Bio-fuel engine test cell facility

An abstracted report from the Biofuels for the Fishing Industry project

prepared for:

The Sea Fish Industry Authority

with support from:

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Non Technical Summary

This report details work carried out on the design and installation of an engine performance test facility located at the Holman's Test Mine, operated by the Camborne School of Mines (CSM), an academic department of the University of Exeter. The work was commissioned by the Sea Fish Industry Authority (SeaFISH) with the aim of developing a facility to permit the testing of biofuels such as biodiesel and biofuel blends in marine diesel engines.

Engine performance test 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. This meant that after commissioning the engine an extensive range of testing was undertaken in order to calibrate the performance of the engine when running on red diesel. In order to perform the calibration and subsequent comparisons with biofuels and red diesel with additives, accurate measurements of power (torque and engine speed) and fuel consumption were essential pre-requisites of the design. Measurement and control of engine torque was achieved by coupling the Perkins 6.3544M marine diesel engine to a Schenk W230 dynamometer and a high precision fuel weighing system (CP Engineering's FMS 1000) was selected for fuel consumption measurement. The physical equipment is designed to operate under computer control during all tests, which ensures a high degree of repeatability when specifying test schedule set points of either i) torque and engine speed, ii) throttle setting and engine speed, iii) torque and throttle setting or iv) combinations of the preceding pairs.

CSM's 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 the site 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 very close to unity. In turn this leads to a capacity for high repeatability in testing and good confidence in the results obtained.

Fuel is delivered to the test engine via a header tank that in turn is topped off using a feed pump that sends fuel stored in an IBC, located just outside the test chamber. Special arrangements were established to provide all necessary infrastructure and services to operate the engine: intake air, cooling water, electrical power and a large diameter, fan assisted, exhaust duct to the surface. Failsafe safety equipment and fire monitoring equipment were installed around the engine and dynamometer to allow prolonged testing to take place while the unit was unattended. The longest tests undertaken comprised continuous running of the engine under a variety of loads for up to 21 hours.

The test engine and dynamometer also have hardware level protection systems with battery backup that will shut the engine down in the event of pre-set thresholds being exceeded or a software control failure.

Obtaining a stable characterisation of the engine, such that it could be taken as a ‘constant’, proved a difficult and prolonged task but it was ultimately achieved. The core of these problems lay in the fact that the test engine was one of a pair recovered from a working vessel and had thus seen many years of service. The rationale behind the selection of a pre-used engine was that it was more typical of the condition of those in use within the Newlyn fleet (for the class of vessel matching its power rating). Before any testing work was undertaken, the engine was stripped down and all its critical elements (bearings, cylinder bores, piston rings, injectors etc.) were examined and replaced only as necessary.

All sensors that interfaced the engine and dynamometer with its computer control system were calibrated before use, if they had not been procured with calibration certificates. The FMS 1000 is calibrated automatically from the control system software by applying a calibration mass to its load cell. In the case of the dynamometer, a specialist calibration arm was fabricated such that it could be calibrated *in-situ*, with any load arising from the flow of cooling water applying.

Various problems and faults with the system arose during the commissioning and early testing stages, all of which became understood and were thus properly rectified – some sooner than others, but all prior to the main testing phase of work undertaken with the test cell. The most difficult problem to arise was an intermittent fault with the fuel measurement system that was eventually tracked down to a faulty printed circuit board, which was replaced. The most significant problem was one of reduced engine power (as determined by diagnostic test runs, run repeatedly) which was found to be caused by air filter cleanliness, incorrect valve clearance settings and failure of Hardy Spicer universal joints on the coupling shaft between dynamometer and engine.

The test engine failed on 2 occasions during the project. In the first case this was attributed to the age of the engine and probably excessive demands placed upon it by a rather aggressive maximum power diagnostic testing schedule. This ranged up to 2700 rpm at full throttle, maintained for periods of time unlikely to be tolerated by skippers with their own engines. Cylinder liners, pistons, piston rods and connecting rod big end bearings were replaced with new parts. This and a slightly less demanding duty of the engine under the diagnostic testing regime (up to 2500 rpm at maximum throttle) solved the problem. The second engine failure occurred during the very last calibration test conducted. The failure was found to be a fractured piston ring and piston rings stuck in their grooves on multiple cylinders. It was attributed to the use of a relatively low quality biofuel, where differences in ignition characteristics of the fuel in comparison to red diesel (for which the engine was timed) become exacerbated under the highest engine loads.

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Introduction

Document Context

This report details work carried out in design and installation of an engine performance test facility located at the Holman's Test Mine, operated by the Camborne School of Mines (CSM), an academic department of the University of Exeter. The work was commissioned by the Sea Fish Industry Authority (SeaFISH) with the aim of developing a facility to permit the testing of biofuels such as biodiesel and biofuel blends in marine diesel engines.

This work was conducted in parallel with other work on Biofuels for the Fishing Industry, also commissioned by SeaFISH, and was reported to SeaFISH in December 2007. At the request of SeaFISH, materials of specific relevance to the design and specification of the test cell facility and its operation and maintenance are separately reported herein by means of abstracting the December 2007 report.

Figure 1: Photograph of the bio-fuel engine test cell facility underground at the CSM Holman's Test Mine. The top of the photograph shows the test cell control cabin. The dynamometer is in the foreground in green, the test cell engine is in blue.

Thus the aim of this report is to provide full technical details of the engine performance testing facility without the reader being unnecessarily burdened with detail concerning testing of the biofuels in sea trials, or details of the construction of a containerised biodiesel batch production plant or the results of testing diesel fuel additives at the facility. The target audience of this report are thus individuals requiring full technical specification of the engine, dynamometer, instrumentation and supervisory control and data acquisition (SCADA) equipment. Readers of this report also interested in the wider biofuels scope should obtain a copy of the full December 2007 report submitted to SeaFISH.

Background

The engine test cell was identified as the core feature of the main project from the outset. Test 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.

System 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 observations 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 Intermediate Bulk Container (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.

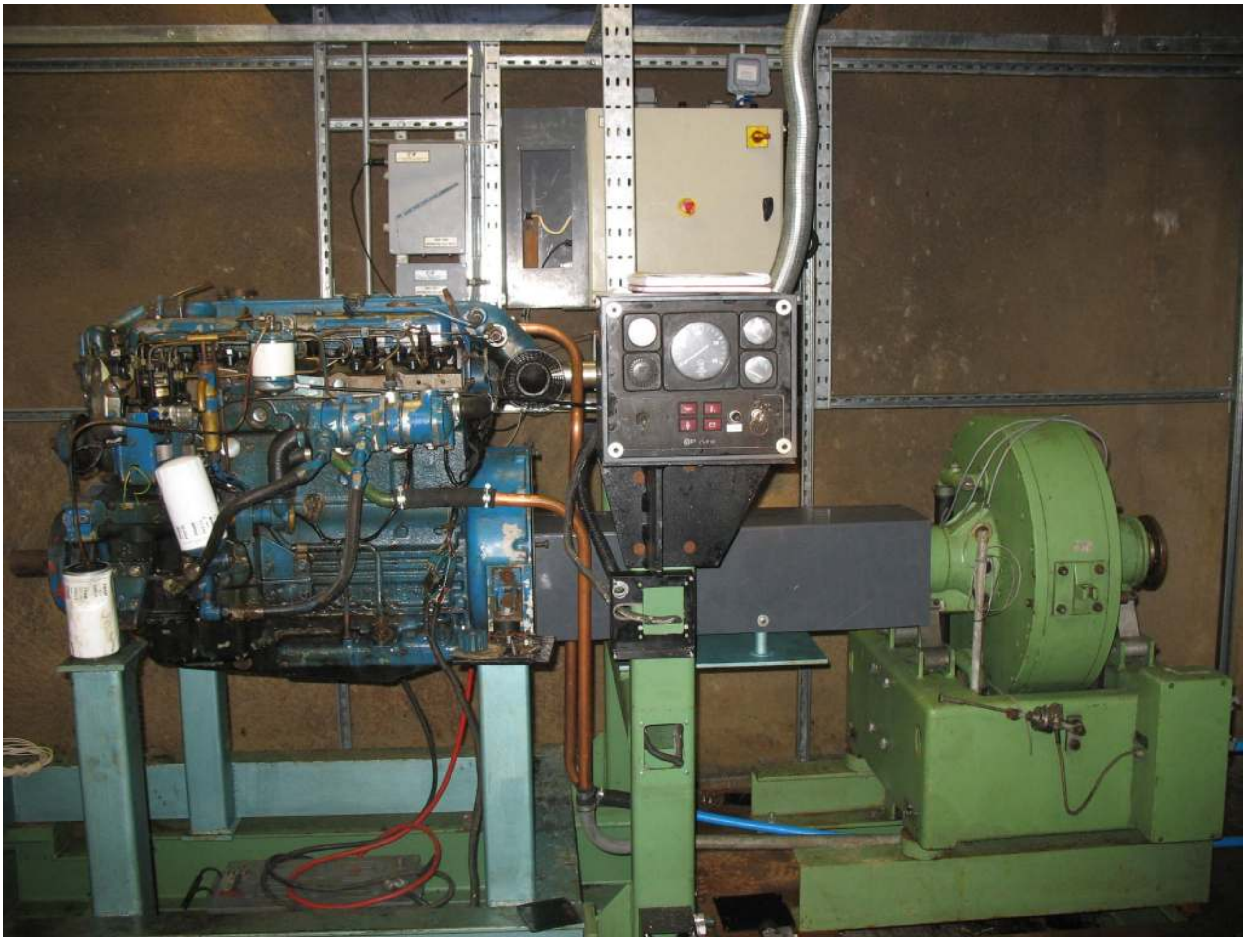


Figure 2: Foreground – Test engine (blue) and dynamometer (green). Background – data acquisition housing (RHS) and fuel measurement system housing (LHS).

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.

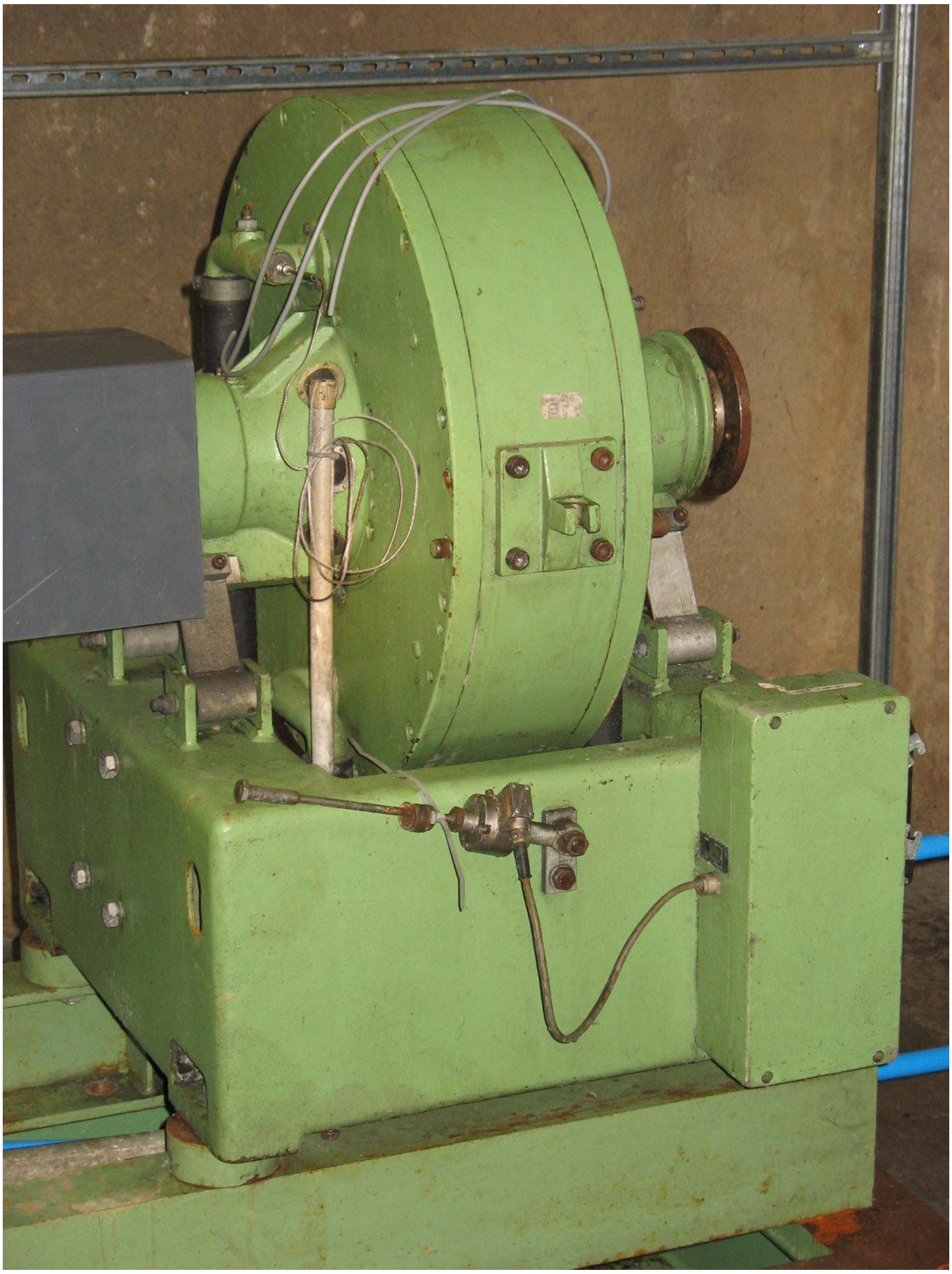


Figure 3: Dynamometer detail (N.B. Load cell unattached)

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

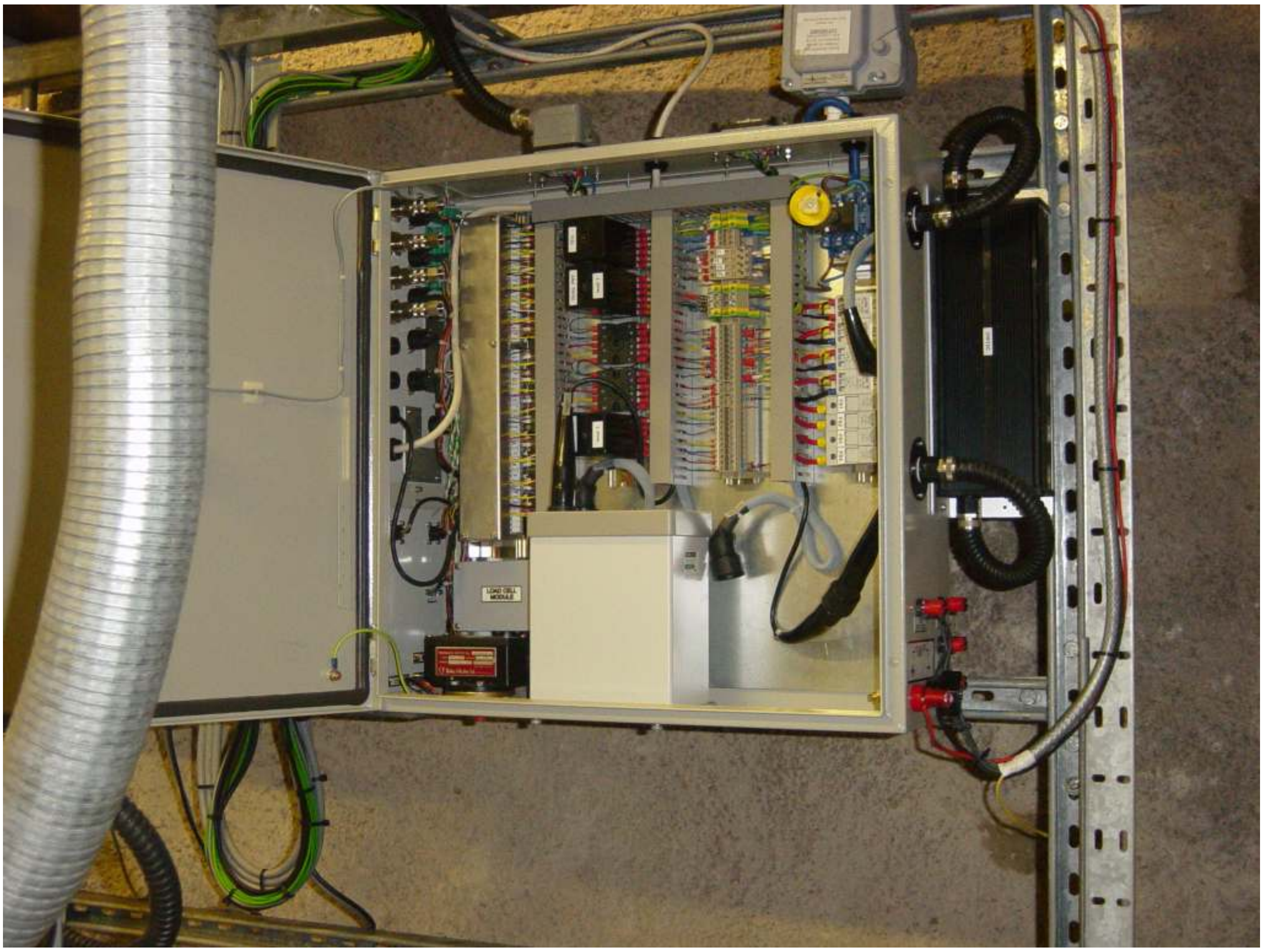


Figure 4: Data logging and control hardware

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.)

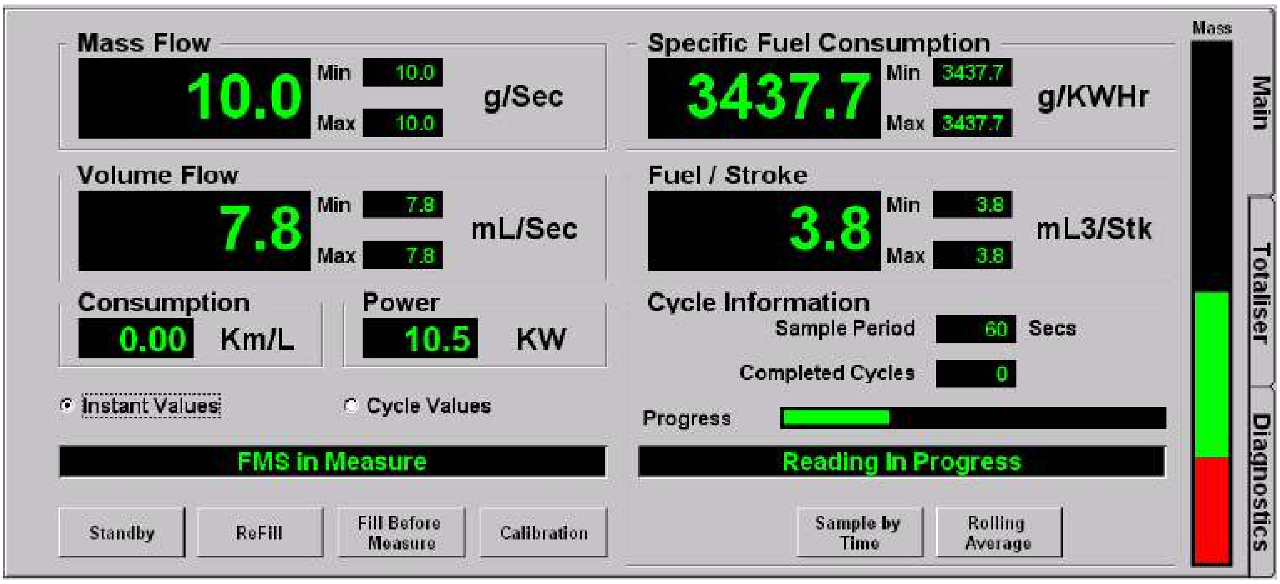
X = 1 digout 1 only connected to com1, the rest to com2
X = 2 digout 1 & 2 connected to com1, the rest to com2
: :
X = 8 digouts 1 through 8 connected to com1
Y = 1 Link to provide watchdog contact
For use with single DL-INT-03 systems

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.



Mass Flow: 10.0 g/Sec (Min 10.0, Max 10.0)

Specific Fuel Consumption: 3437.7 g/KWHr (Min 3437.7, Max 3437.7)

Volume Flow: 7.8 mL/Sec (Min 7.8, Max 7.8)

Fuel / Stroke: 3.8 mL3/Stk (Min 3.8, Max 3.8)

Consumption: 0.00 Km/L

Power: 10.5 KW

Cycle Information: Sample Period 60 Secs; Completed Cycles 0

● Instant Values ○ Cycle Values

FMS in Measure

Reading In Progress

Figure 5: Fuel measurement system main display panel

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

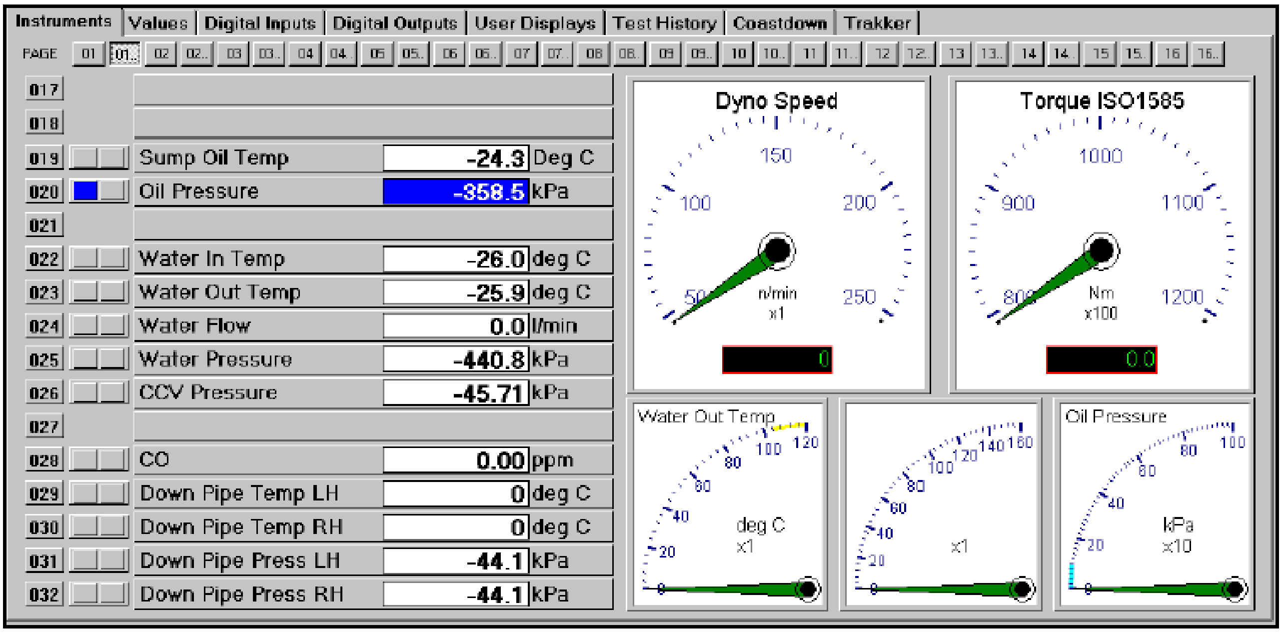
The params file links the hardware to the software. The backplane addresses and resolution of the hardware input and output channels are defined the params file.

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 a test is run).

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.



017			
018			
019	Sump Oil Temp	-24.3	Deg C
020	Oil Pressure	-358.5	kPa
021			
022	Water In Temp	-26.0	deg C
023	Water Out Temp	-25.9	deg C
024	Water Flow	0.0	l/min
025	Water Pressure	-440.8	kPa
026	CCV Pressure	-45.71	kPa
027			
028	CO	0.00	ppm
029	Down Pipe Temp LH	0	deg C
030	Down Pipe Temp RH	0	deg C
031	Down Pipe Press LH	-44.1	kPa
032	Down Pipe Press RH	-44.1	kPa

Figure 6: Example of main instruments display panel of the Cadet Lite system

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)
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
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

User Variable Number	Description
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.

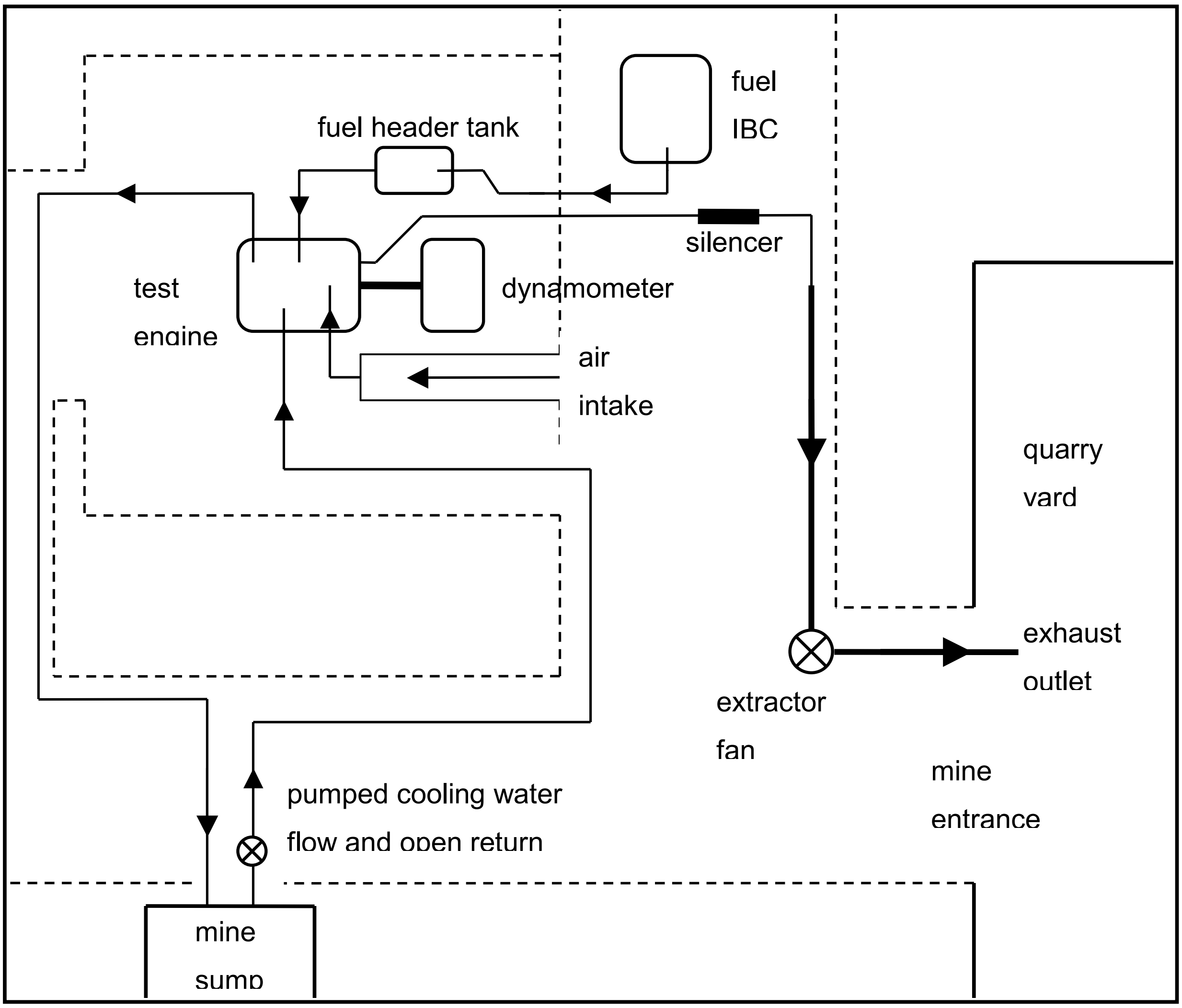


Figure 7: Schematic diagram of test infrastructure within the mine.

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.

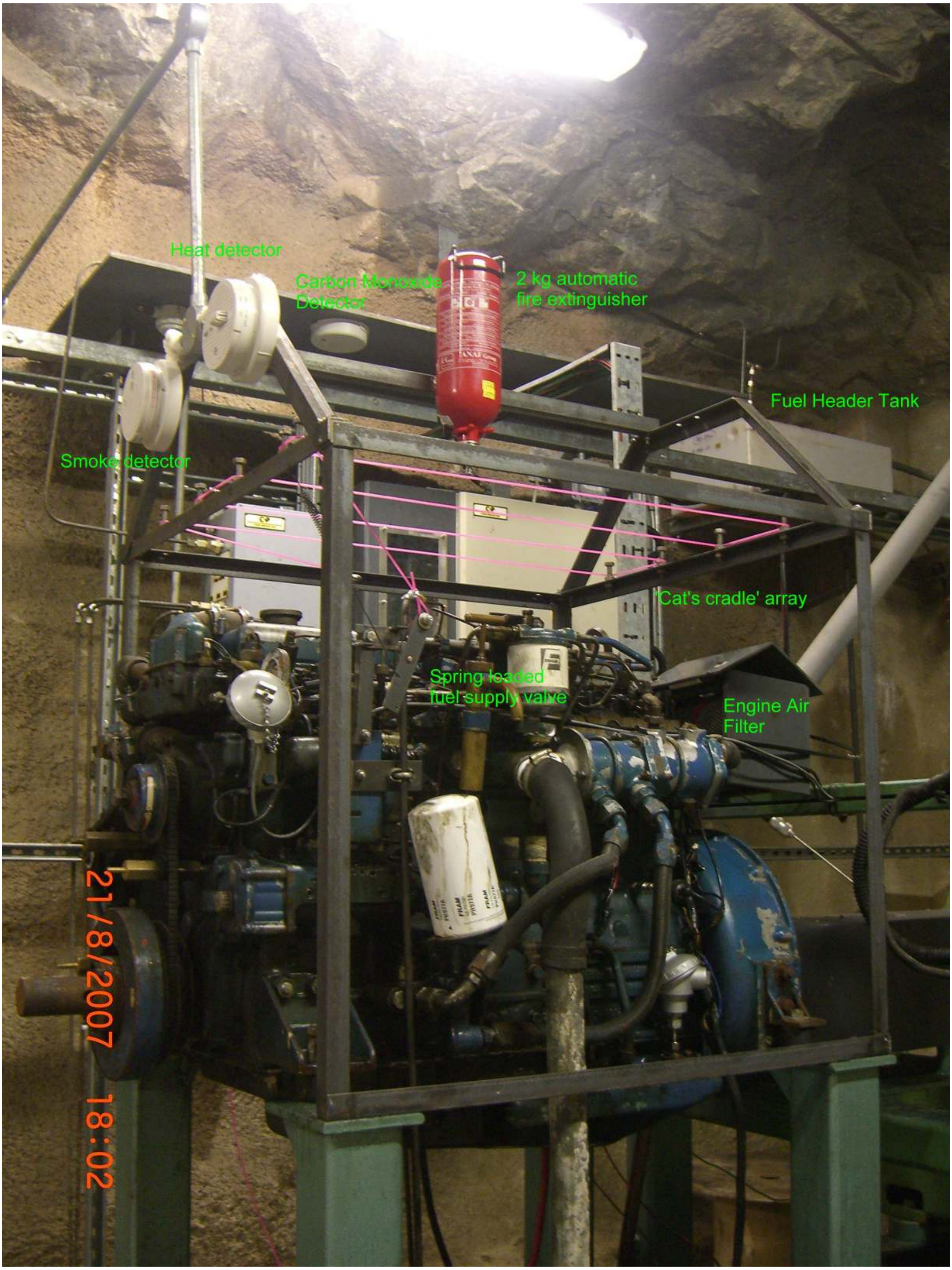


Figure 8: Test engine showing fire protection measures installed to support unattended operations for prolonged testing.

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 9: Broken and seized piston rings

Figure 10: 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.

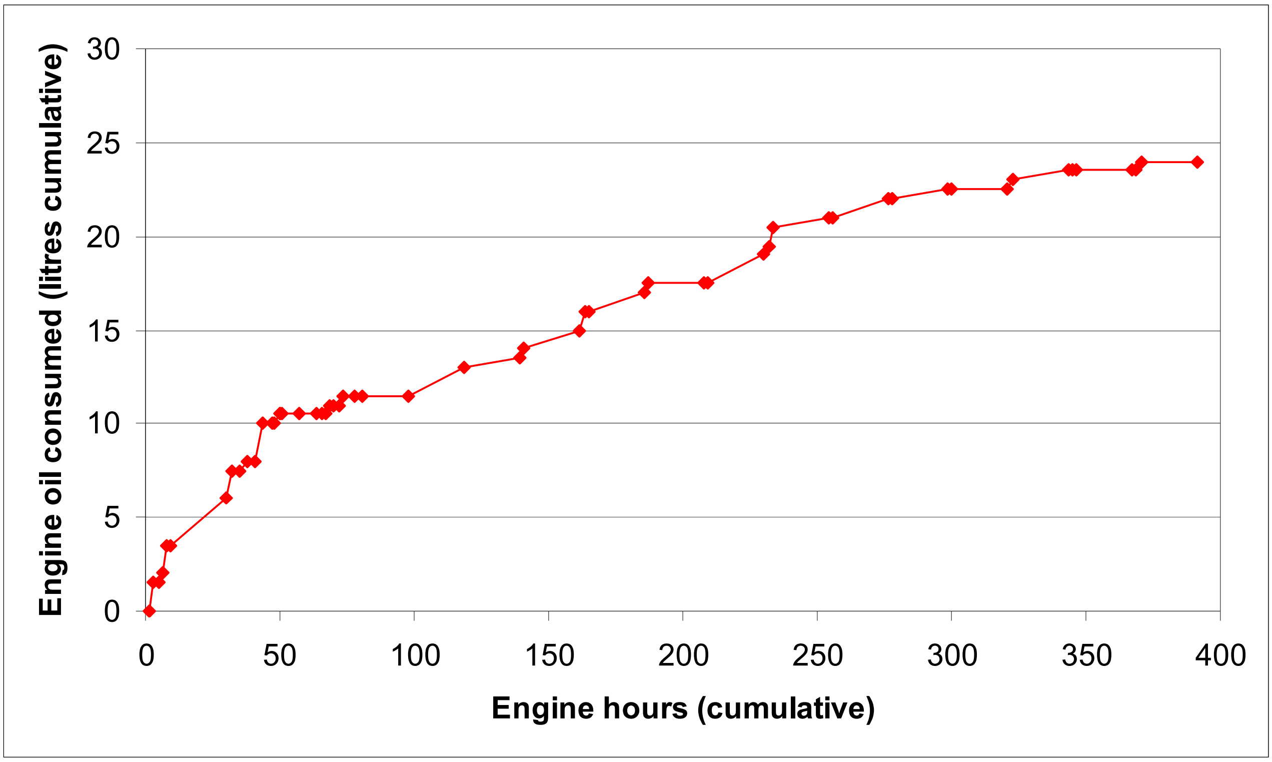


Figure 11: Graphical representation of oil consumption.

Table 1: 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

Summary

The biofuels engine test facility at CSM's Holmans Test Mine was successfully designed, installed, and commissioned. In contrast to many other engine test cells, this facility has been specifically set up with the test engine fully characterised such that comparative performance of a range of measures designed to improve fuel economy (including a complete change of fuel to biofuel) can be established with confidence.

Experience gained in operating the test cell in subsequent phases of work has revealed that the test cell produces a high level of repeatability and good consistency in results. This is in part due to the installation of the engine in the sub-surface where the ambient conditions of temperature and humidity are relatively stable.

A marine diesel engine was chosen as the test engine so that results obtained from the cell would be of direct relevance to the ~10 metre class of fishing vessels that form part of the UK fishing fleet.

The material in this report provides details of the equipment procured, the construction of the facility, the test cell control and data acquisition system, how the test cell was commissioned and the various difficulties encountered during these processes.