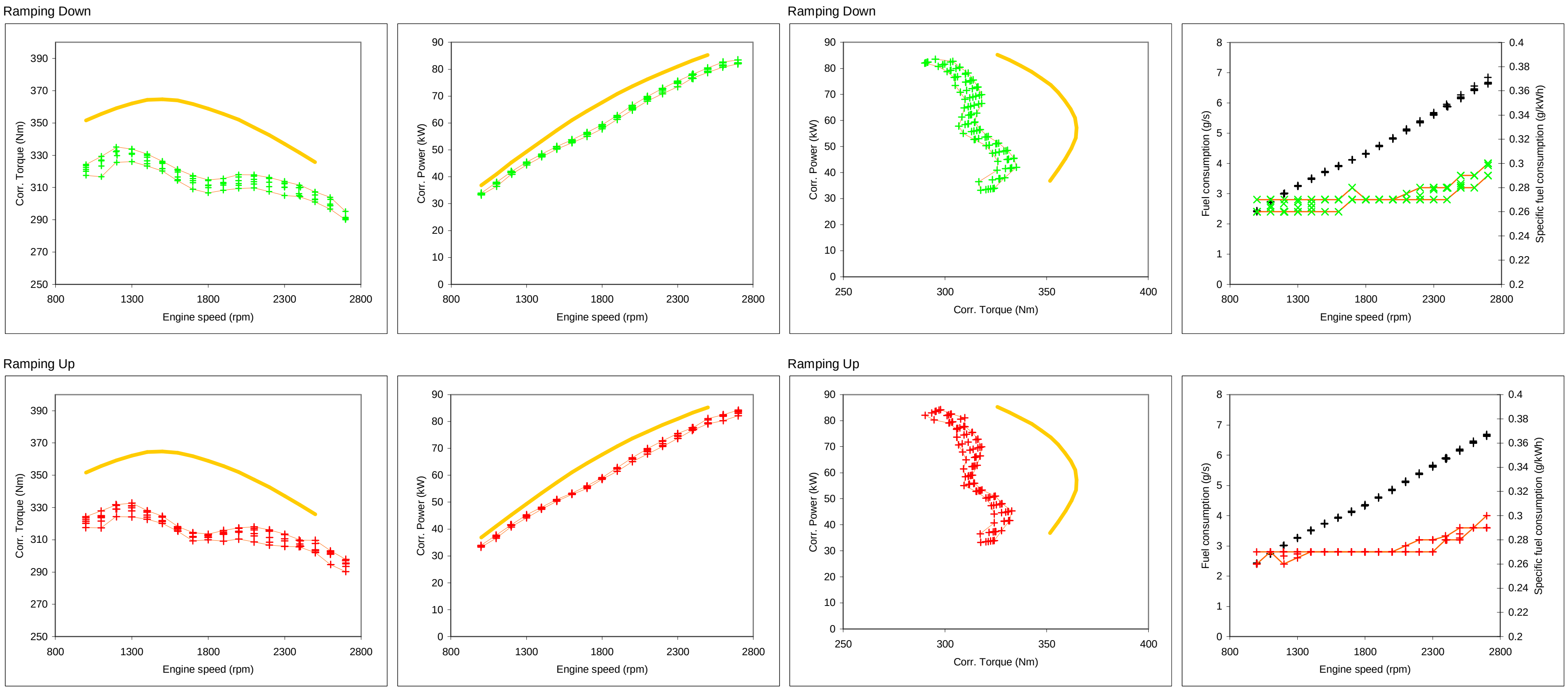
CSM Marine Diesel Engine Test Cell
Baseline engine performance curves
Max power at 100% throttle at all set points
Date of test: 03/12/07

Baseline 003_121 WO

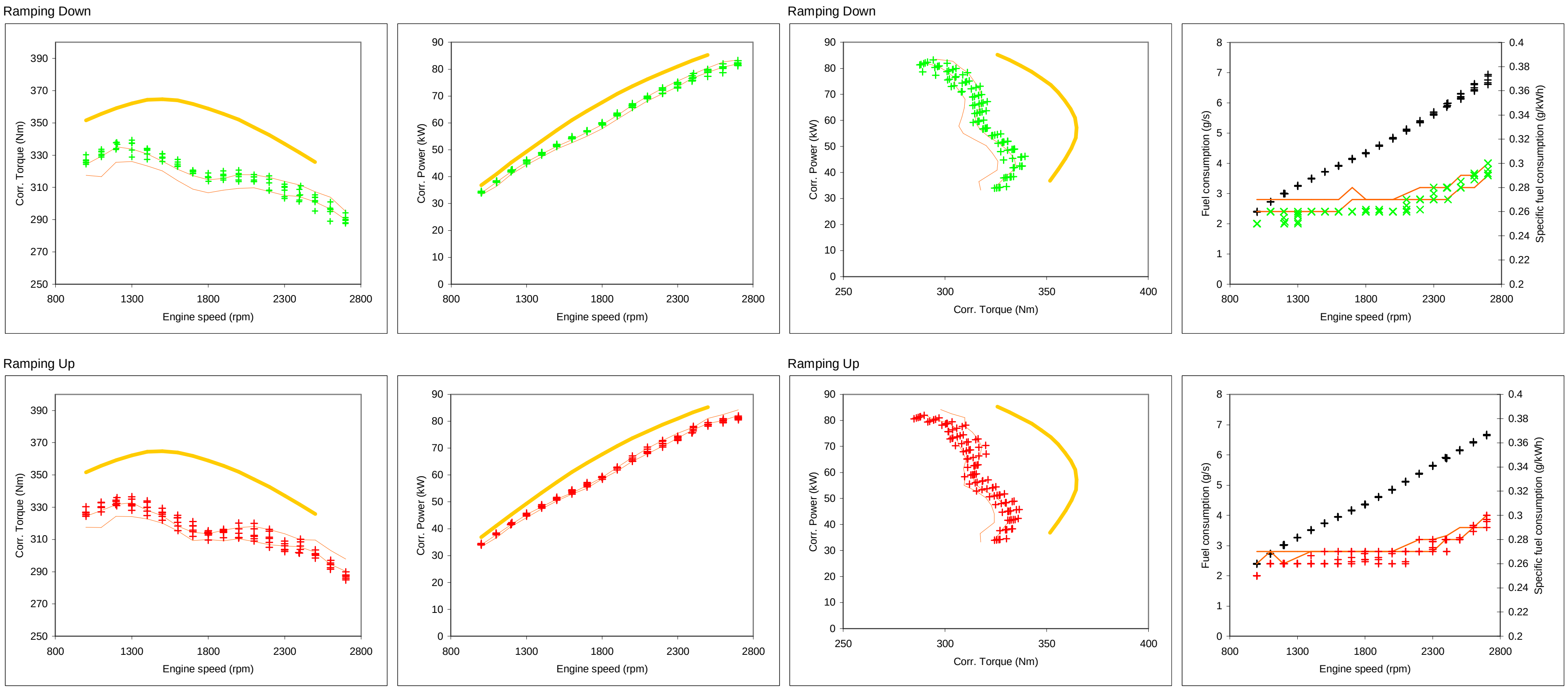
Appendix 7: Engine characterisation sequence with Baseline tests



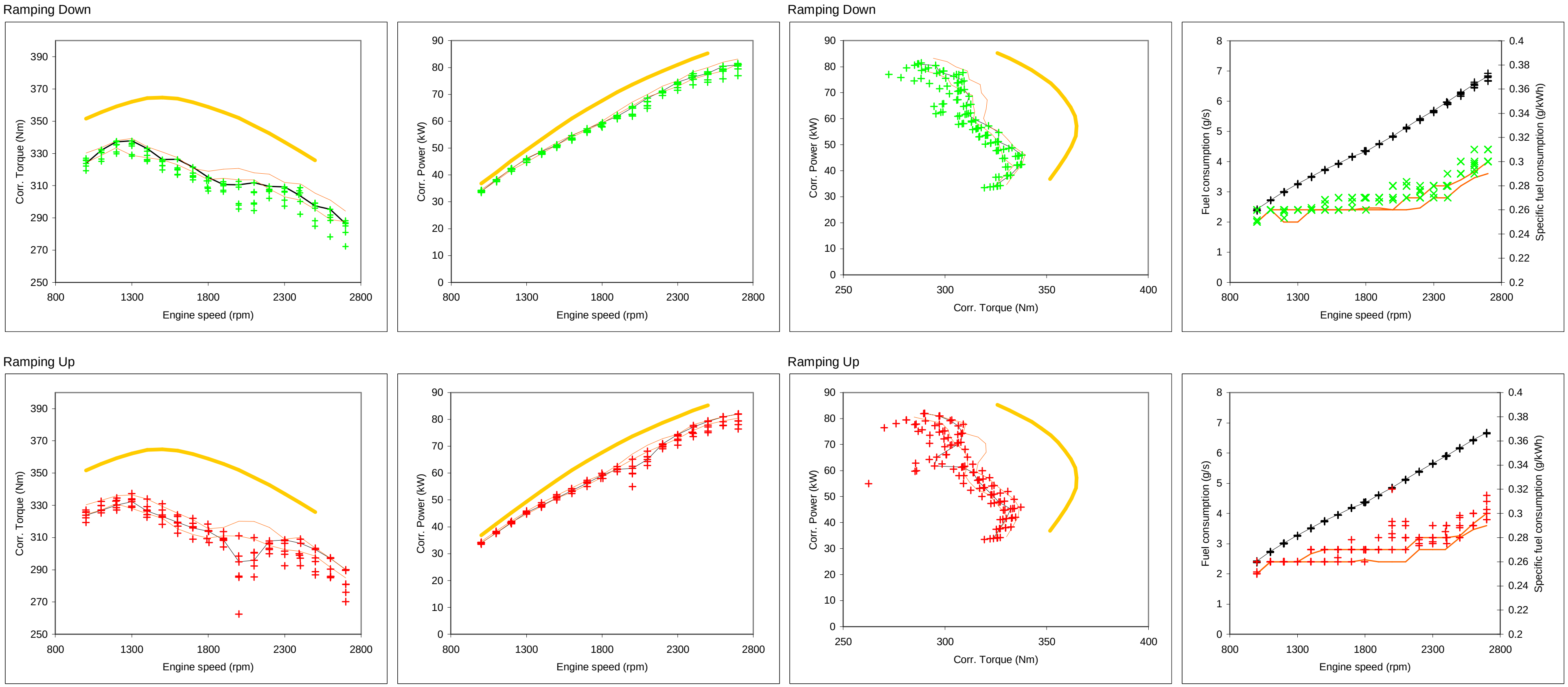
Full Figure 15: Baseline archive plot of tests Baseline_002_001 to Baseline_002_007 inclusive p.79 in main report



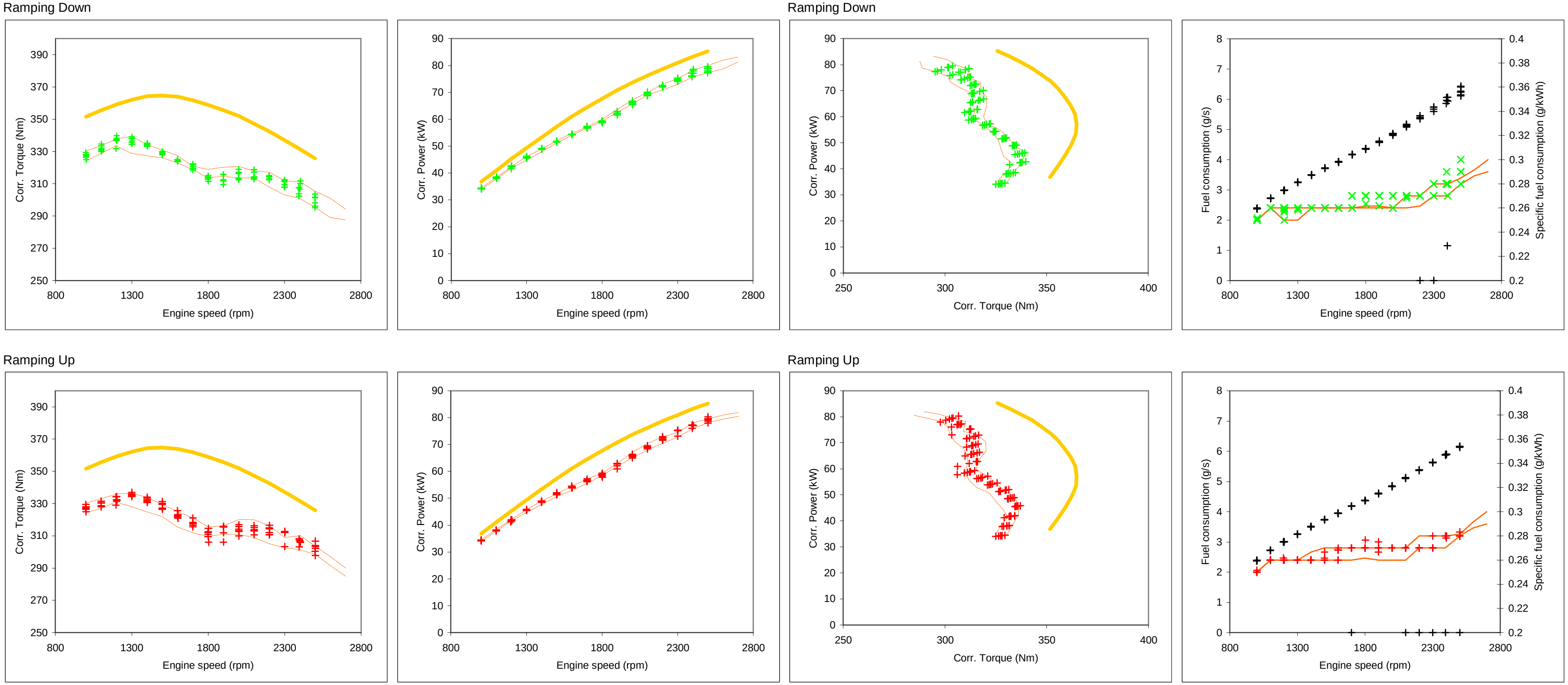
Full Figure 17: Baseline archive plot of tests Baseline_002_001 to Baseline_002_007 inclusive, showing engine performance envelope defined by these tests. p82 in main report



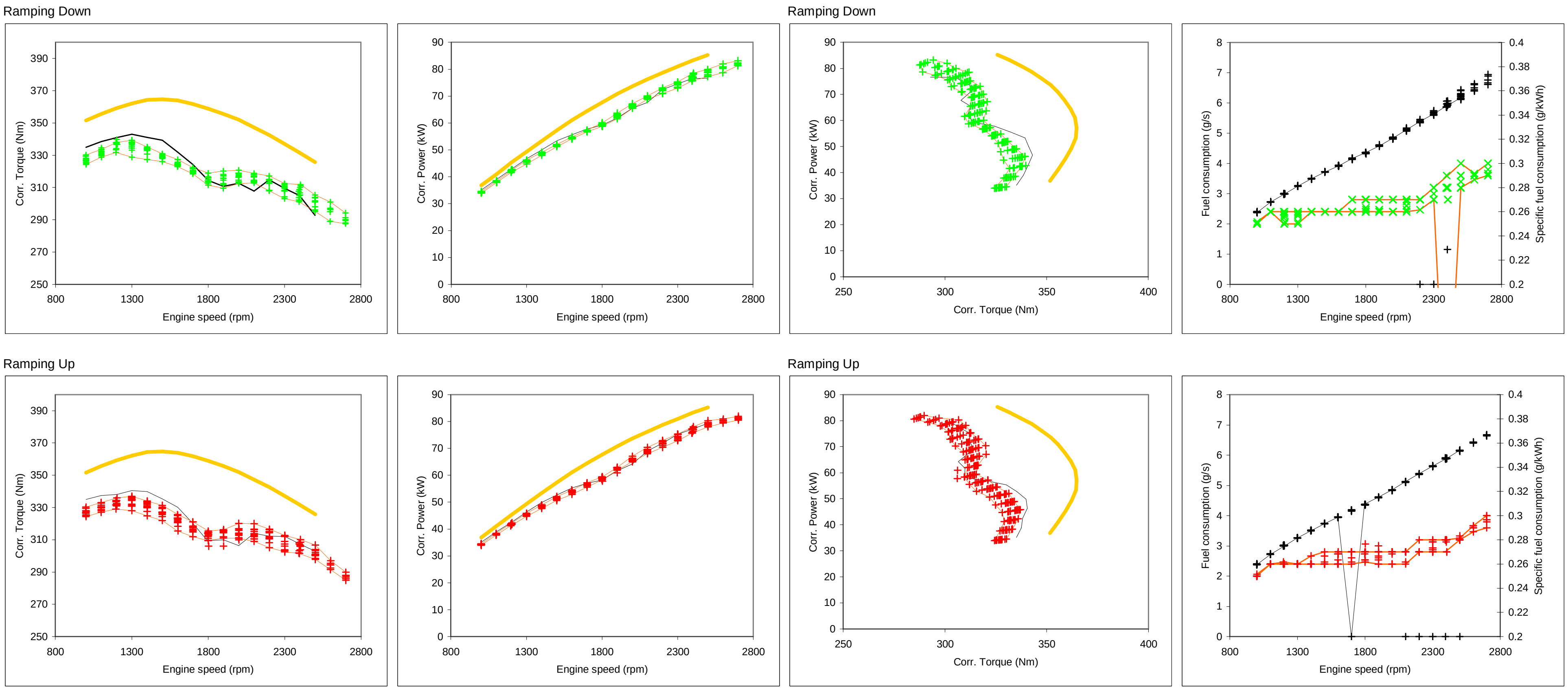
Full Figure 18: Baseline archive plot of tests Baseline_002_008 to Baseline_002_013 inclusive, showing engine performance envelope defined by Full Baseline_002_001 to Baseline_002_007. p83 in main report



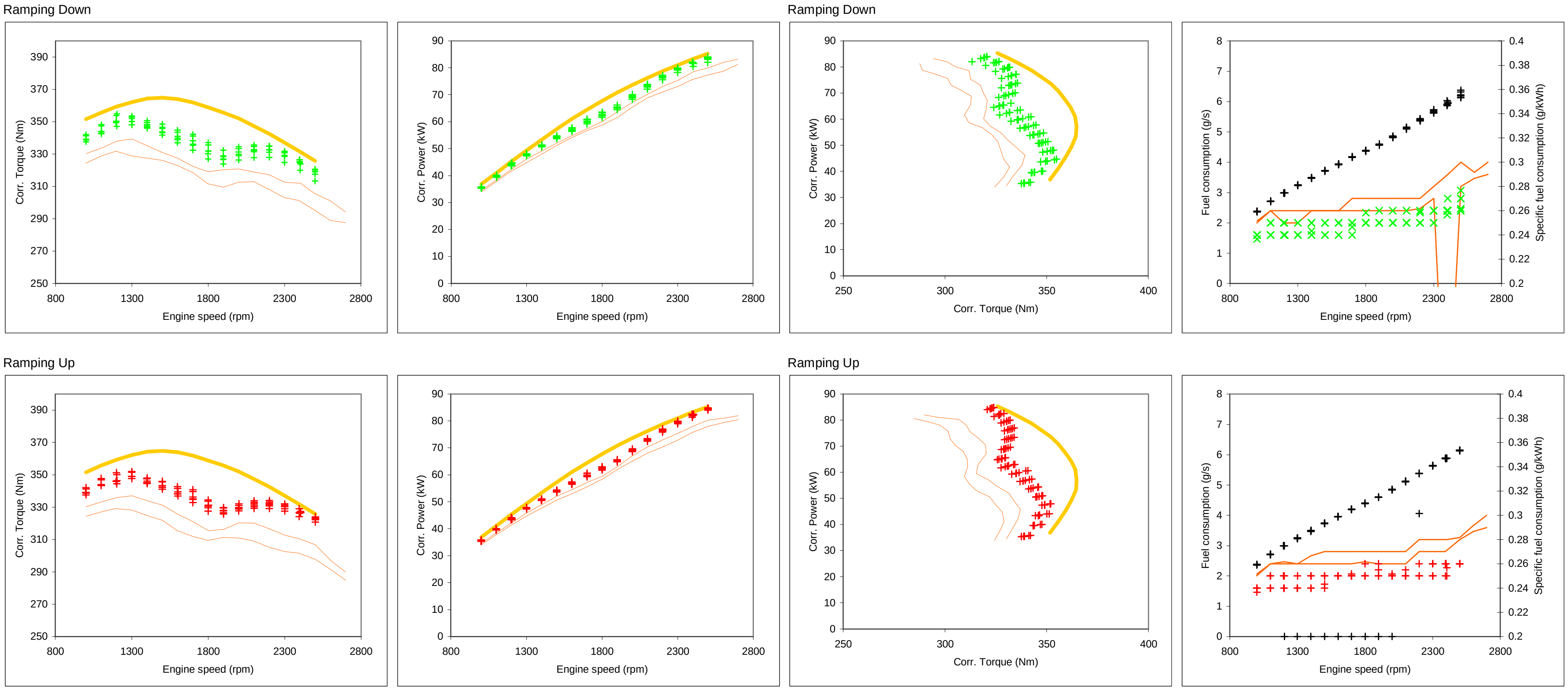
Full Figure 19: Baseline archive plot of tests Baseline_002_014 to Baseline_002_019 inclusive, showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013. Solid, black line – Baseline 002_015 performance. With progressive testing, problem became worse. p84 in main report



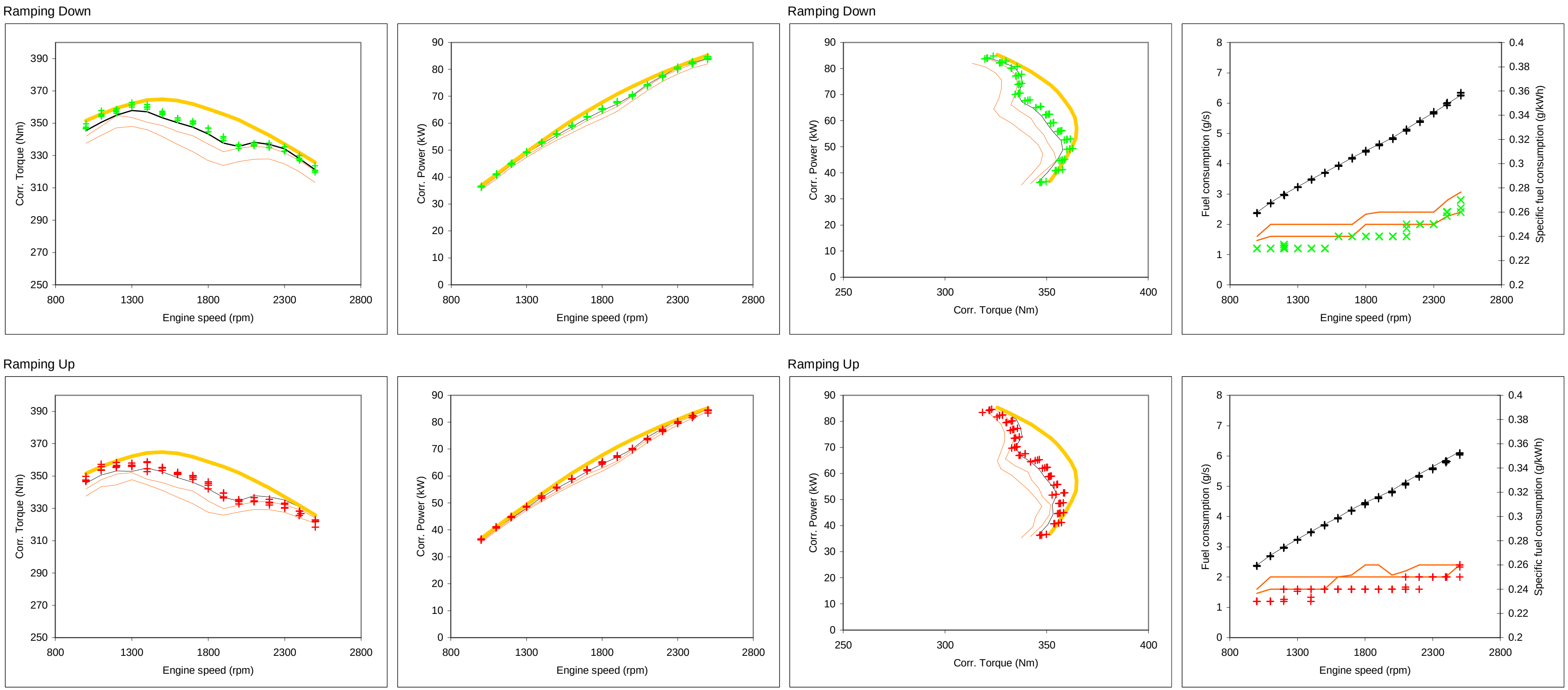
Full Figure 20: Baseline archive plot of Baseline 003_001 to Baseline 003_006 showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013 p85 in main report



Full Figure 21: Showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013 and Baseline 003_001 to Baseline 003_006 with Baseline 003_007 performance curve superimposed (solid black line). p86 in main report

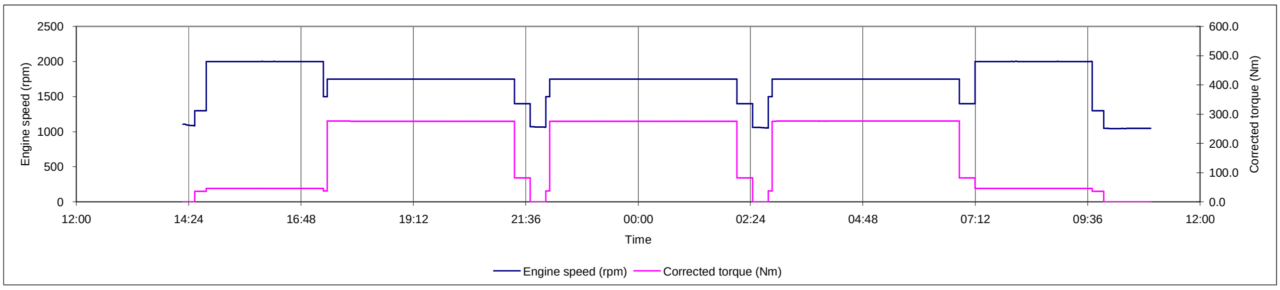


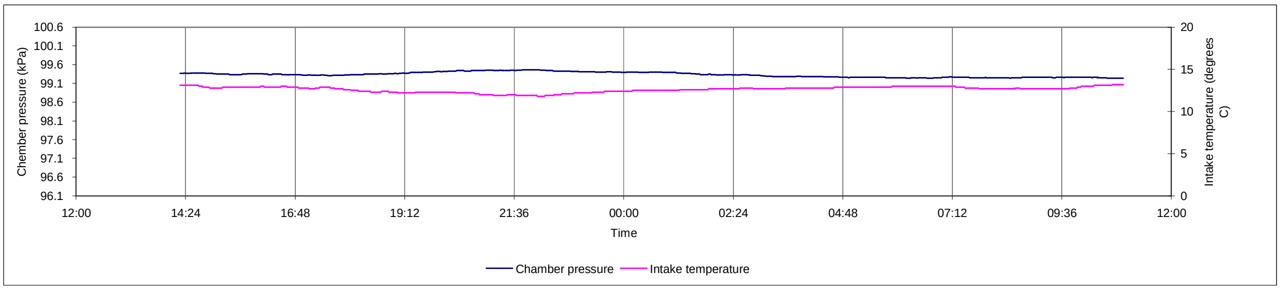
Full Figure 22: Showing engine performance envelope defined by Baseline_002_008 to Baseline_002_013 and Baseline 003_001 to Baseline 003_006 with Baseline 003_101 to Baseline 003_107 performance data shown as discrete points. p87 in main report

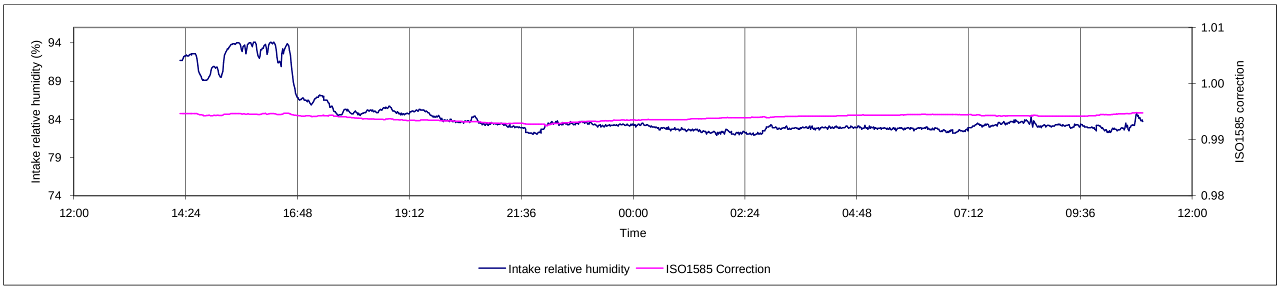


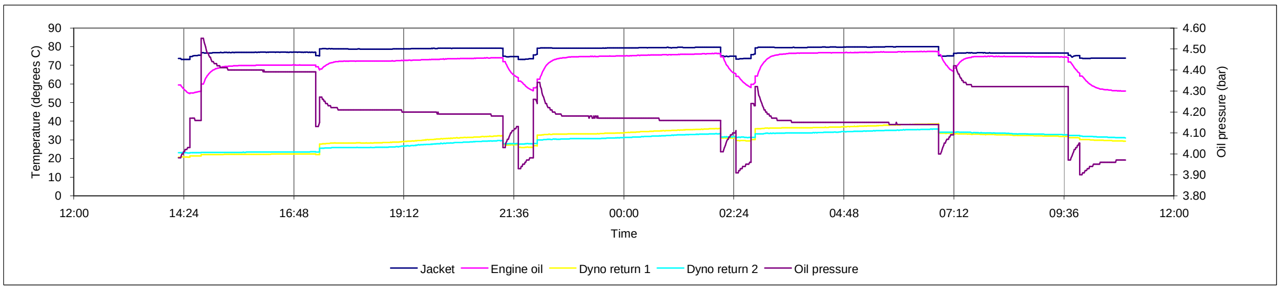
Full Figure 23: Baseline 003_107 (solid line) together with the engine performance envelope established from Baseline 003_101 to Baseline 003_107 and results from Baseline 003_108, Baseline 003_109, Baseline 003_114 and Baseline 003_118 (clusters) p88 in main report

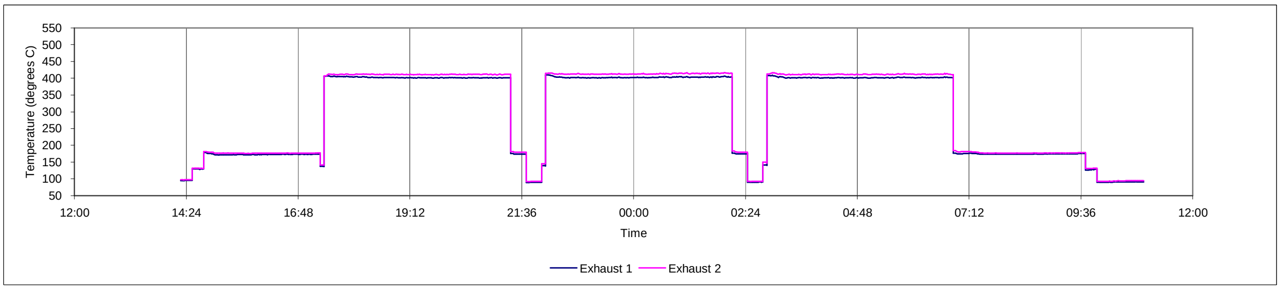
Appendix 8 : Archive of DayTrawl test results

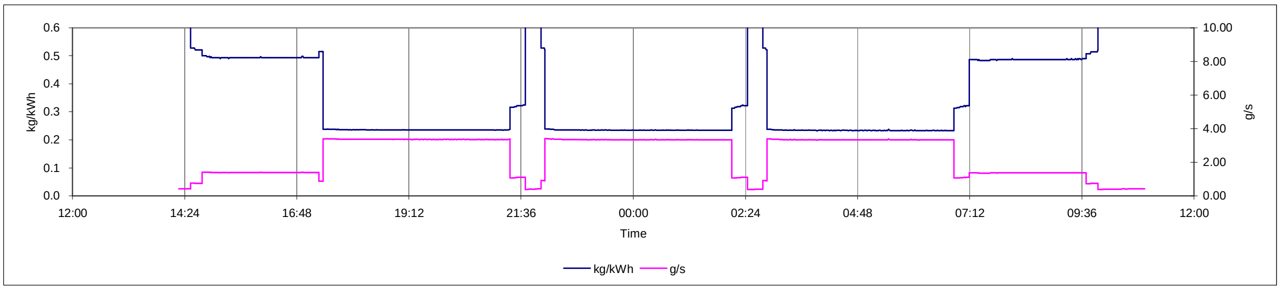




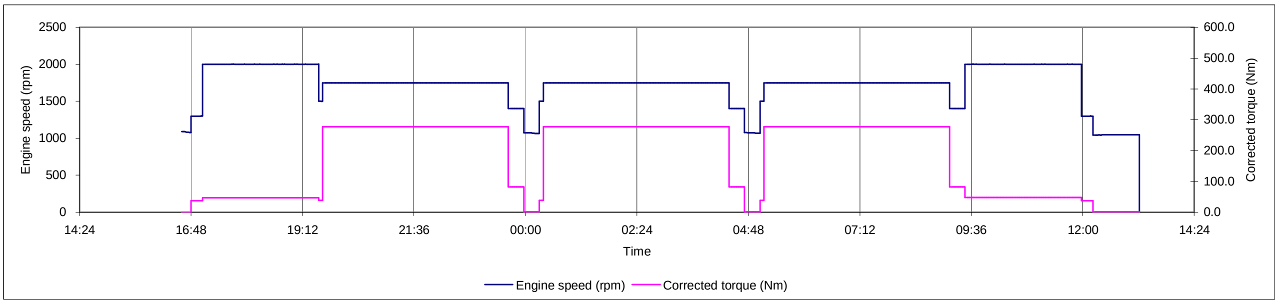


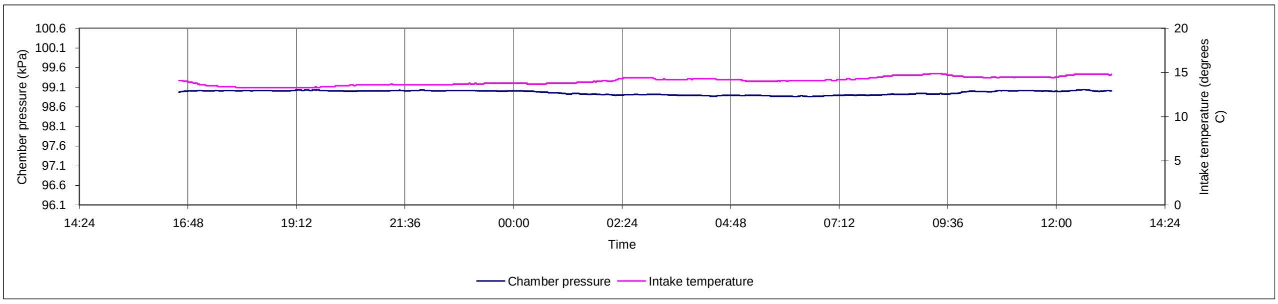


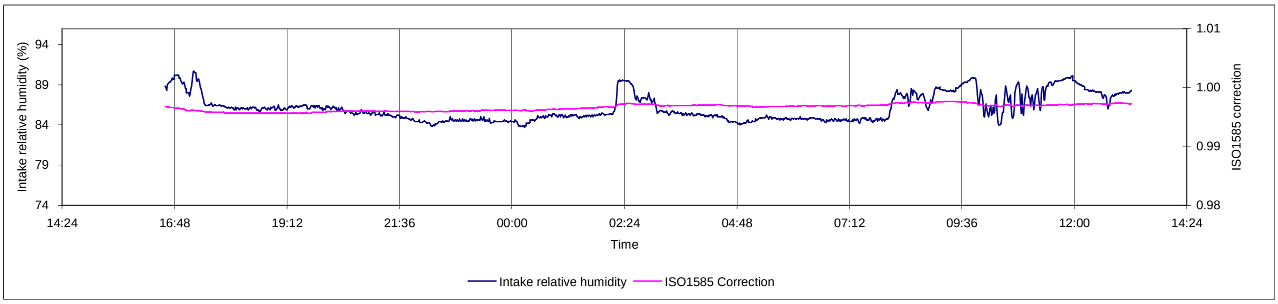


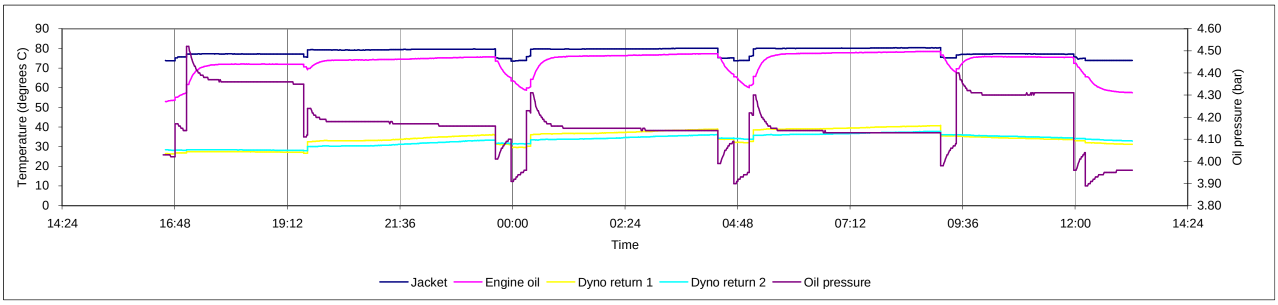


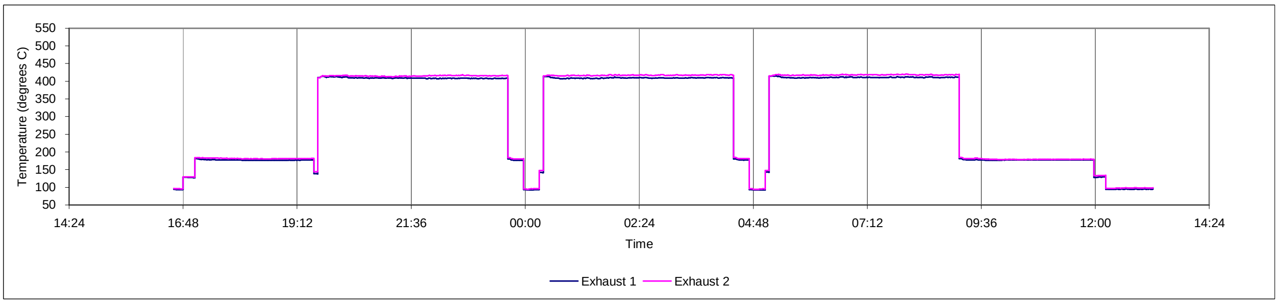
DayTrawl 002_101 (Red) fossil diesel only

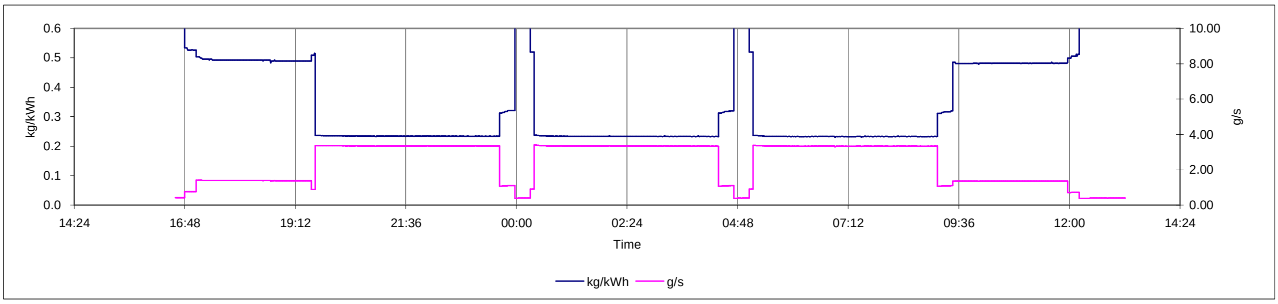




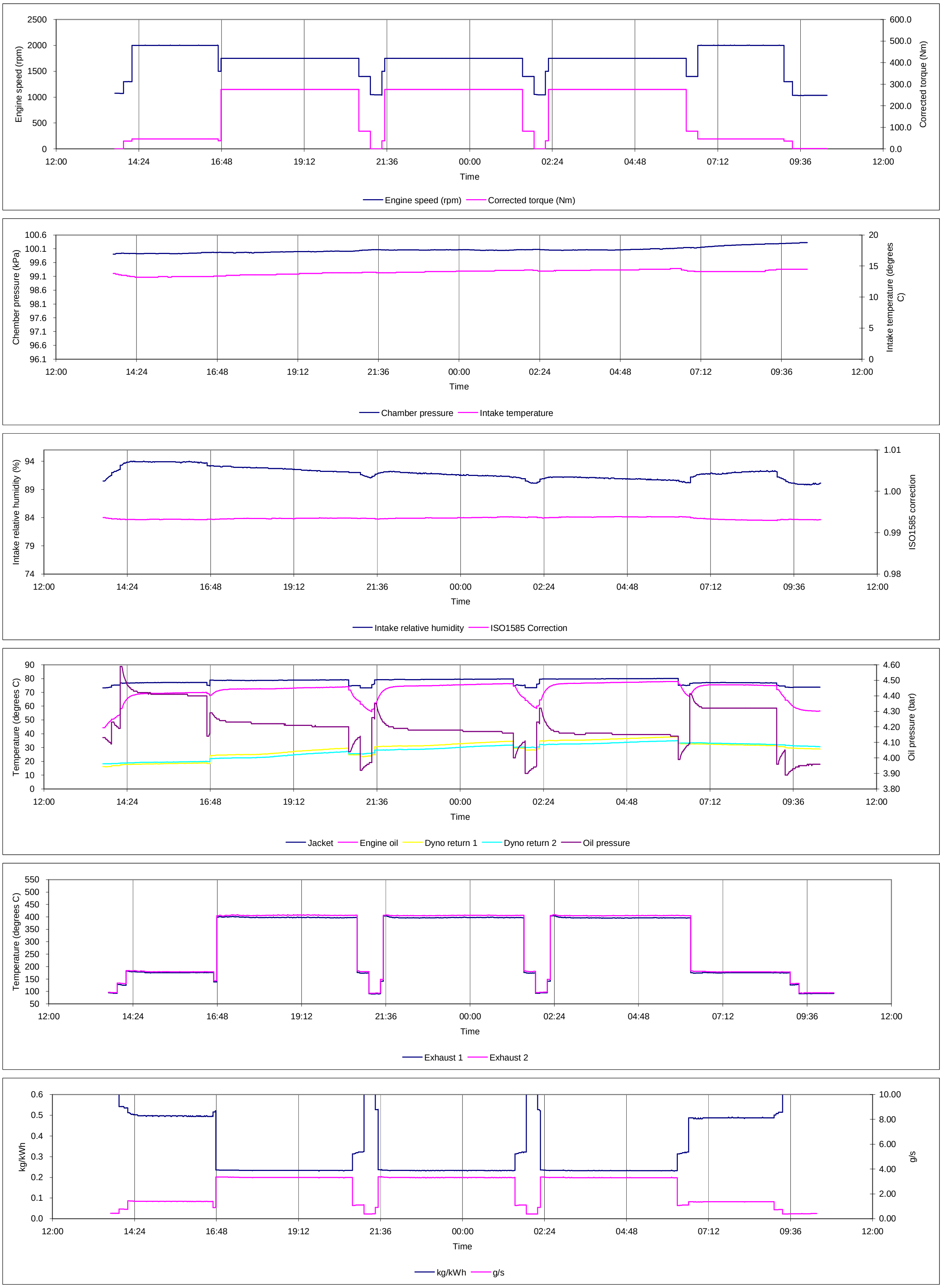




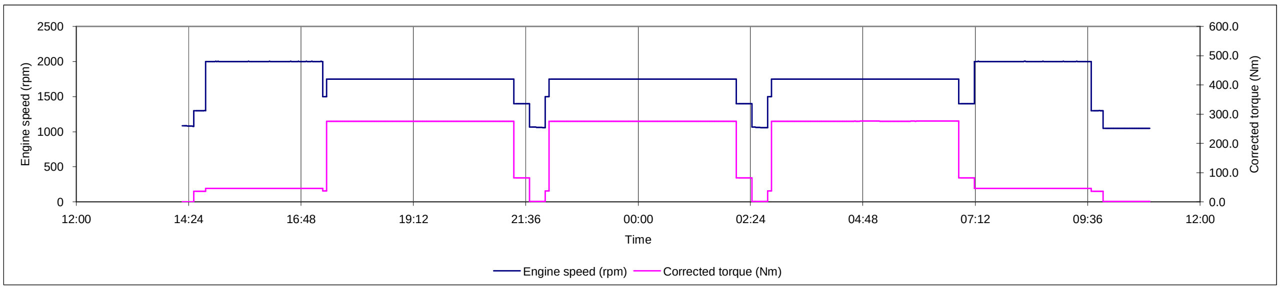


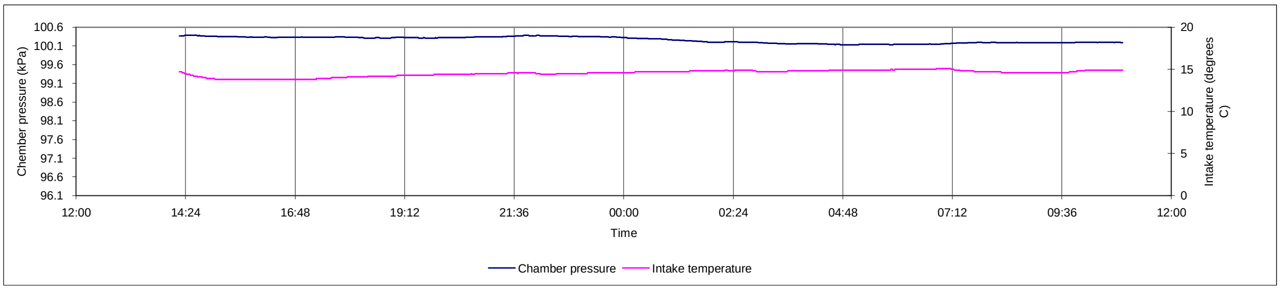


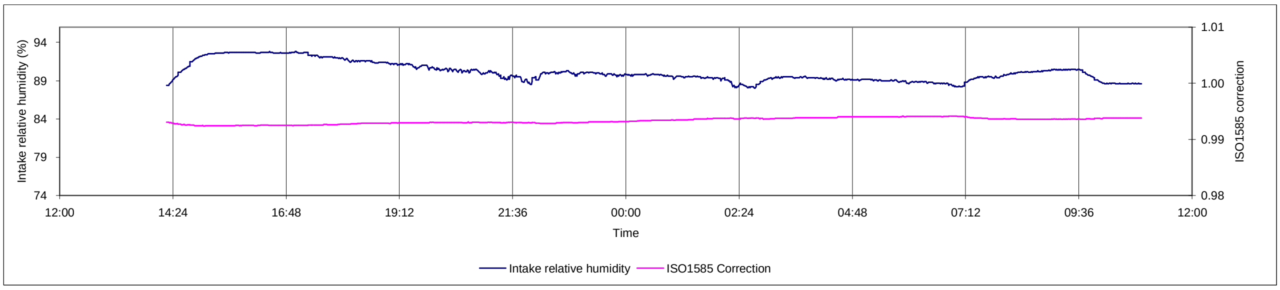
DayTrawl 002_102 (Red) fossil diesel and additive A

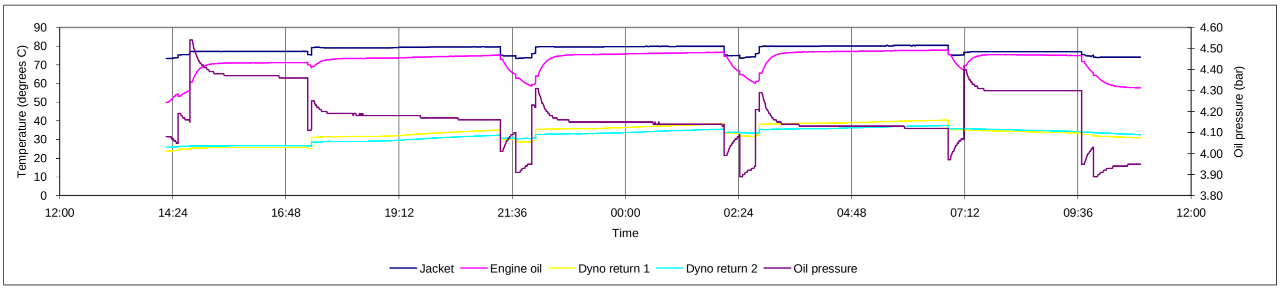


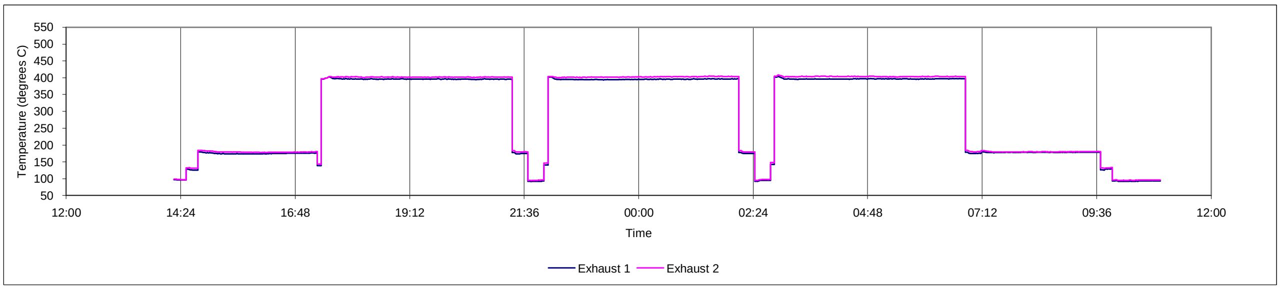
DayTrawl 002_003 (Red) fossil diesel only

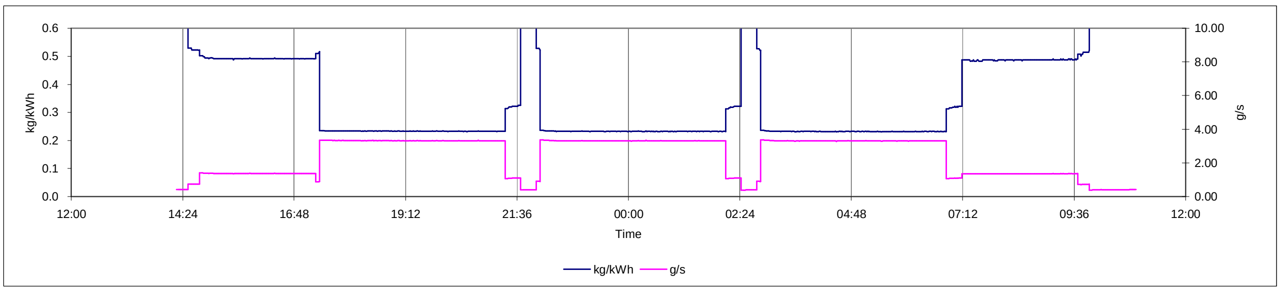




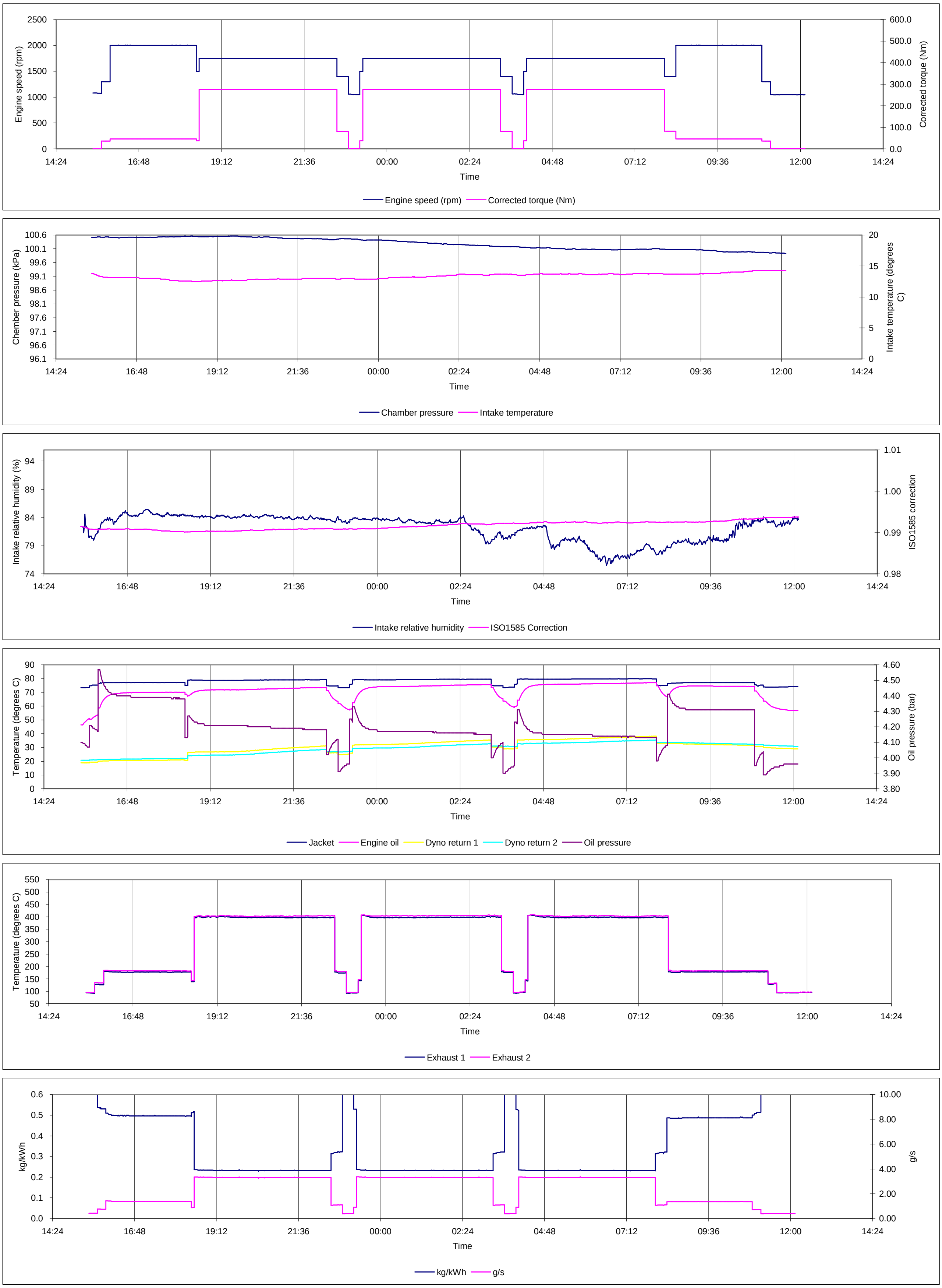




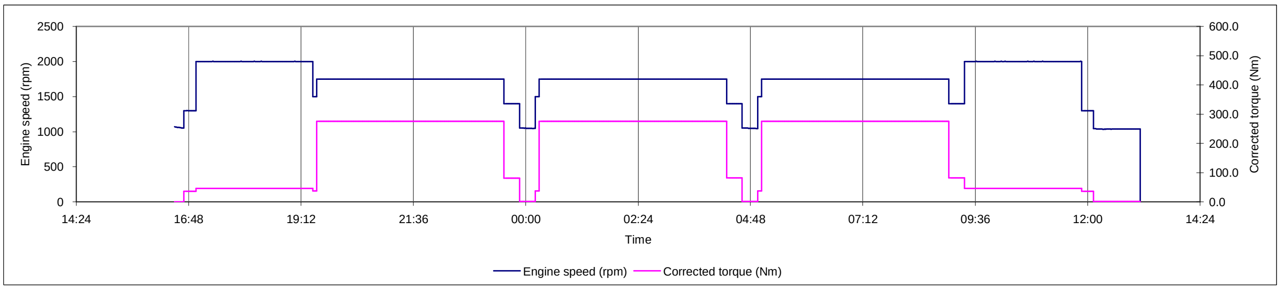


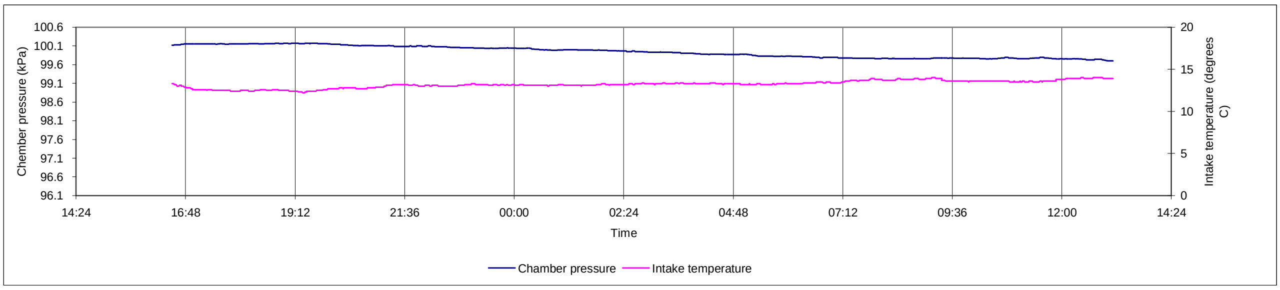


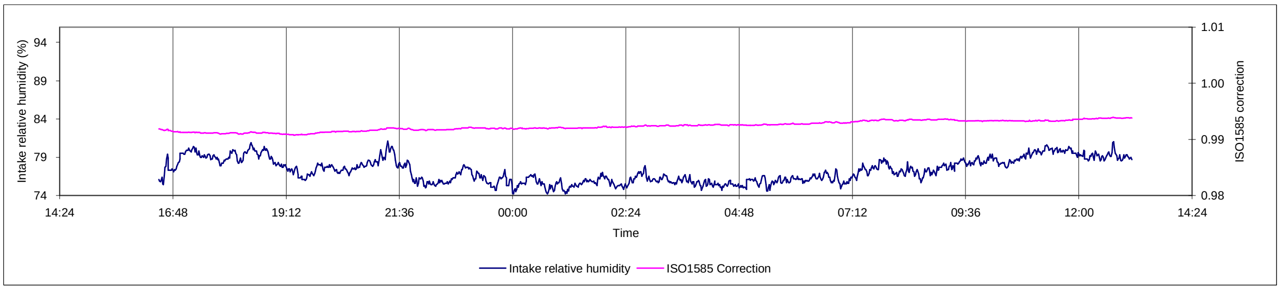
DayTrawl 002_104 (Red) fossil diesel and additive B

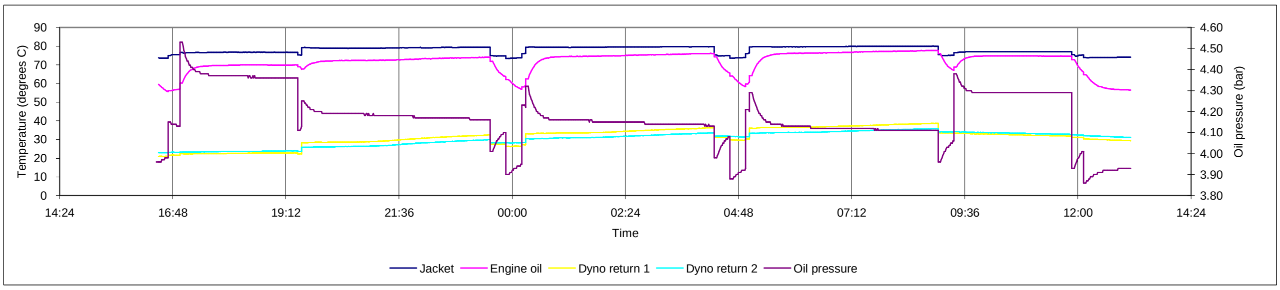


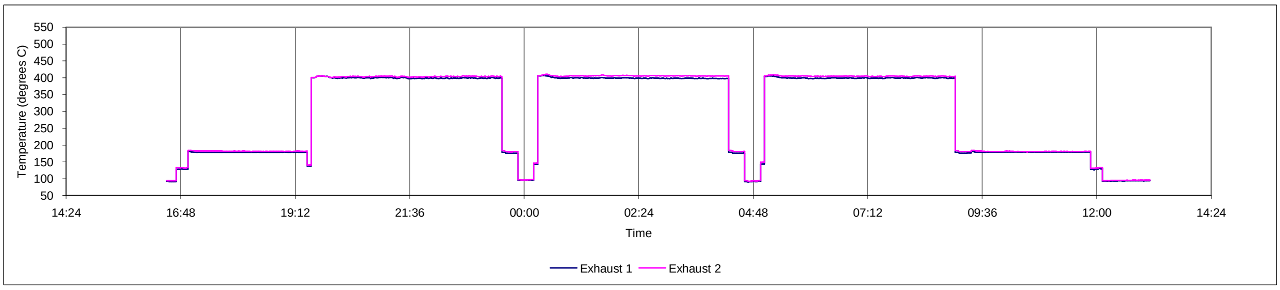
DayTrawl 002_005 (Red) fossil diesel and additive C

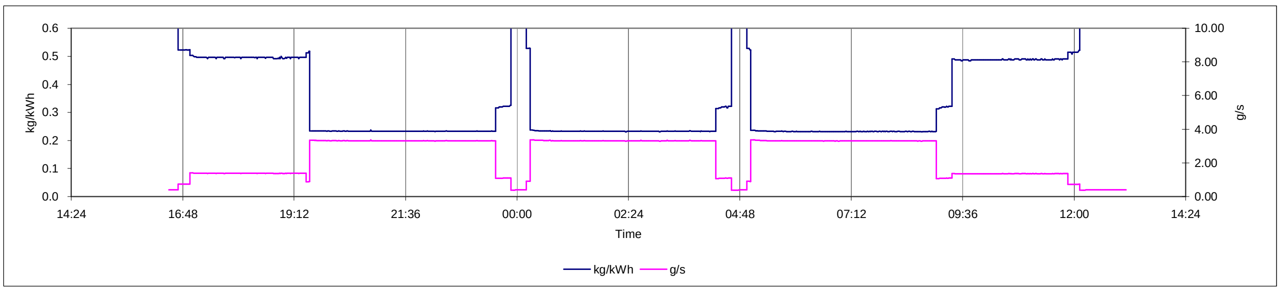




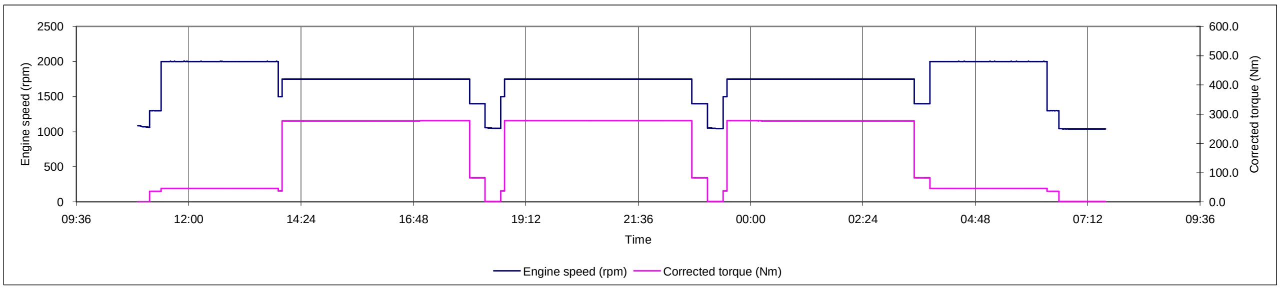


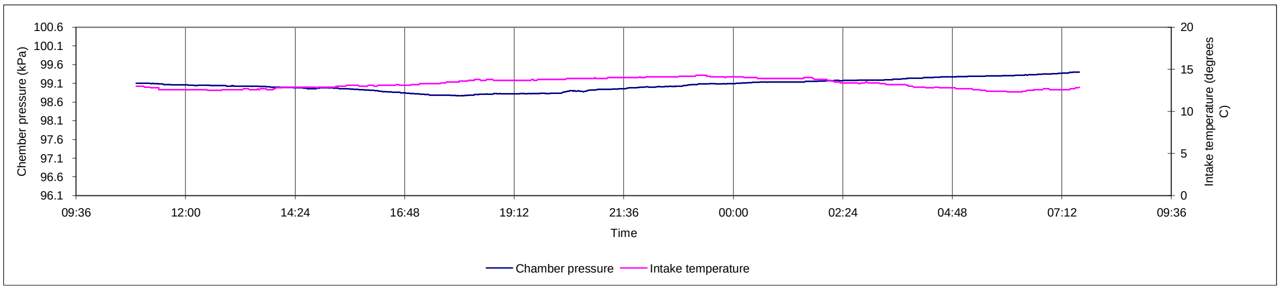


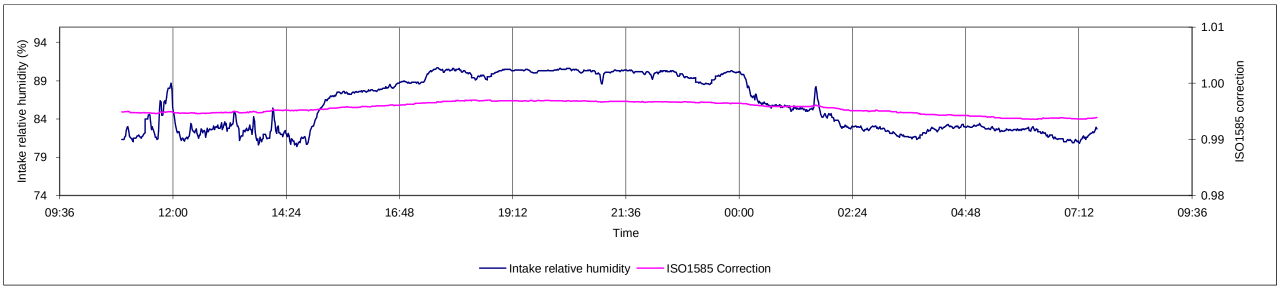


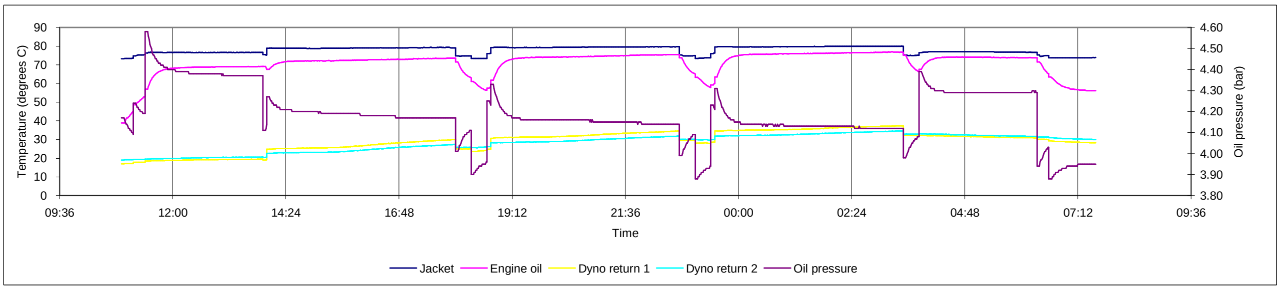


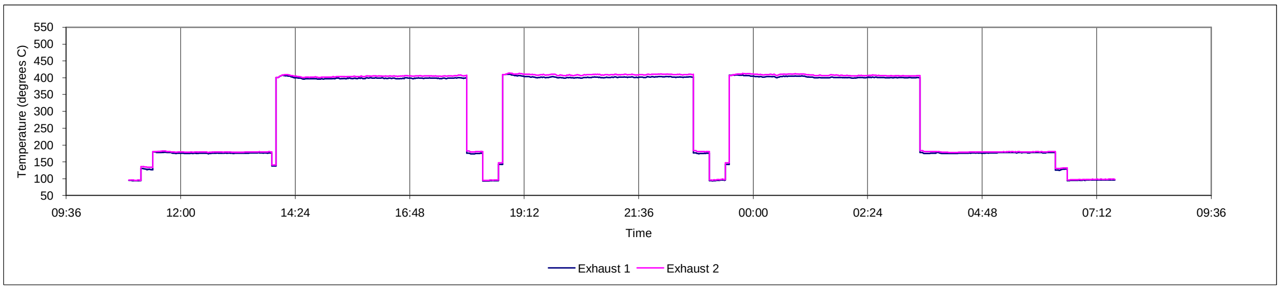
DayTrawl 002_106 (Red) fossil diesel and additive D

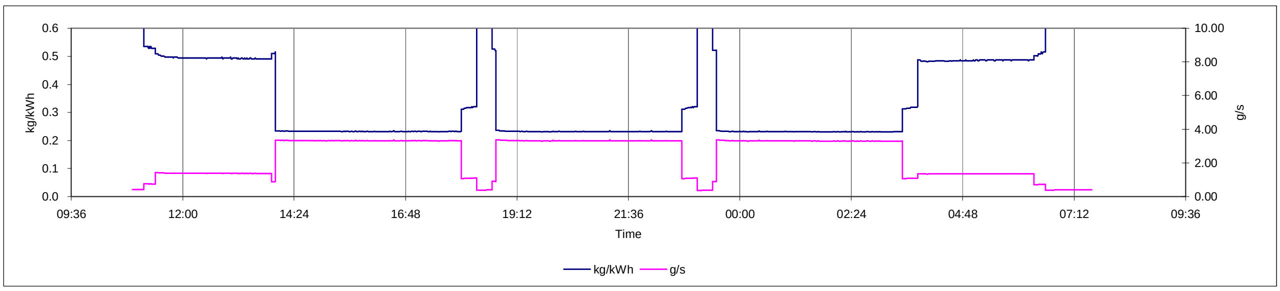




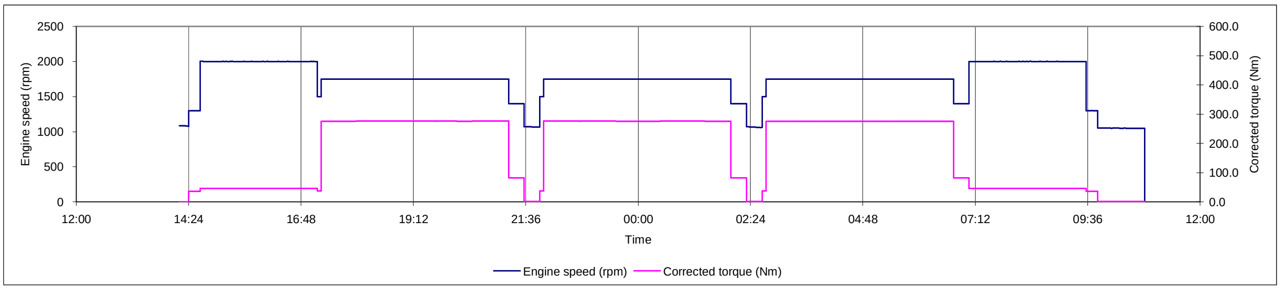


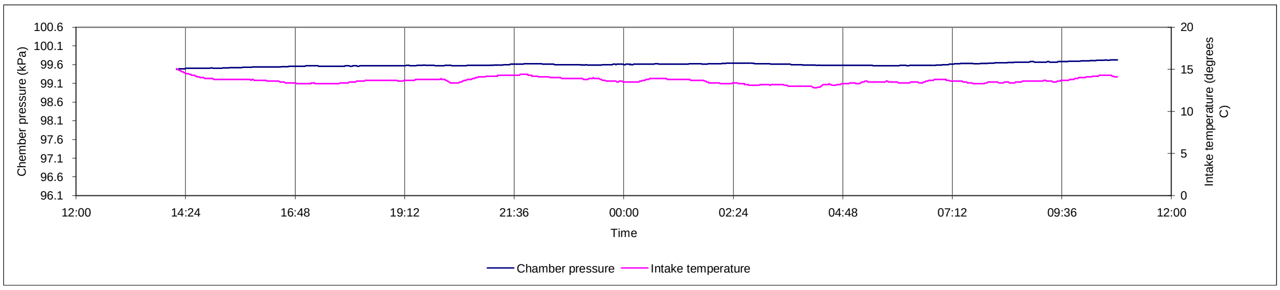


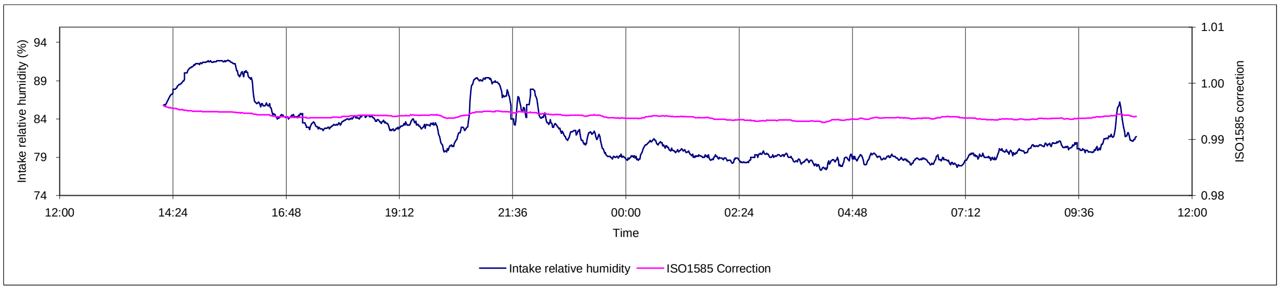


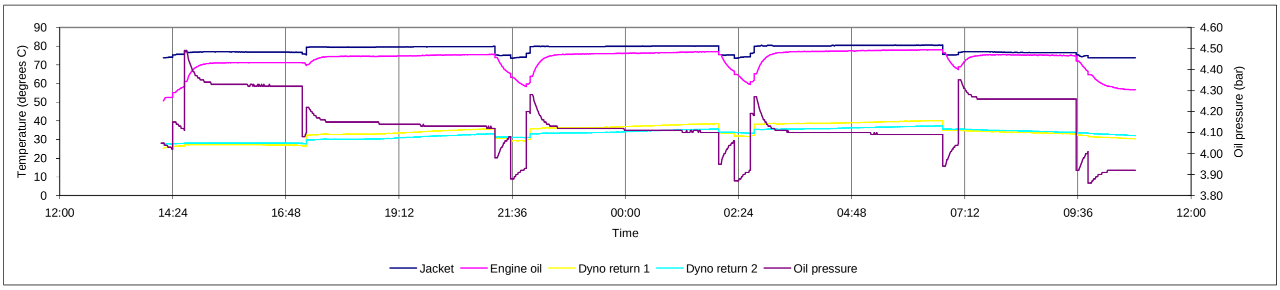


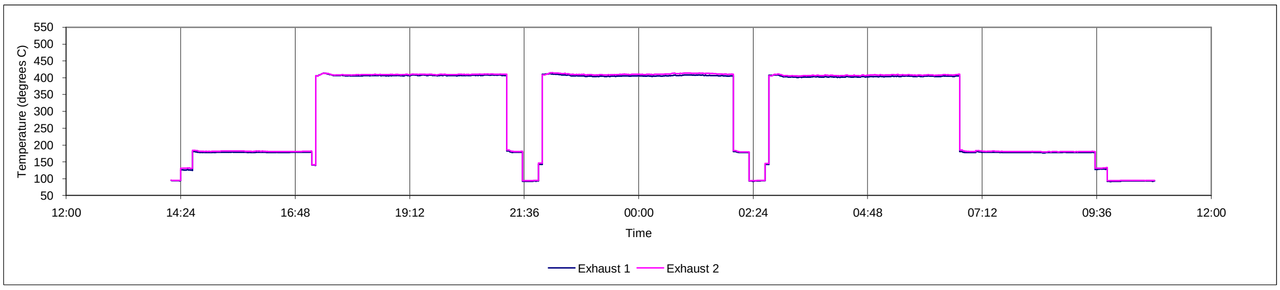
DayTrawl 002_107 (Red) fossil diesel only

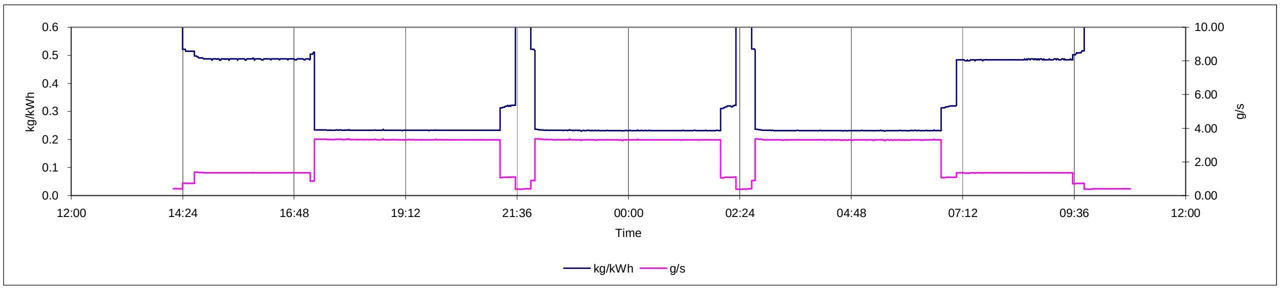




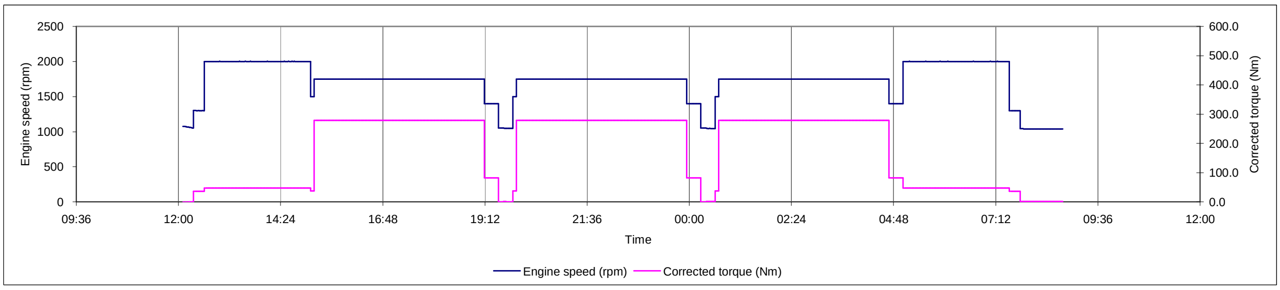


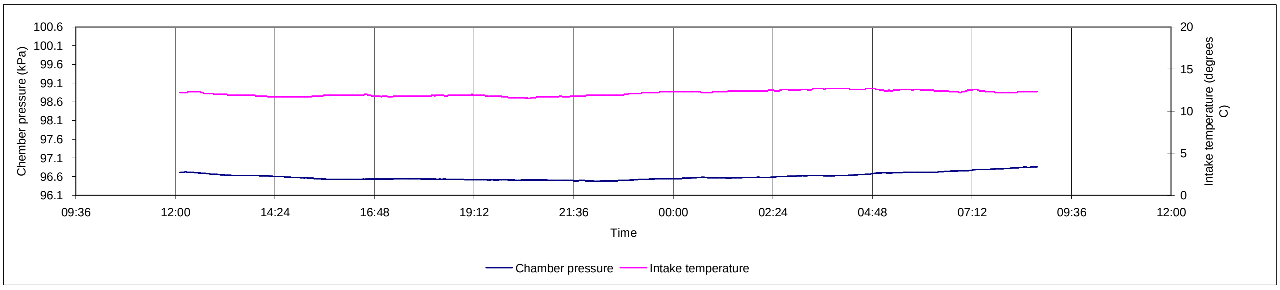


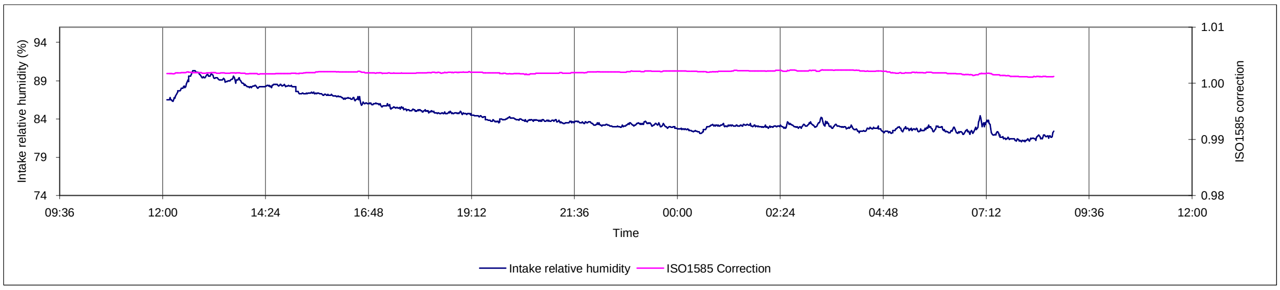


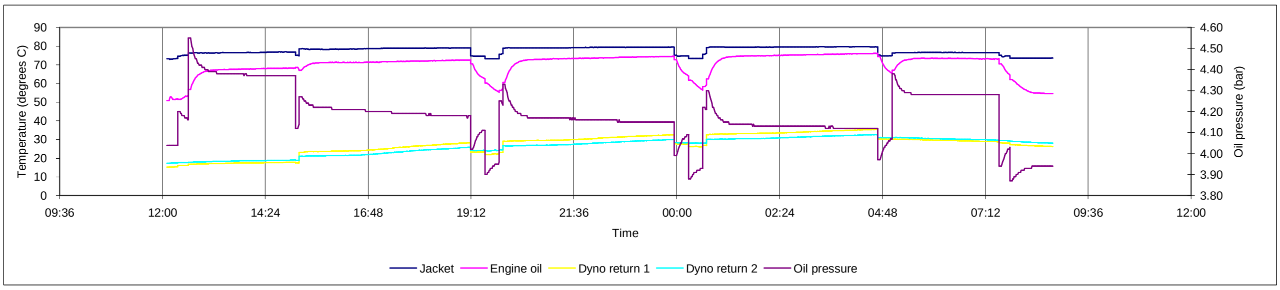


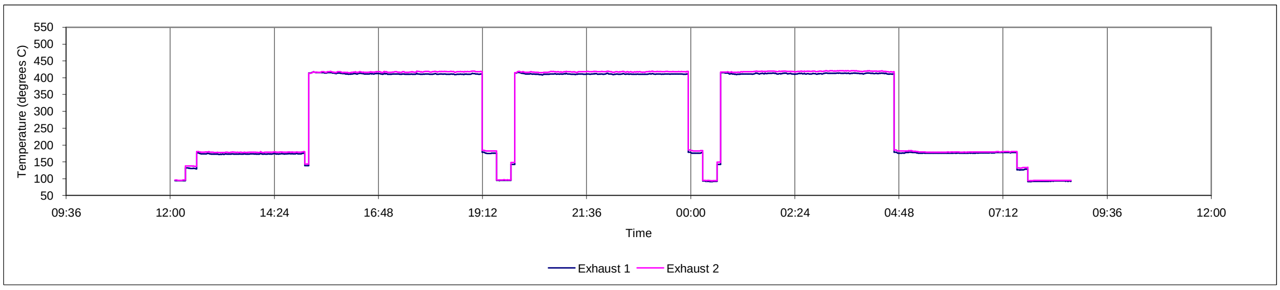
DayTrawl 002_108 (Red) fossil diesel and additive E

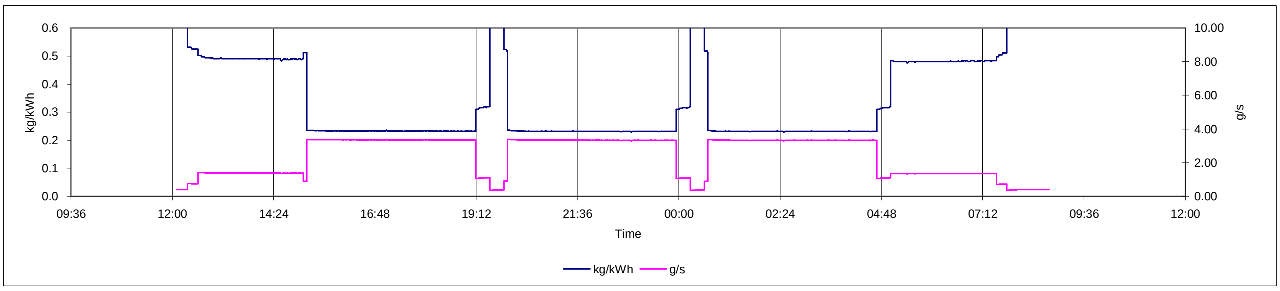




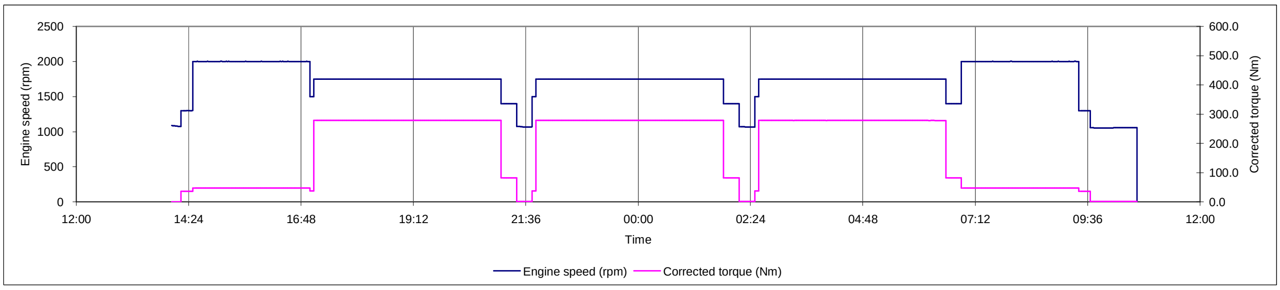


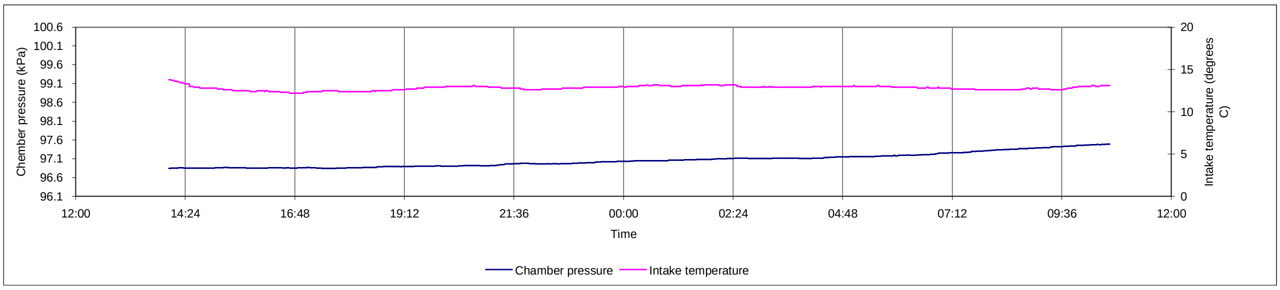


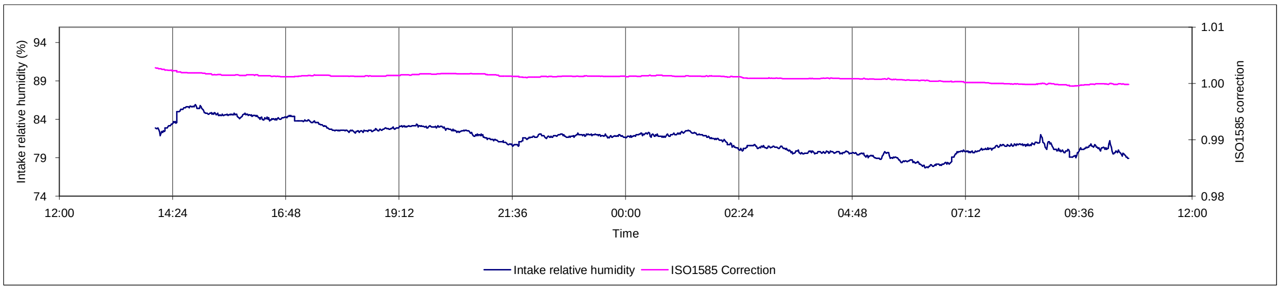


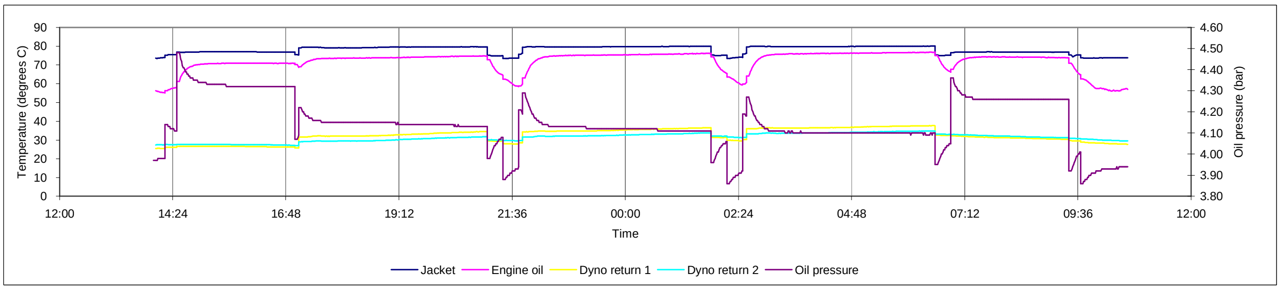


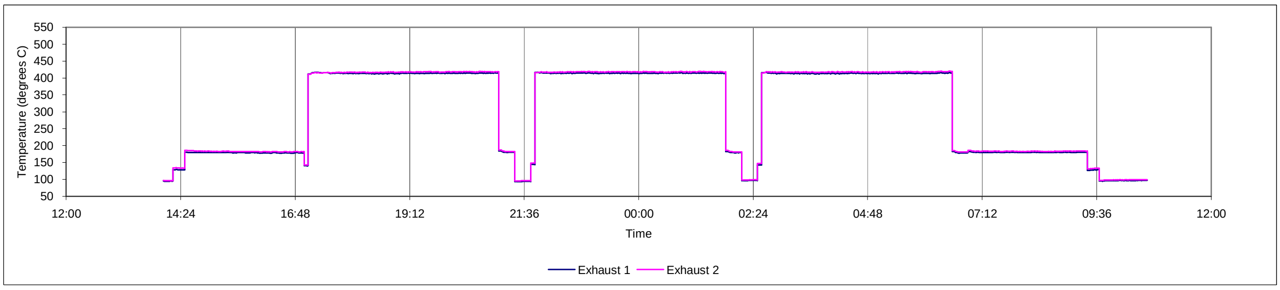
DayTrawl 002_109 (Red) fossil diesel and additive F

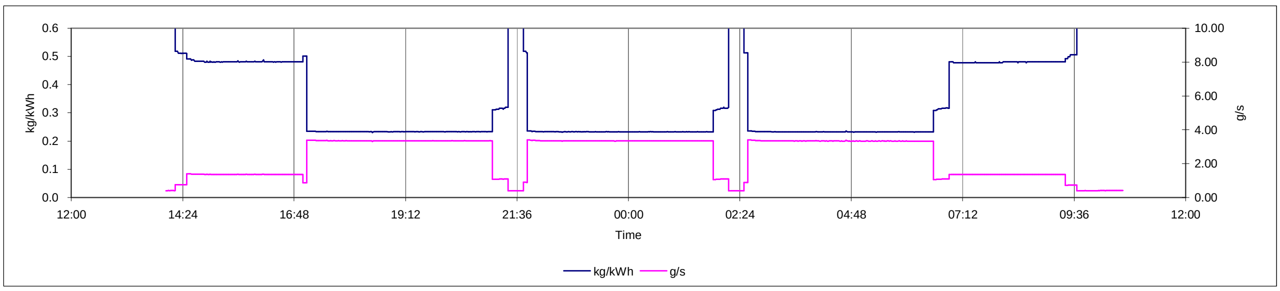




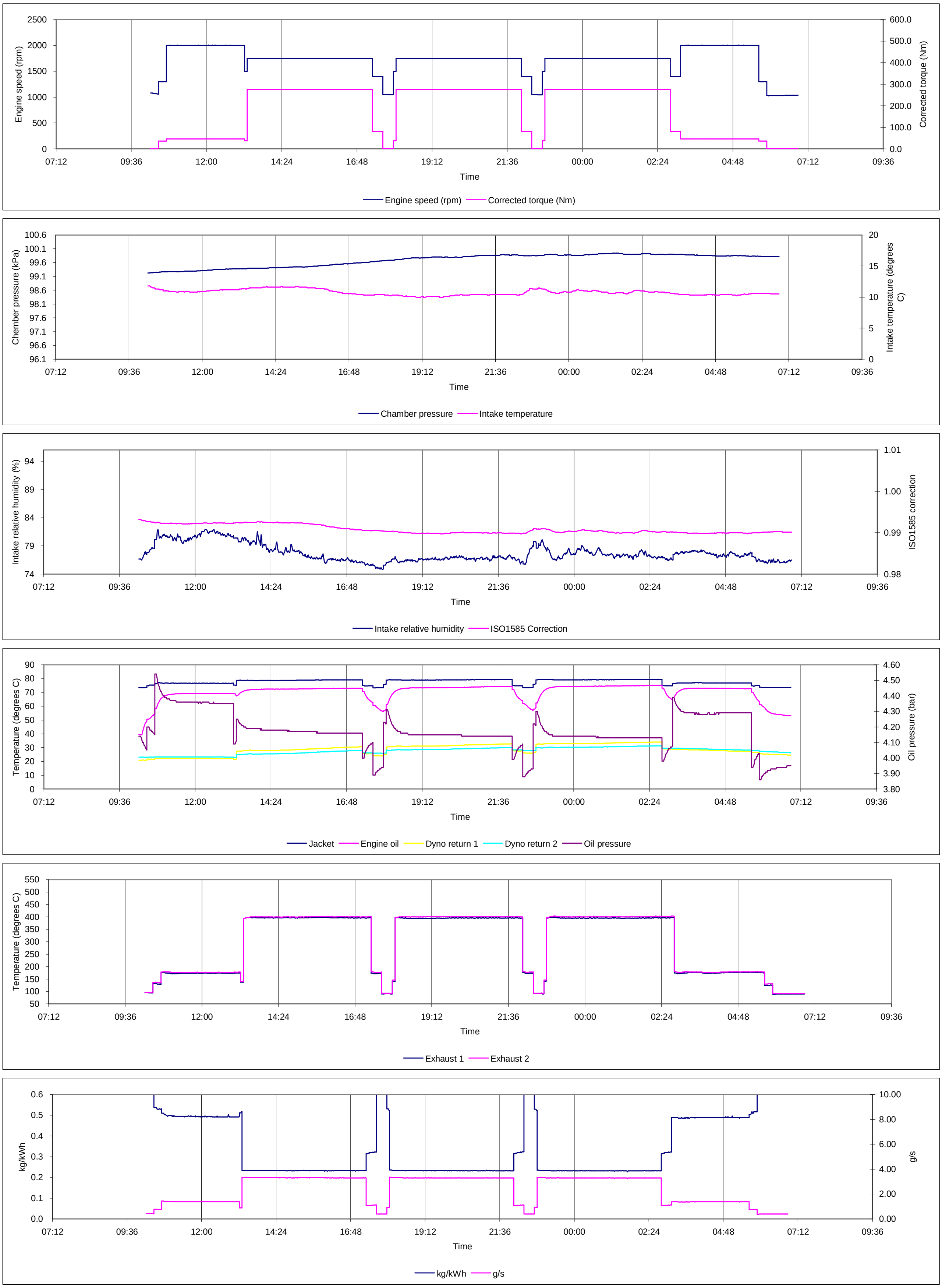




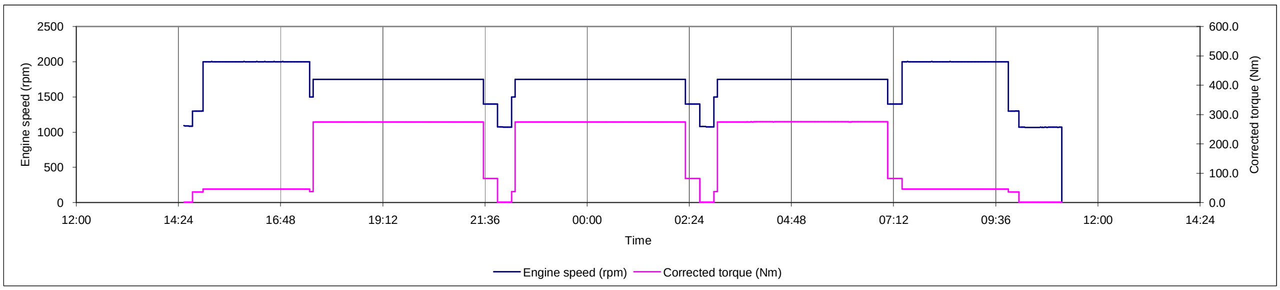


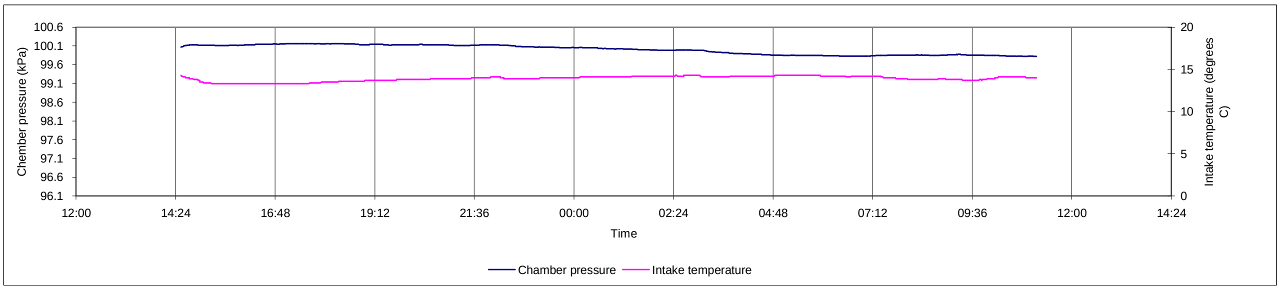


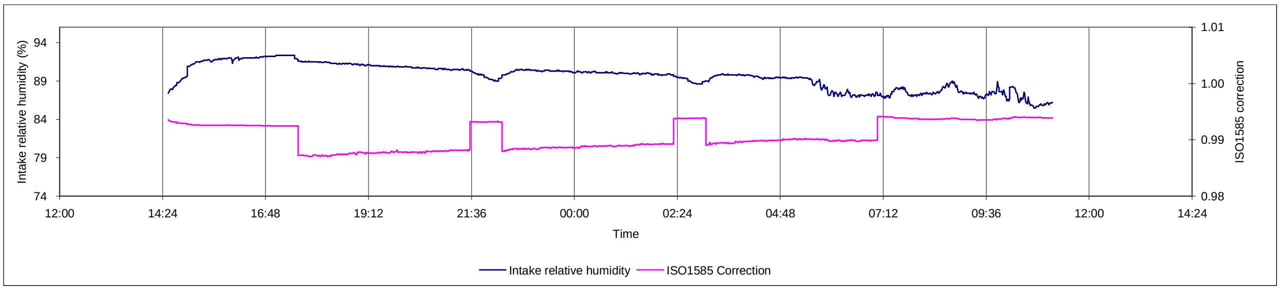
DayTrawl 002_110 (Red) fossil diesel and additive G

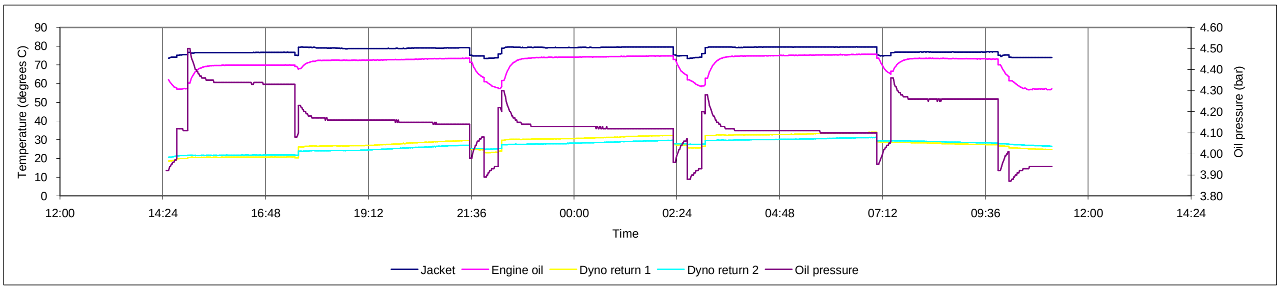


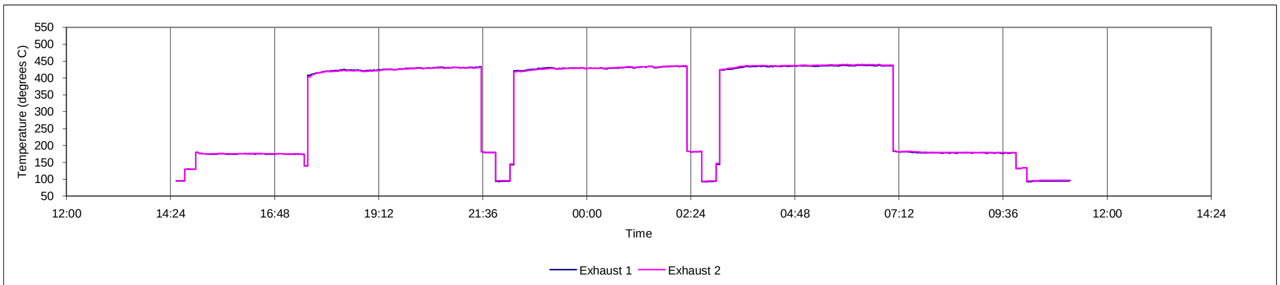
DayTrawl 002_111 (Red) fossil diesel only

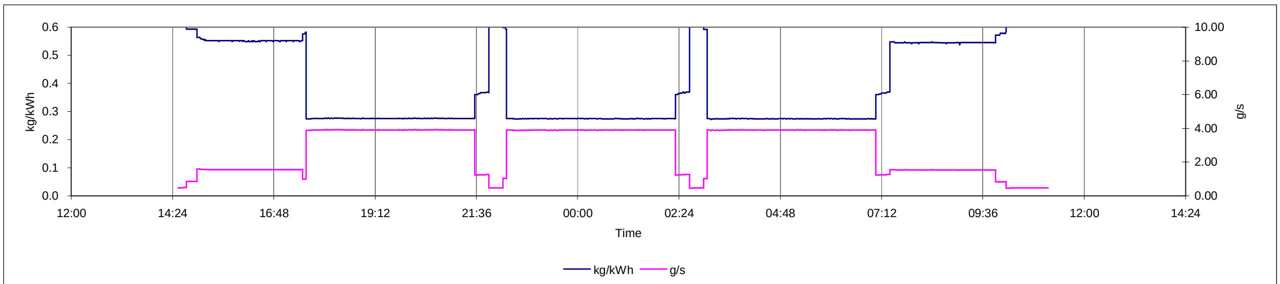




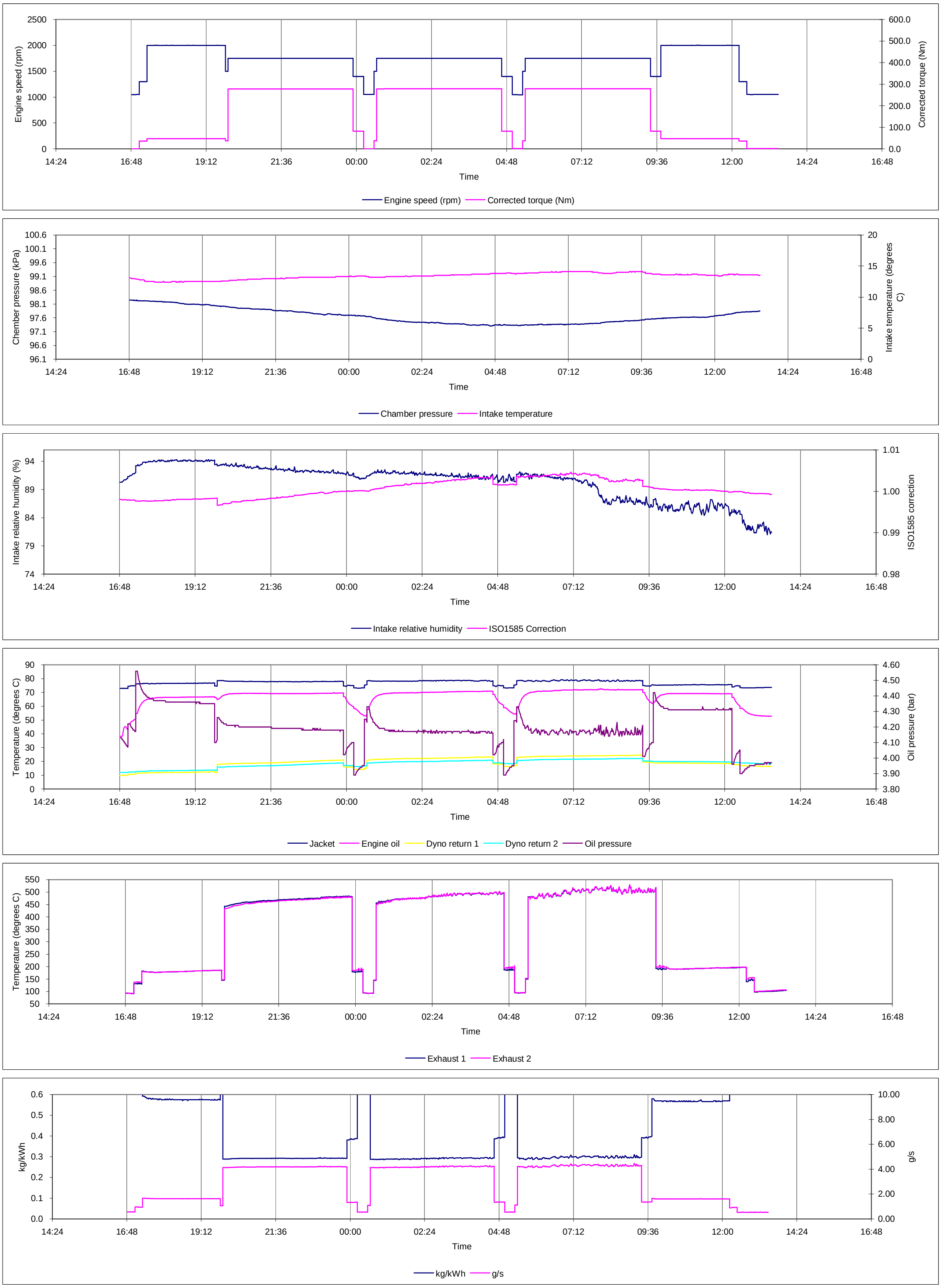








DayTrawl 002_112 BS 14214 standard methyl ester



DayTrawl 002_113 Self-manufactured methyl ester from waste oil feedstock