Programme Area: Carbon Capture and Storage

Project: High Hydrogen

Title: Basis of Design Document for HSL WP2 Task 2 Test rig for ETI

Abstract:

This document provides the rationale for the design and manufacture of the test rig forming Work Package 2 Task 2. This document is one of two for the circular duct experiments and provided the details of the test rig, what parameters it has been designed for to support the test program.

Context:

Hydrogen is likely to be an increasingly important fuel component in the future. This £3.5m project was designed to advance the safe design and operation of gas turbines, reciprocating engines and combined heat and power systems using hydrogen-based fuels. Through new modelling and large-scale experimental work the project sought to identify the bounds of safe design and operation of high efficiency combined cycle gas turbine and combined heat and power systems operating on a range of fuels with high and variable concentrations of hydrogen. The goal of the project was to increase the range of fuels that can be safely used in power and heat generating plant. The project involved the Health and Safety Laboratory, an agency of the Health and Safety Executive, in collaboration with Imperial Consultants, the consulting arm of Imperial College London.

Basis of Design Document for HSL WP2 Task 2 Test rig for ETI

20th March 2014.

An agency of the Health and Safety Executive

ISO 9001 Approved

ISO 14001 Approved

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Version Control

Version	By	Comments	Release Date
V1.00	*Wayne Rattigan*	*Initial Draft Release*	
V1.10	*Keith Moodie*	*Updated Draft Version*	*27th July 2012*
V1.20	*Keith Moodie*	*Updated Draft Version*	*27th August 2012*
V1.30	*Keith Moodie*	*Updated Draft Version*	*28th September 2012*
V1.40	*Keith Moodie*	*Updated Draft Version*	*28th October 2012*
V1.50	*Keith Moodie*	*Updated Draft Version*	*28th November 2012*
V2.00	*Keith Moodie*	*New Version*	*19th March 2013*
V2.10	*Wayne Rattigan*	*Updates to appendices*	*21st June 2013*
V2.20	*Wayne Rattigan*	*'Draft' marking removed. Minor text display issues resolved.*	*20th March 2014*

Contents

1 Introduction

This document provides the rationale for the design and manufacture of the test rig forming Work Package 2 Task 2 (WP 2.2) as required under the terms and conditions of the ETI Contract Number PE02162. Section 6, Task 2: Experimental investigation at increased scale using a circular tube. The rig's installation, commissioning and operating procedures are covered in separate documents.

The rig will provide an experimental facility to investigate the flame out of CCGT/CCGE systems and the consequences of unburnt fuel passing through the turbine (in the CCGT case) and into the exhaust system. In such circumstances the maximum hydrogen concentration in the downstream mixture is not expected to exceed 10-12% v/v hydrogen (when fuelled with pure hydrogen), and be at temperatures of the order of 400–600^{0}C, depending on the exhaust composition and the degree of compression achieved in the compressor. For CCGE applications the hydrogen concentration may be higher by up to a factor of two. If re-ignition in the exhaust system is then assumed to occur, the project seeks to assess the potential consequences, particularly with reference to the flame acceleration and the detonation propensity of the air/fuel mixtures. This rig provides a reduced scale model of an actual turbine exhaust system such that the appropriate scaling criteria can be identified to enable predictions to be made of the hazards at full scale. The rig can also contain a simulated heat exchanger so that its effect on initiating detonations can be examined as a precursor to the definitive heat exchanger tests proposed for the WP2.3 test rig using an actual heat exchanger but scaled down to a representative size.

1.1 Background

The aim of this particular section of the project is to manufacture, then commission and undertake a series of measurements using a test rig, comprising a jet engine, to provide a hot vitiated air flow, and a nominal 600 mm diameter duct, some 12 metres long, in which various test conditions can be examined. These measurements will help quantify the ignition and flame acceleration, in order to investigate the risk of the onset of detonation for the fuel systems selected.

The rationale for using this size of rig is based on the consistent experimental and theoretical evidence for hydrogen mixture compositions with marginal detonation behaviour, for which the detonation cell size is characteristically several times that of a stoichiometric fuel mixture and rises asymptotically towards the detonation limit within a few percent for further mixture dilution. With an established detonation cell width for stoichiometric hydrogen-air of approximately 10 mm at near ambient conditions and a critical channel width for detonation propagation of no more than this, it will be feasible to accommodate, close to the detonation composition limits, a potential hydrogen detonation with multiple cells across the width of the 600 mm duct.

The experiments will test and build on the findings from WP 1 and WP 2.1, using a hot vitiated airflow at several but constant flow rates. These will enable validation to be controlled in a systematic manner for the modelling, test results and the scaling parameters obtained from WP 2.1. The facility may also provide a better appreciation of the technology required to control and operate gas turbine engines running with hydrogen-enriched fuels safely. In particular this will apply to where and when a combustible gas mixture may exist in the exhaust gas stream immediately downstream of the turbine.

1.2 Objectives

The specific objectives of this part of the overall programme of work are to investigate in a nominal 600 mm diameter duct its effect on the results from the small scale study of WP 2.1 into the auto-ignition delay times, limits of flammability, and the propensity for detonation for the selected systems of high-hydrogen fuels as defined in the literature review from WP 1 and the stage gate 2 presentations.

The proposed test programme also seeks to assess the risk of ignition of non-combusted hot exhaust gases on hot surfaces for a specified flow rate and exhaust gas temperature as tested in the WP 2.1 test programme. It will also act as a test bed for the essential configurations and diverse situations that will be encountered with the WP 2.3 test rig in which a replicate heat exchanger will be present such that its influence on the detonation propensity can be fully examined.

2 Description of Rig

The test rig comprises a Rolls-Royce (R-R) Viper gas turbine, Type 301, whose exhaust feeds into the 0.6 m diameter circular duct, which is 12 metres in overall length. The duct comprises four by 3 m long un-insulated sections, flanged and bolted together and designed to withstand a maximum operational pressure of 22 barg with a maximum average wall temperature of 400°C. There are both a transition section and a variable length diverter section incorporated between the engine's turbine and the start of the 0.6 metre diameter duct. The first of these provides a pathway from the engine turbine into the duct. It also provides a means of controlling the amount of exhaust flow that enters the test duct such that a range of velocities, typical of those found in full size CCGT/CCGE systems, can be replicated. A series of nozzles are integrated into this section to provide a means of injecting and mixing the test gas mixtures circumferentially into the main hot gas exhaust flow from the engine. These gases will be injected at about ambient temperature, thus minimising the risk of ignition at this point. The transition section is designed to the same operational parameters as the duct sections.

The diverter section is designed to withstand dynamic pressures of 5 barg maximum, and by doing so is intended to minimise the backpressures reaching the engine. Minimising the back pressure on the engine turbine in the event of a major deflagration/detonation in the test duct is particularly important, as under the intended test conditions there will be a volume of non-combusted gas mixture on either side of the ignition point through which flame and pressure waves may propagate and accelerate. This section is also designed to control the quantity of the engine exhaust flow entering the test duct. To do so it has the facility to spill various amounts of the engine exhaust to atmosphere by diverting some of this flow sideways and away from the test duct.

The rig and its associated components will be manufactured from a suitable grade of stainless steel. A GA drawing of the proposed test rig is shown in Figure 1.

The operating procedure chosen requires the engine to be run for between fifteen to thirty minutes in order to heat the test duct to the desired operating temperature such that the temperature along the duct is stabilised (A typical operating gas temperature, after injecting the test gas and oxygen, is expected to be about 500^0C, however both higher and lower values than this may be achieved possibly in the range of 400 to 600^0C). The engine is then kept running and a high-hydrogen fuel sample together with oxygen, sufficient to restore the level in the exhaust stream to a maximum of 21%, are injected at approximately the same time into the exhaust downstream of the engine turbine. This procedure is expected to reduce the exhaust stream temperature by approximately 100°C, assuming that the gases are injected at ambient temperature and at the maximum flow rates. The flammable gas/oxygen mixture injection process should last for more than 2-4 seconds, during which time ignition of the mixture will be undertaken. This will be via an electrical spark, which will be installed axially downstream of the fuel injection point at an appropriate distance and on the centre line of the duct.

The engine exhaust gas temperatures can vary from 500°C to 720°C depending on the operating conditions being used. Increasing the fuel flow will increase the engine speed, hence increasing the mass flow through the engine and the exhaust temperature as a consequence. Thus there is limited scope to vary the exhaust temperatures to match the desired testing requirements or to maintain conditions at approximately 500°C. The engine output is variable from idle conditions, when the mass flow rate is 5 kg/s, up to maximum power when it is18 kg/s. Once at or above idle the exhaust temperatures remain at approximately 560°C until almost the full power output is reached. As it is not intended to operate the engine at a mass flow rate of more than 15 kg/s, temperatures above 560°C will only be reached by operating the engine at or near to its maximum throughput, which can be done but only for a very limited time.

The complete test facility comprising the jet engine and the duct, with its associated components will be housed in an approximately 15 metre long by 3.0 x 3.5 metre cross section ventilated agricultural style building. The test duct is attached directly to a substantial concrete pad, which is capable of withstanding the dynamic reaction loads resulting should a stoichiometric hydrogen detonation occur within it. The duct is fixed at one point only, through an anchor plate attached at the beginning of the test duct proper. The rest of the duct is simply supported in order to allow for thermal expansion. The R-R viper engine is mounted independently with a variable length connection between the exit from the turbine and the beginning of the diverter section, which controls the amount of engine exhaust flow that is spilled and also allows for thermal expansion.

The engine itself is isolated from the test section by a steel blast wall designed to prevent any fragments from a failed engine reaching the test area. The engine is also housed within a semi open rectangular building made from concrete blocks, with a steel roof. This building is open at one end and is designed to contain any overpressures that may occur should there be an accidental release of flammable gases, which subsequently ignites. The building is also designed to contain any fragments that may result from a failed engine. See section 2.6 for further details.

There are two openings in each side of the pendine block walls through which go two horizontal pipes. These duct the excess exhaust flow from the engine away from the test area when it is operating in a low flow mode.

2.1 Instrumentation

There are two sets of diametrically opposed bosses welded along the length of the tube at 500mm intervals, drilled and tapped to take a range of sensors for measuring pressures, temperatures and flame velocities along the tube. The latter are measured with both ionisation and optical probes, these being the principle means of flame detection, with the ionisation probes detecting flame at the wall and the optical probes across the whole of the cross-section. In addition 80mm diameter viewing ports are provided in each tube section at a distance of 500mm from the beginning of each 3 m length of tube. A single optical quartz window will be provided which can be used in any of the four tubes, the other three ports being blanked off. This will allow LDA measurements to be made of the flow velocities and turbulence intensities across the tube at up to four different downstream positions.

The pressure sensors will measure pressures across the expansion wave fronts in the duct. Two additional fast response pressure sensors will be used to obtain the peak pressures and waveforms across the shock fronts. The thermocouples will measure the gas temperatures outside the boundary layer, whilst other thermocouples will monitor the duct wall temperatures, fully developed turbulent flow being assumed. All of the probes can be used to monitor flame propagation parameters i.e. distance/ time/ velocity. Several additional pressure transducers are available for measuring operational pressures in the duct and around the engine exhaust as necessary. The average temperature and velocity profiles across the exhaust flow will be measured using ‘K’ type thermocouples and pitot probes. These will also be used, together with the Dantec LDA system, to ascertain the mass flow rates within the exhaust flow.

As part of the commissioning procedures the degree of mixedness will be measured using a ‘Cambustion’ fast response FID (HFR500) system, which will be used to detect fluctuations in the concentration of methane (typically up to 4-5%), injected into the exhaust flow.

A multi-channel data logging and processing system will be provided, which will have appropriate sampling rates to match the needs of the various sensors being employed, together with a 16-bit resolution capability.

HSL’s Visual Presentation Services will provide appropriate photographic and video records of the test rig and the tests during both the commissioning and the experimental programme.

2.2 Engine Conversion

The Viper jet engine will provide a maximum mass flow rate of 15-18 kg/s, with a turndown ratio of 4:1. The engine has a power output of 3.0-3.5 MW, and jet velocities in the 600 mm diameter duct will be between 10 - 130 m/s. A dedicated engine intake will be provided so that the airflow is smooth and the inlet mass flow rate can be measured from the pressure drop at the throat of the intake.

It has been decided to run the jet engine on pure butane in order to minimise the possibility of soot particles and other additives affecting the DDT behaviour of the gases being tested. Consequently the design of the gas turbine rig involves modification of the engine prior to commencing the test programme as well as purchasing and installing a 9000-litre liquid butane storage tank. Modifications to the engine to run on butane involve removal of its existing fuel pump and fitting an external variable speed positive displacement pump to meter the fuel flow into the engine and therefore control its speed. To this end expertise from another company, Reaction Engines, who have specialised technology for running a Viper engine on pure butane, has been obtained so that the risks of any unforeseen technical difficulties arising from the conversion of the engine are minimised.

2.3 Control System

The control system for the engine is an adaptation of the established control system used when running the Viper engine in its normal mode on kerosene. A dedicated PLC system will be purchased and programmed to control the engine and ensure the prescribed safe operation of the engine, rig and facility. The specialised experience of Reaction Engines is being used again in the development of the control system, as it needs to accommodate extra safety features relating to the use of butane as fuel. The engine is started using an electrical starter to spin it at 530 rpm; it then uses pilot fuel injectors to spool it to idle (4000 rpm) before switching over to the main fuel injectors.

The control system reads and records a number of engine and rig parameters such as RPM, oil pressure, compressor pressure, exhaust temperature, vibration, pressure and intake mass flow rate. Software will be written to communicate with a National Instruments hardware cRio/PXIe/SCXI system and display these parameters on computer screens as well as storing them on a hard drive. The clock of the engine control system will be synchronised with that of the data acquisition system so that data from other instruments can be correlated with engine parameters.

The cRio/PXI/SCXI will be located in close proximity to the engine whilst that part of the control system responsible for displaying and storing the engine parameters will be in the control room, which for safety reasons is situated approximately 90 metres from the engine and test area. Engine start, speed settings and shutdowns will be carried out from the control room. Failsafe hardware will be installed, which in the event of a power failure, gas leakage, and engine over speed or over temperature will automatically shut down the engine and the rest of the system.

2.4 Gas Mixture Supply

The system of gas supply will consist of two stainless steel pressure vessels with a maximum capacity of 225 litres and a MWP of 300 barg. One vessel will contain oxygen the other the fuel mixture. The latter will comprise mixtures of hydrogen/methane/carbon monoxide and nitrogen as required. Specific gas mixtures will be prepared from individual gas cylinder packs using a Haskel booster pump. Mixtures will be quantified using partial pressures. Mixtures and individual gases up to 100% concentration can be prepared in this way. Both pressure vessels will be mounted on load cells, three per vessel. These will enable the mass flow rates from the vessels to be measured independently of the coriolis mass flow meters.

The means of injecting the gas mixtures will be a flow through system, injecting directly into the exhaust stream and relying on the injection process to ensure that the gases are fully mixed with the exhaust stream. This avoids waste and reduces the risk of a flash back. The mass flow rates of the injected gasses will be measured using individual coriolis mass flow meters and controlled using mass flow controllers. The supply line pressures will be regulated using pressure regulators (60 barg maximum, but typically 40 barg). This method of flow control and monitoring provides a more accurate control system with better resolution and variability than can be obtained by direct injection through fixed diameter orifices. The need to do so has arisen from an assessment of the test data obtained from WP 2.1, which has shown the importance of even small variations in the mixture compositions, hence the need to have precise control over the mixture concentrations injected, together with a wide range of mass flow rates to match the exhaust mass flow ranges. The same method of flow control will be required with respect to the addition of oxygen. This was not proposed in the original contract but has been added as a result of further consideration of the actual flameout conditions, the findings of the literature review, sponsors meetings and the initial results from WP2.1.

The gas supply system will be located in a well-ventilated area and will be piped to the rig. For safety reasons it will be separated from the test rig by a double concrete block wall located to the side of the rig. The pipe work with its associated pressure regulators and flow controllers will be designed and installed to accord with the Pressure Systems Regulations, incorporating non-return valves and flame arrestors.

2.5 Data Collection

SCITEK will design and install the data acquisition system for the rig, using hardware from National Instruments in the form of cRio, PXI/SCXI systems that have fast data acquisition capability (in excess of 200 kHz) as well as signal conditioning capability for different types of sensors. This system will also be interfaced to the engine control system, which is also a PXI/SCXI system. The data collection software will ensure that all critical data is displayed in numerical and graphical form and stored for more detailed analysis in due course. The software for data acquisition and control will be written by SCITEK in LabView, which is the industry standard.

2.6 Commissioning

The completed rig will be installed on a concrete pad that is within the experimental test area of the HSL site. It will be attached by a substantial steel frame to a set of rails, which themselves are attached to the concrete pad forming the base for the rig. The duct section of the rig will be enclosed, for safety reasons within a well-ventilated agricultural type building. This enclosure will provide protection from inclement weather and also provide a suitable working environment.

The engine, diverter and transition sections of the rig will be housed within a rectangular concrete block walled structure. This structure also separates the gas storage and preparation area from the test rig as mentioned previously in Section 2.4. The layout of the whole structure is shown in Figure 3.

There will be a steel roof over the pendine walled section but with a 250mm ventilation gap between it and the top of the concrete block walls. See Appendix 8 for the calculations supporting the roof structure design. The purpose of this structure is to contain any debris and/or blast effects in the highly unlikely event of an engine failure and the subsequent release an ignition of flammable gas mixtures from the entrance to the duct section of the test rig and the engine.

There will also be isolation from the duct section of the rig by a vertical steel blast wall placed between the start of the transition section and the gas injection manifold, at the end of the pendine block work. This wall is also designed to withstand the moderate blast pressures that may be generated by the accidental release and ignition of the test gas mixtures from the duct and engine. It is also designed to contain any fragments that may result from such an event. See Appendix 8 for the calculations supporting the blast wall design.

The rig will be operated from a nearby control room, 90 metres away, where the data collection and processing system will also be housed. An exclusion zone will be declared and maintained around the test rig during its operation. See Figure 19.

The engine will be commissioned first to ensure that its control system is responding correctly such that the operating conditions can be maintained and controlled and the engine starts without flameouts, as these may release unburnt gas.

Engine running tests will follow to ensure that steady state gas flow temperatures are established in all parts of rig within an acceptable time scale. Calculations, based on a mass flow rate of 15 kg/s, suggest that the unlagged rig will reach its steady state operating temperature within 12 minutes, with a gas inlet temperature of 550^0 C. At the minimum operating condition the system will take longer to reach the steady state conditions. The maximum wall temperature will be 450^0 C and the outlet gas temperature will be 15^0 C lower than the inlet gas temperature. The steady state temperatures and operating conditions will be recorded. Once the required gas flow conditions have been achieved further tests will be undertaken to validate the fuel mixture and oxygen injection systems, and to check that adequate mixing is being achieved. Further testing will be done to confirm that the instrumentation is functioning correctly together with the data collection system. See the Commissioning Plan (1).

2.7 Safety Assessment

HSL will undertake a risk assessment of the whole operation and will have responsibility for the safety of the rig; others will contribute to this process particularly with respect to the operation of the Viper jet engine. All work done will be in compliance with the relevant CDM, DSEAR and Pressure Systems Regulations.

As part of the safety measures a gas detection system will be installed within the fuel storage and engine areas to detect any fuel leakages, this will be linked via the engine control system to safety cut-off valves. Other fire prevention measures will be included as necessary.

3 Product Specification

3.1 Tube Section

3.1.1 Description

The tube or duct component of the test rig comprises four sections each of which is 3.0 metres long, together with a 2 metre long transition section and a variable length diverter section. Each section of tube is flanged in accordance with the relevant pipe code. Proof of conformity with the code has been provided by the supplier/ manufacturer for both the tube and flange materials.

The sections mate with adjacent sections such that any radial misalignment between sections does not exceed 0.5 mm at any point around the circumference of the mating surfaces. The sections are spigotted and bolted together without the use of gaskets; the mating surfaces are machine finished, as the joints do not have to be leak proof. (“O” ring seals are used for hydrostatic proof testing purposes only).

The tubes are manufactured from 304L grade of stainless steel, with their seams ground internally to provide a smooth surface along the length of the finished tubes.

Each section of tube has two diametrically opposed series of bosses welded along their length at 0.5 metre intervals, starting at a distance of 0.25 metres from the tube ends. These are drilled and tapped to ¾” BSP parallel female pipe threads, flat bottomed some 8mm above the tube inner diameter and with a 19 mm diameter hole into the tube. Each tube also has a single 80mm diameter optical viewing port at a distance of 0.5 metres from one end. There are also two diametrically opposed 1” BSP tappings drilled and tapped through in each pipe section, which are in line with the first instrument ports but at 90^0 to them. See Figure 2.

Four cradles, whose heights are adjustable, support each of the four tube sections. Each cradle runs within two channels with sideways movement being prevented by adjustable castors. This enables the sections to be moved easily within the enclosing building, and to be aligned and bolted correctly to each successive tube section. Each cradle will support the weight (1.5 tonnes) of each tube section. There are no horizontal loads applied to the cradles.

There is a transition section that connects to the beginning of the tube section of the rig. This has provision for injecting the test fuel mixtures into the exhaust stream circumferentially through a set of three equally spaced radial tubes. Each tube contains 52 small holes sized to deliver the required range of flow rates as a series of under-expanded jets. There are a similar set of three tubes for the delivery of make-up oxygen placed immediately in front of the fuel delivery tubes. This transition section is designed to the same standards and codes as the four main tubular sections. See Figure 6.

The transition section connects to the engine through the diverter section. The latter being designed to control the quantity of the exhaust flow that enters the duct section. Excess exhaust being deflected horizontally away from the test rig. The length of this section can be varied to control the area of the openings taking the deflected flow. It also connects directly to the engine exhaust nozzle and cone, the latter being held within the nozzle by three equally spaced guide vanes. It is not rigidly connected to the engine exhaust turbine housing, as there is a sliding connection to allow for expansion and setting of the correct flow rate. This unit is designed to with stand a maximum dynamic load of 5 barg. See Figure 4.

The Diverter section has two horizontal outlet pipes connected to it by flanged connections. These pipes are 300 mm diameter and take the exhaust gases out of the immediate test area. See Figure 5.

A turbulence generator has also been provided; comprising a removable vertical grid of five tubes whose diameter may be changed from 25mm up to 50mm. Up to three additional grids can be attached to the first set of tubes in order to represent a multi-stage heat exchanger. This unit can be mounted between the first of the four 3.0 metre long tubular sections or at the inlets to any of the other sections. See Figure 7.

The completed tube is fixed, at a centre-line height of approximately1.0 metre above the concrete base. It is anchored at one point only to the underlying concrete. The attachment point is at the flange on the interface section. Thermal expansion of the tube when in operation is accommodated through movement of each section on its respective cradle. The complete assembly is shown in Figure 1.

3.1.2 Assumptions

The tube has an internal diameter of nominally 600mm and is capable of withstanding an operational static pressure of 22 bars maximum. The maximum average wall temperature is taken as 400^{0}C.

The tube is also designed to comply with ASME B31-3 Pressure Piping code (2) and ASME B16-5 Flange Code (2). In addition all components comply with the Pressure Equipment Regulations 97/23/EC (3), and HSL has signed-off all manufacturing drawings prior to manufacturing commencing.

The turbulence generator can withstand in shear an impulsive pressure load of 22 bar acting normally across the full section.

It is assumed that the engine exhaust cone and supporting vanes may be subjected to an impulsive reaction due to a static pressure not exceeding 5 barg acting along the pipe centreline towards the gas turbine. The duct mounting system will also be subjected to this pressure load.

3.1.3 Calculations

Tubes/ flanges and transition section design: all of these components are designed in accordance with ASME B31.3 Pressure Piping Code (2), with the maximum allowable working pressure at 400^0C being 23.9 barg (which is adequate to meet requirements). The theoretical burst pressure of the tubular sections is 140 barg.

Forged flanges, (certified) according to ASME B16.5 in 304L of 300lb dimensions are rated at 23.9 bar at 400^0C and are therefore adequate. These flanges are 914 mm in diameter for a 600 mm pipe. The flange thickness is 111 mm and the weight of each three metre long section of completed tube is 1.5 Tonnes.

The use of this tube size also allows for any unforeseen significant overpressures in the unlikely event of DDT occurring, when very short durations/transient dynamic pressures pulses may occur, with an average pressure of 30-40% in excess of static loading. The relevant design calculations are given in Appendix 1.

The design pressure was obtained from the numerical modeling simulations undertaken under contract by both BAES; see Appendix 2, and Dr. G. Munday, see Appendix 3. The former assumed that a hydrogen detonation occurred under stoichiometric conditions for which the predicted maximum pressure was 22 bars, with peak pressure spikes some 2-5 times greater but lasting for around 10 micro-seconds. Consequently these peak values may be ignored as their duration is well below the period of the natural ringing frequency of the tube, which is $3X10^{-4}$ seconds. This was also confirmed through dynamic finite element calculations simulating the impact of the loading conditions predicted by BAES.

Two sets of injection tubes, each comprising six entry points, are provided in the walls of the transition section. These are close together at the engine end of this section and provide the means of injecting the fuel mixtures and oxygen into, and mixing with, the main exhaust flow from the engine. The relevant calculations are at Appendix 4.

Instrument ports: The bosses are 50mm in diameter and are welded directly to the outside of the tube sections in accordance with the ASME code.

Diverter section: This section is designed and manufactured from 304L stainless steel, to provide a range of input mass flow rates in accordance with the design specification. Consequently it comprises two sections, the first of which is a tapered cone that connects directly to the beginning of the test section and is able to withstand the same loadings. The second provides a means of restricting the inlet flow to the duct and will be used only when the lowest velocity ranges are required. It allows for spillage of the excess exhaust gases from the engine, over its whole operational range. This item is designed to withstand a static pressure of 5 barg. It is shown assembled in Figure 4.

Turbulence generator: The turbulence generator is shown in Figure 7. This unit is currently being modified to enable additional rows of tubes to be connected to it.

Anchor plate: This comprises both the attachment to the tube at the interface section and the mounting to the concrete base underneath the containing tunnel. The reinforced concrete base is located 1.00 metre below the centre-line of the test rig and its dimensions are 32 x 3.25 x 0.375 metres. It weighs some 94 Tonnes. Calculations for the anchor plate design and the attachment bolts to the concrete base are at Appendix 5. It is shown in Figure 8.

3.2 Engine and Butane Fuel Systems

The Rolls-Royce Viper Mk.301 engine is a single shaft axial flow turbojet that produces a maximum thrust of approximately 2500 lbs (1.136 Tonnes). The dry weight of the engine is approximately 250 kg. The two engines purchased for this particular research project were both previously installed on a Hawker Siddeley HS.125 aircraft, a small business jet that was also used by the RAF for navigation training under the designation Dominie T-1. For this experiment one engine has been converted to run on butane fuel in order to reduce the amount of soot produced in the exhaust. The second engine will be kept as a spare for unforeseeable failures with the first.

The engine will be mounted on a frame manufactured by SCITEK, conforming to a standard design such that the centreline of the engine is approximately 0.95m above the floor of the concrete pad. The engine frame will slide along a set of rails and can also be secured to them. This enables the engine to be moved backwards when necessary to allow access to the diverter section and also to be firmly mounted to the ground when testing. Previous experience of running the engine in this configuration has proven to be perfectly satisfactory. The mode in which the engine is being run is not one that generates significant thrust as the exhaust nozzle has been removed.

An electric starter motor is fitted to the underside of the engine, powered by one of two 12V rechargeable batteries. After the starter begins to turn, butane fuel will be introduced into the engine via a flexible pipe coming directly from the fuel system’s engine pump. The volume of fuel introduced and the starter motor operation will all be controlled remotely using SCITEK’s control panel, which will utilise a National Instruments cRIO system (PLC). A number of other parameters, such as the mass flow rate of air in the intake; the engine RPM, the oil pressure, engine vibration and exhaust temperature will also be monitored by the cRIO.

A PC will be used to communicate with the cRIO while at the same time providing a user interface. The cRIO will be housed in a 19-inch rack enclosure and will also feature engine start and stop buttons as well as other hard-wired safety systems.

The butane required to run the engine will be stored 40 metres away from the engine in a single tank with a water capacity of approximately 9000 litres. The tank has been purchased new by HSL. The tank system will be fitted with a refill point, over flow valve, pressure relief valve, level sensor and excess flow valves. These components are the same or similar to those currently installed on a similar butane fuel system at Reaction Engines in Oxford.

The fuel will be pumped from the tank via a boost pump towards the engine and through an existing 25 mm bore pipe. The boost pump specified for the fuel system is a 2.2 kW, M Pumps CT MAG-M6/2S coupled multistage peripheral pump with ATEX certification. This pump requires 3-phase power and is capable of moving approximately 2.5 m^3 of butane around the fuel system per hour.

Nearer the engine the pipe work splits into two lines, one returns fuel to the tank (25 mm bore pipe), the other (38 mm bore pipe) sends fuel to the engine. Approximately 30 minutes before the engine is due to start fuel will be circulated around the return loop in order to ensure that all pipes are filled with liquid prior to engine start-up. At engine start-up a remotely actuated valve fitted to the engine frame is opened and fuel is allowed to flow through to the engine pump.

The engine pump installed will be a 7.5 kW Hydra-Cell diaphragm pump model G25SMCTHFECA. This pump also requires a 3-phase power supply and is capable of achieving the pump's maximum flow rate of 2.5 m^3/hr at 629 rpm. The pump will be fitted with a remotely controlled AC inverter, which will allow its speed to vary. This therefore controls the fuel flow into the engine, effectively throttling the engine and controlling the engine speed.

Four remotely actuated valves will be fitted at various locations around the system. Each valve will be an ATEX certified ball valve and will have ATEX limit switches fitted so that the open/closed position will be relayed back to the control system. The first of these valves will be located on the fuel line leaving the tank, the second immediately before the boost pump, the third on the return line and the fourth immediately before the engine pump. This final valve will also act as an emergency shut off valve in the event of the engine having to undergo an emergency shutdown.

A number of pressure relief valves, manual valves and non-return valves will also be installed in the system. A P&ID drawing based on the aforementioned and also modified to suit the site conditions at HSL Buxton is shown in Figure 13 which also shows the numbers, locations and ratings of these valves.

3.3 Test gases supply system

3.3.1 Description

The test rig requires the supply of mixtures of fuel gases, together with a separate oxygen gas supply system. These two separate gas streams will be contained in two steel pressure vessels, each with a maximum capacity of approximately 225 litres and a MWP of 300 barg. One vessel will contain oxygen only; the other will contain the fuel mixture. This will comprise mixtures of hydrogen/methane/carbon monoxide and nitrogen as and when required. Specific gas mixtures and the oxygen supply will be prepared from individual gas cylinder packs using two separate Haskel booster pumps, Type 8AGD-30, and the mixtures quantified using partial pressures.

The oxygen and the gas mixture will be injected directly into the exhaust stream and will rely on the injection process to ensure that the gases are fully mixed as quickly as possible with the engine exhaust stream. The mass flow rates of the injected gasses are measured using individual coriolis mass flow meters and controlled by mass flow controllers, with the supply line pressures regulated using pressure regulators. Additional control and safety features are provided through the inclusion of stop valves, bursting discs and PRV's.

3.3.2 Assumptions

It is assumed that the mass flow rate from the gas turbine will be variable from 15kg/s down to 5kg/s at idle (Greater mass flow rates to 18 kg/s are possible but for short periods only). The maximum v/v concentration of gas mixture to be injected will be 15% and the minimum will be 4% v/v. In addition makeup oxygen can be injected at a rate sufficient to restore the oxygen levels in the exhaust stream to 21%. The gases injected are stored at ambient temperature and rely on the mixing process to heat them to the required operating temperatures of around 500°C.

It is further assumed that a complete test, from opening the supply valve, achieving the set mass flow rate, igniting the gas mixture, and closing off the fuel and oxygen supplies will last no more than five seconds. Consequently the quantities of gases stored and subsequently released are based on this time.

3.3.3 Calculations

The heating of the unlagged duct by the engine exhaust gases has been calculated for an inlet gas temperature of 550^0 C and a mass flow rate of 15 kg/s, as shown in Appendix 6. This shows that the duct will reach a steady state temperature in approximately 12 minutes from the start of the heating process, and reach a steady state temperature of 452^0 C in this time. It also shows that the gas flow through the duct cools by 15^0 C during its passage along the duct. Calculations when the minimum mass flow rate is being used are also included in Appendix 6, which shows the longer heating time required for this case.

Calculations of the maximum and minimum gas and oxygen flow rates required to give up to 15% v/v in the exhaust flows (15 to 1.25 kg/s) and replenish the oxygen level to 21% are shown in Appendix 7. The calculated values are as follows: - Oxygen: 1.12 - 0.09 kg/s. Hydrogen: 0.2 – 0.016 kg/s. Methane: 1.57 – 0.13 kg/s. Carbon monoxide: 2.74 – 0.23 kg/s. The minimum flow rates will be no less than 25% of these values, in order to reach the LFL of the fuels. The resolution of the measurements is expected to be about 0.5% of FSO, and the Emerson control system is designed to reach the desired steady flow rates within one second. If the maximum oxygen and fuel mixture are introduced at ambient temperature into the 500^0 C exhaust then the exhaust temperature may fall by approximately 100^0 C once the gases are fully mixed. See also Appendix 7.

Valves and piping have been sized in order to give acceptable pressure losses throughout the two systems (oxygen and the gas mixtures). A pressure of approximately 20 barg has been assumed as the pressure downstream of the flow controllers, between them and the injection points. The pipe sizes as specified in the

P&ID (see Figure 14) have been obtained on this basis and to minimise the pressure losses.

If the mass flow rate from the system is 15 kg/s at 500^0 C then the velocity of the flow will be 130 m/s. When the engine is idling at a mass flow rate of 5 kg/s and the majority of this flow is diverted out of the test section then the velocity reduces to 10 m/s in the test section. The corresponding residence times in the duct are 0.1 to 1.2 seconds and the Reynolds Numbers for the maximum and minimum flows are $9.5X10^5$ and $0.7X10^5$ respectively, showing that the flows will be fully turbulent.

Design of gas and oxygen injection and mixing systems: The design of these two systems is based upon the experimental results given in (4). This paper provides an experimental correlation for both the centreline velocity and concentration decay for highly under-expanded gaseous jets as a function of downstream distance, pressure ratio and nozzle diameter.

The axial velocity decay correlation parameter (Q) is :-

$$Q = 0.08(1 - 0.16M_j)\left[\frac{\rho_a}{\rho_{eq}}\right]^{0.5} Z/R_{eq} \quad \text{.................................(1)}$$

The axial concentration decay correlation parameter (C) is :-

$$C = 0.104(\rho_a/\rho_{eq})^{0.5}(Z/R_{eq}) \quad \text{.....................................(2)}$$

Where:- $\rho_{eq} = \rho_c(P_a/P_c)$ and $R_{eq} = D_{eq}/2 = D_j(P_e/P_a)^{0.5}$. Subscript c refers to choked conditions at the orifice exit, where for a sharp edged orifice or convergent/divergent nozzle M=1.

Thus from graph (figure 3) in (4), Q = 15 for a velocity decay to 10%. Then assuming a stagnation pressure of 20 bar the downstream distance to this velocity is 993 mm for an orifice diameter of 2.5 mm.

The equivalent concentration decay from graph (figure 4) in (4) is C = 15. This gives a distance of 652 mm for an orifice diameter of 2.5 mm.

In all cases it is assumed that the jets decay at an angle of 7.5 degrees. Therefore at a distance of 1000 mm downstream, assuming a Gaussian profile, the width of the dispersing jets will be about 280 mm diameter.

Using the maximum flow rates as specified previously it can be shown, *by way of an example,* that for the injection of hydrogen through a sharp edged orifice (C_D=0.5) some 156 holes of 1.59 mm diameter are required. For CO and CH_4 similar hole sizes are required. In the case of oxygen again some 156 holes are required of 1.89 mm diameter.

It is intended to inject the gases through the spray tubes shown in Figure 6 and to inject these gases circumferentially across the duct in order to enhance the rate of mixing. It is also intended to inject the oxygen immediately before the gas mixture, thus allowing it to mix and cool the exhaust gases at about the same time as the gas mixture is injected. The spacing of the injection orifices will be such as to ensure that a constant mass flux across the whole of the cross-section of the duct is achieved. The injection process is currently the subject of a modelling study, using CFD, in order to ensure that the system design is satisfactory and that adequate mixing can be obtained. Design modifications to the injection system may therefore be made depending on the outcome from the modelling work.

During the commissioning phase of the programme, the degree of mixing will be assessed using a fast response hydrocarbon gas analyser FID system, measured downstream of the injection points together with LDA measurements of the flow velocity and turbulence levels, the latter being used to characterise the flow.

3.3.4 Implementation/ design

The proposed installation is shown in the P&ID drawing as Figure 14.

.

3.4 Instrumentation

The proposed circular duct test rig has been divided into four major components, the butane fuel system, the engine, the gas delivery system and the pipe (duct) section. The nominal locations and specifications of the required instrumentation are shown in Figure 15, which is a schematic layout of the engine and pipe sections, excluding the fuel and gas delivery systems.

3.4.1 Engine Instrumentation

The Engine section outlined in Figure 16 will be instrumented in three parts, the intake, the Viper Type 301 engine and the diffuser/transition. At the intake the mass flow rate of air entering the engine will be measured so that the correct mixture of gases can be injected downstream of the turbine. Additional exhaust mass flow measurements will be made at the exit of the duct but only when the diverter section is being used.

To determine the air mass flow entering the engine a specially designed intake (based on methodology recommended by Rolls-Royce) is used. The intake features static pressure tapings at its throat and by measuring the static pressure during operation the mass flow can be inferred.

Typically the mass flow rate is calculated via the following equation:

$$\dot{m} = A_T \sqrt{2\rho(P_{atm} - P_T)} \quad \text{...(3)}$$

Where, $\dot{m}$ is the mass flow rate of air, A_T is the effective flow area of the intake at the throat, ρ is the density of the air, P_{atm} is the atmospheric pressure and P_T is the static pressure in the intake at the throat.

The atmospheric pressure will be measured by a Druck PTX1400 or equivalent absolute pressure transducer with a typical range of 800 mbar to 1200 mbar situated near to, but not on, the engine. The static pressure at the throat of the intake will also be measured by a Druck PTX 1400 or equivalent pressure transducer, but this sensor will measure gauge pressure with a maximum range 500 mbar below ambient. The density of the air is known, however it does vary with temperature, for this reason a PT100 platinum resistance thermometer such as an Omega RTD805/6 will also be installed near the engine.

At present the calibration curve to convert static pressure at the throat to mass flow has been obtained from CFD predictions; however for this experiment a more accurate calibration will be required. This will be done using the LDA system to measure the velocity profiles and together with temperature profiles, obtained separately, will be used to obtain the required mass flow rates and to calibrate the static pressure based measurements.

Six engine parameters will be monitored to track the engine health when in use, the engine RPM, the butane fuel flow and pressure, the engine oil pressure, engine vibration levels and the compressor delivery pressure. A frequency generator on the engine will send a signal that is proportional to the engine RPM back to the control system where it will be interpreted. The butane mass flow rate will be monitored via a turbine flow meter located on the engine. It is envisaged that a flow meter from an existing Viper engine will be used following a recalibration, however if one cannot be sourced an equivalent 3rd party turbine or coriolis flow meter will be fitted to the fuel line. A Druck PTX1400 (or equivalent) pressure transducer with a maximum range of 50 bar will be installed upstream of the flow meter for safety purposes; for example if the fuel pressure recorded falls outside of the operational limits an emergency shutdown of the engine will be triggered. Lastly two further Druck PTX1400 (or equivalent) pressure transducers with a maximum range of 10 barg will be fitted to the engine in order to monitor the oil and compressor delivery pressures. A 50g accelerometer will be used to monitor engine vibration. All of the necessary transducers will be acquired and fitted by SCITEK.

The diverter and transition sections expand from an annular geometry immediately aft of the turbine through to a cylinder at the interface with the pipe section. The temperature of the gas exiting the turbine will be monitored to ensure the engine is not operated outside its safety constraints and for comparison with measurements made throughout the pipe section. Three K-type thermocouples with a maximum temperature rating of 1100 °C will be purchased by SCITEK and inserted into the air stream through equally spaced ports around the circumference of the turbine diffuser.

The engine control system will monitor all of the parameters described here. If, for example, an over temperature in the exhaust or an overspeed in the engine RPM is detected the control system will automatically cut the fuel supply to the engine. This is necessary in order to ensure the longevity of the engine and its safe operation.

For more detailed information on the instrumentation planned for the engine section refer to Table 3-1.

3.4.2 Butane Fuel System Instrumentation

The Viper engine in the proposed circular duct test rig will be fuelled by an on-site butane supply. A large tank, with a water capacity of approximately 9000 L, will be situated 40 m away from the test site and the fuel pumped to the engine via two pumps. The amount of fuel remaining in the tank must be known during testing so a level sensor will be installed in the tank and the data recorded fed directly into the control system. The butane tank will be installed in accordance with the requirements given in (5)

The two pumps feeding the Viper engine with butane are a boost pump and an engine pump. The boost pump, manufactured by M Pumps, circulates fuel around the supply system (see Section 3.5), rotating at a constant rate, thus a remotely operated on/off switch will be used to control it. The engine pump, manufactured by Hydra-Cell, will be fitted with a 3-phase inverter (supplied with the pump by Hydra-Cell) so that varying the pump speed can control the flow of fuel into the engine. The pump RPM will be monitored remotely by the control system whilst in operation.

Four remotely actuated ball valves will be fitted at various locations in the butane fuel system (see Section 3.5). Each ball valve will be ATEX rated and fitted with two ATEX rated limit switches that will return a signal to the control system when activated. This will allow for remote monitoring of the open/closed status of the valve. Finally, to ensure the safe operation of the butane fuel system, a Druck PTX1400 ATEX rated pressure transducer will be installed between the boost pump and the engine pump (immediately before the shut off valve). With a range of 0 to 25 bar, this sensor will send a 4-20 mA signal to the control system allowing the system pressure to be monitored remotely. The signal from the pressure transducer will also be monitored by the emergency stop system, which will be activated if the fuel pressure falls outside of the pre-defined operational limits.

For full details of the butane fuel system see Section 3.5. For more information regarding the instrumentation used in monitoring and controlling the fuel system see Table 3-2.

3.4.3 Gas Delivery System Instrumentation

Mixtures of Hydrogen, Oxygen, Methane and Carbon Monoxide gas will be injected into the engine exhaust stream between the turbine and the test duct. These gases will be obtained from standard pallets of the individual gases, which are at pressures up to 200 barg, depending on the particular gas. Gas mixtures will be prepared using a Haskel boost pump to supply individual gases to the storage vessels. The desired mixture concentrations will be obtained by measuring the partial pressures of the gases as they are pumped into the 225 litre mixing vessel. The mass flow rates of the fuel gas mixtures and separately the oxygen mass flow rates that are injected into the engine must be controlled to a high level of accuracy. This will be done using coriolis mass flow meters and with load cells under the supply reservoirs, to measure the flow rates. These will measure independently the mass flow rates whilst the former are linked to the pneumatically controlled flow control valves. The mass flow rates for each gas are not expected to exceed 0.2 kg/s for Hydrogen, 1.12 kg/s for Oxygen, 2.74 kg/s for Carbon Monoxide and 1.57 kg/s for Methane. If required a PT100 platinum resistance thermometer will accompany each flow controller (depending on type installed) so that the mass flow rate can be corrected for any changes in temperature. For further information on the instrumentation to be used for the gas delivery system refer to Table 3-3.

The oxygen supply system will be cleaned in accordance with the requirements given in (6)

3.4.4 Pipe Section Instrumentation

The pipe section of the rig consists of four 3.0 m long tubes that are flanged together. Each tube will have two sets of six diametrically opposed 3/4” BSP ports aligned along the length of each tube section and spaced 500 mm apart, with the first and last ports 250 mm from each end (see Figure 2). There are a total of 48 such ports along the total length of the tube. These ports will allow a number of different measurements to be made when the rig is operational.

In order to ensure that the rig is at the temperature desired for the deflagration and detonation propensity experiments, the gas temperature immediately adjacent to the wall must be monitored. Eight K-type thermocouples, sheathed in a tube of approximately 3 mm diameter and up to 30 cm in length, will be fitted into a number of the 3/4” ports so that the tip of the sensor is sampling the air temperature within 5 mm of the inner wall surface. The long length of the sheath enables temperature measurements further into the tube to be made if desired. SCITEK will arrange for the purchase of these thermocouples.

Flames produced as a result of igniting the fuel mixtures will be detected using both ionisation and UV optical probes as the primary means of detection. It is expected that up to twenty four ionisation probes and eight optical probes will be used at any one time. These probes will be obtained and tested by HSL.

If a high velocity deflagration or a detonation occurs within the pipe it is likely that a shock wave will travel along its length. By fitting a series of pressure transducers in selected 3/4” ports, the magnitude and velocity of the expansion wave behind the shock wave can be determined. The sensors required for these dynamic measurements must also be able to measure the static pressure to reasonable accuracy within a hot environment (~500° C). Eight Kulite XTEH-10L pressure transducers have been acquired for this purpose. These have a natural frequency of 50 kHz at 50 bar maximum range, the Kulite will measure short transient peaks down to 10 µs. In addition a very rapid response PCB supplied pressure transducer has been acquired together with a cooling jacket. Although not intended for use at the constant high temperatures being used, it is hoped that it can be made to operate in this environment, and thereby measure the extremely short duration peak pressure across the shock front that will precede the expansion wave of the flame front.

The flow from the exhaust of the Viper engine is required to spread evenly and flow uniformly through the tube. In order to confirm this, the flow will be characterised by inserting a combined Pitot tube and temperature rake into the flow stream. The rake, approximately 600 mm long, will enable the temperature and flow velocity across the diameter of the tube to be measured. Temperature measurements throughout the flow will be made using eight small ‘K’-type thermocouples suitably spaced along the rake. Likewise the pitot pressure will be measured at eight locations along the rake. The flow velocity is then inferred from the difference between the head recorded at each transducer and the static pressure measured by the Kulite sensor in a neighbouring port. This rake will be manufactured by SCITEK.

A larger port approximately 80 mm in diameter will be located 500 mm from the front of each tube segment at 90° to the smaller 1” ports. This 80 mm port will take an optical window, which will be fitted when performing flow characterisation experiments using a Laser Doppler Anemometer (LDA). The LDA crosses two beams of collimated, monochromatic, and coherent laser light in the flow of the fluid being measured. The two beams are usually obtained by splitting a single beam, thus ensuring coherence between the two. The transmitting optics focuses the beams to intersect at their waists (the focal point of a laser beam), where they interfere and generate a set of straight fringes. As particles (either naturally occurring or introduced using seeding generators) entrained in the fluid pass through the fringes, they scatter (reflect/refract) light that is then collected by the receiving optics and focused on a photodetector (typically a photo-multiplier tube). The particles are small, typically less than 3 microns, so that they can follow the air flow accurately.

As the particle travels through the fringe pattern (fringe spacing usually around 14 microns) a series of scattered light pulses are seen by the receiving optics. The period of these pulses represents the time taken for a particle to cross two fringes. As the fringe spacing is very accurately known the velocity of each particle can be calculated. The calculated velocity represents the component of particle velocity which lies in the plane of the two laser beams. By using lasers that produce more than one wavelength (colour) and by arranging the fringe pattern produced to be perpendicular to each other all three flow velocity components can be simultaneously measured. For the tests to be carried out in this project a ‘Dantec’ two-component LDA system will be used to measure the axial and tangential component of the flow. The radial component of the flow will not be measured but it is assumed that it will not vary. By measuring thousands of particles the average velocity and the turbulent intensity of the flow can be calculated at a single point.

The SCITEK LDA is a two component Dantec Dynamics system making use of an Argon-ion laser producing two wavelengths (Green and Blue) to measure each component. The processor is a modern FFT processor capable of measuring

100,000 particles per second for each component. The system is capable of measuring flow velocities from near zero to supersonic speeds, so it is well suited to the current project.

A Protech Automotive, IBEX exhaust gas analyser will also be provided in order to measure the exhaust gas composition from the engine. This will be used mainly during the commissioning phase of the programme, however, some measurements will also be undertaking during the testing phase of the programme in order to check that the exhaust gas composition has remained constant.

For further information on the instrumentation required for the pipe section of the rig refer to Table 3-4.

Section	Sub-Section	Measurement	Instrument	Type	Range	Signal	Quantity
Engine	Intake	Air mass flow rate	Absolute pressure transducer	Druck PTX1400 (or equivalent)	0.8 to 1.2 bar	4 - 20 mA	1
		Air mass flow rate	Gauge pressure transducer	Druck PTX1400 (or equivalent)	0.5 bar max.	4 - 20 mA	1
		Air mass flow rate	PT 100 thermometer	Omega RTD 805/6 (or equivalent)	230 °C max.	Conditioned	1
		Air mass flow rate	Five hole probe	Unknown 2/7/12	Unknown	Unknown	1
	Engine	Engine RPM	Frequency generator	Unknown	Unknown	Unknown	1
		Vibration monitor	50G accelerometer	Unknown	0-50G	Unknown	1
		Fuel flow rate	Turbine flow meter	Unknown 2/7/12 – Possibly Viper	Unknown	Unknown	1
		Fuel pressure	Gauge pressure transducer	Druck PTX1400 (or equivalent)	50 bar max.	4 - 20 mA	1
		Compressor pressure	Gauge pressure transducer	Druck PTX1400 (or equivalent)	10 bar max.	4 - 20 mA	1
		Oil pressure	Gauge pressure transducer	Druck PTX1400 (or equivalent)	10 bar max.	4 - 20 mA	1
	Diffuser	Exhaust temperature	K-Type Thermocouple	K-Type sheathed 3 mm	1100 °C max.	Conditioned	3

Table 3-1 Engine instrumentation list for the proposed circular duct test rig

Section	Sub-Section	Measurement	Instrument	Type	Range	Signal	Quantity
Butane fuel delivery system	Fuel lines	Boost pump status	On/Off	On/Off	-	Unknown	1
		Engine pump RPM	Inverter	Hydra-Cell 3 phase inverter	Unknown	4-20 mA	1
		Valve On/Off	Remotely actuated valve	ATEX ball valve with positioning	Unknown	Unknown	4
		Fuel pressure	Gauge pressure transducer	Druck PTX1400 (or equivalent)	20 bar max.	4 - 20 mA	1
	Storage tank	Fuel level	Level sensor	Unknown 2/7/12	Unknown	Unknown	1

Table 3-2 Butane fuel system instrumentation list for the proposed circular duct test rig

Section	Sub-Section	Measurement	Instrument	Type	Range	Signal	Quantity
Gas delivery system	Gas flow	H_2 mass flow rate	Mass flow controller	Emerson Type:	0.20 kg/s max.	Unknown	1
		CO mass flow rate	Mass flow controller	Emerson Type:	2.74 kg/s max.	Unknown	1
		O_2 mass flow rate	Mass flow controller	Emerson Type:	1.12 kg/s max.	Unknown	1
		CH_4 mass flow rate	Mass flow controller	Emerson Type:	1.57 kg/s max.	Unknown	1
		Gas line temperature	PT100 thermometer	Omega PT100	230 °C max.	Conditioned	5

Table 3-3 Gas delivery system instrumentation list for the proposed circular duct test rig

Section	Sub-Section	Measurement	Instrument	Type	Range	Signal	Quantity
Pipe	Gas	Flame detection	Optical/Ionisation probes	In house design and manufacture. Imperial Advised	Unknown	Unknown	8 + 24
		Gas composition	Exhaust Gas Analyzer	Protech – IPEX Analyzer.	1ppm to 100%	Unknown	1
	Flow	Turbulence	LDA System	Dantec 2D	10^6 particles/s	N/A	1
		Free stream velocity (Mass flow rates)	Pressure rake	Array of 8 pressure transducers	10 bar max.	4 - 20 mA	1
	Temperature	Boundary layer T	Thermocouple	K-Type sheathed 3 mm	1100 °C max.	Conditioned	8
		Free stream T	Thermocouple rake	Array of 8 K-Type thermocouples	750 °C max.	Conditioned	1
	Pressure	Dynamic and static	Water cooled transducers	Kulite XTEH-10L-180(m) and PCB Fast response sensor.	50 bar max.	4 - 20 mA	8

Table 3-4 Pipe section instrumentation list for the proposed circular duct test rig

3.5 Rig location and Enclosure

3.5.1 Description

The test rig will be situated near the 50-metre pad at the Turncliff Farm site and will be sited on an existing concrete pad whose dimensions are 32m x 3.2m x 0.375m. An extension to the pad has been laid to accommodate the gas delivery systems.

The engine will be enclosed by concrete block walls on two sides with a blast wall separating it from the tube section and a blast roof to prevent missiles in the event of engine failure.

The instrumentation within the tube section of the rig will be protected from the elements by an agricultural style steel framed shed

Further concrete block walls will be located around the gas delivery systems to give further protection from missiles in the event of physical failure of the rig and to provide separation between the mixed gas and oxygen feed systems.

A layout of the rig showing a cutaway of the rig enclosure is shown in Figure 3

4 References, Codes and Standards

1) Commissioning Plan. HSL WP2 task 2 Test Rig. 19th March 2013.

2) ASME B31-3 Pressure Piping code and ASME B16-5 Flange Code.

3) Pressure Equipment Regulations 97/23/EC*.*

4) "Jets discharging to atmosphere." K. Moodie & B.C.R. Ewan. J. Loss Prev. Process Ind. 1990. Vol 3. January.

5) UKLPG Codes of Practice for the Installation and siting of butane tanks, associated pipework, valves and safety devices.

6) European Industrial Gases Association document IGC 33/97/E 'Cleaning of equipment for oxygen service'

5 Figures

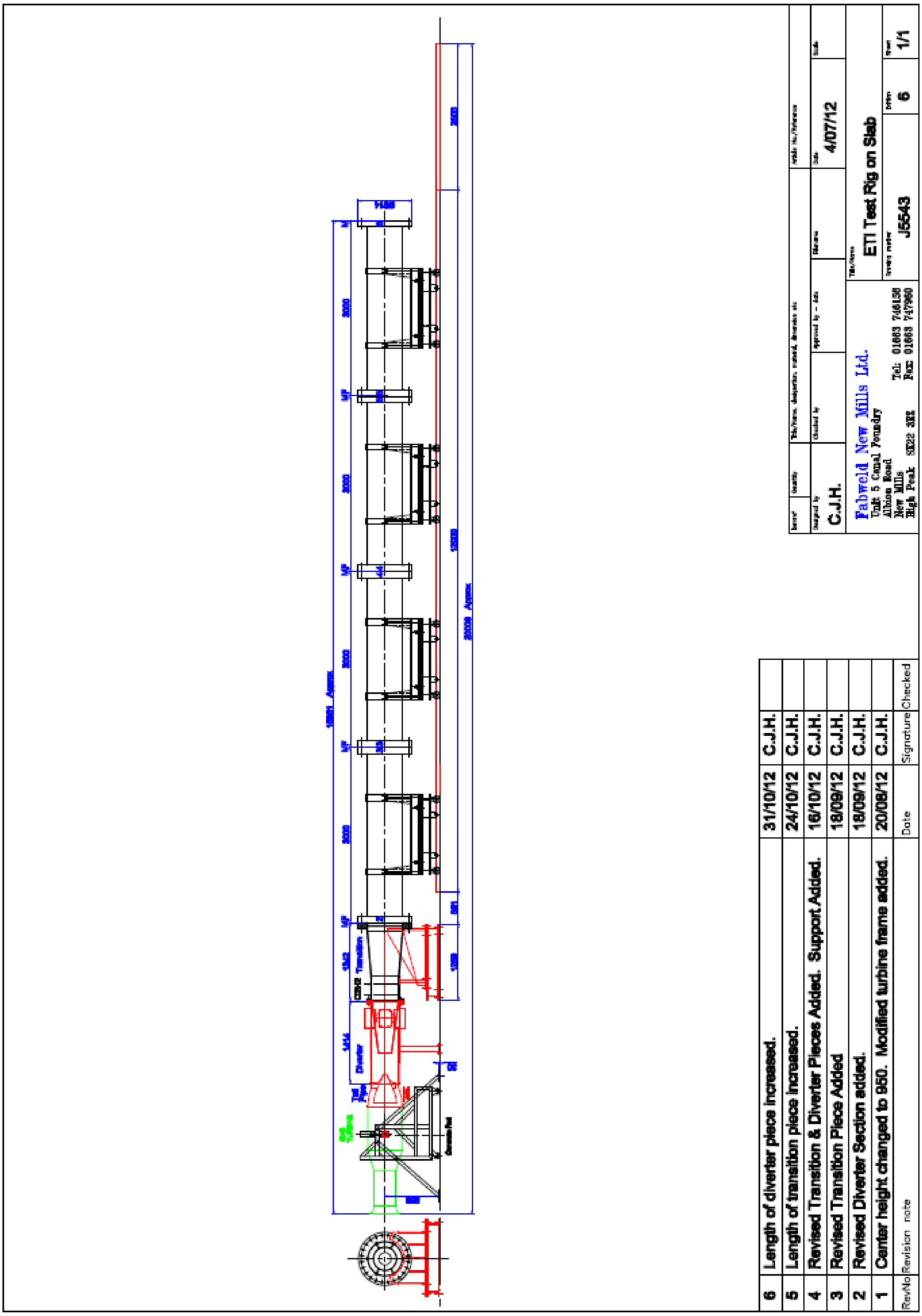


Figure 1 General arrangement drawing of test rig.

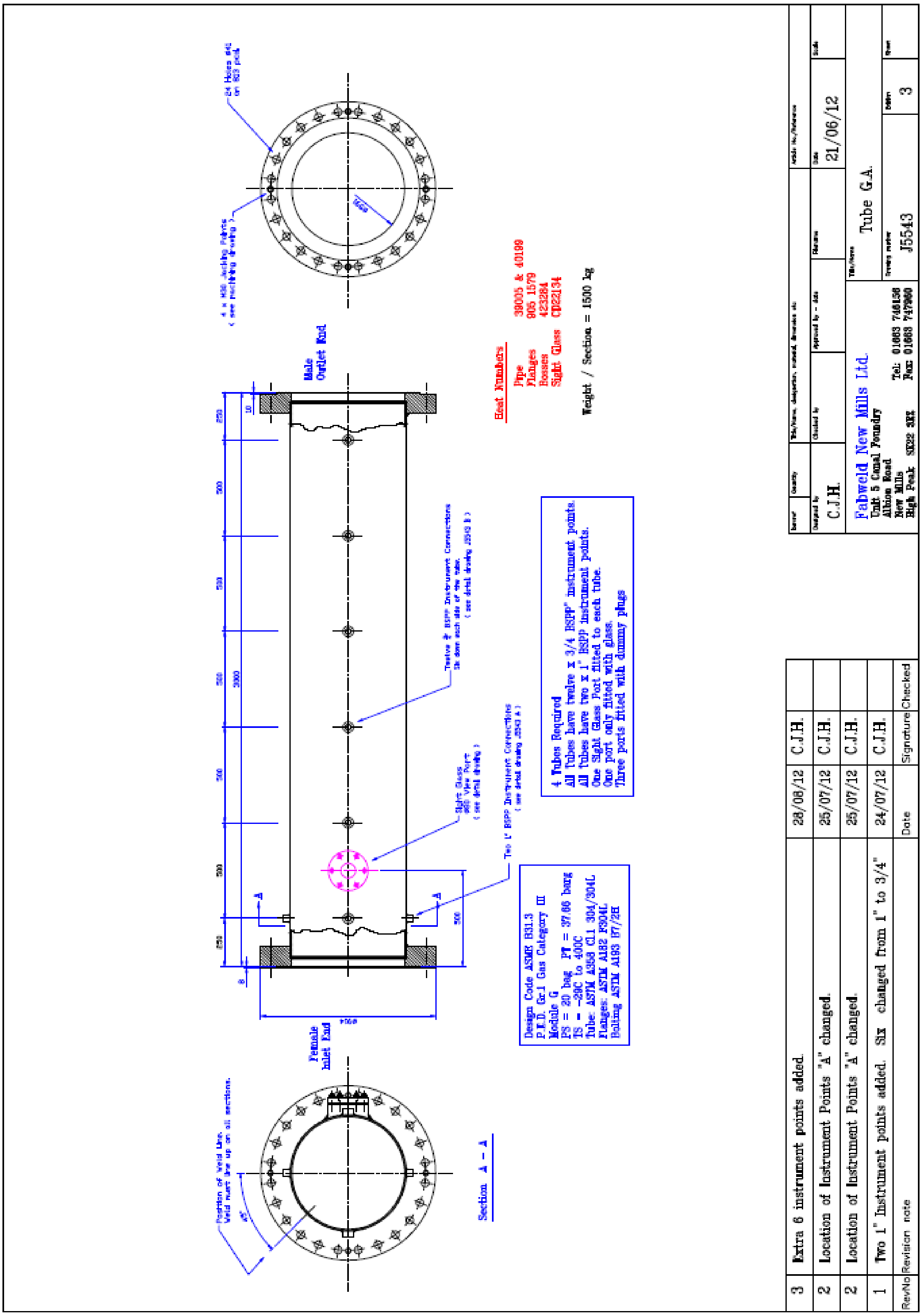


Figure 2 Tube section G.A.

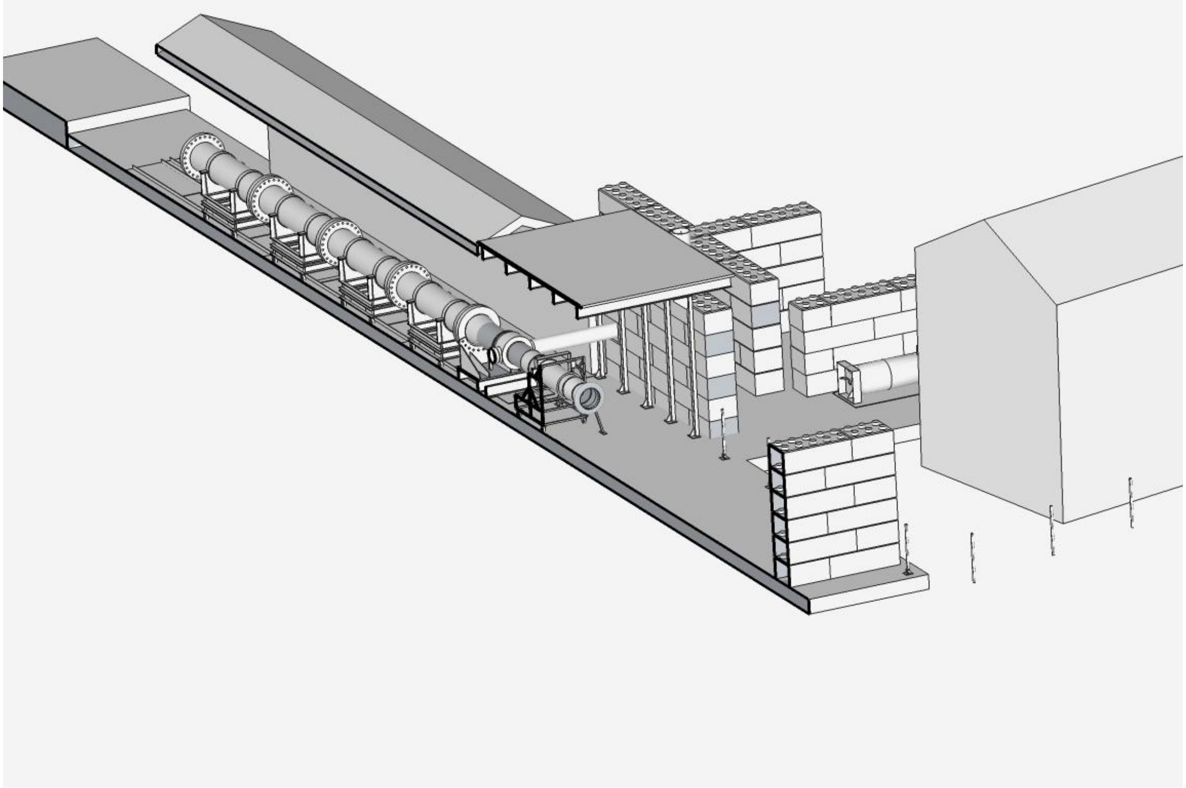


Figure 3 Cut-away view of rig and engine showing blast enclosure

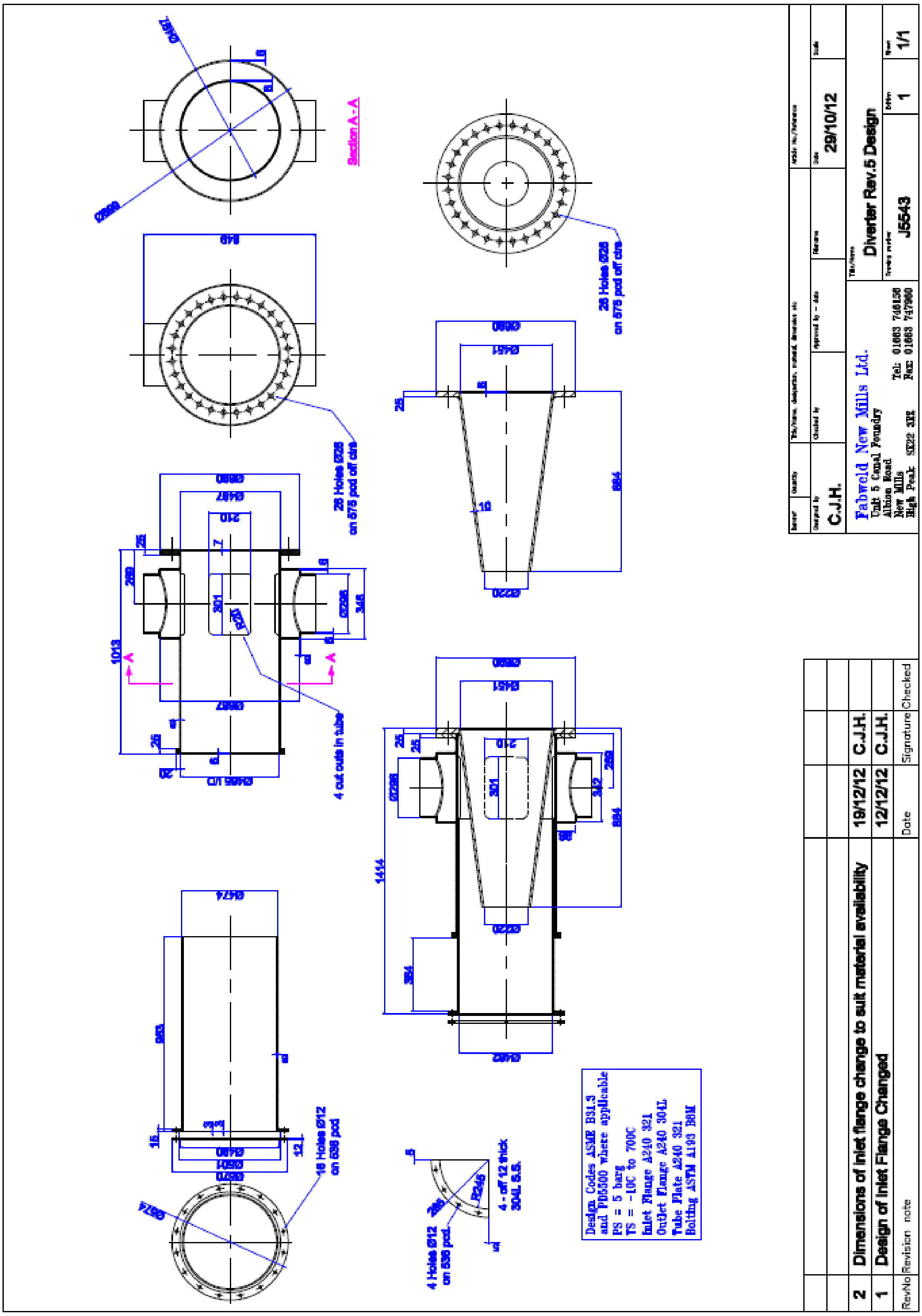


Figure 4 Interface section

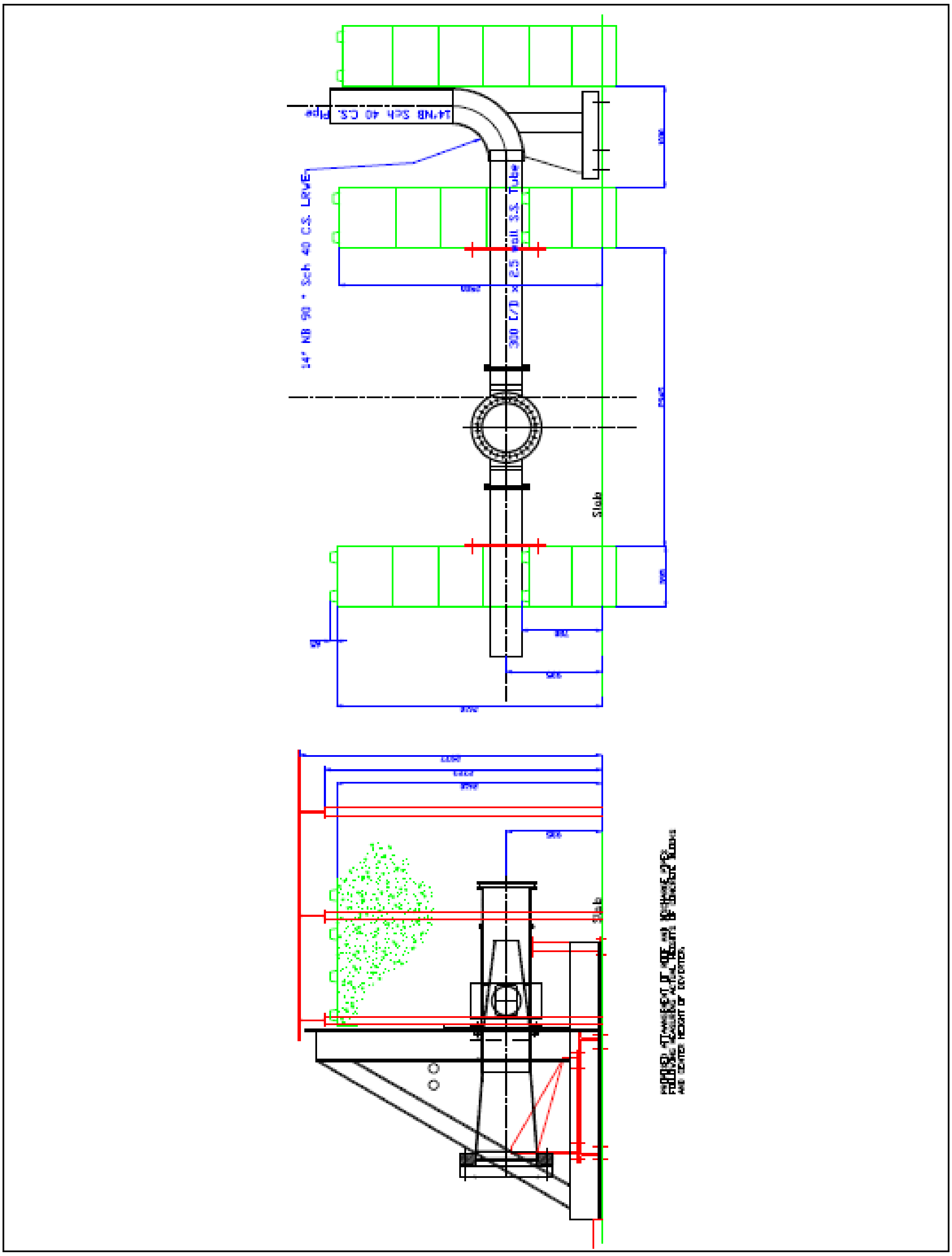


Figure 5 Layout of exhaust ducts from diverter

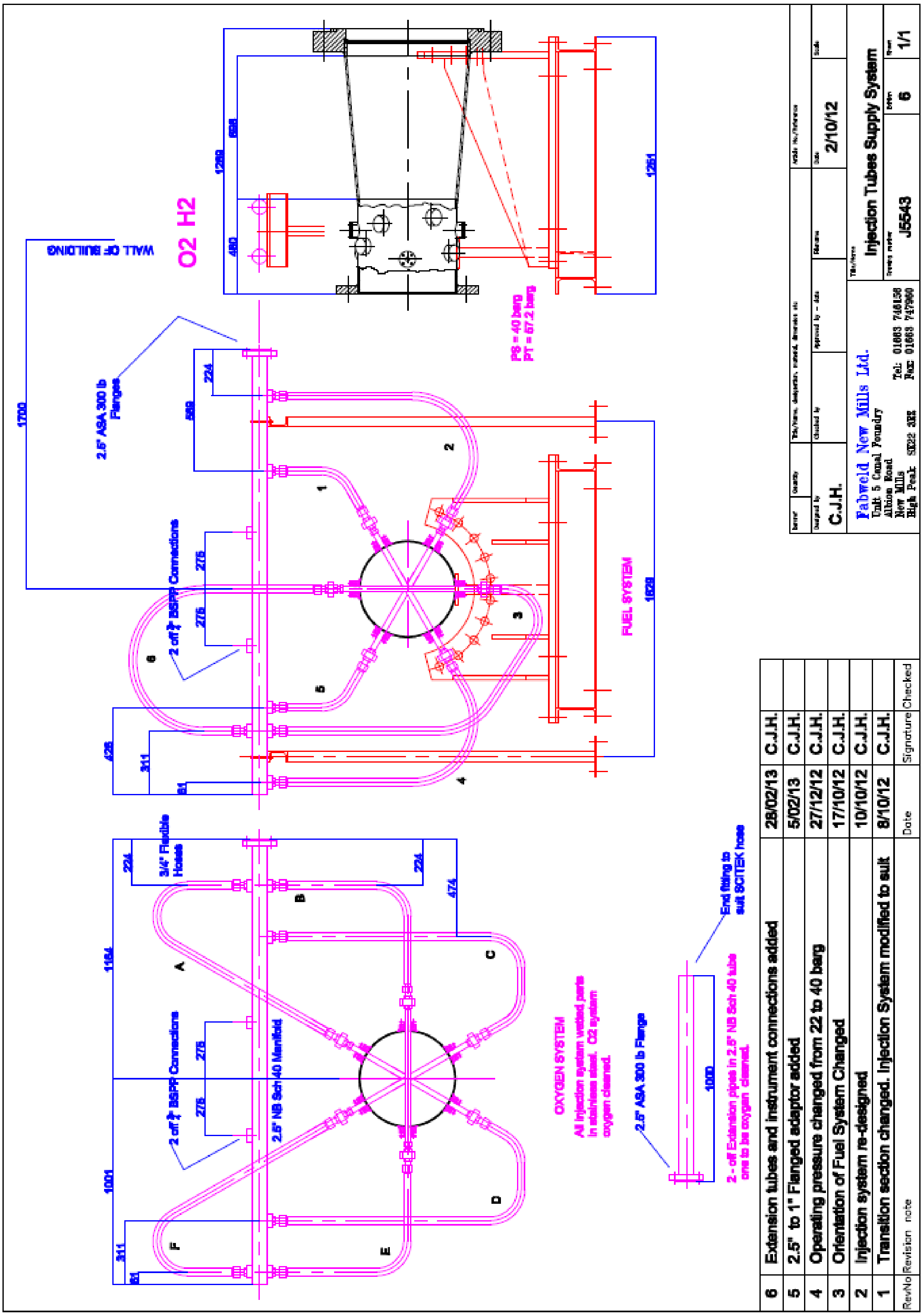


Figure 6 Injection Tubes G.A.

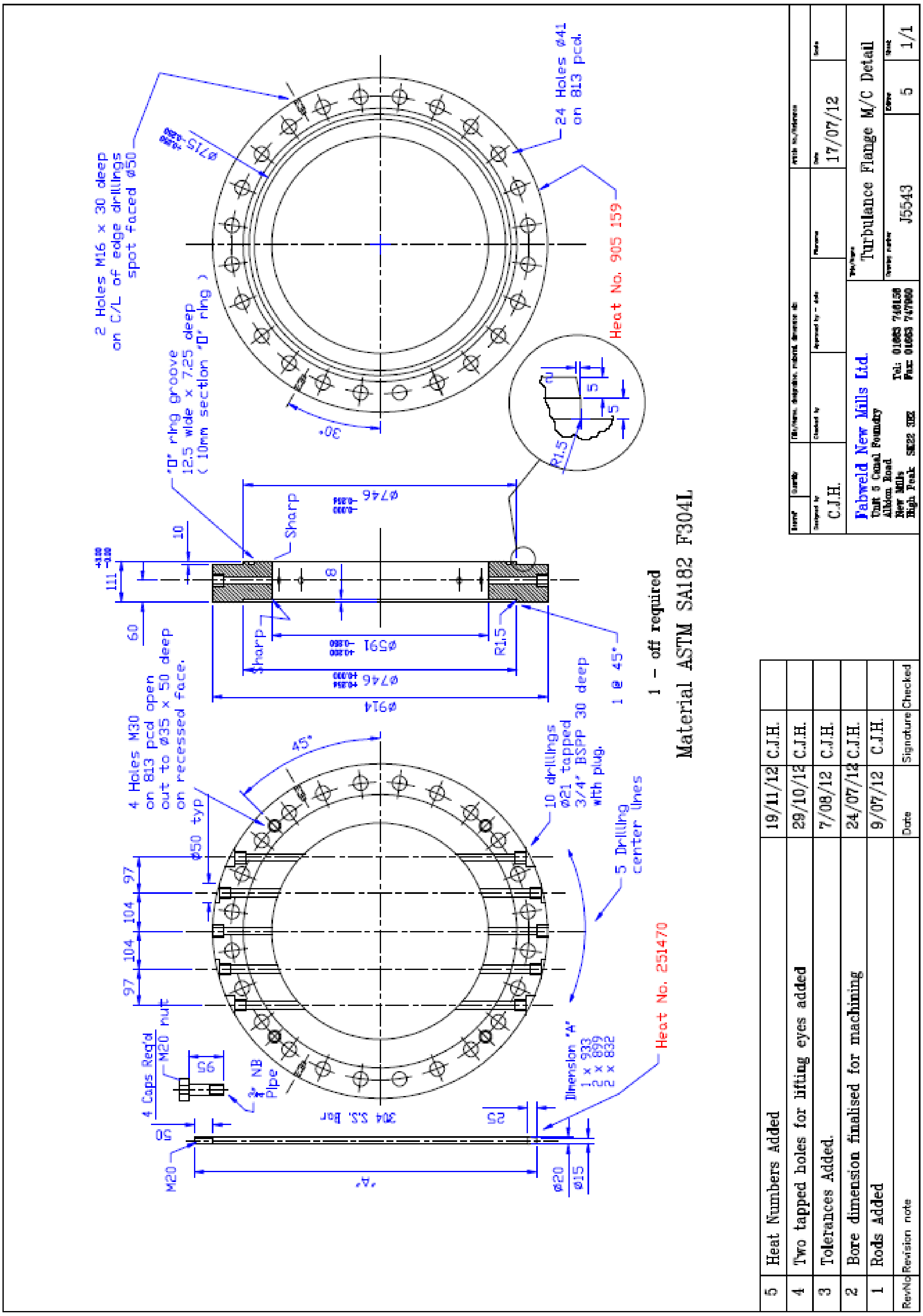


Figure 7 Turbulence generator

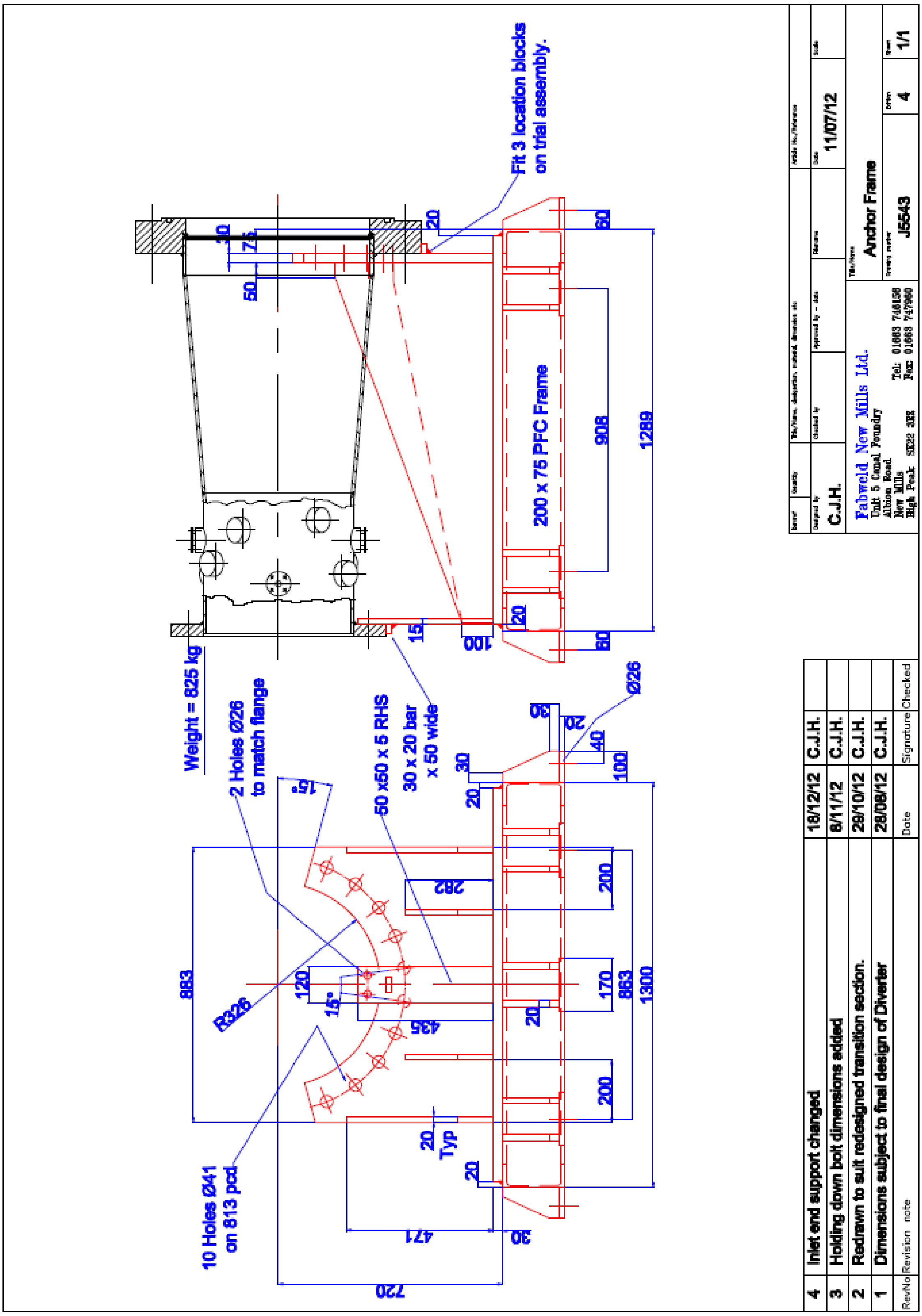


Figure 8 Anchor frame.

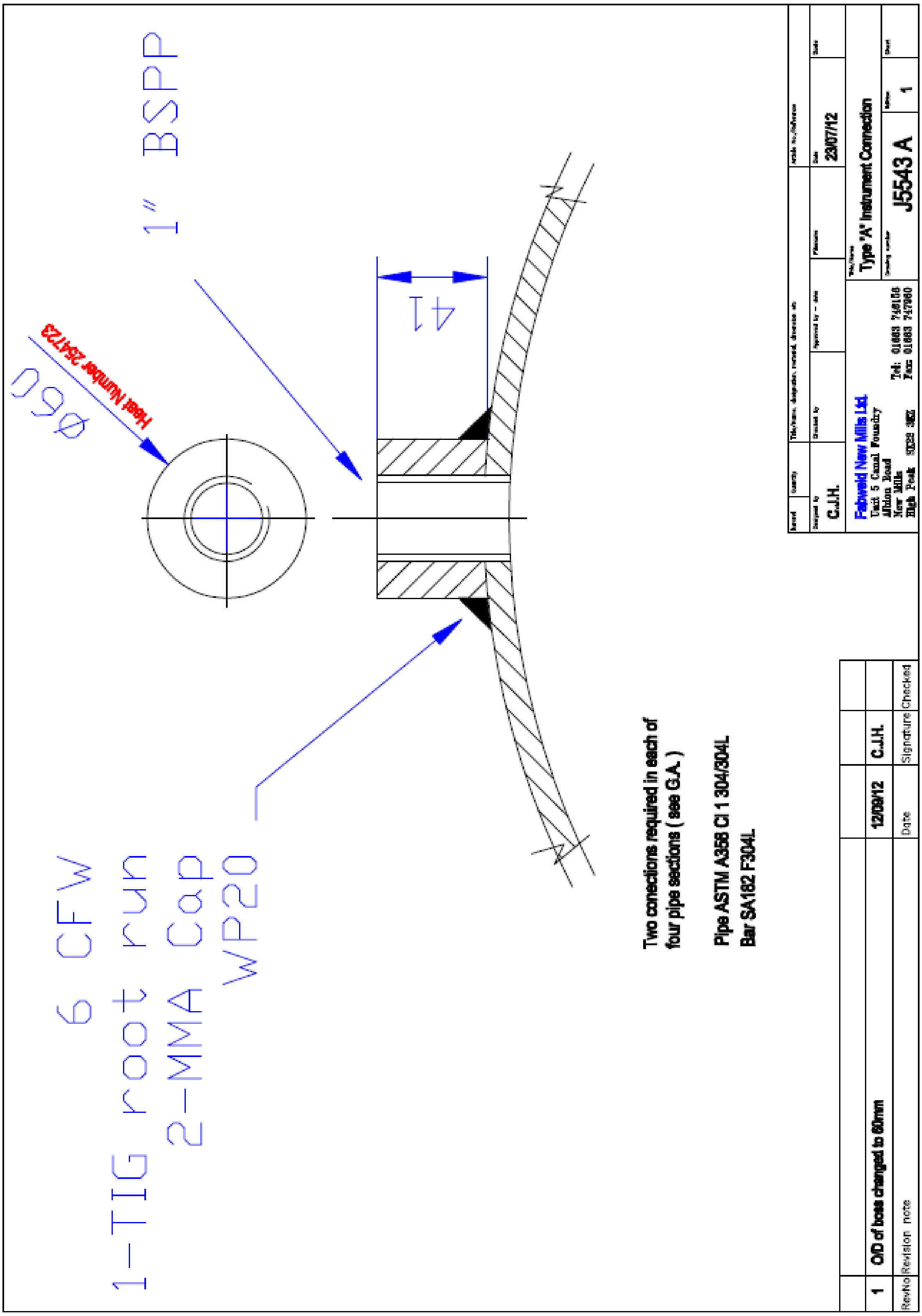


Figure 9 Probe fitting.

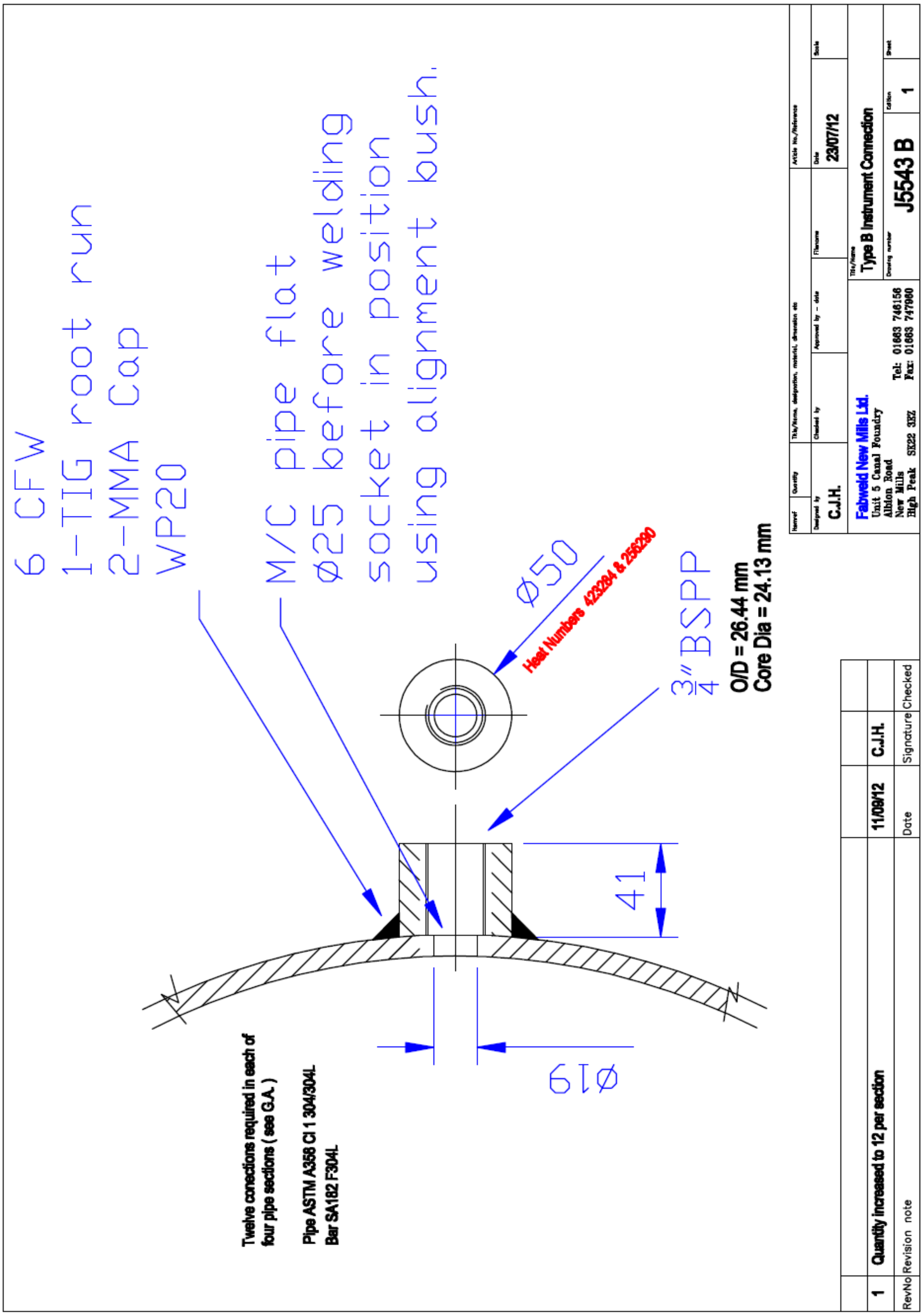


Figure 10 General instrument fitting

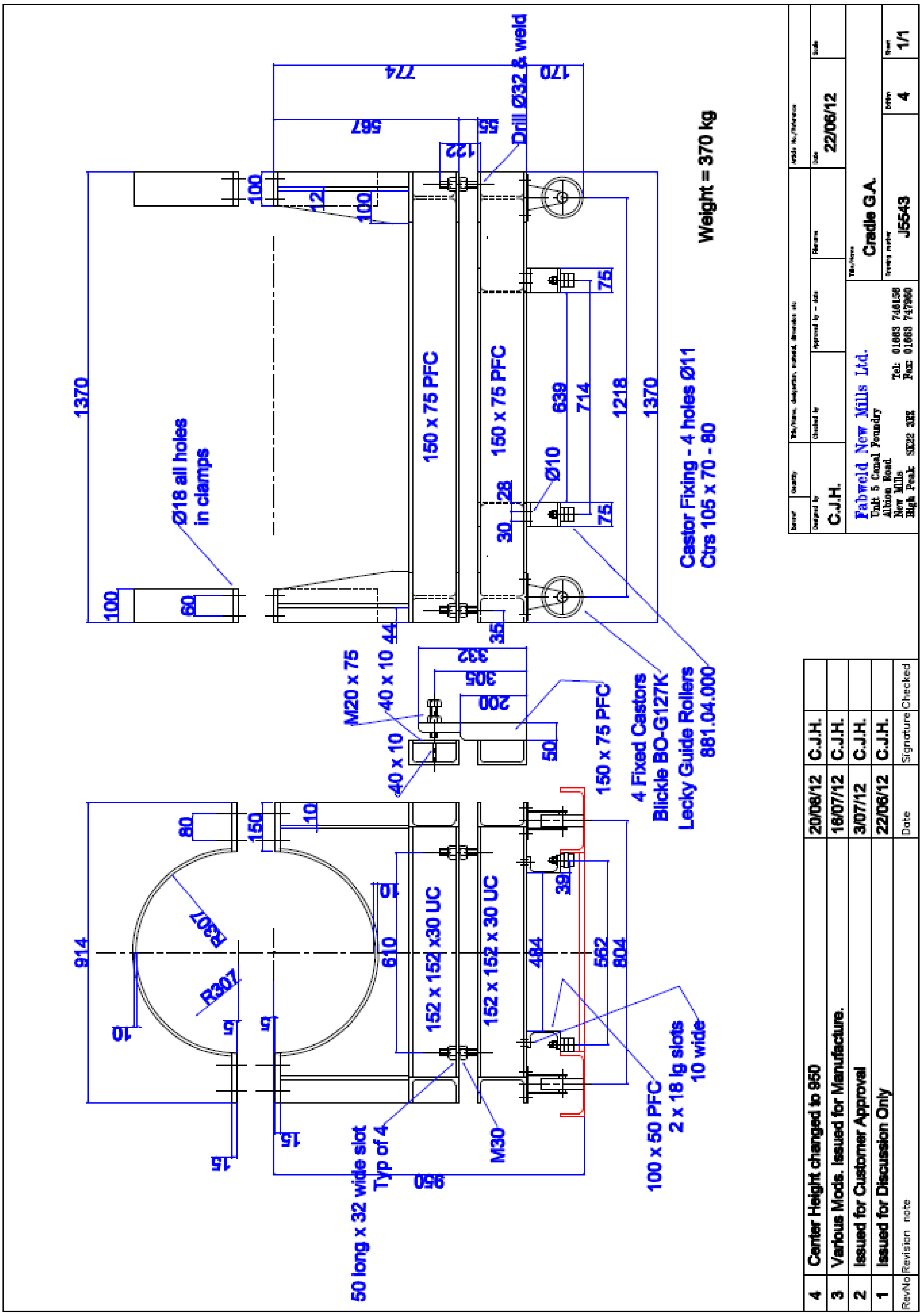
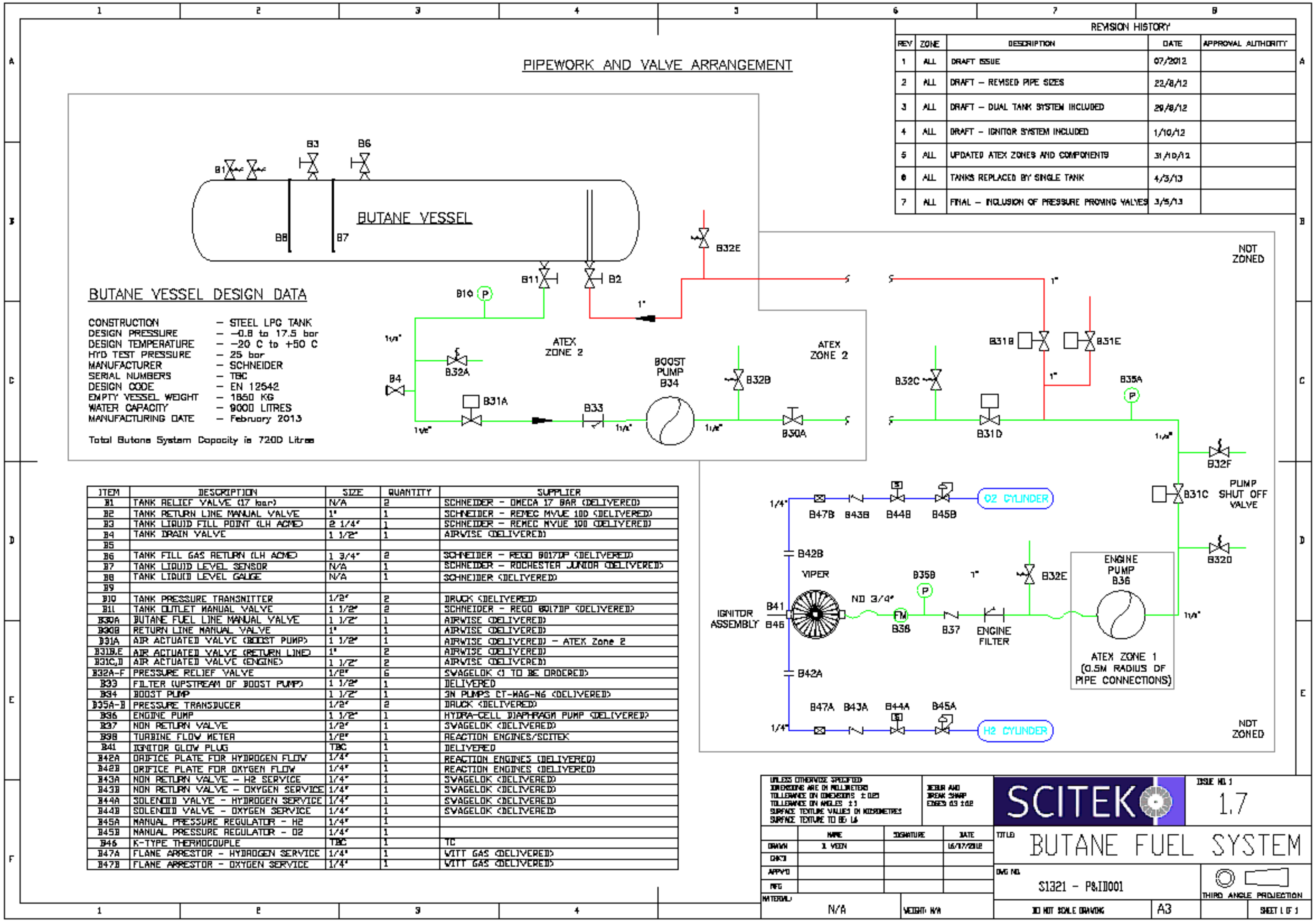


Figure 11 Cradle for supporting the tubes.

Figure 12 Viper engine SN301023 before undergoing conversion to butane.



REVISION HISTORY

REV	ZONE	DESCRIPTION	DATE	APPROVAL AUTHORITY
1	ALL	DRAFT ISSUE	07/2012	
2	ALL	DRAFT – REVISED PIPE SIZES	22/8/12	
3	ALL	DRAFT – DUAL TANK SYSTEM INCLUDED	29/8/12	
4	ALL	DRAFT – IGNITOR SYSTEM INCLUDED	1/10/12	
5	ALL	UPDATED ATEX ZONES AND COMPONENTS	31/10/12	
6	ALL	TANKS REPLACED BY SINGLE TANK	4/3/13	
7	ALL	FINAL – INCLUSION OF PRESSURE PROVING VALVES	3/5/13	

BUTANE VESSEL DESIGN DATA

CONSTRUCTION	– STEEL LPG TANK
DESIGN PRESSURE	– –0.8 to 17.5 bar
DESIGN TEMPERATURE	– –20 C to +50 C
HYD TEST PRESSURE	– 25 bar
MANUFACTURER	– SCHNEIDER
SERIAL NUMBERS	– TBC
DESIGN CODE	– EN 12542
EMPTY VESSEL WEIGHT	– 1850 KG
WATER CAPACITY	– 9000 LITRES
MANUFACTURING DATE	– February 2013

Total Butane System Capacity is 7200 Litres

ITEM	DESCRIPTION	SIZE	QUANTITY	SUPPLIER
B1	TANK RELIEF VALVE (17 bar)	N/A	2	SCHNEIDER – OMECA 17 BAR (DELIVERED)
B2	TANK RETURN LINE MANUAL VALVE	1"	1	SCHNEIDER – REMEC MVUE 100 (DELIVERED)
B3	TANK LIQUID FILL POINT (LH ACME)	2 1/4"	1	SCHNEIDER – REMEC MVUE 100 (DELIVERED)
B4	TANK DRAIN VALVE	1 1/2"	1	AIRWISE (DELIVERED)
B5				
B6	TANK FILL GAS RETURN (LH ACME)	1 3/4"	2	SCHNEIDER – REGO 8017DP (DELIVERED)
B7	TANK LIQUID LEVEL SENSOR	N/A	1	SCHNEIDER – ROCHESTER JUNIOR (DELIVERED)
B8	TANK LIQUID LEVEL GAUGE	N/A	1	SCHNEIDER (DELIVERED)
B9				
B10	TANK PRESSURE TRANSMITTER	1/2"	2	DRUCK (DELIVERED)
B11	TANK OUTLET MANUAL VALVE	1 1/2"	2	SCHNEIDER – REGO 8017DP (DELIVERED)
B30A	BUTANE FUEL LINE MANUAL VALVE	1 1/2"	1	AIRWISE (DELIVERED)
B30B	RETURN LINE MANUAL VALVE	1"	1	AIRWISE (DELIVERED)
B31A	AIR ACTUATED VALVE (BOOST PUMP)	1 1/2"	1	AIRWISE (DELIVERED) – ATEX Zone 2
B31B,E	AIR ACTUATED VALVE (RETURN LINE)	1"	2	AIRWISE (DELIVERED)
B31C,D	AIR ACTUATED VALVE (ENGINE)	1 1/2"	2	AIRWISE (DELIVERED)
B32A-F	PRESSURE RELIEF VALVE	1/2"	6	SWAGELOK (1 TO BE ORDERED)
B33	FILTER (UPSTREAM OF BOOST PUMP)	1 1/2"	1	DELIVERED
B34	BOOST PUMP	1 1/2"	1	3N PUMPS CT-MAG-N6 (DELIVERED)
B35A-B	PRESSURE TRANSDUCER	1/2"	2	DRUCK (DELIVERED)
B36	ENGINE PUMP	1 1/2"	1	HYDRA-CELL DIAPHRAGM PUMP (DELIVERED)
B37	NON RETURN VALVE	1/2"	1	SWAGELOK (DELIVERED)
B38	TURBINE FLOW METER	1/2"	1	REACTION ENGINES/SCITEK
B41	IGNITOR GLOW PLUG	TBC	1	DELIVERED
B42A	ORIFICE PLATE FOR HYDROGEN FLOW	1/4"	1	REACTION ENGINES (DELIVERED)
B42B	ORIFICE PLATE FOR OXYGEN FLOW	1/4"	1	REACTION ENGINES (DELIVERED)
B43A	NON RETURN VALVE – H2 SERVICE	1/4"	1	SWAGELOK (DELIVERED)
B43B	NON RETURN VALVE – OXYGEN SERVICE	1/4"	1	SWAGELOK (DELIVERED)
B44A	SOLENOID VALVE – HYDROGEN SERVICE	1/4"	1	SWAGELOK (DELIVERED)
B44B	SOLENOID VALVE – OXYGEN SERVICE	1/4"	1	SWAGELOK (DELIVERED)
B45A	MANUAL PRESSURE REGULATOR – H2	1/4"	1	
B45B	MANUAL PRESSURE REGULATOR – O2	1/4"	1	
B46	K-TYPE THERMOCOUPLE	TBC	1	TC
B47A	FLAME ARRESTOR – HYDROGEN SERVICE	1/4"	1	WITT GAS (DELIVERED)
B47B	FLAME ARRESTOR – OXYGEN SERVICE	1/4"	1	WITT GAS (DELIVERED)

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
TOLLERANCE ON DIMENSIONS ±0.25
TOLLERANCE ON ANGLES ±1
SURFACE TEXTURE VALUES IN MICROMETRES
SURFACE TEXTURE TO BE 1.6

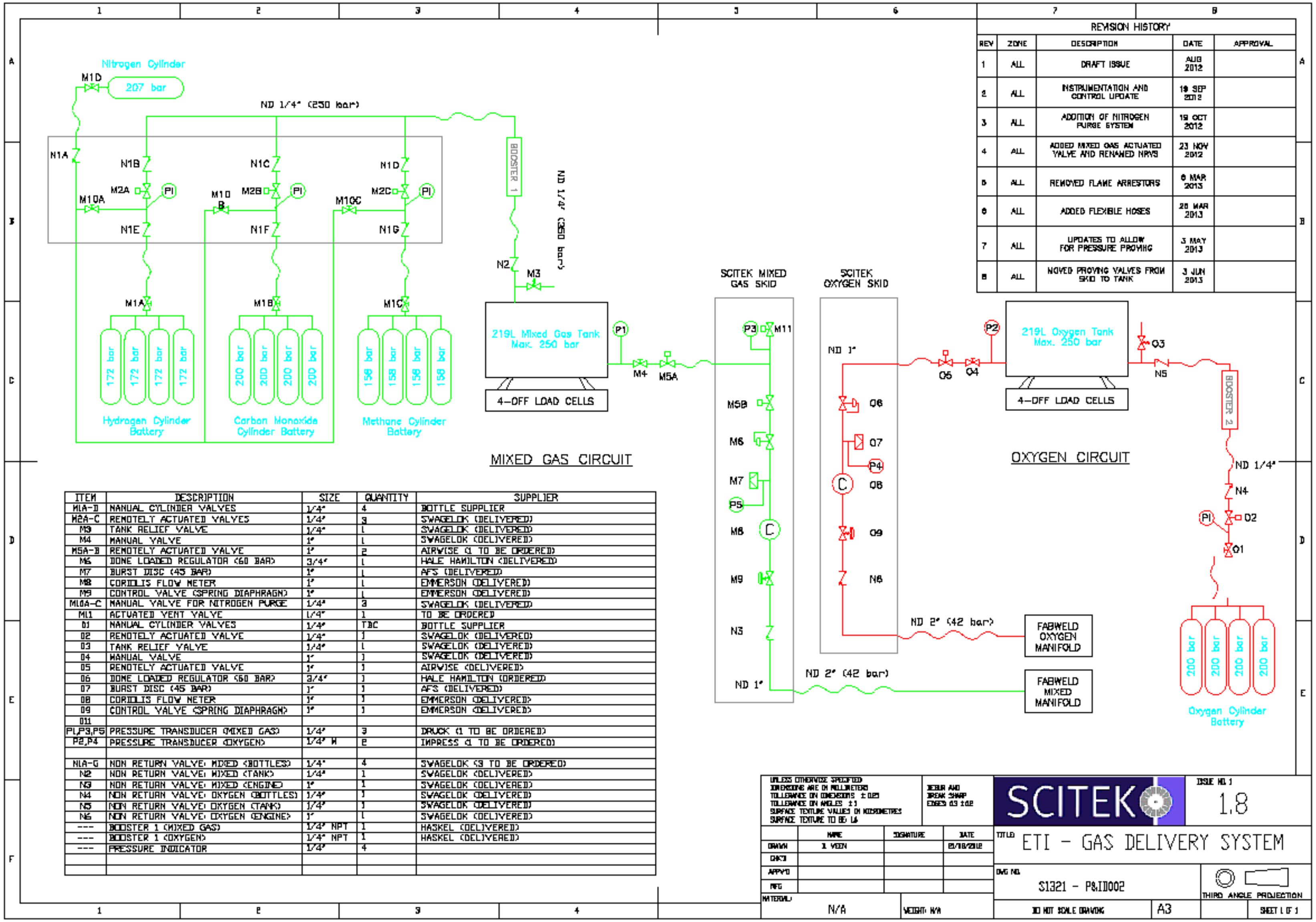
DEBUR AND BREAK SHARP EDGES 0.3 ±0.2

	NAME	SIGNATURE	DATE
DRAWN	I VEEN		16/07/2012
CHK'D			
APPV'D			
MFG			

MATERIAL: N/A
WEIGHT: N/A

ISSUE NO. 1.7
TITLE: BUTANE FUEL SYSTEM
DWG NO. S1321 – P&ID001
DO NOT SCALE DRAWING
A3
SHEET 1 OF 1

Figure 13 P&ID for butane fuel supply system



REVISION HISTORY

REV	ZONE	DESCRIPTION	DATE	APPROVAL
1	ALL	DRAFT ISSUE	AUG 2012	
2	ALL	INSTRUMENTATION AND CONTROL UPDATE	19 SEP 2012	
3	ALL	ADDITION OF NITROGEN PURGE SYSTEM	19 OCT 2012	
4	ALL	ADDED MIXED GAS ACTUATED VALVE AND RENAMED NRVS	23 NOV 2012	
5	ALL	REMOVED FLAME ARRESTORS	6 MAR 2013	
6	ALL	ADDED FLEXIBLE HOSES	26 MAR 2013	
7	ALL	UPDATES TO ALLOW FOR PRESSURE PROVING	3 MAY 2013	
8	ALL	MOVED PROVING VALVES FROM SKID TO TANK	3 JUN 2013	

ITEM	DESCRIPTION	SIZE	QUANTITY	SUPPLIER
M1A-D	MANUAL CYLINDER VALVES	1/4"	4	BOTTLE SUPPLIER
M2A-C	REMOTELY ACTUATED VALVES	1/4"	3	SWAGELOK (DELIVERED)
M3	TANK RELIEF VALVE	1/4"	1	SWAGELOK (DELIVERED)
M4	MANUAL VALVE	1"	1	SWAGELOK (DELIVERED)
M5A-B	REMOTELY ACTUATED VALVE	1"	2	AIRWISE (1 TO BE ORDERED)
M6	DOME LOADED REGULATOR (60 BAR)	3/4"	1	HALE HAMILTON (DELIVERED)
M7	BURST DISC (45 BAR)	1"	1	AFS (DELIVERED)
M8	CORIOLIS FLOW METER	1"	1	EMMERSON (DELIVERED)
M9	CONTROL VALVE (SPRING DIAPHRAGM)	1"	1	EMMERSON (DELIVERED)
M10A-C	MANUAL VALVE FOR NITROGEN PURGE	1/4"	3	SWAGELOK (DELIVERED)
M11	ACTUATED VENT VALVE	1/4"	1	TO BE ORDERED
O1	MANUAL CYLINDER VALVES	1/4"	TBC	BOTTLE SUPPLIER
O2	REMOTELY ACTUATED VALVE	1/4"	1	SWAGELOK (DELIVERED)
O3	TANK RELIEF VALVE	1/4"	1	SWAGELOK (DELIVERED)
O4	MANUAL VALVE	1"	1	SWAGELOK (DELIVERED)
O5	REMOTELY ACTUATED VALVE	1"	1	AIRWISE (DELIVERED)
O6	DOME LOADED REGULATOR (60 BAR)	3/4"	1	HALE HAMILTON (ORDERED)
O7	BURST DISC (45 BAR)	1"	1	AFS (DELIVERED)
O8	CORIOLIS FLOW METER	1"	1	EMMERSON (DELIVERED)
O9	CONTROL VALVE (SPRING DIAPHRAGM)	1"	1	EMMERSON (DELIVERED)
O11				
P1,P3,P5	PRESSURE TRANSDUCER (MIXED GAS)	1/4"	3	DRUCK (1 TO BE ORDERED)
P2,P4	PRESSURE TRANSDUCER (OXYGEN)	1/4" M	2	IMPRESS (1 TO BE ORDERED)
N1A-G	NON RETURN VALVE: MIXED (BOTTLES)	1/4"	4	SWAGELOK (3 TO BE ORDERED)
N2	NON RETURN VALVE: MIXED (TANK)	1/4"	1	SWAGELOK (DELIVERED)
N3	NON RETURN VALVE: MIXED (ENGINE)	1"	1	SWAGELOK (DELIVERED)
N4	NON RETURN VALVE: OXYGEN (BOTTLES)	1/4"	1	SWAGELOK (DELIVERED)
N5	NON RETURN VALVE: OXYGEN (TANK)	1/4"	1	SWAGELOK (DELIVERED)
N6	NON RETURN VALVE: OXYGEN (ENGINE)	1"	1	SWAGELOK (DELIVERED)
---	BOOSTER 1 (MIXED GAS)	1/4" NPT	1	HASKEL (DELIVERED)
---	BOOSTER 1 (OXYGEN)	1/4" NPT	1	HASKEL (DELIVERED)
---	PRESSURE INDICATOR	1/4"	4	

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
TOLLERANCE ON DIMENSIONS ± 0.25
TOLLERANCE ON ANGLES ±1
SURFACE TEXTURE VALUES IN MICROMETRES
SURFACE TEXTURE TO BE 1.6

DEBUR AND
BREAK SHARP
EDGES 0.3 ±0.2

SCITEK

ISSUE NO. 1
1.8

	NAME	SIGNATURE	DATE
DRAWN	I VEEN		21/10/2012
CHK'D			
APPV'D			
MFG			

MATERIAL: N/A
WEIGHT: N/A

TITLE: ETI - GAS DELIVERY SYSTEM
DWG NO. S1321 - P&ID002
THIRD ANGLE PROJECTION
DO NOT SCALE DRAWING
A3
SHEET 1 OF 1

Figure 14 P&ID of Gas Delivery System

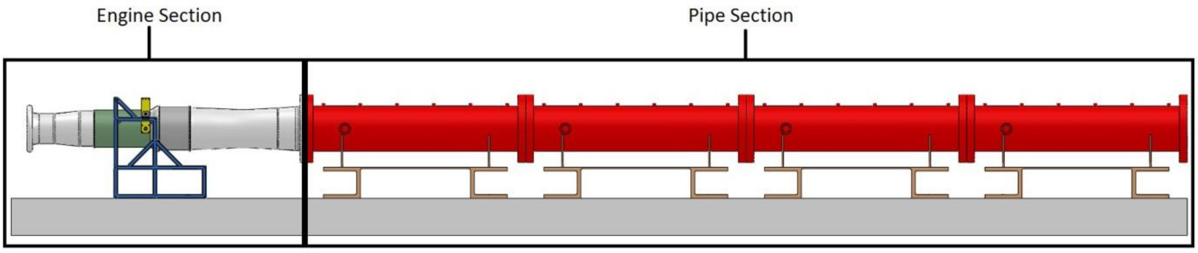


Figure 15 Representative diagram of the proposed circular duct test rig

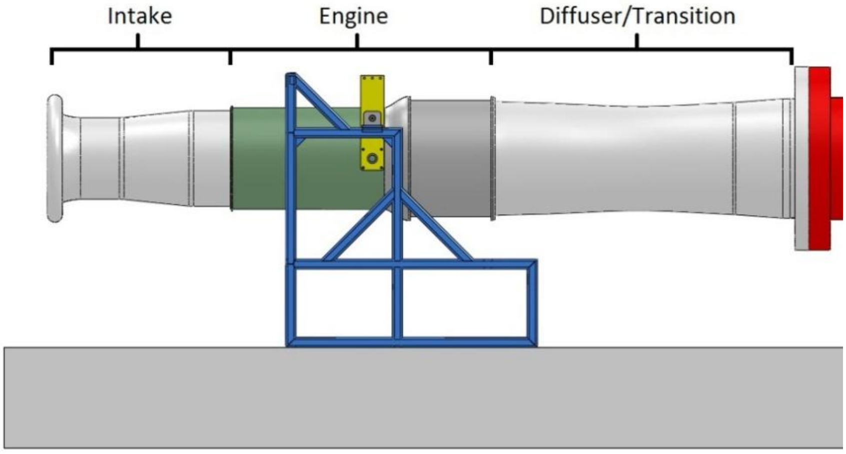


Figure 16 Representative diagram of the proposed engine section of the circular duct test rig

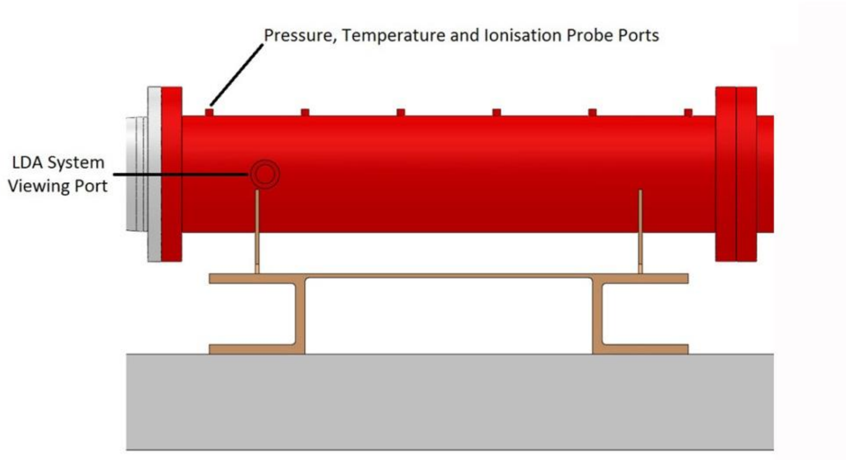


Figure 17 Representative diagram of a segment of the proposed pipe section of the circular duct test rig

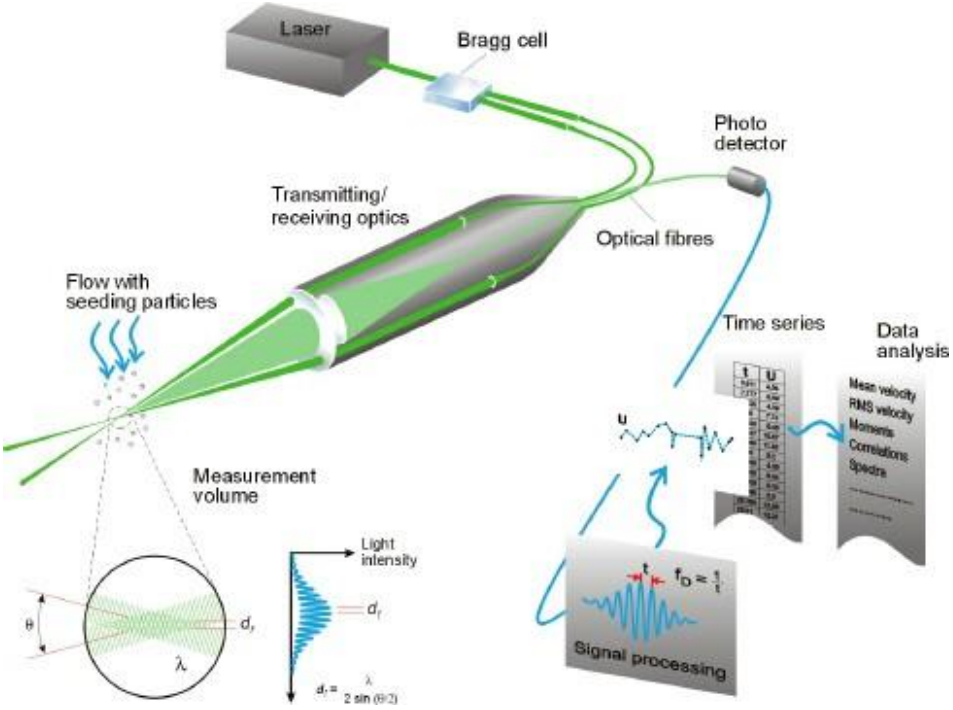


Figure 18 Schematic diagram of a Laser Doppler Anemometry System

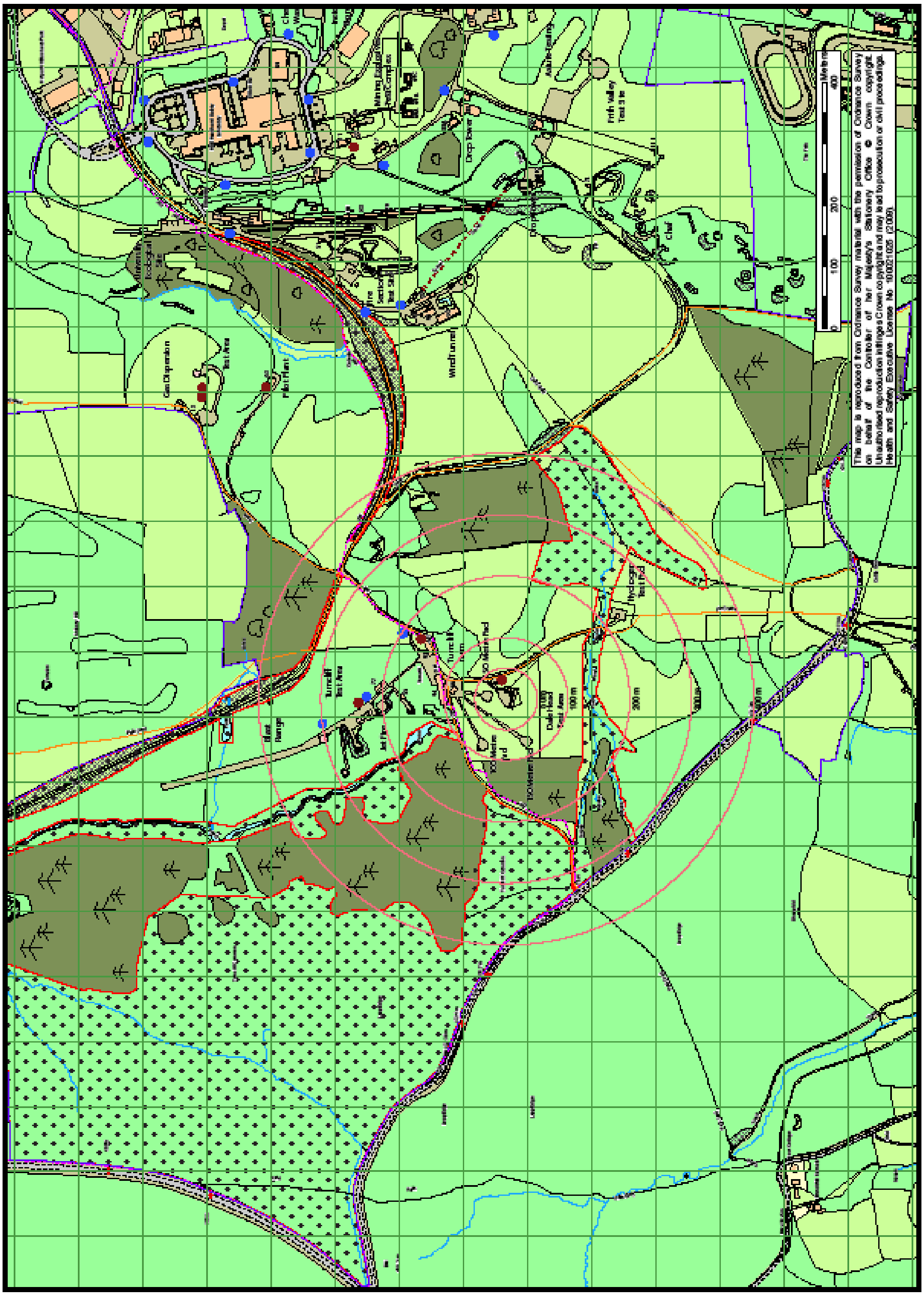


Figure 19 Location of proposed test site at HSL, Buxton relative to main buildings and with exclusion zones marked

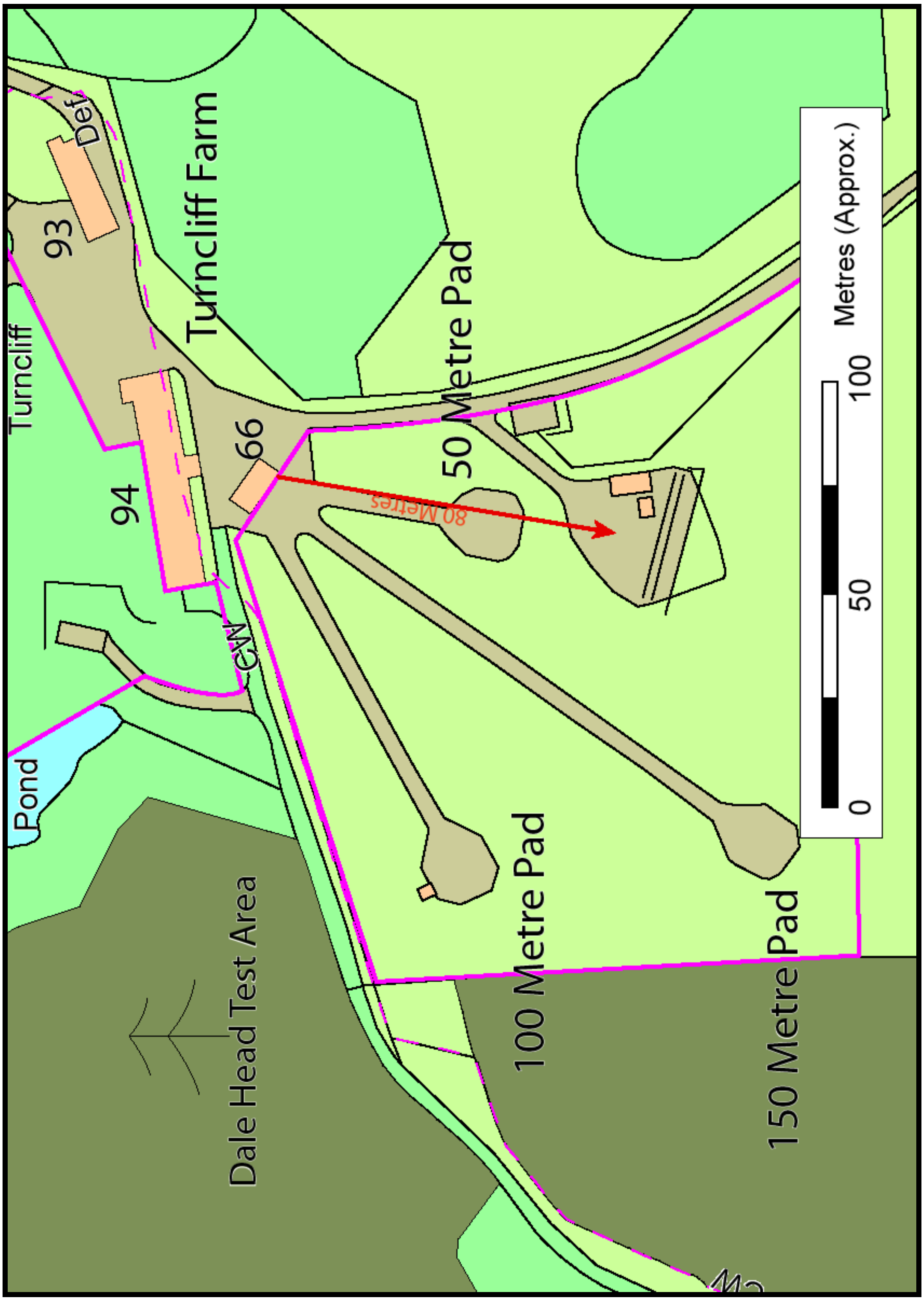


Figure 20 Proposed test site

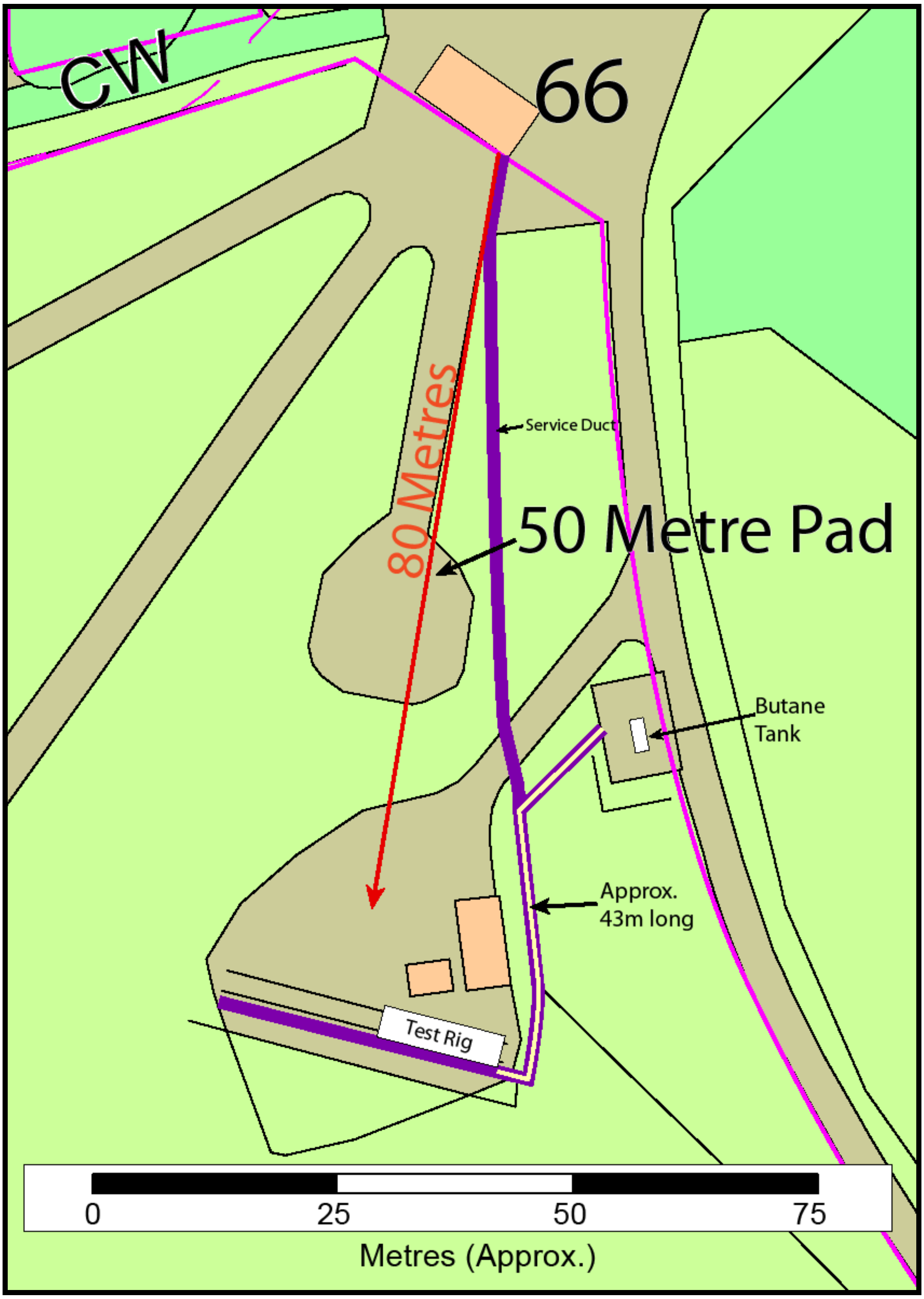


Figure 21 Plan of proposed test rig site showing location of butane tank and service trenches

6 Instrument Datasheets

Druck

PTX/PMP 1400

Industrial Pressure Sensors

- Pressure ranges to 600 bar
- Gauge and absolute formats
- 0 to 5V or 4-20mA outputs
- 0.15% typical accuracy
- Low cost, Ex-stock delivery
- Intrinsically Safe, CE marked, PED compliant

The PTX/PMP 1400 Series of Industrial Pressure sensors have been designed for use with aggressive pressure media found in many industrial and process applications.

The stainless steel isolation diaphragm and fully welded stainless steel pressure module ensures excellent media compatibility without compromising the performance from Druck's own micro-machined silicon pressure diaphragm.

Integral electronics provide a 2 wire 4 to 20 mA (PTX 1400) or 3 wire 0 to 5V (PMP 1400) output proportional to applied pressure. Integral non-interactive zero and span controls ensure system interchangeability and ease of calibration.

The PTX/PMP 1400 incorporates developments from aerospace applications and volume manufacturing to achieve high performance with competitive pricing. Ex-stock delivery is provided by holding a stock of compensated and calibrated sensors in DIN pressure ranges.

These sensors feature compact, rugged design with field proven electronics to ensure long term reliable measurement and low cost of ownership.

PTX/PMP 1400

Industrial Pressure Sensors

Druck

STANDARD SPECIFICATIONS

Operating Pressure Ranges
0 to 100, 250, 400, 600mbar,1, 1.6, 2.5, 4, 6, 10, 16, 25, 40, 60 bar gauge and absolute.
0 to 100, 160, 250, 400, 600 bar sealed gauge and absolute.
Barometric (PTX 1400 only) 800 to 1200mbar abs.

-1 to 1.6 bar gauge (compound)
-1 to 2.5 bar gauge (compound)
-1 to 4 bar gauge (compound)

Overpressure
The rated pressure range can be exceeded by the following without degrading performance:
1 bar for 100 and 250mbar ranges
2 bar for 400 and 600mbar ranges
2 x (180 bar max) for ranges 1 bar to 100 bar
2 x (900 bar max) for ranges 160 to 600 bar.

Pressure Media
Fluids compatible with a fully welded assembly of 316 stainless steel and Hastelloy C276.

Supply Voltage
PMP 1400: 9 to 30V d.c.
PTX 1400: 9 to 28V d.c. Min supply voltage that must appear across transmitter terminals is 9V and is given by Vmin= Vs - (0.02 x RL) where Vs = supply volts, RL = total loop ohms

Output Voltage
PMP 1400: 0 to 5V (3 wire pedestal configuration) (calibrated between 5-100% FS)
PTX 1400: 4-20mA (2 wire configuration)

Load Impedance (PMP version)
Greater than 100k ohms for quoted performance.

Zero Offset and Span Setting
Factory set to 0.5%, then 5% site adjustable by sealed, non-interacting potentiometers.

Long Term Stability
0.2% FS range per annum typical.

Accuracy
Combined Non-linearity, Hysteresis and Repeatability: 0.15% typical, 0.25% maximum Best Straight Line Definition.

Operating Temperature Range
-20° to 80°C.

Temperature Effects
Total Error Band 1.5% typical, 2% maximum, -20° to 80°C. For ranges below 400mbar values increase pro-rata with calibrated span.

Weight
200 grams nominal

Pressure Connection
G$^{1}/_{4}$ female.

Electrical Connection
DIN 43650 plug supplied with mating socket.

Ingress Protection
Sealed to IP65

Voltage Spike Protection
Units will withstand 600V spike test to ENV 50142 without damage, applied between excitation lines and case.

Safety

EMC emissions	EN50081-1
EMC Immunity	EN50082-1
Certification	CE marked.

PED compliant CE Category 1 Pressure Accessory to Pressure Equipment Directive (PED) 97/23/EC. Note: 'Operating Pressure Range' is equivalent to maximum working pressure (Ps) as referred to in the PED.

PTX 1400 supplied Intrinsically Safe certified as standard, for use with barrier systems to Ex 97D 2058 EEx ia IIC T4 amb 80°C.

OPTIONS

(B) Screw-in male/male adaptors with bonded seal
  G1/4 male (P/N 190-040)
  1/4 NPT male (P/N 190-038)
  7/16 UNF male to MS 33656 (P/N 190-042)
  M14 x 1.5 male (P/N 190-036)
  G1/2 (pressure gauge) (P/N 190-039)
  All adaptors 316 stainless steel construction.
(C) Vented 6 core cable (5.7mm) (P/N 192-004)
  Specify required length on order.
(D) Pressure snubber adaptor (DA0639-1-02)
  Screw in adaptor providing a G1/4 female thread. Protects against unwanted fast transient pressure spikes. Refer to Snubber Product Note for further detail.

ORDERING INFORMATION

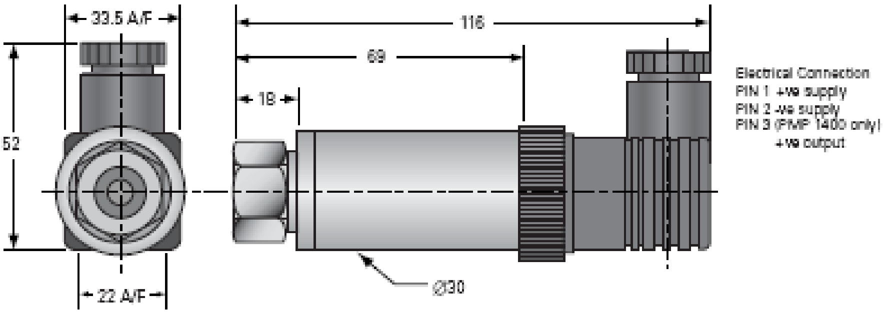
Please state the following:
(1) Type number PTX 1400 or PMP 1400
(2) Operating pressure range
(3) Gauge or absolute
(4) Options - As above. Order as separate line items (supplied unfitted).

RELATED PRODUCTS

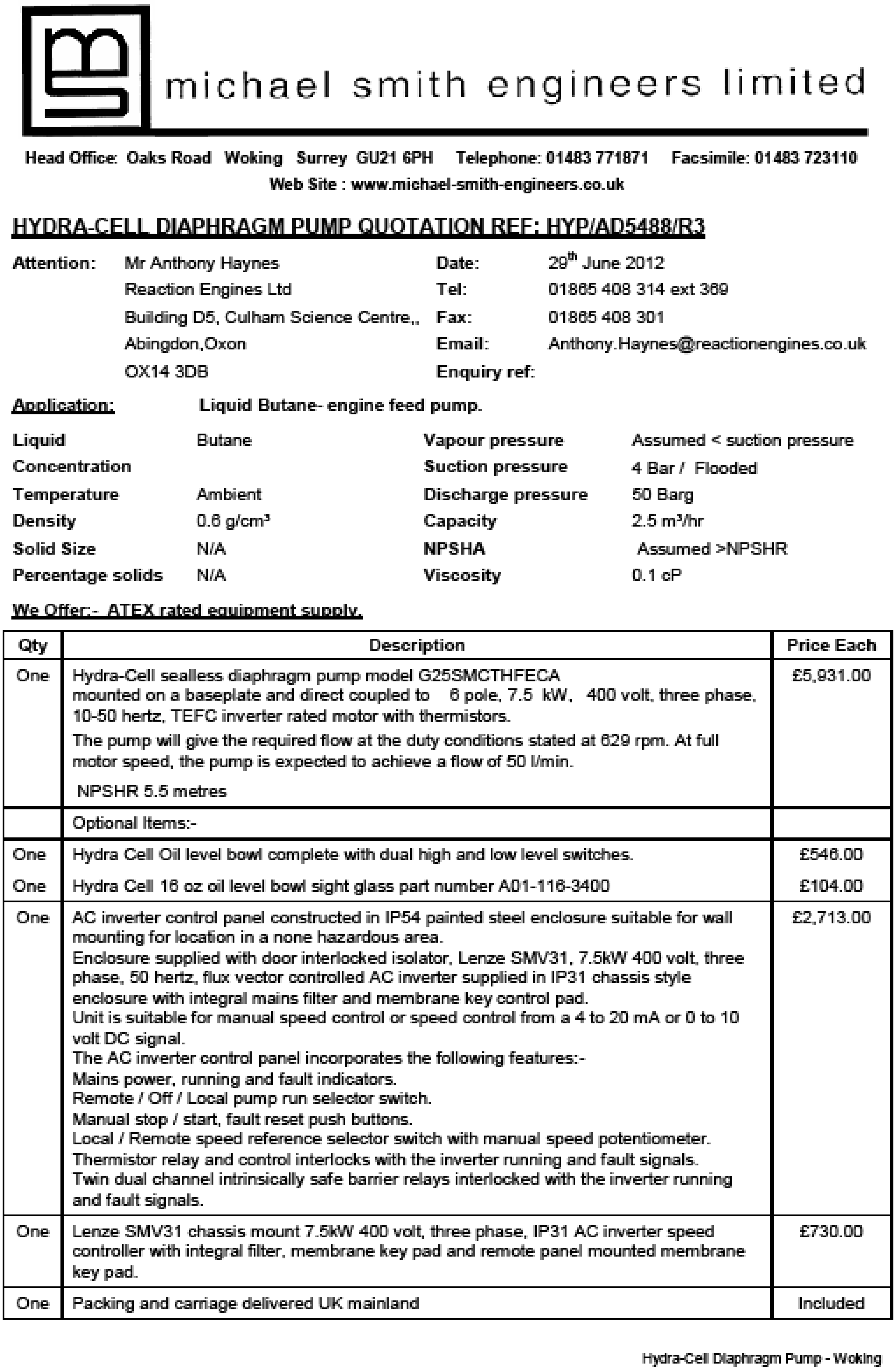
Druck manufactures a comprehensive range of pressure sensors, indicators, controllers and calibrators. Product datasheets available.

Continuing development sometimes necessitates specification changes without notice.

INSTALLATION DRAWINGS - Dimensions in mm



Agent:



michael smith engineers limited

Head Office: Oaks Road Woking Surrey GU21 6PH Telephone: 01483 771871 Facsimile: 01483 723110
Web Site : www.michael-smith-engineers.co.uk

HYDRA-CELL DIAPHRAGM PUMP QUOTATION REF: HYP/AD5488/R3

Attention:	Mr Anthony Haynes	**Date:**	29th June 2012
	Reaction Engines Ltd	**Tel:**	01865 408 314 ext 369
	Building D5, Culham Science Centre,,	**Fax:**	01865 408 301
	Abingdon,Oxon	**Email:**	Anthony.Haynes@reactionengines.co.uk
	OX14 3DB	**Enquiry ref:**	

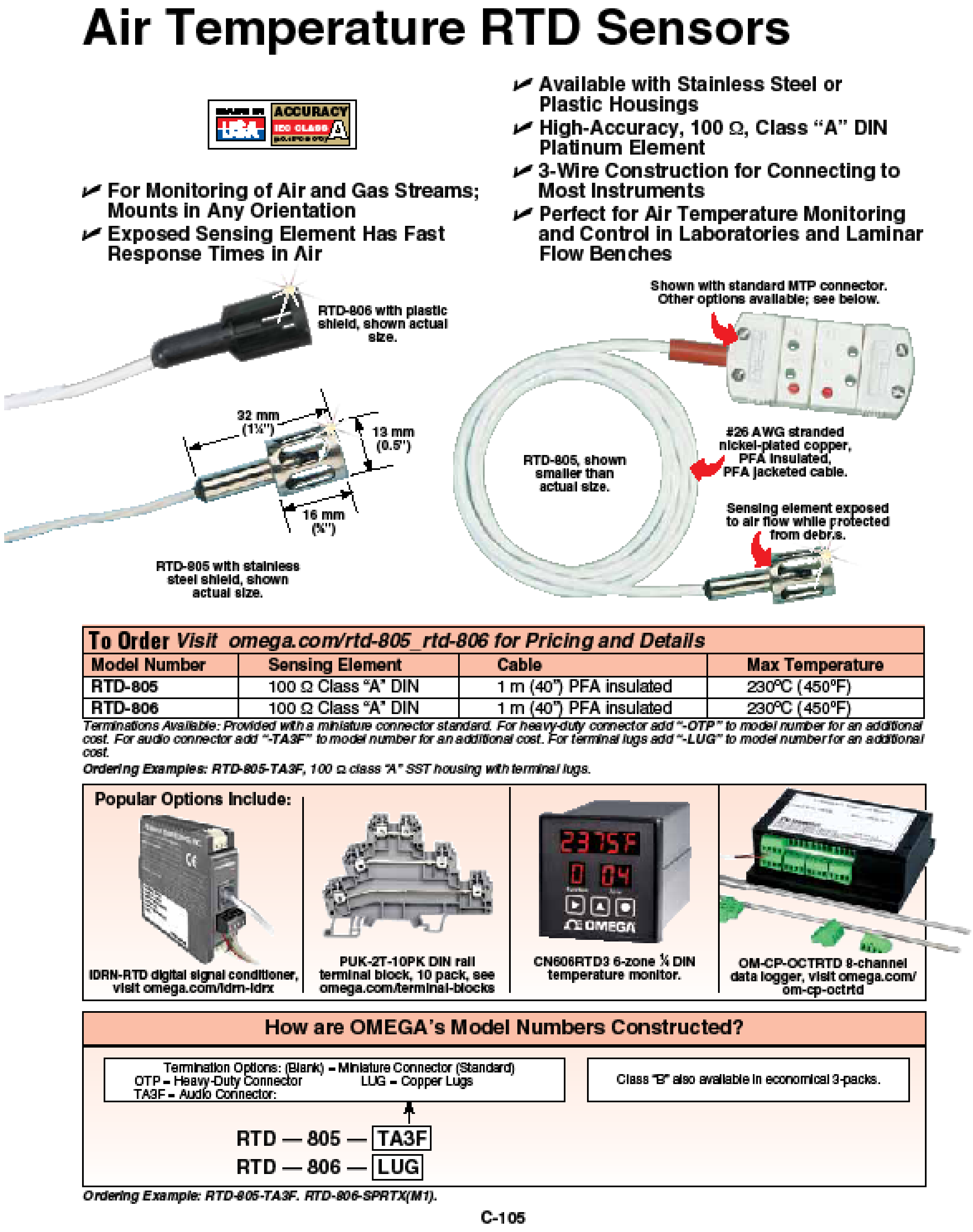
Application: **Liquid Butane- engine feed pump.**

Liquid	Butane	**Vapour pressure**	Assumed < suction pressure
Concentration		**Suction pressure**	4 Bar / Flooded
Temperature	Ambient	**Discharge pressure**	50 Barg
Density	0.6 g/cm³	**Capacity**	2.5 m³/hr
Solid Size	N/A	**NPSHA**	Assumed >NPSHR
Percentage solids	N/A	**Viscosity**	0.1 cP

We Offer:- ATEX rated equipment supply.

Qty	**Description**	**Price Each**
One	Hydra-Cell sealless diaphragm pump model G25SMCTHFECA mounted on a baseplate and direct coupled to 6 pole, 7.5 kW, 400 volt, three phase, 10-50 hertz, TEFC inverter rated motor with thermistors. The pump will give the required flow at the duty conditions stated at 629 rpm. At full motor speed, the pump is expected to achieve a flow of 50 l/min. NPSHR 5.5 metres	£5,931.00
	Optional Items:-	
One	Hydra Cell Oil level bowl complete with dual high and low level switches.	£546.00
One	Hydra Cell 16 oz oil level bowl sight glass part number A01-116-3400	£104.00
One	AC inverter control panel constructed in IP54 painted steel enclosure suitable for wall mounting for location in a none hazardous area. Enclosure supplied with door interlocked isolator, Lenze SMV31, 7.5kW 400 volt, three phase, 50 hertz, flux vector controlled AC inverter supplied in IP31 chassis style enclosure with integral mains filter and membrane key control pad. Unit is suitable for manual speed control or speed control from a 4 to 20 mA or 0 to 10 volt DC signal. The AC inverter control panel incorporates the following features:- Mains power, running and fault indicators. Remote / Off / Local pump run selector switch. Manual stop / start, fault reset push buttons. Local / Remote speed reference selector switch with manual speed potentiometer. Thermistor relay and control interlocks with the inverter running and fault signals. Twin dual channel intrinsically safe barrier relays interlocked with the inverter running and fault signals.	£2,713.00
One	Lenze SMV31 chassis mount 7.5kW 400 volt, three phase, IP31 AC inverter speed controller with integral filter, membrane key pad and remote panel mounted membrane key pad.	£730.00
One	Packing and carriage delivered UK mainland	Included

Hydra-Cell Diaphragm Pump - Woking



Air Temperature RTD Sensors

- For Monitoring of Air and Gas Streams; Mounts in Any Orientation
- Exposed Sensing Element Has Fast Response Times in Air
- Available with Stainless Steel or Plastic Housings
- High-Accuracy, 100 Ω, Class "A" DIN Platinum Element
- 3-Wire Construction for Connecting to Most Instruments
- Perfect for Air Temperature Monitoring and Control in Laboratories and Laminar Flow Benches

RTD-806 with plastic shield, shown actual size.

RTD-805 with stainless steel shield, shown actual size.

Shown with standard MTP connector. Other options available; see below.

RTD-805, shown smaller than actual size.

#26 AWG stranded nickel-plated copper, PFA insulated, PFA jacketed cable.

Sensing element exposed to air flow while protected from debris.

To Order *Visit omega.com/rtd-805_rtd-806 for Pricing and Details*

Model Number	Sensing Element	Cable	Max Temperature
RTD-805	100 Ω Class "A" DIN	1 m (40") PFA insulated	230°C (450°F)
RTD-806	100 Ω Class "A" DIN	1 m (40") PFA insulated	230°C (450°F)

Terminations Available: Provided with a miniature connector standard. For heavy-duty connector add "-OTP" to model number for an additional cost. For audio connector add "-TA3F" to model number for an additional cost. For terminal lugs add "-LUG" to model number for an additional cost.

Ordering Examples: RTD-805-TA3F, 100 Ω class "A" SST housing with terminal lugs.

Popular Options Include:

IDRN-RTD digital signal conditioner, visit omega.com/idrn-idrx

PUK-2T-10PK DIN rail terminal block, 10 pack, see omega.com/terminal-blocks

CN606RTD3 6-zone ¼ DIN temperature monitor.

OM-CP-OCTRTD 8-channel data logger, visit omega.com/om-cp-octrtd

How are OMEGA's Model Numbers Constructed?

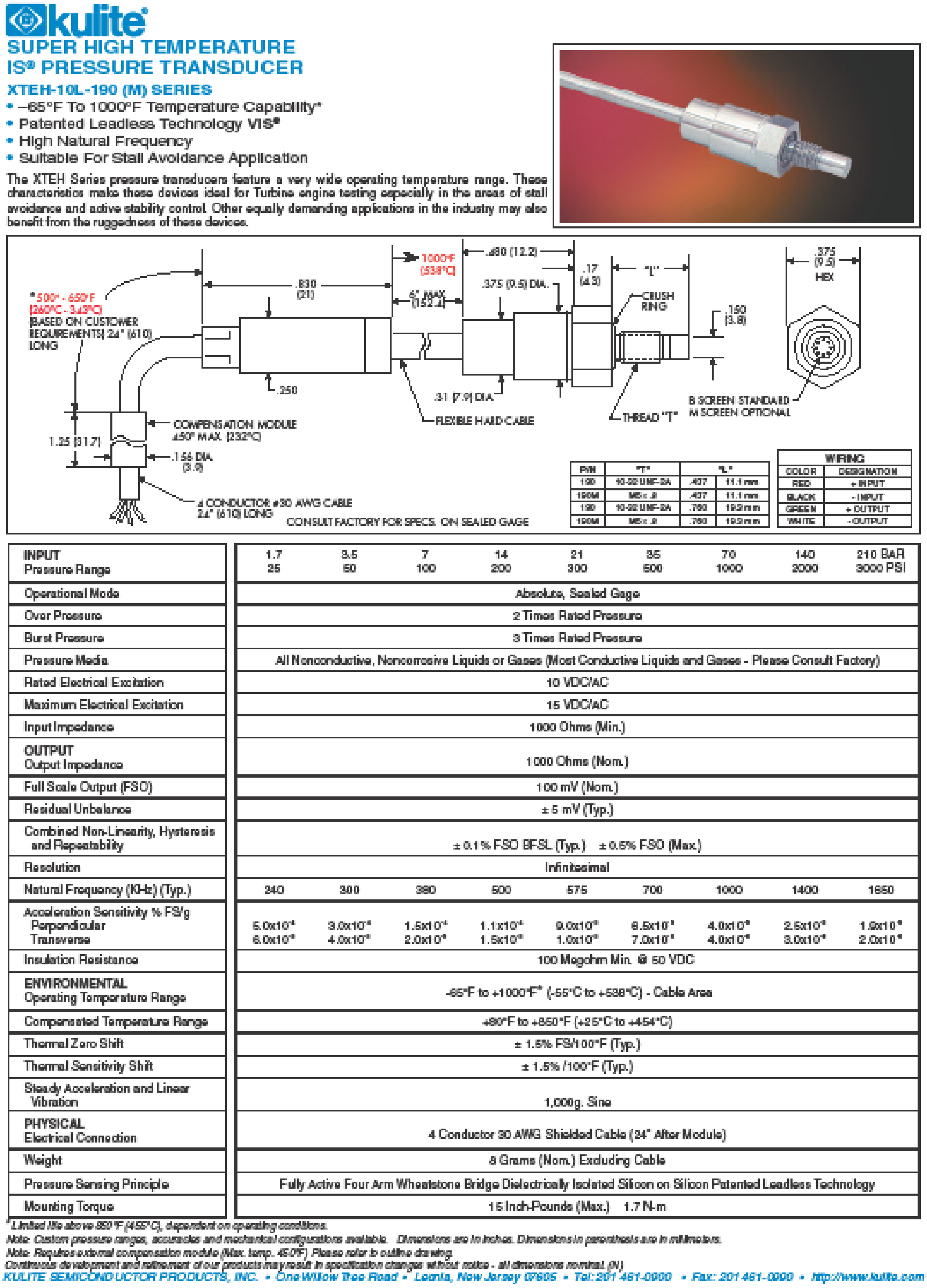
Termination Options: (Blank) = Miniature Connector (Standard)
OTP = Heavy-Duty Connector LUG = Copper Lugs
TA3F = Audio Connector:

Class "B" also available in economical 3-packs.

RTD — 805 — TA3F
RTD — 806 — LUG

Ordering Example: RTD-805-TA3F. RTD-806-SPRTX(M1).

C-105



kulite®

SUPER HIGH TEMPERATURE IS® PRESSURE TRANSDUCER

XTEH-10L-190 (M) SERIES

- –65°F To 1000°F Temperature Capability*
- Patented Leadless Technology VIS®
- High Natural Frequency
- Suitable For Stall Avoidance Application

The XTEH Series pressure transducers feature a very wide operating temperature range. These characteristics make these devices ideal for Turbine engine testing especially in the areas of stall avoidance and active stability control. Other equally demanding applications in the industry may also benefit from the ruggedness of these devices.

P/N	"T"	"L"	
190	10-32 UNF-2A	.437	11.1 mm
190M	M5 x .8	.437	11.1 mm
190	10-32 UNF-2A	.760	19.3 mm
190M	M5 x .8	.760	19.3 mm

WIRING	
COLOR	DESIGNATION
RED	+ INPUT
BLACK	- INPUT
GREEN	+ OUTPUT
WHITE	- OUTPUT

INPUT Pressure Range	1.7 25	3.5 50	7 100	14 200	21 300	35 500	70 1000	140 2000	210 BAR 3000 PSI
Operational Mode	Absolute, Sealed Gage								
Over Pressure	2 Times Rated Pressure								
Burst Pressure	3 Times Rated Pressure								
Pressure Media	All Nonconductive, Noncorrosive Liquids or Gases (Most Conductive Liquids and Gases - Please Consult Factory)								
Rated Electrical Excitation	10 VDC/AC								
Maximum Electrical Excitation	15 VDC/AC								
Input Impedance	1000 Ohms (Min.)								
OUTPUT Output Impedance	1000 Ohms (Nom.)								
Full Scale Output (FSO)	100 mV (Nom.)								
Residual Unbalance	± 5 mV (Typ.)								
Combined Non-Linearity, Hysteresis and Repeatability	± 0.1% FSO BFSL (Typ.) ± 0.5% FSO (Max.)								
Resolution	Infinitesimal								
Natural Frequency (KHz) (Typ.)	240	300	380	500	575	700	1000	1400	1650
Acceleration Sensitivity % FS/g Perpendicular Transverse	$5.0x10^{-4}$ $6.0x10^{-5}$	$3.0x10^{-4}$ $4.0x10^{-5}$	$1.5x10^{-4}$ $2.0x10^{-5}$	$1.1x10^{-4}$ $1.5x10^{-5}$	$9.0x10^{-5}$ $1.0x10^{-5}$	$6.5x10^{-5}$ $7.0x10^{-6}$	$4.0x10^{-5}$ $4.0x10^{-6}$	$2.5x10^{-5}$ $3.0x10^{-6}$	$1.9x10^{-5}$ $2.0x10^{-6}$
Insulation Resistance	100 Megohm Min. @ 50 VDC								
ENVIRONMENTAL Operating Temperature Range	-65°F to +1000°F* (-55°C to +538°C) - Cable Area								
Compensated Temperature Range	+80°F to +850°F (+25°C to +454°C)								
Thermal Zero Shift	± 1.5% FS/100°F (Typ.)								
Thermal Sensitivity Shift	± 1.5% /100°F (Typ.)								
Steady Acceleration and Linear Vibration	1,000g. Sine								
PHYSICAL Electrical Connection	4 Conductor 30 AWG Shielded Cable (24" After Module)								
Weight	8 Grams (Nom.) Excluding Cable								
Pressure Sensing Principle	Fully Active Four Arm Wheatstone Bridge Dielectrically Isolated Silicon on Silicon Patented Leadless Technology								
Mounting Torque	15 Inch-Pounds (Max.) 1.7 N-m								

*Limited life above 850°F (455°C), dependent on operating conditions.

Note: Custom pressure ranges, accuracies and mechanical configurations available. Dimensions are in inches. Dimensions in parenthesis are in millimeters.

Note: Requires external compensation module (Max. temp. 450°F) Please refer to outline drawing.

Continuous development and refinement of our products may result in specification changes without notice - all dimensions nominal. (N)

KULITE SEMICONDUCTOR PRODUCTS, INC. • One Willow Tree Road • Leonia, New Jersey 07605 • Tel: 201 461-0900 • Fax: 201 461-0990 • http://www.kulite.com

7 Appendices

Appendix 1	Tube structural strength calculations (separate document)
Appendix 2	BAE systems report re: maximum pressures (separate document)
Appendix 3	G Munday report (separate document)
Appendix 4	Design calculations for interface section (separate document)
Appendix 5	Design calculations for anchor points (separate document)
Appendix 6	Calculation of duct wall and duct gas temperatures during heat-up
Appendix 7	Gas turbine mass flow calculation
Appendix 8	Design calculations for engine blast enclosure (separate document)

Appendix 6 Calculation of duct wall and duct gas temperatures during heat-up

The calculation of the duct system transient due to the passage of the gas turbine exhaust is estimated in order to determine the timescale for duct heating to a target level, the influence of duct heating and heat loss on the downstream gas temperature and whether or not duct external insulation should be applied.

Method

* The duct is divided into short lengths (0.1m) over the full 12m length.

* Heat transfer coefficients are estimated for the heat transfer to the steel surface from the bulk flow and heat loss from the steel surface due to radiation and natural convection at the outer surface. The heat transfer coefficient through the steel wall is ignored since this is large compared to the coefficient for external cooling.

* The time domain is divided into 60 sec increments

* At each time step, and for each specific section length, the heat transferred from the gas to the surface is calculated based on the adjacent gas volume for each section and the associated wall surface temperature at the same location. At each corresponding location, the heat loss from the outer surface is also calculated.

* The net heat accumulated in the surface steel section is used to update the surface temperature at each section location and the heat transferred from the gas is used to calculate the gas temperature at the adjacent downstream section.

* The process is repeated for the next time step using the updated values for surface and gas temperatures along the duct.

* The calculation is started with the wall at 298 K along the full length. The gas entry temperature is taken as 823 K.

Heat transfer coefficients

For the heat transferred from the gas (T_{gas}) to the wall (T_s) for each section area (A)

$$Q_1 = h_1 \times (T_{gas} - T_s) \times A$$

Where $h_1 = Nu_1 \frac{k_h}{D}$ and $Nu = 0.023\, Re^{0.8}\, Pr^{0.3}$

k_h = duct gas thermal conductivity under hot conditions

Nu_1 = Nusselt number

Re = Reynolds number

Pr = Prandtl number (taken as 0.7)

D = duct diameter (taken as 0.6 m)

The gas velocity is calculated from the specified mass flow rate of 15 kg/s and the inlet gas temperature. This is estimated as 133 m/s. The Reynolds number is estimated as 9.5×10^5.

With the above values, Nu = 1210 and $h_1 = 101\ W/m^2\ K$.

For heat loss from the external wall, the two contributions are radiation and natural convection.

For radiation loss :

$$Q_2 = \varepsilon\sigma\ T_s^4 - T_a^4\ \times A$$

Where: ε = emissivity (taken as 0.25)

σ = Stefan-Boltzmann constant

Ts = duct wall temperature

Ta = environment temperature (taken as 298 K)

For natural convection loss

$$Q_3 = h_3 \times\ T_s - T_a\ \times \mathrm{A}$$

where $h_3 = Nu_3 \frac{k_c}{D}$ and $Nu_3 = \ 0.6 + \frac{0.387Ra^{\frac{1}{6}}}{{1+\ {\frac{0.559}{Pr}}^{\frac{9}{16}}}^{\frac{8}{27}}}$

Where Ra = Rayleigh number $Ra = \frac{g\beta\ T_s - T_a\ D^3}{\alpha v}$

and k_c = duct gas thermal conductivity under ambient conditions

g = $9.81\ m/s^2$

β = $0.0025\ K^{-1}$

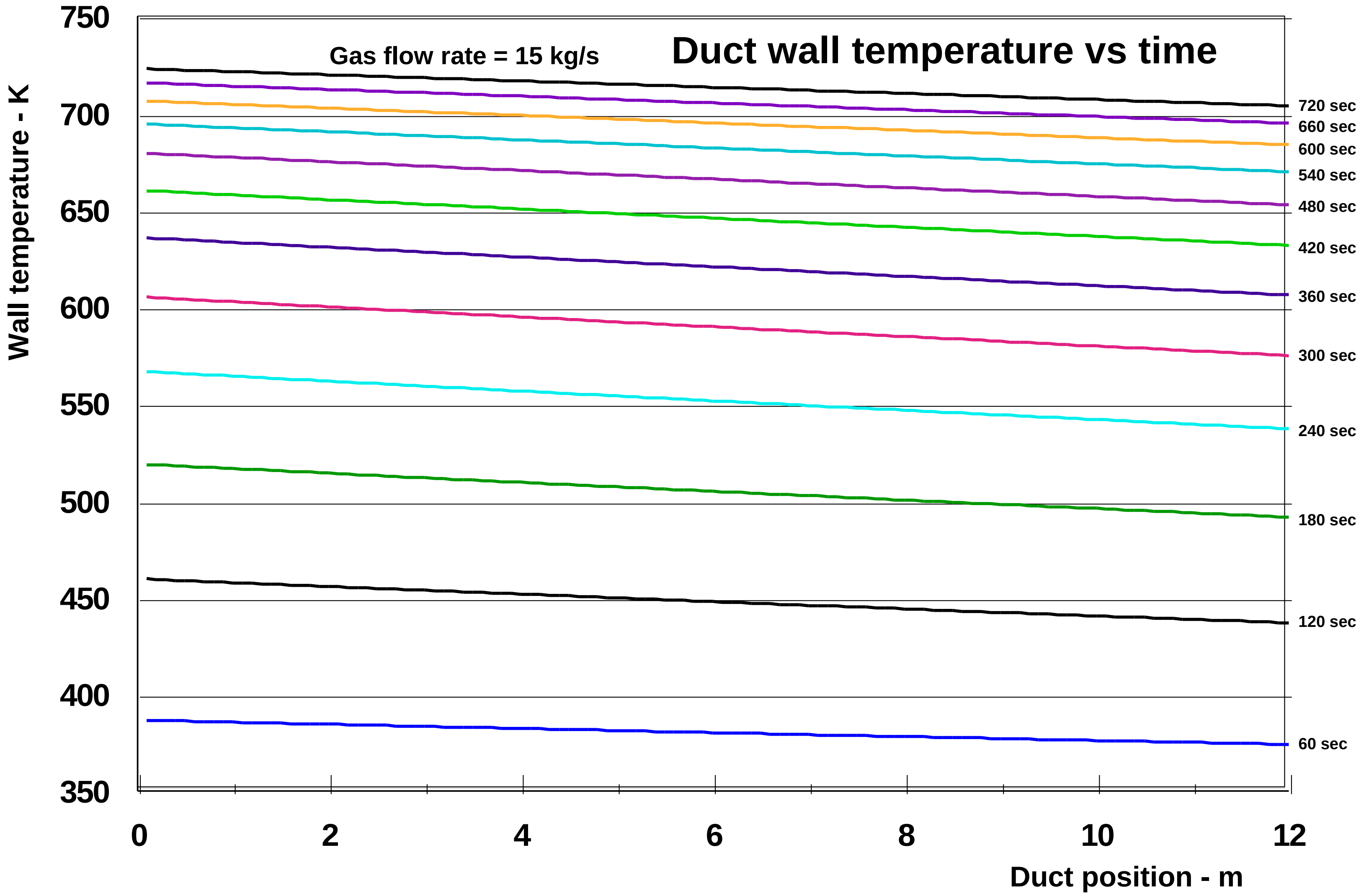
α = thermal diffusivity for air (taken as $3.28 \times 10^{-5}\ m^2/s$)

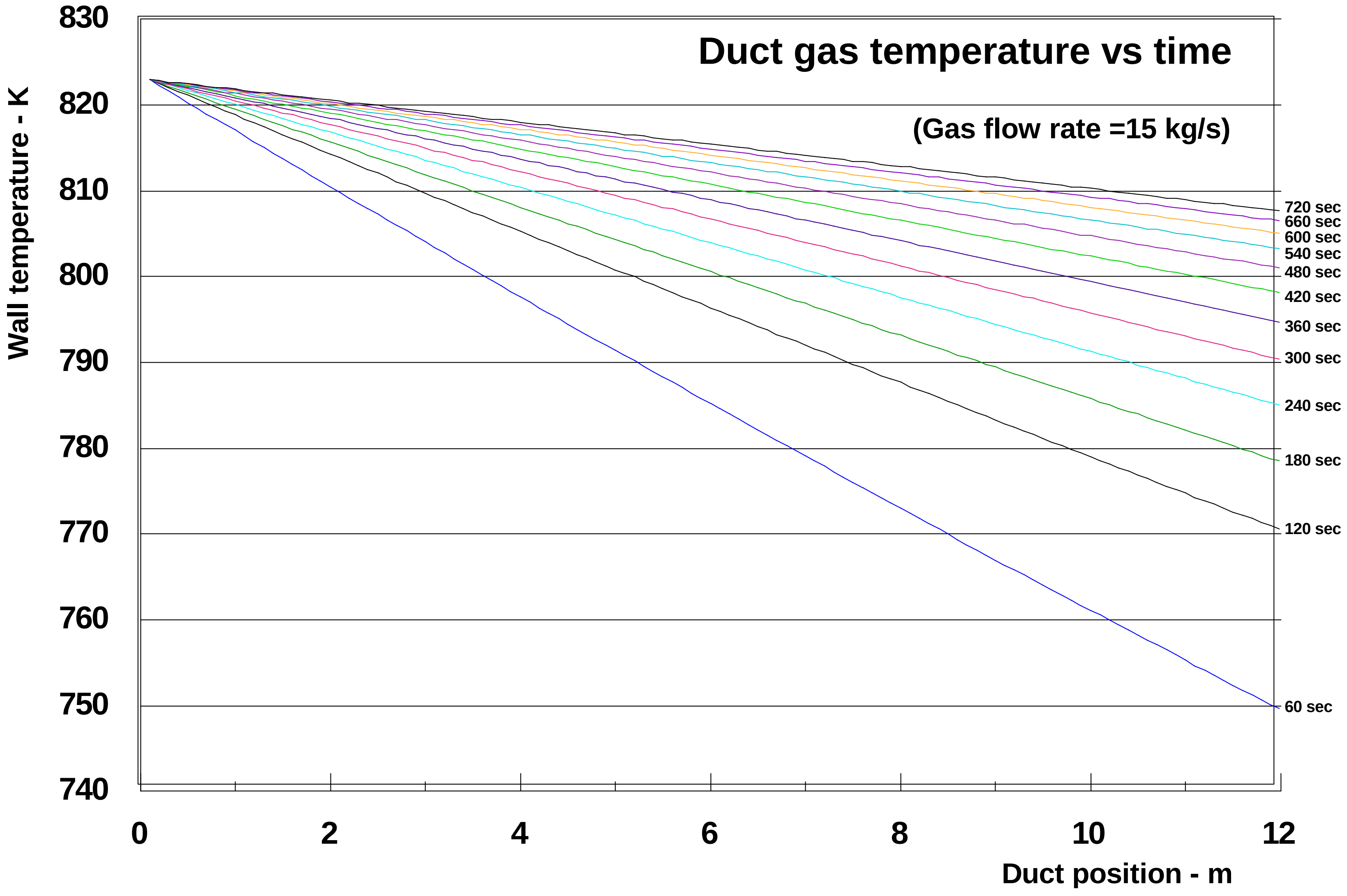
ν = kinematic viscosity for air (taken as $2.28 \times 10^{-5}\ m^2/s$)

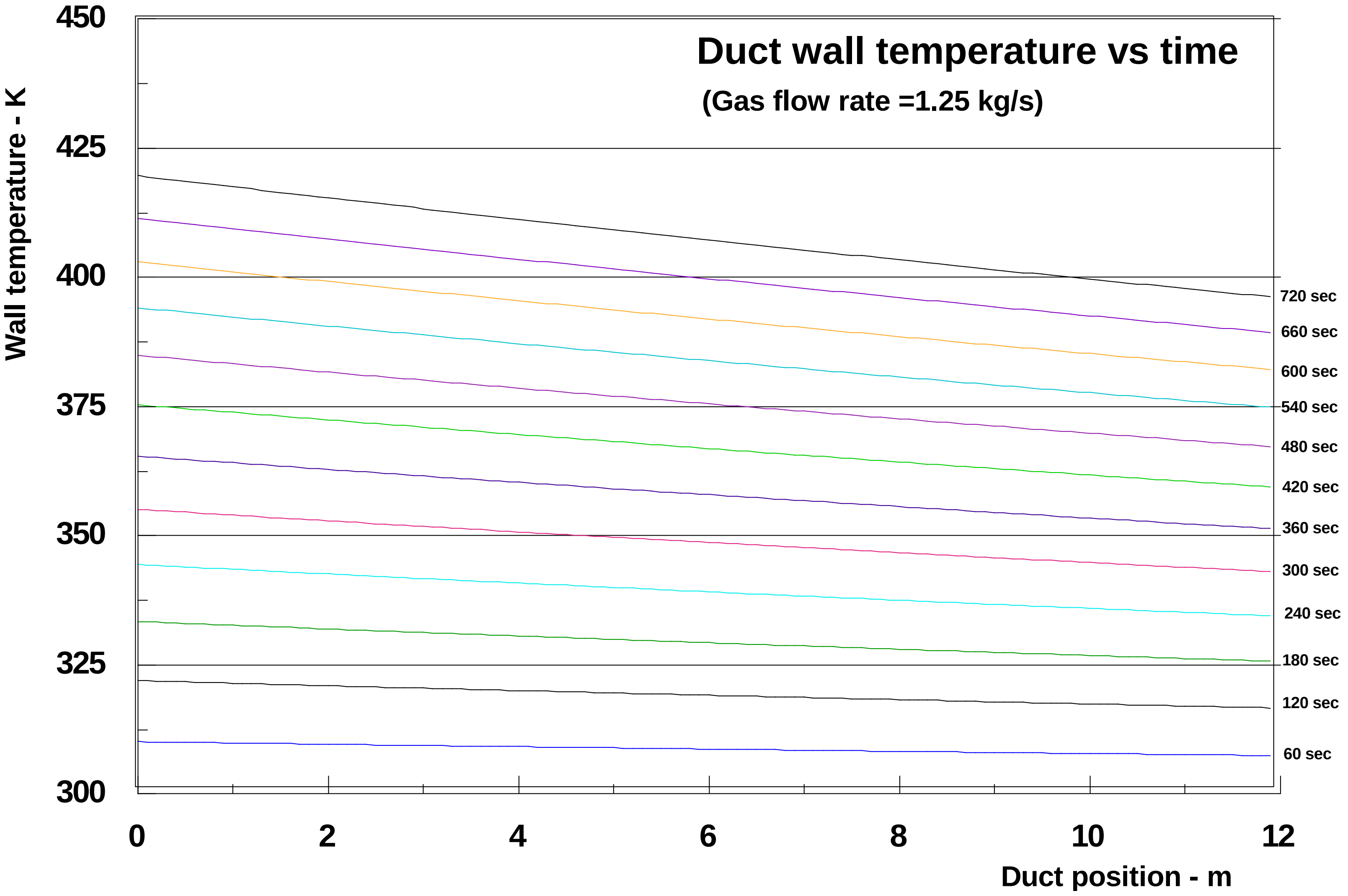
The results are given in the two graphs below for duct temperature along its length at a range of time steps and similarly for the exhaust gas.

It can be seen that, over a period of 12 minutes, the duct entry temperature rises to 725 K and the exit temperature is around 705 K.

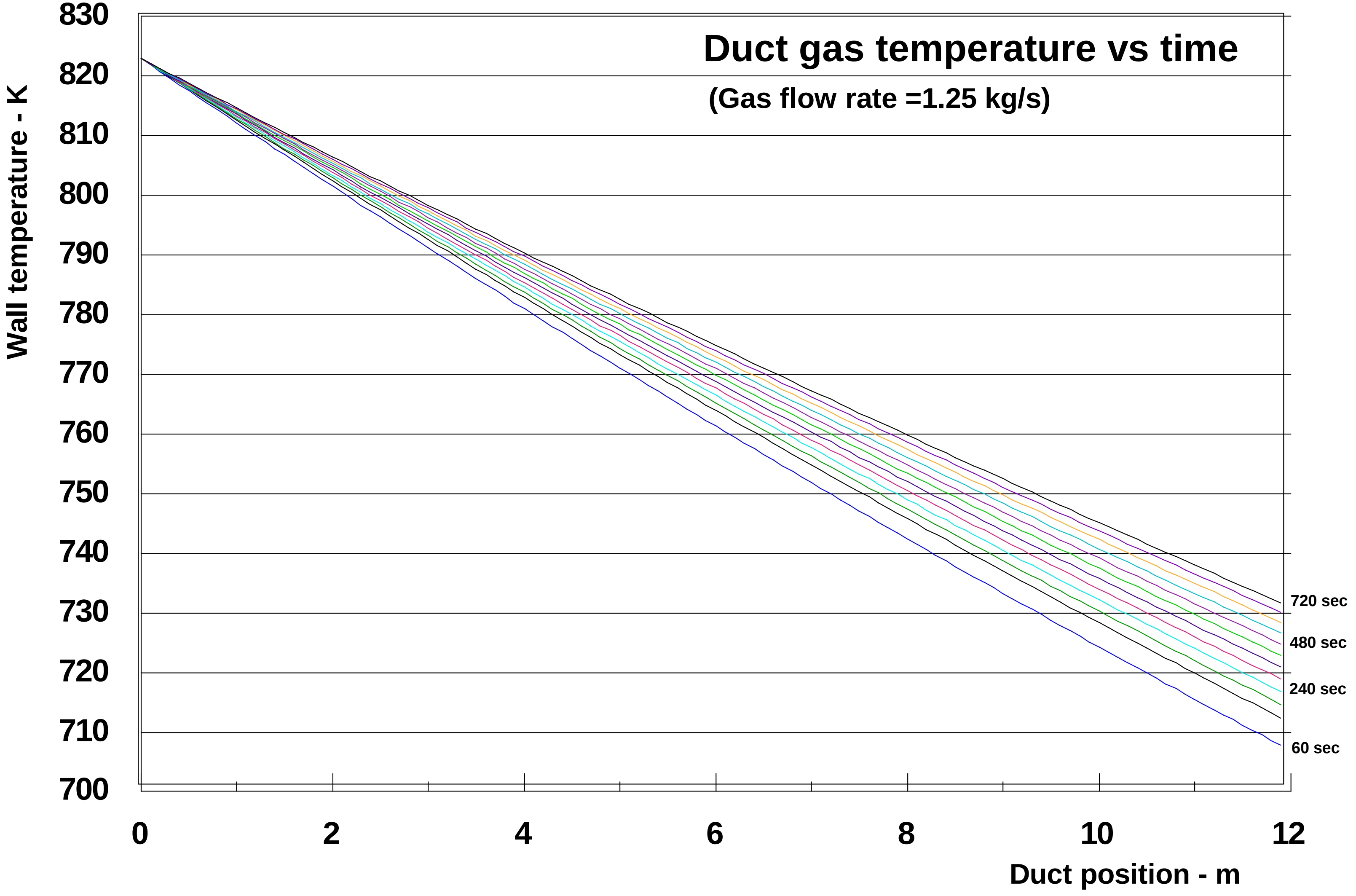
For the gas, the entrance temperature is always 823 K and after 12 minutes, the gas exit temperature has risen to 808 K, from an initial exit value of 750 K.

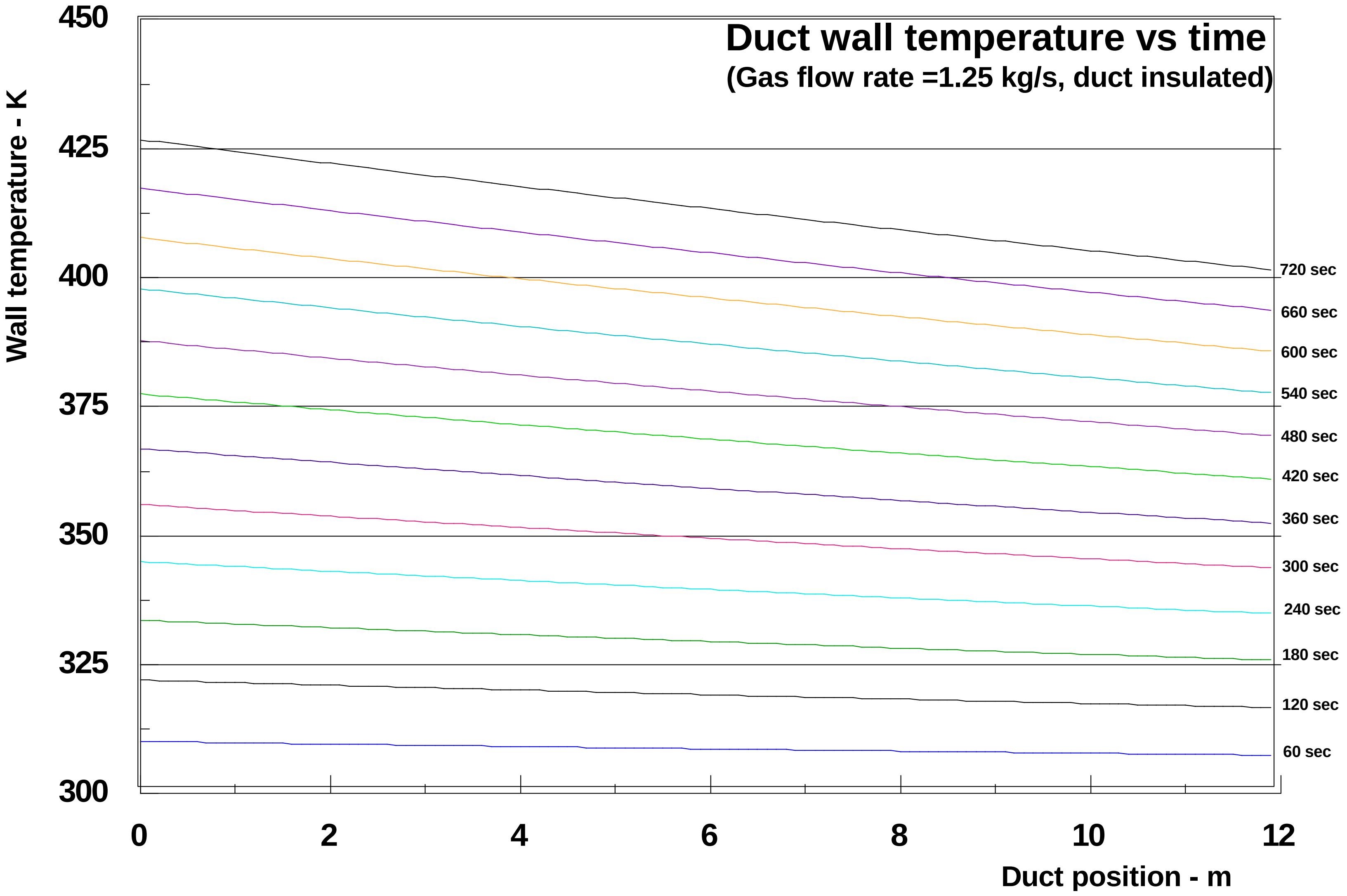

Duct wall temperature vs time
Gas flow rate = 15 kg/s
Wall temperature - K
750
700
650
600
550
500
450
400
350
0
2
4
6
8
10
12
Duct position - m
720 sec
660 sec
600 sec
540 sec
480 sec
420 sec
360 sec
300 sec
240 sec
180 sec
120 sec
60 sec

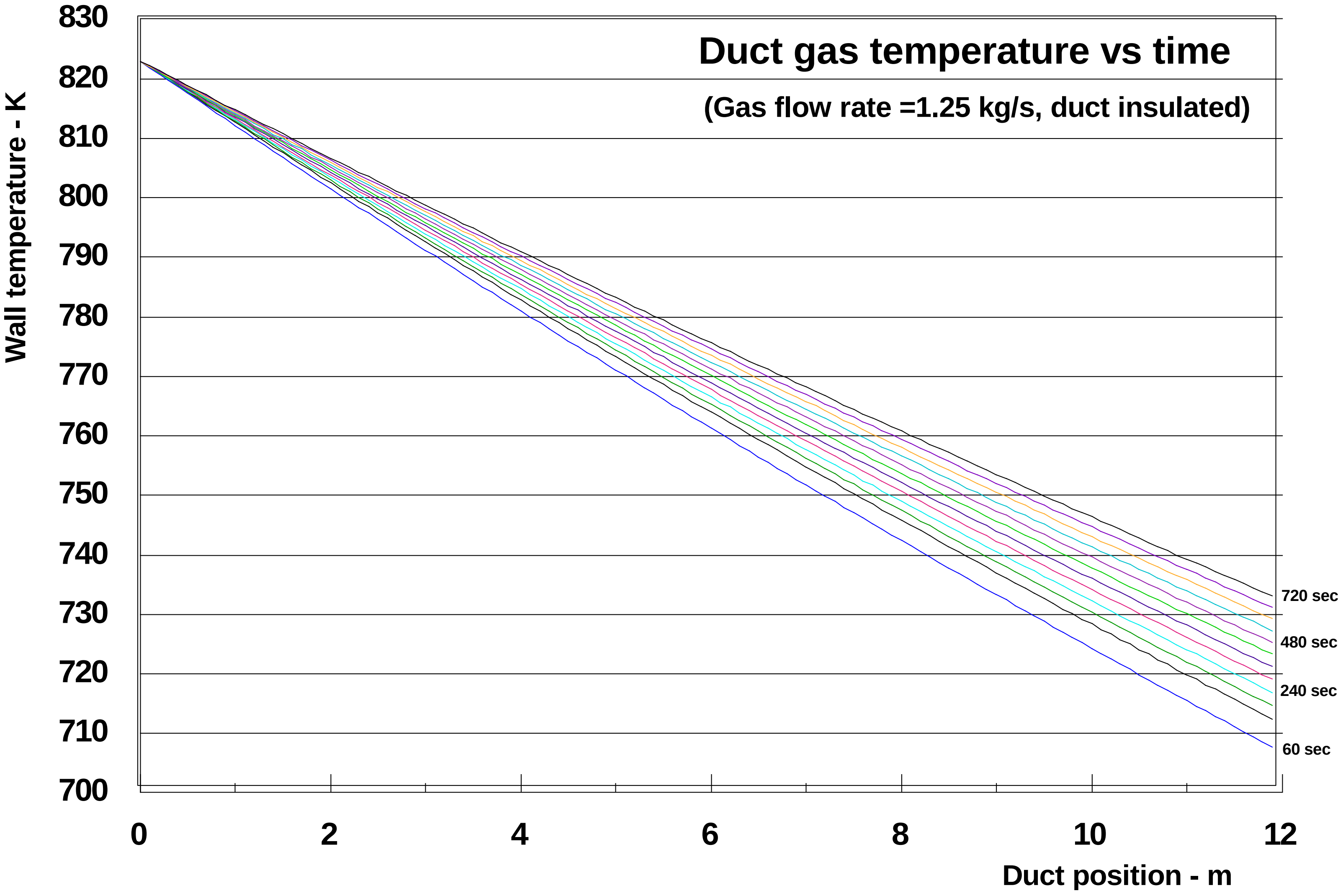

Duct gas temperature vs time
(Gas flow rate =15 kg/s)
Wall temperature - K
830
820
810
800
790
780
770
760
750
740
0
2
4
6
8
10
12
Duct position - m
720 sec
660 sec
600 sec
540 sec
480 sec
420 sec
360 sec
300 sec
240 sec
180 sec
120 sec
60 sec



Duct wall temperature vs time
(Gas flow rate =1.25 kg/s)
Wall temperature - K
450
425
400
375
350
325
300
0
2
4
6
8
10
12
Duct position - m
720 sec
660 sec
600 sec
540 sec
480 sec
420 sec
360 sec
300 sec
240 sec
180 sec
120 sec
60 sec


Duct gas temperature vs time
(Gas flow rate =1.25 kg/s)
Wall temperature - K
830
820
810
800
790
780
770
760
750
740
730
720
710
700
0
2
4
6
8
10
12
Duct position - m
720 sec
480 sec
240 sec
60 sec


Duct wall temperature vs time
(Gas flow rate =1.25 kg/s, duct insulated)
Wall temperature - K
450
425
400
375
350
325
300
0
2
4
6
8
10
12
Duct position - m
720 sec
660 sec
600 sec
540 sec
480 sec
420 sec
360 sec
300 sec
240 sec
180 sec
120 sec
60 sec


Duct gas temperature vs time
(Gas flow rate =1.25 kg/s, duct insulated)
Wall temperature - K
830
820
810
800
790
780
770
760
750
740
730
720
710
700
0
2
4
6
8
10
12
Duct position - m
720 sec
480 sec
240 sec
60 sec

Appendix 7 Gas turbine mass flow calculations

Define the following variables :

m_{ex} = mass flowrate of exhaust. - specify this
M_{ex} = molecular weight of exhaust - calculated
M_f = molecular weight of fuel - calculated
F_{CO} = mole fraction of CO in fuel mixture - specify this
F_{H2} = mole fraction of H_2 in fuel mixture - specify this
F_{CH4} = mole fraction of CH_4 in fuel mixture - specify this
Ff = mole fraction of fuel in exhaust - specify this
F_{EXO2} = mole fraction of oxygen in exhaust - given as 0.15718
m_{O2} = mass flowrate of additional oxygen
M_{O2} = molecular weight of oxygen
m_f = mass flowrate of fuel
m_{ex}/M_{ex} = molar flowrate of exhaust
m_f/M_f = molar flowrate of fuel

Additional oxygen molar flow rate required to bring concentration in exhaust up to 0.21 mole fraction is calculated from :

0.21 = (oxygen from exhaust + additional oxygen)/(exhaust + oxygen)

$$0.21 = \frac{F_{EXO2}\frac{m_{ex}}{M_{ex}} + \frac{m_{O2}}{M_{O2}}}{\frac{m_{ex}}{M_{ex}} + \frac{m_{O2}}{M_{O2}}}$$

Rearrange to give (1) :

$$m_{O2} = \frac{\frac{m_{ex}}{M_{ex}}(0.21 - F_{EXO2})}{(1 - 0.21)}$$

Mole fraction of fuel in exhaust calculated from the flowrates of fuel and modified exhaust flow:

$$F_f = \frac{\frac{m_f}{M_f}}{\frac{m_{ex}}{M_{ex}} + \frac{m_{O2}}{M_{O2}} + \frac{m_f}{M_f}}$$

Rearrange to give (2):-

$$m_f = \frac{M_f\, F_f \left(\frac{m_{ex}}{M_{ex}} + \frac{m_{O2}}{M_{O2}}\right)}{1 - F_f}$$

Equations 1 and 2 are mass flow rates of additional oxygen and fuel - calculated by spreadsheet.

Calculation of temperature reduction due to injection of oxygen and fuel mixture.

The reduction in exhaust gas temperature is estimated to be 96 deg.C from a set point of 500 deg.C this is calculated as follows :- Using the following specific heat values; Cp air = 1.005, Cp hydrogen = 14.3. Cp oxygen = 0.91. Maximum mass flow rates are hydrogen 0.2 kg/s, oxygen 1.12 kg/s and combustion products (air) 15 kg/s. Injection temperature 20 deg.C.

Thus:- 14.3x0.2x(x-20) + 0.91X1.12X(x-20) = 1.005X15X(500-x). Where x is the new temperature after injecting fuel and oxygen. Thus x = 404 deg.C.

This assumes that the gases are injected at an ambient temperature of 20^0 C.