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**Sasol Advanced Fuels Laboratory**  
**UNIVERSITY OF CAPE TOWN**

***Development of a Constant-Volume Combustion  
Apparatus for Fuels Research***

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***A dissertation submitted to the Department of Mechanical Engineering,  
University of Cape Town, in fulfilment of the requirements for the degree  
of Master of Science in Engineering***

Cape Town, South Africa  
16 February 2007

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## Declaration

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**Mr Andre Swans** – SAFL; Assistance with combustion thermodynamics

**UCT Staff** – Machine-shop and general assistance

**Mr Graham McPhillips** – Assistance with the electronics

**Mr Adrian Velaers** – Assistance with experimental setup

## Terms of Reference

The briefings for this project occurred at two stages. Initially, the project was presented to Mr Geoff Miller by Dr Andy Yates of Sasol Oil (Pty) Ltd, in Sasolburg. Upon arrival at the University of Cape Town (UCT), the student was given further briefings by Mr Paul Schaberg, also of Sasol Oil, stationed full-time at the university.

This project was to form part of a concerted research effort based at the Sasol Advanced Fuels Laboratory (SAFL) in collaboration with the UCT Mechanical Engineering Department.

The task given was as follows. SAFL required a piece of laboratory apparatus that would enable optical access to single combustion events, similar to those produced in internal combustion engines. The apparatus had to:

- a) be able to create an environment of sufficiently high temperature and pressure so as to induce spontaneous ignition of compression ignition fuels within the same time frame as that of diesel engines;
- b) be flexible in the ranges of temperatures and pressures that could be created independently from one another;
- c) allow for sufficient optical access such that optical techniques requiring line-of-sight and orthogonal views of the combustion event could be implemented;
- d) require only a small quantity of fuel in order to run an experiment to test that fuel, and
- e) allow for the measurement of the ignition delay, between the time of injection of the test fuel and the start of combustion.

In addition to these requirements, it was mentioned that it may be useful if the apparatus could be used to characterise spark ignition fuels, in the hope that a more integrated understanding of spark and compression ignition fuels might be achieved.

## Synopsis

This project, initiated by the Sasol Advanced Fuels Laboratory at UCT, was to develop a piece of apparatus in which single compression ignition events could be viewed and studied. The pressure and temperature at injection were to be independently variable.

Following a literature survey into previous fuels research work and the associated equipment used, such as rapid compression machines and continuous flow combustion chambers, the decision was made to develop a constant volume combustion chamber (CVCC). This option provided the greatest potential for optical access. The development of the high pressure and temperature environment was to be achieved using a pre-charge combustion event as opposed to electrical heating. The combustion of a lean mixture of flammable gas resulted in the desired conditions being developed rapidly, avoiding the material strength limitations of sustained electrical heating.

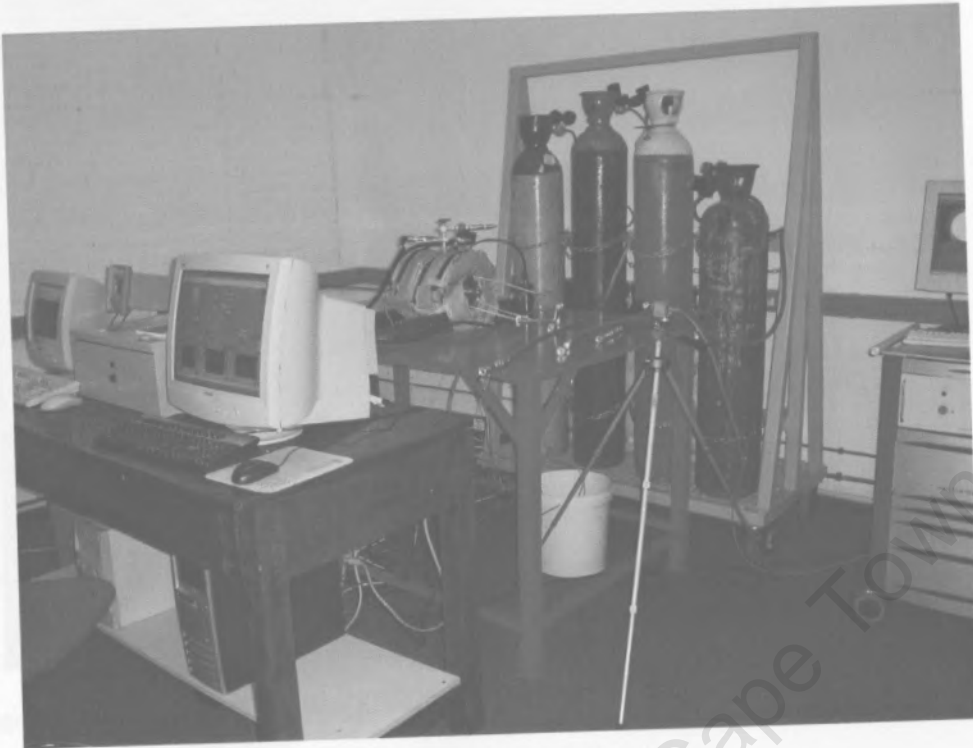
The CVCC has a cylindrically shaped chamber, 100mm in diameter and 50mm deep, which is formed by a martensitic tool steel vessel of 230mm nominal diameter. The chamber is optically accessible by means of sapphire windows on both ends as well as from a maximum of three 38mm diameter (medium-sized) circumferential ports. Flexibility of the experimental setup was ensured by the use of common porting, whereby the two ends, the four medium-sized ports and the four small circumferential ports were interchangeable with one another. All ports were sealed with Viton O-rings that permitted a maximum operating temperature of 200°C. The CVCC could be electrically heated to 150°C to prevent condensation on the windows. The exhaust valve, which also served as a safety relief valve, was pneumatically powered and automatically controlled by a solenoid valve.

The high pressure and temperature environment required for compression ignition combustion events were achieved by the introduction of predetermined

amounts of Hydrogen and/or Acetylene, Nitrogen and Oxygen into the chamber. The gases were metered into the CVCC by means of a pressure transmitter feedback loop and a solenoid valve, both of which were controlled by the main computer that made use of a data acquisition card. The mixture was ignited by a spark plug, resulting in complete pre-charge combustion and a rapid pressure and temperature increase. Following pre-charge combustion, the temperature and pressure dropped relatively gradually due to heat lost to the walls of the vessel. At a pre-selected pressure, the fuel being tested was injected into the chamber by an electronically controlled high pressure injector via a common rail or accumulator system. The predetermined component of residual oxygen in the chamber, being dependent on the original constituents, could yield either an inert environment (for non-combustive fuel spray studies) or a range of environments supporting compression ignition (i.e. a range of oxygen concentrations including an equivalent atmospheric fresh charge). In this way, visual observations could be made of controlled compression-ignition combustion events. These events were also recorded in a high-speed pressure trace from the quartz pressure transducer within the chamber.

A thermodynamic model was set up to determine the required fill pressure of each gas to be metered into the vessel. Testing up to 180bar was achieved and results showed that peak pressures were repeatable to within 4%. Up to 60 high-quality image experiments were achieved in one day without significant fouling of the windows or degradation of the seals. A discrepancy of approximately 15% existed between predicted peak pressures and measured pressures (being lower). Several losses were known to cause this pressure shortfall, such as slight gas leakage from the exhaust valve, radiation losses through the windows and heat lost to, and reaction quenching at, the walls of the chamber. Recommendations for improvements to the CVCC included reducing the causes and rates of leakage and quantifying the impact of surface-area to volume ratio on losses at the internal surfaces.

Images of the CVCC and of its capability:



Original experimental set-up

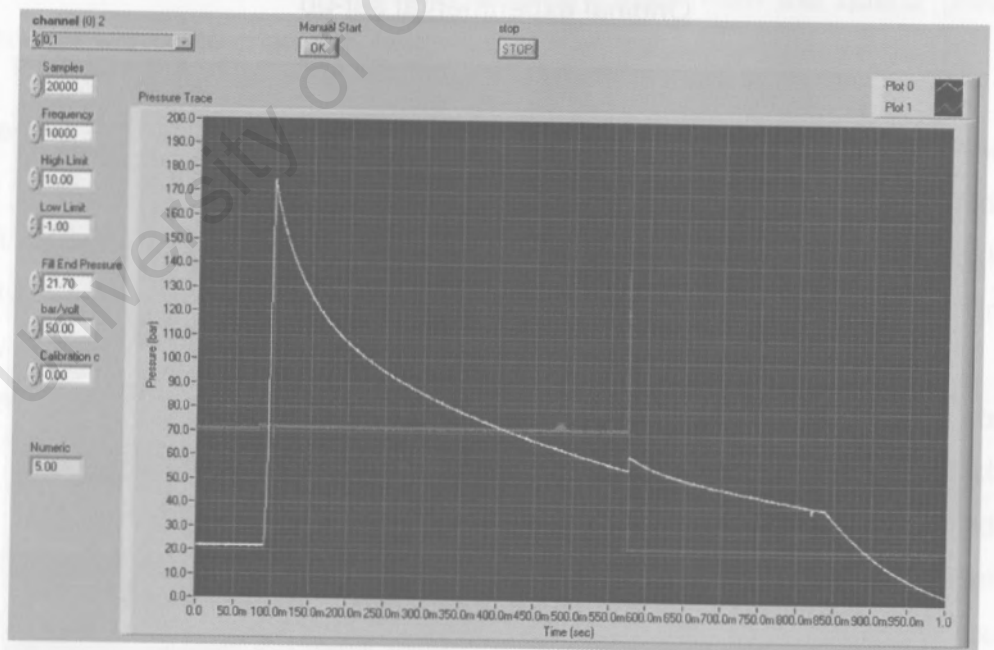


A view into the CVCC, through a sapphire window on the near end





Diesel combustion in CVCC as captured by CCD camera



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# 1. Introduction

The aim of this chapter is to provide the framework for the dissertation on the development of a constant-volume combustion vessel in light of the terms of reference that are reported in a preceding section.

## 1.1 Background

Studies of combustion events similar to those found in internal combustion engines have been undertaken for many decades. In the 1930's, at least two combustion "bombs" were developed for this purpose. The advantage of an apparatus producing a single combustion event is that the potential for variations in conditions affecting the combustion event can be reduced.

Many studies on combustion events and fuel sprays have made use of optical techniques to record useful data for flame and spray analyses. From the determination of the onset of ignition, to the formation of soot, to the liquid penetration length, various techniques such as the Schlieren, Laser Induced Fluorescence and Charge Coupled Device (CCD) photography have been used with success. For purposes such as these, single combustion event machines can provide the significant advantage of greater optical access.

Sasol Advanced Fuels Laboratory (SAFL) wanted to have a piece of laboratory equipment that could produce a range of optically accessible single combustion events. As this sort of research is conducted by only a few institutions in the world, this type of apparatus is not something that can be bought "off the shelf. For this reason and for the purpose of gaining in-house knowledge on such devices, this M.Sc. project was initiated.

## **1.2 Objectives of the Project**

In this section, the objectives of the project are presented. These were developed from a combination of the brief given and thoughts regarding the end-user's requirements, both experimental and practical.

### **1.2.1 Pressure and Temperature Capabilities**

The single combustion event apparatus with optically accessible chamber was to be primarily intended for the study of compression ignition fuels. It was thus an aim for the design of the apparatus to allow for operational pressures in excess of the peak compression-derived pressures developed in diesel engines, i.e. approximately 100 bar.

The temperature capabilities of the apparatus from an experimental perspective hinge on the maximum temperature that can be produced (even if only momentarily) for the injection event. It is desirable to have as great a range as possible, but at least 1000 Kelvin was determined to be a useful maximum injection temperature.

### **1.2.2 Determined Desired User Applications**

The primary variables that the user may want to vary for sets of experiments are pressure and temperature. The objective of the apparatus in this respect is to have the flexibility of varying one variable while keeping the other constant. With this capability, variable-specific influences can be studied and a wide variety of conditions can be generated, including most of those found in engines.

It was also considered desirable for the user to be able to simulate exhaust gas recirculation in an engine, independently of pressure and temperature. In effect, this would mean being able to control the oxygen component in the charge.

The apparatus to be developed was to have, as a primary requirement, sufficient optical access to allow for as many optical techniques to be used as possible. The major requirements to fulfill this are complete in-line transparency and orthogonal (or angled) optical access of the combustion event for such techniques as the Schlieren (in-line transparency is the preferred access, though a reflective surface can be used — See Section 2.2) and Mie Scattering, respectively.

Lastly, a critical indicator that the user may want to incorporate into studies is that of the ignition delay of the fuel. The start of combustion is generally determined from a pressure trace, as this is not always visible. The start of injection can be determined either optically or by using other electronic means. It was thus an objective of this project that the ignition delay could be determined from data recorded during an experiment.

### 1.2.3 Ergonomics, Set-up Flexibility and Safety

The practicality and ease of use of the apparatus was an important goal that would have significant impacts on the design. As the intention for the equipment was that it would be extensively used in future research projects, the end-user's time, effort and comfort were to be taken into account.

Due to the various optical techniques that were to be catered for, the orientation of the apparatus and optical window placement needed to be as adjustable as possible.

The safety of the end-users and the protection of the equipment itself were to be made a priority throughout the project.

### *1.3 Project Design*

The first stage of the project was to decide what type of apparatus would most effectively fulfill the given briefing, taking into consideration the limitations such as time, manufacturing capabilities and money. A lengthy concept development and design process then followed. The UCT Mechanical Engineering workshops were commissioned to manufacture all the components of the final design. The assembly and testing of the sub-systems and complete rig were then performed by the student.

### *1.4 Objectives and Structure of the Dissertation*

The dissertation seeks to present the influential work that has led to the development of the constant-volume combustion chamber (CVCC). The descriptive sections have been sub-divided by theoretical bases for ease of reference and logical thought-flow. Significant technical details have mainly been reserved for the appendices; however, where they had a critical influence on design decisions, they have been included in the main text.

The thesis begins by presenting and discussing the literature body that had an influencing role on the CVCC's development. This forms the background to the design process, the initial part of which is presented in the Concept Formation chapter. Following this section are the descriptive chapters on the various design aspects and sub-systems of the CVCC. A presentation of the experiments that were carried out in order to test the different components and functionalities of the apparatus is then proceeded by a final chapter that discusses the present CVCC and makes recommendations for further work. Several appendices follow, in which relevant drawings, calculations and information for further development are given.

## 2. Literature Review

Many papers have been published, particularly by the Society of Automotive Engineers, in which automotive fuels research was carried out using various alternatives to engine tests. These will be discussed under categories applicable to the different aspects of the design. In addition, the review covers optical access equipment and optical research techniques.

### ***2.1 Fuel Research Alternatives to Engine Tests***

In addition to engine tests, many other methods of testing fuels and their combustion characteristics have been developed and used successfully. Reasons for moving away from engines for certain tests include: the creation of a more controlled environment with smaller fluctuations and fewer influencing parameters; and the need to be able to perform tests with limited quantities of fuel. The following paragraphs discuss various alternatives that have been developed thus far.

#### **2.1.1 Rapid Compression Machines (RCM)**

As their name suggests, RCMs are not constant volume machines but use a piston-in-cylinder arrangement to achieve engine-like conditions in a single compression event. However, the combustion event itself occurs in a constant volume environment, since the piston is usually held in place following compression. RCMs have been used successfully by many researchers including Heywood (1988) and Bysveen et al. (1998), who used a hydraulically actuated piston in their rig to study the combustion of low heating value gas by means of the Schlieren Technique (See Section 2.2.4). The primary disadvantage of an RCM is that despite providing greater optical access potential than a single cylinder research engine, optical access is still compromised by the necessity of having a piston. Bysveen et al. (1998) made use of four circumferential windows in their RCM.

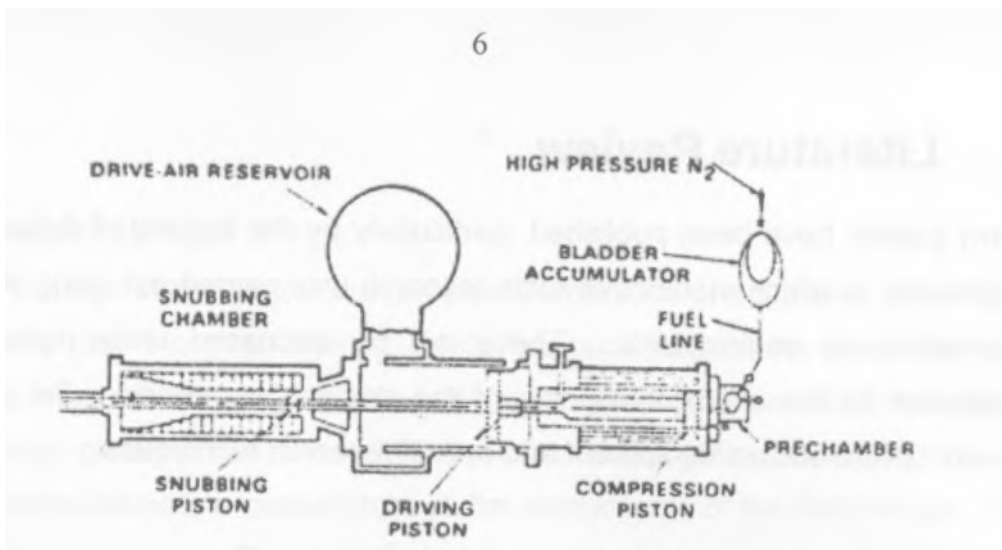


Fig. 2.1.1: An Early Rapid Compression Machine (Rife and Heywood, 1974)

### 2.1.2 Constant Volume Combustion Apparati (CVCA)

The term "combustion bomb" has been used for decades to refer to CVCA, of which there are two major types: electrically heated and pre-charge combustion. This distinction between CVCA types stems from the manner in which engine-like conditions are emulated in the constant volume chamber.

#### 2.1.2.1 Electrically heated combustion bombs

CVCA in which engine-like conditions are achieved by electrical heating alone can be further sub-divided into three main categories. Constant mass CVCA will be discussed first, followed by continuous flow types and then a rapid transfer device.

##### Constant Mass CVCA

A constant-mass, electrically-heated CVCA is one in which a sealed chamber is heated using electrical resistance heaters in order to cause the charge to develop temperatures and pressures that resemble engine-like conditions. The constant mass CVCA used by Ryan and Stapper (1987) of the Southwest Research Institute used resistance heaters to develop a maximum of 41 bar and 538°C. The design pressure of **the** vessel was 350 bar, to cater for the increase in pressure following diesel combustion. Important to note is that the combustion chamber had no optical access and had narrow cylindrical dimensions of 025 x 100mm, as shown in the following figure.



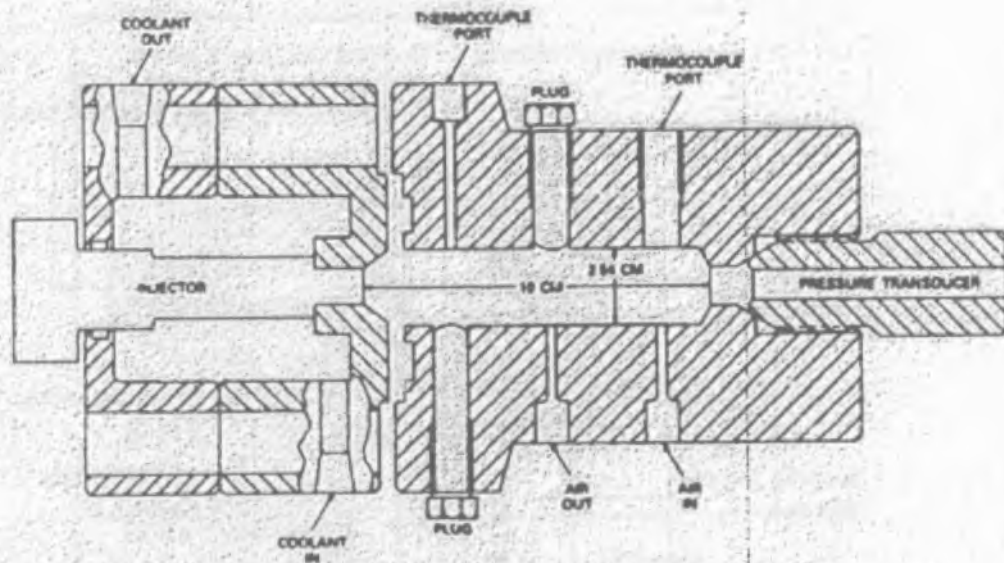


Figure 2.1.2.1a: A Constant-Mass, Electrically-Heated CVCA

Another example of a CVCA of this type, but with optical access for viewing diesel combustion, was that used by Wang et al. (1994). The design temperature and pressure were 1100K and 100 bar, while the internal diameter and the diameter of the windows were 150mm and 100mm respectively. As with all types of electrically heated CVCA, the maximum attainable temperature of the charge within the combustion chamber is limited by the effect of temperature on the strength of the steel used for the vessel.

### Continuous Flow CVCA

Continuous flow CVCA generally provide a constant feed of slow-moving, electrically-heated air into a chamber in which controlled diesel injections are administered. They have been used primarily for optical research work, having the advantage of reduced window fouling, but they do tend to be designed for lower charge pressures. Examples of this were the CVCA of the Institute of Thermodynamics RWTH (Pischinger et al., 1986) with a design air pressure of 60 bar and of AEA Technology (Astill, Smith and Stopford, 1997) with a design air pressure of 41 bar. The combustion chamber used by Pischinger et al. (1986) is shown in the following figure.

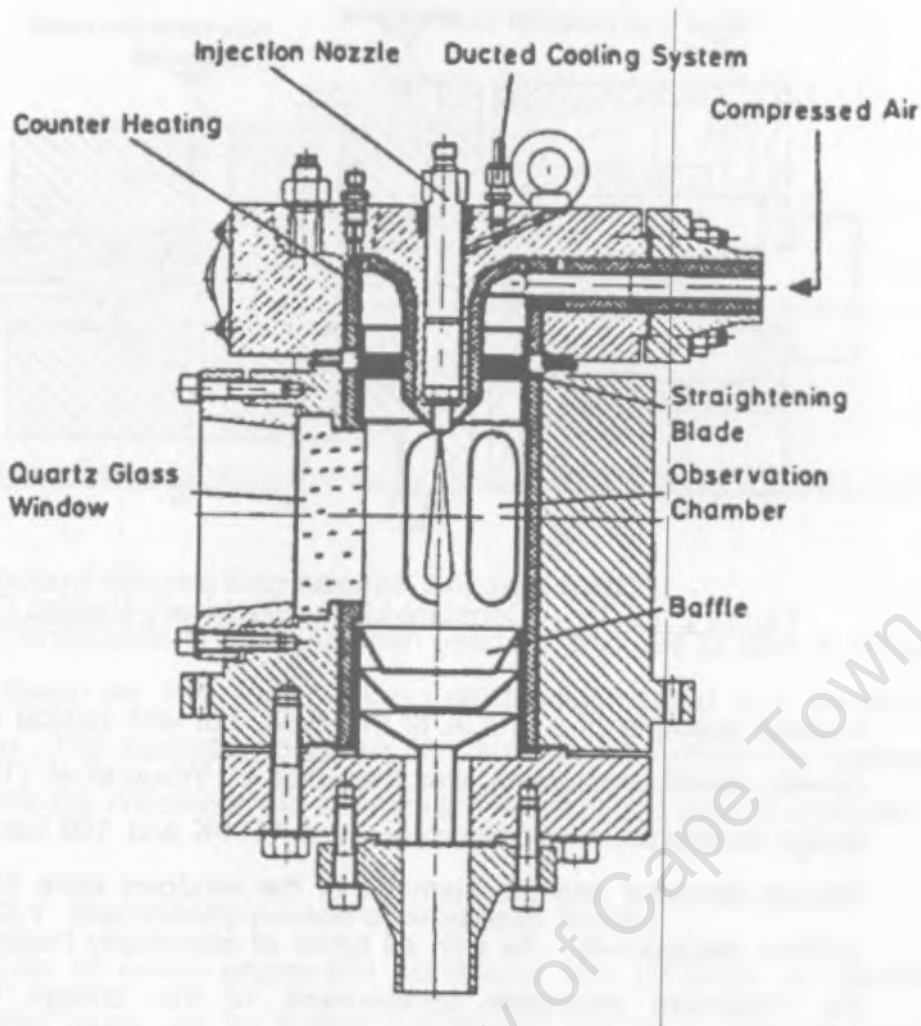


Figure 2.1.2.1b: Longitudinal Section of a Continuous Flow CVCA

### Rapid Transfer CVCA

The concept of a rapid transfer CVCA was developed at the Royal Institute of Technology (KTH) in Sweden by Sjöberg et al. (1999). The idea behind its operation was to make use of an electrically heated Inconel vessel of 700 cc to produce a typical air charge of 600°C and 200 bar, which was then transferred rapidly to the combustion chamber of 400 cc. This arrangement is shown schematically in the following figure (Sjöberg et al., 1999).

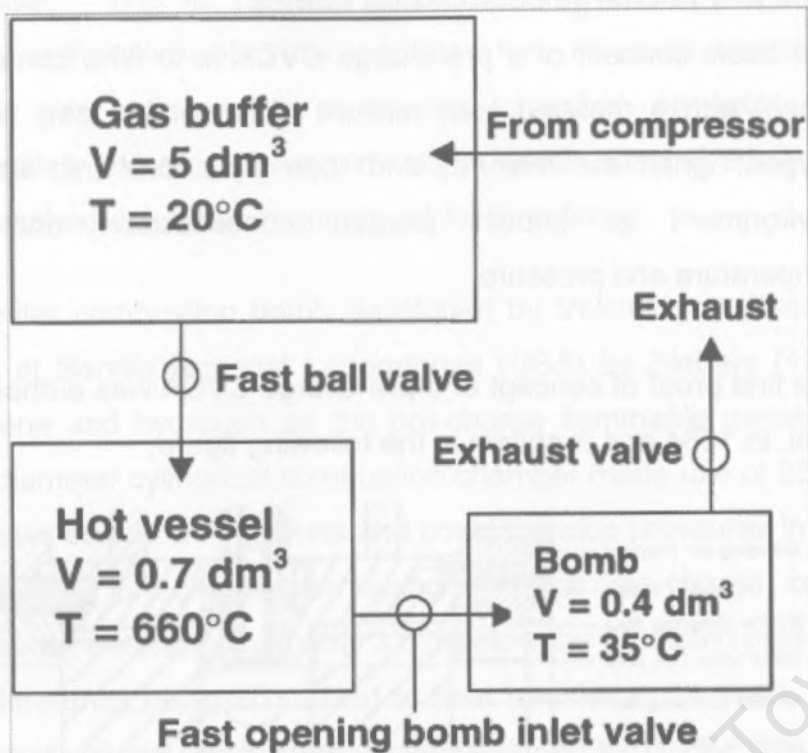


Figure 2.1.2.1c: Schematic Representation of Rapid Transfer CVCA

In theory, the conditions that would be obtained in the combustion chamber by the rapid in-flux would reach  $620^\circ\text{C}$  and 80 bar. In reality, heat losses were greater than expected and only  $425^\circ\text{C}$  was reached in the combustion chamber. This concept did have the advantages of turbulence-creation without the use of a fan and of low combustion chamber wall temperatures. However, despite the claim by Sjoberg et al. (1999) that a smaller combustion chamber would increase the peak temperature, it was considered that the temperature performance of a rapid transfer CVCA would remain inadequate for the objective of 1000 Kelvin, as expressed in Section 1.2.1.

### 2.1.2.2 Pre-charge combustion bombs

The basic concept of a pre-charge CVCA is to fill a constant volume vessel with a metered lean mixture of flammable gas, nitrogen and oxygen; ignite the mixture; and then inject fuel into the produced environment of known oxygen concentration and increased temperature and pressure.

The first proof of concept of a pre-charge CVCA was authored by Oren et al. in 1984 and is shown in the following figure.

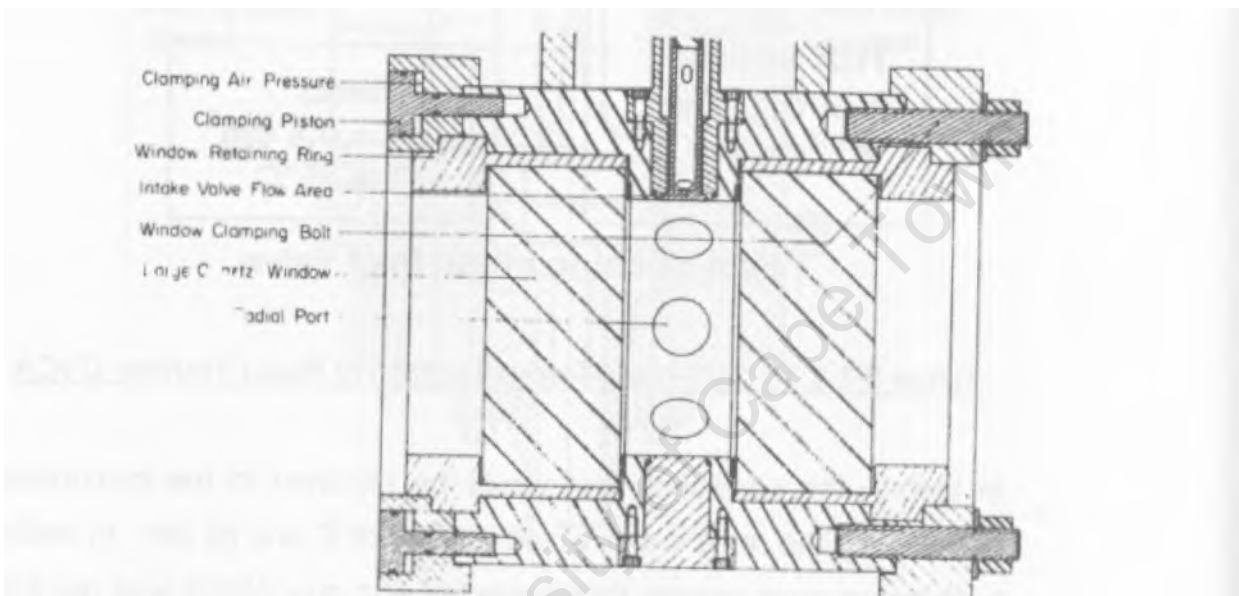


Figure 2.1.2.2a: Cross-Section of the First Pre-Charge CVCA

Their bomb used either acetylene or hydrogen as the pre-charge flammable gas and used two quartz windows of 50.8 mm thickness on the ends of a cylindrical combustion chamber. The design pressure of the vessel was in excess of 80 bar and the windows, though initially sealed using O-rings, were later sealed using gaskets. The reason for moving away from O-rings was cited to be the large crevice volumes they produced, which resulted in inconsistent pre-charge combustion and O-ring burning (the O-rings lasted about ten experiments). However, as indicated by the "Sealing Element" in Figure 3.2.5a, the O-rings were positioned unfavourably in the author's opinion, such that the crevice volume would increase due to the pressure rise caused by combustion. A mixing reservoir was used to create the desired gas mixture composition and conditions before filling the combustion

chamber. The fill process produced swirl within the combustion chamber that eliminated the need for a fan. However, due to heat loss of the gas entering the combustion chamber, an extra degree of uncertainty existed for experiments in which thermal equilibrium was not reached due to the requirement for turbulence.

A similar combustion bomb developed by Volkswagen Research and used at Sandia National Laboratories (USA) by Siebers (1985) used ethylene and hydrogen as the pre-charge flammable gases. The 80 mm diameter cylindrical combustion chamber made use of 25 mm thick windows sealed with gaskets and could develop pressures in excess of 50 bar by pre-charge combustion. Peak pre-charge combustion pressures were approximately 3.5% below the predicted pressures with the difference being accredited to heat transfer to the walls. A similar constant volume combustion vessel designed for higher pressures was used at Sandia by Naber and Siebers (1996). The windows were made of sapphire and had conical circumferences, seemingly for improved strength characteristics as discussed in Section 3.2.5. The vessel could withstand pressures of up to 350 bar. A further development at Sandia was that of a cubical combustion chamber, also with a design pressure of 350 bar (Siebers, 1998), shown in the following figure.

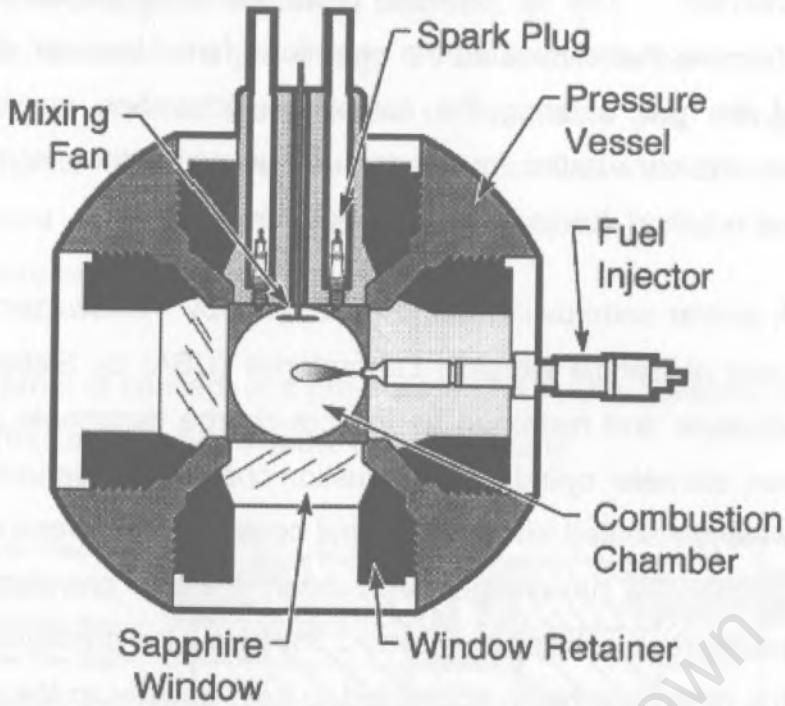


Fig. 2.1.2.2b: Schematic Cross-Section of Sandia Combustion Vessel

Despite not having direct line-of-sight optical access right through the entire chamber, the 108 mm-sided cubical chamber had four window ports of 105 mm in diameter, providing unparalleled line-of-sight and orthogonal optical access. From personal communication with Lyle Pickett of Sandia National Laboratories in 2003, it was learnt that the ports of this vessel were sealed using U-cup seals.

## **2.2 Optical Access Equipment and Research Techniques**

When researching fuels and their combustion characteristics, it is of particular benefit to have optical access to the chamber in which the combustion or spray occurs. Generally, all of the apparatus in Section 2.1 lend themselves preferentially over research engines to having optical access to their combustion chambers due to their geometrical flexibility. The benefit derived from this optical access is a much greater scope for accurate measurement and for knowledge attainment of combustion characteristics. The equipment required to provide optical access and the research techniques that require it will be discussed in the following paragraphs.

### 2.2.1 Windows for Optical Access in High Temperature Applications

To obtain optical access to a combustion vessel, a transparent material that satisfies the temperature requirement and has sufficient strength properties to suit the application must be found. The majority of constant volume combustion vessels in the past have made use of quartz or fused silica windows. **The** softening point of optical grade fused quartz occurs at approximately 1730°C and the recommended maximum service temperature for continuous use is 1150°C (for type KV of Almaz Optics, Inc.). The temperature performance of ultraviolet grade synthetic fused silica (type KU-1 of Almaz Optics, Inc.) is poorer than that of the quartz with a recommended maximum service temperature of 950°C. The tensile strength of fused quartz or silica is about 50 MPa; however, according to General Electric Quartz, it is common practice to use 6.8 MPa for safety and fatigue reasons.

The main advantage of fused silica over fused quartz is its transmissivity in the ultraviolet range. This difference is clearly revealed in the following figures. However, a significant difference in price exists between the two materials; fused silica being the more expensive.

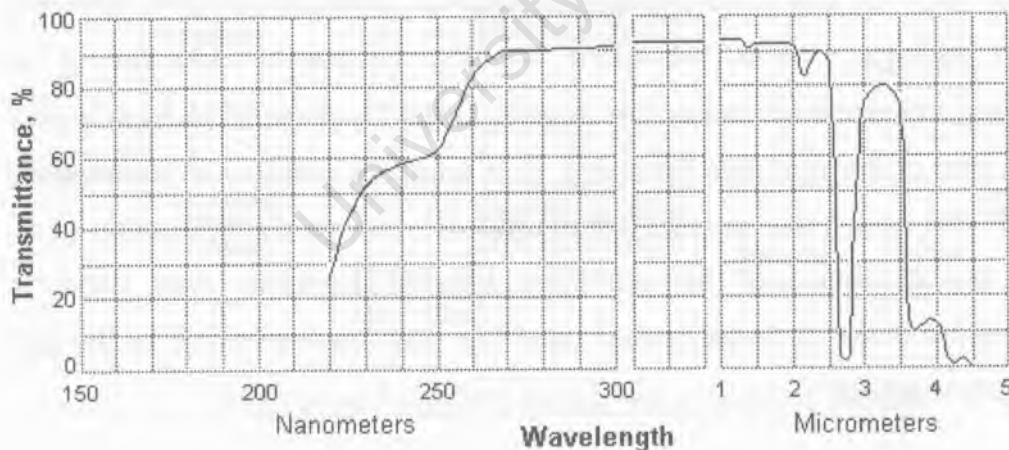
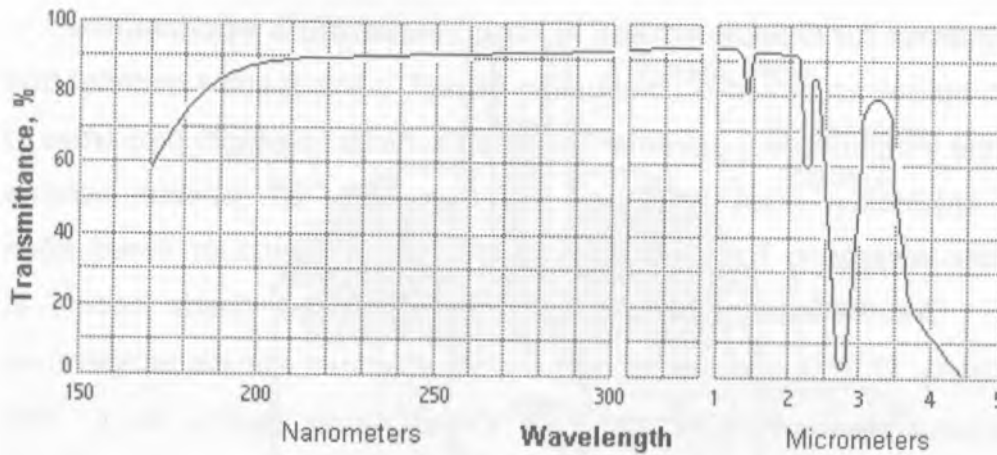


Figure 2.2.1a: Wavelength Transmittance of Optical Grade

Fused Quartz — type KV

(Transmittance through 10mm thickness — reflective losses included)

(Almaz Optics, Inc.)



**Figure 2.2.1b: Transmittance of Ultraviolet Grade  
Synthetic Fused Silica — type KU-1**

(Transmittance through 10mm thickness — reflective losses included)  
(Almaz Optics, Inc.)

In more recent constant volume combustion vessel designs, sapphire windows have been used. Single crystal Sapphire windows have many properties well suited to combustion environments: broad radiation transparency range (wavelength: 0.2 — 5 μm), melting point of about 2030°C, tensile strength of 275 MPa at 500°C (lowest value compared with those at 25°C and 1000°C) and good chemical resistance ([www.almazoptics.com](http://www.almazoptics.com) and [www.mkt-intl.com](http://www.mkt-intl.com)). The maximum working temperature according to MarkeTech International should not exceed 1800°C. Due to its high yield / fracture stress, the required thickness of a sapphire window is significantly less than that of a fused quartz / silica window. In a study by Dimitriu et al. (1990), the detection of flame-emitted infrared radiation was used to determine the onset of diesel ignition, and this was made possible by the use of sapphire windows.

### 2.2.2 Spray and Flame Photography

With optical access to the combustion vessel made available, the simplest method of visualisation is direct photography. This has been used to study fuel spray geometry and penetration by Araneo et al. (2000). Radiation from combustion flames has been captured both by high speed photography (Wang et al., 1994 and Siebers, 1985) and by intensified Charge Coupled



Device (CCD) camera (Winklhofer et al., 1993). The images produced using the CCD camera were representative of the reactive flame front; however, the actual structure of the turbulent interface between burned and unburned gases was unresolved by flame radiation photography.

### 2.2.3 High-Speed Shadowgraphy

Shadowgraphy is a simple optical technique that gives an indication of the second derivative of density in the flow field (Holman, 2001). Its basic principle is that collimated light entering a target section will be refracted where a density gradient exists, forming dark and light regions. This technique has been used fairly widely in combustion bomb research, generally in addition to other optical-imaging methods (Astill, Smith and Stopford, 1997, Wang et al., 1994 and Siebers, 1985). In the following diagram from Wang et al. (1994), an optical arrangement for the simultaneous capture of both a photograph and a shadow graph is shown. For this arrangement, line-of-sight optical access was required.

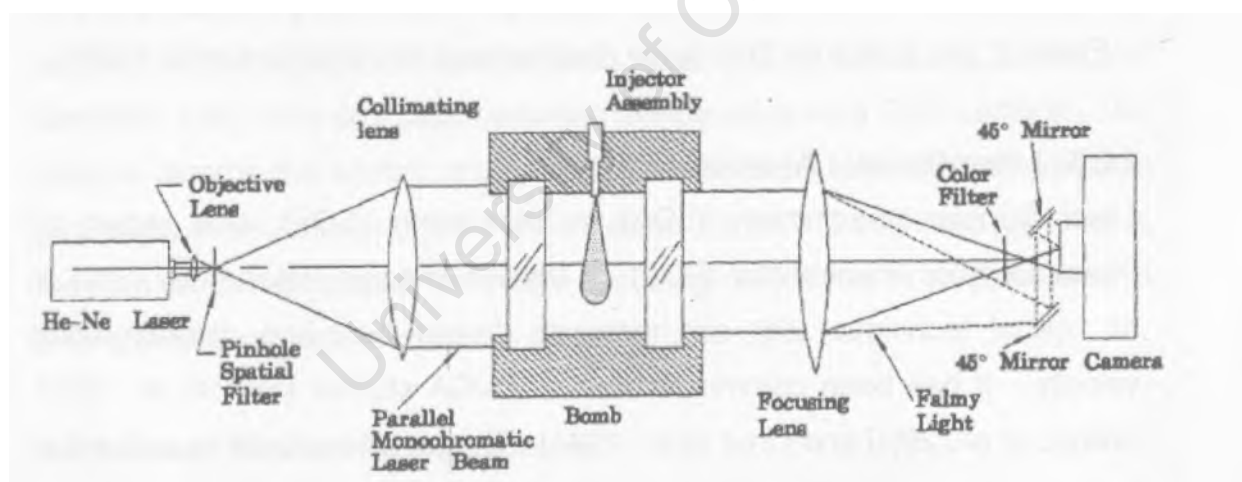


Figure 2.2.3: Optical Set-Up for a Shadow Graph

### 2.2.4 The Schlieren Technique for Density Images

The Schlieren technique makes use of a combination of a slit light source, lenses and/or mirrors and a diaphragm (incorporating a "knife-edge") to produce an image that highlights contrasts and reveals density gradients (Holman, 2001). Despite the gradients revealed, the technique gives limited information on the **conditions** within the flame due to its line-of-sight display

(Bysveen et al., 1998). This limitation restricts a detailed reconstruction of the 3-dimensional flame path. Nevertheless, the Schlieren technique has been used successfully for optical-imaging in fuel spray and combustion research (Pischinger et al., 1986 and Araneo et al., 2000).

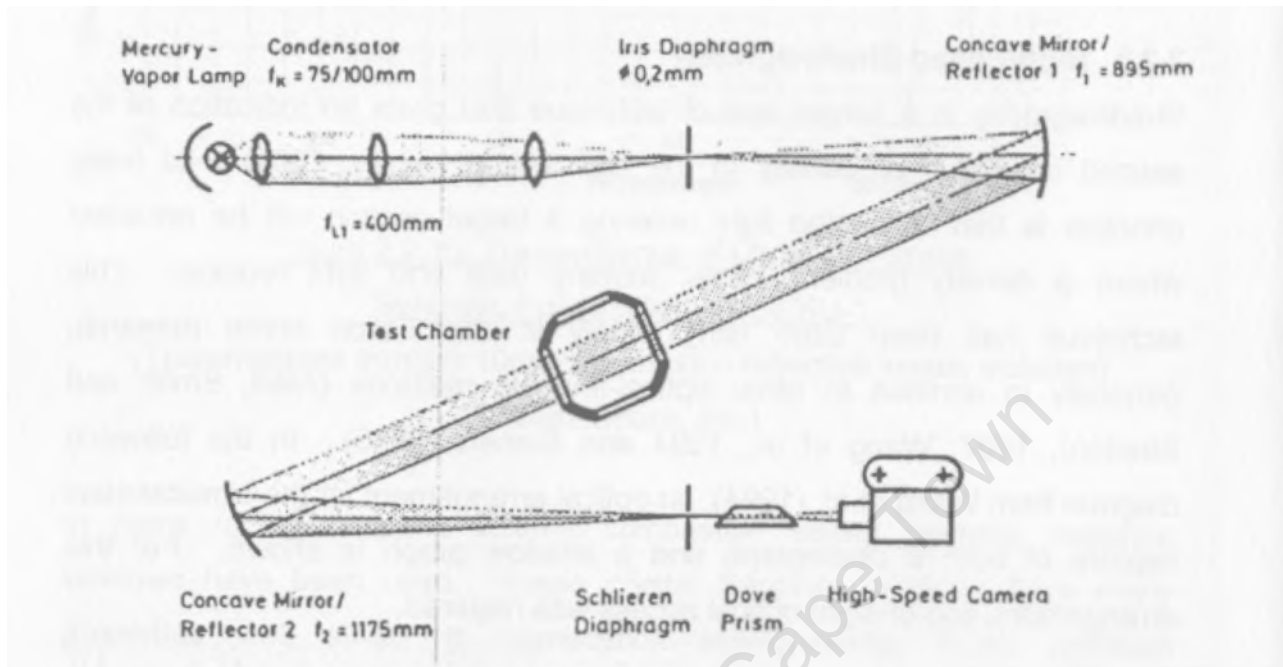


Figure 2.2.4: Schlieren Technique Arrangement of Pischinger et al. (1986)

### 2.2.5 Laser Doppler Anemometry

Laser Doppler Anemometry (LDA) or Velocimetry (LDV), also known as Phase Doppler Anemometry (PDA), or Particle-Imaging Velocimetry (PIV), is an optical technique that can measure droplet size and droplet/particle velocity. It has been commonly used in CVCA studies (Sick et al., 2001, Araneo et al., 2000 and Oren et al., 1984). The particle velocity in a chamber is an important variable in the study of the effects of turbulence and mixing of fuel sprays. The technique generally requires a Helium-Neon or an Argon Ion type laser, the beam of which is split into two equal lengths. One path however, is angled at the target point of measurement due to scattering of the beam as a result of the particles / impurities in the stream. The scattered light experiences a Doppler shift in frequency that is directly proportional to the flow velocity (Holman, 2001). The beams are rejoined before entering a photomultiplier tube, after which electronic processing is required. In the

following optical arrangement from Oren et al. (1984), the rotating grating serves to split the beam in two.

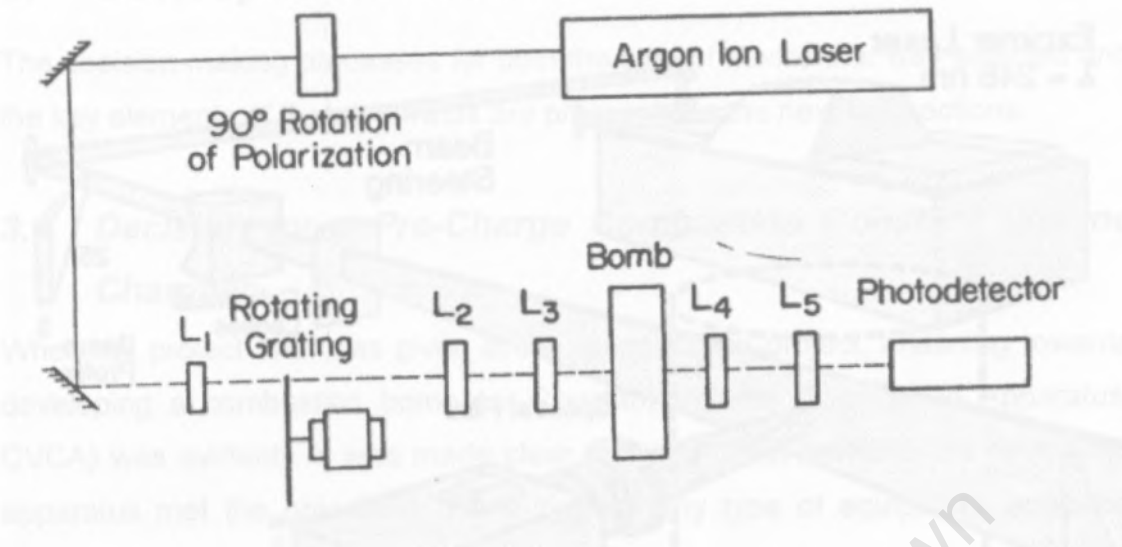


Figure 2.2.5: Optical Arrangement for Measuring Gas Velocity

### 2.2.6 Mie Scattering

The Mie scattering technique requires a collimated sheet of laser light (from an Nd:YAG laser in the cases of Sick et al. (2001) and Astill, Smith and Stopford, 1997) and an image-capturing device, such as a CCD camera. The camera records the signals originating from scattered laser light off particles (e.g. soot) in the volume under consideration. Since it is scattered light that is required for this technique, the image-capturing device has to be positioned at an angle (e.g. orthogonally) to the incoming laser light.

### 2.2.7 Laser Induced Incandescence

Laser Induced Incandescence in CVCA's has been used primarily to study soot formation and distribution in combustion research ([www.ricardo.com](http://www.ricardo.com) — "Combustion Tools and Techniques" and Astill, Smith and Stopford, 1997).

### 2.2.8 Laser Induced Fluorescence

Laser Induced Fluorescence has been used to image fuel vapour distribution (Winklhofer et al., 1993). The fluorescence radiation of hydrocarbon molecules can be induced by pulsed laser light sheet and observed with an

intensified (CCD) camera. The following figure shows the orthogonal optical access used by Winklhofer et al. (1993) for this technique.

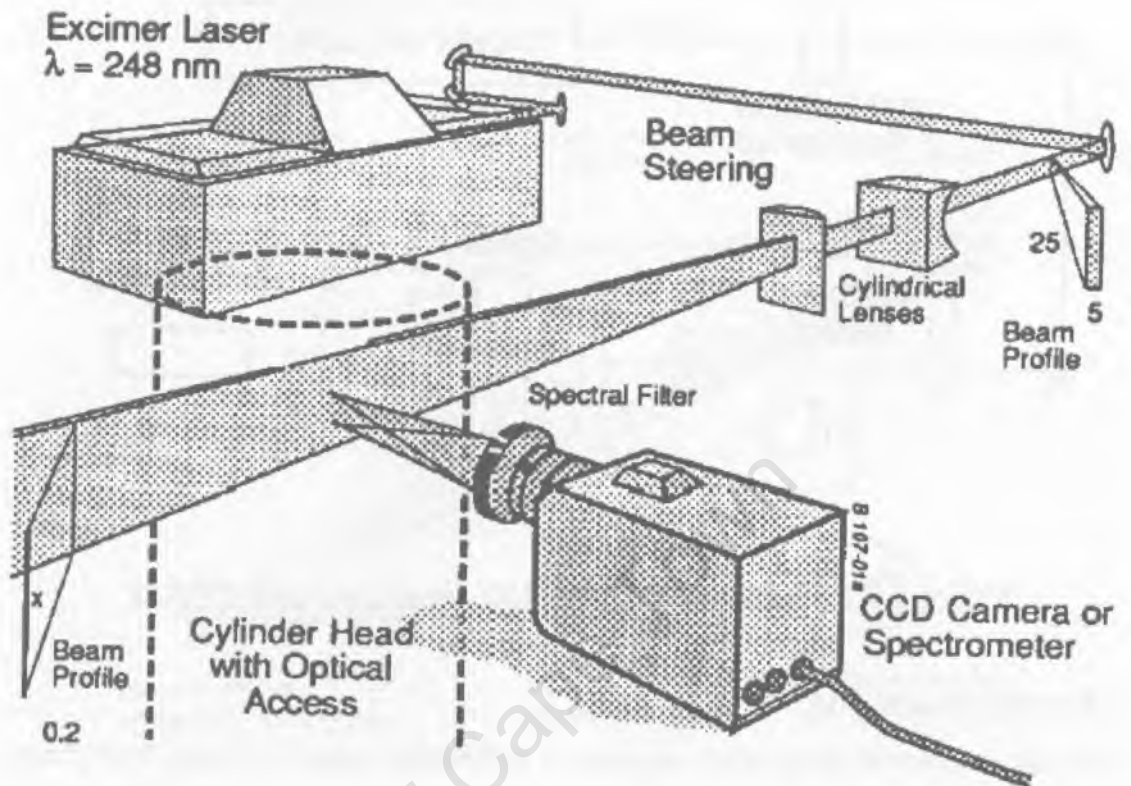


Figure 2.2.8: Optical Arrangement for Laser Induced Fluorescence

### **3. Concept Formation**

The decision-making processes for both the type of device that was selected and the key elements of that apparatus are presented in the next two sections.

#### ***3.1 Decision for a Pre-Charge Combustion Constant Volume Chamber***

When the project brief was given at the outset of the project, a leaning towards developing a combustion bomb (or Constant Volume Combustion Apparatus, CVCA) was evident. It was made clear, however, that provided the developed apparatus met the objectives of the project, any type of equipment would be acceptable.

The first decision to be made concerning the most suitable type of apparatus was whether to select a constant volume device or a rapid compression machine (RCM). Both have been used successfully in this type of research, as shown in Section 2.1, and both had the potential to meet the requirements of the project brief. They also both had advantages and drawbacks, but one key aspect of a rapid compression machine resulted in it not being selected. An RCM inherently has a disadvantage with regard to optical access, when compared with a CVCA, because of the compression piston. The concept of transparent pistons in research equipment is not unknown; however, the attainment of complete line-of-sight through the combustion chamber of an RCM would still prove to be a challenge. The requirement of maximal optical access to the combustion chamber was thus most simply achieved by the selection of a CVCA over an RCM.

The decisions concerning the details of a CVCA still remained. The options that were considered to achieve the desired maximum temperature at the time of injection of 1000 K (Refer to Section 1.2.1) were as follows: electrically heated, rapid transfer, continuous flow and pre-charge combustion (Refer to details in

Section 2.1.2). The first three methods all involve electrical heating to the desired temperature at the time of injection, which significantly affects vessel strength, limiting peak pressure. Other major drawbacks of these CVCA types that would have to operate at high temperatures are that the sealing of windows and components and the cooling of sensitive components becomes difficult. As described in Section 2.1.2.1, the rapid transfer and continuous flow types do have advantages over the standard electrically heated CVCA, but also carry the respective disadvantages of a secondary complex vessel and a low maximum operating pressure. The pre-charge combustion method of achieving the desired peak conditions was chosen as it avoids the disadvantages associated with constant high temperature operation.

### ***3.2 Development of Key Design Characteristics of the Constant Volume Combustion Chamber (CVCC)***

Five design aspects identified as requiring major mechanically-significant decisions with closely contesting feasible alternatives are discussed in the following paragraphs.

#### **3.2.1 Geometry of the Combustion Chamber**

The shapes of combustion chamber that were considered for the CVCC were cylindrical (various proportions), cubical, spherical and extruded oval (discussed in Section 3.2.2). A spherical vessel does not lend itself to extensive optical access or to simple manufacture. From the literature studied, only Siebers et al. (1998) used a cubical chamber. Such geometry does lend itself to extensive optical access. However, it has the disadvantages of an intricate manufacturing process and a large chamber volume, which requires greater pre-charge gas quantities and greater injection volumes for pressure trace detection.

A cylindrical chamber has the following advantages:

- It is possible to achieve total line-of-sight optical access of the entire chamber.

- It is not too far removed from the geometry in an engine cylinder, in which the piston is close to Top Dead Centre, and hence lends itself to use with standard injector nozzles in the following respects.
  - Both fuel impingement and flame quenching on chamber walls can be easily avoided.
  - The optical access attainable for a relatively small chamber volume is favourable.
- Finally, temperature homogeneity is easy to achieve by means of forced turbulence.

The optimal dimensions of a cylindrical chamber are discussed in Section 4.2. For a time, it was considered to have a cylindrical chamber of variable depth by making use of different bases, with the primary purpose of being able to emulate piston geometry. This idea, however, was abandoned for this fundamental development stage as the implementation of it could result in detrimental effects on optical accessibility and crevice-volume reduction.

### **3.2.2 Combined Compression and Spark Ignition Apparatus**

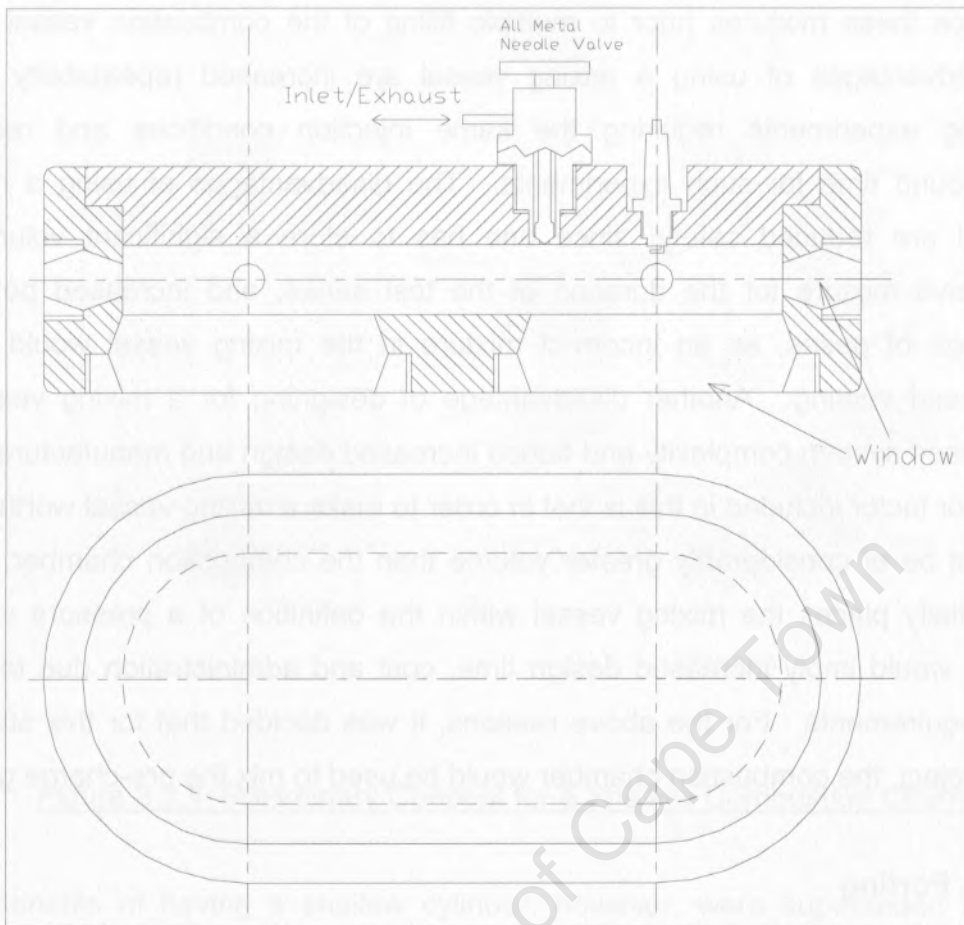
Though from the outset the priority of the apparatus was not to provide for spark-ignition fuel testing, it was considered and received the necessary attention in the conceptual phase. The testing of spark-ignition fuels in a combustion apparatus may take on various forms depending on the purpose of testing.

If a more universal testing method is desired for bridging the gap between spark and compression ignition fuels, in light of Homogenous Charge Compression Ignition engine research, then the following can be implemented. An entire range of fuels from compression-ignition to spark-ignition fuels (possibly with an added lubricant to prevent pump damage if necessary, provided the lubricant doesn't significantly alter results) could be injected directly into a CVCA following pre-charge combustion using a diesel injection system. Alternatively, a high pressure

Gasoline Direct Injection system could be used for spark-ignition fuels to emulate (delayed) compression ignition combustion events.

The conventional form of testing spark-ignition fuels that may be desired is that in their standard homogenous state. The primary purpose of such tests would be to view the onset of auto-ignition in end gases. It was initially thought that gasoline could be injected into a pre-combusted environment (as with diesel, but at an appropriately lower temperature) and allowed to fully evaporate before sparking. However, it was determined that this method would not be satisfactory using a pre-charge CVCA for the following reason. In order to initiate ignition by sparking at engine-similar conditions, the gasoline/air charge would have to be exposed to higher-than-engine temperatures for a significant period of time, in which unwanted chemical reactions would occur. Therefore, the alternative method, considered to be a viable form of testing homogenous fuel/air mixtures, is to use the combustion of the charge itself to create auto-ignition conditions in the end gas. The homogenous mixture could be achieved and ignited at the initial temperature and pressure conditions. In the very early stages, it was thought that flexibility in the flame-path length would be useful in the attainment of auto-ignition (knock) in the end gas. An example of an early idea to have an extended vessel chamber is shown in the following sketch.





**Figure 3.2.2: Sketch of Early Idea for Extended Chamber for Knock Viewing**

The primary drawback of an extruded oval-shaped combustion chamber would be the difficulty of sealing, while maintaining optical accessibility. This idea was soon replaced by that of a cylindrical chamber of fair diameter having the flexibility of electrical heating, spark plug positioning and variable initial pressure. It was thought that autoignition of a useful range of spark-ignition fuels could thus be induced in the end gas.

### 3.2.3 Mixing Vessel

A pre-charge CVCA requires a predetermined, accurate preparation of gases in order to produce the desired environment for fuel injection. Leading CVCA developers, e.g. Daniel Oren and Dennis Siebers, have used mixing vessels to

produce these mixtures prior to multiple filling of the combustion vessel itself. The advantages of using a mixing vessel are increased repeatability when running experiments requiring the same injection conditions and reduced turnaround time for such experiments. The disadvantages of using a mixing vessel are reduced safety, since one has to store a significant volume of explosive mixture for the duration of the test series, and increased potential wastage of gases, as an incorrect mixture in the mixing vessel would imply increased venting. Another disadvantage of designing for a mixing vessel is increased system complexity and hence increased design and manufacture time. A major factor included in this is that in order to make a mixing vessel worthwhile, it must be of considerably greater volume than the combustion chamber. This potentially places the mixing vessel within the definition of a pressure vessel, which would imply increased design time, cost and administration due to OHS Act requirements. For the above reasons, it was decided that for this stage of the project, the combustion chamber would be used to mix the pre-charge gases.

#### **3.2.4 Porting**

The circumferential porting of the CVCC was developed as the design phases became more detailed. It was preferable to have as shallow a cylindrical chamber as possible for the purposes of minimising chamber volume and attaining top-dead-centre similarity. As a result, without all the practicalities having been considered, a typical conceptual sketch was drawn up as follows.

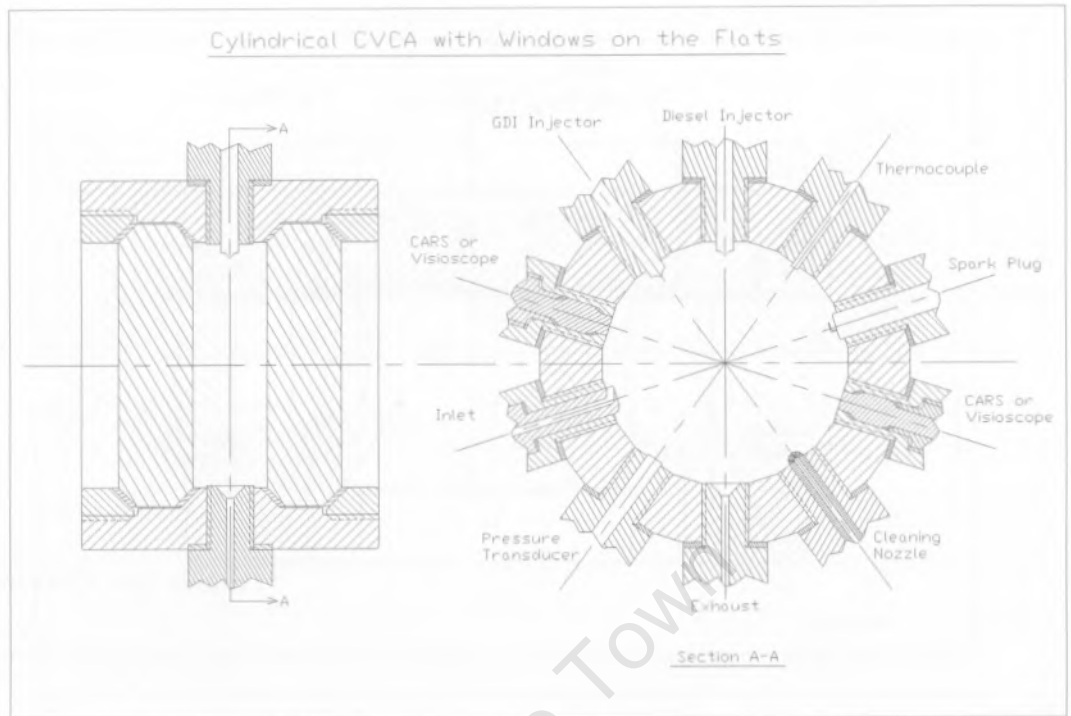
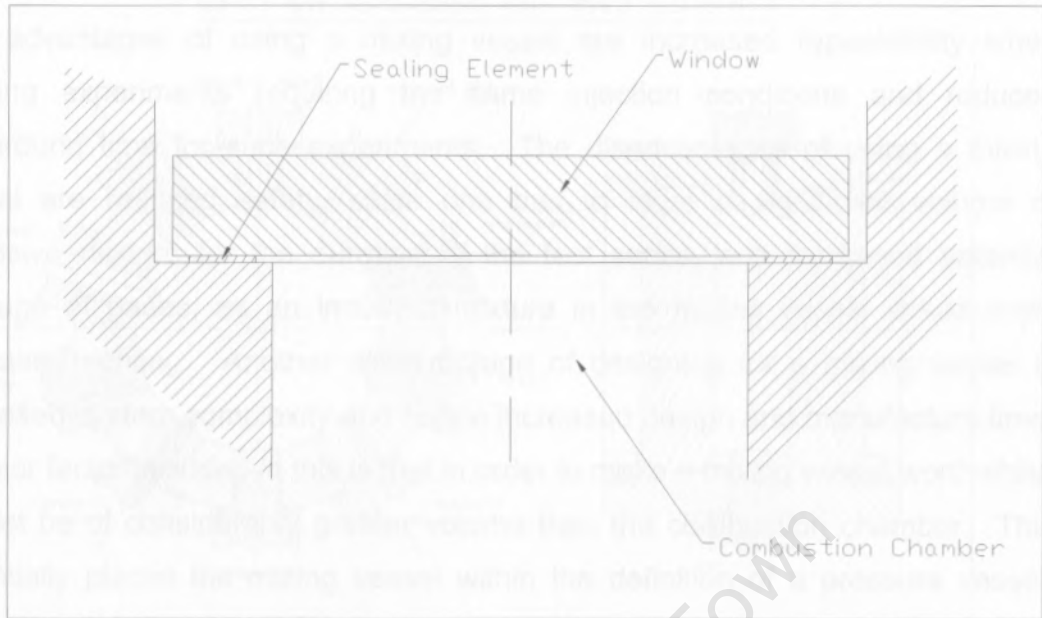


Figure 3.2.4: Preliminary Concept for a Shallow Combustion Chamber

The benefits of having a shallow cylinder, however, were superseded by the requirement to have adequate optical access orthogonal to the centreline of the cylinder. This required a deeper combustion chamber and larger ports. In order to maintain a sufficient number of circumferential ports, it was necessary to design both large and smaller circumferential ports. In the final design, these are alternating and number eight in total. An added benefit of having larger ports was that standard parts, such as spark plugs, could be used in the circumferential inserts.

### 3.2.5 Window Shape

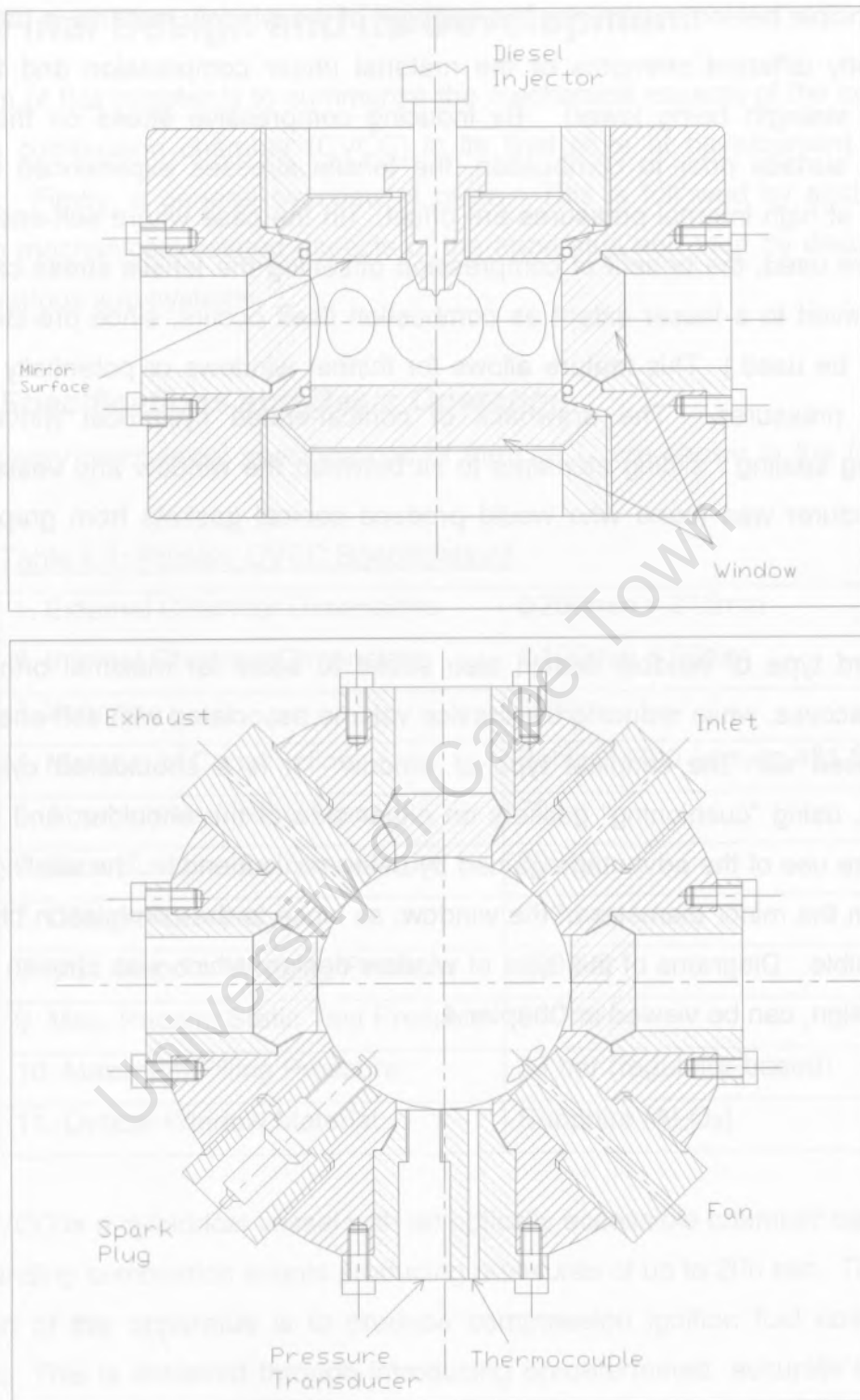
Three major options present themselves when **considering the** shape for optical windows. The simplest of these is a cylindrical window that would seal on a shoulder of the vessel, as shown in the following sketch.



**Figure 3.2.5a: Sketch of Simplest Form of Optical Window**

The only advantage of such a window is low cost, due to ease of manufacture. This arrangement does not lend itself to all-round optical access, as strength constraints of the sealing shoulder limit the extent of orthogonal optical access. The problematic sealing issues associated with such a design are described in Section 4.9.

A better window design that would improve all-round optical access potential as well as maximise the strength of the window material was to have conical ends, as shown in the following concept diagram views.



**Figure 3.2.5b: Concept Showing Optical Windows with Conical Ends**

The principle behind maximising the strength of the window material is based on the vastly different strengths of the material under compression and tension (tensile strength being lower). By inducing compressive stress on the outer window surface prior to combustion, the tensile stresses experienced by this surface at high internal pressures are offset. (In the case where self-energising seals are used, the benefit of compression offsetting the tensile stress can also be achieved to a lesser extent as combustion itself occurs, since pre-stressing can not be used.) This feature allows for thinner windows or potentially higher internal pressures. The drawback of conical-ended cylindrical windows is obtaining sealing / sliding elements to sit between the window and vessel. No manufacturer was found who would produce conical gaskets from graphite or Teflon.

The third type of window design also seeks to allow for maximal orthogonal optical access, while reducing the crevice volume associated with self-energising seals used with the simplest type of window. It is a shouldered cylindrical window, using "cushioning" gaskets on either side of the shoulder, and it does not make use of the advantage gained by using conical ends. The sealing takes place on the minor diameter of the window, as close to the combustion chamber as possible. Diagrams of this type of window design, which was chosen for the final design, can be viewed in Chapter 4.

## 4. Final Design and its Development

The aim of this chapter is to summarise the mechanical aspects of the constant-volume combustion chamber (CVCC) in its final state of development for this project. Firstly, a general overview is given. This is followed by sections on specific mechanically-related aspects of the apparatus and then by descriptions of the various sub-systems.

### 4.1 Specifications and Basic Operation

The primary mechanical specifications of the CVCC are shown in the following table.

Table 4.1: Primary CVCC Specifications

1. External Chamber Dimensions	ø250mm × 215mm
2. Internal Chamber Dimensions	ø100mm x 50mm
3. Volume	393cc
4. Material of Construction	Bohler M300 (sim. to 431 SS)
5. Approximate Vessel Mass	70 kg
6. Max. Sustainable Temperature	200°C
7. Design Pressure	200 bar
8. Max. Recom. Working Pressure	200 bar
9. Max. Recom. Static Test Pressure	300 bar
10. Maximum Filling Pressure	34 bar (regulator-based)
11. Optical Window Material	Sapphire (Al <sub>2</sub> O <sub>3</sub> )

The CVCC is a cylindrical vessel with an optically accessible chamber capable of withstanding combustion events producing pressures of up to 200 bar. The basic function of the apparatus is to produce compression ignition fuel combustion events. This is achieved through introducing predetermined, accurate amounts of Acetylene, Hydrogen (depending on requirements), Nitrogen and Oxygen into the chamber. The mixture is ignited resulting in complete combustion (pre-charge combustion) and a rapid pressure and temperature increase. The

temperature and pressure drop relatively gradually due to heat lost to the walls of the vessel. At a pre-selected pressure, the fuel being studied is injected into the chamber. The predetermined component of residual oxygen in the chamber, being dependent on the original constituents, yields either an inert environment or a range of environments supporting compression ignition. In this way, visual observations can be made of controlled fuel sprays and compression-ignition combustion events.

#### ***4.2 General Arrangement of the Apparatus***

The CVCC can be positioned on the steel table with its cylindrical axis either vertical or horizontal, depending on the experimental requirements. The high-pressure test fuel unit is set up on a separate table, which is placed adjacent to the main experimental table, as are the fill-gas cylinders. Two personal computers are used to control and acquire data from the CVCC.

The two ends of the CVCC's cylindrical chamber are formed by either windows or metal inserts that are each fastened in place by a retaining ring. The windows allow for complete viewing of the combustion chamber. The metal insert is either a blank or one which can house either a spark plug or an injector. Eight other ports exist around the chamber's central circumference, with medium and smaller sized ports alternating at 45° to one another. The ports can be used for windows, a spark plug, an injector, the instrument insert including a pressure transducer and thermocouples, the inlet and exhaust valves, the mixing fan, or they can be blanked off. A basic schematic model of the CVCC itself is shown in the following diagram (further detail can be seen in sections 4.4 & 4.5 as well as in Appendix A).



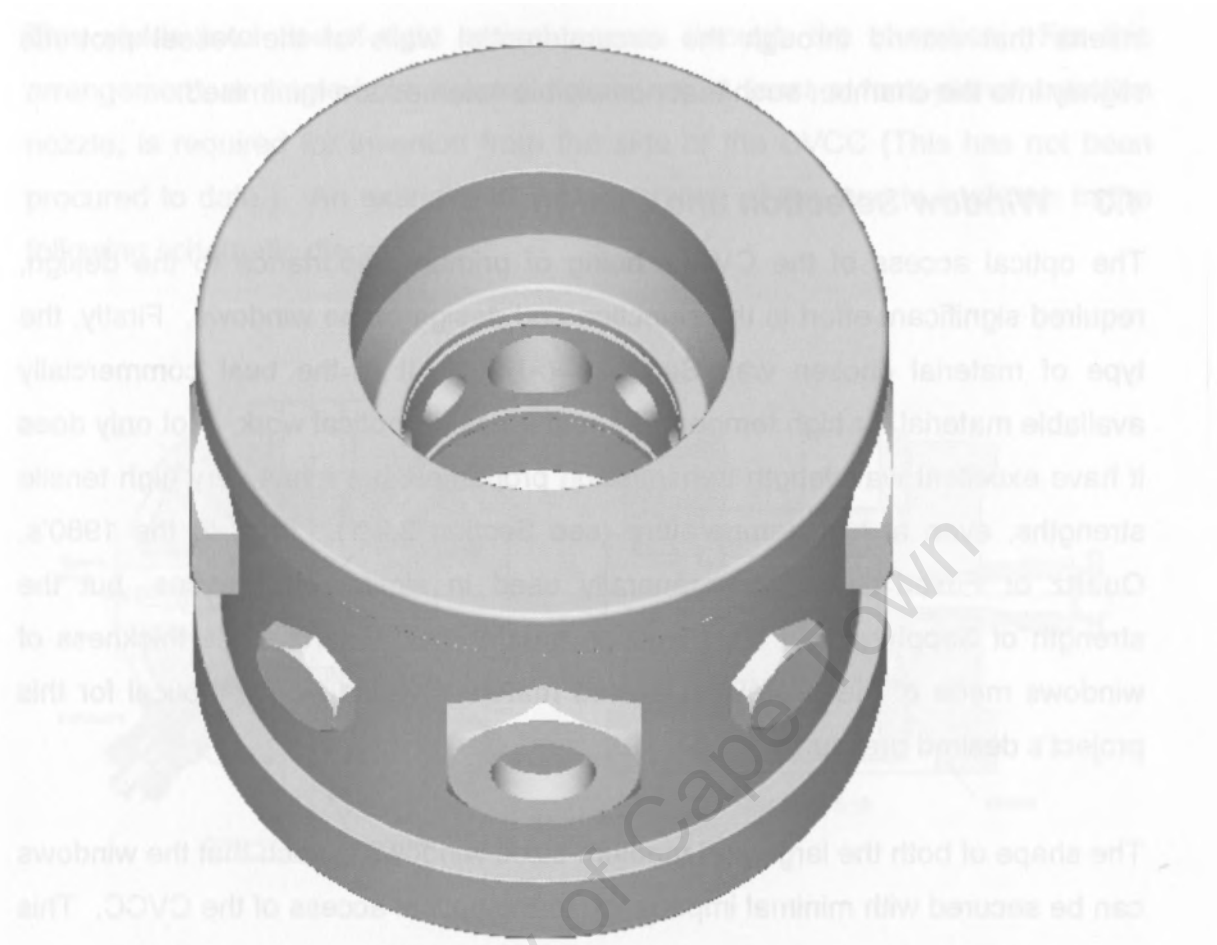


Figure 4.2: Model of CVCC Vessel and Basic Inserts

The internal shape of the CVCC was finally decided upon to be cylindrical, with the diameter being 100mm and the height, 50mm. A cylindrical chamber has these main advantages; it is fairly straightforward to achieve complete visual access and its machining is not too complicated (See Section 3.2.1 for other advantages.). The diameter's dimension is such that the combustion events of most light duty diesel engines can be simulated without spray interference with the walls. The height of the chamber was mainly determined by the need to have sufficient optical access orthogonal to the centreline as well as enough space for equipment inserts. This was balanced by the desires to minimise the volume of the vessel and to not be too far removed from engine geometry. Finally, the

inserts that extend through the circumferential walls of the vessel protrude slightly into the chamber such that non-visible volumes are minimised.

### ***4.3 Window Selection and Design***

The optical access of the CVCC, being of primary importance to the design, required significant effort in the selection and design of the windows. Firstly, the type of material chosen was Sapphire (Al<sub>2</sub>O<sub>3</sub>). It is the best commercially available material for high temperature and pressure optical work. Not only does it have excellent wavelength transmission properties, but it has very high tensile strengths, even at high temperature (see Section 2.2.1). Prior to the 1980's, Quartz or Fused Silica was generally used in similar applications, but the strength of Sapphire is at least 5 times greater than Quartz. The thickness of windows made of these previously-used materials would be impractical for this project's desired pressures.

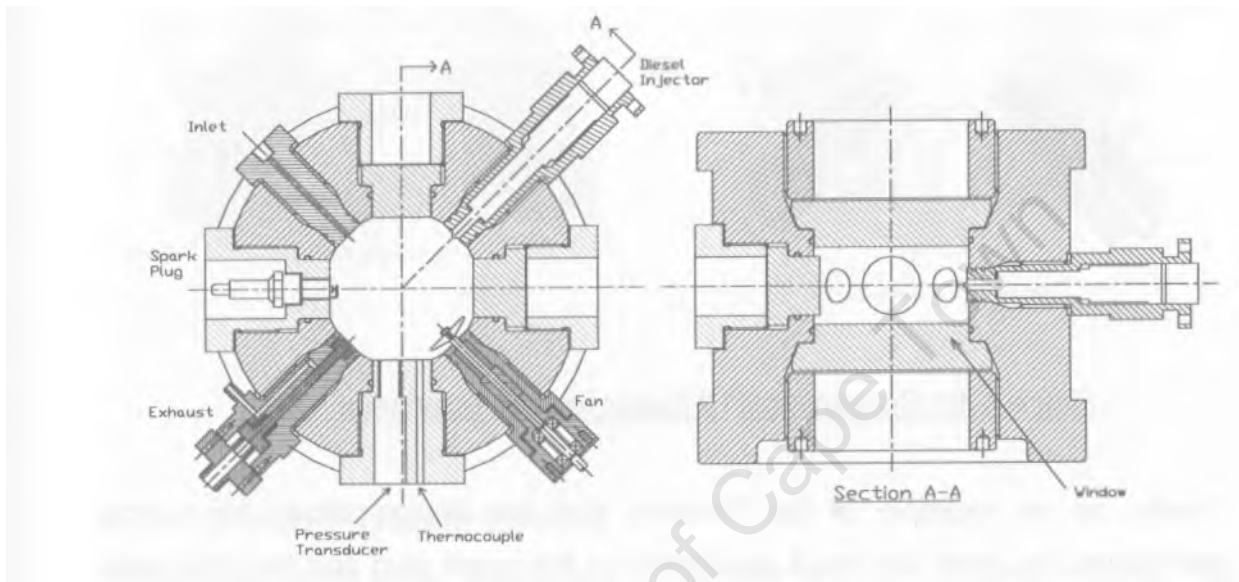
The shape of both the large and medium-sized windows is such that the windows can be secured with minimal impedance to the optical access of the CVCC. This required intricate machining for this material (Sapphire) and resulted in only a few possible suppliers worldwide and long lead-times. The windows were designed to form a seal on their circumferences for reasons mentioned in Section 4.9. The surface finish and optical quality of the windows was of critical importance and the details of these specifications for the procured windows can be found in Appendix A.

### ***4.4 Compression Ignition Arrangements***

In response to the important user requirement of flexibility in the use of optical techniques for compression ignition events, a significant design emphasis was placed on this aspect.

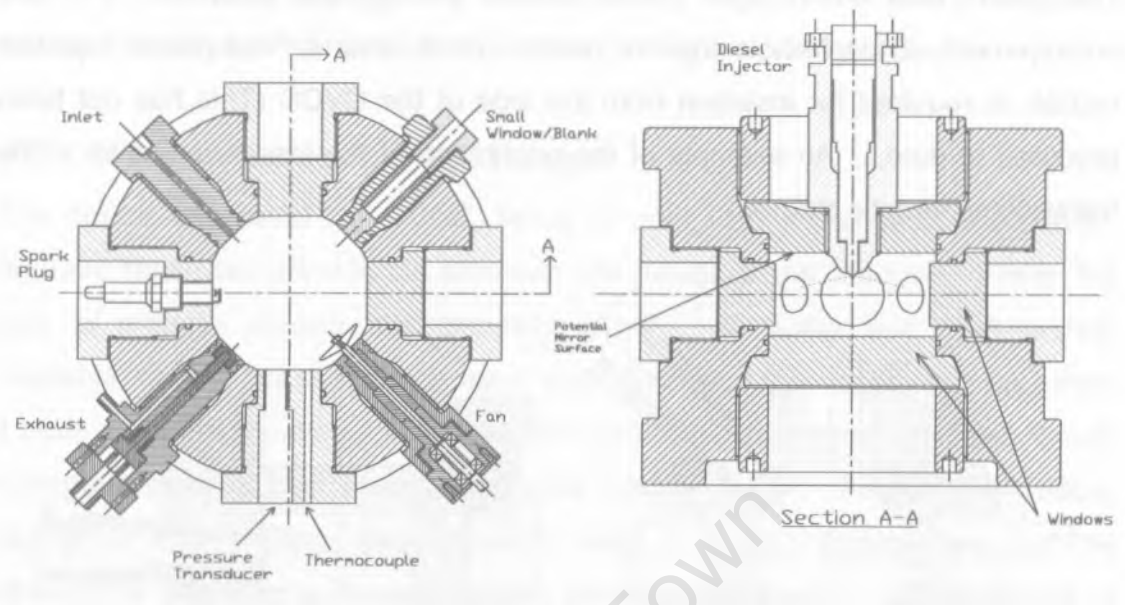
The pre-eminent arrangement of the apparatus for viewing compression ignition events is to use the two large windows on either end of the cylindrical chamber.

This yields total line-of-sight optical access through the chamber. For this arrangement, a single-hole injector nozzle, or at least a "one-plane" injection nozzle, is required for insertion from the side of the CVCC (This has not been procured to date.). An example of the orientation of the inserts is shown in the following schematic diagram.



**Figure 4.4a: Preferred Compression Ignition Arrangement**

The other major orientation is to use a conventional direct injection diesel injector installed centrally in a metal end, used in place of a large window (see Fig. 4.4b). As with the former arrangement, two medium-sized windows can be used from the sides, either in-line or orthogonal to one another. The metal-end arrangement opens up a small port on the side of the vessel, which can either be blanked or used for a 10mm aperture window. The metal end is not polished in its present state, but the material of construction (Bohler M300) will yield a mirror surface on polishing. This may be necessary for certain optical techniques if the entire chamber requires imaging, e.g. high-speed shadowgraphs as used by Toyota Central Research (Hayashi et al., 1984).



**Figure 4.4b: Conventional DI Diesel Injector Arrangement**

Finally, as an example of the flexibility that the design allows for optical techniques, by using the metal end insert for the spark plug and the one-plane injector from the side, three medium-sized windows can be used together with the large window.

#### **4.5 Homogenous Charge Spark Ignition Arrangements**

The CVCC was also designed with homogenous charge combustion in mind, though this was not a priority in the design. The potential for achieving a homogenous charge exists either by way of a pre-mixing chamber for fuel and gas or by way of a fine fuel injector used in conjunction with the internal fan. The spark plug can be installed either from the side or in the metal end (as shown in the following figure), depending on the requirements for auto-ignition and the viewing thereof.

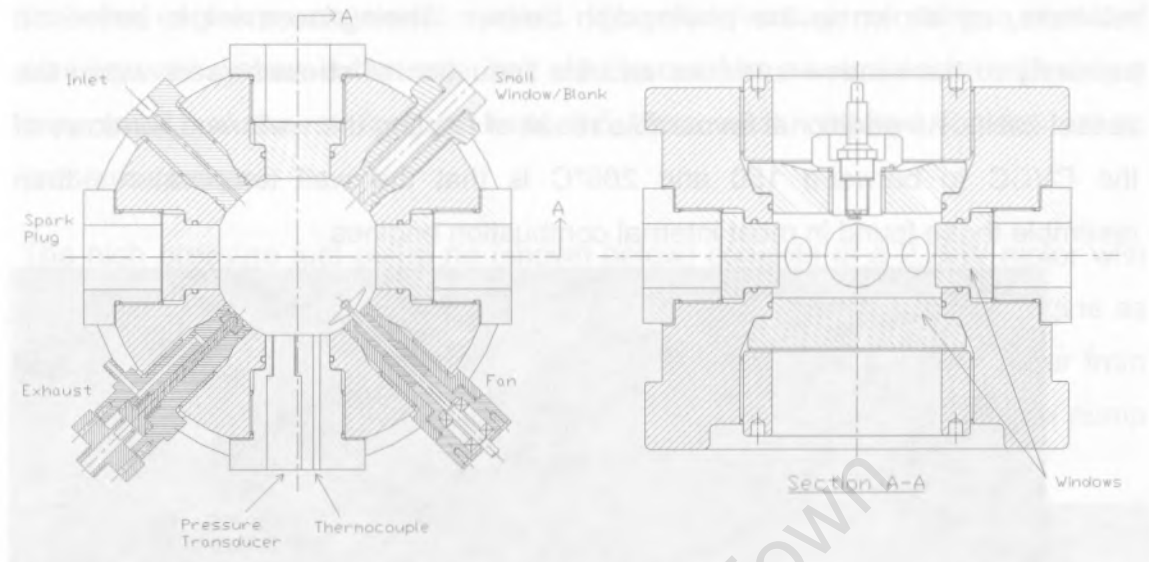


Figure 4.5: A Homogenous Charge Spark Ignition Arrangement

#### **4.6 Heating System Design**

Pre-charge combustion produces a significant amount of water vapour, the fraction depending on the reactant constituency. Because the walls and windows of the CVCC are at a relatively low temperature compared with that of the environment produced, the potential exists for condensation to occur on these surfaces. For optical access to fuel sprays or combustion events, the relative humidity based on window temperature and chamber pressure at the time of injection must be below 100%.

It was determined that a temperature range of 150 to 200°C on the CVCC surfaces would be sufficient for the range of desired heated experiments to prevent water condensation on the windows during the injection event (See Appendix C). A temperature of 150°C can be produced using eight 200 Watt cartridge heaters controlled by a temperature controller and solid-state relay. The temperature controller reads the temperature from a K-type thermocouple that terminates within 3mm of the surface of the window-equivalent Instrument

Plug. Four cartridges are placed equidistantly in each of the end-window (large) retainers, as shown in the photograph below. Their placement is based on proximity to the window surfaces and the reduction of stress raisers within the vessel itself. An additional favourable result of heating the walls and windows of the CVCC to between 150 and 200°C is that the wall temperatures then resemble those found in most internal combustion engines.

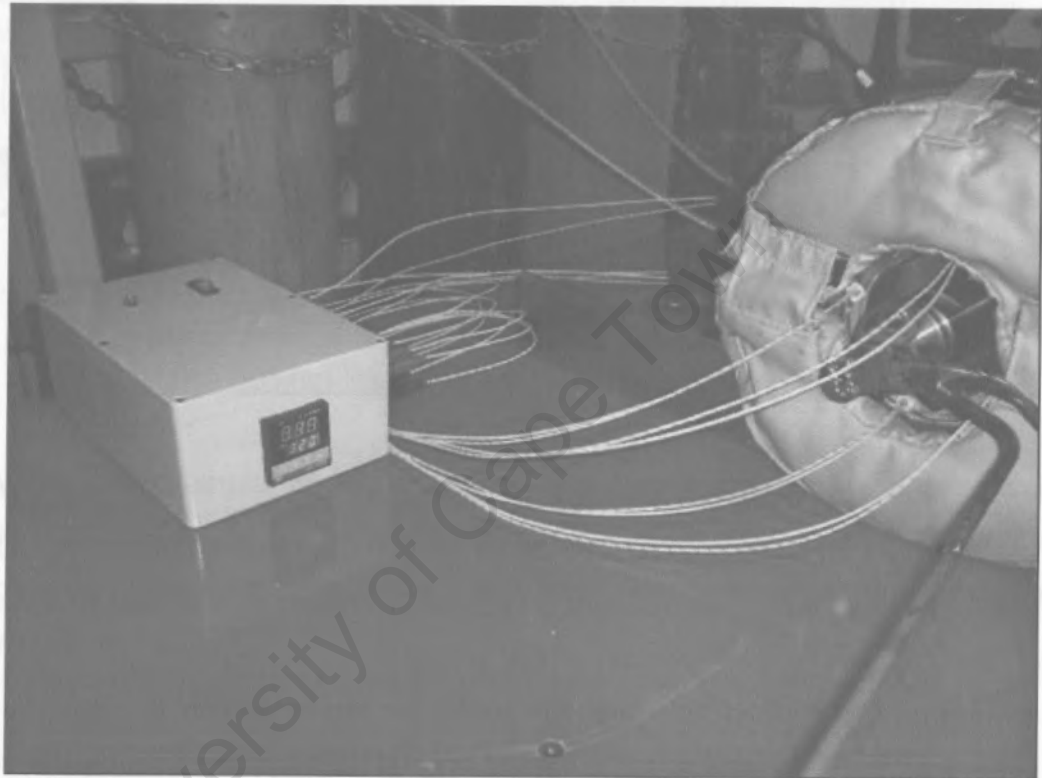


Figure 4.6: Heating Cartridges in Retainer and Temperature Controller

The time taken to heat up the CVCC to 150°C is approximately 1% hours. For personnel safety reasons as well as maximum temperature generation, lagging is required. Fitted fire-proof insulation blankets were installed for this purpose.

#### **4.7 High Pressure Fuel Pump Rig**

It was thought that the simplest and best method to achieve a timed single injection event would be to make use of a modern common rail diesel injection system. The major advantage of **such** a system is the relative ease with which a

single event can be generated by simulating signals that would normally emanate from the engine management system. The disadvantage of using a standard common rail system is that one isn't able to conduct an experiment with only a very small volume of fuel; at least 0.5 litres were required for the set-up presented herein.

The high pressure fuel pump rig (shown below) consists of a 2.2kW motor with controller, a high-pressure (HP) diesel pump from a 2003 BMW 320d engine as well as a 2<sup>nd</sup> generation common rail (accumulator), injector and fuel filter from the same model. A standard fuel filter and a low pressure (LP) Bosch fuel pump are used to supply the BMW equipment with fuel at the required pressure.



Figure 4.7: High Pressure Fuel Pump Rig

The system is rated to deliver fuel to the injectors at pressures up to 1600 bar, but with the 2.2kW motor (which was all that UCT had available), it was deemed safe to operate only between 400 and 900 bar. (The power consumption of the HP pump in the 320d can be as much as 3.5kW and vibration of the motor-driven

rig became excessive at pressures above 900 bar.) The injection pulse is controlled via a counter on the National Instruments data acquisition board and consequently can be set to periods matching those that pilot injection regimes require.

#### **4.8 Strength, Temperature and Material Considerations**

The philosophy behind the calculations to determine the required strength for the CVCC was influenced mainly by the time available for the design and the benefit-to-effort ratio for such a research tool. This led to the decision that the student would not venture into the realm of Finite Element Analysis (FEA), but that the stress analysis would be carried out largely using basic principles. Though excessive strength would result in impractical wall thicknesses, it was determined that a conservative safety factor would not be significantly detrimental to the operability or cost of the apparatus and would speed up the design process.

The safety factor for the stressed metal components of the CVCC varies because it was unnecessary to always design on the limit; but a factor of 2.5 was set as the minimum. (This represented a 33% margin for the anticipated pressure test *and* was thought to be prudent in light of no FEA being done.) The material strengths at worst-case-scenario temperatures were used for all calculations. For the vessel itself, the philosophy for determining strength incorporated the principle of material replacement for nozzles and was as follows. The required thickness was calculated for the chosen inner radius of a vessel without any ports; the volume of material required was then equated to that of a vessel with ports and used to calculate the new outer diameter. The safety factor for the vessel is 2.7, based on the proof stress of the material of construction, for an internal surface temperature of 600°C at 200 bar. Stresses on all threads, sleeves and stressed portions of the CVCC were calculated and all designs were made to yield safety factors above the set minimum. The optical windows were designed with a minimum safety factor of 4.0 because of their brittle nature and



catastrophic mode of failure. The major calculations referred to in this paragraph are presented in Appendix B.

Many factors came into play when deciding on the material to be used for the CVCC; viz. corrosion resistance, high-temperature strength, machinability, post-machining treatment and cost, in descending order of importance. The details of the decision process are presented in Appendix B.1.2. Another factor excluded from this list was the availability of materials. Due to time and cost constraints, it was decided that only South African suppliers would be used. The final decision was between two Bohler steels: tool steel W302 (heat-treated) and mould steel M300, either in the annealed state or the hardened & tempered state. Both materials have good corrosion resistance properties, and this was considered essential with one objective being the desire for a long term research tool. The major advantage of annealed M300 (similar to AISI 431 SS) over W302 was that after machining, it was not necessary for it to go through a heat-treatment process to attain the necessary strength, a process which could cause deformation of the components. Consequently, Bohler M300 was chosen as the preferred material of construction for the CVCC vessel.

#### ***4.9 Sealing Mechanisms***

The predominant issue with regards to sealing methods for the CVCC is that of sealing the windows. The difficulty with non self-energising sealing, i.e. using gaskets, is two-fold. Firstly, since sapphire (like most ceramics) is exceptionally hard and brittle, it is very susceptible to cracking due to Hertzian stresses (point and linear loads). In a gasket sealing arrangement, such stresses could develop on the windows' surfaces due to grit on the sealing surfaces, uneven bolt forces or excessive tolerance on the cylindricity of the retaining rings. Secondly, the torque required to ensure that a threaded retainer ring produces a seal for 200 bar on the larger windows is impractical, as would the number, size and length of bolts be, if used.

The two types of self-energising seals that were considered were O-rings and U-cup seals. U-cup seals are capable of sealing higher pressures, but unfortunately the lack of availability in South Africa left them only as a contingency plan. O-rings are normally rated to 100 bar without a backing strip, but with tight clearances, sealing of 200 bar is possible even without a backing strip (O-rings have been used successfully by MIT for pressures even up to 1000atm, Hu and Keck, 1987). Viton rubber is used for O-rings in high temperature applications and can withstand a maximum temperature of 200°C. O-rings have been used before in CVCC's, **but** without satisfactory success in the case of Oren et al. (1984), who found the crevice volume created by using O-rings to cause irregularities in the diesel combustion event as a result of pre-charge combustion residuals. It was decided that despite this, O-rings would be used, but that two design features would be used to minimise this detrimental occurrence. Both design features are dependent on the positioning of the O-ring relative to the window / metal insert. As mentioned in Section 4.3, the O-rings seal on the windows' unpolished inner circumference, as shown in the following figure.

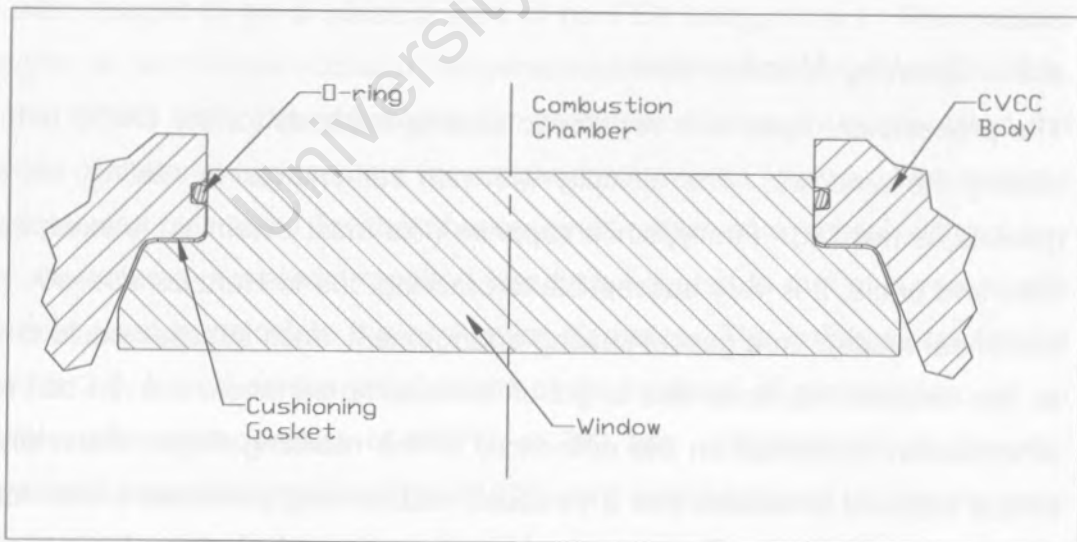


Figure 4.9: O-ring Sealing on Windows

The first advantage of this design is that the crevice volume does not increase in size when the window moves outward, due to the pressure increase during pre-charge combustion. Secondly, this design allows the crevice length leading up to the O-ring groove to be minimised. Finally, this arrangement allowed for the potential re-machining for U-cup seal grooves if the O-rings proved to be unsatisfactory in their performance.

#### **4.10 Exhaust Valve Design**

The exhaust valve of the CVCC is actuated by pressurised air that is controlled via a solenoid valve. The reason for using air as the actuating medium is because the temperatures of the exhaust gas from the CVCC would be too high for a solenoid valve to withstand directly. The setup is such that the exhaust valve will remain closed in case of a loss of electrical power, but that a purely manual exhaust can be achieved by cutting off the air supply.

The exhaust valve system also performs the function of a pressure relief safety valve. Since the exhaust valve needle is only kept closed by air pressure, if the force exerted by the internal pressure exceeds that produced from the supplied air pressure, the exhaust valve will open. The user inputs the required safety relief pressure into the appropriate programme and the value of the required air pressure to be supplied to the solenoid valve is returned. The required pressure is then set by means of the air pressure regulator.

An assembly drawing of the mechanical elements of the exhaust valve are shown in the following figure. The air is supplied via the solenoid valve to the internal thread (in red on the left) and the exhaust gases exit via the external thread at the top of the drawing (in blue).

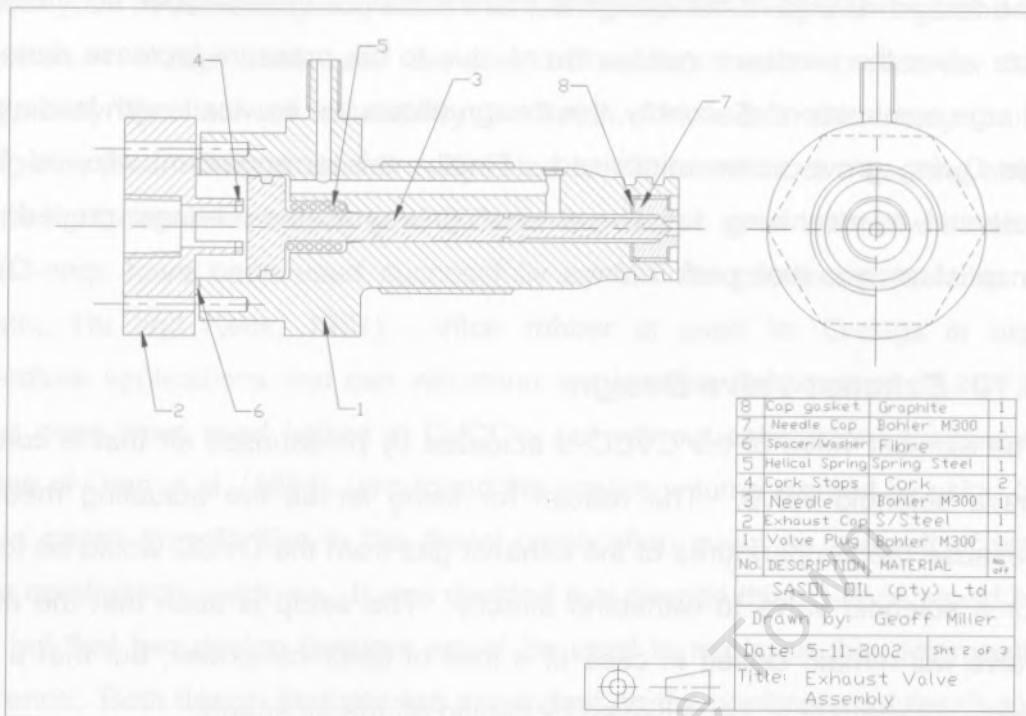


Figure 4.10: Assembly Drawing of Exhaust Valve Mechanicals

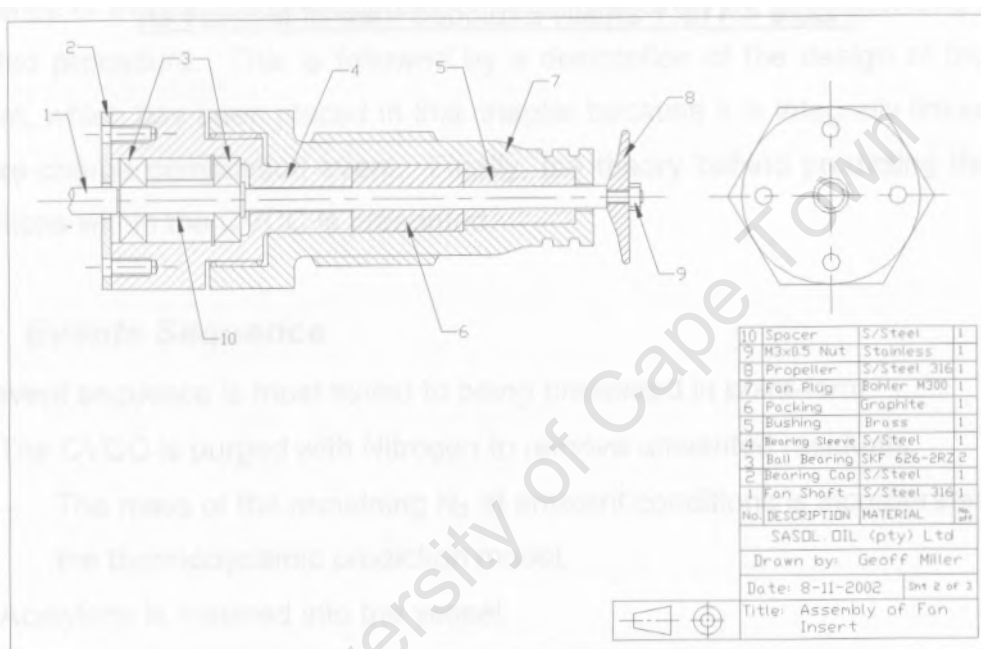
#### 4.11 Mixing Fan Design

The mixing fan is required for experiments in which the vertical temperature gradient that forms after pre-charge combustion is undesirable. (The temperature difference over 65mm can be as much as 500°C according to Siebers, 1985).

Two of the major pre-charge constant volume combustion apparatus development groups, viz. those under Daniel Oren and Dennis Siebers, have used mixing fans in their chambers. Both used rotational speeds in excess of 8000 rpm. The gas linear velocities generated within the chamber were in the order of 2m/s, negligible in comparison with diesel injection speeds, and have proven to have no significant affect on ignition delay (Siebers, 1985).

The fan needed to be able to resist the temperature of the surrounding walls, which would be at a maximum of 200°C. This posed a problem for bearings, as

high-temperature standard bearings could only resist 150°C. The high pressures that needed to be sealed against a rotating shaft also proved to be a challenge. In the end, it was decided to seal the shaft using graphite packing. The unit which compresses the packing is also used to house the bearings and is situated away from the walls of the CVCC. The two-blade propeller was hand-filed and because its function was purely to produce turbulence, calculations were not used to determine the angles of the blades. An assembly drawing and photograph of the mixing fan assembly are shown in the following figures.



**Figure 4.11a: Assembly Drawing of Mixing Fan**

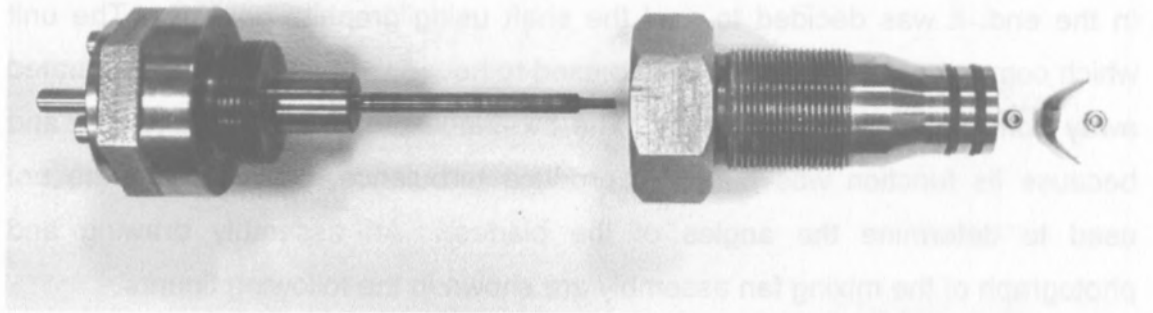


Figure 4.11b: Partially Exploded View of Mixing Fan

University of Cape Town

## 5. Pre-Charge Combustion

The intent of this chapter is to describe the practical and theoretical aspects of the pre-charge combustion event that produces the desired environment for the injection of the fuel under study. Certain aspects have already been discussed and will not be repeated, viz. the exclusion of a mixing vessel (Section 3.2.3) and the basic operation of the pre-charge combustion event in the Constant Volume Combustion Chamber (CVCC) (See Section 4.1). Firstly, the detail of the sequence of events will be described in order to provide an understanding of the adopted procedure. This is followed by a description of the design of the inlet system, which has been placed in this chapter because it is integrally linked with the pre-charge combustion event. Finally, the theory behind predicting the end conditions within the CVCC is presented.

### 5.1 Events Sequence

The event sequence is most suited to being presented in point-form:

- The CVCC is purged with Nitrogen to remove unwanted residuals.
  - The mass of the remaining N<sub>2</sub> at ambient conditions is incorporated into the thermodynamic prediction model.
- Acetylene is metered into the vessel.
  - The standard (welding) regulators on Acetylene cylinders have a low maximum pressure, necessitating this fill position.
- Hydrogen is metered into the vessel.
  - Though hydrogen causes an increased propensity for condensation, it enables lower resultant temperatures and lower densities in experiments.
- The low filling pressure, pressure transmitter is isolated and vented.

This is to avoid overpressure of the device, which is used for accurate measurements at low pressures

- Nitrogen is metered into the vessel.
  - The reason for leaving Oxygen till the end is to minimise the risk of having a combustible mixture in the CVCC.
- Oxygen is metered into the vessel.
  - The remaining gases in the inlet system, though primarily oxygen, are considered to have a negligible altering effect on the intended composition of the gases within the CVCC, due to the small volume of the inlet system.
- The manual inlet valve is closed.
- The inlet system is vented to protect the high pressure transmitter and the system itself, in case of valve leakage.

#### Ignition:

The CVCC is now primed for pre-charge combustion and the mixture will be ignited in accordance with the procedure of the controlling computer programme. The programme ensures that all necessary aspects for the recording of the pressure trace by the secondary computer are in place. The controlling computer causes the spark plug to fire several times to reduce the chance of a misfire. The ignition system consists of a MOSFET switching arrangement, an ignition module, a 40kV ignition coil (**with** capacitor) and a motorcycle spark plug (See Appendix G for details).

## **5.2 Inlet System Design**

The **inlet** system will be described, explained and then some intricacies will be discussed.

### **5.2.1 General Arrangement and Quick-Coupler Philosophy**

The inlet system comprised of the following major components, moving outwards from the chamber:

- Inlet Insert with 3mm diameter bore
  - As small a bore as was practical for the length required



- Manual Needle Valve
  - For shut-off at high temperature and pressure
- High fill-pressure pressure transmitter
  - For accurate measurements from 4 - 40 bar
- Low fill-pressure pressure transmitter with 3-way vent
  - For accurate measurements from 0 - 4 bar and to isolate from inlet system to prevent over-pressure (8 bar). [This instrument was added late in the design phase after considering the accuracy of the 0 - 40 bar pressure transmitter for the critical filling of the fuels.]
- Inlet System Vent
  - To prevent over-pressure of system in case of manual needle valve leakage
- Solenoid Inlet Valve
  - Controlled by computer
- Check Valve
  - To prevent back-flow through solenoid valve. [This was only added after discovering that the solenoid inlet valve couldn't hold high pressures in the reverse direction.]
- Non-closing Quick-Coupler
  - The needle-shaped non-closing connection was chosen over the enveloping closing connection (that each gas hose has) so that the operator would not have to couple against high pressures.

Each gas hose had a quick-coupler connection that sealed on release and a check valve to prevent back-flow and flashback. The high-pressure hoses for the Oxygen and Nitrogen also had relieving ball valves to release the pressure in the hose.

The philosophy behind having one inlet quick-coupler connection to which each of the four gas quick-couplers must be connected sequentially was as follows. The intention for the inlet system was to have as small a volume as possible to

avoid inaccurate mixtures resulting from residual gases in the system. Though a manifold with each of the four gases connected via a solenoid valve would have made the filling procedure more automated, it would have increased the volume of the inlet system. Secondly, such a manifold arrangement would mean that a flammable mixture of gas could at times exist in a volume outside the CVCC itself. This was considered a safety risk. Finally, the period that saw the development of the inlet system was following the purchasing of the optical windows. Consequently, budgetary concerns further swayed the decision towards the single solenoid valve option.

### **5.2.2 Fill Pressure Measurement and Flow Considerations**

As mentioned in Section 5.2.1, two pressure transmitters were used to measure the pressure during each fill stage to an appropriate accuracy. The rate of filling of each gas prior to reaching the desired end pressure was of critical importance to accurate and repeatable gas mixtures. Two related aspects influenced this rate, viz. the difference in pressure between the set regulator pressure and the required pressure; and the restriction to flow of the inlet system. If these aspects were unfavourable, the inlet solenoid valve closed the moment **the** pressure in the inlet system reached the required pressure and the pressure then dropped due to equalising flow into the CVCC. To overcome this potential problem, an operational and a mechanical device were employed. Firstly, the gas regulators were to be set only marginally above the required pressure of each fill. Secondly, a restriction orifice was installed upstream of the inlet solenoid valve to reduce the flow rates. The details regarding these solutions are described in Section 8.2.1 under "Fill Procedure Improvements".

### **5.3 Thermodynamic Model of Pre-charge Combustion**

The theory and method used for predicting the required fill pressures of the pre-charge gas constituents was as follows. The user entered the desired end temperature and pressure, the percentage of "Exhaust Gas Recirculation" to be simulated and the CVCC wall temperature into the spreadsheet-based model.

With these requirements and parameter, the CVCC pressure for each gas was calculated. The accumulative pressures were based on Amagat's mole-based Gas Mixture Law for Ideal Gas Mixtures. The model solved for the partial pressures of the reactants that would satisfy the user requirements by performing an Internal Energy balance with the products, based on the initial and final temperatures. (The products included Carbon Monoxide and Hydrogen from dissociation reactions.) The internal energies of the products and reactants were calculated from Specific Heat constants at Constant Pressure ( $C_p$ ) for the applicable temperature ranges (Calculations in Appendix C). The model simultaneously solved for the dissociation products from the Water Gas Shift ( $H_2O + CO \leftrightarrow CO_2 + H_2$ ) and Carbon Dioxide ( $CO_2 \leftrightarrow CO + \frac{1}{2}O_2$ ) dissociation reactions. The dissociation equilibrium compositions were calculated using the Gibbs Function,  $dG$  (which is defined as:  $dG = dh - Tds$ ), and were assumed to be reached instantaneously. Finally, the relative humidity was calculated for the set pressure at the time of injection and was based on the set wall temperature. This served as an indicator of the potential clouding effect of water vapour condensation on the windows for the selected CVCC wall temperature.

Originally, the software programme used to control the in-filling of each gas took into account the usual scenario of ambient temperature gas entering the heated CVCC. The gas was metered into the chamber in two stages, the first pressure being equal to the required fill pressure multiplied by the ratio of ambient temperature over CVCC wall temperature. The programme then waited until the chamber's gas temperature equalled the wall temperature, at which point the second filling stage to the required fill pressure was implemented. This aspect of the programme was removed after discovering that the temperature of the gas on entering the CVCC was actually marginally greater than the measured wall temperature. This was because the gas heats up rapidly on passing through the narrow bore of the inlet port insert, which was approximately three degrees Celsius higher than the point of wall temperature measurement.

## 6. Practical Design and Ergonomics

This chapter presents the thinking and outcomes of designs incorporated into the Constant Volume Combustion Chamber (CVCC) that were influenced by practical limitations and ergonomic requirements. These aspects of the design process were not concerned with the direct running of an experiment but rather deal with issues regarding assembly, maintenance, experimental set-up and safety.

### 6.1 Flexibility of CVCC Orientation

The primary purpose of the CVCC was to allow for optical access to combustion events. The optical access preferably had to provide the opportunity for setting up a laser, optics and an optical recording device. To this end, a steel table with attachments was designed and manufactured to allow the CVCC to be positioned vertically or horizontally, with sufficient flat surface area for the installation of the various optical applications. In addition to this, the table legs were adjustable and the nominal height of the table surface was such that work could be carried out with relative ease both above and below the surface.

### 6.2 Design and Inter-changeability of Components

An objective of the CVCC was that it would be highly flexible in its component setup. This was achieved using similar porting in the vessel, as described in the following paragraphs.

#### 6.2.1 Retainer Rings at CVCC Ends

The ends of the cylindrical vessel are similar and the retainer rings interchangeable. An advantage of a single thread retainer ring over bolting is that uneven forces on the window or metal end are **less likely**. Another potential advantage that influenced the decision for a single thread fastener was speed of removal. Since it was known that at least one end would have to be opened regularly for cleaning, it was thought that a single fastener would improve the

recycle time of the experiments. This is still thought to be the case of the present apparatus; however, the advantage is significantly reduced by having a much finer thread than is standard for such a diameter. The fine thread was chosen for ease of machining, following the recommendation of the manufacturer. The increased time to remove the retainer ring was partially counteracted by simple tools that were developed to facilitate removal, but scope still exists for the improvement of such tools.

### 6.2.2 Circumferential Ports

The circumferential or side ports of the CVCC consist of eight alternating ports of different design. The larger of the two types of port was a major determinant in the depth or length of the cylindrical chamber, as sufficient orthogonal optical access was desired. The size of this port necessitated a smaller type of intermediate port, purely due to the geometry, to provide adequate porting for the operation of the CVCC. The design intent was that for both types of ports, their inserts would be totally interchangeable for flexibility in experimental setup. (This was almost perfectly achieved; however, two machining mishaps on the larger ports have meant that the Instrument Insert is uniquely threaded for a port and the Spark Plug Insert is best used with the tight-seal port. Refer to Appendix F 2.) As with the large ends, the retainer ring principle holds, especially for quick removal of the circumferential ports.

## **6.3 Safety Considerations and Measures**

Though most of the physical applications of safety measures have been mentioned in their relevant sections, it is appropriate to describe the philosophy behind such measures and considerations.

The philosophy regarding safety in the operation of the CVCC was to consider safety as a priority in the design for operation. However, since the CVCC is not classed as a pressure vessel according to the Occupational Health and Safety Act of South Africa, legal implications were not considered but rather engineering

judgement and consideration for the end-user were used as a basis for decisions involving safety. Consequently, simple yet effective methods were employed to ensure that operating the CVCC was as safe as was deemed necessary and practicable.

To elaborate on the details of one safety measure, the design of which has not been mentioned, the insulation will be described. As mentioned in Section 4.6, the lagging's primary purpose is personnel protection, but the energy saving and shorter heat-up times are advantageous. The insulation manufactured for the CVCC is fire-proof and is resistant to temperatures in excess of 600°C. It is flexible and made up of several sections such that it can accommodate the varied set-up of the CVCC.

The aspects of safety, both hard- and software, that form part of the instrumentation and control of the CVCC will be discussed separately in the following chapter.

## **7. Instrumentation and Control**

In this chapter, the reasons behind the decisions made with regards to the control and data acquisition of the Constant Volume Combustion Chamber (CVCC) will be discussed. This will cover the philosophy of control by personal computer (PC), the choices of hardware, the methods of software utilisation and the safety considerations involving control.

### ***7.1 Philosophy behind PC-Controlled Experiments and Data Acquisition***

The decision to use personal computers to control the functions of the CVCC and to acquire the data generated from it was not a highly in-depth process. Though suggestions were made to use programmable microchip technologies for these purposes, such technology was not chosen despite the benefit it provides of control and acquisition that is independent of software timing. The reasons for choosing PC control and acquisition were as follows:

- Easy development from simple to more complex capabilities.
- Ability to rapidly alter the programs, both during and following the work involved for this dissertation.
- Familiarity of equipment and software capabilities amongst supervisors and others willing to give assistance.

The potential for being limited in certain functions by software timing was not deemed insurmountable, as either faster PC's or more advanced data acquisition cards could later be employed.

### ***7.2 Instruments and Hardware Used***

Many of the instruments have been mentioned in various preceding sections; however, for completeness' sake, the following table summarises the instruments and operable pieces of equipment that yield and require signals respectively. In addition, other signals used by the controlling PC are included in the table.

(Details of the instrumentation mentioned in this section are displayed in Appendix D.)

Table 7.2: Instrumentation, Operable Pieces of Equipment and Signals

<b>No.</b>	<b>Instrument</b>	<b>Signal</b>
1.	ESI 0 — 4 bar Pressure Transmitter	Analogue Input
2.	ESI 0 — 40 bar Pressure Transmitter	Analogue Input
3.	Internal 1/8" Type-K Thermocouple	Analogue Input
4.	AVL Water-cooled Pressure Transducer	Analogue Input
5.	Bosch Common Rail Pressure Transmitter	Analogue Input
<b>No.</b>	<b>Operable Piece of Equipment</b>	<b>Signal</b>
6.	Inlet Control Valve	Digital Output
7.	Exhaust Control Valve	Digital Output
8.	Spark Plug	Digital Output
9.	Injector	Counter Output
10.	Mixing Fan	Digital Output
11.	Low Pressure <b>Fuel</b> Pump	Digital Output
12.	Common Rail Relief/Return Valve	Counter Output
<b>No.</b>	<b>Other Signals Used By Controlling PC</b>	<b>Signal</b>
13.	Check to ensure running of other programme	Digital Input
14.	Signal to start recording of pressure trace	Analogue Output

Hardware:

The instrumentation and control hardware used for the CVCC is listed below (Note: The control hardware of the cartridge heater and fuel injection systems is addressed in their relevant sections.):

- Two Pentium 2 personal computers (One was later changed to a Pentium 4.)
- A National Instruments PCI 6014 Data Acquisition (DAQ) Card with 2 useable counters, 2 analogue outputs, 8 dedicated digital ports and 16 analogue inputs, installed in the controlling PC



- An Eagle PCI 703S DAQ Card installed in the PC that records the buffered pressure trace
- An electronic MOSFET-based power-switching board to convert signals into timed power supplies
- A thermocouple converter (0 – 400°C to 0 – 5V)
- A charge amplifier for the pressure transducer

### 7.2.1 Reasons for Choice of Instruments

The reason for having two pressure transmitters for the fill procedure is covered in Section 5.2.1. The reason for choosing powered transmitters was because they did not require calibration. Their update rate was more than sufficient for the filling requirement.

The reason for using Type-K thermocouples was their availability and their high-temperature resistance (relative to Type-J). Since a rapid temperature measurement response time was not critical for either thermocouple position, the sturdier thermocouple was used for the internal measurement. As space did not allow for two 1/8" thermocouples, **a narrower one** (1/16") was used for the wall measurement.

A piezo-electric pressure transducer was required to capture a smooth and detailed pressure trace of the combustion events within the CVCC. A water-cooled pressure transducer capable of measuring 0 – 200 bar was selected since it would be subjected to temperatures in the order of 200°C for extended periods. The model chosen was an AVL QH32C.

### **7.2.2 Reasons for Choice of Hardware**

The requirement for an accurate, recordable pressure trace of the combustion events in the CVCC was definite. This was attempted on the controlling PC; however, in order to obtain such a trace, a buffered acquisition was required. During such an acquisition, all other operations on the PC were halted. Since in the controlling programme the computer needed to be performing calculations during this period, a buffered acquisition could not be achieved using a single PC. The second computer was set up with the available Eagle DAQ card to capture the pressure trace. (Refer to Ch. 9.4.4 for the reason why this card was not used as the controlling card.)

The NI 6014 DAQ Card was selected from the National Instruments range as the most cost effective board capable of performing the required functions. Since a new DAQ card was to be acquired, it was thought that it would be programmatically advantageous to procure one from the same company that developed the software (LabVIEW) used for the CVCC.

The MOSFET board was a large improvement on the first board that was developed, which made use of transistors instead of MOSFETS for switching. The function of these boards was to convert the output signals from the DAQ board to timed deliveries of the required power outputs to the operable pieces of equipment. The MOSFET board was developed by Mr G. McPhillips and operated by "pulling down to ground" the negative power lead of the item that had its dedicated signal wire activated. The advantage of using certain MOSFETS over transistors was their ability to switch large currents cleanly, as was necessary for the fuel injector for example.

The choice to use an industrial thermocouple converter over building a circuit to convert the milliVolt signal from the thermocouple to a 0 — 5 Volt output with Cold Junction Compensation was purely a time versus cost benefit decision.

### **7.2.3 Power Supply to the System**

All pieces of operable equipment that were controlled via the MOSFET board required 12V DC power. The two pressure transmitters required a 13 — 30V DC supply according to the manufacturer's specifications; however, testing showed that the transmitters deliver reliable results down to a supply of approximately 11V DC. The Bosch pressure transmitter on the common rail required a 5V DC supply. Consequently, it was decided that a 12V DC dual power supply with an included 5V output would be purchased. This power supply could deliver 6 Amperes of current in parallel mode. Due to the high current requirement of the injector and the ignition system, a 12V battery was incorporated into the power supply system to deliver these peaks. In normal operation, the power supply delivered the required current to perform the other functions and it was set to "trickle charge" the battery, which shared the same power rails.

All other systems requiring power ran off the 220V AC mains. The power supplied to the variable speed drive of the motor was from a separate source to the other systems to avoid noise interference via the mains.

## **7.3 Software Control of Experiments**

The software used to control and acquire data from the CVCC was National Instruments' LabVIEW 6.1. This graphical programming language was well-suited for this application. It basically allowed one to create a graphical user interface (GUI) that formed the basis from which the programming was developed graphically in a background screen.

Both computers used LabVIEW; the controlling PC ran the larger and more complex programme while the other PC used LabVIEW to accurately capture and present the data from the experiments.

The basic sequence of events of a typical CVCC experiment that LabVIEW controlled and captured is presented in the following paragraph, while the detailed programme flow diagram of the controlling PC is presented in App. E.

Basic Control Sequence and DAQ for a CVCC Experiment:

- The programme is started and the fill pressure values are "UPDATED" from Excel if required.
- The "Fill Sequence" is started and the Acetylene and/or Hydrogen is metered into the CVCC by the programme opening the inlet solenoid valve until such time as the measured pressure equals the prescribed fill pressure. This feedback loop cycles as fast as the computer can loop.
- The programme then ensures that the low pressure transmitter is isolated before the Nitrogen and Oxygen are metered into the CVCC in the same manner.
- The high pressure fuel pump rig ("Diesel Rig") is started and after initiating all necessary signals, the programme asks the user to start the high pressure diesel pump motor.
- The "FIRE SPARK" sequence is initiated and the programme performs the following actions:
  - It checks that the high speed DAQ programme on the secondary computer is running.
  - It sends a signal to the secondary programme to initiate the buffered, hardware-timed data acquisition period.
  - It delivers several sparks in quick succession (within 50 milliseconds).
- As the pre-charge combustion event occurs, the programme continuously samples the pressure reading from within the combustion chamber at the loop speed of the controlling computer. When a descending pressure equal to the set injection pressure is reached, an injection signal is sent to the injector. (This signal is also wired to the secondary computer which records a hardware-timed trace of this signal along with the pressure.)

- The exhaust event is controlled in an identical fashion to that of injection. The exhaust valve remains open, however, because once the set exhaust pressure is reached, the digital output signal to the valve is just toggled once.
- Finally, the "END" button is activated to shutdown the high pressure fuel pump rig.

#### **7.4 Safety Measures in Control**

The safety measures that were implemented in the main controlling programme were as follows.

- During the filling procedure, the "fill" buttons of the various gases are disabled until the point in the sequence has been reached when the gas is to be metered into the CVCC. This prevents a mouse-click error from causing an incorrect quantity of gas to be metered into the chamber.
- After the fuel gases have been metered into the chamber, the programme reminds the operator to isolate the low pressure transmitter. If this is not done, then before 4 bar is reached during the filling of Nitrogen, the inlet valve will close automatically until the pressure transmitter is isolated. This is to protect the LP transmitter from an overpressure of 8 bar.
- Once the filling procedure is complete, no spark can be initiated if the inlet system's pressure is significantly above zero gauge. The pressure is relieved once the manual needle valve has been closed and the inlet system 3-way vent valve has been swung. The safety intent of this software check is to prevent a high pressure from being created in the inlet system if the manual needle valve were to leak through.

## 8. Design-Verification Tests

The first significant phase of testing began once all components required for pressure retention in the Constant Volume Combustion Chamber (CVCC) were completed and assembled. This testing led to some adjustments in sub-systems and these will be discussed in the first section. The second section describes the work that was done, and presents the results that were obtained, to verify the functionality of the CVCC for pre-charge combustion and the accuracy of the thermodynamic model as presented in Section 5.3. Following this, the testing carried out on the diesel rig to produce useful injection events will be discussed. Finally, the work and outcomes of the testing of the whole system will be presented.

### 8.1 Hydrostatic Pressure Tests

The hydrostatic testing of the CVCC was achieved by filling the chamber with oil and using a dead-weight tester to deliver a known pressure. Unfortunately, the only testers available to the student were not capable of delivering the required test pressure of 300 bar g. Although the tester that was used had the potential to deliver well above this pressure, it was not able to deliver the additional volume required to produce this pressure. The extra volume of oil required is due to the CVCC volume increase on pressurisation (o-ring and gasket compression), air pocket compression (air pockets were kept to a minimum), the density increase of the oil and the strain in the vessel itself. Consequently, it was only possible to pressure test the CVCC to its design pressure of 200 bar g. This was achieved successfully for both the metal inserts and windows. It was deemed unnecessary to hold the pressure for an extended period of time, as some leakage was inevitable through the gland packing of the fan and through the exhaust valve. The hydrostatic testing did show, however, that these two sub-systems required some attention in order to seal adequately and this is described in the following two sections.

### **8.1.1 Exhaust Valve Sealing and Safety Relieving Verification**

The exhaust valve sealed against the pressure inside the CVCC by using a metal-to-metal needle and seat arrangement (both of Bohler M300 stainless tool steel). In order to perform a satisfactory seal on activation, it was found that thorough grinding between needle and seat was required. Once an adequate seal was achieved, the safety relieving mechanism of the exhaust valve was tested. To prove its operation and the calculations to determine the safety relieving pressure, the supply air pressure was set at 2.1 bar g. The anticipated full-relieving pressure for this set pressure was 99 bar g. The exhaust valve maintained a seal beyond 90% of the anticipated full-relieving pressure, at which point oil began seeping out of the outlet. As the expected full-relieving pressure was reached, a steady stream of oil emitted from the outlet of the exhaust valve, proving its adequate functioning.

### **8.1.2 Running-in of the Mixing Fan**

The pressure test revealed that the gland of the mixing fan was not sealing satisfactorily. This situation was not improved by tightening the compacting sleeve (also called the bearing housing). The fan was then run-in using an air die-grinder rotating at 8000 – 20000 rpm for several minutes. This action caused graphite (from the gland packing) to coat the surface of the fan shaft and resulted in a far superior seal.

The fan was also run within the CVCC to verify that air-mixing was achieved. This was not carried out quantitatively, but a rudimentary experiment revealed visible evidence of air movement when the fan was operated within the sealed CVCC. It was thought that if the mixing proved to be inadequate in magnitude, a different propeller could be produced in a short time.

## **8.2 Pre-Charge Combustion**

Following the hydrostatic pressure tests and associated work, the oil was cleaned out from the Constant Volume Combustion Chamber in preparation for pre-charge combustion testing. In this phase, the first requirement was to achieve a fully functional apparatus for the execution of pre-charge combustion events. Once this was achieved, the ability of the thermodynamic model of pre-charge combustion to predict end pressures was determined.

### **8.2.1 Achieving Pre-Charge Combustion Functionality**

A pre-charge combustion event comprised of three main phases, viz. the fill, ignition and exhaust phases. Adjustments needed to be made to improve the functionality of all three phases. Though some of these improvements are mentioned in Chapters 5 and 7, they will be described in the following paragraphs under the appropriate phase headings.

#### Fill Procedure Improvements:

On pressurisation of the CVCC with Nitrogen during fill procedure checking, it was discovered that even once closed, the inlet solenoid valve was allowing gas to pass into the CVCC, despite it being rated for 50 bar service. The solution to this problem was found in reversing the installation of the inlet solenoid valve, which caused the gas to tend to escape from the CVCC once the supply pressure was removed. By adding a sensitive check valve (1kPa differential pressure required to induce flow) upstream of the inlet solenoid valve, back-flow was prevented.

In order to meter in accurate volumes of gas, indicated by the pressure transmitter readings, it was necessary to make both an operational and technical adjustment. The problem experienced was that when the solenoid valve closed once the pressure transmitter read the required pressure, the pressure reading would drop rapidly before reaching a more stable value. The reason for this occurrence is thought to be that pressures greater than those in the combustion



chamber developed in the inlet system during filling due to the restriction caused by the manual needle isolation valve. An operational method of reducing this pressure drop-off was to set the pressure regulator of the fill gas marginally above the required pressure. This reduced the filling rate as the required pressure was approached and decreased the pressure difference between inlet system and combustion chamber. Since the accuracy of the pressure regulators was not such that they could be set to satisfactorily reduce the pressure drop-off problem, a small bore (0.5mm) orifice fitting was introduced upstream of the solenoid inlet valve. The effect of this was to reduce the potential flow rates into the CVCC to a level that, in combination with appropriately set pressure regulators, yields negligible pressure differences between inlet system and chamber. If the orifice was sized so that it alone solved the problem no matter how much higher the regulator set pressure was above the required pressure, the filling time would have become excessively long.

Several software improvements for the fill procedure were implemented following initial pre-charge combustion testing, however none of the changes were core to the functionality of the CVCC. These fill procedure improvements, which concern safety, are discussed in section 7.4 and are presented in Appendix E.

#### Spark-Ignition Improvements:

A description of the difficulties experienced and the physical changes made during the development of a satisfactory ignition system is given in Section 9.4.2. A software improvement was also implemented during pre-charge combustion testing. It was discovered that on standing for just a short period (in the order of a minute), the ignition system would not always deliver a spark after the first time the coil was charged. Generally, only the second and following times that a spark event was initiated would a visible spark actually occur, and this was not influenced by the dwell (charge) time. The solution implemented was simply to produce several spark events on single activation of the command on the main controlling programme. The sparks fired consecutively and rapidly in the

programme and no significant experimental difference was observed as a consequence of the multiple sparks.

#### Exhaust Phase Tuning:

Though the criticality of the exact exhaust pressure was insignificant in comparison to the pressure at the time of injection, the exhaust event had to occur only when the pressure in the chamber was decreasing and as close to the desired set-point as possible. To achieve this, experiments were carried out to determine the following values by trial and error. To ensure that exhausting only took place during a decreasing pressure trend (i.e. not during pre-charge combustion or due to slight variations in pressure readings), a value of negative 0.05 bar was determined as the smallest figure for the difference between consecutive pressure transducer readings. It was also determined that for the Pentium 2 computer used and for exhaust set pressures of 15 – 20 bar, a value of 0.3 bar was ideal as an additional pressure below which exhausting was to take place (e.g. exhaust pressure of 20 bar required a set pressure of 20.3 bar).

#### **8.2.2 Verification of Thermodynamic Model**

Though the design maximum operating pressure for the CVCC is 200 bar g, the flammable gas cylinder regulators limited the amount of gas that could be metered into the chamber. Consequently, the maximum pressure obtained by pre-charge combustion was 180 bar g. The following figure, taken from the auxiliary computer that captured the high-speed pressure trace, shows a pre-charge combustion event reaching 175 bar g.

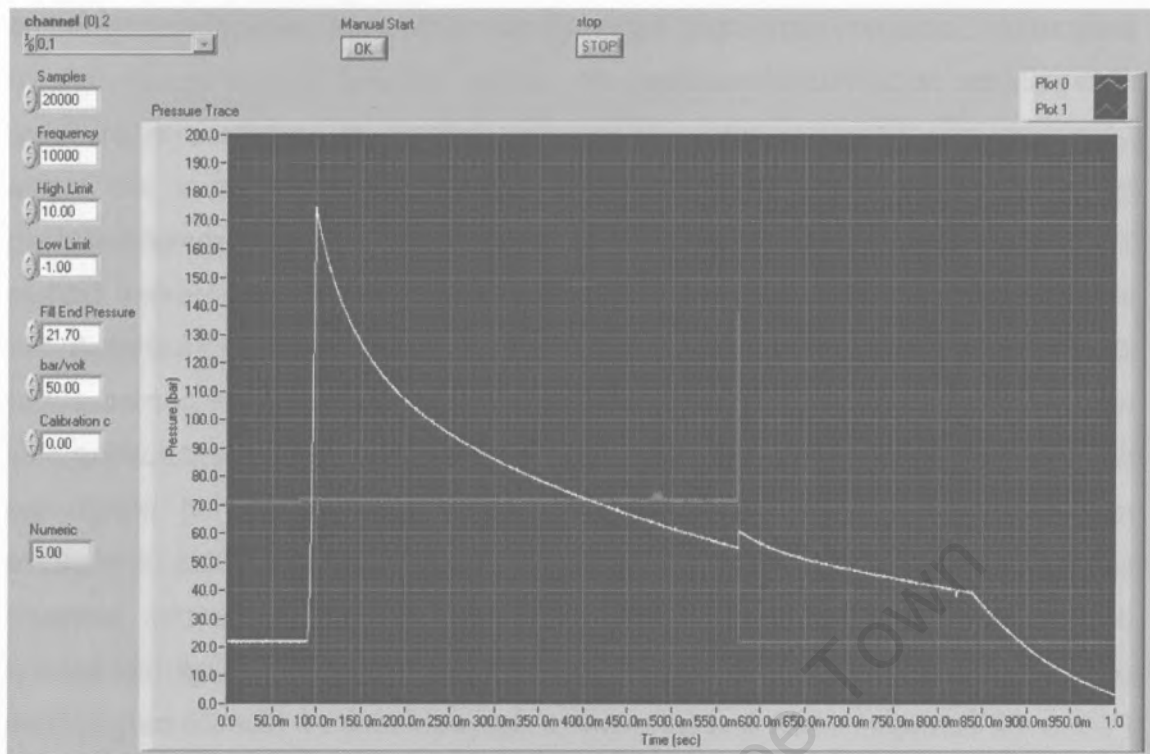


Figure 8.2.2a: Pressure Trace from CVCC Combustion Event

### Pressure Discrepancy

Measured pre-charge combustion pressures tended to be significantly lower than predicted peak pressures. Such discrepancies are known to have been experienced by other research groups, viz. Doshisha University, Japan, who experienced pressure discrepancies of about 20% (Senda, 2006) and Sandia National Laboratories, who experienced a 10% reduction in their cubically-shaped combustion chamber (Pickett, 2006). Testing of the CVCC showed that the pressure discrepancy became increasingly severe as peak pressures of the experiments were increased. Hydrogen experiments proved to be less adversely affected when compared with acetylene and yielded approximately 15% discrepancies for a predicted peak pressure of 160 bar. A major contributing factor to this difference between hydrogen and acetylene is thought to be greater radiation losses from the more luminous acetylene flame. Several losses are known to have contributed towards this pressure shortfall, viz. slight gas leakage; radiation losses through the windows; Nitrogen Dioxide formation; CVCC volume

change; incomplete combustion at the surfaces; and heat lost to the walls of the chamber (which is accelerated by condensation). The pressure discrepancy remained relatively constant for peak temperatures ranging from 2250 K to 3700 K. Despite higher temperatures causing greater rates of heat loss and Nitrogen Dioxide formation, the constant discrepancy is explainable by the following. For lower peak temperatures, the initial fill pressure had to be higher (causing greater leakage prior to ignition) and the rate of pre-charge combustion was slower due to the leaner combustible mixture (allowing more time for heat loss).

#### *Gas Leakage Losses*

Gas leakage occurred mainly through the exhaust valve and consequently, varied from experiment to experiment due to the condition of the exhaust valve. Though the modification to form the ball bearing sealing arrangement was successful in reducing leakage (See Section 9.4.1), the seal was never perfect. In addition, even stainless steel ball bearings corroded within several days of testing, resulting in increased leakage. Tests were performed to determine whether or not the safety relief mechanism of the exhaust valve operated prematurely, "lifting" during the pre-charge combustion event. No evidence of such an occurrence was found.

#### *Radiation Losses*

Due to the design intention to maximise optical access, radiation losses via the sapphire windows were unavoidable. The potential impact of radiation losses on the peak pre-charge pressure was small, however, amounting to 0.7% (See Appendix C). Experimentation verified that by covering the large window, peak pressures were not improved beyond the repeatability tolerance (Refer to Figure 8.2.2b).

### *Nitrogen Dioxide Formation*

Nitrogen Dioxide formed during pre-charge combustion events with high peak temperatures, as evidenced in Figure 9.4.5. However, this occurrence did not appear to be a dominant factor in reducing measured peak pressures. Tests were carried out to produce equivalent end-pressures for predicted peak temperatures of 2285 K, 2650 K, 3000 K and 3715 K. The results did not show a trend of reducing peak pressure with increasing peak temperature as would be expected if Nitrogen Dioxide formation was the primary cause of the pressure discrepancy. Nonetheless, the presence of Nitrogen Dioxide in the pre-charge combustion products must have been a contributing factor to the reduced measured pressures, even if offset by other factors at higher temperatures.

### *CVCC Volume Change*

Due to the use of compressible graphite gaskets for cushioning between the windows and the steel retainer rings and the use of o-rings, as well as the strain experienced by the vessel, it was inevitable that a minor volume increase of the CVCC would occur during pre-charge combustion. The approximate combined effect of these elastic strains was determined to be a 1% increase in volume.

### *Incomplete Combustion at Internal Surfaces*

The relatively cold ( $< 200^{\circ}\text{C}$ ) internal surfaces of the CVCC walls, windows and crevices had a quenching effect on the pre-charge combustion reaction at the boundary layers. This is mentioned as a theoretical probability, since the extent of this effect was not quantified nor visually ascertained. Together with heat lost to the internal surfaces, reaction quenching is exacerbated by increased surface-area to volume ratio. These effects are most likely the major reason for the differences in pressure discrepancies mentioned previously in this section between Sandia, Doshisha and the CVCC under discussion. The relative surface-area to volume ratios for these three constant volume combustion vessels were 1, 2.41 and 1.44 respectively.

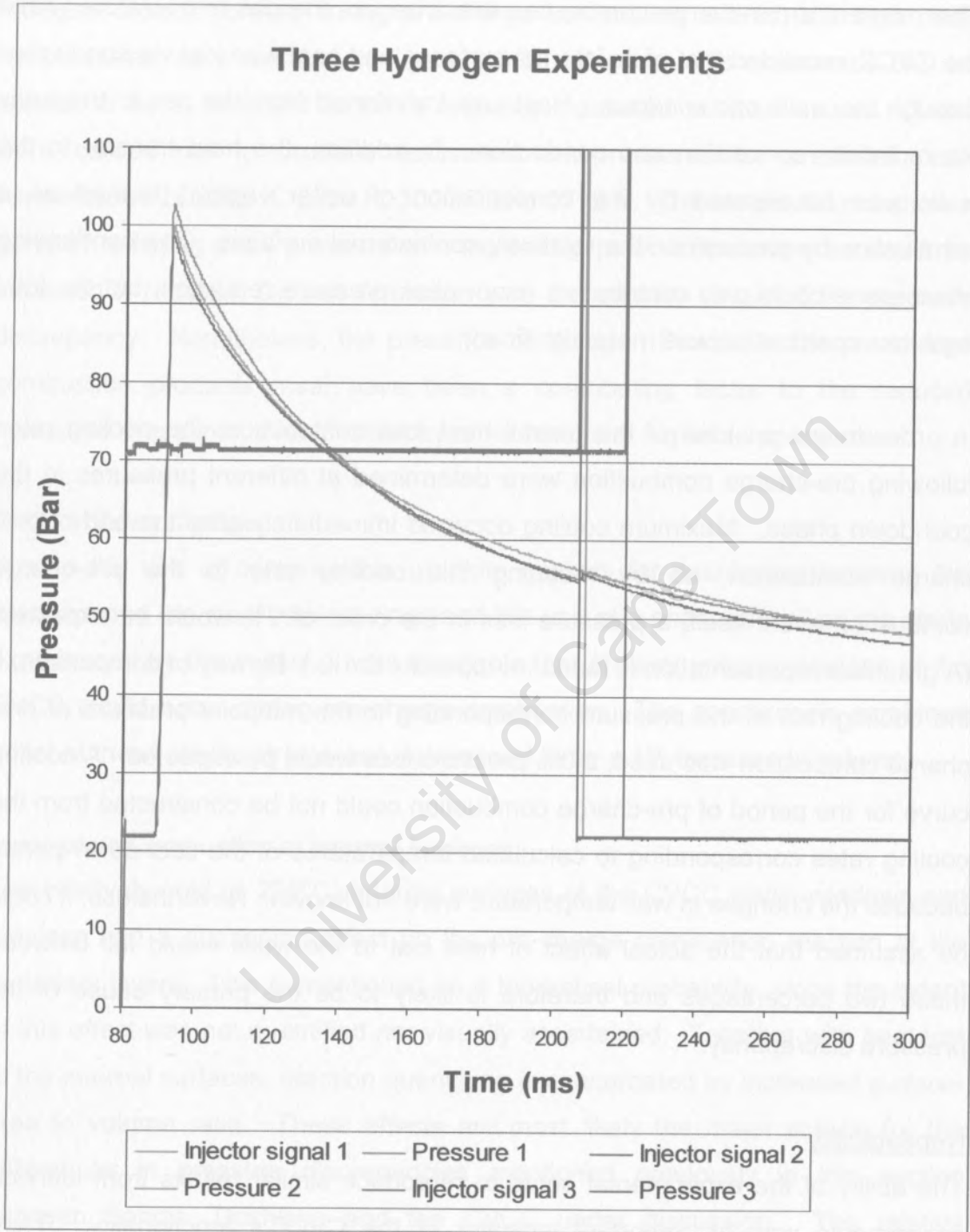
### *Heat Losses to Internal Surfaces*

The moment a pre-charge combustion event began, the gas temperature within the CVCC exceeded that of its internal surfaces and heat was lost via conduction through the walls and windows. Heat was transferred from the gas to the walls via radiation, convection and conduction. In addition, the heat transfer to the walls was accelerated by the condensation of water vapour (formed as a combustion by-product) on the relatively cool internal surfaces. The condensing effect alone could only contribute a minor peak pressure reduction, but the total heat loss contribution was more significant.

In order to get an idea of the overall heat loss contribution, the cooling rates following pre-charge combustion were determined at different pressures in the cool-down phase. Maximum cooling occurred immediately after the end of pre-charge combustion, so by mapping this cooling rate to the pre-charge combustion event itself, a pressure loss in the order of 9% would be expected. (A graphical representation is found in Appendix C.1.9.) By way of comparison, if the cooling rate at the pressure corresponding to the midpoint pressure of pre-charge combustion was used, a 3% pressure loss would be expected. A cooling curve for the period of pre-charge combustion could not be constructed from the cooling rates corresponding to calculated temperatures of the cool-down period because the changes in wall temperature were not known. Nevertheless, it could be assumed that the actual effect of heat lost to the walls would fall between those two percentages and therefore is likely to be the primary cause of the pressure discrepancy.

### Repeatability

The ability of the experimental setup to reproduce similar results from identical experiments was an important indicator of the CVCC's functionality. Tests proved that the repeatability of experimentation using the CVCC was such that useful experiments could be undertaken. The following graphs demonstrate this capability.



**Figure 8.2.2b: Repeatability of Hydrogen Experiments**

Though insufficient dedicated experiments were performed for the purposes of a detailed statistical evaluation, Figure 8.2.2b does reveal that pre-charge combustion peak pressures varied by 4% for these three experiments. Though the reasons for the repeatability not being better are likely to be influenced slightly by most of the reasons that contributed towards the pressure discrepancy, the primary contributing factor to reduced repeatability was that of gas leakage from the CVCC.

### ***8.3 High Pressure Fuel Pump Rig Tests and Calibration***

Since the high pressure fuel pump rig consisted of several BMW components, not all the signals **for** the various pieces of equipment were known. The first section describes how these were determined, generated and tested. Following this, the calibration of the primary variables of the high pressure fuel pump rig is discussed.

#### **8.3.1 Signal Determination and Generation**

The required signals for the High Pressure (HP) Diesel Pump and the Common Rail (or Accumulator) return valve were not known. In order to determine these, probes were placed on the appropriate leads on a BMW 320d engine on a test bed. The engine was run at varying speeds and loads and an oscilloscope was used to record the signals at these conditions. The measurements were taken at stable engine conditions and the signal to the HP diesel pump remained relatively unaltered for the different rail pressures. It was found that only the rail return valve signal changed significantly and proportionally (indirectly) to the rail pressure, as shown in the following table.



Table 8.3.1: Engine Common Rail Return Valve Power Signals

Corn. Rail Press. (bar)	Duty Cycle (%)	Peak-to-Peak (Volts)
<b>590</b>	70	15.3
620	<b>68</b>	<b>15.4</b>
<b>750</b>	<b>63.5</b>	<b>15.5</b>
<b>900</b>	59.5	15.4
1235	<b>49</b>	<b>15.4</b>

**Notes:**

- 1) **Signal Shape: Square** Wave
- 2) Frequency: 1000 Hz

An attempt was then made to run the high pressure fuel pump rig by generating these signals in LabVIEW and delivering them via the power-switching board. The effect of sending the appropriate signal to the HP Diesel Pump was to reduce the delivered diesel flow rate, when compared with no signal. Later it was determined that the effect of this signal on Common **Rail** pressures was insignificant; hence the signal was removed for further operation. Delivering the power signals as shown in Table 8.3.1 proved ineffectual in increasing the Common Rail pressure above the nominal pressure that was developed when no signal was supplied. The reason for this phenomenon or that of the solution could not be determined. The discovered solution is presented in the following section.

### 8.3.2 Rail Pressure and Injection Delivery Verification

Through trial and error, it was discovered that by sending a power signal with a duty cycle of around 80%, increased pressure was developed in the Common Rail. The strange result was that by slight increases in the duty cycle, the rail pressure was increased, as shown by the measured values in the following table.

Table 8.3.2: Rig Common Rail Return Valve Power Signals

Duty Cycle (%)	Rail Pressure (bar)
80	400
80.5	500
81	600
81.5	700
82.5	900

Notes: 1) Signal Shape: Square Wave

2) Frequency: 1000 Hz

3) The supplied voltage (excluding minor losses due to MOSFET resistance) was 13.9 V

4) Equivalent Engine Speed: 1995 rpm (28Hz on controller) for all pressures

Despite not being able to explain the results in Table 8.3.2, they nonetheless formed a useful **range** of controllable injection pressures for CVCC operation.

For the purposes of future experimentation and the verification of the controllability of the diesel system, the diesel injection delivery performance was calibrated for a set of parameters considered to be optimal for the high pressure fuel pump rig. This was achieved by performing a series of injection **runs** consisting of 200 injection events each. Increasing injection durations were used to provide a range of injection volumes that could be used in future experiments. The calibration results are presented in Appendix D. Interesting to note was that at durations characteristic of automobile diesel engines (in the order of 1 millisecond), the correlation between injection signal duration and injection volume was far from linear. This was because the solenoid switching speed impacted significantly on the volume of diesel discharged at short **injection** signal durations. This effect was exacerbated in the case of the CVCC because the injector driver did not provide a boosted opening current, followed by a reduced hold current, as is typical for engines.

## **8.4 Full Experiments**

Successful complete experiments were carried out for demonstrative purposes using the CVCC. Since the primary purpose of the apparatus was to provide optical access to compression-ignition combustion events, examples of this will be presented in this section. The details of specific variations of full experimentation that were carried out to verify the attainment of desired user applications have been left for Section 9.1.2.

The pressure and injection signal trace shown in Figure 8.2.2a was typical of a full compression-ignition combustion experiment. The sharp pre-charge combustion pressure rise (white trace) after ignition by the spark plug was followed by a pressure decrease as heat was lost to the internal surfaces of the CVCC. The initial rate of pressure decrease was reduced if the wall-heating system was used, but the rate decreased sufficiently in any event to allow for the injection event to take place at a more stable pressure. In the experiment recorded in Figure 8.2.2a, the injection event (signal in red) was set to occur at 55 bar. The reason for the pressure rise following injection being small was due to the relatively small volume of fuel injected (comparable to that used in a motorcar engine) in comparison with the large chamber volume. Finally, the exhaust valve was set to open at 40 bar and this event is clearly evident from the pressure trace.

As evidence of the CVCC's fulfilment of its primary purpose, Figure 8.4a shows a 6-plume diesel injection event as captured on a single shot CCD camera.

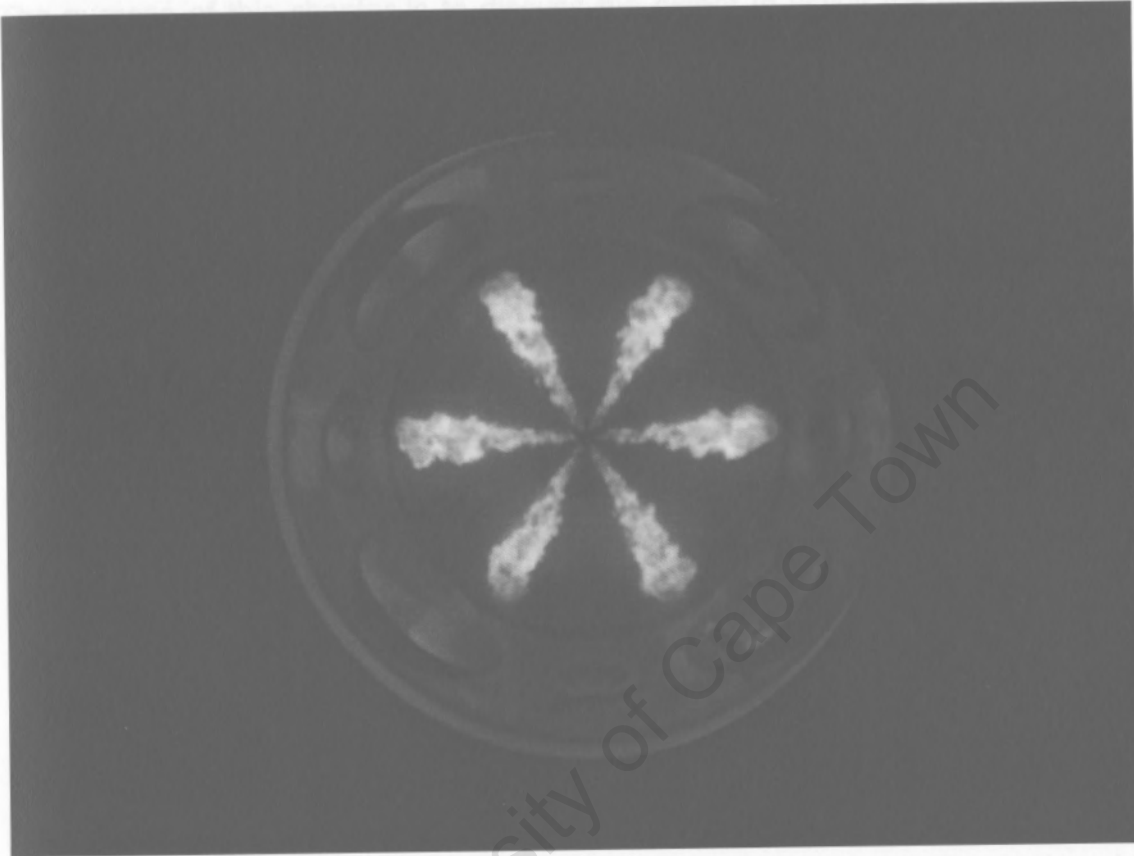


Figure 8.4a: Diesel Combustion

combustion afterglow was observed at 70 bar. This is thought to be caused by Carbon Monoxide, formed by dissociation, returning to the more stable Carbon Dioxide as the temperature decreases. This problem could not be adequately analysed because no high-speed camera was available to accurately measure the presence of afterglow.

The following figure shows a sequence of images of individual experiments with increasing camera delays so as to create the impression of a single combustion event.

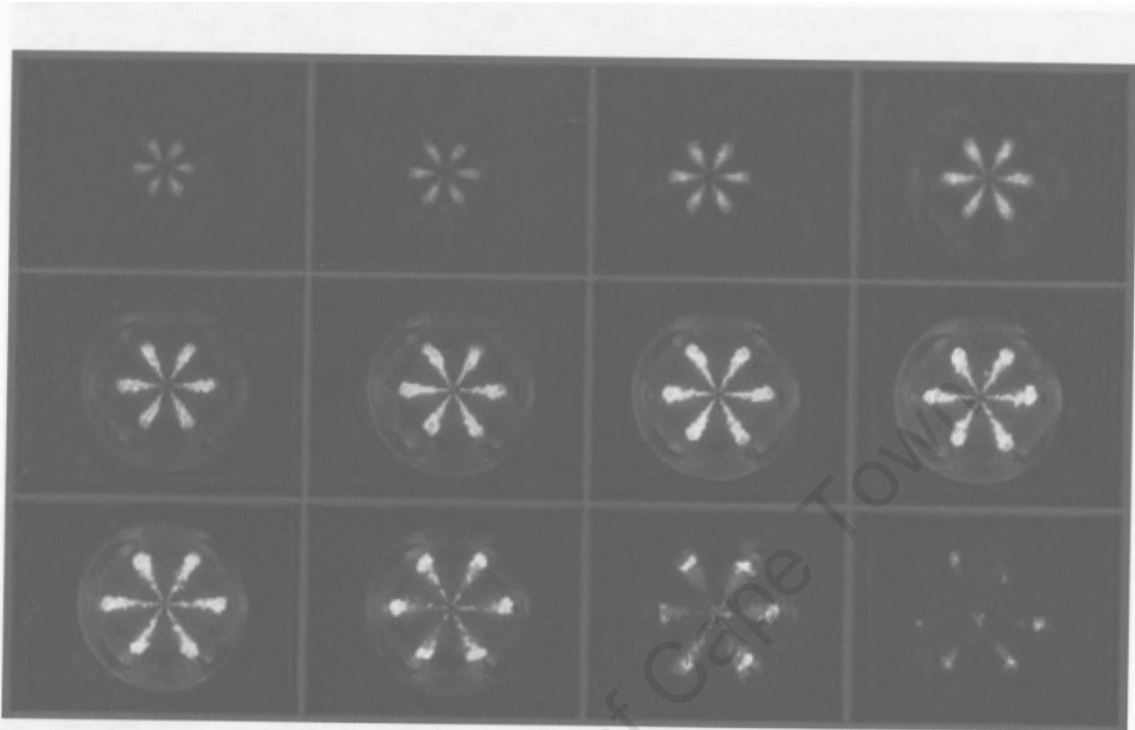


Figure 8.4b: Diesel Combustion Sequence

exhaust valve was set to 100% at 1.0000 s. The exhaust valve was set to 100% at 1.0000 s. The exhaust valve was set to 100% at 1.0000 s.

## 9. Discussion and Recommendations for Further Development

The purpose of this chapter is to discuss the extent to which the objectives for the project were attained and then to give recommendations for improvement and further development.

### 9.1 *Evaluation of the Attainment of the Objectives*

In this section, the attainment of the objectives for the project, which were described in Section 1.2, will be evaluated.

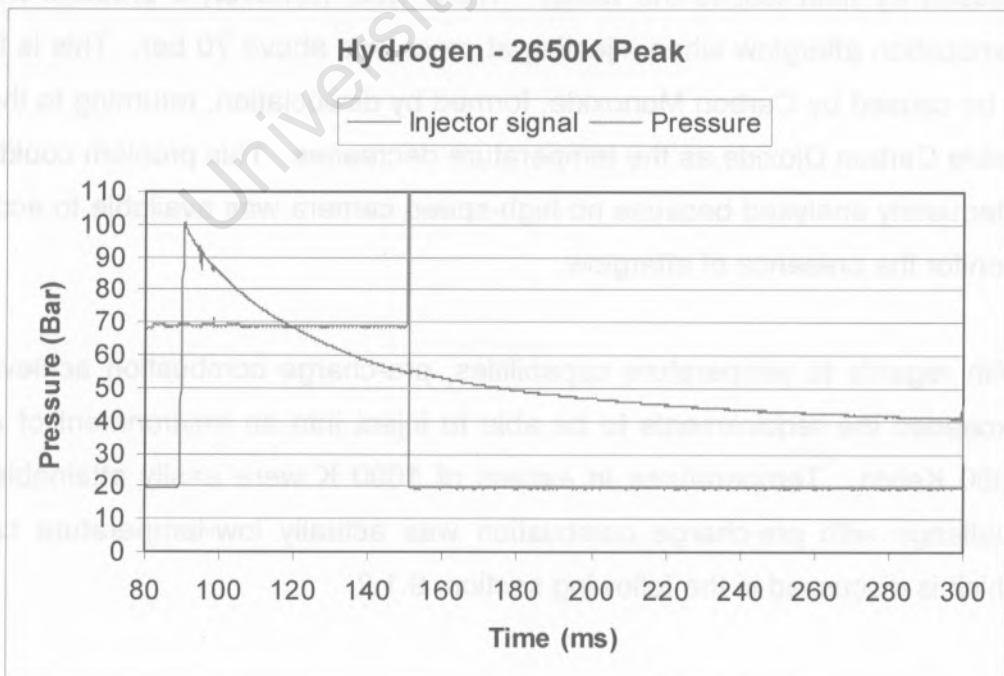
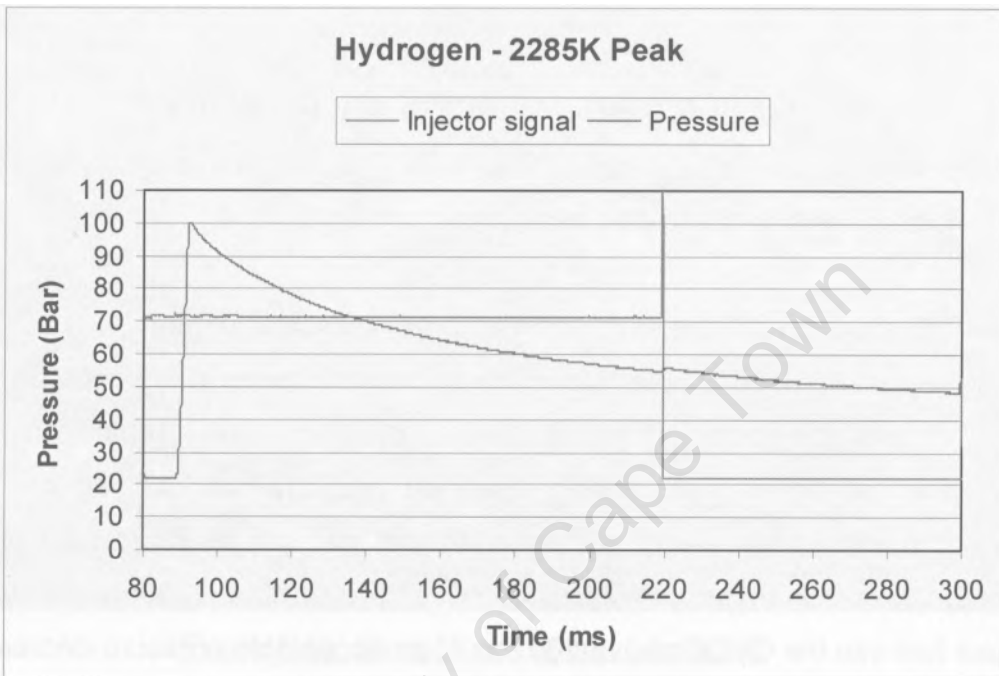
#### 9.1.1 Evaluation of Pressure and Temperature Capabilities

The pressure capability objective of the Constant Volume Combustion Chamber (CVCC) was to be able to inject at pressures in excess of 100 bar. Though the CVCC is capable of withstanding operating pressures of 200 bar, it was only tested to 180 bar peak pressure due to fuel gas supply pressure limitations. Nonetheless, this tested peak pressure does provide the platform from which to inject **fuel into the CVCC** above 100 bar at an acceptable pressure-decrease **rate (caused by heat** lost to the walls). There was, however, a problem with **pre-combustion** afterglow when injecting at pressures above 70 bar. This is thought to be caused by Carbon Monoxide, formed by dissociation, returning to the more stable Carbon Dioxide as **the temperature** decreases. This problem could not be adequately analysed because no high-speed camera was available to accurately monitor the presence of afterglow.

With regards to temperature capabilities, pre-charge combustion achieved and exceeded the requirements to be able to inject into an environment of at least 1000 Kelvin. Temperatures in excess of 1600 K were easily attainable. The challenge with pre-charge combustion was actually low-temperature creation, which is discussed in the following section, 9.1.2.

### 9.1.2 Evaluation of User Applications

The expected intention of the user to be able to vary the temperature and pressure of an experiment independently was met in the capabilities of the CVCC. In the following figure, three experiments of varying temperatures at the same peak pressure are shown.



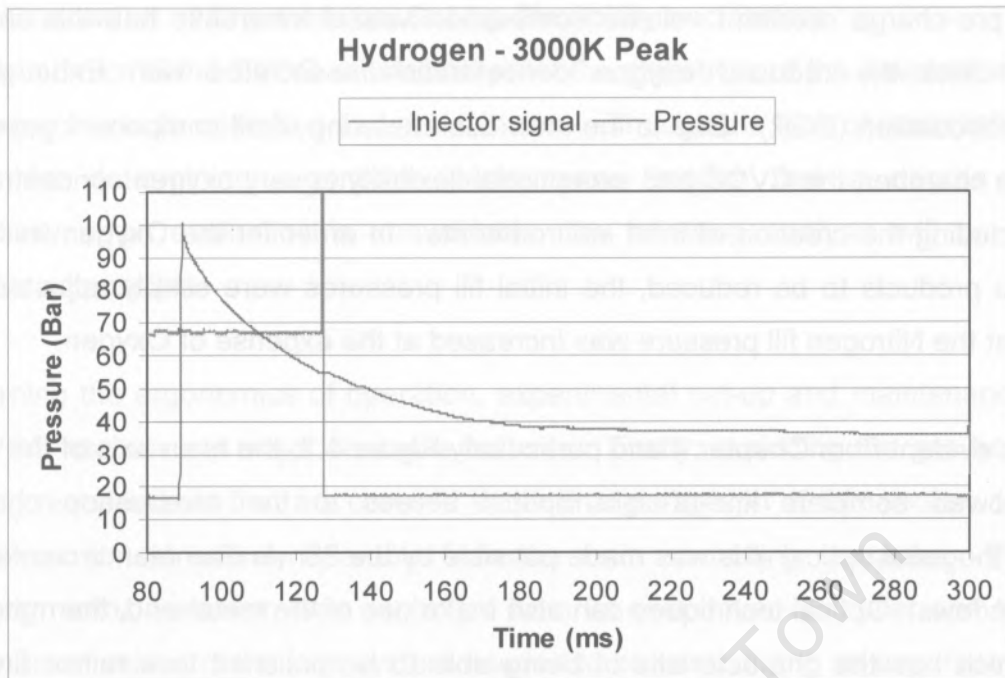


Figure 9.1.2: Pressure and Temperature Independence

The ability to vary the pressure for the same peak temperature is a given, since except for dissociation effects that are minor, this can be achieved by increasing the initial fill pressure using the same composition.

Though the peak temperatures were high in comparison with engine temperatures, the temperature at which injection takes place can match the range found in engines. Low temperature tests at low pressures do not pose a challenge since a high pressure test can be allowed to cool down for a longer period before injecting. Attempting to create a relatively high pressure environment at a relatively low temperature, e.g. 80 bar at 500°C, may bring pre-charge flammability issues into play. Injection conditions that required peak temperatures to be below 2000 K were problematic due to lack of ignition and slow pre-charge burning.



A pre-charge constant volume combustion vessel inherently has the ability to simulate the reduced oxygen concentration associated with Exhaust Gas Recirculation (EGR). Due to the individual metering of all component gases into the chamber, the CVCC had exceptional flexibility to vary oxygen concentrations, including the creation of inert environments. In order for the Oxygen fraction in the products to be reduced, the initial fill pressures were simply adjusted such that the Nitrogen fill pressure was increased at the expense of Oxygen.

As evident from Chapter 4 and particularly Figure 4.2, the main axis of the CVCC allowed complete line-of-sight optical access to the combustion chamber. Orthogonal optical axis was made possible by the 38mm diameter circumferential windows. Optical techniques can also make use of the metal-end, the material of which has the characteristic of being able to be polished to a mirror finish, in place of a large window.

Though graphs of pressure trace and injection signal (such as Figure 9.1.2) appear to show little detail regarding ignition delay, 10000 data points were captured for each trace during the selected time interval. These data points allowed the user to determine at which point the injection signal was sent to the injector and at which subsequent point in time the pressure in the chamber began to deviate from the decreasing pressure trend of cooling. This in itself does not necessarily provide the exact ignition delay, but does provide a means of comparing the ignition delays of different experiments. In order for exact ignition delays to be determined, a needle-lift sensor or another true injection-timing measurement device will need to be installed and coupled to the pressure trace recording.

### **9.1.3 Evaluation of Ergonomics, Set-up Flexibility and Safety**

The ergonomics of the CVCC satisfactorily met the objectives of the development with respect to both operation and maintenance. Though the lack of quantitative means for determining ergonomic performance implies that a degree of subjectivity in an evaluation is unavoidable, the following analysis will be as objective as possible.

Concerning the ergonomics of operation, experimental set-up and maintenance, the CVCC has several major desirable features. Firstly, excluding the gas-hose coupling requirements that are covered in the final paragraph of this section, the CVCC was almost entirely operable from the main controlling computer. The diesel rig motor, however, was controlled from its own driver-controller and the three manual valves of the inlet system needed to be used during an experiment. Experimental set-up and maintenance were made quicker, simpler and less arduous by single retainer rings for each port, described disassembly methods (See Appendix F 5) and effective tools for disassembly/assembly. In addition, the working height was comfortable for standing and the height of the table top was such that work could *be* carried out underneath without severe crouching. The use of o-rings for sealing had the positive ergonomic advantage that very low tightening torques were required for the majority of CVCC seals.

Considerable set-up flexibility was achieved in both the orientation of the CVCC and the inter-changeability of component placing (Refer to Sections 6.1 and 6.2).

The safety of the entire system was given high priority in its development. This is described in several preceding chapters, viz.: Mixing Vessel decision in Section 3.2.3, Section 4.8 for CVCC construction, Section 5.1 and 5.2 for the Events Sequence and Inlet System Design respectively, Lagging in Section 6.3 and in Section 7.4, the safety measures in computer control. In addition, the incremental testing procedure followed in Chapter 8 was of a precautionary nature, bringing safety into the operational arena.

## **9.2 Shortfalls in the Design and Corresponding Recommendations**

In this section, the non-ideal aspects of the design of the CVCC will be discussed. Where appropriate, recommendations will be made for improvements or alternatives to the current design.

### **9.2.1 Similar Material Seizure**

The student was not fully aware of the tendency for similar materials, especially stainless steels, to seize under conditions of increased friction. This was first understood following a manufacturing mishap when an insert seized with one of the small circumferential ports (See Appendix F 5). Though the primary steel of construction was Bohler M300, a Martensitic stainless mould steel in the annealed condition, it exhibited this unfortunate property. The procedure following this mishap was to ensure that all mating surfaces were well lubricated using an anti-seize compound; no more seizure issues were experienced. It was considered to have either the main vessel or all the inserts Nitrided to increase the surface hardness and change the nature of one of the mating surfaces so as to prevent cold seizure. However, since Nitriding is a relatively high temperature process ( $> 550^{\circ}\text{C}$ ), it was decided not to go ahead with it for fear of slight distortion as well embrittlement of the thread apexes. Therefore, it is recommended that the procedure of applying anti-seize compound prior to assembly is continued as a contingent solution to this problem.

### **9.2.2 Filling Procedure**

The inlet quick-coupler and corresponding filling procedure philosophy is described in Section 5.2.1. Though it was known that by having one inlet quick-coupler, a significant increase in experiment time and operator actions would result, it was decided that due to safety, inlet-volume and cost, this arrangement would still be employed.

What was not predicted of the filling procedure was the slow leak rate from the CVCC that would occur (See Section 8.2.2). The longer the time the fuel gases remained under pressure inside the combustion chamber, the more severe the deviation from predicted pre-charge combustion due to leakage. The total automation of the filling procedure, through the implementation of a four-gas manifold with individual solenoid valve control, would have the additional benefit of reducing leakage.

Nonetheless, safety was seen as the priority in this matter and no actions to alter the filling procedure were taken. It is recommended, however, that after the CVCC has been in experimental use for an evaluation period, the filling procedure of the single inlet quick-coupler design is reviewed.

### **9.2.3 Mixing Fan Driver**

**The method** of driving the mixing fan was to use a utility air turbine die-grinder driver. The device could rotate at up to 20000 rpm and was coupled to the fan by a simple rubber sleeve. The arrangement was temporary as no stand had been fabricated and the driver had to be hand held. A recommendation for further development of the mixing fan is to install a small electric motor with a pulley and belt arrangement to achieve rotational speeds of approximately 10000 rpm for the fan.

## ***9.3 Repeatability of Experiments and Recommendations***

In the following paragraphs, the issues regarding the repeatability capability of the CVCC will be discussed. Recommendations are made for further study to be carried out where certain aspects of repeatability are yet to be quantified accurately.

### **9.3.1 Computer-related Repeatability**

The computer used to control the CVCC at the time of initial testing was an old Pentium 2. The processing speed and power of this machine negatively

impacted on repeatability. A critical aspect in the repeatability of experiments was the accurate timing of the injection event relative to the decreasing pressure in the chamber following pre-charge combustion. In order to inject at the user-defined pressure, the programme needed to calculate, as fast as it could loop, whether or not the decreasing pressure fell below the desired pressure. The faster the computer could perform these calculations and loop, the less the actual injection pressure would deviate from the desired value. A vast improvement was achieved by changing the main controlling computer to a Pentium 4. Using the Pentium 2, variations in pressure at the time of injection were as much as 2 bar, as recorded by the main controlling programme. This was reduced to below 0.01 bar with the Pentium 4. However, this aspect of reliability ultimately needs to be quantified using the buffered pressure traces from the secondary computer. The "actual" injection pressure recorded by the main controlling programme was subject to inaccuracies due to the pressure being captured before certain software events that were required to initiate the injection event. Initial results from buffered pressure traces showed that even by using a Pentium 4, the injection signal to the injector may have been as delayed as 0.6 bar below the desired injection pressure. Following the improvements in pressure trace quality (Refer to Section 9.4.6), it is recommended that fine-tuning of the controlling programme be carried out based on buffered pressure traces, in order to improve injection pressure repeatability and accuracy.

### **9.3.2 Effect of Crevice Volumes**

In Section 4.9, the decision to go ahead with Viton o-rings for sealing within the CVCC is discussed. As mentioned in that section, the effect of the crevice volumes created by the o-ring sealing was anticipated to be marginally detrimental to the repeatability of the environment produced by pre-charge combustion. However, this effect was sought to be minimised by the design, and no perceptible (visual or pressure-related) irregularities specific to the o-ring crevices were noted.

The other major crevice volume was that of the inlet insert, where a 3mm hole runs its length. Once again, no perceptible irregularity was noted as a direct consequence of this volume during critical periods of the experiment; however, during the exhaust event, it was very clear that a gas mixture of differing properties exited from this passage. It is thought that the visible portion of that mixture is likely to have been water droplets (picked up from the cool walls of the hole, where condensation was likely to have occurred) but may also have consisted of soot caused by incomplete combustion of the acetylene. The effect of potential incomplete combustion in the inlet insert on the repeatability of the experiments has not been observed or quantified yet and may need to be investigated further.

The study of the potentially detrimental effects of crevice volumes could be more comprehensively carried out if a high-speed video camera was made available.

### **9.3.3 Pre-Charge Combustion Prediction Recommendations**

In section 8.2.2, it was surmised that some of the reasons given for the pressure discrepancy could also have contributed a minor role to reduced repeatability, but that gas leakage was the primary reason in common. Recommendations will be made in response to the reasons given in Section 8.2.2 and will include suggested instrumentation changes.

- The inlet system was tested and found to be free of gas leaks under pressure. It is recommended that the exhaust valve and pressure transducer be targeted as the major potential sources of gas leakage.
- To comprehensively quantify radiation losses experimentally, it is recommended that once repeatability has been improved, all windows in the CVCC are replaced with their corresponding metal blanks and thorough testing be carried out to determine the resulting difference in peak pressures.

- Similarly with respect to nitrogen dioxide formation, once repeatability has been improved, the impact of increased peak temperatures on peak pressures, if any, should be investigated once again.
- The effect of high pressures on the volume of the chamber ought to be determined. It is thought that this could be achieved using a deadweight tester with visual access to the additional oil required to pressurise the chamber. By tightening all the inserts that make use of compressible gaskets, the potential volume change of the CVCC will be minimised.
- By replacing one of the metal ends of the cylindrical chamber with a metal insert with an increased surface area, it would be possible to quantify the impact of surface-area to volume ratio on heat loss and reaction quenching. It is also recommended that several thermocouples are used to measure the internal chamber temperature during a fill event to ensure that temperature homogeneity is characteristically achieved.
- It is recommended that the pressure transducer diaphragm be protected from the thermal pulses of combustion by a perforated shield. As an initial test, a thin silicone RTV adhesive sheet over the diaphragm could be used.

#### ***9.4 Difficulties Experienced and Recommendations***

The purpose of this section is to highlight the problem-solving that was required in order to produce an operational piece of equipment. An additional intention is that successive development may be carried out with the background knowledge of previous difficult areas. Following from this intention, recommendations for further development will be given where applicable.

##### **9.4.1 Exhaust Valve Sealing**

Testing showed that the previous exhaust valve needle and seat design did not continue to perform satisfactorily for extended periods of experimentation. The needle and seat arrangement tended to build up with an exhaust residual paste and this caused leakage after several combustion experiments. The procedure used to determine the severity of this build-up and the methods that were used to

overcome it are described in Appendix F 4.1. The copper washer that formed the seal between the seat and the exhaust insert was changed for a Viton o-ring, but no noticeable improvement in exhaust valve sealing was detected. Despite the easier installation, using an o-ring brought about the potential for seat misalignment following needle and seat grinding. The sealing issue was greatly improved by the removal of the tip of the needle and its replacement with an appropriately sized ball bearing.

#### 9.4.2 Ignition System

The generation of a reliable spark at all operating pressures proved to be a lengthy development. Initially, a spark was generated using the MOSFET board to break the current to a standard ignition coil. This system worked (seemingly randomly at times) for low fill pressures, below 8 bar.

The effect of different gases and increased pressure on spark generation was investigated. Since Nitrogen was used to test for sparks, it was thought that possibly it was more resistant to ionisation than air-fuel mixtures developed in IC engines. However, Nitrogen is only negligibly more resistant to spark transmission than Oxygen. Although the theoretical effect of the presence of hydrocarbons in the mixture was not established, later experimentation showed that a similar trend of sparking was observed with both Nitrogen and air-fuel mixtures. Increased pressure is widely known to have a negative effect on spark generation. Therefore, it was determined that the voltage being generated across the electrodes was not sufficient for all operating fill pressures of the CVCC.

After systematically adding and changing components, and performing manual (i.e. non-computer-timed) switching to eliminate uncertainty, a solution was found. The only arrangement that performed satisfactorily for fill pressures beyond 20 bar was found in using a superior ignition coil (40 kV) with a capacitor (to create a clean voltage break) and a Lucas Ignition Module for the electrical



switching. **The module** received the timing signal via the MOSFET board; however, the power itself was directed through the module.

#### 9.4.3 Eagle Data Acquisition (DAQ) Card

As mentioned in Section 7.2.2, two computers were required to operate the CVCC to its full extent. Initially however, it was thought that one machine would be adequate, and an Eagle card, PCI 703S, was employed as the controlling DAQ card. After several tests, it was determined that the card was faulty. The problem was that when continuous analogue input sampling occurred, random on-off digital signals would be sent out to the digital channels. This was problematic as during the fill procedure, when pressure was being sampled, digital stability was required to control the solenoid valves, for example. On contacting the **manufacturers, Eagle** Technology, they admitted to there being a fundamental **flaw in** their simultaneous sample-and-hold cards, including the PCI 703S.

In the application where the PCI 703S was only used for **a timed** and buffered analogue input, no digital signals were required during the acquisition. One digital signal would be transmitted following each acquisition and no irregularities were noticed with its functioning. It was unlikely **that erroneous signals** would emanate from digital channels during acquisition as a result of the card's flaw, due to the consuming nature of the acquisition process (See Section 7.2.2). However, a general warning is given for future development if it is desired to require the use of a signal (i.e. any non-neutral, activated signal) during a single buffered acquisition. Experience showed, for example, that digital signals were automatically turned off at the start of acquisition.

#### 9.4.4 Offset Visual Effect on Combustion

In some of the demonstrative photos that were taken of diesel injection and spontaneous combustion, it was evident that an undesirable photographic offsetting phenomenon was occurring, as shown in Figure 9.4.4.

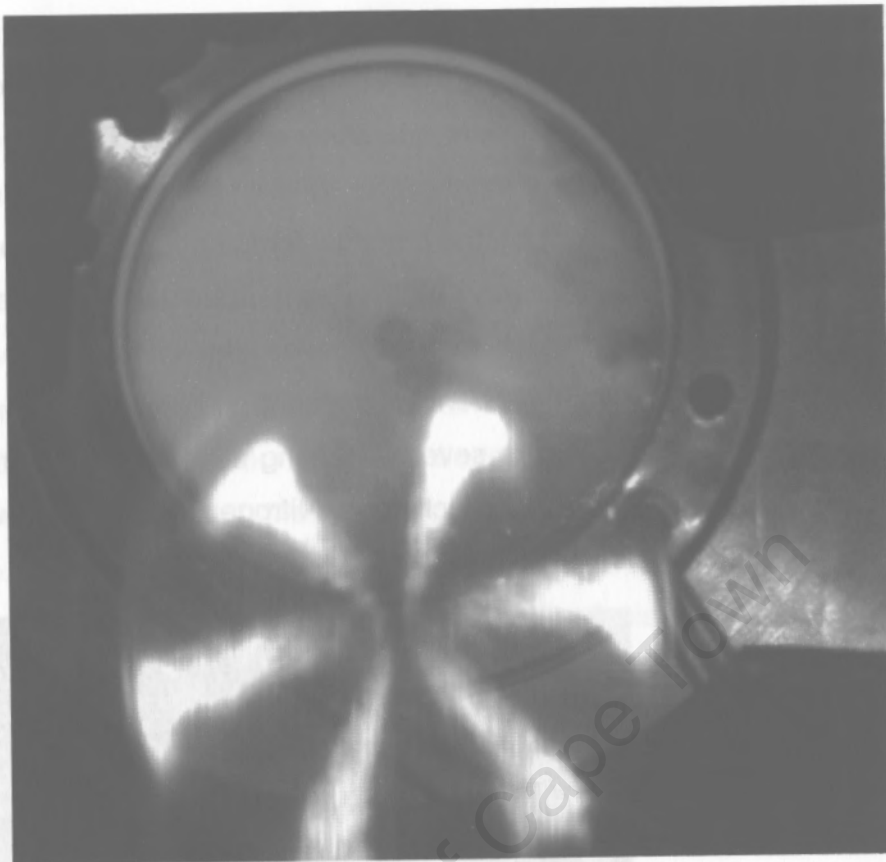


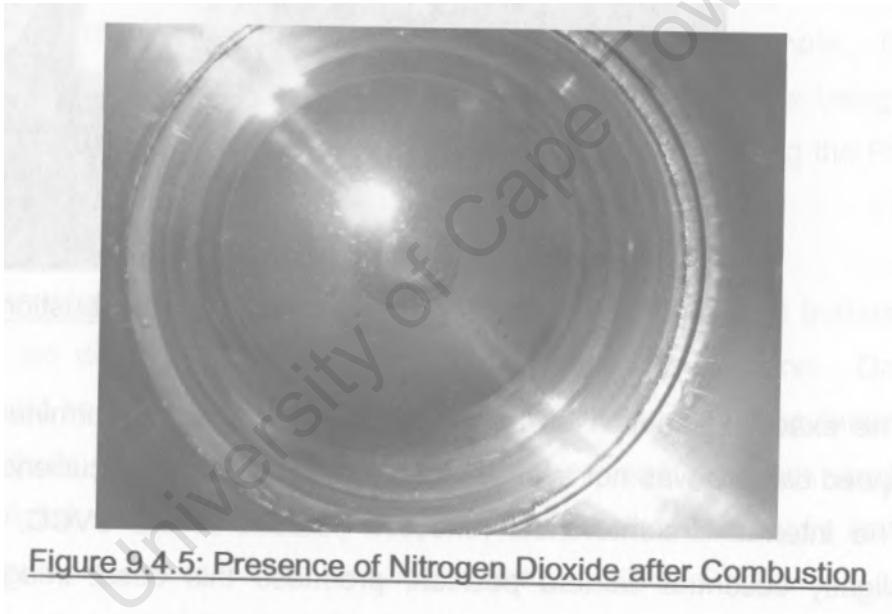
Figure 9.4.4: Offset Effect on Combustion

The exact explanation of this phenomenon was not determined, since a high-speed camera was not available, but the cause of this occurrence was deduced. The internal circumferential reflective portions of the CVCC, together with a slightly eccentric camera position, produced this offset image of the diesel combustion plumes. It is recommended that the alignment of photographic recording equipment with the cylindrical axis of the CVCC is ensured prior to the commencement of recording.

#### **9.4.5 Corrosion of Internal CVCC Components**

Corrosion of the diesel injection nozzle and the spark plug was found to be highly destructive if the CVCC was left standing for even a few days, despite being purged with Nitrogen before being left to stand. The cause of this corrosion was predominantly the formation of acids from the combustion products. When the

CVCC was operated without wall-heating, condensation of the water vapour in the combustion products occurred. Since the combustion gases included Carbon Dioxide and sometimes significant quantities of Nitrogen Dioxide (as evidenced by the reddish-brown colour of the gas mixture after an experiment, prior to exhausting — See Figure 9.4.5), the potential for Carbonic, Nitric and Nitrous Acid formation existed. Though the CVCC was purged with Nitrogen after every experiment to dry it and rid it of other gases, the effect of the acids on the susceptible metal components continued during storage. It was observed that the rate of corrosion was more severe following a high temperature experiment, indicating that the acid-forming reactions of Nitrogen Dioxide and water were the major cause of corrosion within the CVCC.



The solution to this problem is not as straight forward as buying stainless steel components throughout, as both injector nozzles and spark plugs are off-the-shelf items. In addition, even the stainless steel components showed signs of surface rust following high-temperature experiments. The recommendations to reduce corrosion effects are firstly to run the CVCC with heated walls and at minimal peak temperatures. Secondly, it is recommended that the injector and spark plug be removed if experimentation is to be halted for a significant period of time. For short breaks in experimentation, the CVCC should be held under

Nitrogen pressure to ensure no ingress of Oxygen, thereby mitigating corrosion mechanisms.

#### **9.4.6 Electromagnetic Interference of Signals**

Electromagnetic interference was a significant problem during experimentation. The cause of this interference was isolated to the variable speed drive of the high-pressure fuel pump motor. Actions that were carried out to reduce the interference included providing a different mains power supply to the motor and ensuring that all electrical "ground" connections were connected to the mains earth cable. Nonetheless, these improvements were not sufficient for satisfactory experimental work and it was recommended that the variable speed drive of the motor be targeted specifically to reduce the "noise".

(The ultimate solution was achieved by Mr Adrian Velaers, who hard-wired the motor to the mains power supply, thereby eliminating **the** use of the variable speed drive altogether. A re-arrangement of the pulleys was required to ensure correct rotational speed of the high-pressure fuel pump. The only drawback of this change was that the variability of the rotational speed of the high-pressure fuel pump was lost, but varied pressures in the common rail (accumulator) were still achievable by means of the common rail pressure relief valve.)

### **9.5 Suggestions for Future Applications**

The following paragraphs describe ideas for future additional uses of the CVCC. The CVCC was developed with them in mind; however, due to these applications falling outside the core requirements of the development, they were not implemented.

#### **9.5.1 Spark-Ignition Fuel Studies**

In the Terms of Reference, it was given that "it may be useful if the apparatus could be used to characterise spark ignition fuels, in the hope that a more integrated understanding of spark and compression ignition fuels might be

achieved'. Two main contexts for testing spark ignition fuels were identified, viz. by direct injection, in the compression ignition sense, and secondly by igniting homogenous charges.

The primary advantage of testing spark ignition fuels as compression ignition fuels is that of comparison with diesels. A spark ignition fuel could be injected into the chamber at the same conditions to that of a diesel injection event, most likely at the higher end of the temperature spectrum, and though a great difference in ignition delay would exist, a direct comparison could be drawn. The injection of petrol could possibly be achieved by two methods. Firstly, in a similar fashion to the diesel injection system, a Gasoline Direct Injection (GDI) system could be set up to supply fuel at an appropriate pressure for the conditions produced by pre-charge combustion. Alternatively, either petrol could simply be injected using the diesel system or, if greater lubricity was required for the HP pump and an additive could be found that had no influence on the variables being investigated, petrol with such an additive could be used.

The purpose of igniting a homogenous charge of spark ignition fuel would be primarily for comparison with other spark ignition fuels. Of particular interest may be the characterisation of the onset of auto-ignition (knocking) for such fuels. The comparison of this for different fuels could be achieved by altering the initial fill pressure and to a lesser extent, the temperature prior to ignition. Another flexible aspect in inducing knock in the end-gas would be the positioning of the spark plug, which can be placed centrally or on the circumference of the CVCC. The attainment of a homogenous fuel-Oxygen-Nitrogen mixture would require some development. Two major options for creating a homogenous mixture exist; viz. to inject a fine spray of the fuel into the CVCC following the metering in of the Nitrogen and Oxygen, while maintaining turbulence with the mixing fan; or to develop a separate mixing chamber in which this is achieved and then meter in the desired mixture volume to the CVCC chamber via the inlet system. The latter, however, has a detrimental impact on the overall safety of the system and

would have to be considered in a similar manner to that outlined in Section 32.3 for a pre-charge mixing vessel.

### **9.5.2 Fuel Impingement Studies**

**The** CVCC internal diameter, being 100 mm, is such that studies of diesel combustion can be made without interference with the walls of the chamber. However, a fairly simple development would enable one to simulate fuel-on-wall/piston impingement if desired. For example, using the flat-end centre position for the injector, one could use an extended metal window-replacement in one of the larger circumferential ports to model a cylinder wall or piston bowl. The end of the extended metal window-replacement would have to be milled and may require a transparent section to ensure maximal optical access. An independently controlled heater cartridge could also be installed in this extension to increase the degree of simulation by providing specific temperature control to the simulated wall and/or piston.

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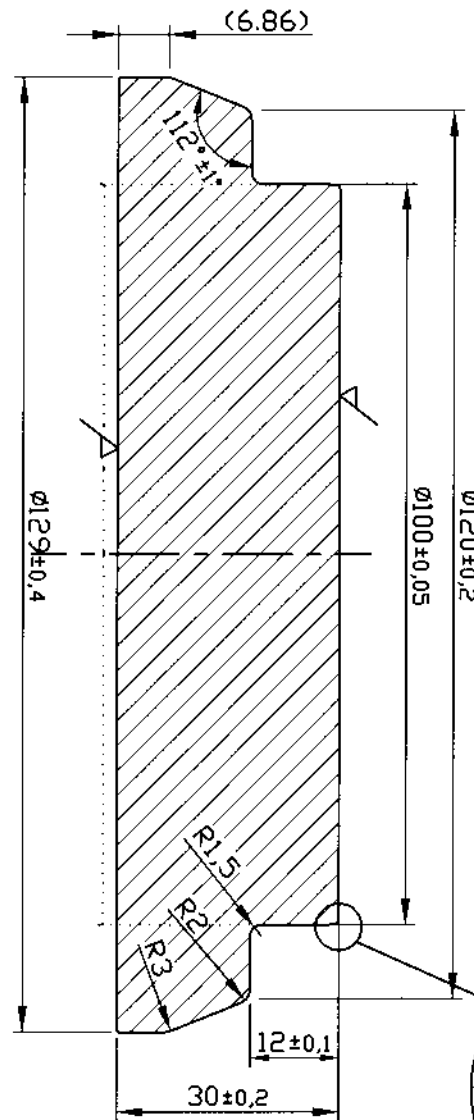
## **APPENDIX A— COMPONENT DRAWINGS**

The following pages in this appendix contain the part drawings of the components manufactured for incorporation into the assembly of the Constant Volume Combustion Chamber.

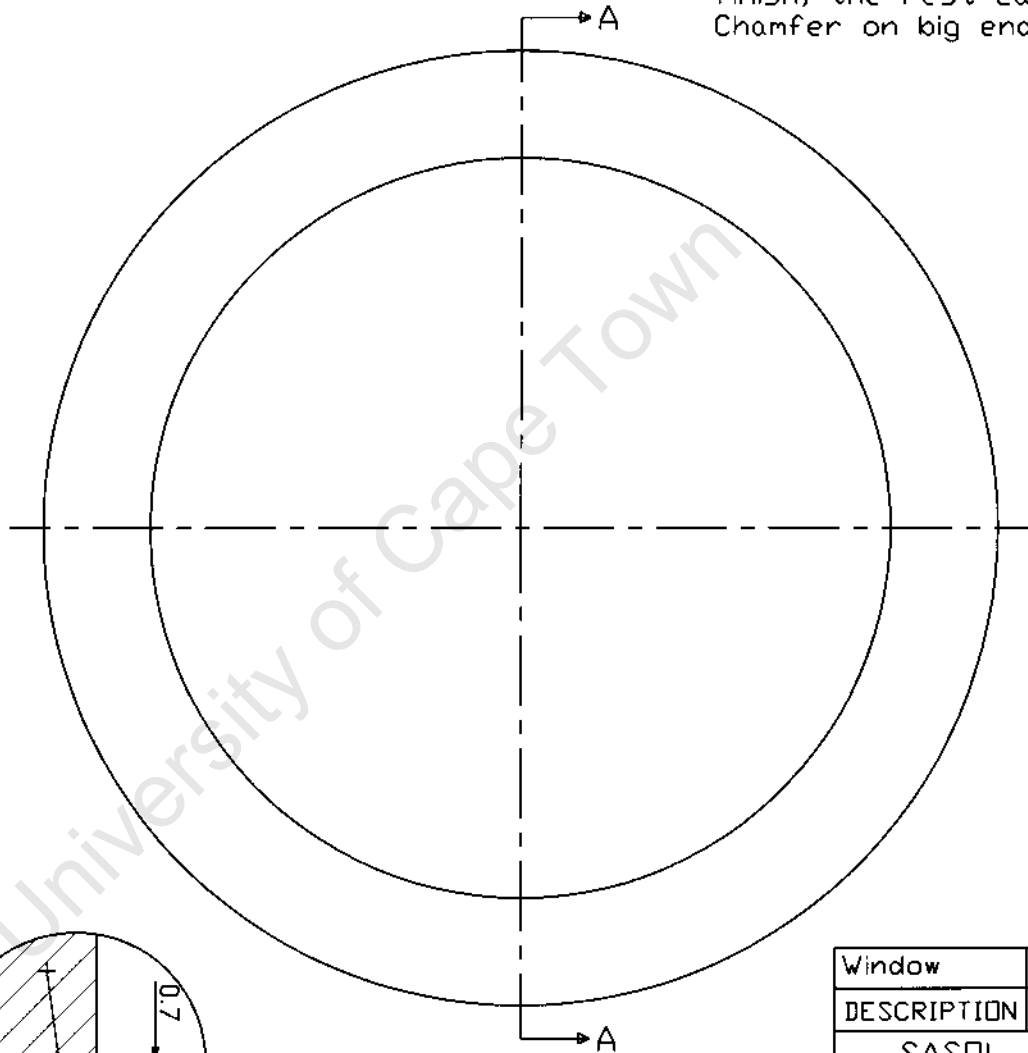
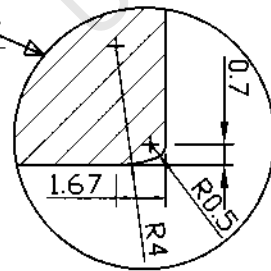
University of Cape Town



Notes:  
 Surfaces marked with ✓ are to be polished to a 60/40 scratch/dig finish; the rest can be fine ground.  
 Chamfer on big end is 0.2mm x 45°



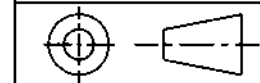
Section A-A



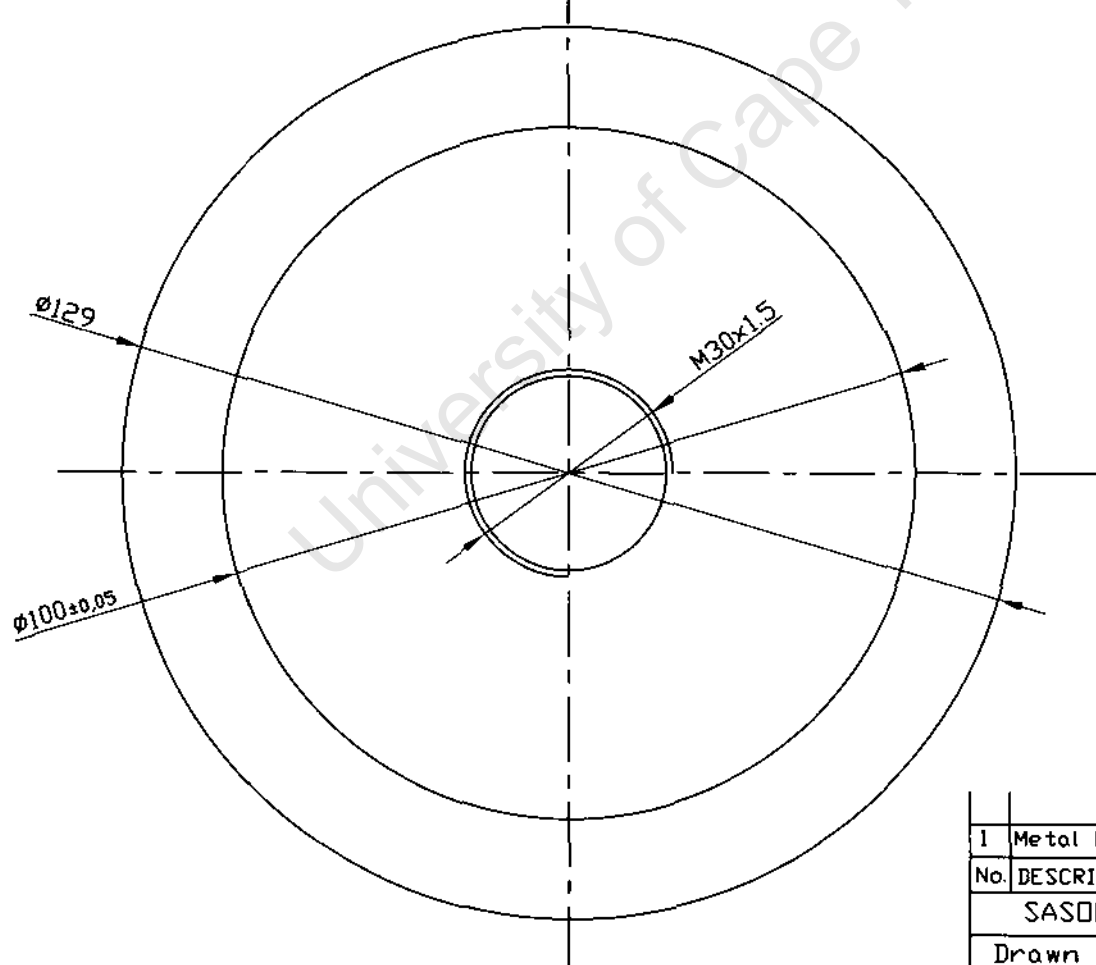
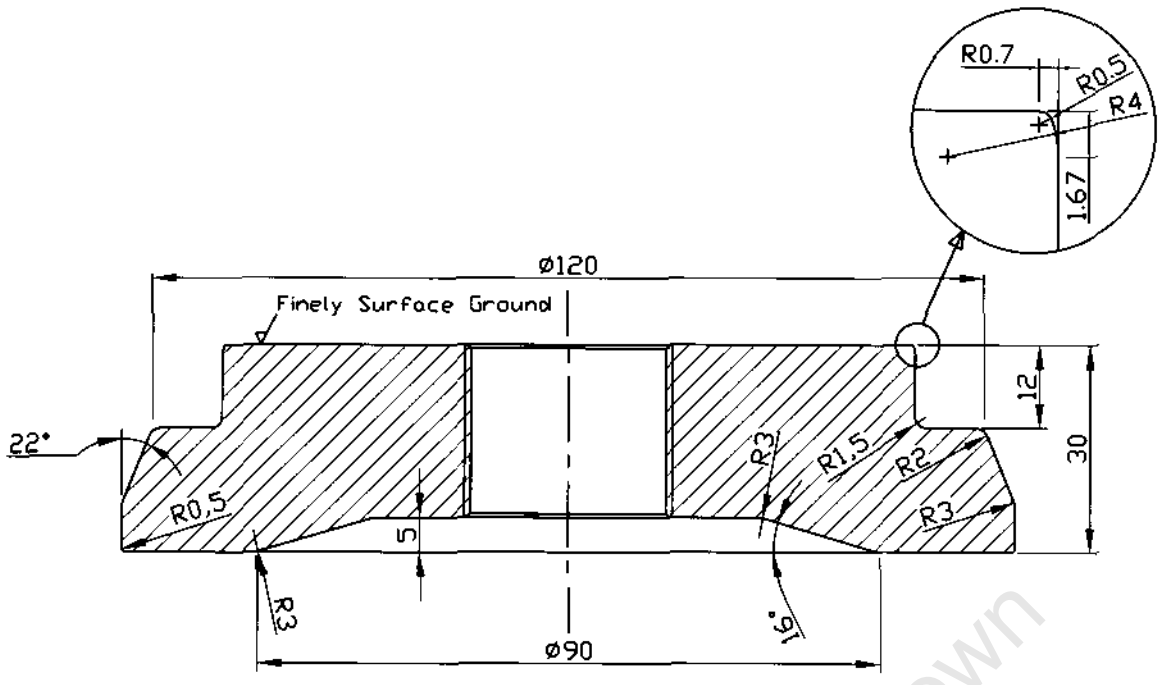
Window	Opt. Gr. Sapphire	2
DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd		

All dimensions in mm  
 Tolerances to ±0.1mm  
 where not specified

Drawn by: Geoff Miller  
 Date: 26-11-2002 sht 2 of 2

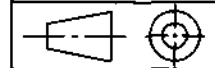


Title: Large Window



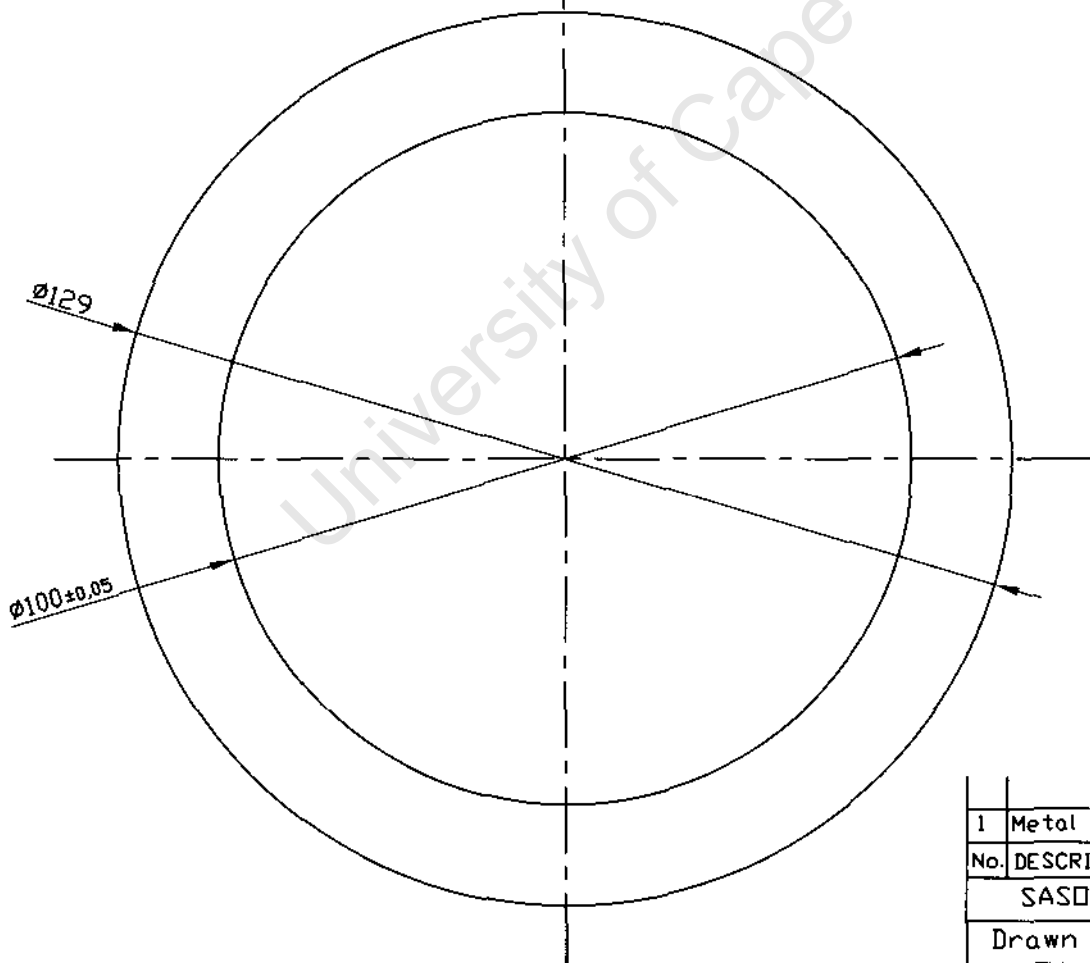
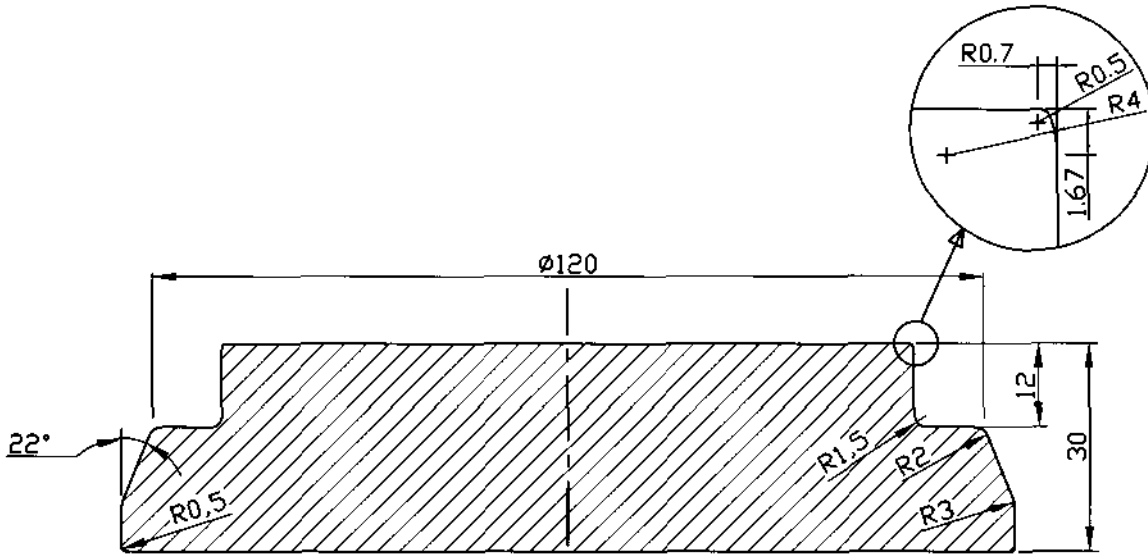
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No.	DESCRIPTION	MATERIAL	No. OFF
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			

Tolerances to  $\pm 0.2\text{mm}$  where not specified



Date: 30-09-2002 Sht 2 of 3

Title: Metal End for Injector/Spark Plug



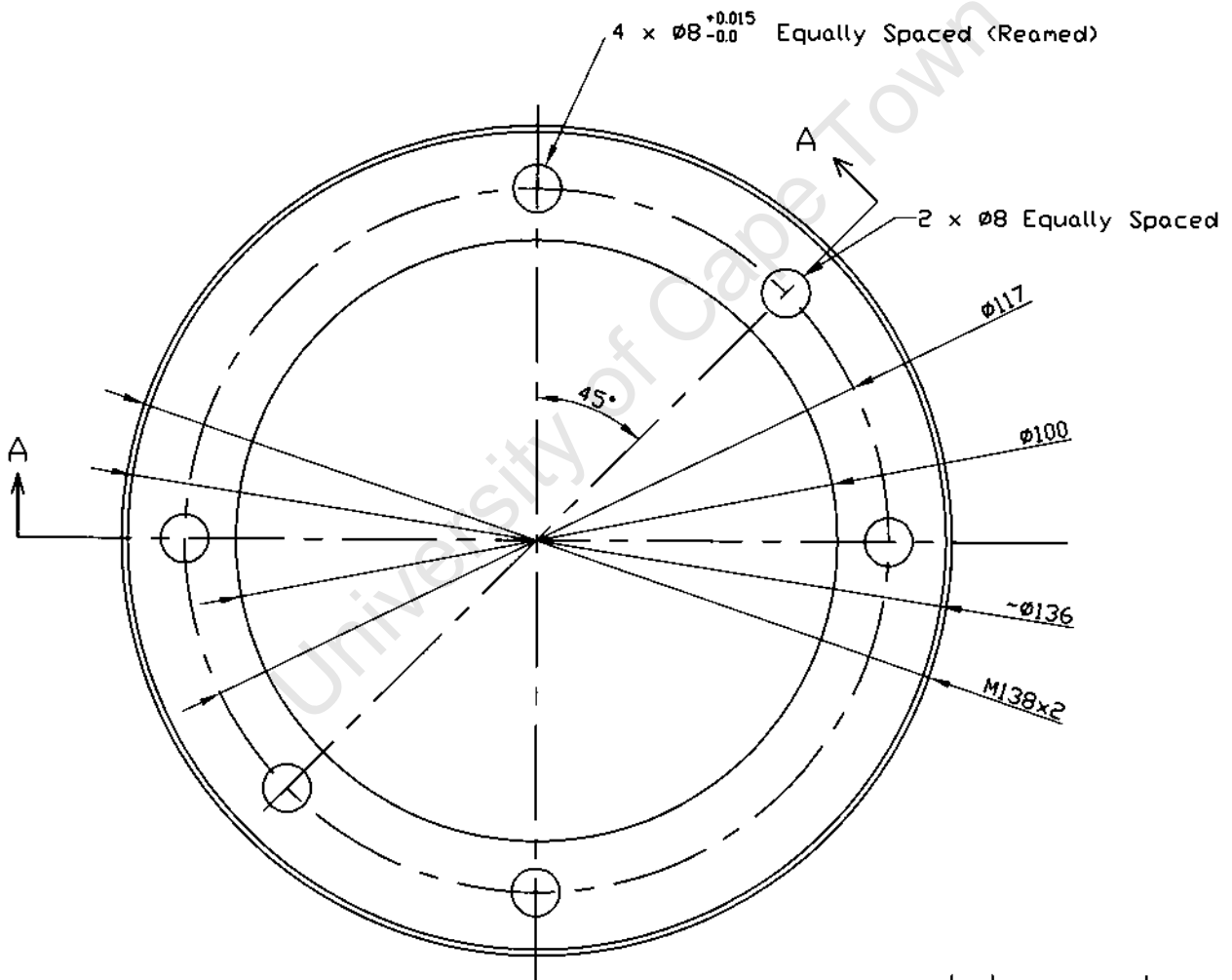
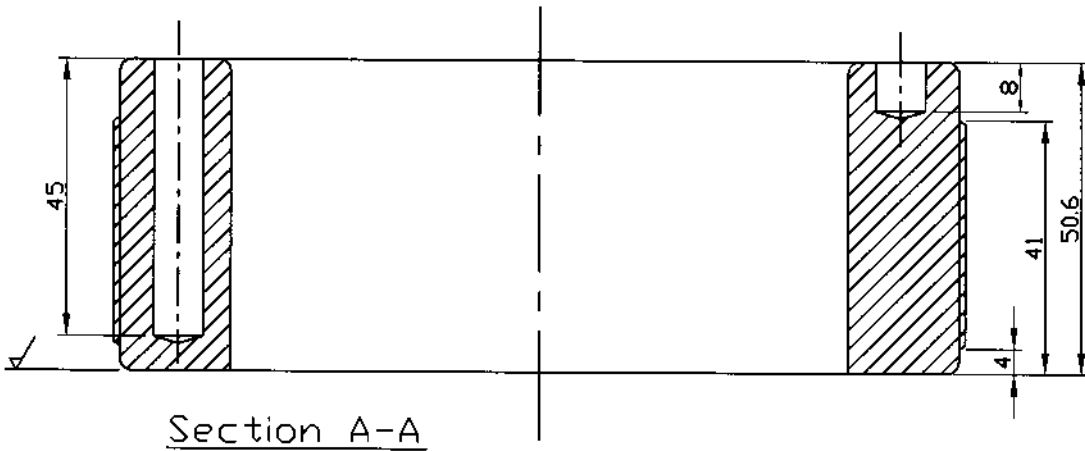
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No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			

Tolerances to ±0.2mm where not specified

Date: 30-09-2002 Sht 2 of 3



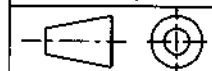
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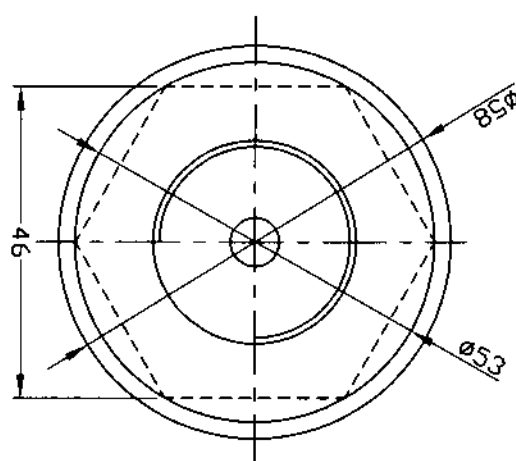
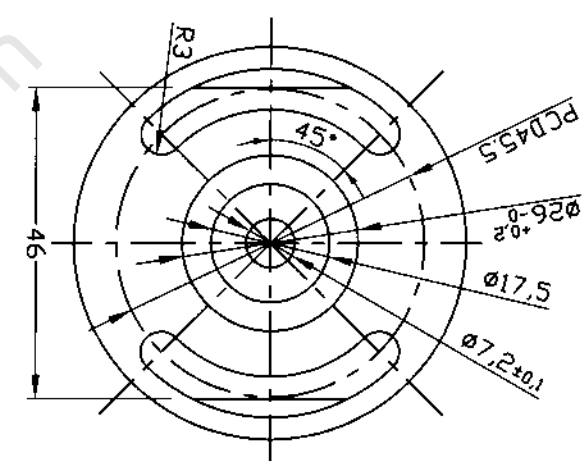
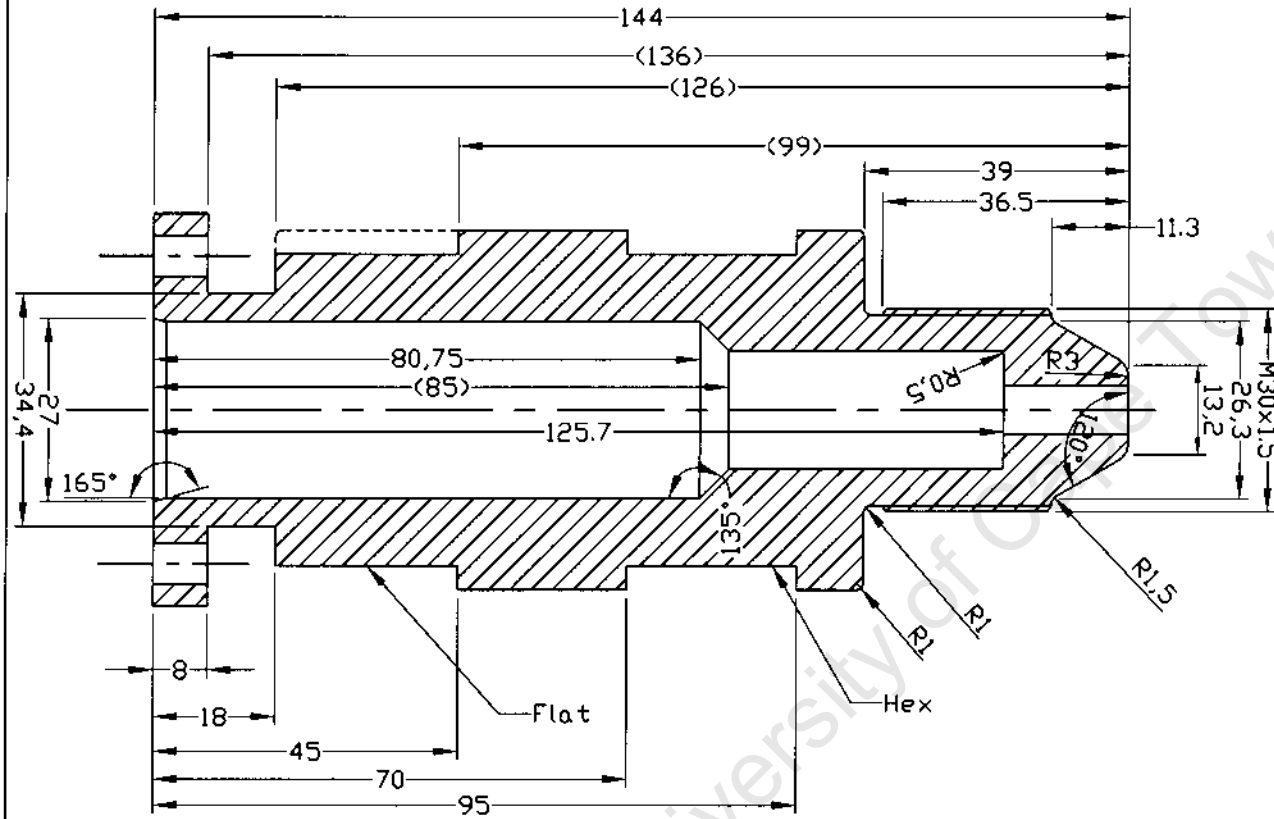
**Notes:**

✓ = Surface Ground (smooth & flat)  
 All radii to be 2mm

Tolerances to  $\pm 0.2\text{mm}$   
 where not specified

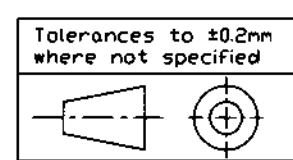


1	L. Retainer	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. of
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 9-6-2003			sht 2 of 3
Title: Large Retainer for Metal End			

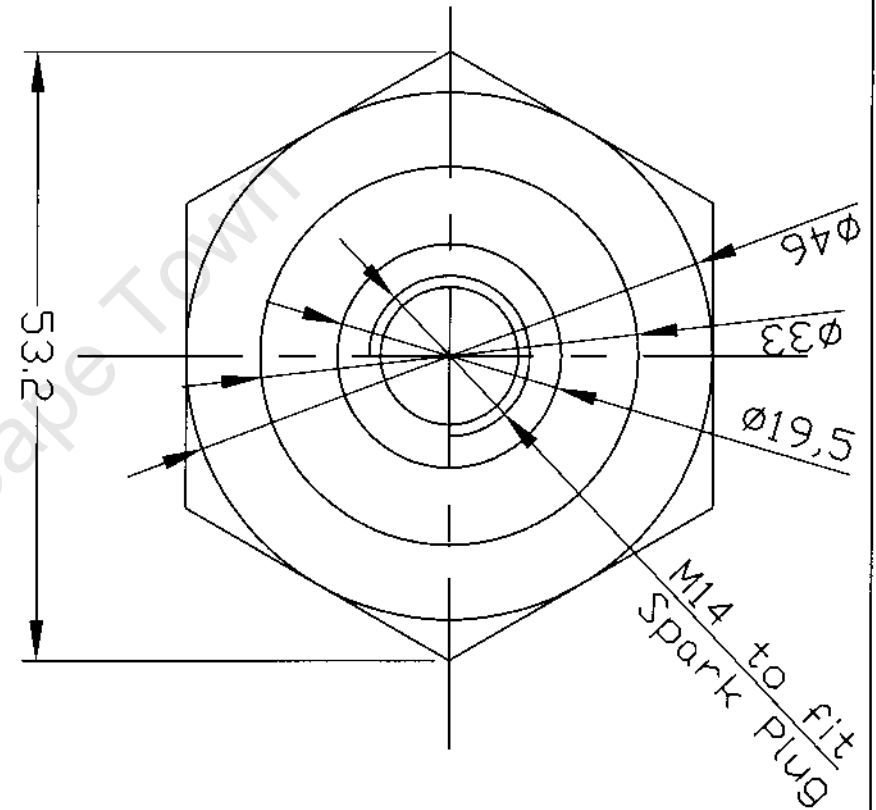
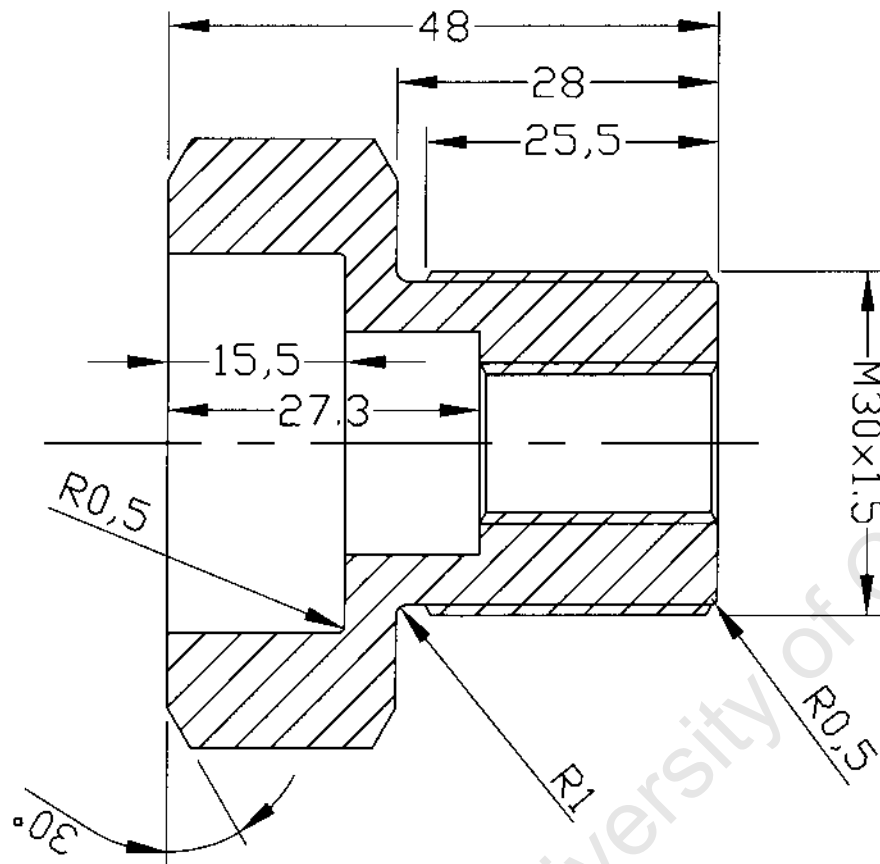


View from the Right

1	Top Plug	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 30-09-2002		Sht 2 of 3	
Title: Top Plug for Injector			







1	SP Nozzle	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off

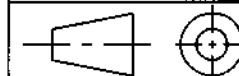
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Drawn by: Geoff Miller

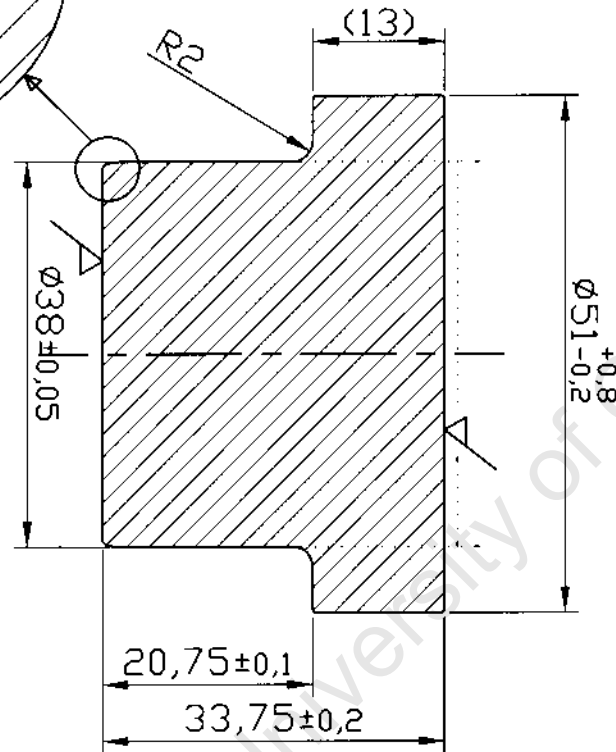
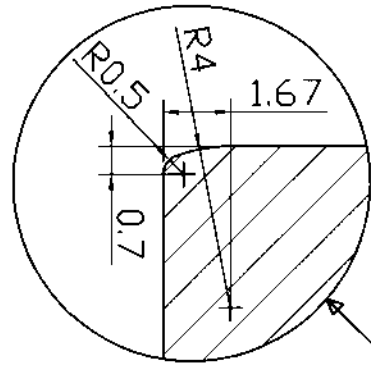
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Date: 15-10-2002

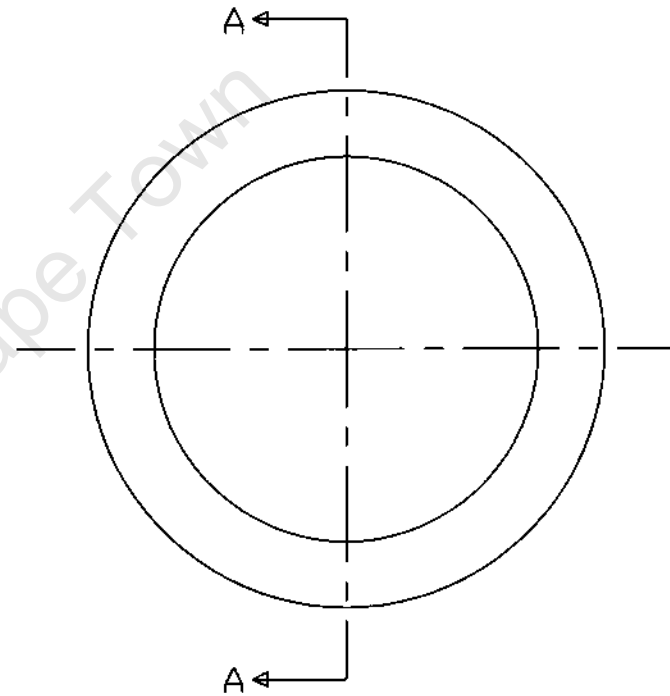
Sht 2 of 3



Title: Spark Plug Nozzle  
for Flat End



Section A-A



Notes:  
 Surfaces marked with  $\checkmark$  are to be polished to a 60/40 scratch/dig finish; the rest can be fine ground. Chamfers on big end are 0.2mm x 45°

Window	Opt. Gr. Sapphire	3
DESCRIPTION	MATERIAL	No. off

SASOL OIL (pty) Ltd

Drawn by: Geoff Miller

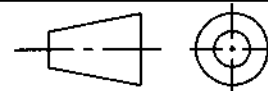
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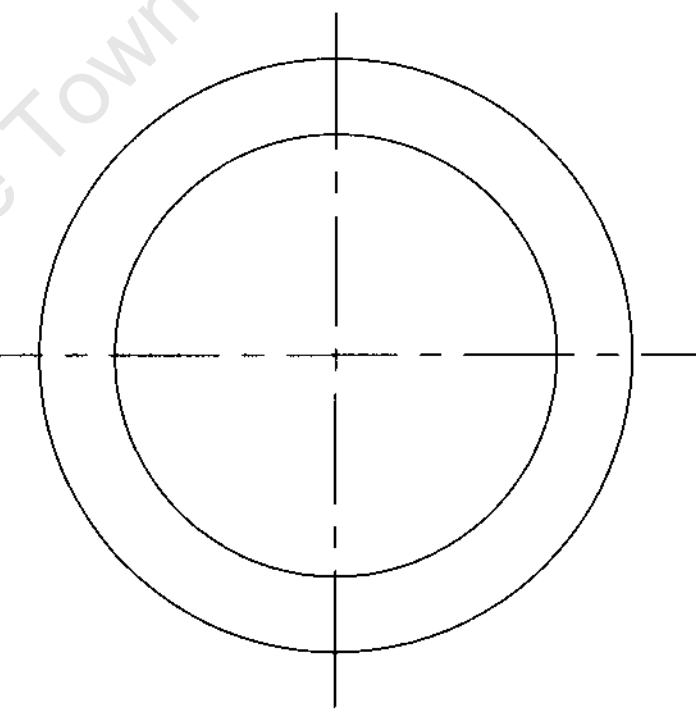
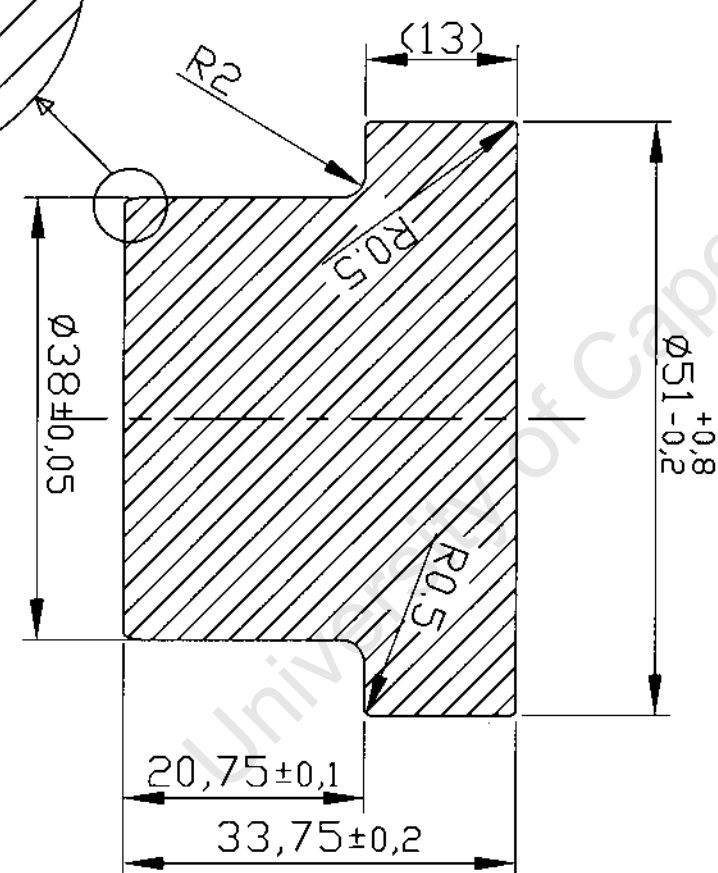
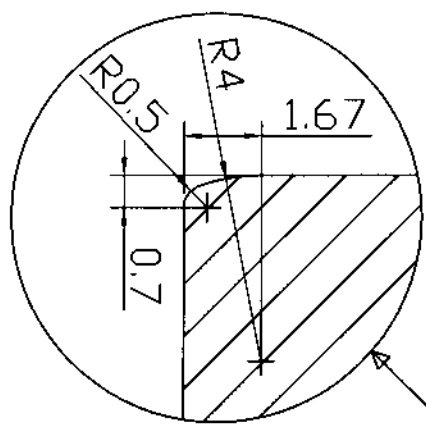
Sh't 1 of 2

Title: Medium Window

All dimensions in mm

Tolerances to  $\pm 0.1$ mm where not specified





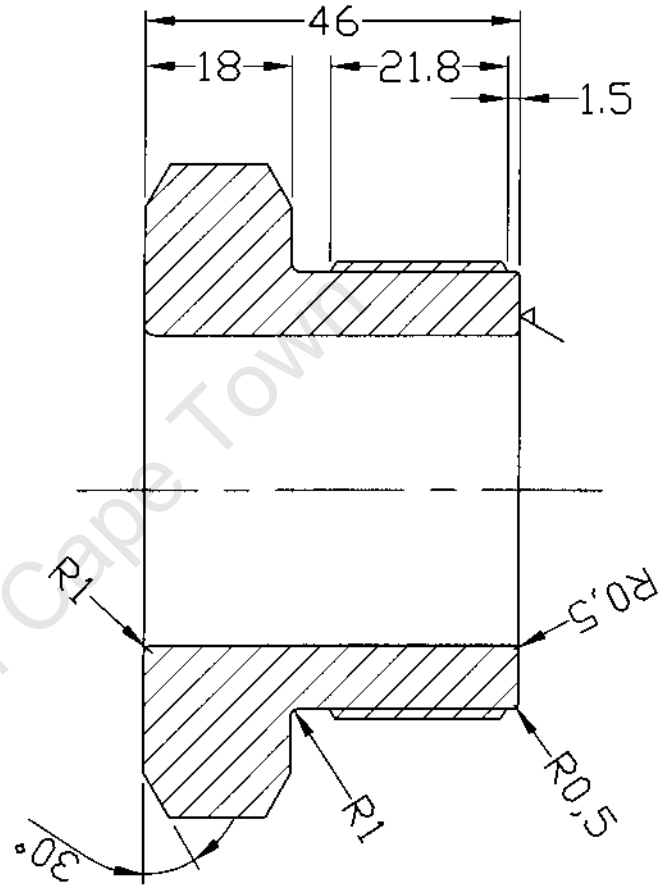
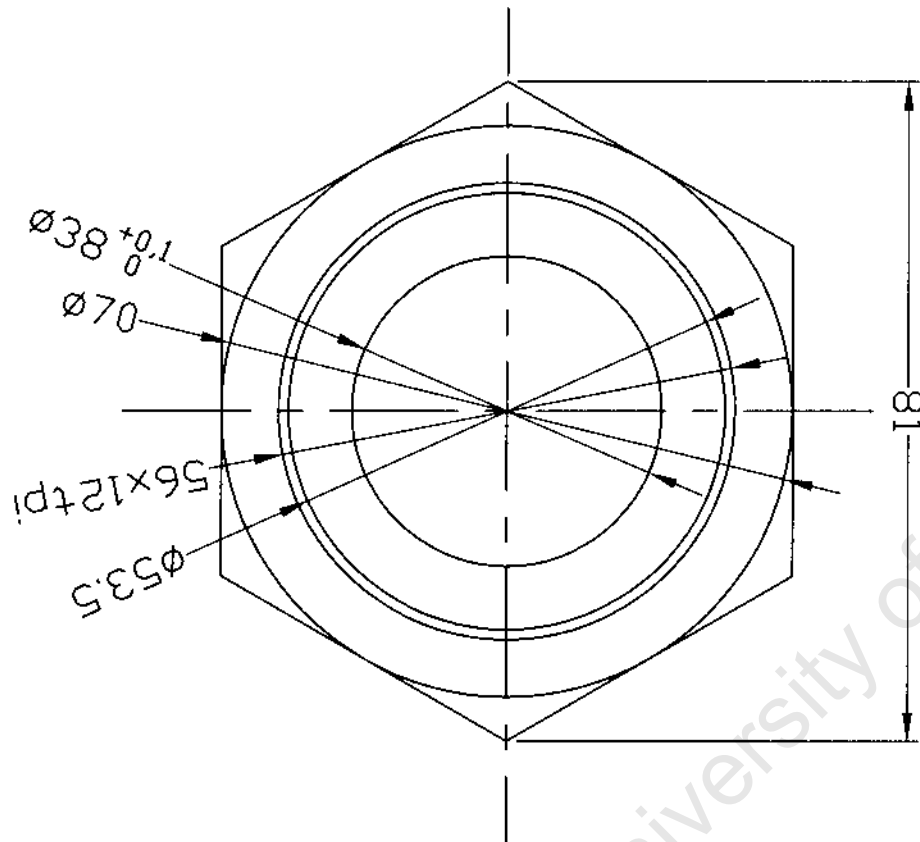
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SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			

Tolerances to  $\pm 0.2$ mm where not specified



Date: 30-09-2002    sht 2 of 3

Title: Metal Blank for Window Replacement



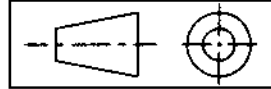
✓ = Surface Ground

1	M. Retainer	Bohler M300	3
No.	DESCRIPTION	MATERIAL	No. off

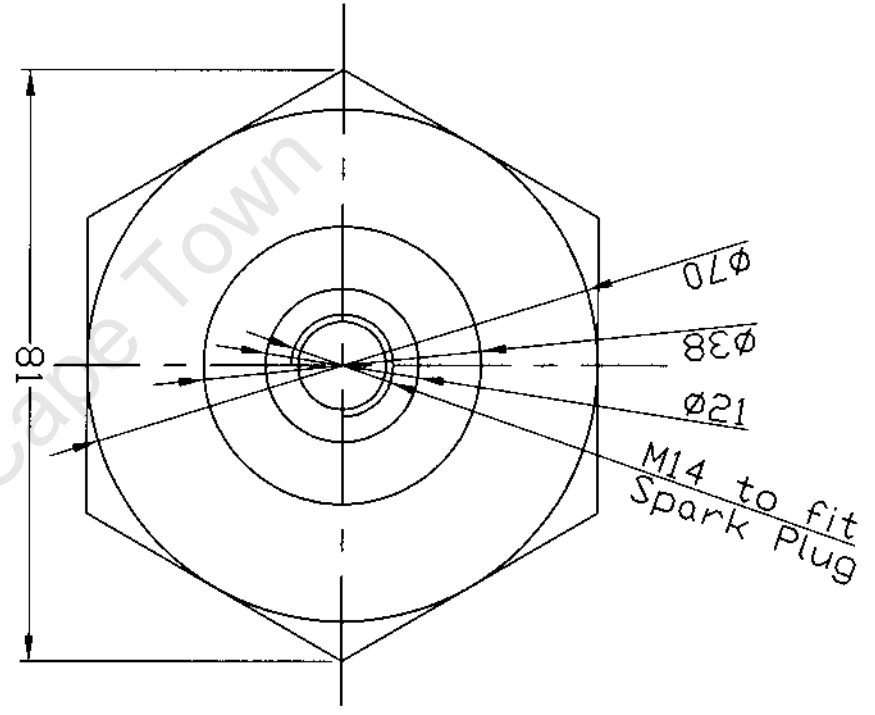
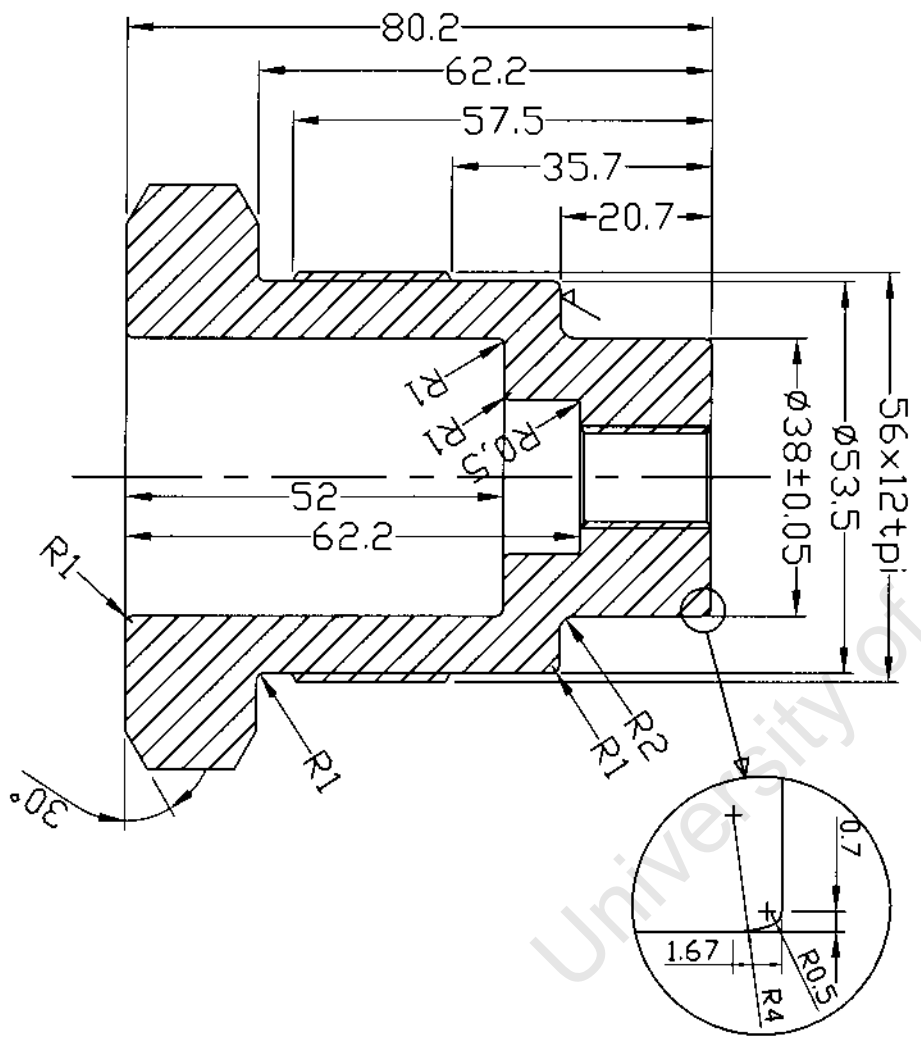
SASOL OIL (pty) Ltd  
 Drawn by: Geoff Miller

Tolerances to  $\pm 0.2\text{mm}$   
 where not specified

Date: 3-10-2002    Sht 2 of 3

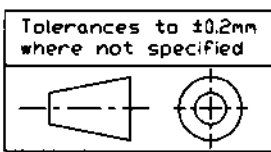


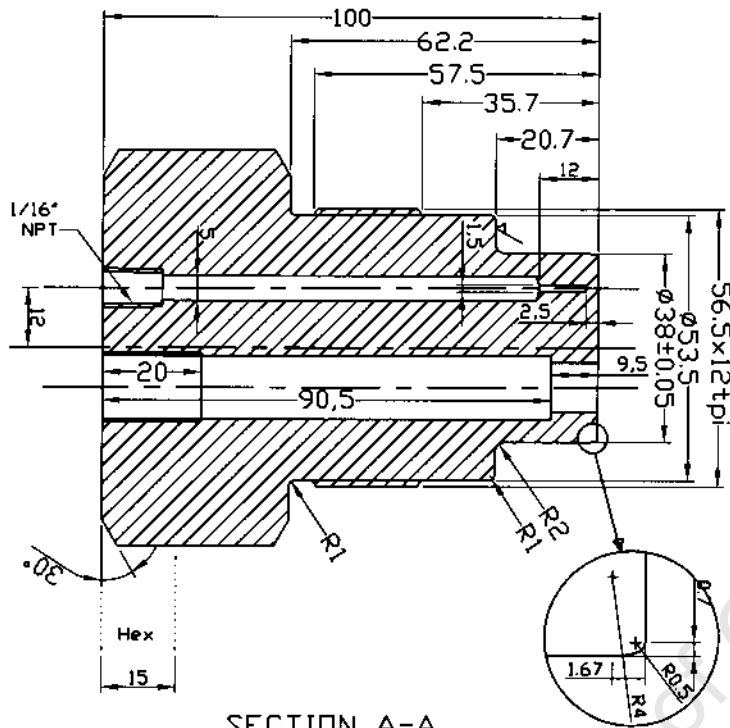
Title: Retainer for Medium  
 -sized Windows



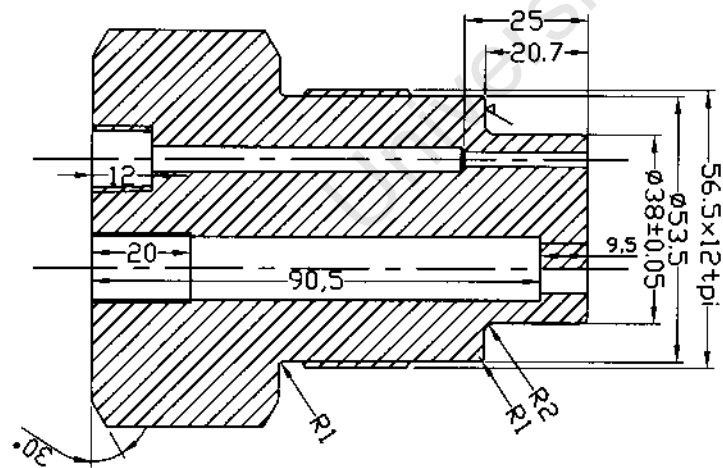
✓ = smooth surface finish

1	M. Retainer	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 3-10-2002		Sht 2 of 3	
Title: Retainer for Spark Plug			

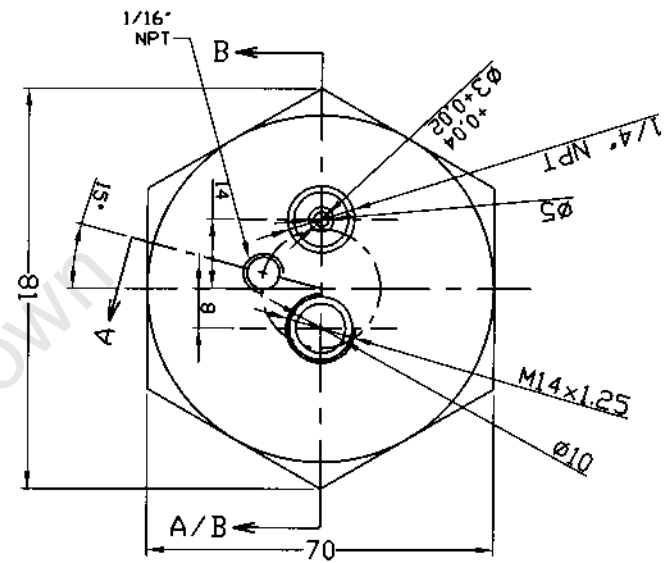




SECTION A-A



SECTION B-B

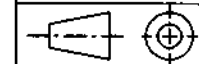


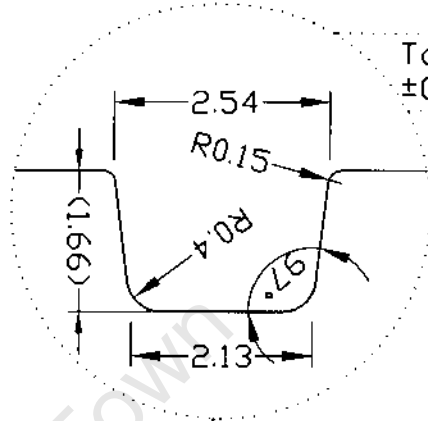
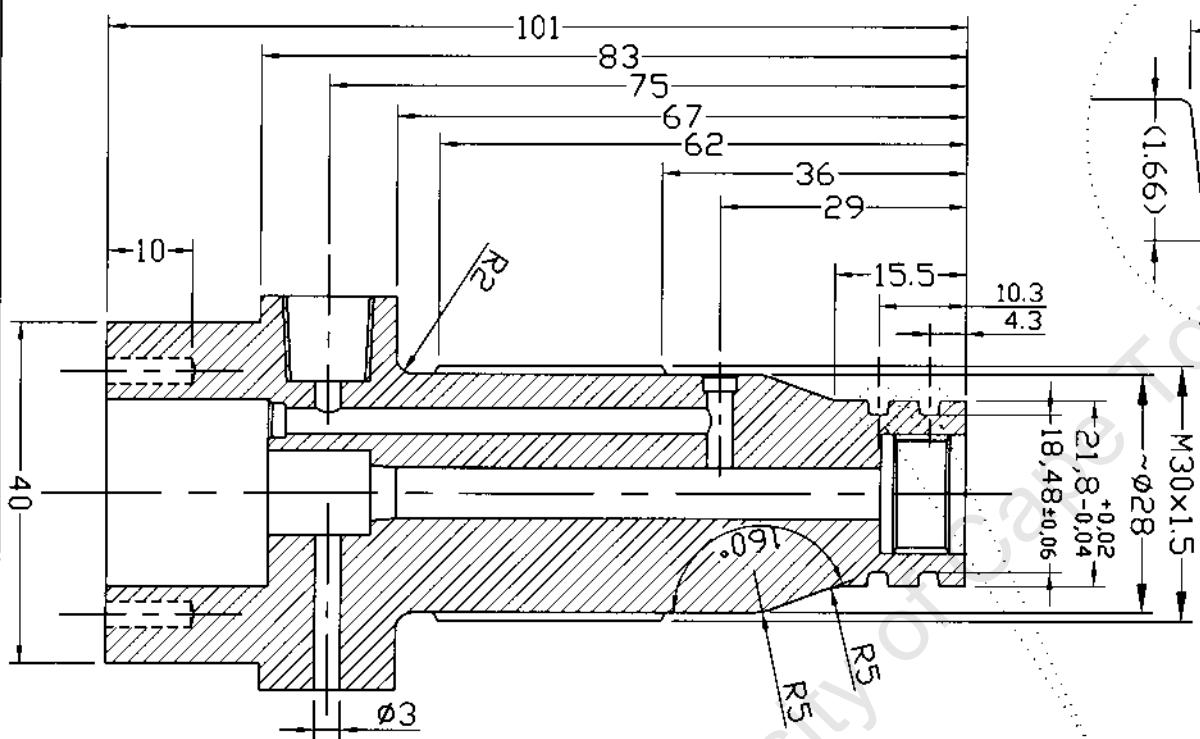
Note: The  $\varnothing 1.5$ mm plug has to resist 300bar pressure.

✓ = smooth surface finish

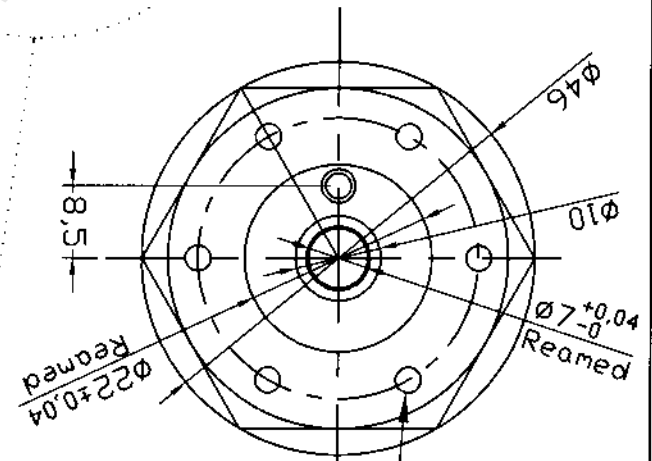
1	Med. Plug	Bahler M300	1
No.	DESCRIPTION	MATERIAL	No. of
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 13-11-2002		Sht 2 of 3	
Title: Instrument Plug			

Tolerances to 0.1mm where not specified

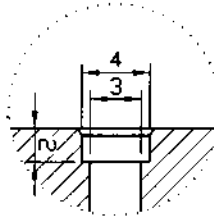
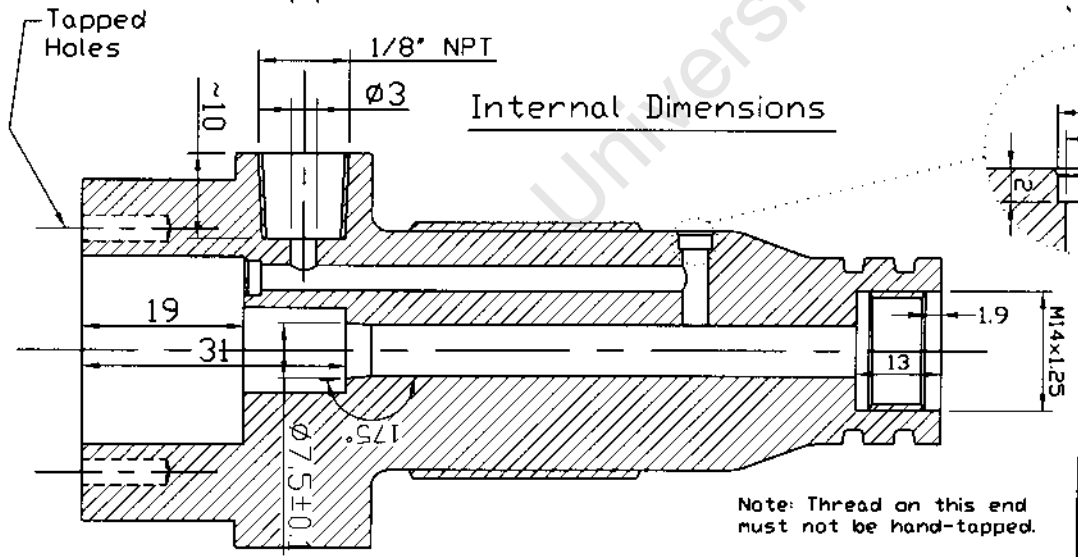




Tolerances  
±0.04mm

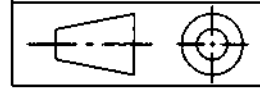


M3 Equally Spaced PCD33



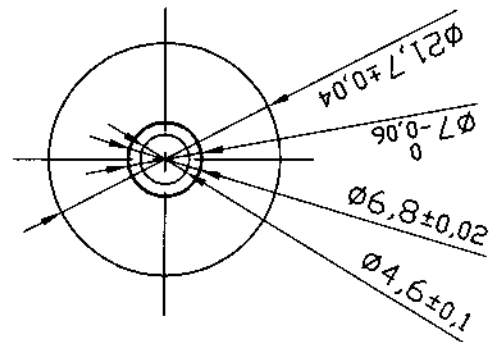
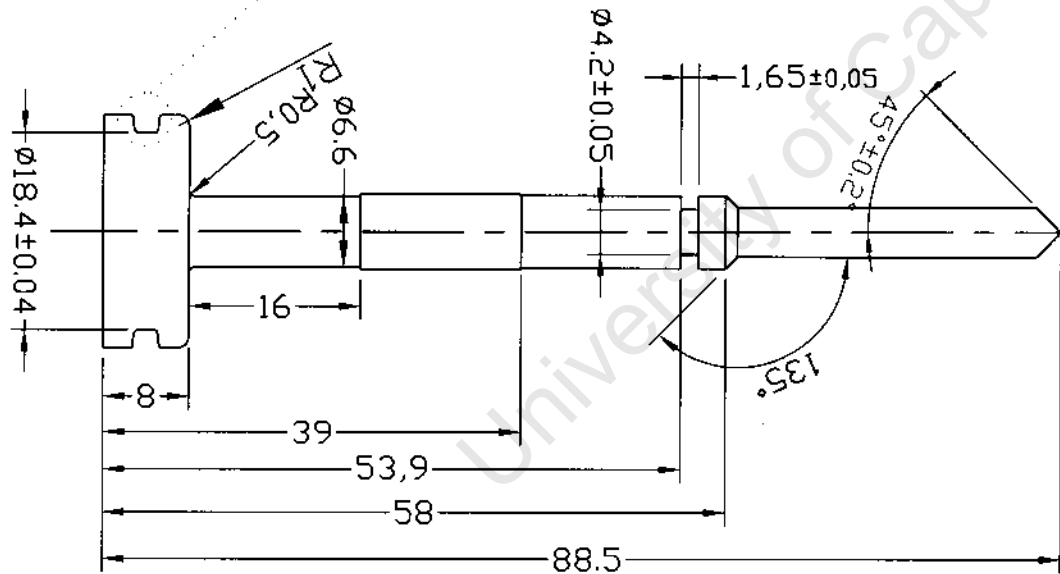
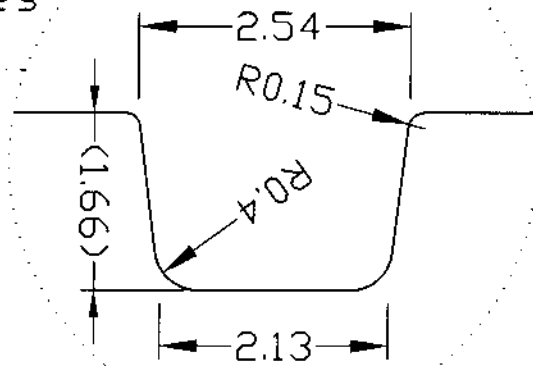
Note: Thread on this end must not be hand-tapped.

Tolerances to ±0.2mm where not specified

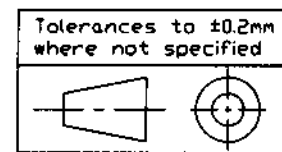


1	Valve Plug	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 23-10-2002		Sht 2 of 3	
Title: Outlet Valve Plug			

Tolerances  
±0.04mm

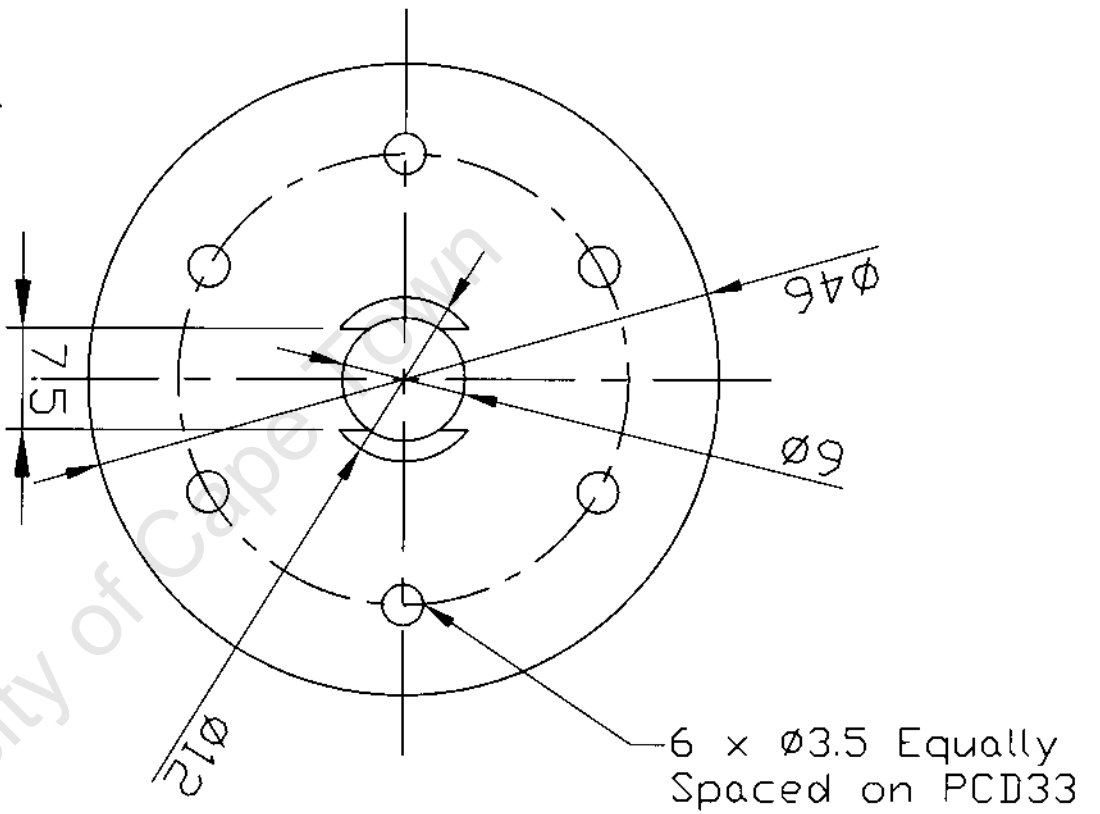
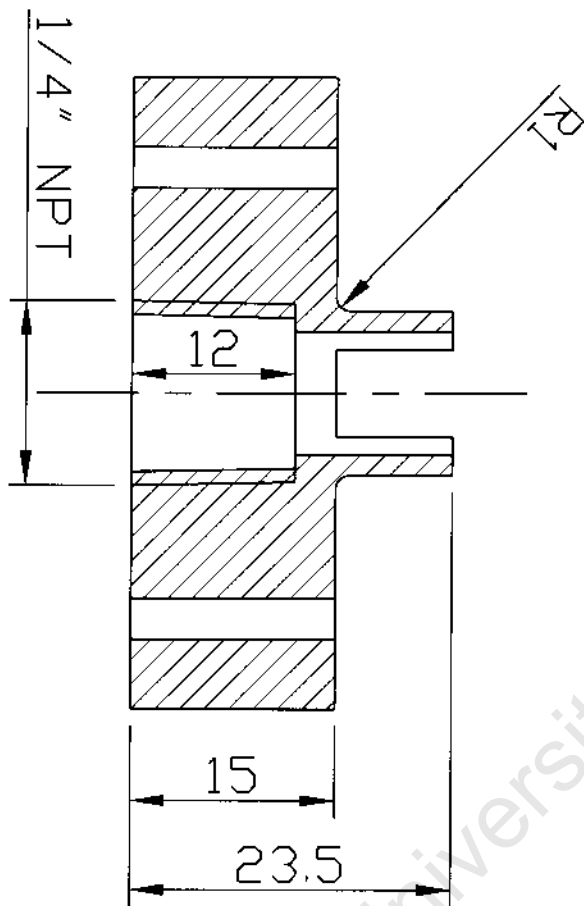


1	Needle	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 1-04-2003		Sht 2 of 3	
Title: Exhaust Valve Needle			



Tolerances to ±0.2mm where not specified





1	Exhaust Cap	S/Steel	1
No.	DESCRIPTION	MATERIAL	No. off

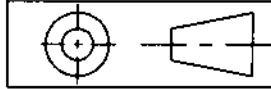
SASOL OIL (pty) Ltd

Drawn by: Geoff Miller

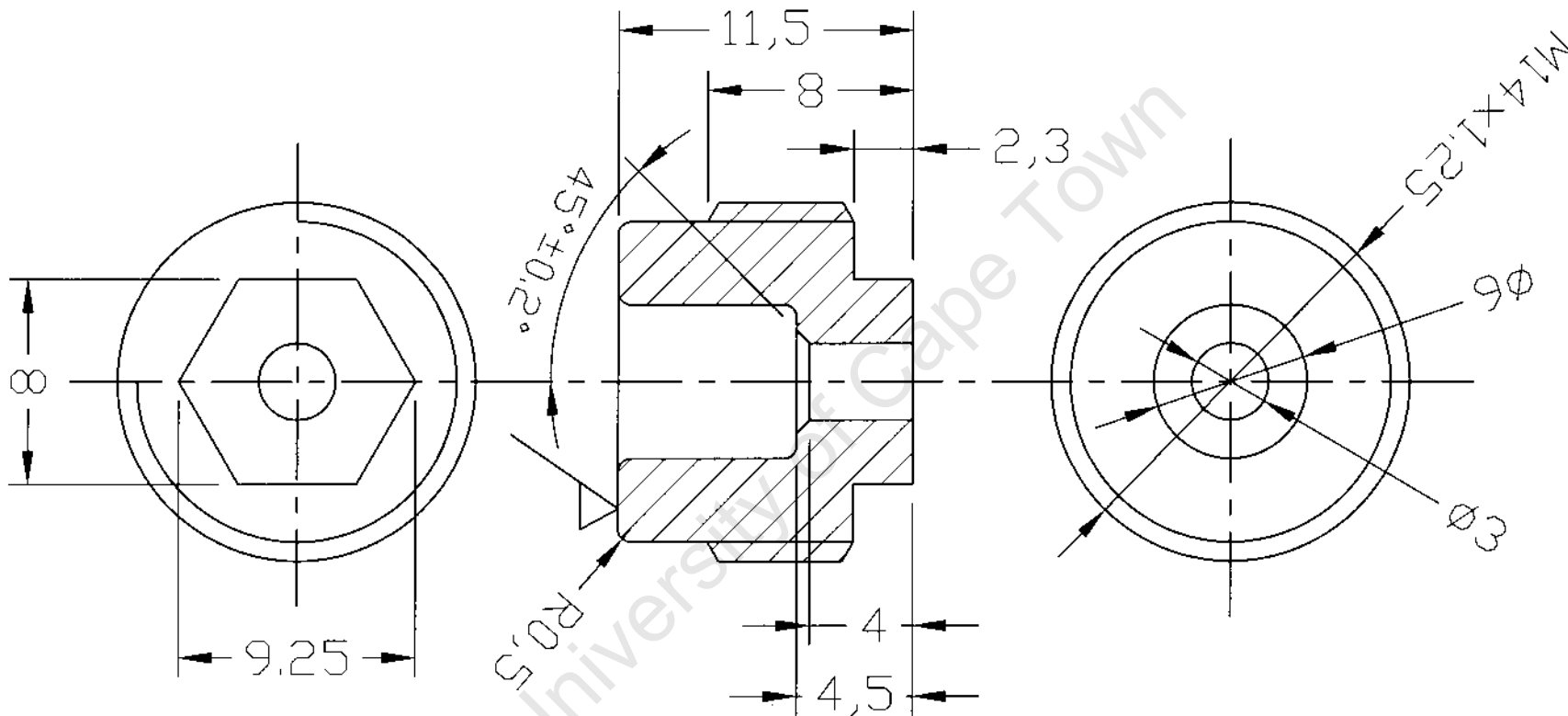
Tolerances to  $\pm 0.2\text{mm}$  where not specified


Date: 11-11-2002

Sht 2 of 3



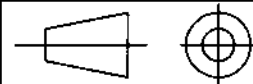
Title: Exhaust Valve Top Cap

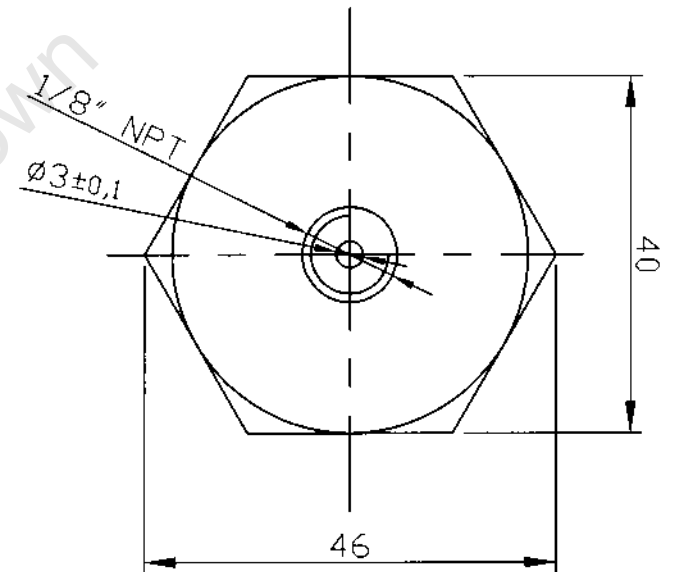
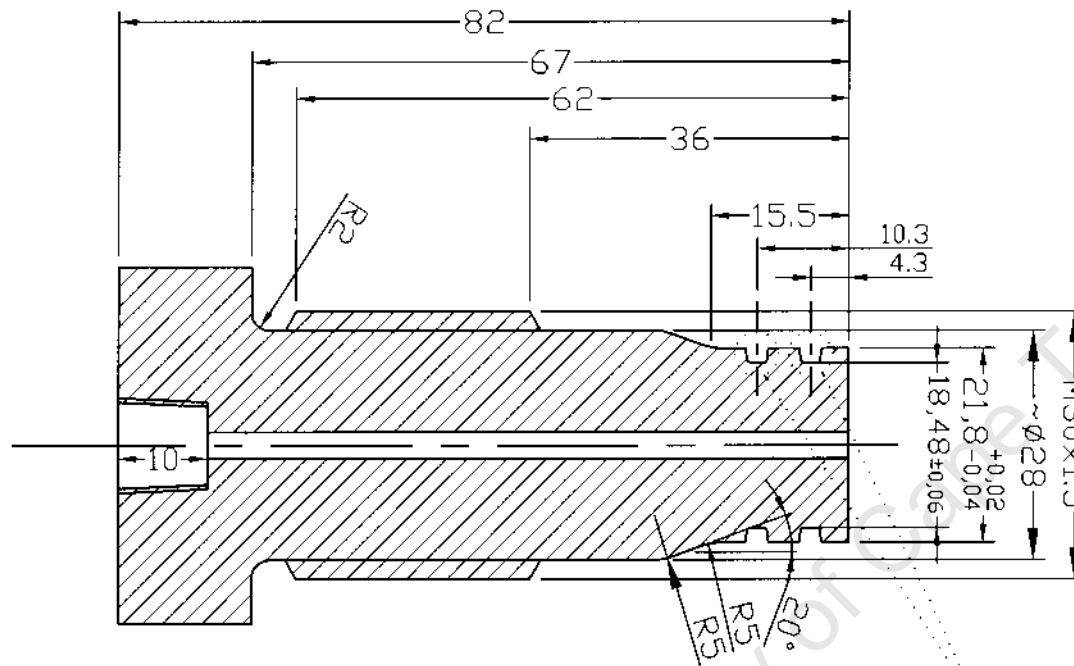


 = Surface Ground  
 Unspecified inner radii: R0.5

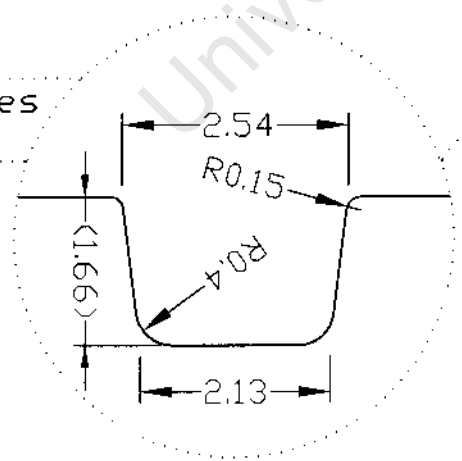
1	Needle Cap	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 15-11-2002		Sht 2 of 3	
Title: Exhaust Valve Needle Cap			

Tolerances to  $\pm 0.1\text{mm}$  where not specified

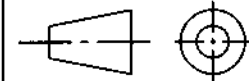




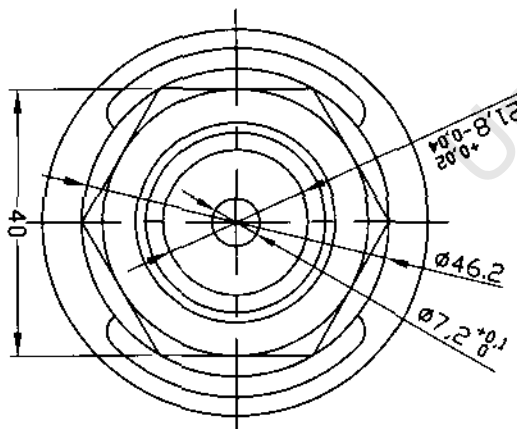
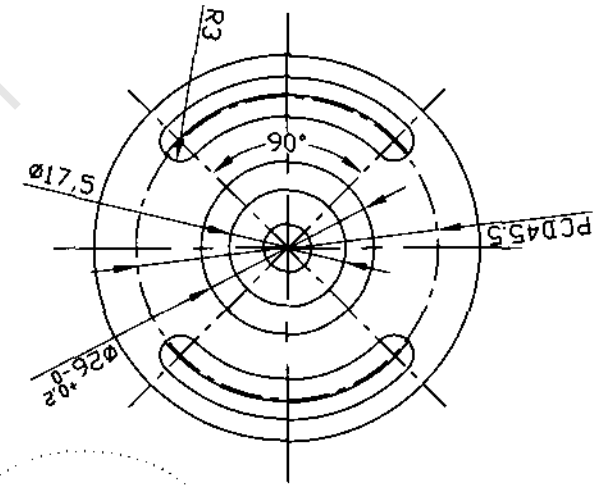
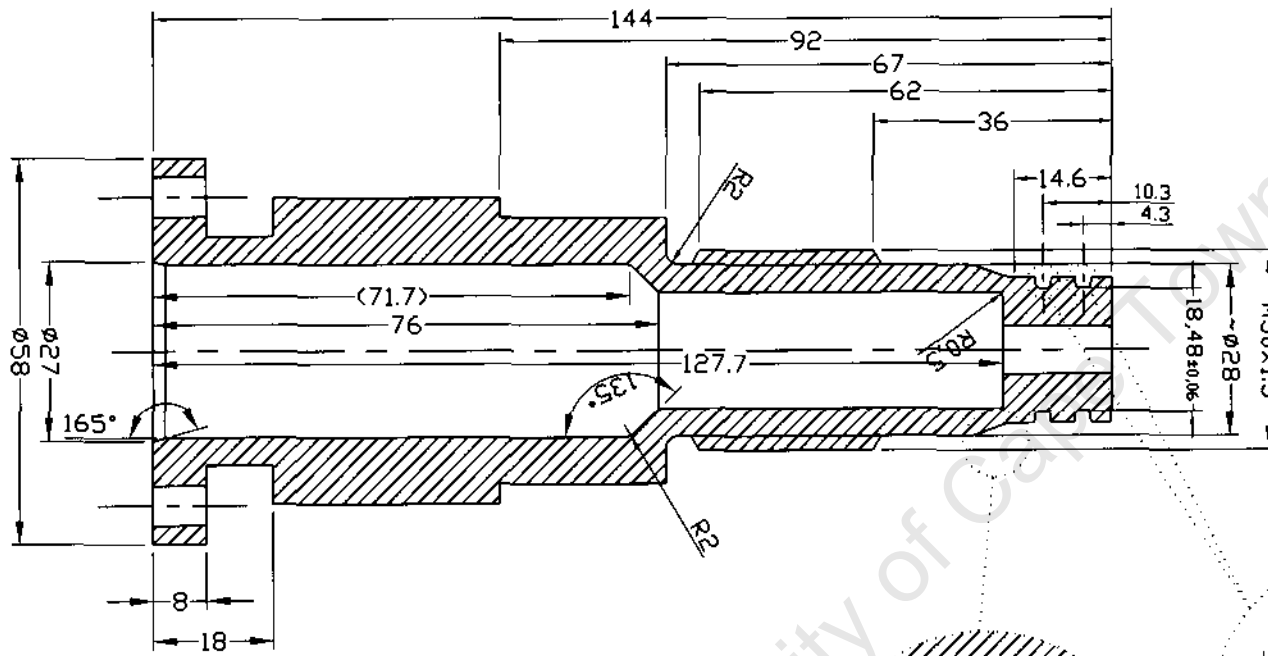
Tolerances  
±0.04mm



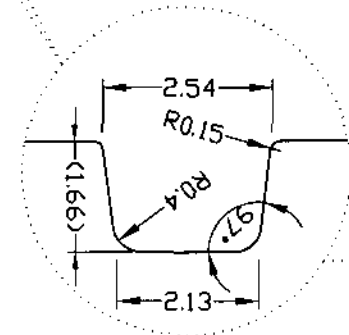
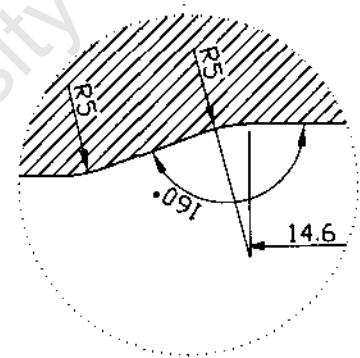
Tolerances to ±0.2mm  
where not specified



1	Valve Plug	Bohter M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 23-10-2002		Sht 2 of 3	
Title: Inlet Valve Plug			

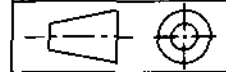


View from O-ring Side

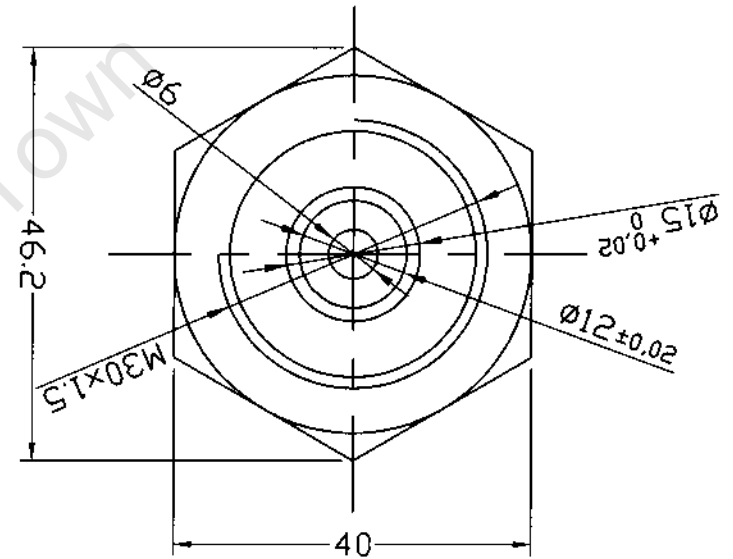
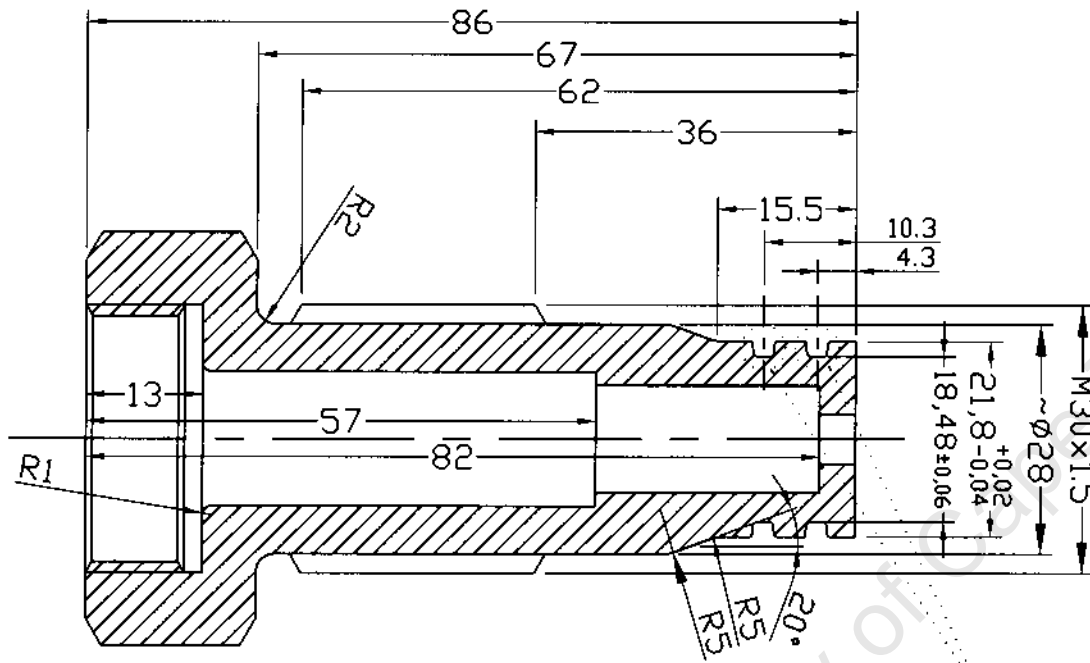


Tolerances  
±0.04mm

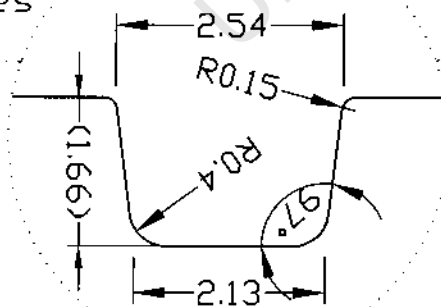
Tolerances to ±0.2mm  
where not specified



1	Inj. Sleeve	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 15-11-2002		Sht 2 of 3	
Title: Smallest Plug for Injector			



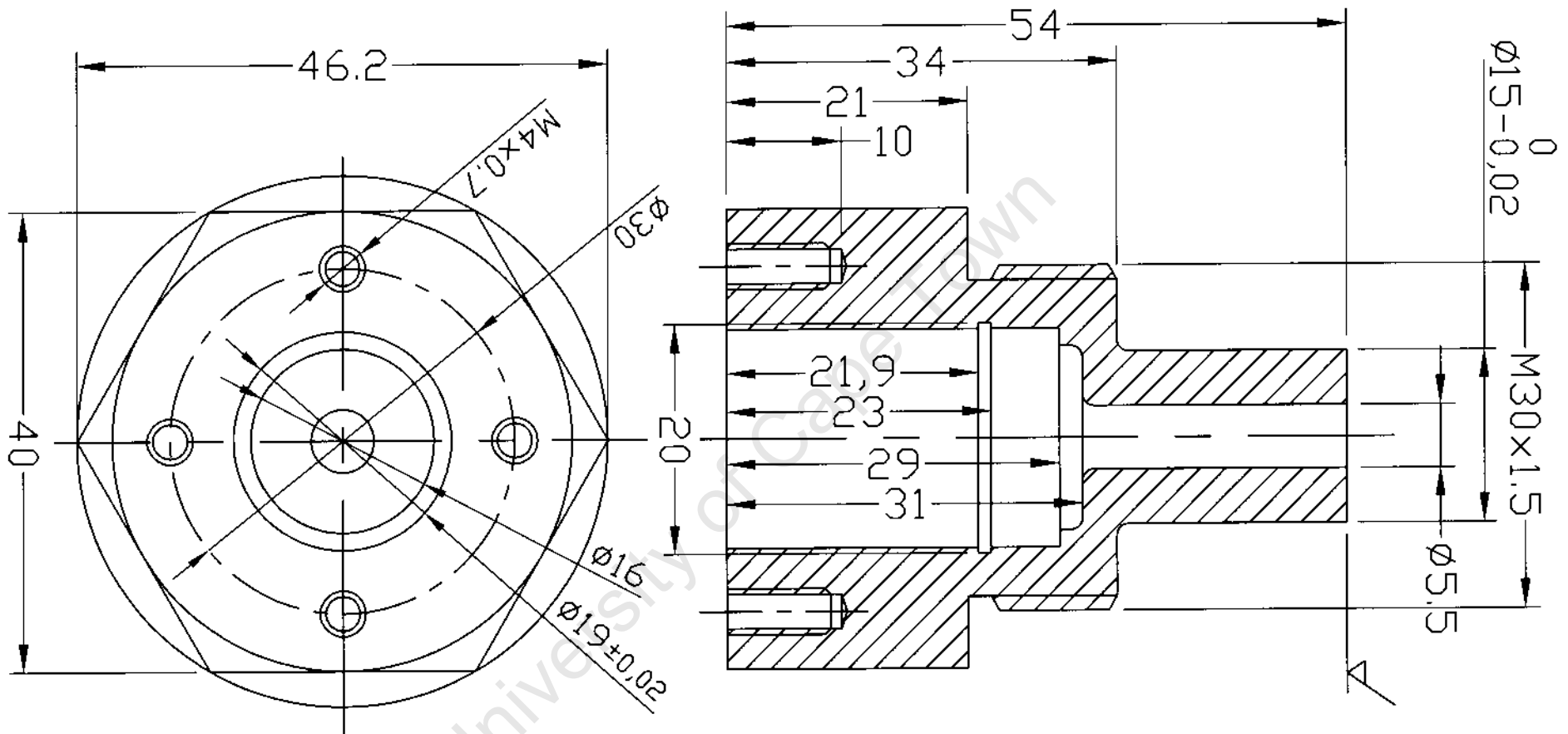
Tolerances  
±0.04mm



Tolerances to ±0.2mm  
where not specified

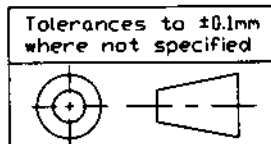


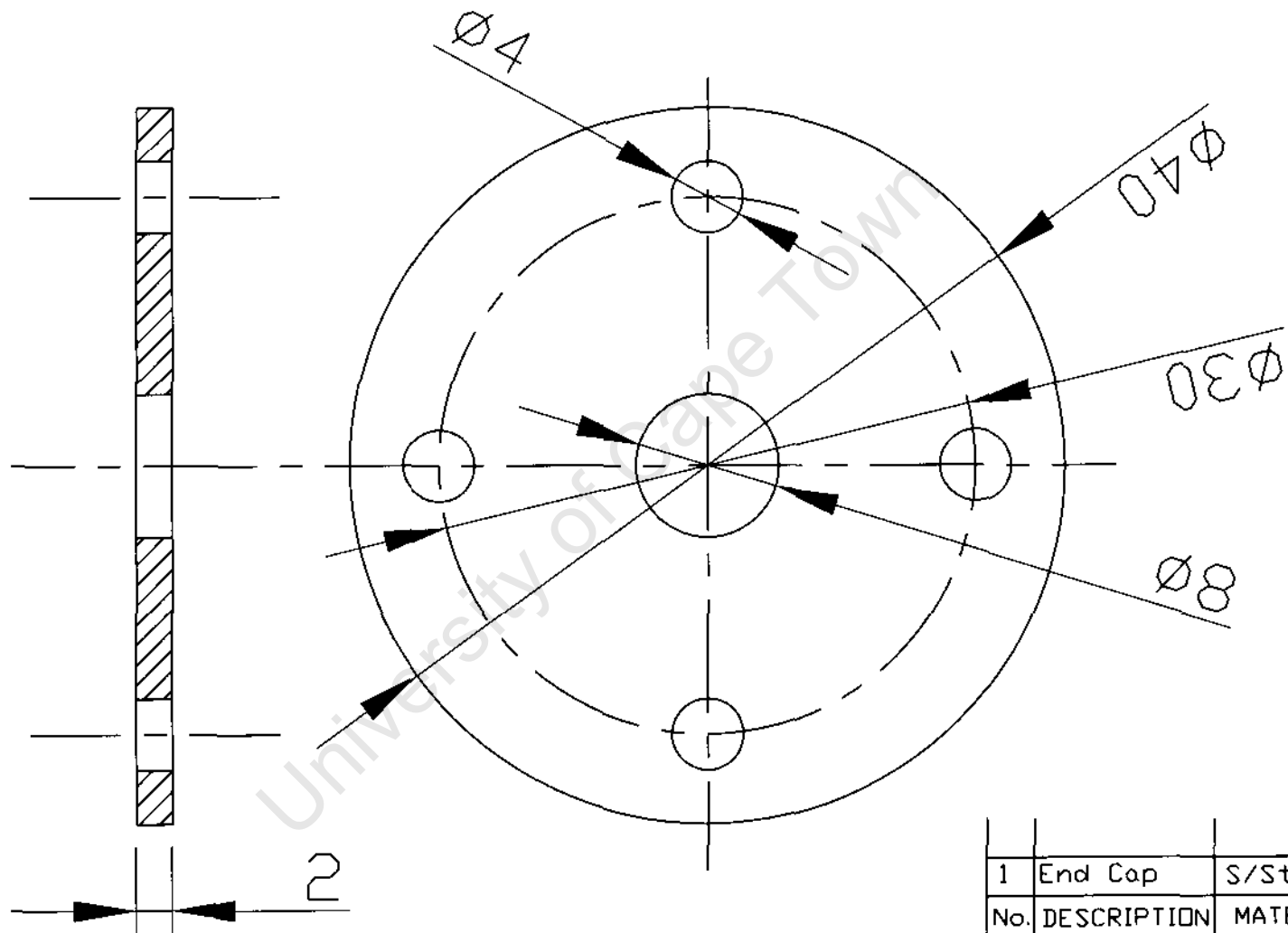
1	Fan Plug	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 18-11-2002		Sht 2 of 3	
Title: Fan Plug			



Notes: All radii are R1  
 ✓ = Emery paper finish

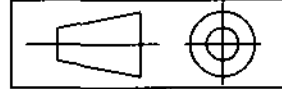
No.	DESCRIPTION	MATERIAL	No. OFF
1	Housing	S/Steel	1
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 21-11-2002			sht 2 of 3
Title: Bearing Housing for Fan Shaft			

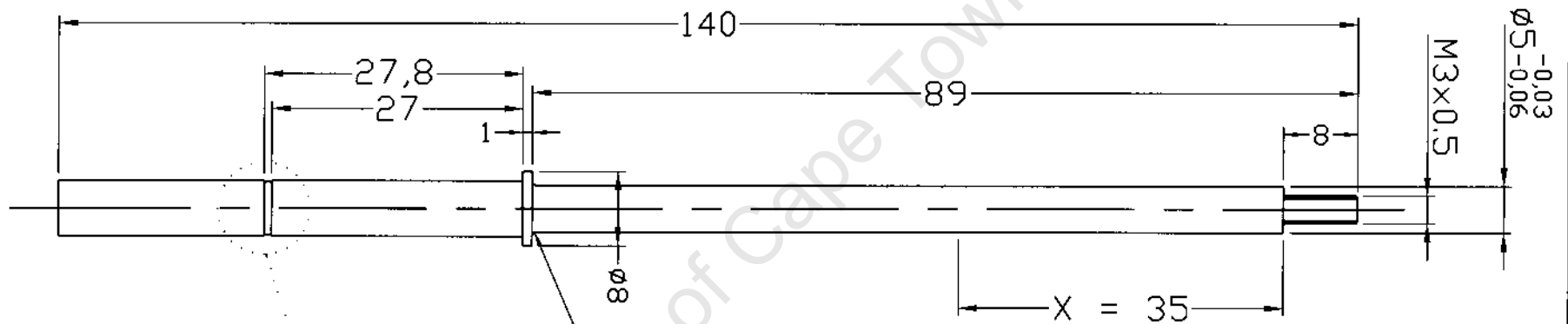




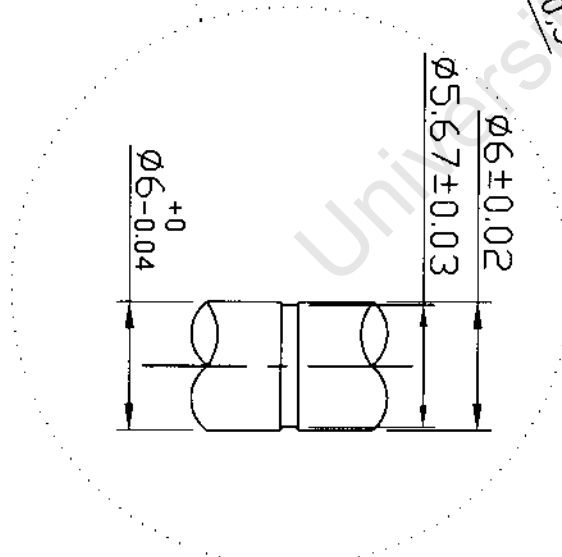
1	End Cap	S/Steel	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 21-11-2002		Sht 2 of 3	
Title: Bearing Sleeve End Cap			

Tolerances to  $\pm 0.2\text{mm}$   
where not specified



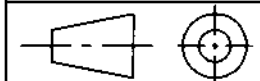


Note: X represents length of shaft to be machined to the tight tolerance (with smooth surface finish).

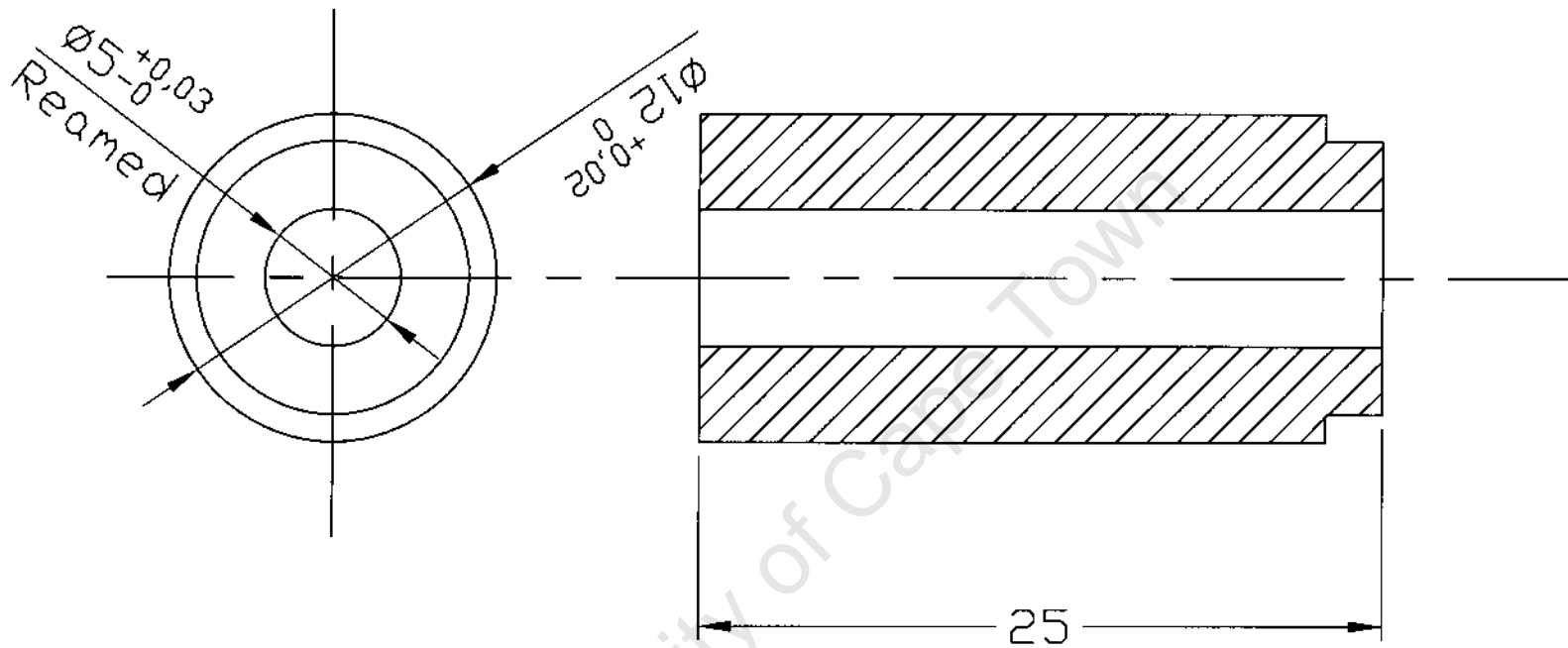


1	Shaft	S/Steel 316	1
No.	DESCRIPTION	MATERIAL	No. OFF
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 21-11-2002		Sht 2 of 3	
Title: Fan Shaft			

Tolerances to  $\pm 0.1\text{mm}$  where not specified



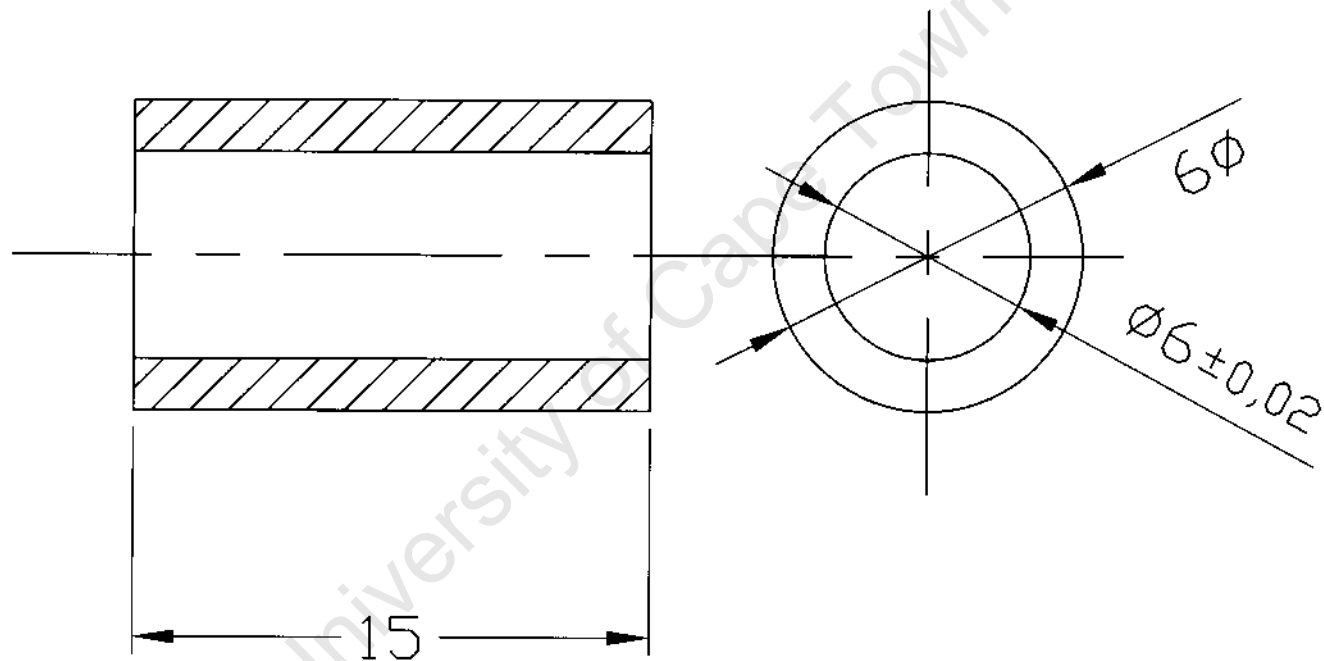




Note: Cut-Away is 1 x 2 mm

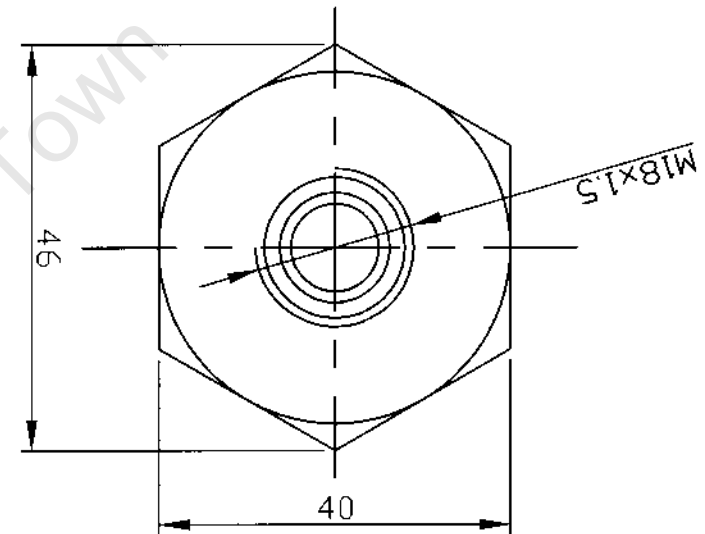
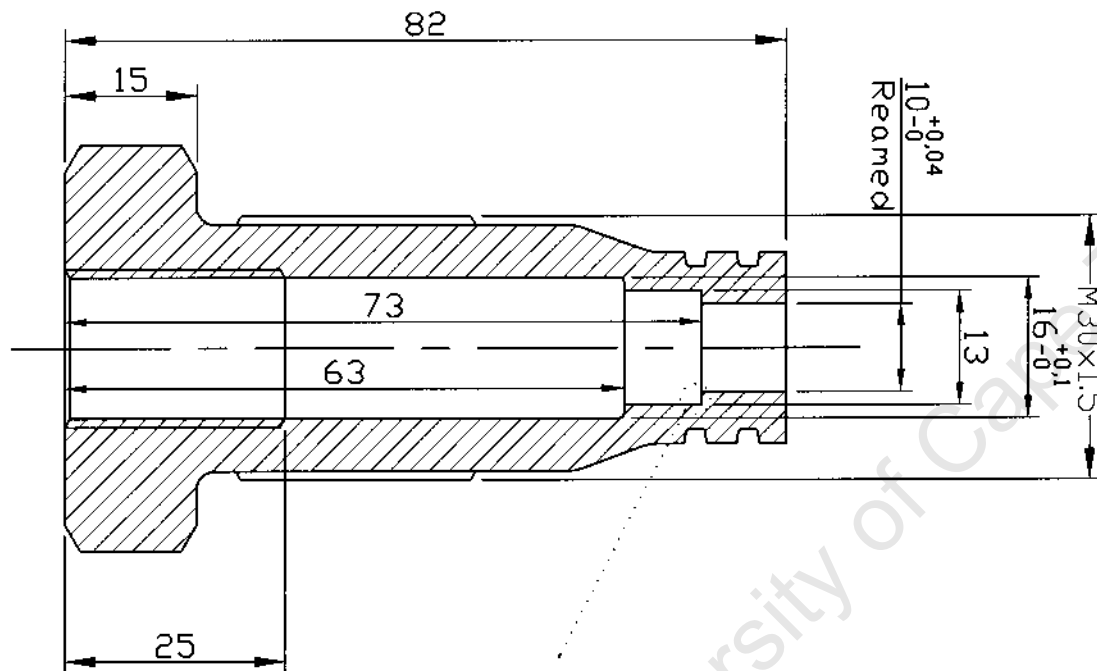
1	Bushing	Brass	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 20-11-2002		Sht 2 of 3	
Title: Bushing for Fan Shaft			

Tolerances to  $\pm 0.2\text{mm}$   
where not specified



1	Spacer	S/Steel	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 21-11-2002		Sht 2 of 3	
Title: Spacer for Fan Shaft			

Tolerances to ±0.1mm where not specified



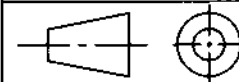
Drill depth for tap

Flat-bottomed please (No radii or chamfers).

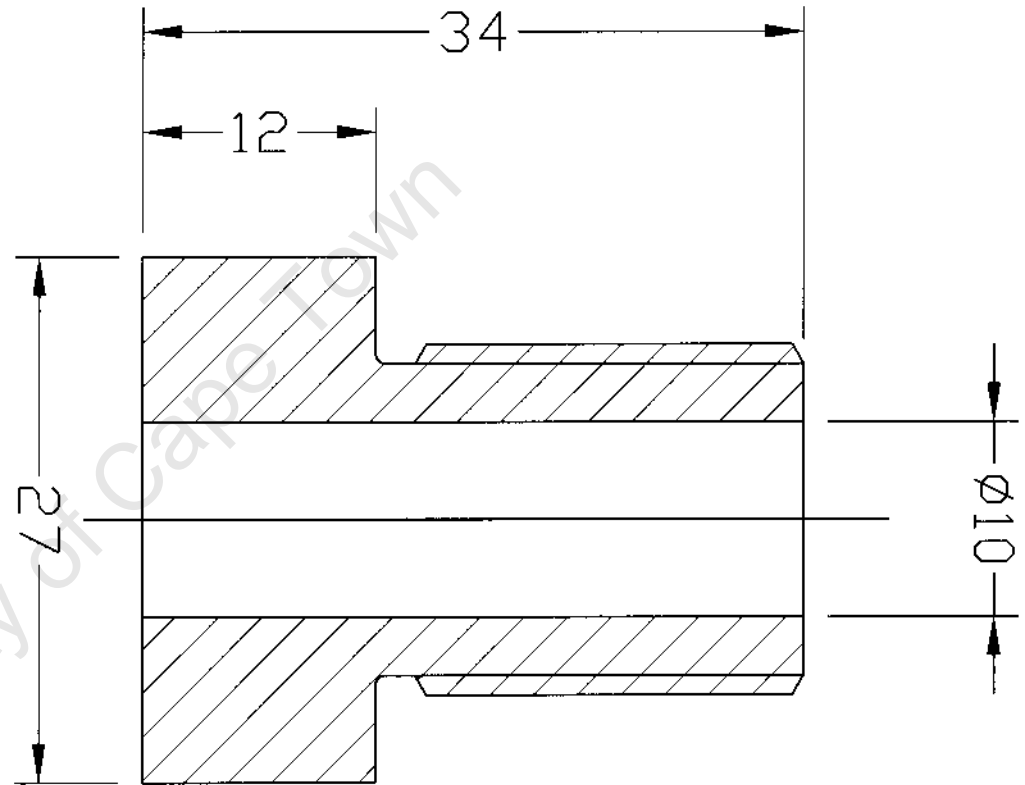
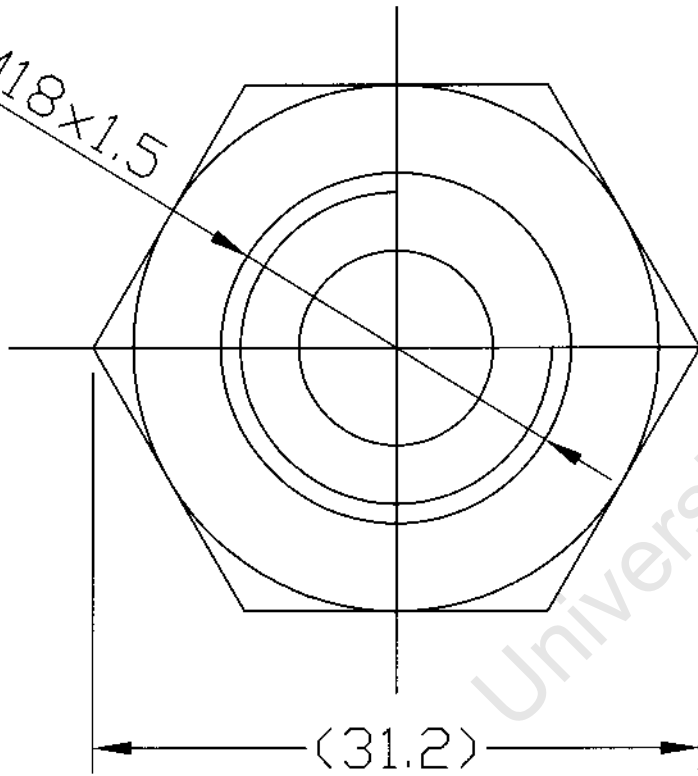
Note: If the pitch specified is not available for the M18, please speak to me about changing it.

1	Valve Plug	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. OFF
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 23-10-2002		Sht 2 of 3	
Title: Smallest Window Plug			

Tolerances to  $\pm 0.1\text{mm}$  where not specified

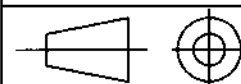


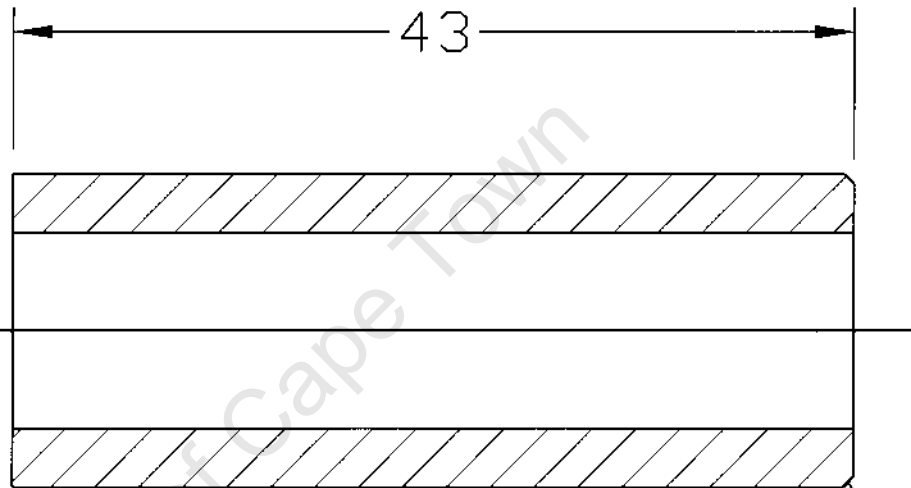
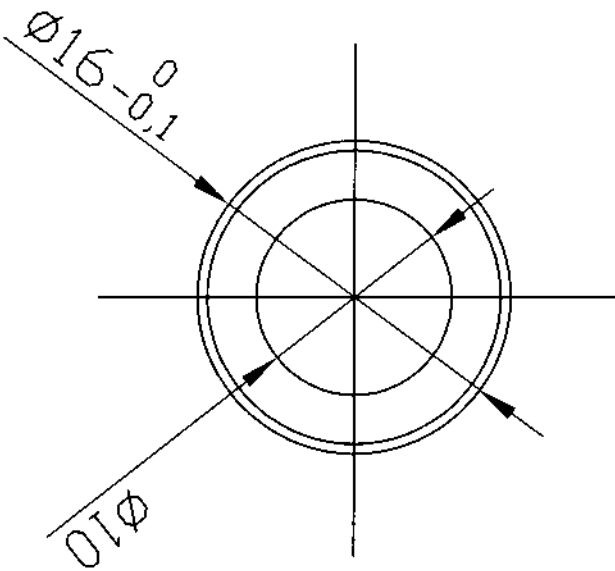
M18x1.5



1	Sleeve Nut	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 13-12-2002		Sht 2 of 3	
Title: Sleeve Nut for Smallest Window			

Tolerances to ±0.1mm where not specified

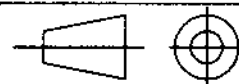


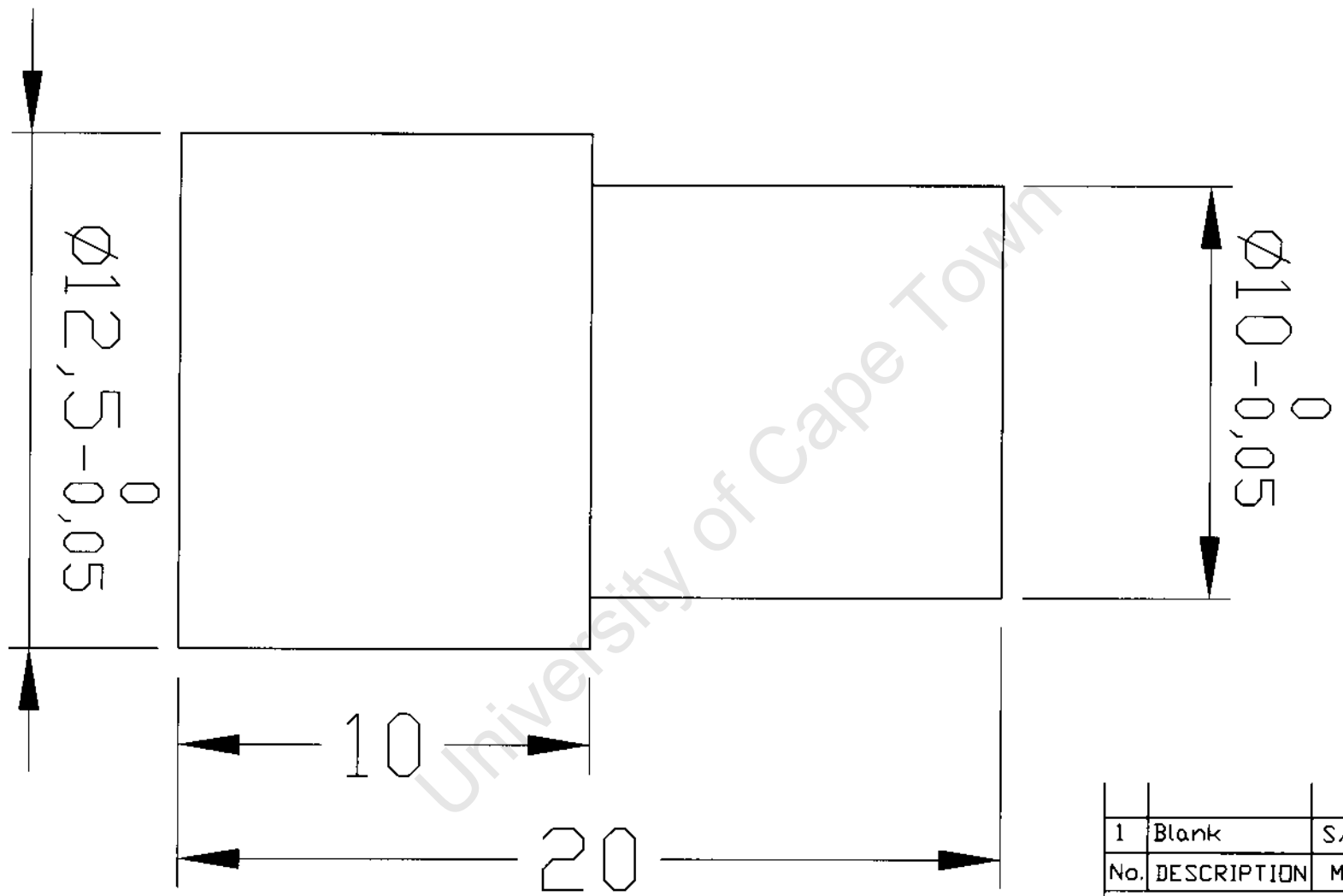


0.5x45°

1	Sleeve	Bohler M300	1
No.	DESCRIPTION	MATERIAL	No. of f
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 13-12-2002		Sht 2 of 3	
Title: Sleeve for Smallest Window			

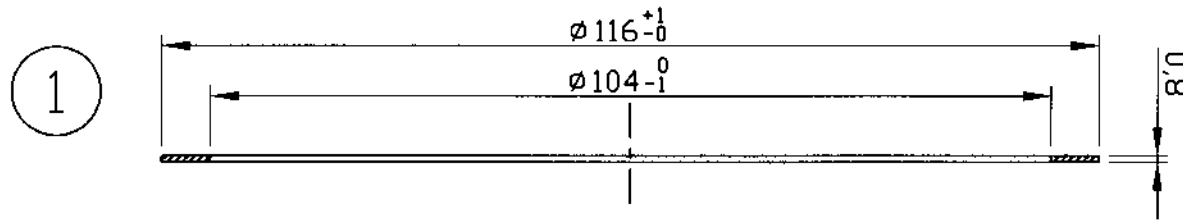
Tolerances to  $\pm 0.1\text{mm}$   
where not specified



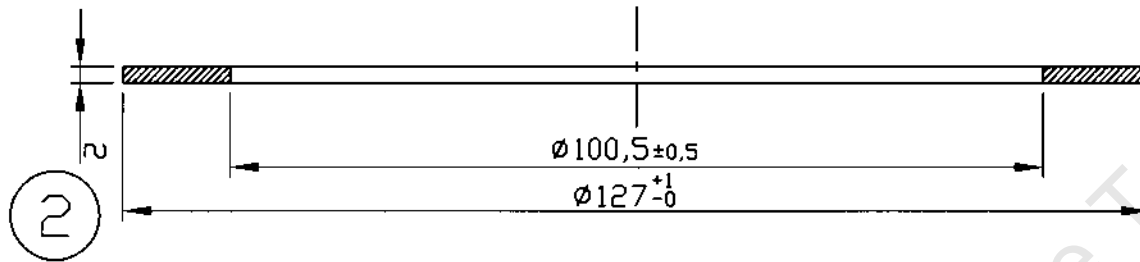


1	Blank	S/S or M300	1
No.	DESCRIPTION	MATERIAL	No. of
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 13-12-2002		Sht 2 of 3	
Title: Blank for Smallest Window			

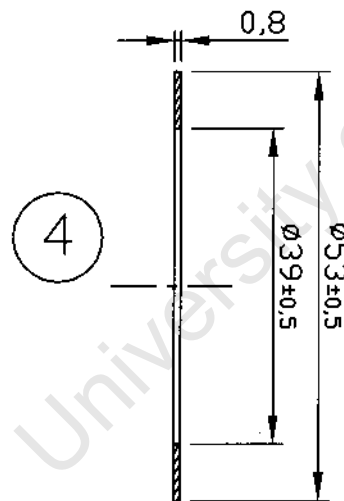
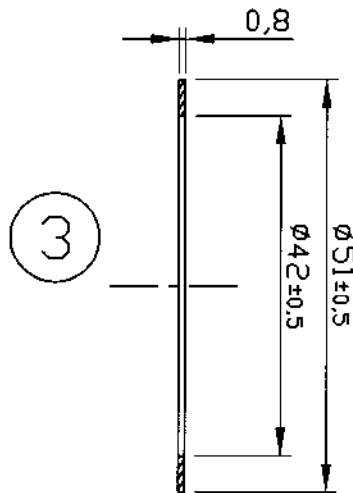
Tolerances to  $\pm 0.1\text{mm}$  where not specified



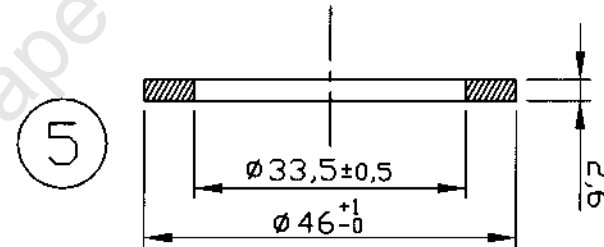
Notes for 1.) Shown in uncompressed state. Densify with 25 ton press.



Notes for 2.) Shown in uncompressed state. Includes 1mm flat metal insert. Use 50 ton press.



Notes for 3. and 4.) Shown in uncompressed state. Densify with 25 ton press prior to cutting out ID.



Notes for 5.) Shown in uncompressed state. Includes 1mm flat metal insert. Densify with 25 ton press prior to cutting out ID.

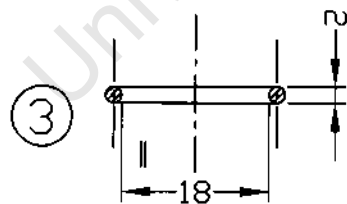
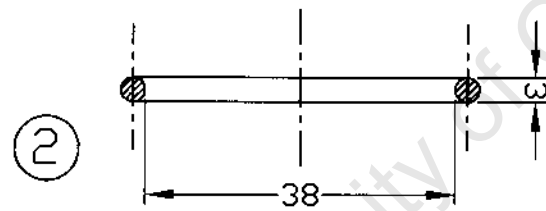
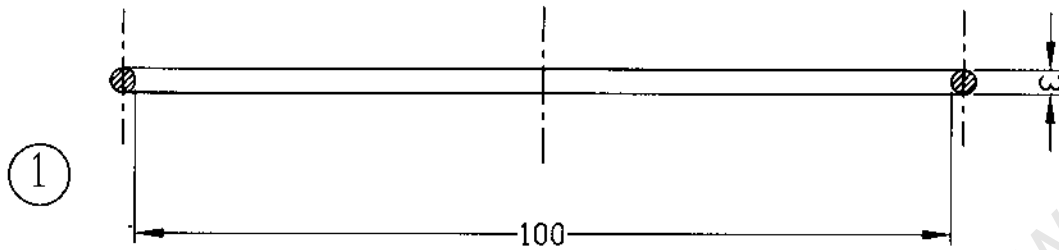
5	Top Nozzle	Graphite/Metal	5
4	Small Fixt.	Graphite	10
3	Small Seat	Graphite	20
2	Big Fixture	Graphite/Metal	10
1	Big Seat	Graphite	10
No.	DESCRIPTION	MATERIAL	No. OFF

SASOL OIL (pty) Ltd

Drawn by: Geoff Miller

Date: 25-09-2002 | Sht 1 of 2

Title: Gaskets for Combustion Vessel



3	Small O-ring	Viton FPM80	40
2	Med. O-ring	Viton FPM80	20
1	Large O-ring	Viton FPM80	10
No.	DESCRIPTION	MATERIAL	No. off
SASOL OIL (pty) Ltd			
Drawn by: Geoff Miller			
Date: 23-10-2002			sht 2 of 2
Title: O-rings for Combustion Vessel			



## APPENDIX B — STRESS CALCULATIONS AND DETAILS

### Contents:

#### B.1 Stress Calculations and Considerations for the Vessel

##### B.1.1 Thick-Wall Cylinder Calculations

##### B.1.2 High Temperature and Material Considerations

##### B.1.3 Stress Concentration Minimisation

#### B.2 Window Stress Calculations

#### B.3 Thread and Porting Stress Calculations

University of Cape Town

## B.1 Stress Calculations and Considerations for the Vessel

### B.1.1 Thick-Wall Cylinder Calculations

The calculations in this section represent the work that was carried out to determine the required thickness of the CVCC vessel. The Thick-walled Cylinder Theory of Lamé was primarily used, where:

$$\text{Longitudinal Stress, } \sigma_L = A$$

$$\text{Radial Stress, } \sigma_r = A - \frac{B}{r^2}$$

$$\text{Hoop Stress, } \sigma_H = A + \frac{B}{r^2},$$

where A and B are the Lamé Constants and  $r$  is the radius.

Using the Maximum Shear Stress Failure Theory:

$$\text{Yield Shear Stress, } \tau_y = \frac{\sigma_y}{2} = 70 \text{ MPa at } 600^\circ\text{C}$$

$$\text{Maximum Shear Stress, } \tau_{\max} = \frac{\sigma_1 - \sigma_3}{2}$$

For an internally pressurised thick-walled cylinder, where at the inner radius, the tensile hoop stress is the largest principal stress and the radial stress, being compressive, is equal to the internal pressure, the above equation becomes:

$$\tau_{\max} = \frac{\sigma_H - \sigma_r}{2}$$

Which when substituting in the Lamé equations yields:

$$\tau_{\max} = \frac{B}{r_i^2}$$

$$\Rightarrow B = \tau_{\max} \times r_i^2$$

Solving for B by incorporating the safety factor of 2.5:

$$B = \frac{\tau_{\max}}{2.5} \times r_i^2$$

$$= \frac{70\,000\text{kPa}}{2.5} \times (0.05\text{m})^2$$

$$= 70\text{kN}$$

Now since the radial stress at the inner radius is equal to the design internal pressure:

$$\sigma_r = -20\,000\text{kPa} = A - \frac{B}{r_i^2}$$

$$\Rightarrow A = \frac{70}{0.05^2} - 20\,000$$

$$= 80\,000\text{kPa} = \sigma_L$$

The longitudinal stress is simply equal to the force exerted on the cylinder ends divided by the annular area of the vessel. The outer radius of the vessel is thus the only unknown and solving yields,

$$\text{Outer Radius, } r_o = 93\text{mm}$$

#### Correction for Porting

The material volume for the cylindrical vessel with outer radius of 93mm and depth of 50mm is 965 cc. The method for correcting for the strength reduction caused by the ports in the vessel was to "replace" this material loss through a greater outer radius. Thus the volume removed by porting (based on the outer radius of the vessel) was subtracted from the material volume and the outer radius was determined iteratively to yield 965 cc. The required outer radius thus became,

$$\text{Outer Radius, } r_o = 106\text{mm}$$

Based on the available roundbar and the desire for a shoulder on the CVCC ends, an outer radius of 115mm was chosen. By re-working the calculations in the opposite direction, the final safety factor of the vessel became 2.67.

### B.1.2 High Temperature and Material Considerations

The decision of which material was to be used for the vessel of the CVCC, as outlined in Section 4.8, is presented in the following table.

#### Decision-Making Matrix for the Material of the Vessel

Criteria	Importance	M300 H & T	W302 H & T	M300 Annealed
Machinability	7	6	8	7
Cost	3	4	2	5
High Temperature Strength	9	6	9	5
Heat Treatment Complications	5	5	2	9
<b>Total</b>		<b>133</b>	<b>153</b>	<b>154</b>

Note: All steels are Bohler Steels.

Conservative values of 0.2% Proof Stress were used for the determination of maximum allowable stresses at various temperatures.

530 Mpa	at 200 C
510 Mpa	at 300 C
480 Mpa	at 400 C
360 Mpa	at 500 C
140 Mpa	at 600 C

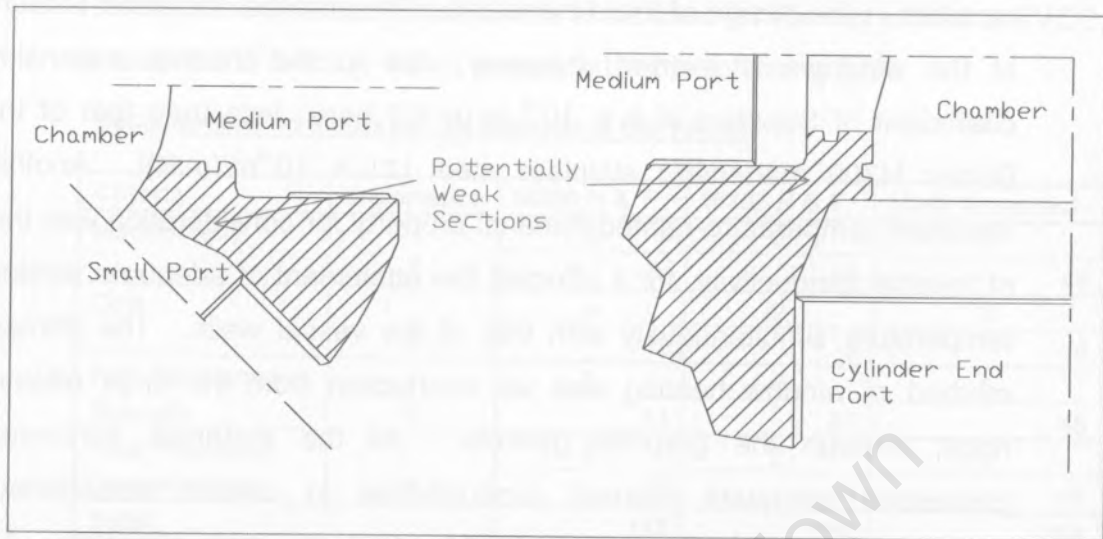
The temperature at which each component requiring stress calculations was evaluated was the maximum it would experience or a conservatively high estimate in those cases where it could not be determined. For example, the allowable thread stress of the large retainer rings was based on the proof stress at 300°C because the maximum operating temperature of the CVCC before combustion took place would be 200°C. Similarly, the main vessel was evaluated at 600°C because the most stressed surface would be exposed to the combustion temperatures.

Considering the tight tolerances between the sapphire windows and the corresponding apertures in the stainless steel vessel, the thermal

expansion coefficient of these materials was an important property to consider in the design of the dimensions. The potential for brittle fracture of the windows is averted, however, due to the thermal expansion coefficient of Sapphire [ $5.6 \times 10^{-6} \text{ m}/(\text{m.K})$ ] being less than that of the Bohler M300 martensitic stainless steel [ $11 \times 10^{-6} \text{ m}/(\text{m.K})$ ]. Another important temperature-related material property for consideration was that of thermal conductivity, for it affected the attainment of adequate window temperature simultaneously with that of the vessel walls. The primary method of window heating was via conduction from the large retainer rings, through the graphite gaskets. All the materials concerned possessed adequate thermal conductivities to ensure homogenous temperature attainment: Bohler M300,  $19.6 \text{ W}/(\text{m.K})$ ; Graphite,  $4.0 \text{ W}/(\text{m.K})$ ; and Sapphire,  $35.1 \text{ W}/(\text{m.K})$ . It is interesting to note the superiority of Sapphire over Fused Quartz in this property. The thermal conductivity of Fused Quartz is  $1.4 \text{ W}/(\text{m.K})$ .

### **B.1.3 Stress Concentration Minimisation**

Throughout the detailed design phase, decisions regarding the placement and sizing of features in the vessel and the finishing of corners and edges were made with stress-concentration minimisation in mind. As Finite Element Analysis was not adopted for the determination of the most stressed areas caused by porting in the vessel, it was deemed essential to employ fillets and rounds wherever appropriate. The diameters of the medium-sized windows and small circumferential ports were influenced by a consideration for stress concentrations and machining weak points potentially set up by the diameters' interaction with one another and with the cylinder end ports, as shown in the following diagram.



## B.2 Window Stress Calculations

Though calculations for all the windows were completed, only those concerning the large windows will be presented below, because the calculations were similar and the large windows were the most critical. The calculations for the stresses set up in a window are based on the assumption that the window is taken as a uniformly loaded circular plate with edges freely supported. Though the edges are actually clamped, the graphite gaskets used for seating the windows are not significantly compressed during assembly. Hence, the gaskets will compress non-uniformly during CVCC pressurisation and a greatly reduced moment (from that predicted in the clamped scenario) will be applied. Therefore, the decision was made to apply the theory of the freely supported scenario, which also generally results in stresses more than 1.5 times those of the clamped scenario, and thus, was the more conservative option.

The maximum stresses in the window are given by:

$$\sigma_{r_{\max}} = \sigma_{z_{\max}} = \frac{3qR^2}{8t^2}(3+\nu)$$

(Equa. 7.27, Hearn, 1997)

where,

$\sigma_{r_{max}}$  = Maximum Radial Stress

$\sigma_{z_{max}}$  = Maximum Tangential Stress

$q$  = Distributed Load = Design Pressure = 20 000kPa

$R$  = Radius of Window = 0.05m

$t$  = Thickness of Window

$\nu$  = Poisson's Ratio = 0.3 (conservative)

Since Sapphire's compressive strength is far greater than its tensile strength, only the external surface needed to be investigated for yield/fracture stress. Using the Maximum Principal Stress Theory, which is applicable to brittle materials, the maximum allowable radial and tangential stresses were,

$$\sigma_{max} = \frac{S_y}{sf} = \frac{275MPa}{4} = 68.75MPa$$

where,

$S_y$  = Tensile Yield/Fracture Stress of sapphire at design temperature

$sf$  = Safety Factor

Substituting  $\sigma_{max}$  into the initial equation and solving for the thickness,

$$t = 30mm$$

The freely supported scenario results in radial and tangential stresses of zero at the supports. However, shear stresses are developed at the support and since the applicable thickness is less because of the shoulder design, the shear stress at the shoulder was calculated.

Force on Window,  $F$  = Design Pressure  $\times$  Window Area

$$= 20\,000kPa \times \pi \times 0.05m^2$$

$$= 157.1kN$$

$$\text{Shear Force, } \tau = \frac{F}{\pi \times D \times t} = \frac{0.1571MN}{\pi \times 0.1m \times 0.018m} = 27.8MPa$$

Since for brittle materials, the ultimate shear strength is approximately equal to that of the ultimate tensile strength, the safety factor for the shoulder is thus,

$$sf = \frac{275MPa}{27.8MPa}$$

### B.3 Thread and Porting Stress Calculations

All thread designs in the CVCC were designed to have adequate strength to resist plastic deformation in each respective application. The thread stress calculations of the large retainer rings, being the most critical, are presented below.

The average screw-thread shearing stress is given by:

$$\tau = \frac{2 \times F}{\pi \times d_r \times h}$$

(Equa. 8-7, Shigley, 1986)

where,

$F$  = Total Force resisted by the retainer ring = 157.1kN

$d_r$  = Minor Diameter of screw-thread = 0.135m

$h$  = Height of screw-thread = 0.035m

Substituting yields,

$$= 20.6MPa$$

With a maximum allowable shear stress at 300°C of 255MPa, this equates to a safety factor of 12.0, considerably greater than the specified minimum of 2.5. Though this safety factor appears unnecessarily high, indicating that perhaps the thread height could have been reduced, it should be noted that this figure represents the average shear stress. By way of example, for fine-pitch threads on an M12 nut, 230% of the average thread stress is concentrated on the first



thread and for coarse-pitch it is about 180%. Considering that the retainer ring has an M138 thread, the 2mm pitch that was selected for machining ease, is relatively very fine. Thus, if a concentration increase of 300% is employed for the first thread, the safety factor reduces to 4.0. This value was considered sensible in light of stress-concentration factors increasing with finer pitch screw-threads.

"Porting Stress Calculations" refers to those calculations that were carried out to determine the various stresses set up in the circumferential and cylinder-end inserts of the CVCC. These stresses included compression (primarily) and tension in sleeves, as well as bending stresses (e.g. in o-ring grooves) and torsional and circumferential shear stresses in the washer-sealed cylinder-end applications. The most critical of the above stresses due to space limitation was the tensile stress in the circumferential injector insert induced by the clamping bolts. The calculation of the safety factor, for this insert is presented below.

Rule of thumb used (by Gasket & Shim Industries of Montague Gardens, Cape Town) for copper washer sealing:

$$\text{Seal Pressure, } P_s = \frac{4.75 \times F_p}{A_w} + 90 \text{MPa}$$

where,

$F_p$  = Separation Force caused by the pressure = 792N

$A_w$  = Area of the washer = 137mm<sup>2</sup>

Substituting yields,

$P_s = 117.4 \text{MPa}$

and a Sealing Force,  $F_s = 16.1 \text{kN}$

Using the following formula for Tightening Torque,

$$T = 0.2 \times F_s \times d$$

(Equa. 8-16, Shigley, 1986)

$$T = 0.2 \times 8.05 \text{kN} \times 6 \text{mm} = 9.7 \text{Nm} \quad [ \text{For 2 bolts} ]$$

Rounding the tightening torque to 10 Nm, the total sealing force becomes,

$$F_s = 16.7 \text{ kN}$$

The minimum annular area of the injector insert subjected to this force is,

$$A = 133 \text{ mm}^2$$

$$\text{Tensile Sleeve Stress, } S = \frac{F_s/A_i = \frac{16667 \text{ N}}{133 \text{ mm}^2}}{A_i} = 126 \text{ MPa}$$

At a metal temperature of 400°C, the proof stress,  $S_p$ , of the insert material is 480 MPa.

$$\text{Safety Factor} = \frac{S_p}{S} = \frac{480 \text{ MPa}}{126 \text{ MPa}} = 3.8$$

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## APPENDIX C — THERMODYNAMIC CALCULATIONS AND MODEL

### Contents:

#### C.1 Thermodynamic Calculations for Pre-Charge Combustion

C.1.1 Calculation of Enthalpy

C.1.2 Calculation of Constituent Mass

C.1.3 Internal Energy Balance

C.1.4 Calculation of End Pressure

C.1.5 Calculation of Gibbs Functions

C.1.6 Dissociation Equilibrium Calculations

C.1.7 Calculation of Relative Humidity

C.1.8 Determination of Radiation Losses

#### C.2 Working of the Pre-Charge Combustion Model

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## C.1 Thermodynamic Calculations for Pre-Charge Combustion

The determination of the required accumulative fill pressure of each gas was achieved through several simultaneously-solved iterative calculations. This process will be described as best possible in a stepwise and compartmentalised manner.

### C.1.1 Calculation of Enthalpy

The user selected initial and peak gas temperatures based on the condensation effect on the windows and the required injection temperature, respectively. Based on these temperatures for each reactant and product, separate sets of constants ("a" to "e") were selected from a Chemkin database for use in polynomials yielding each ideal-gas specific heat (in J/[mol.K] at constant pressure,  $C_p$ ). From this same database, reference enthalpies at 298 K were drawn for each component, depending on which set of  $C_p$  constants were selected. Thus the actual enthalpy of each component,  $h$  (in J/mol), at the end temperature,  $T$ , could be calculated using:

$$\bar{h} = \int C_p(T) dT = aT + \frac{b}{2}T^2 + \frac{c}{3}T^3 + \frac{d}{4}T^4 + \frac{e}{5}T^5 + \bar{h}_{298}$$

(Equa. 3-51, Cengel and Boles, 1998)

### C.1.2 Calculation of Constituent Mass

The partial pressure of each reactant gas was solved for in the model. These pressures were converted into accumulative fill pressures (taking into account the presence of Nitrogen at atmospheric pressure after flushing) and then worked back into the mass and number of moles of each component. The calculation from partial pressure into constituent mass was the technically significant one and will be presented below.

Dalton's Law of Additive Pressures for ideal gas mixtures was applied to the ideal gas law to determine each reactant mass,  $m$ .

$$\text{Therefore, } m_{\text{reactant}} = \frac{P_{\text{partial}} \times V_{\text{vessel}}}{R_{\text{reactant}} \times T_{\text{mixture}}}$$

where: P is for pressure, V is for volume, R is for the Gas Constant and T is for temperature.

### C.1.3 Internal Energy Balance

Since the enthalpy of each reactant and product was calculated, a simple calculation could be performed to determine the internal energy,  $u$  (in J/mol), of each component using the formula,

$$u = h - R_u T$$

Because internal energy is a function of  $C_{v,u}$ , the specific heat at constant volume, it was used as the basis for balancing the products with the reactants in the iterative solutions that were found for the constant volume pre-charge combustion events. In order to balance the internal energies of the products and the reactants, it was required to multiply the internal energy of each component by the number of moles of that component. For the products, the numbers of moles were determined by an atom balance with the reactants, with the dissociation products being solved for in the model.

### C.1.4 Calculation of End Pressure

The formula that was used to calculate the pressure attained at the completion of pre-charge combustion was the gas law for constant mass and volume, in which compressibility factors were incorporated to account for real behaviour:

$$P_p = \frac{P_r \sum Z_r \sum R_r}{\sum Z_p \sum R_p}$$

where the subscript  $p$  stands for "products", the subscript  $r$  stands for "reactants", and "Z" represents the compressibility factor.

The compressibility factors for the reactants and products mixtures were calculated using Kay's Rule, which makes use of a pseudocritical pressure,  $P'_{cr}$ , and temperature,  $T'_{cr}$ , for the mixture. These pseudocritical properties of the mixture were calculated by summing the products of mole fraction,  $y$ , and the critical property for each mixture component as follows:

$$P'_{cr} = \sum y P_{cr} \quad \text{and} \quad T'_{cr} = \sum y T_{cr}$$

(Equa. 12-11a & b, Cengel and Boles, 1998)

The pseudocritical properties were used in the standard equations for calculating the reduced pressure,  $P_R$ , and temperature,  $T_R$ , for use within compressibility charts. Therefore, as applied to the reactants and products mixtures,

$$P_R = \frac{P}{P'_{cr}} \quad \text{and} \quad T_R = \frac{T}{T'_{cr}}$$

### C.1.5 Calculation of Gibbs Functions

The model also solved for two dissociation reactions, viz. the Water Gas Shift reaction and the Carbon Dioxide dissociation reaction. The Water Gas Shift reaction is as follows:  $CO + H_2O \rightleftharpoons H_2 + CO_2$ , and the Carbon

Dioxide dissociation reaction is  $CO_2 \rightleftharpoons CO + \frac{1}{2} O_2$ . In the calculations for

the determination of the influence of dissociation on the product composition, it was assumed that dissociation equilibrium was maintained throughout pre-charge combustion. In other words, the impact of the rate of reaction of dissociation on the attainment of dissociation equilibrium at peak conditions was assumed negligible. In order to determine the influence of the two dissociation reactions selected for having the greatest impact, it was necessary to calculate the equilibrium constant,  $K_p$ , for the product mixture in two ways. This enabled the model to solve for the actual product mixture composition. The first method of calculating the equilibrium constant was by means of the standard-state Gibbs function change, the calculation of which is shown below.

The definition of the Gibbs function,  $g$ , is,

$$\bar{g} = \bar{h} - T\bar{s}$$

This was calculated for each component in the dissociation reactions. The standard-state Gibbs function change,  $\Delta G^*(T)$ , was then calculated as follows:

$$\Delta G^*(T) = \nu_C \bar{g}_C(T) + \nu_D \bar{g}_D(T) - \nu_A \bar{g}_A(T) - \nu_B \bar{g}_B(T)$$

(Equa. 15-11, Cengel and Boles, 1998)

where the  $\nu$ 's stand for the stoichiometric coefficients of the dissociation reaction.

### C.1.6 Dissociation Equilibrium Calculations

The equilibrium constant,  $K_p$ , of each dissociation reaction was calculated using the standard-state Gibbs function change by use of the following formula,

$$K_p = e^{-\Delta G^*(T)/(R_u T)}$$

(Equa. 15-14, Cengel and Boles, 1998)

The second method of calculating the equilibrium constant was by means of the following formula,

$$K_p = \frac{N_C^{v_C} N_D^{v_D}}{N_A^{v_A} N_B^{v_B}} \left( \frac{P}{N_{total}} \right)^{\Delta v}$$

(Equa. 15-15, Cengel and Boles, 1998)

where  $N$  stands for the number of moles,  $P$  stands for the mixture pressure at peak conditions,  $N_{total}$  is the total number of moles of product and  $\Delta v = v_C + v_D - v_A - v_B$ .

### C.1.7 Calculation of Relative Humidity

In order to gain an indication of the likelihood of water vapour condensing on the windows such that optical access would be impaired at the time of injection, calculations were made to determine the relative humidity of the pre-charge combustion product mixture at the wall temperature and injection pressure.

The absolute or specific humidity,  $\omega$ , was determined from the calculated masses of the components of the product mixture,

$$\omega = \frac{m_v}{m_{dm}}$$

(Equa. 13-6, Cengel and Boles, 1998)

where  $m_v$  stands for the mass of water vapour and  $m_{dm}$  stands for the mass of the dry mixture.



Based on the wall temperature, the corresponding saturation pressure,  $P_{g1}$ , was calculated from tabulated values. This was used to calculate the saturated specific humidity as follows:

$$\omega = \frac{0.622 \times P_g}{P - P_g}$$

(Equa. 13-8, Cengel and Boles, 1998)

where  $P$  is the total pressure of the pre-charge combustion product mixture at the injection pressure.

Thus the relative humidity,  $\phi$  at the boundary layers of the internal surfaces of the windows was determined:

$$\phi = \frac{\omega P}{(0.622 + \omega)P_g}$$

(Equa. 13-11a, Cengel and Boles, 1998)

### **C.1.8 Determination of Radiation Losses**

Though not core to the determination of the required fill pressures for pre-charge combustion, the determination of the impact of radiation losses through the CVCA windows on the peak pressure prediction was carried out. The following calculations were performed as part of a fault-finding process in order to quantify losses that contributed toward actual peak pressures being lower than expected. Most of the assumptions that were made favoured greater heat loss in order to ascertain the potential magnitude of radiation losses.

The Stefan-Boltzmann constant,  $\sigma$ ; an emissivity,  $\epsilon$ , of 1 for the product gas mixture (the maximum possible, though highly unlikely); and the combined area of the windows,  $A$  (1 x large window and 2 x medium-sized windows), were used in the formula below to calculate the rate of radiation heat loss,  $q$ :

$$q = \sigma A \epsilon (T_1^4 - T_2^4)$$

(Equa. 8-43a, Cengel and Boles, 1998)

where  $T_1$  represents the gas temperature and  $T_2$  represents the external ambient temperature. Since the chosen emissivity was 1, any shape factor in the denominator of the above equation reduced to 1.

The formula was applied as follows. The average time frame of a pre-charge combustion event was 10 milliseconds. Since the initial temperature was known and the final temperature was predicted, the increase in temperature throughout pre-charge combustion event was divided into 10 degree increments. (Though the rate of temperature increase is dependent on the positioning of the spark plug, it was assumed that a linear increase with respect to time would be adequate for the preliminary study.) At each temperature, the radiation rate was calculated and hence the energy lost for each corresponding incremental time period of the combustion event. The sum of these radiation losses for an experiment with a predicted end-temperature of 3000K amounted to 110 Joules.

Having the radiation energy,  $Q$ , lost from the chamber during pre-charge combustion, the end-temperature reduction,  $\Delta T$ , could be calculated.

$$\Delta T = \frac{Q}{nC_v}$$

where  $n$  is the number of moles and  $G$  is the specific heat in J/(mol.K) at constant volume. The  $C_v$  for the gas mixture was calculated from the  $C_p$  values of the product gases evaluated at the average temperature between the initial temperature and the predicted end-temperature. This yielded a temperature reduction of 20°C.

Finally, in order to determine the impact of such a temperature reduction on the peak pressure of pre-charge combustion, the following was carried out in the combustion model (See the next section for more details).

- the reactant composition and volumes were kept the same
- the end temperature was reduced by 20°C
- the required internal energy of the reactants was reduced by 110 Joules
- the internal energy and dissociation errors were then minimised by changing the dissociation product values

The resultant prediction for peak pressure was reduced by 0.7%.

## C.2 Working of the Pre-Charge Combustion Model

In this section, the combining of the calculations presented in Sections C.1.1 — 6 that were used in the simultaneous solving of the model will be described. The model was developed in Microsoft Excel and made use of the Solver Function. Iterations were carried out by changing the following values:

- the partial pressures of the reactant gases,
- the number of moles of Hydrogen and Carbon Monoxide in the product gases (dissociation products),

until the sum of the following errors satisfactorily approached zero:

- (required peak pressure — calculated peak pressure) <sup>2</sup>
- (internal energy of reactants — internal energy of products) <sup>2</sup>
- (difference in equilibrium constants for each dissociation reaction) <sup>2</sup>
- (required O<sub>2</sub> concentration — calculated O<sub>2</sub> concentration) <sup>2</sup>,

The required user inputs to the model were the desired peak temperature and pressure, the initial wall temperature and the desired simulated EGR percentage (which determined the required oxygen concentration in the products). The outputs of the model were the accumulated fill pressures for the reactant gases and the relative humidity at the internal surfaces of the CVCA.

Lastly, the lower flammability limits of the fuel gases being used were highlighted and compared with the calculated concentrations of the gases in order to predict the ease with which ignition by spark-plug would occur.

## APPENDIX D — INSTRUMENTATION AND ELECTRICAL INFORMATION

The first purpose of this appendix is to present the details of the instrumentation and electrical components used in the operating of the Constant Volume Combustion Chamber. The intention is that it would serve as a source of information that aids with replacements and/or optimisation.

Secondly, the appendix includes the results of two sets of calibration that were carried out. The calibration of the diesel injection system provides a basis from which injection durations can be determined for various injection volumes. The initial calibration of the BMW Accumulator pressure transmitter was used for calculating the rail pressure in LabVIEW and is included herein.

<b>Component</b>	<b>Details</b>	<b>Supplier</b>
<b>Ignition Coil</b>	Magfire 40kV	Unknown
<b>Battery</b>	Topin 12V 7.5Ah	Communications, Salt River
	Trickle charge at 13.9V	
<b>Thermocouple Converter</b>	Model: IQ 1120T	Unknown
	Supply: 230V, 50Hz	
	Input: Type K (range 0 - 400 deg C)	
	Output: 0 - 5 V DC	
<b>Thermocouples</b>	Type K, 1/8", 1 off	Unitemp, Landsdowne
	Type K, 1/16", 1 off	Unitemp, Landsdowne
<b>Pressure Transducer</b>	AVL	AVL List
<b>Solenoid Valves</b>	Asco: 2-way, 1/4" female	West Beach Instrumentation
	Air Range: 0 - 50 bar	
	Parker: 3-way	West Beach Instrumentation
	2 x 1/8" female, 1 x 1/4" flared	
<b>Pressure Transmitters</b>	Ellison Sensors International	Atlas Industrial Systems
	Genspec GS4101 0 - 4 bar g	
	Genspec GS4001 0 - 40 bar g	
	Supply: 13 - 30 V DC	
	Output: 0 - 5 V DC	
	Linearity: +/- 0.1%	
	GS4101 Overpressure: 8 bar g	
<b>Rail Pressure Transmitter</b>	Supply: 5 V DC only	BMW Auto Atlantic, Claremont
<b>Cartridge Heaters</b>	200 Watt, 40 x 8 mm	Unitemp, Landsdowne
<b>Solid-State Relay</b>	25 Amperes	Unitemp, Landsdowne

### Diesel Rig Calibration

**Parameters:**

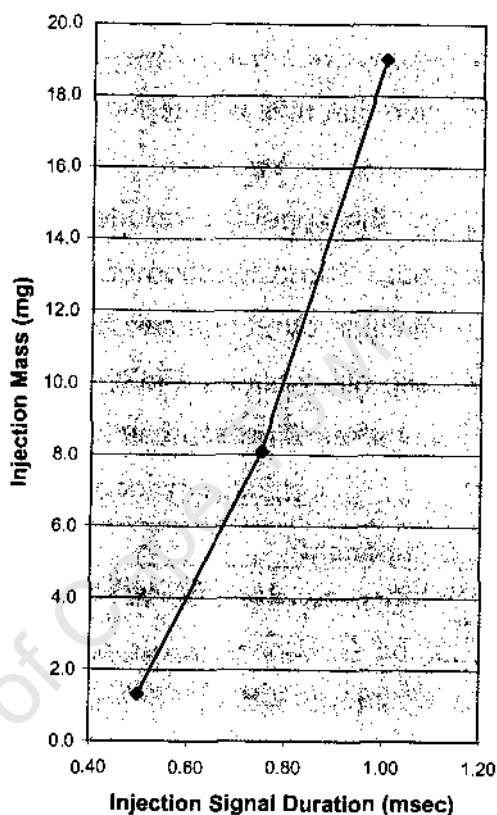
Thyristor Drive Frequency	28 Hz
Rail Pressure Relief Duty Cycle	81.5 %
Duration of Test Injection Set	10 sec
Test Injection Frequency	20 Hz
Rail Pressure (approximate)	650 bar
Fuel was 50:50 Sasol GTL and Euro Diesel '05 blend	

Duty Cycle of Injection Event		0.01
Duration of Injection Event		0.50 msec
Reading	Mass of Set (g)	Mass per Injection (mg)
1	0.2730	1.365
2	0.2561	1.280
3	0.2614	1.307
Average		1.317 mg

Duty Cycle of Injection Event		0.015
Duration of Injection Event		0.75 msec
Reading	Mass of Set (g)	Mass per Injection (mg)
1	1.6126	8.063
2	1.6212	8.106
Average		8.084 mg

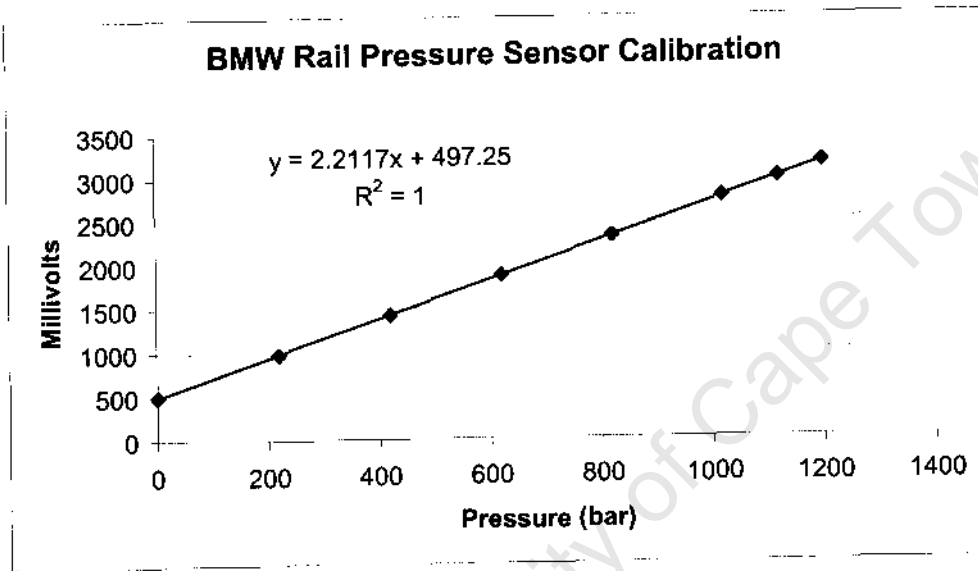
Duty Cycle of Injection Event		0.02
Duration of Injection Event		1.00 msec
Reading	Mass of Set (g)	Mass per Injection (mg)
1	3.9571	19.786
2	3.6584	18.292
3	3.7927	18.963
Average		19.014 mg

**Injection Mass vs Duration**



### BMW Accumulator Pressure Transmitter Calibration

Pressure (bar)	Volts (up)	Volts (down)	Millivolts
0	0.4975	0.4975	497.5
220	0.983	0.983	983
420	1.426	1.426	1426
620	1.869	1.869	1869
820	2.312	2.312	2312
1020	2.753	2.753	2753
1120	2.974	2.974	2974
1200	3.151	3.151	3151



## **APPENDIX E — CONTROL LOGIC FLOW-DIAGRAM**

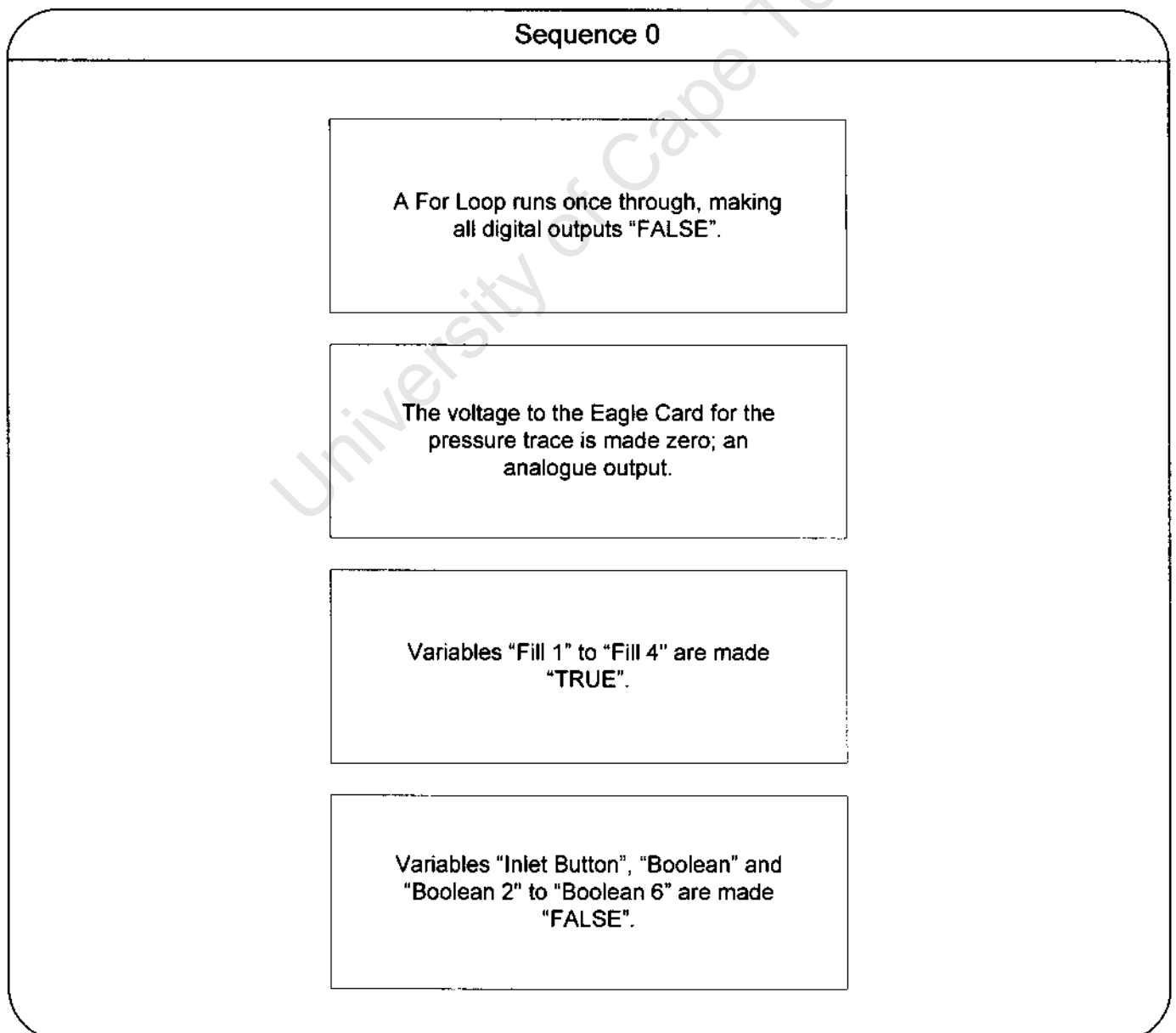
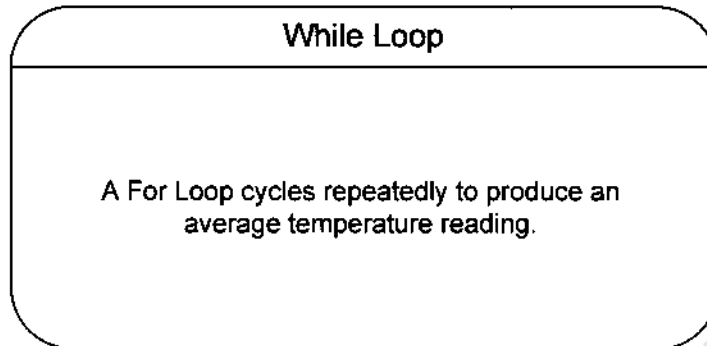
The following pages in this appendix contain the block flow-diagrams of the control logic that was used in the main controlling programme of the Constant Volume Combustion Chamber. The presentation format follows that of the computer language that was used to create the programme, viz. LabVIEW 6.1.

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# Main Controlling Programme Logic Flow-Diagram

The first While Loop below ran continuously until the programme ended (end of Sequence 5), unless it was manually stopped prematurely. The Sequences ran one after the other, proceeding to the following Sequence only once all actions within its frame had been completed and all internal While loops were ended.



# Sequence 1

## While Loop

### Sub-Sequence 0

User Dialogue Box (UDB) asks if the manual valves are in the correct position.

### Sub-Sequence 1

UDB asks if the charge amplifier settings are correct.

### Sub-Sequence 2

Checks if Exhaust Set Pressure > Final Fill Pressure → FALSE → UDB Warning

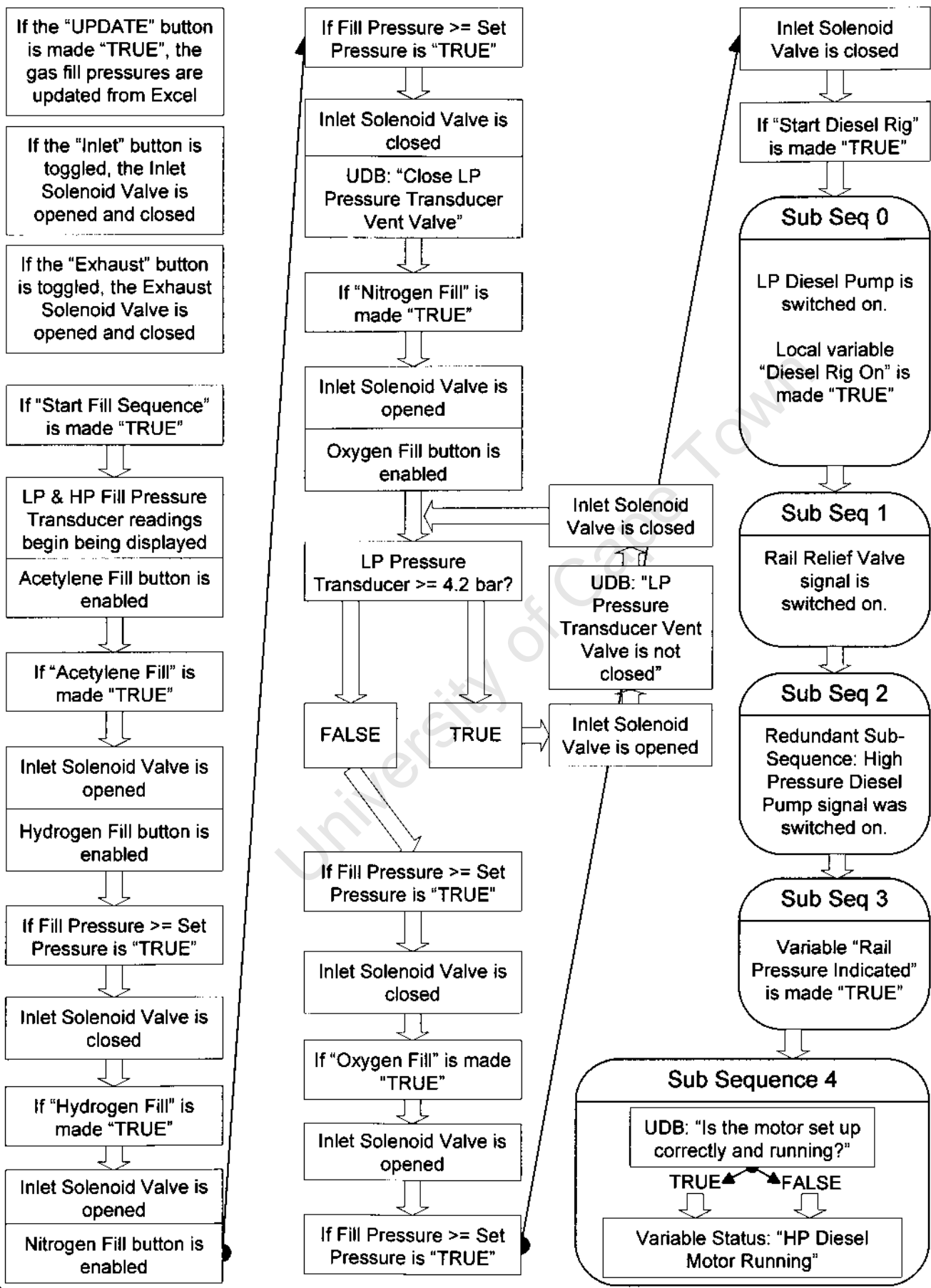
### Sub-Sequence 3

Checks if Exhaust Set Pressure > Injection Pressure → TRUE → UDB Warning  
→ FALSE → TRUE Signal → Stop While Loop

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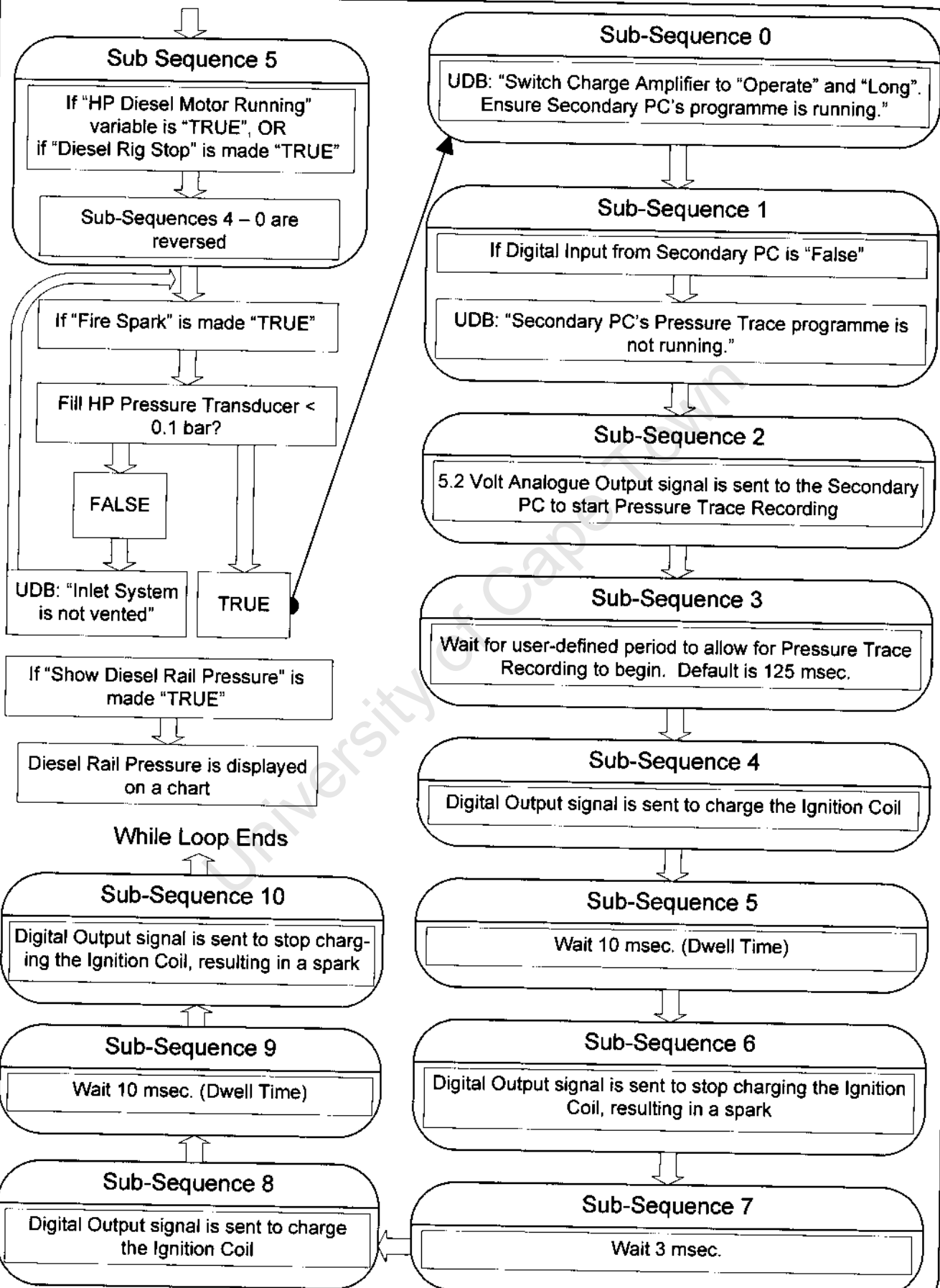
## Sequence 2 (Part A)

### While Loop



## Sequence 2 (Part B)

### While Loop (cont.)



## Sequence 3

### While Loop

Pressure transducer values are measured and displayed in a chart until the While Loop ends. Every time the loop runs, the current pressure value and the previous pressure value are used as follows:

If the "Diesel Rig On" variable is "TRUE", then

- 1) the difference in pressure is measured to determine if the pressure is decreasing,
- 2) the current pressure,  $P$ , is checked to see if:  
 $(\text{Injection Pressure} - X) < P < (\text{Injection Pressure} + Y)$   
where  $X$  and  $Y$  are small values so as to produce a range.

If 1) and 2) are "TRUE", then the counter-controlled injection event takes place.

If Statement is closed after the injection event.

If the "Auto Exhaust" variable is "TRUE", then

- 1) the difference in pressure is measured to determine if the pressure is decreasing,
- 2) the current pressure,  $P$ , is checked to see if:  
 $(\text{Exhaust Pressure} - W) < P < (\text{Exhaust Pressure} + Z)$   
where  $W$  and  $Z$  are small values so as to produce a range.

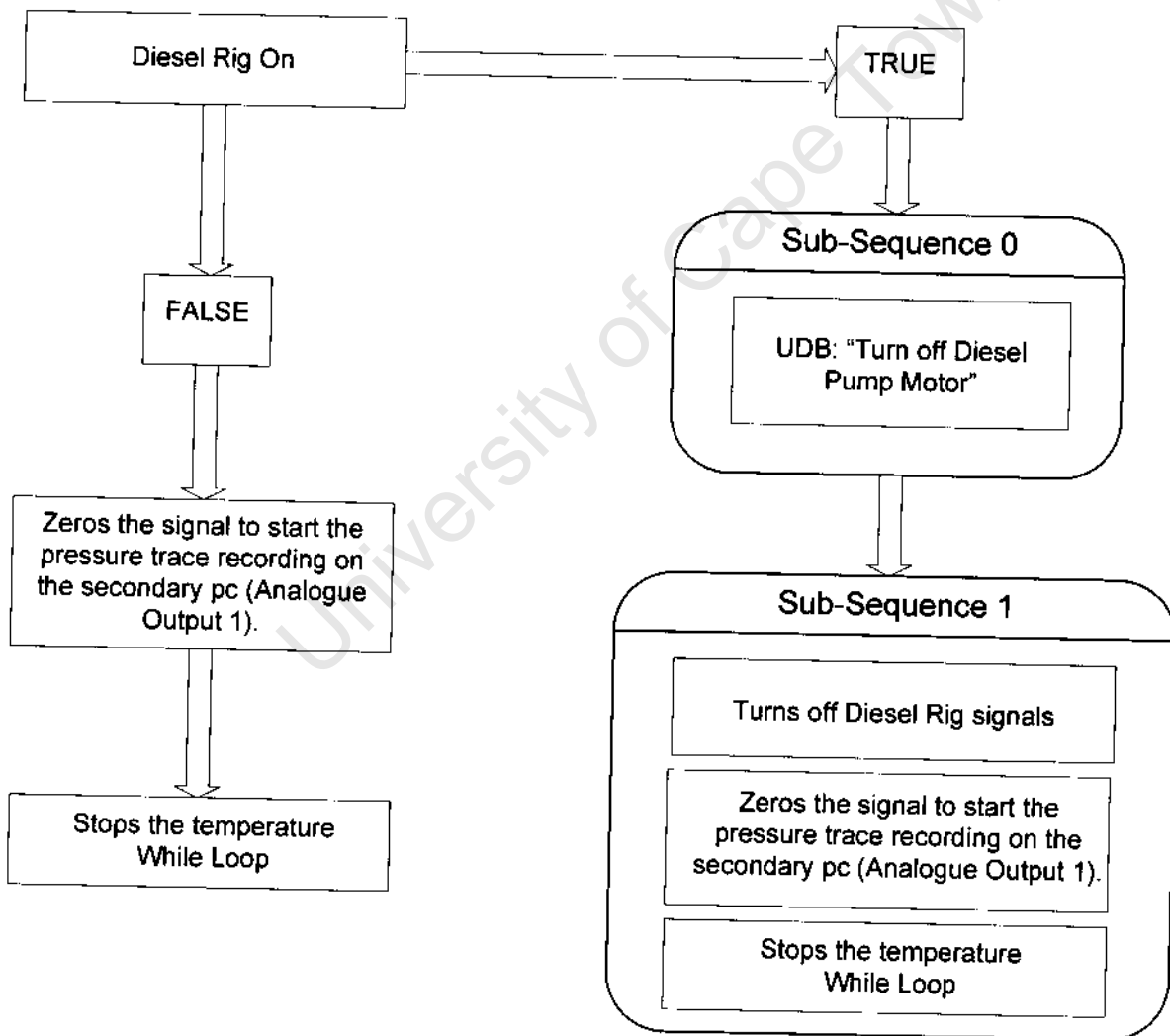
If 1) and 2) are "TRUE", then the exhaust valve is opened. If the signal to open the exhaust valve is missed, there remains the ability to enable a manual exhaust event. Following this enablement or the automatic opening of the exhaust valve, this If Statement as well as the While Loop is closed.

### Sequence 4

#### While Loop

In this While Loop, the initiation of a manual exhaust event is possible. Upon "Shutdown System" being made "TRUE", this While Loop is ended.

### Sequence 5



**PROGRAMME ENDS**

## APPENDIX F — OPERATIONAL ASPECTS FOR THE CVCC USER

### Contents:

#### F.1 Setting Up

F.1.1 CVCC Orientation

F.1.2 Diesel Rig and Injector Orientation

F.1.3 Peripheral Set-up

F.1.4 Power Supply Set-up

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#### F.2 CVCC Component Configurations

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#### F.4 Common Maintenance Requirements

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#### F.5 Assembly and Disassembly

#### F.6 Troubleshooting

F.6.1 Diesel Rig

F.6.2 LabVIEW Errors

F.6.3 Heating System

## **F.1 Setting Up**

### **F.1.1 CVCC Orientation**

The Constant Volume Combustion Vessel (CVCC) can be positioned horizontally or vertically. (For vertical position operation, the attachment of the base plate to the table needs to be completed.) The horizontal position utilizes the two angle-iron struts that are bolted down to the table. The two Nickel half-rings are used at the bottom half of the CVCC to secure it in place. For vertical operation, the base plate is attached to the bottom of the table and the half-rings are used to secure the CVCC on the bottom outer ridge against the insulating gasket which sits on the base plate.

### **F.1.2 Diesel Rig and Injector Orientation**

Currently (at the time of writing), only one high pressure diesel line from the common rail to the injector exists. This limits the positioning of the diesel rig to being adjacent to the table and the injector to being positioned horizontally, either at the cylinder end or circumferentially on either side in case of a horizontal CVCC, or circumferentially on a vertical CVCC. (There is no reason why a longer or second diesel line can not be used for more flexibility (eg. for vertical injector) and this can easily be manufactured by any of the diesel service centres in Paarden Eiland, eg. Diesel Electric.) Moving the diesel rig further away from the CVCC by using a longer diesel will just require longer instrumentation and electrical leads for the diesel rig. It is highly recommended that the thyristor drive for the diesel rig AC motor is placed as far away from the table as possible and is shielded in some way, as this is the cause of most of the instrumentation noise.



### **F.1.3 Peripheral Set-up**

It is recommended that the controlling pc is placed on the same side as the gas cylinders and quick-coupler of the CVCC. In this way, time will be saved during the fill procedure. It is not advised that the operator be lane with an optical window when controlling from the main pc. Mirrors can be used to still gain visual access to the CVCC.

### **F.1.4 Power Supply Set-up**

It is recommended that at least 3 power points be made available for the CVCC's operation. Preferably, one of them should be from as separate a supply point as possible, ie. a different distribution board is ideal. This point should be used for the thyristor drive, though this desirable may have negligible benefit on instrument noise mitigation. The second power point is to be used for the heating system and specifically the temperature controller. The third point (and others if available) is used for the Topward power supply, the two pc's, the thermocouple converter, the charge amplifier and the cooling water pump. If the Visioscope or some other optical recording equipment is used, it should use another power point purely due to overloading concerns.

### **F.1.5 Control System Set-up**

For standard CVCC operation with the recording of an accurate pressure trace, two pc's are required. The main controlling pc contains the National Instruments card and this is connected to the connector block. From here, the digital and counter signals to the power switching board emanate, the instrument signals terminate, and an input and output signal from/to the Eagle card in the second pc connect. The second pc's only other leads are the inputs from the pressure transducer and the injector signal. The pin assignments for the NI and Eagle cards are presented in the following table.

## **F.2 CVCC Component Configurations**

Due to a couple of machining mishaps, the flexibility in component configurations for the CVCC is not quite as it appears. Both limitations occur on the larger circumferential ports. The Instrument Insert containing the pressure transducer and thermocouples must only be used in the port stamped "IP". This is due to a different thread size. In the port stamped "X", the o-ring groove requires a different o-ring to the other ports and the fit is somewhat tighter. For this reason, it is recommended that the Spark-plug Insert is used in this port. It must just be noted that if a window is used in this port, difficulty may be experienced in removing it. The exhaust valve is currently at the bottom of the vessel. If this is moved, a connecting piece of 'A' stainless steel pipe will need to be made. If the fan is used, consideration for its driving mechanism needs to be taken into account, as the horizontal position is the easiest for the handheld air-turbine driver. The injector orientation is addressed in Section 1.2.

## **F.3 Running a Basic Experiment**

### **F.3.1 Preliminary Checks and Procedures**

Open the main controlling LabVIEW programme as well as the Diesel Rig and General Utilities programmes on the main pc. Open the Acquisition programme on the secondary pc. If the experiment requires heated windows for clear optical access, start the heating system (Getting up to temperature may take over an hour.). As there is a large thermal lag, step up to the final desired temperature, eg. if you desire a wall temperature of 150°C, step up to 100°C and then to 130°C before settling 150°C as your set point. Start running the cooling water to the pressure transducer. Set your utility air pressure at the desired pressure for auto-relief (See Fill Elements Calculator, but 4.5 bar is adequate for 200 bar experiments). Using the General Utilities programme, test the operation of the inlet and exhaust valves as well as that of the spark-plug. Hook-up the Nitrogen supply to the CVCC and flush the chamber with Nitrogen. If the diesel

injector has been disconnected since previous use, run the Diesel Rig using its programme until diesel is detected in the return line from the injector. To be absolutely certain of the injector's operation, test it using the same programme while purging the CVCC with Nitrogen. Make power available to the Diesel Rig, push the reverse direction button on the control box (thyristor drive) and increase the frequency to 28hz. Ensure that all other units have power.

### **F.3.2 Running the Experiment**

Connect up the Acetylene supply to the CVCC. Ensure that all other gases have been relieved of pressure in their delivery hoses (this is for easy connecting). Start running the Acquisition and main programmes. Having determined the required Fill Pressures for the gases from the Fill Elements Calculator in Excel, update the fill pressures in LabVIEW if Excel has been set up accordingly, alternatively, transfer the values by hand into the main LabVIEW programme. Note, if only Acetylene is used as pre-charge fuel, set the desired Acetylene pressure as the Hydrogen pressure in LabVIEW and Acetylene pressure itself a little lower. (This way, an accurate measure of Acetylene is achieved in two fill events.) Proceed with the main programme as prompted. Then initiate the fill phase and each gas in the given order to the prescribed pressure, following the prompts. After connecting each gas hose to the quick-coupler, set the pressure regulator's pressure to approximately 10 kPa above the desired pressure in the case of Acetylene and Hydrogen and 0.5 bar above for the Nitrogen and Oxygen. (This is to promote accurate filling pressures — see Section 8.2) Disconnect the Oxygen, close the manual isolation valve and vent the inlet system using the 3-way valve. Click on the "Start Diesel Rig" button and push the operate button on the thyristor drive. Click on the "Fire Spark" button, follow the prompt instructions and ensure that optical recording is taking place before clicking on "OK". The CVCC should fire, inject and exhaust automatically, according to the values set on the main

programme GUI. Click on "End" in the top right hand corner and press the stop button on the thyristor drive before clicking "OK", as prompted. Save the acquired data on the secondary pc to an Excel file, if desired.

### **F.3.3 Completing an Experiment**

Following every experiment, connect the Nitrogen to the CVCC, open the isolation valve and swing the main 3-way valve. Using the General Utilities programme, flush the chamber with Nitrogen until all visible water droplets have evaporated. If the CVCC is to be left standing for any length of time, remove the injector and spark plug to avoid corrosion of these items. (Even if left for 24hrs, visible corrosion starts occurring.)

## **F.4 Common Maintenance Requirements**

### **F.4.1 Exhaust Valve**

The item most frequently requiring maintenance is the exhaust valve. The needle and seat arrangement tends to build up with an exhaust residual paste and this causes leakage. It is not always imperative to clean the exhaust valve when it reaches this state. Firstly, despite slow exhaustion of the vessel, sometimes a good seal is still maintained. Secondly, following a combustion event or a high pressure gas release, the exhaust valve can be cleaned to a degree by the high flow rate generated. If however a good seal is not attainable, it is necessary to remove the exhaust valve, re-grind the needle and seat, clean it and reassemble. The small end of a regular valve-grinding stick from a motor-spares outlet and fine grinding paste has proved to work satisfactorily. Care should be taken when removing/replacing the needle spring so as to avoid scoring the o-ring, if it is left in position.

#### **F.4.2 O-ring Seals**

The o-ring seals perform very reliably in cold operation, ie. no heated walls. However, it is anticipated that for heated wall experiments, they will have to be replaced approximately every 10 experiments. Note must be taken when ordering new o-rings that all o-rings used in the CVCC are made of Viton for temperature resistance.

#### **F.4.3 Window Fouling**

**Fouling of** the windows does occur slowly, the rate depending on the quantity of fuel injected and the EGR ratio employed. The quality of the optical access required will determine how often the windows need to be cleaned. For visual access only, a minimum of 5 experiments should be possible. The windows should be cleaned only with alcohol swabs, available from camera shops, to avoid scratching the polished surfaces.

#### **F.5 Assembly and Disassembly**

O-rings should be lubricated with a silicon-based lubricant, eg Q8, to avoid influence on combustion events. All threads must receive an anti-seize compound coating, such as Weicon High-Tech paste, to avoid similar metal cold seizure. (Note: one of the small circumferential ports has had an air-tight threaded sleeve inserted into it due to cold seizure and consequent damage of the threaded portion during the manufacturing stage.) Graphite gaskets have been manufactured by Gasket and Shim Industries for all mating surfaces. The gaskets become permanently compressed following pressurisation of the CVCC and hence, the inserts require retightening to avoid excessive window movement on combustion. Two gaskets are required for the inside collar of the large ends to avoid contact with the main body.

For the disassembly of windows, the easiest method is to pressurise the CVCC to a low pressure, say 0.5 bar, and then unscrew the large window retainer. The gas pressure forces the window beyond the o-ring, from where it is no longer

necessary to maintain the pressure since the window can be removed by hand. Once the large window has been removed, cleaning is simple and circumferential windows can be pushed out. If difficulty is experienced in removing circumferential windows, a special tool (See Appendix A) has been made to insert into the opposite port and screw out the window (it has a thrust bearing and gasket pad for contact with the window). A secondary tool can be screwed through this one to force out a large window using another thrust pad, but the gas-pressure method is much preferred.

Recommended tightening torques are as follows:

Spark Plug **25 Nm**

Pressure Transducer **15 Nm**

Injector Clamp Bolts **10 Nm**

A socket for removing the spark-plug large-end insert is available in the UCT NDE Laboratory. The gland packing of the fan need not be more than finger tight and only effects a seal following being run-in. Finally, extreme care must be taken when handling and especially removing both metal inserts and windows. The metal components are very prone to denting and the brittle nature of the windows means that chips and cracks occur easily.

## **F.6 .Troubleshooting**

### **F.6.1 Diesel Rig**

The HP Diesel Pump will not deliver any diesel if it does not have sufficient suction pressure. The flow rate in the return line between the 12V LP Diesel Pump and the HP pump must be controlled by the 3-way valve such that sufficient pressure is available at the HP pump's inlet while avoiding straining the LP pump with too high a discharge pressure.

Increasing the frequency control of the thyristor drive significantly above 28 Hz tends to cause excessive vibrations of the rig. Inherently the rig is

under-powered since the HP pump can draw over 3kW of power from the BMW engine.

The HP pump has never been run in the wrong direction for any length of time. It is strongly advised that great care is taken to remember to push the "reverse" button on the thyristor drive on powering up.

The pressure transmitter on the Common Rail must never receive more than 5V across it. It can easily be permanently damaged due to too high a voltage placed across it.

If an error occurs in LabVIEW and the Diesel Rig remains in operation, the "stop" button must first be pressed on the thyristor drive and then the (preferably open) Diesel Rig programme must be started. This will cause the signals to the Diesel Rig to be stopped. The reason for this order is to avoid running the HP pump without feed.

#### F.6.2 LabVIEW Errors

When running the main LabVIEW programme, from time to time fatal exceptions have occurred, causing the programme to "freeze". As this occurrence appears not to be based on any specific actions performed by the user, but rather tends to occur randomly, it is thought that it is due to the relatively slow pc that is used. If this error does occur while running an experiment, the procedure to stop the Diesel Rig as described in Section F 6.1 must be performed if it is running and then the General Utilities programme can be used to exhaust the CVCC contents and flush the chamber. Currently this programme could also be used to fire the CVCC in such an event, however the pressure trace would not be recorded (this could easily be programmed though) and neither would the injection or exhaust events occur automatically.

### F.6.3 Heating System

Difficulties were experienced with the heating system, described in Section 4.6. The apparent common faulty occurrence is that of cartridge elements short-circuiting partially causing excessive current to be drawn by the system. Usually this caused fuses in the wall plug to blow. The present operational system relies on the mains' hip as current protection. It would seem that the cartridges do not have a long shelf life and need to *be* "run-in" shortly after purchasing. The effect of this is to remove any traces of water vapour present in the porous ceramic that may cause damage to the element.

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## APPENDIX G — PROCURED PARTS LIST AND SUPPLIERS

This appendix contains a table consisting of information pertaining to the parts purchased for use with the Constant Volume Combustion Chamber. Instrumentation and electrical component details have not been included as they are presented in Appendix D.

Application	Part	Quantity in Store	Supplier
<b>Diesel System</b>	BMW 320d Injector	0 (1 dummy)	Auto Atlantic, Claremont
	BMW 320d Injector Clamp	0 (1 fabricated)	Auto Atlantic, Claremont
	BMW 320d Accumulator (Common Rail)	0	Auto Atlantic, Claremont
	BMW 320d High Pressure Diesel Pump	0	Auto Atlantic, Claremont
	BMW 320d Fuel Filter	0	Auto Atlantic, Claremont
	Bosch 12V Low Pressure Fuel Pump	0	Tonnesson Motor Spares
	Contitech 345L Timing Belt	0	Bearing Man, Maitland
	Fenner 40L 100 Pulley 8 1610 Taper Lock Bush	0	Bearing Man, Maitland
	Fenner 19L Pulley 8 1108 Taper Lock Bush	0	Bearing Man, Maitland
	High Pressure Diesel Tube	0	J.E.G. Diesel, Paarden Eiland
<b>Mixing Fan</b>	SKF 626-2RS Ball Bearings - 2 off	0	Bearing Man, Maitland
	6 x 6mm Graphite Packing	-200mm	Gasket & Shim Industries, Montague Gdns
<b>0-rings</b>	Viton 0-rings, 18 x 2	30	Gasket & Shim Industries, Montague Gdns
	Viton 0-rings, 100 x 3	8	Gasket & Shim Industries, Montague Gdns
	Viton 0-rings, 38 x 3	16	Gasket & Shim Industries, Montague Gdns
	Won 0-rings, 10x 2	4	Bearing Man, Maitland
	Viton Oxings, 15 x 2	5	Bearing Man, Maitland
	Won 0-rings, 37.77 x 262 (for Port "Kr)	9	Bearing Man, Maitland
	Viton 0-rings for Exhaust Valve Needle	6	Unknown
<b>Exhaust Valve</b>	Exhaust Valve Needle Springs	2	Unknown (spring shop in Paarden Eiland)
<b>Gaskets</b>	All Graphite Gaskets (Details with Spares)	See Store	Gasket & Shim Industries, Montague Gdns
<b>Windows</b>	Sapphire Windows (See Drawings for Details)	Procured: 2 L 8 3 M	Marketed, International, Inc., Washington Tel: (877) 452-4910; Fax: (360) 379-6907
	Quartz Window (Pressure Transducer Size)	2	Procure via Andre Swarts of Sasol Oil
<b>Air System</b>	Air Pressure Regulator and Accessories	0	Festo, Maitland
<b>Tube Fittings</b>	Ferrule & NPT Stainless Steel and Brass Fittings	0 (see general store)	Hy-Design, Paarden Eiland, & Others
<b>Insulation</b>	Fireproof Insulation Blankets	0	Andres Auto-Trimmers, Sasolburg