University of Southern Queensland - Toowoomba Campus

FACULTY OF ENGINEERING

The Development of a Small Scale Gas Turbine to assist in the analysis of Coal Seam Gas as an Alternative Stationary Jet Fuel for Australia

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Abstract

This project aims to investigate Coal Seam Gas (CSG) as an alternative fuel for stationary gas turbine engines. CSG is a new and emerging technology especially in Queensland which has extensive and very attainable reserves. Technological and infrastructural developments are making CSG more attainable and more cost effective as an alternative fuel for domestic use, as a replacement for petrol and diesel fuels, heating and cooling, and also for export.

There are two essential facets of this project being a detailed analysis of the transportation and distribution issues, and the development of a small scale gas turbine engine.

The model turbine has been built as a basis for experiment to compare fuel consumption, and thermal efficiency of CSG compared to another appropriate fossil fuel.

Transportation and distribution will be analysed through research into CSG extraction and refinement, existing CSG infrastructure, expected points of use in the context of stationary jet engines, and the required infrastructure to provide the gas to the expected points of use.

Based on the research and preliminary testing conducted in this report it was concluded that CSG is a very feasible fuel which will only become cheaper with time due to significant investments in infrastructure and technology relating to CSG. The running cost calculations based on the model engine's collected test data provided a running cost saving of 58.1% for CNG over LPG. This is a significant margin which does not consider case by case variables such as specific infrastructure installation costs however does allow for significant initial investment due to the significant saving in running costs.

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Glossary of Technical Terms

- CSG – Coal Seam Gas – A naturally occurring Methane rich gas.
- NG – Natural Gas – A Methane rich gas.
- LPG – Liquefied Petroleum Gas – A commonly used petroleum based fuel gas.
- CBM – Coal Bed Methane – Another name for Coal Seam Gas.
- CNG – Compressed Natural Gas – Natural gas is compressed to increase the energy density for storage and transport.
- LNG – Liquefied Natural Gas – Natural gas is liquefied to increase the energy density for storage and transport.
- Co-generation – a term referring to the extraction of multiple energy sources from one process (eg. Heat energy and shaft power from a gas turbine)
- USQ – The University of Southern Queensland
- Hydrocarbon – An organic compound consisting of hydrogen and carbon.
- Biogas – A form of natural gas produced by the biological breakdown of organic matter.
- Conventional natural gas – Natural gas sourced from oil fields or natural gas fields.
- Un-conventional natural gas – Natural gas sourced all other sources.

- Dewar – A heavily insulated and evacuated storage vessel for LNG.
- Octane number – A measure of a fuels resistance to auto-ignition.
- Thermal efficiency – A ratio of the work output to the supplied heat energy.
- CH_4 – Chemical formula for Methane.
- NO_x – Nitrogen Oxides produced during some combustion processes.
- Stoichiometric – A measure of how well the fuel is burnt in the combustion process.
- Lean burn operation – A process where the air/fuel ratio is decreased significantly allowing savings in fuel consumption.
- Ppm – Parts per million - A measurement of gas quantities.
- Kinetic energy – The energy an object posses as a result of its motion.
- Adiabatic – A thermodynamic process where no heat is transferred to the working fluid.
- AutoCAD – An engineering drawing suite.
- 2-D – Two Dimensional.
- 3-D – Three Dimensional.
- CFD – Computational Fluid Dynamics.

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Chapter 1 – Introduction

1.1 Introduction

Throughout the known history of mankind natural resources have existed in abundance and been exploited in varying ways for our benefit. Today – in the 21^{st} century – essentially the same process is conducted on an ever increasing scale. Energy consumption rates have increased exponentially with the world population growth as more people in developing countries are expecting to live the western energy intensive lifestyle.

A sobering fact is conventional non-renewable energy sources, as the name suggests, are finite in reserves and will run out in the not too distant future. This has become more obvious in recent times since the cost of exploration, extraction, production, and distribution of crude oil based fuels is increasing to a point where society is pushing for a viable alternative. Environmental pressure, political pressure, and increasing tax and levy rates are also pushing this development in alternative fuels.

It is widely accepted that renewable energy sources are without doubt the long-term solution for our energy needs. Development of these technologies is making unprecedented progress, however this technology faces several issues. Some of these include low natural energy density available for collection, inability to provide peak power at times of high demand without an energy storage system, highly energy intensive equipment construction, and associated high cost. These issues will certainly be addressed in the upcoming years with technological developments powered by investment, and renewable energy sources will prevail as the energy source of choice, however in the interim period an alternative energy source needs to be implemented.

Coal Seam Gas (CSG) (also known as Coal Bed Methane – CBM) is naturally occurring methane rich gas mostly held within the coal molecular structure under pressure. This pressure is essential for the gas to stay within the structure of the coal, so when the coal seam is drilled and this pressure is released, then so too is the gas. An advantage of CSG is it mostly contains much less heavier hydrocarbons such as propane or butane, and also less carbon dioxide than fossil natural gas. CSG can be transported in compressed (CNG) or liquid form (LNG) just as other natural gasses.

Although not a permanent solution, CSG is an excellent alternative to conventional fossil fuels for the purpose of energy production and transport. In Queensland significant reserves of CSG are located in the Surat and Bowen basin, and in an increasingly carbon constrained economy these reserves will play a big role in energy generation in the near future. An advantage about using CSG for these purposes is existing vehicles or power plants can easily be converted to run on the new fuel. Natural gas fuelled power plants can be constructed based on gas turbines using co-generation technology and achieve significantly higher efficiencies than conventional coal fired power stations (around 80% compared to 36%)[5]. When used in electricity generation, natural gas fired power plants emit approximately 45% of the emissions of coal fired power stations(10).

This report is targeted at all gas turbines aside from those found in aircraft (or any application where weight is an issue). These can be ships, large hovercraft, and especially high efficiency power plants and co-generation applications. Currently gas turbines operate on many different fuels mostly depending on their location and application. This report will assess the feasibility of the fuel conversion and provide recommendations toward the transition to CSG.

1.2 Aims and Objectives

This project aims to investigate Coal Seam Gas (CSG) as an alternative fuel for stationary gas turbine engines (in particular gas turbine based co-generation systems). In order to satisfactorily complete this project there are two essential aspects which need to be covered.

- The first is a detailed analysis of the transportation and distribution issues. These issues are a major part of this project because of the nature of Natural Gas (NG) and its associated low energy density. Research into CSG extraction and refinement will help create an understanding of what CSG is, and where it comes from. Existing CSG infrastructure will also be researched which will help in making conclusions about CSG as an alternative fuel by assessing the void between the existing infrastructure and the required infrastructure. Research into stationary turbine applications in Australia and expected points of use for the gas is also important when considering infrastructure needs for CSG.

- The second is the development of a small scale gas turbine. To give this project a practical aspect this model engine will be developed and used to obtain experimental results in order to deduct conclusions about CSG as a widespread alternative fuel for stationary gas turbine engines. From this engine fuel consumption, combustion chamber pressure, and exhaust temperature data will be collected. Ideally the engine would be run on both CSG and LPG, however attaining any sort of methane rich gas to get comparative tests has proven to be impossible because it is not sold in compressed and bottled form (CNG) in Queensland. An equivalent CSG fuel consumption can still be calculated using the measured LPG consumption (easily attainable broad-spread fossil fuel). A computer flow analysis of the constructed model combustion chamber will also be completed which will help provide a better picture of how this model engine works. Despite completing this step this project has been carefully steered away from designing the turbine because this was believed this to be a completely different undertaking to what was initially pictured for this project. It was the intention that the model engine would be used only as a means of attaining experimental results from a turbine to aid in making conclusions about CSG as an alternative fuel. Research was conducted into buying a used turbine however this alternative has proved to be far too expensive to justify for this project or the engines were damaged beyond repair.

Once the research into the transportation and distribution issues has been completed, and all test results have been collated from the model engine an analysis of distribution needs, environmental impact, potential market and associated locations can be completed and conclusions made about the feasibility of CSG as an alternative fuel.

1.3 Methodology

When conducting an engineering project focus, discipline, and methodology are important factors. When researching aspects for this project it is important that only relevant information is included in the report and referenced correctly as to the source of the information. Also when conducting the experimental work there is a degree of danger which must be managed by associated risk assessments (see chapter 7 and appendix A) and safety measures.

1.4 Resource Requirements

- During the first stage of this project many resources were required when constructing the jet. Many of these were scrap material at a welding and fabrication shop. Some parts still had to be bought such as fittings, bolts, and hoses but all steel was supplied (see section 6.7 for full details). All costs were covered by myself for the construction as it was intended to be completed before the start of semester one this year (2010). This was not the case, so some assembly was left to be completed at university.

- The last of the assembly at university was the second stage of the process. This required few resources, only a lab to complete the assembly in (s-block basement engineering lab), and some machining to be completed by the engineering workshop (discussed further in chapter 6). This work was submitted to the workshop and completed using the allocated budget for the project to pay for this work.

- The next stage is research which requires resources from the USQ library and the internet. The books needed for the research had been previously chosen and they were researched to have relatively good availability.

- The last stage is testing the model and collecting experimental data (see chapter 7). This stage requires a location to run the jet, LPG in a portable cylinder form, and appropriate safety equipment as outlined in the risk assessment document (Appendix A). The safety equipment was provided by the university, and the LPG gas is easy to get hold of. Much effort has been invested into attaining a methane rich gas however it is not available for purchase in bottled form so existing data on Natural Gas will have to be used.

Chapter 2 – Project Background

2.1 Introduction

This chapter aims to provide appropriate background information on all aspects of this project. This information has been summarised as a result of research from many information sources and will be essential in the analysis and scoping of the work to be conducted in this project.

2.2 Natural Gas Introduction, Composition, Sources and Availability

As reported by Ingersoll (1996), Natural gas occurs naturally as a mixture of methane, hydrocarbons, and non-hydrocarbons. Ingersoll is specifically assessing conventional natural gas however because the composition of conventional Natural Gas and Coal Seam Gas are very similar (ie. very high methane content) it is still relevant to this project.

Most commercially sold natural gas is found as a bi-product from oil fields, or natural gas fields and is known as Fossil Natural Gas (an exception to this is Biogas which can be extracted from decaying organic matter). Lawrence and Kapler (1989) reported that the 1985 world gas conference had estimated that unconventional (ie. other than the by-product of crude oil extraction) natural gas supplies could reach 6 – 9% of the world's natural gas demands by the year 2000, and 9 – 11% by the year 2020. They also said that these figures would rely heavily on the development of improved gas recovery technologies.

Ingersoll also stated in the same publication that natural gas was once considered a waste product from oil wells. Now however, the value of natural as an energy source has been realised and the gas is captured and used for energy production.

2.3 Natural Gas Extraction, Refining, Transportation and Storage

Ingersoll (1996) reported natural gas extraction can be a complex and difficult process which can vary depending on the geological structure of the surrounding area. Ingersoll also stated that coal bed methane extraction can be achieved using either closely spaced holes or horizontal drilling. Sometimes methods from tight shale deposits and tight sands can also be used for coal seal gas to enhance production.

Natural gas has extremely low energy density when extracted from the ground so post extraction gas storage is a serious concern. To increasing the economic viability of distributing the gas it is ether liquefied (LNG) or compressed to very high pressures (CNG).

CNG is natural gas compressed at the refinery and distributed in reinforced solid containers. Very high pressures are achieved (3000 – 3600psi) at atmospheric temperature. CNG is much cheaper to produce than LNG however it has a mere 25% of the energy density of Diesel fuel (see table 3.2) and so requires a much larger storage container per unit of useable energy. CNG can also be compressed at the refinery to slightly less pressure than that in cylinders and transported by pipeline to a required site or distribution centre. Once the infrastructure is in place this is by far the cheapest way of transporting natural gas however there must be a large demand in a particular place to justify laying a pipeline.

LNG is gas converted to liquid form for storage and transportation. Maxwell and Jones (1995) report that to store natural gas in liquid form (LNG) it must be brought to and maintained at cryogenic temperatures (−162 °C). This process is mainly used for gas transportation over long distances where pipelines do not exist because LNG can have an energy density of up to 60% (see table 3.2) of diesel fuel (i.e. much more economical to transport than CNG). The end user then re-gasifies the product and distributes it accordingly. Unfortunately the liquefication process is expensive, energy intensive, and all transport vehicles need to be modified to keep the payload in cryogenic conditions. In the same document the significant advantage of LNG over CNG is described as volumetric energy density. To store an equivalent 20 gallons of gasoline in a vessel a tank volume of 2.7 ft^3 is required for gasoline, 11.3 ft^3 is required for CNG stored at 3600 psi and 4.6 ft^3 is required for LNG.

A heavily insulated and evacuated storage vessel similar to a thermos and called a Dewar is needed to maintain these temperatures. Maxwell and Jones (1995) then continues on to say that there are more issues with storing the gas for extended periods of time, and there are significant safety concerns whilst refuelling. They also briefly mentions that LNG production facilities are not widespread and fuel availability can be a big issue in some circumstances. For the purpose of this project LNG will not be considered due to the problems with producing and storing it.

Figure 2.1: Insulated Liquefied Natural Gas tank on a truck [29].

Maxwell and Jones (1995) also reported on the distribution infrastructure of natural gas. They say that one of the largest problems associated with the widespread use of natural gas as a fuel is the availability of refuelling stations. Significant investments in infrastructure must continue to occur or fuel availability will continue to be a major underlying issue. Although the article centres on the use of natural gas in the context of a vehicle fuel in America, it still encapsulates the major problem associated with natural gas very well. This problem is more applicable in Australia than America which has a comprehensive and developed natural gas distribution pipeline network already in place.

2.4 Natural Gas As A Fuel For Combustion Engines

Fortunately natural gas has several aspects which make it appealing as a fuel aside from cost. These advantages have been reported on many times including by Ingersoll (1996) who stated natural gas has a very high octane number of around 130, has superior environmental emissions, and reduced engine wear characteristics to conventional fuels. Ingersoll's assessment is of fossil natural gas in America as an alternative vehicle fuel, however talking about high octane numbers and reduced engine wear is also relevant to gas turbine engines.

Maxwell and Jones (1995) also reports on the significant increase of thermal efficiency of a well tuned natural gas engine over a conventionally fuelled engine. This is because of the high octane number (130) of natural gas, the engine's compression ratio can be increased which will increase the overall thermal efficiency.

2.5 Coal Seam Gas

Ingersoll (1996) suggested coal seam gas is an exciting emerging energy source, especially in Queensland where significant reserves exist. Ingersoll reports that coal bed methane was generated over long periods of time when organic material is transformed under pressure to form coal. The significant amount of methane trapped in the coal seams is held within the coal molecular structure. The book then says that this gas, which was once considered as a hazard to coal miners, is now recognised as a valuable fuel source. This reflects the positive change in attitude toward our energy sources over time.

2.6 Safety Issues When Working With Natural Gas

Maxwell and Jones (1995) reported that natural gas has been demonstrated to be safe over the years of operation. This is because of two main reasons: NG is lighter than air so it dissipates quickly in the event of an accidental spillage, and its ignition point, 1200°F, is much higher than that of gasoline, 600°F. No burn accidents, other injuries, or fatalities have been reported during 500 million miles of natural gas vehicle operation (in 1995). These figures are for natural gas powered vehicles in America, however the natural gas safety figures are still applicable to all types of natural gas including within Australia.

2.7 Emissions Of Natural Gas Engines

One of the major advantages and selling points of natural gas fuelled engines is the comparatively low environmental impact due to cleaner exhaust emissions. Maxwell and Jones (1995) reported that well tuned natural gas engines have exceptionally low emissions of carbon monoxide, reactive hydrocarbons, and particulate matter. This is mostly due to the efficient combustion process caused by the methane (CH_4) molecules oxidising with almost no intermediate hydrocarbon constituents. Ideally an engine would achieve 100% combustion efficiency however in reality the exhaust contains NOx and particulate matter.

Natural gas engines suffer from high NOx emissions (just as gasoline and diesel engines do) which are formed as a result of high temperature gas created by the combustion process reacting with the nitrogen in the intake charge. The NOx emission can contain non-reacted and partially-reacted fuel due to inefficiencies and cold/hot spots in the combustion chamber, Nitrous Oxide (NO), Nitrogen Dioxide (NO2), and Sulphur Oxides. The NOx emissions from any engine can be reduced by exhaust gas recycling (EGR), lean burn operation, development in fuel mixing and stoichiometric control technology, and a typical three way catalyst in a combination closed loop exhaust oxygen level feedback.

Maxwell and Jones add the principle pollutant from a NG fuelled combustion engine is unburnt methane which is a result of improper fuel/air ratios and incomplete mixing. While their discussion specifically relates to NG fuelled reciprocating engines (such as those found in cars, trucks and buses), emissions and emission controls are still relevant to gas turbines.

2.8 Stationary Gas Turbine Applications Within Australia

Research has concluded that stationary gas turbines have many applications within Australia including power generation, co-generation, ships, hovercraft, and demonstration/test engines.

Sinklair Knight Merz (2007) reported that they were undertaking a project with TRU energy constructing a 400MW Combined Cycle Gas Turbine (CCGT) Power Station at Yallah which is situated 13km South of Wollongong in southern NSW.

Sinklair Knight Merz (2007) have also completed a project in conjunction with AGL in South Australia where the steam and power requirements of Coopers Brewery, Regency Park, Adelaide have been fulfilled since 2003 by a gas turbine based co-generation plant. This system was based around a Solar Turbines Centaur 50S gas turbine unit rated at 4.4 MW. This particular turbine is achieving an impressive 8ppm NOx emission thanks to extra NOx burners which were installed at an extra cost of $200,000.

Figure 2.2: Natural gas turbine based co-generation plant by Sinklair Knight Merz [5].

GHD have provided engineering consulting, design and estimation services to many gas turbine co-generation plants. On the GHD website they outline many different gas turbine projects which they have provided services for all over Australia. Most of these projects have served remote communities, mine sites, large industrial manufacturing sites or refineries and smelters which have particularly high electricity or heat energy demands.

Gas turbines are also utilised in ships and large hovercraft. The Australian Academy of Scuba Diving website also gives details on the propulsion system of the HMAS Canberra military destroyer. This ship was powered by two electronically controlled gas turbines which gave the ship a versatile, responsive and powerful propulsion system (AOS Australia website). The Hovercraft Homepage also reported that large capacity jet turbine engines (or in particular gas turbines) were used in large military or commercial hovercraft.

2.9 Manufacturers of Stationary Gas Turbines

For medium to large scale installations most turbine and generator designs are specified for on a case by case basis and specially ordered. This will ensure the exact needs of the customer are met and the turbine is not under or over worked to meet the energy demands. Some small companies however manufacture small scale energy co-generation plants such as Turbec in Italy. They produce and sell small scale gas turbine based gas turbine based electricity and co-generation plants. One of their products, the T100 CHP micro-turbine has been successfully manufactured for several years and has clocked **3.617.384** reliable operating hours (Turbec website).

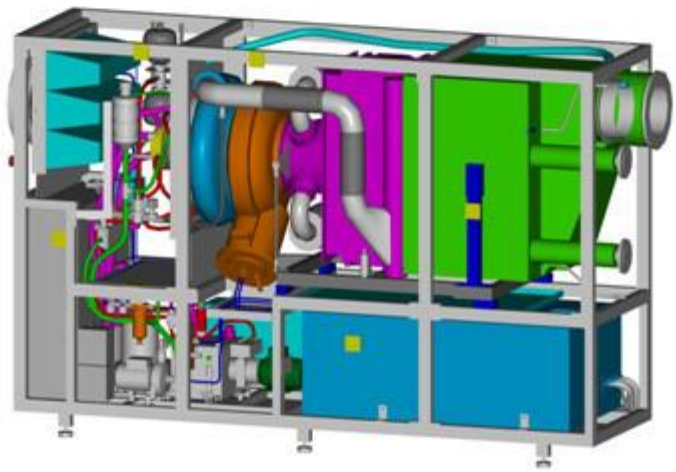

Figure 2.3: Turbec manufactured gas turbine based co-generation plant [30].

2.10 Comparison Of Gas Turbine Engines To Compression Ignition Engines

Mattingly (1996) reported that jet propulsion is a momentum change of a fluid by the propulsion system. The fluid may be gas used by the engine itself (e.g. turbojet), it may be a fluid available in the surrounding environment (e.g. air used by a propeller), or it may be stored in the vehicle and carried by it during the flight (e.g. rocket). These few points briefly outline jet engines and how they change the kinetic energy of the working fluid to provide propulsion. This is different to Compression Ignition engines which use the change in fluid volume by the combustion process (by heat addition) to create mechanical energy.

2.11 Summary

It has been found that coal seam gas is a naturally occurring methane rich gas which is stored in the molecular structure of underground coal seams. It was formed as organic matter sitting underground has been transformed to coal over long periods of time and under very high pressures. Coal seam gas was once considered a hazard and hindrance to coal miners, however with the change in attitude toward energy sources over time it is now considered a valuable resource.

Natural gas must be stored at very high pressure as Compressed Natural Gas (CNG) or at very low temperature as Liquefied Natural Gas (LNG). This is because at atmospheric pressure and temperature natural gas has a very low volumetric energy density and so would be un-economical to transport and store. Even when natural gas is converted to CNG or LNG it still has relatively low energy density compared to conventional fossil fuels so energy density continues to be a major drawback of the technology. Because of these issues natural gas is mostly transported via piped networks which are very expensive and difficult to construct.

Natural provides an excellent fuel source for combustion engines for several reasons. It has been documented that, compared to conventionally fuelled engines, natural gas engines have lower exhaust emissions of carbon monoxide, reactive hydrocarbons, and particulates. This is because natural gas has a very high octane number of around 130 which allows for high compression and lean-burn technology to be used on conventional engines. Natural gas engines however suffer from high NOx emissions mostly consisting of partially reacted fuel, nitrous oxide, nitrogen dioxide, and sulphur oxides. High NOx emissions can be dealt with using Exhaust Gas Recycling (EGR), lean burn operation, development in fuel mixing and stoichiometric control technology, and a typical three way catalyst in a combination closed loop exhaust oxygen level feedback.

Natural gas safety is a very important factor, and it has been documented that no burn accidents, other injuries, or fatalities have occurred in America as a result of natural gas despite more than 500 million miles of natural gas vehicle operation. This is because of two main reasons: NG is lighter than air so it dissipates quickly in the event of an accidental spillage, and its ignition point, 1200°F, is much higher than that of gasoline, 600°F.

Gas turbine engines operate on similar principles to conventional reciprocating engines where heat energy from the combustion process expands the working fluid. The difference however is that gas turbines change the kinetic energy of the working fluid through a constant combustion process, and then extract energy from the exhaust using a turbine. This turbine is connected to a compressor wheel which forces more air in the intake. Conventional reciprocating engines utilise the expanding working fluid in a controlled volume to move a piston creating mechanical energy.

Stationary gas turbine engines have many applications including energy generation, ship propulsion, and hovercraft propulsion. More specifically for this report stationary gas turbine engines are being used more frequently for low to medium scale co-generation projects. These projects have been most popular in remote communities, mine sites, large industrial manufacturing sites, refineries, or smelters which have particularly high electricity or heat energy demands. Most medium scale gas turbine based energy generation plants are specified and designed on a case by case basis however there are a several companies manufacturing small generic units and documenting excellent reliability data.

Chapter 3 – Coal Seam Gas Industry

3.1 Introduction

This chapter will firstly go over a brief industry overview including an explanation why Coal Seam Gas is undergoing a period of such rapid growth, the areas where Coal Seam Gas is located in Queensland, and an estimate of the quantity of attainable Coal Seam Gas in Queensland. A brief overview of existing natural gas distribution infrastructure will then be provided followed by a cost analysis of different fuels.

3.2 Industry Overview

With ever increasing environmental pressure and supplies of conventional fossil fuels past the peak supply, and exponentially increasing demand the price has been rising. It was anticipated that this price rise would promote a change in attitude toward the use of these fuels however household budgets have adopted to the price increase and demand has continued to exponentially grow. There will be a point however where the cost of these fuels reaches a point where it is too expensive to use crude oil based products in the current fashion. At this point alternate energy sources will be required to fulfil the requirements of our developed energy intensive western lifestyle.

It is widely accepted that when this occurs renewable energy sources will be the long-term solution for our energy needs. Ideally the transition to renewable energy sources could begin immediately however the technology suffers from several problems. Some of these include low natural energy density available for collection, inability to provide peak power at times of high demand without an energy storage system, highly energy intensive equipment construction, and associated high cost. Development of these technologies is making unprecedented progress, however at the current level of technological development they are not a viable alternative for large scale main-stream energy generation. These issues will certainly be addressed by technological advances in the upcoming years and renewable energy sources will prevail as the energy source of choice, however in the interim period an alternative energy source needs to be implemented.

Because of this the natural gas industry (especially in Queensland) is going through a period of unprecedented growth and development.

Coal Seam Gas can be produced wherever coal seams are present. For economic reasons however the accessibility which includes coal seam depth, soil/rock type, and the surrounding water table are all important considerations when analysing the extraction process. In Queensland Coal Seam Gas is currently produced from the Surat and Bowen basins however coal seams also exist in the Cooper, Clarence Moreton, and Galilee basins.

Figure 3.1: Major Coal basins in Queensland [17].

Domestic natural gas consumption in Australia is rising, and is expected to be around 1750 Petajoules by 2020 [17]. The following graph shows the natural gas consumption trend, and projected trend.

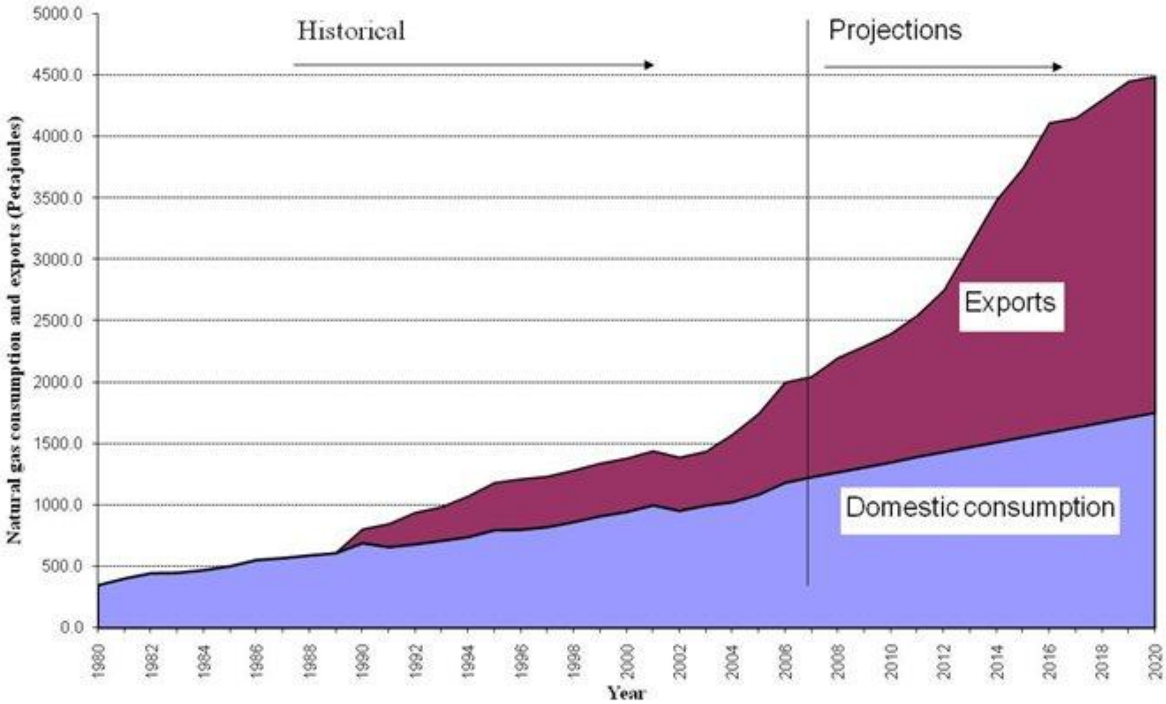

Table 3.1: Australian natural gas consumption [17].

Increasing domestic natural gas consumption will increase the feasibility of natural gas as an alternative fuel. This will promote an increase in investment of distribution infrastructure and therefore providing the fuel to more areas at a cheaper rate.

Natural gas exports are expected to rise significantly in 2013 when several large LNG projects will be complete in Gladstone on the central Queensland coast. There are eight proposed coal seam gas projects worth in excess of $40 billion. These projects propose an annual gas production of 50 million tonnes of LNG from over 8600 wells piped to liquification plants in Gladstone and mostly exported [21].

Some of the current project proposals which are currently in place in Queensland are:

- **Santos Ltd/Petronis** proposes to construct an LNG plant near Gladstone along with a 450km pipeline.

- **Queensland Gas Company (QGC)** proposes to construct an LNG plant near Gladstone along with a 430km pipeline.

- **LNG Limited/Arrow** proposes to construct an LNG plant near Gladstone.

- **ConocoPhillips/Origin Energy** proposes to construct an LNG plant near Gladstone.

- **Shell (CSG) Australia Pty Ltd** proposes to construct an LNG plant near Hamilton Point.

- **Sojitz Corporation** proposes to construct an LNG plant near Gladstone.

- **Impel (Southern Cross LNG)** proposes to construct an LNG plant near Gladstone along with a 400km pipeline.

- **Energy World Corporation** proposes to construct an LNG plant at Abbott Point.

Most of these projects are aimed at LNG production on the mid Queensland coast, and exportation. Unfortunately at the time of writing there was no information on projects developing the distribution infrastructure within metropolitan areas of Australia.

3.2.1 Existing Distribution Infrastructure

As discovered in the background research, due to the low energy density of natural gas, transporting the fuel by road tanker is rarely feasible. Therefore the largest issue with natural gas is the distribution of the fuel. Assessing the infrastructure shortfalls is an important aspect of this project. The installation of small to medium scale gas turbine co-generation plants around industrial and suburban areas (such as those proposed in this project) must be assessed on a case by case basis. Essential factors which will make or break the feasibility of the project is the heat energy demands of the area and especially the shortfalls of the natural gas pipelines. If the station will be situated 20m from an existing pipeline then the project may be feasible, however if it is 12 km through a metropolitan area then the cost of laying the pipe may outweigh any benefits the plant can offer.

Because of this need for individual case analysis to assess the feasibility of the project, then this report cannot make conclusions on individual cases without receiving further specific information, however an analysis of existing infrastructure will be conducted.

Major Queensland natural gas transmission lines include:

- The Roma to Brisbane Pipeline (RBP) from Wallumbilla (Roma) to Brisbane (438 km) [16]

- The South West QLD Pipeline (SWQP) from Ballera to Wallumbilla (Roma) (756 km) [16]

- The Queensland Gas Pipeline (QGP) from Wallumbilla (Roma) to Gladstone and Rockhampton (627.1 km) [16]

- The Carpentaria Gas Pipeline (CGP) from Ballera to Mt Isa (840 km) [16]

- The North QLD Pipeline (NQGP) from Moranbah to Townsville (391 km) [16]

These pipelines are designed to transport natural gas from the field to large industrial customers, local distribution networks, and also natural gas power plants. In addition to these pipelines the Queensland - South Australia - New South Wales pipeline was commissioned in 2009, and the Queensland Hunter Gas Pipeline was approved for construction in early 2009. Both of these pipelines will link the top 4 above pipelines with large customers south of the border further powering the Queensland natural gas economy.

Localised gas distribution networks fed from the above transmission lines are located in Brisbane, the Gold Coast, Toowoomba, Ipswich, Dalby, Roma, Oakey, Bundaberg, Maryborough, Gladstone, Rockhampton, and Hervey Bay [16].

3.3 Natural Gas Cost Analysis

The costs associated with coal seam gas production can vary greatly depending on the source location, type of terrain, geological makeup of the soil, distance from source to point of use, and the tariffs on the pipelines used. Some of these costs can commonly include:

- Geological area analysis
- Exploratory drilling
- Securing land access
- Drilling production wells
- Compressing the gas

- Treatment of CSG well water
- Pipeline tariffs

These costs can be subject to change, and other costs can also occur depending on the circumstances.

Despite the above costs one of the major advantages of natural gas over conventional fossil fuels is said to be the price. Gastech in Melbourne have quoted the price of natural gas to be $0.38/m^3$ (Baxter, R 2010, pers. comm., 2 June) at atmospheric pressure. Currently this gas is a blend of conventional natural gas and CSG. Predicting the cost of CSG in Queensland when it becomes available in a pure form is impossible however it is said to be similar to the above figure.

From the above quoted figure and using atmospheric pressure (P_{0psi}) as 101.325 kPa

$$P_{0psi}\, V_{0psi} = P_{3600psi}\, V_{3600psi}$$

$$101325 \times 1 = 2.48 \times 10^{7} \times V_{3600psi}$$

$$V_{3600psi} = 4.086 \text{ Litres}$$

Therefore the cost of CNG per litre = \$0.38/4.086 = \$0.093/L

The approximate cost of LNG was now needed to successfully compare relative fuel prices and was quoted by Westfarmers as \$0.48 per litre (Hazel, B 2010, pers. comm., 3 June). With this information the following table can be completed.

Table 3.2: Fuel cost and volume analysis.

Fuel	Petrol	Tax free Diesel	Compressed Natural Gas	Liquefied Natural Gas	LPG
Cost/Litre (cents)	109.9	91.9	9.3	48	62
Energy Density (MJ/L)	34.9 [23]	38.6 [23]	9 [23]	23.16 [23]	25.3 [23]
Cost for 100L ($)	109.90	91.90	9.30	48.00	62.00
Relative cost to diesel/Litre	119.6 %	N/A	10.1 %	52.2 %	67.5 %
Volume of fuel for 3860 MJ (L)	110.6	100	428.9	166.7	152.6
Cost for 3860 MJ ($)	121.55	91.90	39.89	80.02	94.61
Relative cost to diesel/Energy Volume	132.2 %	N/A	43.41 %	87.07 %	102.95 %

The above table shows the interesting comparison between the different available fuels. Several important points about the above table include:

- Each fuel has different energy densities so for purposes of comparison each fuel has been compared to tax free diesel by analysing the cost of purchasing the equivalent energy of 100L of diesel (3860 MJ). The relative cost per litre, and then per energy volume has then been provided for purposes of comparison.

- The above prices and price comparisons do not include transport/delivery costs, or costs of installing specialised CNG lines which could dramatically affect the above figures.

- Each of the above fuel prices were attained at the time of writing, and were either local average fuel price, or quoted prices for conventional natural gas in Melbourne at the time of writing.

3.4 Conclusion

This chapter aimed at increasing the scope of the analysis of CSG by looking at an industry overview, where CSG is located, and how much of it can be reasonably extracted. An overview of existing natural gas distribution infrastructure was then provided followed by a cost analysis of different fuels.

Coal Seam Gas (CSG) is going through a un-precedented period of growth due to the push for alternative energy sources while development of renewable energy generation technology advances to a point where it can be widely used. In Queensland there are eight proposed coal seam gas projects worth in excess of $40 billion. These projects propose an annual gas production of 50 million tonnes of LNG from over 8600 wells piped to liquification plants in Gladstone and mostly exported. This is causing significant interest and investment in the technology, and it will provide a significant boost to employment and to the Queensland economy.

CSG is sourced from anywhere that underground coal seams exist. In Queensland Coal Seam Gas is currently produced from the Surat and Bowen basins however coal seams also exist in the Cooper, Clarence Moreton, and Galilee basins.

Natural gas consumption is expected to rise over the upcoming years mostly due to the export projects stated above, and also the continued development and consumption of natural gas domestically.

Major Queensland gas distribution pipelines were briefly summarised and local distribution networks in Brisbane, the Gold Coast, Toowoomba, Ipswich, Dalby, Roma, Oakey, Bundaberg, Maryborough, Gladstone, Rockhampton, and Hervey Bay were identified.

The costs of natural gas production were then outlined and a costing analysis of different fuel types was conducted. Because of the different energy content per volume the fuels cannot be directly compared using the cost per litre. The energy content had to be employed to compare these fuels per contained energy volume. It was discovered that natural gas purchase was 43.41 % that of diesel per energy volume. This will be a very important tool in summarising the feasibility of CSG as an alternative fuel in later chapters.

Chapter 4 – Consequential Effects

In this chapter the consequential effects of the work conducted in this project will be reviewed. To help in this analysis the 'Engineering Frameworks for Sustainability' published by the Institution of engineers Australia will be used.

4.1 Sustainability

Sustainability is becoming an issue of great significance in modern society. If a new technology is introduced (such as CSG in gas turbines) the environmental and sustainability aspects will be key issues which will need to be closely assessed. Sustainability of the technology can be assessed using the 'Towards Sustainable Engineering Practice: Engineering Frameworks for Sustainability', Institution of engineers, Australia, Canberra, 1997. This document outlines ten aspects of sustainability, some of which have relevance to this project.

1. *Development today should not undermine the development and environmental needs of future generations.* – This project certainly has an impact on the use of finite resources which are not renewable. It is however using the finite resource CSG instead of crude oil based products. Crude oil based products are still commonly used despite knowledge of their lack of sustainability, and substituting their use in some areas such as fuels is going to help the existing crude oil reserves last longer for our future generations. CSG has potential uses in fuels and domestic gas supplies so using it for gas turbines is a good application. Australia and in particular Queensland has extensive reserves of CSG so using a domestic energy source also saves on inter-continental transportation of energy.

2. *Environmental protection shall constitute an integral part of the development process.* – Environmental protection is another important aspect of assessing alternative fuels. Most environmental protection issues lay with gas exploration, extraction, transportation, and exhaust emissions once burnt. A detailed analysis of the environmental issues with extraction, transport, and storage are beyond the scope of this report however they are still important and should be considered closely by the energy supplier. Initial research suggests that emissions are much more favourable whilst burning CSG as opposed to other crude oil based fuels.
3. *Engineering people should take into consideration the global environmental impacts of local actions and policies.* – Development of CSG technology would lead to a spread of CSG use all over the world which would decrease reliance on crude oil, decrease running costs, create new jobs, and save significant environmental emissions.
4. *The precautionary approach should be taken – scientific uncertainty should not be used to postpone the measures to prevent environmental degradation* – CSG is a new and emerging technology which has some big advantages over crude oil based fuels. An approach to a new technology such as CSG should be approached proactively instead of the general rule of caution. The advantages of this technology should be realised and development should be pushed forward to make it happen as soon as possible. The environmental benefits of NG have been documented many times over and action toward technological development, documentation of results, and community awareness needs to be taken.
5. *Environmental issues should be handled with the participation of all concerned citizens.* – All citizens in western societies will be affected by the reduced reliance on crude oil based products. A significant reduction of environmental emissions by energy production and significant saving to transportation from converting engines to run on CSG will be seen.
6. *The community has a right of access to, and an understanding of, environmental issues.* – All sections in this project have been structured in

such a way that all environmental aspects, results, and conclusions are readily accessible and easily understood.

7. *The polluter should bear the cost of pollution and so environmental costs should be internalised by adding them to the cost of production.* – All potential pollution costs are assumed to be the responsibility of the energy provider because it is assumed that they will occur in the CSG exploration, extraction, and transportation stages of the process. All environmental emissions from burning CSG have been determined to meet all regulations.
8. *The eradication of poverty, the reduction in differences in living standards and the full participation of women, youth and indigenous people are essential to achieve sustainability.* - This project has no impact on diversity, racism, ageism, or sexist issues. It is likely to bring money to remote communities where indigenous ratios are quite high, which could be used toward helping local issues.
9. *People in developed countries bear a special responsibility to assist in the achievement of sustainability.* – If CSG was to spread all over the world the benefit to both developed and un-developed communities would be equal. Developed communities would receive a reliable source of energy which has low price variation, requires minimal modification to existing infrastructure, and is more environmentally friendly. Due to the nature of CSG it is spread all over the world so un-developed countries would benefit by selling the gas which would help their economies, create jobs, and develop political relationships with other countries.
10. *Warfare is inherently destructive of sustainability, and, in contrast, peace, development and environmental protection are interdependent and indivisible.* – CSG is located all over the world and is not necessarily in high concentrations where the demand is located. This will promote international trading between countries. Over history this has proven to be both beneficial and a significant hindrance to worldwide political relationships. It would be hoped that only positive relationships between countries would develop from trading CSG but that is nearly impossible to accurately predict.

4.2 Ethical Responsibility

Any engineering activity has ethical responsibility which is assumed by the conductor of the activity. A large portion of this particular project is risk free (the research) however it is important to conduct the research ethically. Another portion of the project being final assembly of the model engine, and operation of the engine to gain experimental data has significant health and safety issues associated with it.

Considering this, a review of the Engineers Australia Code of Ethics was necessary for some guidance on how to conduct this task ethically. Upon review Tenets 2, 4, and 7 of the Engineers Australia Code of Ethics were chosen as relevant to this task and are as follows:

2. Members shall act with honour, integrity and dignity in order to merit the trust of the community and the profession.
4. Members shall act with honesty, good faith and without discrimination toward all in the community.
7. Members shall express opinions, make statements or give evidence with fairness and honesty and only to the basis of adequate knowledge.

After reading these guidelines it was concluded that two essential guidelines must be adhered to when completing this project. The first is to conduct research with honour, integrity, and dignity. This meant that work was written to the best of the available knowledge and also truthfully. Also all work had to be correctly referenced with careful citation to the information source in order to give the original authors due credit for their work. The second guideline was that the risks associated with conducting the work with my model had to be managed as best as possible. This is covered in the next section and also appendix A.

4.3 Natural Gas as a Fuel

Safety issues of using natural gas as a fuel are very important in this project. Natural gas has been found to be lighter than air so it dissipates quickly in the event of an accidental spillage. This is a good property in the case of an accidental leak as the gas will quickly dissipate minimising risk to surrounding personnel. Natural gas also has an ignition point of 1200°F which is much higher than that of gasoline, 600°F so a much better ignition source is required to ignite the fuel.

4.4 Safety Issues

It was decided that the best risk management procedure was to complete risk assessments for all activities being conducted to minimise the possibility of something going wrong. There are essentially two major activities which have been risk assessed and these are general assembly and soldering, and running the engine to gain experimental results. These assessments are attached respectively in Appendix A.

Chapter 5 – Gas Turbine History and Principles of Operation

5.1 Introduction

Combustion engines operate using a working fluid (mostly air) and subject it to process which allow the engine to extract energy from it. This chapter briefly looks at the history of gas turbines and the general principles which allow combustion engines to successfully operate. It then looks at the basic layout of a simple cycle gas turbine engine and summarises the cycles occurring and the components involved.

5.2 Gas Turbine Origins

Experimentation into gas turbine engines began in the 1930's and it took several years until the design was refined enough to build the first practical engine for service in 1940. Design issues that stunted the expansion of the gas turbine in the early stages of development were lack of hi-tech materials capable of withstanding the high temperatures and velocities of the turbine blades, and low combustor and compressor efficiencies. These issues were improved over time and the expansion of gas turbine engines into service has seen an exponential growth since.

5.3 Basic Engine Cycles

In all heat (combustion) engines there are cycles which represent each process of operation. In most engines these cycles are adiabatic compression (1-2), heat addition (2-3), adiabatic expansion (3-4), and heat rejection (4-1) as illustrated in the diagram below.

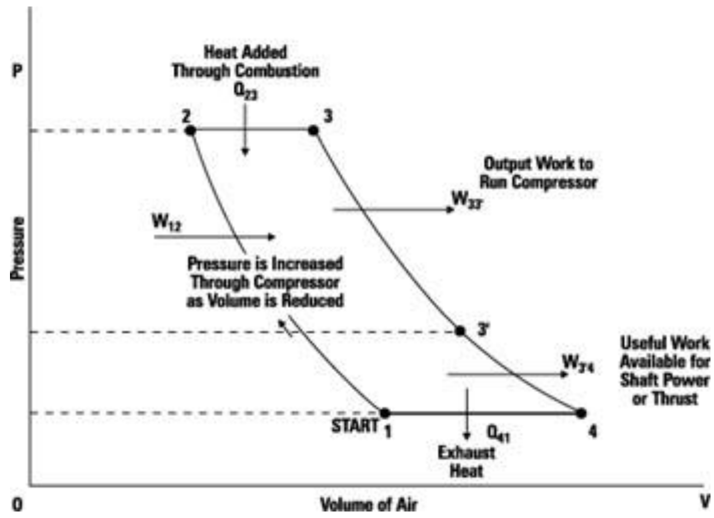

Figure 5.1: The Brayton cycle.

5.4 *Principles of Operation*

The simple cycle gas turbine engine has several essential components to ensure the basic thermodynamic cycles can occur and the engine can operate successfully. The basic components are outlined below.

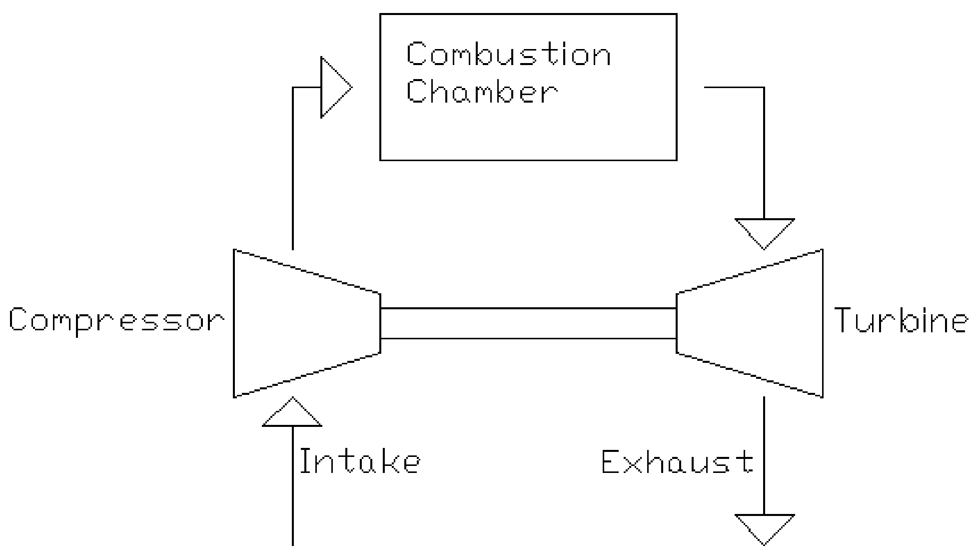

Figure 5.2: The simple cycle gas turbine layout.

The thermodynamic cycles occurring in a simple cycle gas turbine include:

1. Intake – the working fluid is accelerated through the intake by the compressor from quiescent ambient conditions to a velocity at the compressor inlet.

2. Compression – working fluid then undergoes reversible adiabatic compression by the compressor wheel of the turbocharger usually within a pressure ratio of 4 to 1 to 15 to 1. This air is then forced through piping into the intake of the combustion chamber.

3. Heat addition – the fuel is then injected in the first part of the combustion chamber and the working fluid undergoes heat addition at constant pressure.

4. Expansion - the heated working fluid then undergoes reversible adiabatic expansion in the second part of the combustion chamber. This high velocity stream of gases flows over the turbine of the turbocharger which in turn drives the compressor wheel.

5. Exhaust – heat is then rejected from the working fluid at constant pressure through the exhaust system beyond the turbine.

Gas turbine engine can exist in both axial and radial flow layout. In axial flow engine the working fluid flows from the compressor in an axial direction to the engine shaft. Most commercially produced engines are of this design to minimise losses in the working fluid path. Simple cycle gas turbine engine based on automotive turbochargers however are radial flow (ie. the working fluid flows from the compressor in a direction perpendicular to the engine shaft). A diagram of such engines is provided below.

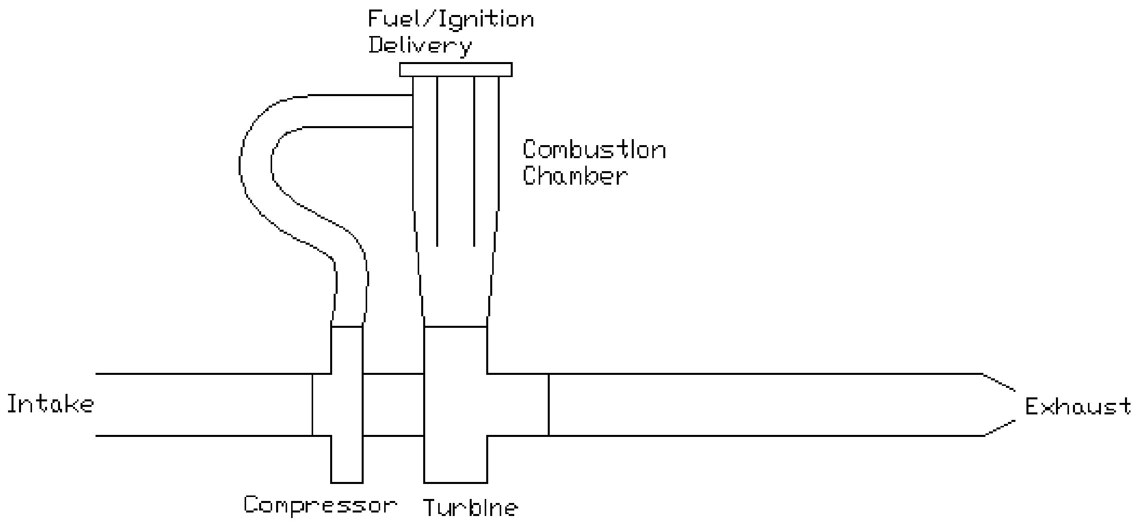

Figure 5.3: A radial flow simple cycle gas turbine engine based on a turbocharger.

5.5 Conclusion

The model test apparatus developed in the following chapter must successfully achieve the thermodynamic cycles outlined in this chapter. The basic design of the engine is known and further analysis and design justification is in the following chapter.

Chapter 6 – Model Design and Construction

Objectives

The objective of this chapter is to design and construct a model gas turbine engine to run on a gaseous fuel and gain experimental results to aid in the analysis of Coal Seam Gas as an alternative stationary jet fuel.

6.1 Introduction

This chapter firstly aims to analyse the design constraints and requirements of the model gas turbine engine which will be constructed for this project. The processes of a simple cycle gas turbine will then be revised before the conceptual design process is started. Design requirements and expected results will be used as criteria when refining the conceptual design. A successful conceptual design will be judged on the ability to provide the desired results once constructed. Once the concept is refined a 2-D conceptual jet design will be drafted on AutoCAD which will include more detailed dimensions. A 3-D model will then be created of the combustion chamber in order to undertake CFD analysis and get a better understanding of how the engine works in areas a that could not otherwise be seen. Once these drawings and models are complete the process of materials selection, creating a cutting list, and construction can begin. Once the jet is complete experimental work will be carried out and parameters such as fuel consumption, exhaust temperature, and combustion chamber pressure will be measured and recorded for further analysis. Finally the design and construction process will have a full appraisal and any future work and design changes will be noted.

6.2 Design Requirements & Constraints

The design requirements of an engineering project are guidelines which outline the direction and parameters of the system design process.

These include:

1. The engine must operate reliably enough to attain the desired results

   This report is based on the analysis of coal seam gas as an alternative stationary jet fuel. The purpose of the model is to achieve experimental data on gas fuel consumption and calculate thermal efficiency of the model to aid in the reflection of the jet design process conducted in this report. It is essential that the engine is reliable enough to attain these results. Despite this engine being of primitive design and construction, and also having a relatively low expected thermal efficiency it will still be a good tool to aid in the analysis of CSG as an alternative fuel.

2. The engine must be compact and portable

   The engine must be constructed and transported from storage sites to test areas which may be significant distances apart. The engine is also expected to spend some time in the university engine test labs (not for operation but simply storage and minor modifications). Because of these two factors the engine must be compact and portable. Moving the jet on a removalist trolley from location to location would be ideal. For this reason the jet will be constructed within an outer frame and all associated components will be housed within this exo-skeletal structure.

3. There must be built in safety systems to reduce risk

   Safety is an essential factor in any engineering project and this project is no exception. There is significant danger involved in the operation of a model jet such as the design being considered for this project. The turbocharger on which this jet is based on is being used in such a way that it was never designed for whilst the engine is achieving very high temperatures and very high turbocharger shaft speeds. Three essential steps will be undertaken to increase the safety of this model. The first is to install and exhaust temperature sensor close to the exhaust turbine of the turbocharger. This will be monitored during operation, and the engine will be shut down if the temperature rises above a selected point. The second is to make an exclusion zone in the exhaust of the jet to prevent any bystanders from being struck from any debris whilst in operation. The last is to conduct a risk assessment of the operation of the jet to minimise any potential risks.

The design constraints of an engineering project are limitations which outline the direction and parameters of the system design process. It is possible for a design to address all of the design requirements but not satisfy the constraints, so it is important to consider these in the design process.

These include:

1. The engine must be manufactured for less than $1000 (excluding labour)

   The engine design and construction process must be kept in perspective for this project. Building a model jet which costs $20,000 and takes 1 year to manufacture is beyond the scope of this project. In the case of a gas turbine the extra expense will only achieve greater thermal efficiency which will not benefit the outcome of the experimental process.

2. All manufacturing process must be conducted by myself

   For the purpose of proper model analysis it was decided that all manufacturing was to be conducted using no machining processes. At the time of construction such machines were not available, and getting machining professionally done would quickly exceed the project budget. Therefore all construction was done using a welder, angle grinders, and other basic tools.

3. The Combustion chamber must be designed for the turbocharger

   For this particular project a suitable turbocharger had already been sourced so the combustion chamber on this particular engine was to be built around this device. For this reason detailed turbocharger selection details will not be included but a brief overview can be seen in section 6.4.1.

Now the requirements and constraints of the design are known the design process can begin.

6.3 System Processes

The simple cycle gas turbine engine this model will be based on will have the same cycles as outlined in section 5.3. This design relies on the turbocharger to provide a compressor and turbine, and the intake, combustion chamber, and exhaust will be constructed. Each of these processes is essential to the operation of the engine, so these cycles will be used in the design analysis and final design selection process.

6.4 Conceptual Design Analysis

For this model engine the most essential part of construction is the correctly sized design of the combustion chamber for the selected turbocharger. The combustion chamber will therefore be designed, and the rest of the engine layout will be built around it.

6.4.1 Turbocharger Considerations

If the combustion chamber is to be built around the selected turbocharger then turbo selection is less important. There are several steps to take to ensure successful operation of the model engine. These are:

1. Ensuring the turbocharger is in healthy working condition by checking for chips on the compressor and turbine wheels, and feeling for axial shaft play.

2. Choosing the turbocharger for the desired engine size.

3. Ensuring the turbocharger is not out of budget.

For this particular project a Garrett GT 4082 journal bearing turbocharger was chosen for use. This turbocharger has a compressor inducer diameter of 58 mm and a high flow capacity.

This turbocharger was chosen mainly because it was available at a low cost at the time of the build, and also its large size and high flow capacity would allow a larger engine to be built. This particular turbocharger also has an internal wastegate for its intended application on a compression ignition engine on a bus. This device is used to control boost levels in these engines and will be disabled as it is of no use in an engine of this design.

6.4.2 Combustion Chamber Design

This section will look at some basic background theory of combustion chamber design specifically in the purpose and design of the combustion liner, and also measures to improve the efficiency of the system.

The combustion chamber of a gas turbine engine introduces fuel to the compressed working fluid and, ideally, achieves efficient combustion. Minimising heat and pressure loss within the combustion chamber is essential in maximising the thermal efficiency of the system.

Realistically the combustion chamber will have heat and pressure loss which will decrease the thermal efficiency of the system. As a solution the outer wall of the combustion chamber will be constructed from relatively thick material to minimise heat flow to the atmosphere.

A combustion chamber can be designed to minimise the excess air passing through the system (say around 10-20%) which would also increase the thermal efficiency of the system. Unfortunately however certain parts of the turbine cannot operate at the elevated temperatures that would be produced by operating an engine in this way.

Consequently a successful combustion chamber design must make careful allocation of a significant portion of the working fluid to the dilution and cooling of the combustion gases before they hit the turbine. This is achieved by dividing the compressed working fluid into two streams, the primary and secondary flows. The primary flow is subject to heat addition via fuel injection and ignition. The secondary flow is then progressively introduced to the primary flow lowering the outlet temperature of the combustion chamber and completing the combustion process.

For this style of jet engine the primary flow is separated from the secondary flow using a combustion liner inside the combustion chamber. This liner is around half the diameter of the outer wall of the combustion chamber and has holes drilled in it to allow only a portion of the air to mix with the fuel. More drawings and discussion of this liner will be provided later in the report.

For engines of this design the combustion chambers have been found to be much larger diameter than the size of the turbine inlet on the exhaust housing of the chosen turbocharger. For this reason there will have to be a transition area to force the mixed post combustion working fluid into the entrance of the turbine. This transition area must be carefully designed to minimise head loss from sharp orifice like pathways for the working fluid. The combustion chamber will be gradually reduced in diameter at an angle of no greater than 20 degrees measured from the axis of the combustion chamber.

6.4.3 Combustion Chamber Sizing

As mentioned previously the sizing of the combustion chamber to the turbocharger is essential. If the combustion chamber is too small the engine will have a low thermal efficiency and may not reach full throttle because of flow restrictions. If the combustion chamber is too large the working fluid velocity may not be high enough to attain proper combustion and the engine may overheat and prematurely suffer turbine failure.

The essential measurement for combustion chamber sizing is the inducer diameter which was previously stated as 58mm. As this is expected to be the smallest area through which all the working fluid must pass it is essential that no part of the system have a smaller diameter than this. The combustion chamber construction will also be heavily dictated by the available material and construction constraints such as access for welding and minimising heat loss in heat affected areas.

In the design process of the finalised combustion chamber the GR1 combustor formula attached in appendix D was used as a rough guide to pipe sizes. This formula was found in the research process and has been written by the website author Don Giandomenico after many projects similar to the one proposed in this report. It was decided that this formula would give an appropriately accurate component sizing guide for the context of this report.

6.4.4 Combustion Chamber Pipe Work Layout

This section will analyse the purpose and requirements of the pipe work carrying the compressed working fluid from the compressor outlet to the intake of the combustion chamber. Ideally these engines will have minimal pipe work between the heat addition process and the turbine to minimise frictional losses of the high speed gases. For this reason most combustion chambers in engines of this simple cycle design are bolted directly to the turbochargers turbine. The pipe work then provides the link between the compressor outlet and the top of the combustion chamber which sits perpendicular to the turbocharger shaft.

As stated above the smallest diameter allowed for primary pipe work is 58mm so all pipe work will be a minimum of 2.5 inch (63.5mm) diameter.

The pipe work would therefore start at the compressor outlet and be welded into the top of the combustion chamber. In order to increase symmetry and efficiency of the fuel mixing and post combustion cooling the intake pipe would be split, and feed into the top of the combustion chamber on opposite sides. This will decrease ‘cold spots’ in the combustion chamber where effective mixing does not occur and combustion is incomplete of non-existent. The pipes will also be set into the combustion chamber with an offset to create a whirlpool swirling like effect of the gases within the combustion chamber.

6.4.5 Combustion Liner Design

The combustion chamber liner is an essential component to the success of a gas turbine engine design. The purpose and reasoning behind this has been covered in section (6.4.2.). This section of the report will cover the sizing of the liner, and also the size and placement of the holes allowing the separation of the primary working fluid flow.

A successful combustion chamber liner must:

1. Contain all fuel injection and ignition components
2. Separate the working fluid into primary flow and secondary flow
3. Achieve an approximate 1:4 primary to secondary flow ratio
4. Successfully mix the secondary with the primary flow post combustion

Achieving these criteria means there are several essential aspects of design which must be accurate to the criteria. The combustion liner must have an appropriate diameter such that there is sufficient room for a fuel injector and spark plug in the top, there is sufficient room for successful and non-restricted combustion to take place, and there is sufficient room for the secondary flow to bypass the liner and mix with the primary flow post combustion.

Primary and secondary fluid flow separation is achieved by creating an area for the primary fluid flow to enter the combustion liner. This is nominally achieved by drilling evenly spaced holes in the liner. The number and size of the holes is carefully controlled to ensure their total area is 20% of the compressor inducer area.

The total inducer area is $A_i = \pi \times (d_i/2)^2$

$$A_i = \pi \times (58/2)^2$$

$$A_i = 2642.08 \text{ mm}^2$$

Assuming constant working fluid velocity (V_1), the volumetric flow rate (Q_1) is related directly to the area (A_1) through

$$Q_1 = V_1 A_1$$

The actual working fluid velocity however will be significantly less than that at the inducer. This is because the area which the working fluid has to flow through increases significantly upon entrance to the combustion chamber. Estimating the total combustion liner hole area (A_B) of around 20% of the inducer area will therefore suffice. Combustion chamber testing will ensure successful separation of primary and secondary flow of the ratio and complete combustion is occurring before the gases are exposed to the turbine.

$$A_B = 528.42 \text{ mm}^2$$

These approximate dimensions have also been taken from the GR1 combustor formula talked about in chapter 6.4.3 and shown in appendix D.

6.4.6 Afterburner design

For an afterburner to successfully work on an engine of this design it must make a seal around the exhaust outlet from the turbocharger and allow the exhaust velocity to slow slightly. This is done by increasing the flow area (or pipe/duct diameter) and introducing fuel through a secondary injector which combusts utilising the remaining oxygen from the secondary flow within the combustion chamber. The flow must then be restricted post combustion to increase the velocity of the working fluid.

6.5 Materials Selection

Given all the above design parameters and the available material at the time of construction the following materials have been selected for the combustion chamber:

- Primary combustion chamber shell – It has been discussed that the combustion chamber will have a thick primary shell to minimise the heat energy losses to the surrounding environment before the turbine. Because of this 5 inch (127 mm) thick walled mild steel pipe was chosen for its availability and heat retention capability.

- Combustion liner - No information was available at the time of construction on the sizing of the combustion liner however many pictures were available on existing combustion liners. The available material was assessed and 3 inch (76.2 mm) thin walled mild steel exhaust pipe was chosen. With a liner this size there would be adequate room to drill holes for separating the primary and secondary flow, and also for the secondary flow to bypass the liner and mix with the primary flow before the turbine.

- Pipe work – As stated earlier all pipe work will be 2.5 inch (63.5 mm) diameter to avoid flow restriction to the compressed working fluid. All pipe work within 200mm of the combustion chamber will be 2.5 inch thick walled steel steam pipe bends to aid in the construction of the bends, for ease of welding, and also for heat retention. All other pipe work will be thin walled mandrel bent exhaust pipe.

6.6 3-D Prototype creation and analysis

The next step in the design and construction process was to make a 3-D model of the proposed combustion chamber design. Solidworks was chosen as the preferred drawing suite due to previous experience using the program, and also the ability to complete CFD analysis on the finalised model. The completed 3-D model is shown below.

Figure 6.1: The completed pre-construction 3-D model of the combustion chamber.

This model then had boundary conditions applied to it and solved for working fluid velocity and pressure distribution (no heat is added in the model so the velocities and pressures post combustion will be inaccurate). The boundary conditions were set at a uniform velocity of 100m/sec in the inlet and atmospheric pressure at the outlet. The results are as follows:

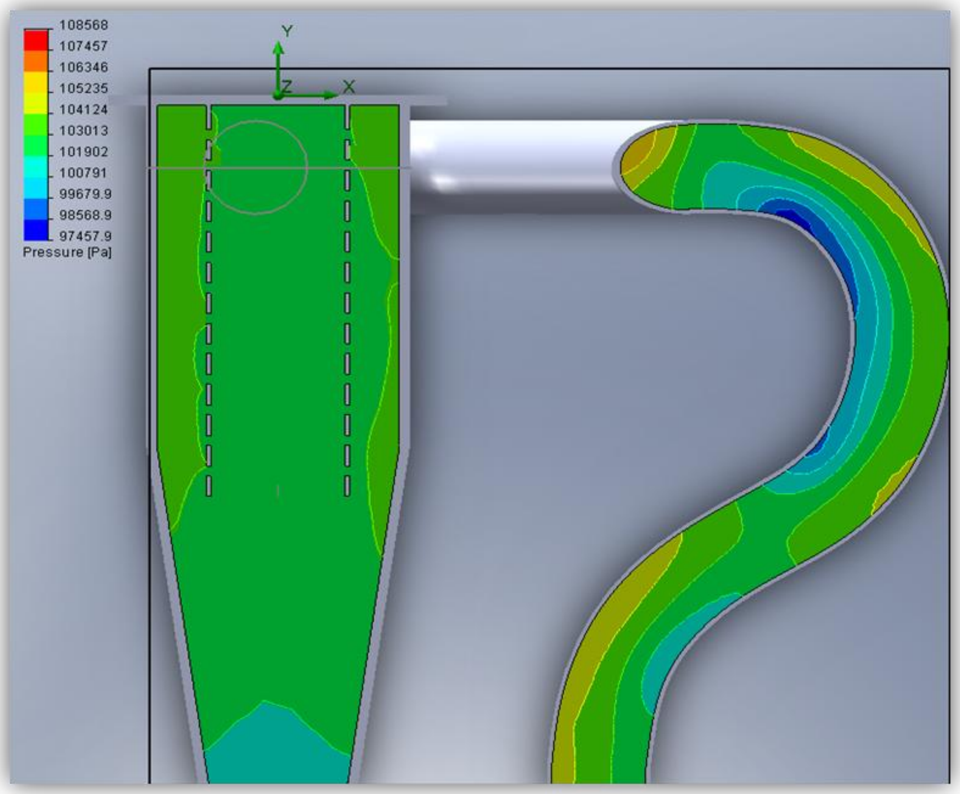

Figure 6.2: Pressure distribution within the 3-D model

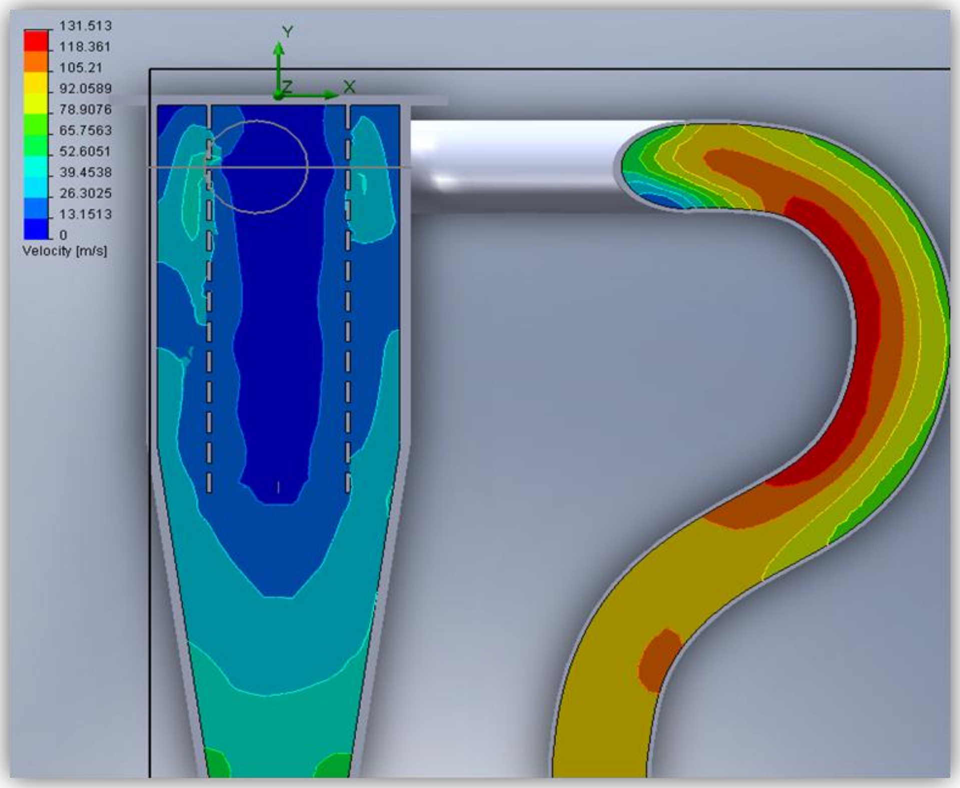

Figure 6.3: Velocity distribution within the 3-D model

These plots, especially the velocity, show how effective the combustion liner is separating the flow of gases by minimising the velocity within the combustion liner. A majority of the flow bypasses the combustion liner and effectively mixes with the primary flow post combustion. No obvious flow restrictions or high pressure points exist so model construction can begin.

6.7 Cutting List

Based on the above materials, construction of the combustion chamber could begin. The following table is a list of materials used in this process.

Table 6.1: Initial costing of the combustion chamber construction

Component	Material	Length/quantity	Source	Cost
Main Shell	5 inch MS pipe	350 mm	Off cut from steel supplies	\$5.00
Liner	3 inch MS exhaust pipe	230 mm	Exhaust shop	\$10.00
Pipe Bends	2.5 inch 90° steam pipe bends	6	Steel supplies	\$6.95 each
Thin Walled Pipe	2.5 inch exhaust pipe	600 mm	Exhaust shop	\$15.00
Chamber Cap	6mm MS plate	85 mm radius circle	Supplied	\$0.00
Bolts	M8x35mm Zinc plated	8	Bolt shop	\$15.95
Fuel Injector	Modified countersunk brass orifice	1	Hose supplies	\$1.95
Spark Plug	NGK B8S	1	Automotive shop	\$4.95
Welding Materials	Welding gas, wire, shield, glove	-	Supplied	\$0.00
Angle Grinders	5 and 9 inch grinders with grinding, cutting, and flap disc wheels to suit	-	Supplied	\$0.00
Oxy-acetylene Torch	Oxygen, acetylene, wand, glasses	-	Supplied	\$0.00
Paint	High temperature enamel in a can	1	Paint store	\$14.95

From this table it can be seen that the total construction cost (not including labour) of the combustion chamber is \$94.50. As planned the construction process on the rest of the jet can now be costed.

Table 6.2: Initial costing of the complete model construction

Component	Material/Specification	Length/Quantity	Source	Cost
Combustion chamber	MS	1	Previously analysed	$94.50
Frame	MS 25x50mm RHS, and 50x5mm flat	4x700mm, 12x700mm	Steel shop	$36.50 $44.50
Turbocharger	-	1	Supplied	$0.00
Oil pump	Procon P/No. 630177 150 Lt/h built in regulator	1	Pump shop	$220.00
Oil pump engine	-	1	Electrical shop	$37.50
Oil pump bracket	Alloy	1	USQ machine shop	USQ project budget allocation
Oil lines	Reinforced rubber	4m 3/8 inch, 1m 7/8 inch	Hose supplies	$5.95/m $8.95/m
Coil and points	-	1	Automotive shop	$76.95 total
Exhaust/afterburner	MS	800mm 6 inch, 2 x 4 to 6 inch adaptor, 1 x 4 to 3 inch adaptor	Truck exhaust shop	$51.85 total
Intake	MS	400mm 4inch	Truck exhaust shop	$10.00
Hoses and clamps	Reinforced silicone/rubber and stainless steel	1 4inch x 50 mm, 1 2.5inch x 50mm, 2 x 4 inch clamps, 2 x 2.5 inch clamps, 2 x 7/8 inch clamps, 18 x 3/8 inch clamps	Hose supplies	$84.65 total
Oil pressure gauge	-	1	Supplied	$0.00
Boost pressure gauge	-	1	Supplied	$0.00
Deep cycle 105 Ah battery	Lead acid	1	Automotive shop	$180.00
Wires	Insulated copper	1	Electrical shop	$61.95 total
Oil cooler	-	1	Supplied	$0.00
Thermo fan	-	1	supplied	$0.00
Welding Materials	Welding gas, wire, shield, glove	-	Supplied	$0.00
Angle Grinders	5 and 9 inch grinders with grinding, cutting, and flap disc wheels to suit	-	Supplied	$0.00
Paint	Gloss black enamel can	3	Paint store	$11.85 total

From this table it can be seen that the total construction cost (not including labour) of the model jet is $943.00. This falls within the specified budget and so is deemed a successful construction plan.

Table 6.3: Initial experimental apparatus cost

Component	Length/quantity	Source	Cost
9kg LPG gas bottle	1	BBQ supplies	$39.95
Garden leaf blower	1	supplied	$0

It can be seen from the above tables that the construction process has been costed within the prescribed budget so construction can now begin.

6.8 2-D Prototype Engineering Construction Drawings

Engineering construction drawings were now produced to aid in the construction of both the combustion chamber and the combustion liner (see appendix E).

6.9 Construction

This section of the report will go through the steps taken in the construction process. These steps are as follows:

1. Gather all specified construction materials

2. Construct combustion chamber including combustion liner, fuel injector, and spark plug

3. Attach combustion chamber to the turbocharger

4. Build an appropriately dimensioned frame (exact dimensions unimportant)

5. Build mounts on the frame for the turbocharger and the combustion chamber

6. Install jet onto frame

7. Construct exhaust and afterburner and attach

8. Install oil system including pump, motor, cooler, thermo fan, and lines

9. Add a dash panel and install all gauges

10. Complete all wiring and install battery

11. Touch up all painted surfaces

Each step will now be explained in further detail as to the method used

Step 1: *Gather all specified construction materials*

The first step in the construction process was to gather all specified construction materials in the above tables for ease of work once construction had begun. Fortunately all materials were sourced from local suppliers so this process was relatively easy, and was complete within a day.

Step 2: *Construct combustion chamber including combustion liner, fuel injector, and spark plug*

It was decided earlier in this chapter that the most crucial component to the success of the engine, the combustion chamber, would be constructed first with all proceeding pieces fabricated to work in conjunction with it.

The first step in this process was to modify the lower half of the 5 inch pipe such that it converges to a square outlet the same size as the turbine inlet on the turbocharger (73 x 50 mm). To do this, 4 wedges were cut axially along opposing sides of the pipe, and the pipe was worked into the desired shape using a 12 pound sledge hammer. This was the seam welded, ground off, and buffed with a flap disc. The combustion liner was then cut to a length such that there was adequate bypass area for the secondary flow between the liner and the shell. The liner was then welded to the cap and bolted to the top of the pipe forming a removable lid in the combustion chamber. The pipe work was tacked into place to match the 3D model and fully welded. All welds were then cleaned with a 5 inch grinder and flap disc, and the whole assembly was painted to avoid corrosion.

Figure 6.4: Side view of the completed combustion chamber

Figure 6.5: Top view of the completed combustion chamber

Figure 6.6: Side view of the completed combustion liner

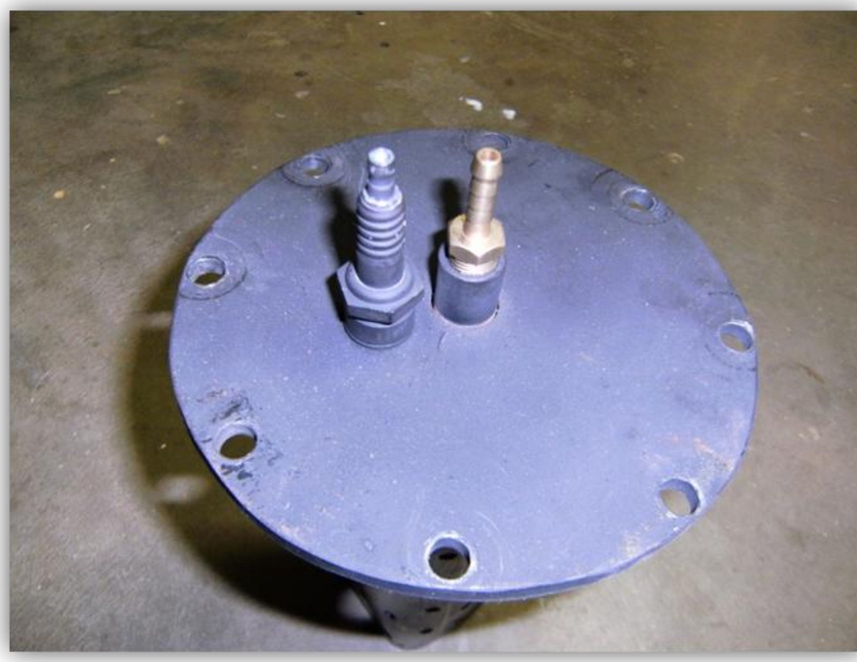

Figure 6.7: Top view of the completed combustion liner with fuel and spark inlet

Step 3: *Attach combustion chamber to the turbocharger*

The combustion chamber was then bolted to the turbocharger.

Step 4: *Build an appropriately dimensioned frame (exact dimensions unimportant)*

It was now time to build an appropriately dimensioned frame to house the jet and all associated components for operation (excluding the LPG bottle). When considering the layout of the components an important factor is the position of perishable components or flammable liquids in relation to hot surfaces. For this reason it was decided to mount the jet horizontally on top of a rectangular frame. This would also help with the oil drain of the turbocharger which needs to freely drain away. A frame was therefore constructed from available 25 x 50 RHS and 50 x 6 flat bar to appropriate dimensions for the application.

Step 5: *Build mounts on the frame for the turbocharger and the combustion chamber*

Mounts on the completed frame were then constructed to safely mount the turbocharger and combustion chamber assembly perpendicular on top of the frame. Mounting points on both the turbocharger and the top of the combustion chamber were used for a secure attachment due to potential forces exerted on them during moving and operation.

Step 6: *Install jet onto frame*

Once all welding and grinding was complete the frame received a coal of gloss black enamel and the jet was installed for the last time.

Step 7: *Construct exhaust and afterburner and attach*

All materials for the afterburner were sourced from a truck exhaust shop specialising in large diameter thin walled mild steel exhaust pipe and reducers. Construction was started with an adaptor fitting which clamped to the turbocharger exhaust outlet. This adaptor was the attached to the length of 6 inch exhaust pipe using a reducer. Two reducers were then welded on the end of the afterburner to reduce the pipe outlet size to 3 inch. A fuel injector was then made from steel brake line and welded through a hole created just after the turbine.

Figure 6.8: Side view of completed afterburner

Figure 6.9: Top view of the completed afterburner showing secondary fuel injection

Step 8: *Install oil system including pump, motor, cooler, thermo fan, and lines*

The oil system is a crucial component of the successful and reliable operation of the turbocharger. The chosen oil pump was a rotary vane pump with inbuilt and adjustable pressure regulator (see appendix B for full specifications). This pump was mounted on a custom fabricated bracket and powered by a 12 V electric motor via a belt drive. This system was installed along with the drain line from the turbocharger, intake line, filter, and appropriate connection for the oil gauge line.

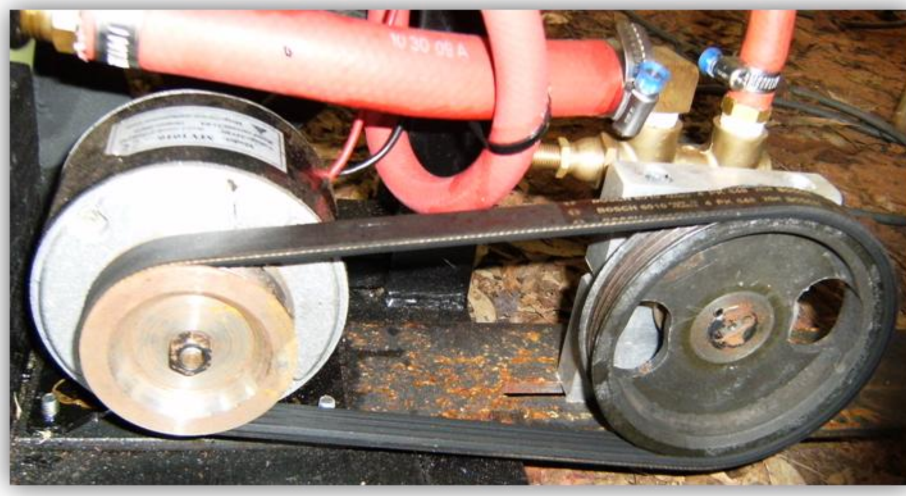

Figure 6.10: Belt driven oil pump apparatus

Step 9: *Add a dash panel and install all gauges*

A simple dash panel was created from some scrap aluminium checker plate in which gauges and switches would be mounted within. The switches installed would control the power to the oil pump, and also power to the thermo fan mounted on the oil cooler. The gauges installed include oil intake pressure, combustion chamber pressure, and exhaust temperature.

Figure 6.11: Dash with installed control switches and gauges

Step 10: *Complete all wiring and install battery*

All wiring was now to be completed including installing the ignition system. The chassis of the engine was grounded directly to the negative terminal of the battery and all positive power lines were wired through switches if appropriate. The ignition coil was secured in a non heat-affected area using cable ties and the lead was run to the spark plug.

Step 11: *Touch up all painted surfaces*

Once all construction was completed all painted surfaces were touched up, wiring was secured with cable ties, and the model was ready to run.

Figure 6.12: Completed model apparatus ready for testing

6.10 Conclusion

The design and construction has been an initial success with the model being complete on time and within budget. Upon initial inspection the engine seems to adhere to the specified design requirements and constraints however a full design appraisal for this model will be conducted after the end of the testing in chapter 7.

Chapter 7 – Small Engine Performance

7.1 Introduction

As stated in section 1.3, the second aim of this project was to develop a small scale gas turbine engine which will be used to attain experimental data to aid in making conclusions about CSG as an alternative fuel. The previous chapter has extensively covered the construction process, so this chapter will cover the experimental testing process and provide attained test data, and basic calculations.

7.2 Aims and Objectives

The aims of an engineering experimental test procedure have both general aspects, and also project related aspects. The general aspects include:

- Be conscious of risks as outlined in the risk assessment (appendix A)
- Complete all activities with respect to the environment
- Act in an ethical and professional manner
- Ensure all results are as accurate as possible to what is occurring

Some more specific aims are:

- Attain all desired results

- Maintain a constant watch on engine vitals including oil pressure and especially exhaust temperature to minimise risk of a catastrophic failure

- Ensure test apparatus does not allow the fuel supply to come in contact with heat

These experimental aims are important considerations when planning the test apparatus and procedure to ensure the completion of the experiment safely and successfully.

7.3 *Test Apparatus*

With these aims in mind an experimental apparatus can be designed such that all experimental aims, specifically safety, are fulfilled by the experimental procedure. Given the nature of this type of engine safety of all operators and on-lookers will be the first priority. With this in mind the following points must be adhered to:

- All flammable substances including lubricating oil and fuel must be kept as far away as practically possible from all heat and ignition sources

- All persons must stay out of an exclusion zone in the exhaust stream and a 45 degree tangent from it (see below diagram)

- All on-lookers must stay at least 10 metres away from the operating engine in all other directions (see below diagram)

- Only essential persons are allowed within these exclusion zones and these people must wear personal protection equipment

There are several measures taken to ensure the above points are implemented. An appropriate exclusion zone is outlined. No one including the operators are allowed in the exhaust exclusion zone due to the risk of flying debris, and only essential operators including the starter in the start procedure, and the fuel flow control and engine vital monitoring person are allowed in this area. The fuel supply (an LPG bottle) is kept away from all heat and ignition sources by a 2 metre long supply line (see below diagram).

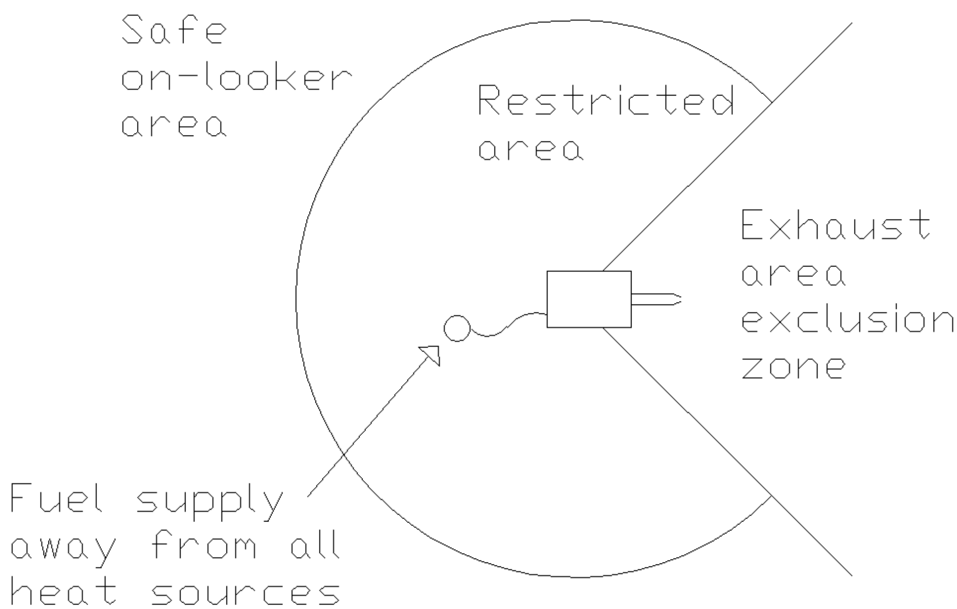

Figure 7.1: Test apparatus.

To address the more specific experimental aims outlined in the previous chapter the exhaust temperature will be monitored with a thermocouple temperature meter capable of reading very high temperatures (an EMTEK EMT-502 provided by the USQ Faculty of Engineering). The combustion chamber pressure and lubricating oil pressure will be monitored with an automotive boost gauge mounted on the dash panel of the model engine. The fuel supply (LPG bottle) will also be mounted on electronic scales to compare the change in mass with time. This will provide a fuel mass flow rate which will be useful in future calculations.

7.4 Test Procedure

On the day of the experiment the following plan was outlined for the experimental procedure to ensure the safety and success of the procedure:

1. Decide on an appropriate location to test the apparatus.

2. Carefully transport all test apparatus and associated components to the chosen location.

3. Set up the engine in an orientation such that the exhaust fumes and smoke will not affect any of the surrounding structures of wildlife.

4. Outline specified exclusion zones with orange safety cones.

5. Set up electronic scales in a location on the intake side of the engine and at a distance such that the length of the fuel feed line will be fully utilised.

6. Sit LPG bottle onto scales and connect to the fuel line.

7. Have a discussion with all operators and on-lookers to ensure there is a clear understanding of the exclusion zones, and plan the sequence of starting events with the starter.

8. Connect the battery.

9. Turn on the oil pump and monitor the rise and stabilisation of oil pressure to the turbocharger.

10. Have the starter start the leaf blower and align with the engine intake.

11. Apply full power to the leaf blower, turn on fuel slowly whilst pressing the ignition button repeatedly and wait to hear a ‘pop’ sound which signifies the start of the combustion process.

12. With the leaf blower still attached and on full power, slowly increase the supply of the fuel and listen to the engine turbine speed which will sound like a high pitched whine.

13. Throttle the engine up to a point where the leaf blower is no longer needed (the starter will know this because the leaf blower engine revs will increase as the turbine sucks air through the device and takes load off the engine).

14. Remove the leaf blower and adjust fuel supply to maintain a steady idle speed.

15. Take a reading of the mass of the LPG bottle and start the stopwatch.

16. Run the engine for the desired period of time (60 seconds was appropriate on this test day) and then take another reading of the LPG cylinder mass.

17. The fuel mass flow rate will be the change of mass divided by the time taken.

18. Repeat this fuel measuring procedure for a variety of throttle settings including full throttle and record all data.

19. Ensure exhaust temperature and oil pressure is monitored throughout the entire test and shut the engine down immediately if these readings fall above or below pre-specified thresholds.

20. Once all tests are complete shut the fuel supply down to the engine to stop the combustion process.

21. Keep the oil pump running for several minutes after shut down to help cool the turbocharger bearings.

22. After this time turn the oil pump off, disconnect the battery and LPG cylinder and pack all test apparatus away being very careful of hot surfaces.

Following these procedures, actioning the risk assessments and utilising common sense would increase the chance of a successful and safe experiment. These points were adhered to on an initial test day and the outcomes of this day are outlined below.

7.5 Results

On the day of the experiment the above procedure was followed and the results recorded at the lowest throttle setting required to maintain operation.

The data recorded is as follows:

- The LPG mass changed from 16.3 kg to 15.5 kg in 8 minutes of total operation
- The surrounding temperature on the day was 15°C
- The average exhaust temperature was 530°C
- The average combustor pressure was 3.75 psi

As discussed in the previous chapter results from a variety of throttle settings were required however premature turbine failure due to a lack of oil supply resulted in the test being incomplete (see section 7.7 for further analysis). Despite this unfortunate failure, analysis on the recorded data can still be conducted.

The process of analysis of a gas turbine engine assumes steady flow of the working fluid (air) during each of the operating cycles. The gas turbine relies on energy addition to the working fluid by an external source (fuel) and other variables are also assumed constant or are neglected such as pressure loss in the combustor, and change of working fluid specific heat between compression and exhaust.

7.6 *Thermal Efficiency Calculation*

From the experimental data the change in internal energy (U) could be found from reducing the steady state flow energy equation.

The Steady State Energy Equation is given by:

$$\dot{Q} - \dot{W} + \dot{m}_1\left(\frac{{U_1}^2}{2g} + Z_1 + h_1\right) - \dot{m}_2\left(\frac{{U_2}^2}{2g} + Z_1 + h_2\right) = \Delta E_s$$

Because there is no input heat energy (Q), or input work (W) then these values are zero. Also there is no change in mass flow rate (m), or potential energy (Z) from the intake to the exhaust of the engine so these values can be neglected. There is also no input energy to the system (U_1) so this value is zero. The Steady State Energy Equation is reduced to:

$$h_1 = \frac{{U_2}^2}{2g} + h_2$$

$$C_{pair}T_{\infty} = \frac{{U_2}^2}{2g} + C_{pair}T_{out}$$

$$T_{\infty} = \frac{{U_2}^2}{2C_{pair}} + T_{out}$$

Where

- $\dot{Q}$ = Input heat energy (Joules)
- $\dot{W}$ = Input work (Joules)
- $\dot{m}$ = Mass flow rate of the working fluid (kg/sec)
- U_1 = Input energy to the system (Joules)
- U_2 = Output energy of the system (Joules)
- Z_1 = Input potential energy to the system (Joules)
- Z_2 = Output potential energy of the system (Joules)
- h_1 = Input enthalpy to the system (Joules)
- h_2 = Output enthalpy of the system (Joules)
- g = Gravitational acceleration (m/sec^2)
- C_{pair} = Specific Heat (J/kg.K)

- T_∞ = Surrounding outside air temperature (°C)

- T_{out} = Exhaust outlet temperature (°C)

To find output energy (U_2) the inlet and outlet temperature (T_∞ and T_{out} respectively) of the running engine was required. The surrounding temperature (T_∞) was taken with a thermometer and a thermocouple attached to an EMTEK EMT-502 receiver was placed in the exhaust stream to find the T_{out}.

Therefore:

$T_\infty = 15\ ^oC$

$T_{out} = 530\ ^oC$

$\dot{M}$ = 0.8 kg in 8 mins

= 1.67×10^{-3} kg/sec

C_{pair} is sourced from Principles of Heat Transfer[11] in table A26. It is read as 1012 J/kg.K at 20^oC and 1076 J/kg.K at 500^oC. Because these values are different an average will be taken.

$$15 = \frac{{U_2}^2}{2\left(\frac{1012 + 1076}{2}\right)} + 530$$

$$U_2 = 1036.98 \text{ Joules}$$

(note the absolute value of U_2 is used when taking the square root)

It can be said the system work (W) is the change in energy of the system.

Therefore

$$W = \Delta U$$

We know

$$U_1 = 0$$

So

$$W = U_2 = 1036.98 \text{ Joules}$$

We know thermal efficiency is the ratio of work output over heat energy within the supplied fuel[13]. This efficiency shows the amount of energy contained in the consumed fuel that is actually converted to power. This efficiency is expected to be quite low due to the nature of the engine however the results will still be useful to get a comparative CSG fuel consumption.

Therefore

$$\eta_t = \frac{W}{Q_{in}} = \frac{W}{\dot{m_{fuel}} \times LCV}$$

Where

- LCV = Lower Calorific Value (J/kg)
- W = System work (Joules)
- Q_{in} = Input heat energy (Joules)

The LCV of LPG has been found as 45.8 x 10^6 J/kg [12]

Therefore

$$\eta_t = \frac{1036.98}{(1.67 \times 10^{-3}) \times (45.8 \times 10^{6})}$$

$$\eta_t = 0.01356$$

$$\eta_t = 1.356\ \%$$

From this stage the comparative CSG fuel consumption can be calculated assuming similar burn characteristics and similar thermal efficiency.

We know

$$Q_{in} = \dot{m}_{fuel} \times LCV$$

$$\dot{m}_{fuel} = \frac{Q_{in}}{LCV}$$

The LCV of CSG has been found as 38.7 x 10^6 J/kg [12]

$$\dot{m}_{fuel} = \frac{76486}{38.7 \times 10^{6}}$$

$$\dot{m}_{fuel} = 1.98 \times 10^{-3} \text{ kg/sec}$$

For comparative purposes this mass flow rate equates to 0.9504 kg of fuel in 8 minutes compared to the 0.8 kg of LPG in the same time. This figure is an increase of 18.8 % fuel consumption compared to LPG.

This comparison of fuel consumption by mass is of limited use in the analysis of CSG. This figure must be converted to volumetric fuel consumption to be of any use.

The density of LPG is 1.882 kg/m^3, and CSG is 0.8 kg/m^3 [15].

$$\dot{M} = \rho \times Q$$

$$\frac{\dot{M}}{Q} = \rho$$

$$\frac{1}{Q} = \frac{\rho}{\dot{M}}$$

$$Q = \frac{\dot{M}}{\rho}$$

Where

- Q = Volumetric flow rate (m^3/sec)
- $\dot{M}$ = Mass flow rate (kg/sec)
- ρ = Gas density (kg/m^3)

Therefore the volumetric flow rate (Q) of each fuel is found to be:

$$Q_{LPG} = 8.86 \times 10^{-4} \frac{m^3}{sec} = 3.19 \frac{m^3}{hour}$$

$$Q_{CSG} = 2.48 \times 10^{-3} \frac{m^3}{sec} = 8.93 \frac{m^3}{hour}$$

These volumetric flow rates will be summarised later in the chapter.

From table 3.2 it can be seen that 1000L (ie. 1 m^3) of CNG costs $93.00 compared to $620.00 for 1000L of LPG. That makes the running cost of the engine $1977.80 /hour on LPG and $830.49 /hour on CNG. It can therefore be concluded that the running costs of a CNG powered engine would be 41.9% that of an LPG engine (a 58.1% saving).

7.7 Design Appraisal and Discussion of Turbine Failure

The first step of the design analysis stage was to set requirements and constraints to dictate the direction of the model construction stage of the project.

The design requirements were:

1. The engine must operate reliably enough to attain the desired results

2. The engine must be compact and portable

3. All manufacturing process must be conducted by myself

The design constraints were:

1. The engine must be manufactured for less than $1000 (excluding labour)

2. There must be built in safety systems to reduce risk

3. The Combustion chamber must be designed for the turbocharger

The success of this design will be how well it reflects these design requirements and constraints. If the design does not satisfy one or more of these criteria then the design process has partially failed and the process must be reflected to assess when the error occurred.

The first design requirement, reliability, is an important factor of the finished model. Despite this upon initial testing of the model engine unfortunately the turbocharger has suffered a premature failure of the exhaust wheel and bearing (see below pictures). This failure has been traced to a leaking oil seal in the turbocharger which caused abnormally high lubricating oil consumption. This eventually used the 2L of oil in the reservoir and while the engine was operating the oil pump ran dry. Lubricating oil is essentially important for the bearings of a turbocharger so this failure caused significant wear on the bearing which allowed slight play in the shaft causing the exhaust wheel to come into contact with the exhaust housing damaging it. This failure was caused by two factors. The first was the defective seals in the turbocharger, and the second was the lack of oil level monitoring built into the design. It was assumed that if the oil level was checked between every run then a monitoring system was not needed. This turned out to be un-true and the failure of the system is partially a result of that.

Figure 7.2: Close up of turbocharger turbine wheel pre-failure

Figure 7.3: Close up of turbocharger turbine wheel post-failure (note chips on blade edges)

The second requirement, compactness and portability, was deemed important for storage and transportation reasons. This was achieved well in the design process. The frame is large and heavy enough to resist movement at full engine throttle but compact enough to be moved by one person easily.

The third and final requirement, all manufacturing work to be completed by myself, was also completed successfully with the exception of one piece. All welding and construction of the frame and combustion chamber, the wiring, and the plumbing was completed by myself as per the requirements. The oil pump bracket however was manufactured by the USQ machine shop. During the construction process it was decided that the accuracy of the belt drive and pump mount was essential for the stability of the oil supply. This could be done under the project budget allocation from the university and so would not affect the project budget. Despite this action being against one of the design requirements it was well worthwhile upon reflection.

The first specified design constraint was the model had to be manufactured for less than $1000. As specified in the costing and cutting lists earlier in this chapter the construction process was completed within this budget so the construction process was a success in relation to this point.

The second specified restraint was the inclusion of safety systems to minimise the risk to the operator and by standers during engine operation. Because of this an exhaust temperature monitoring device was installed to monitor the temperature of the exhaust. If the temperature rose beyond a pre-determined threshold the engine would be shut down to reduce the risk of premature failure. The lack of oil monitoring causing the previously discussed failure will be considered a safety failure due to the obvious safety concerns if the turbine was to fail at full throttle.

In summary, most design requirements and restraints were achieved successfully. An exception to this was the lack of lubrication oil level monitoring which partially contributed to a premature turbine failure and was therefore considered a safety risk. Another exception was the oil pump bracket which was manufactured by the USQ machine shop against one of the design requirements. This was however an important decision which did not affect any other requirements including the project budget. Because of this it will not be considered a failure in the design and construction process.

7.8 Conclusion

The testing procedure for the model set out to cover the experimental testing process and provide attained test data, and basic calculations.

The test apparatus was designed in such a way as to minimise risk to experimental operators and on-lookers by thinking about the possible causes of failure, and taking precautionary measures to minimise the risk of these occurring. In the design of the exclusion and restriction zones outlined in figure 7.1, the potential dangers to operators and on-lookers was also predicted and danger areas were outlined as a result of this. All activities were also conducted in a professional and ethical manner, and also with respect to the environment.

The experiment was carried out according to the test procedure outlined in section 7.3. During this experiment the engine was started and all measurements taken for one throttle setting. Once this period was over the oil pressure of the lubricating oil was observed to be rapidly dropping. The engine was promptly shut down however permanent damage to the turbocharger has occurred as a result of this. The turbine failure was as a result of excessively high oil consumption in the final minutes of operation most likely due to failed oil seals within the turbocharger.

It was also concluded that the final model engine design did not have an oil level monitoring system built in which would have allowed the operator to monitor the oil level and potentially shut the engine down before failure. This failure has resulted in the model and testing procedure failing to meet some of the outlined requirements.

When conducting the design of the model a design requirement was that 'The engine must operate reliably enough to attain the desired results'. These required results were at a variety of throttle settings which was not fulfilled by the testing procedure. An aim of the testing procedure was also to 'Attain the desired results' which was also not completed. Despite this, future work on this model can repair the turbocharger and conduct further tests to attain the initially desired results.

From the obtained results however initial analysis of the data was conducted resulting in some very interesting conclusions. The thermal efficiency of the model engine was calculated to be 1.356 %. This figure is, despite appearances, a very acceptable figure for a home built model engine. Despite the relatively low thermal efficiency the calculations using results produced by this engine will still provide an accurate indication of the relative CSG fuel consumption and running cost.

The equivalent fuel consumption of CSG was then calculated, and both mass flow rate fuel consumptions were converted to volumetric fuel consumptions using the gas densities. Using table 3.2 it was observed that from the possessed data 1000L (ie. 1 m^3) of CNG costs $93.00 compared to $620.00 for 1000L of LPG. The running cost of the engine was then calculated to be $1977.80 /hour on LPG and $830.49 /hour on CNG.

These results produced a running cost saving of 58.1% for CNG over LPG. This result is an excellent conclusion for the case of CNG as an alternative fuel. 58.1% is a significant margin for saving and would produce significant saving in electricity which could be passed on to the consumer.

It must be said however that gas turbine based electricity generation plants do not commonly operate on LPG and ideally a comparison of CSG running costs to Jet A1 (a common petroleum based jet fuel), or kerosene would be conducted. It was however concluded that the evaporation and injection system required for a liquid fuelled gas turbine would dramatically affect the performance so it would not be accurate to compare these fuels to LPG in the way that CSG has been compared with LPG. This is maybe an excellent place for future work to be conducted on this project.

Chapter 8 – Project Conclusion

8.1 Introduction

This section of the report aims to conclude the findings of the work completed in this project, reflect on what objectives were outlined for this project and how effective the work has been in achieving these objectives, and outline any future work to be completed for this project.

8.2 Summary

This project essentially had two essential facets both aimed at assessing Coal Seam Gas (CSG) as an alternative fuel for power generation using gas turbine based co-generation plants. The first facet of this project was aimed at finding out what CSG is, where it comes from, and also what distribution infrastructure existed. The second facet was to develop a test engine from which experimental results could be attained to aid in the overall conclusion of the suitability of CSG as an alternative fuel.

Research into background information relating to CSG found it is a naturally occurring methane rich gas which is stored in the molecular structure of underground coal seams. It was formed as organic matter sitting underground has been transformed to coal over long periods of time and under very high pressures. CSG was once considered a hazard and hindrance to coal miners, however with the change in attitude toward energy sources over time it is now considered a valuable resource.

This research also concluded that natural gas at atmospheric pressure and temperature has very low volumetric energy density and so would be un-economical to transport and store. Because of this natural gas must be stored at very high pressure as Compressed

Natural Gas (CNG) or at very low temperature as Liquefied Natural Gas (LNG). Even when natural gas is converted to CNG or LNG it still has relatively low energy density compared to conventional fossil fuels so energy density continues to be a major drawback of the technology. Because of these issues natural gas is mostly transported via piped networks which are very expensive and difficult to construct.

Natural gas poses as an excellent fuel source for combustion engines due to several reasons. It has been documented that, compared to conventionally fuelled engines, natural gas engines have lower exhaust emissions of carbon monoxide, reactive hydrocarbons, and particulates. This is because natural gas has a very high octane number of around 130 which allows for high compression and lean-burn technology to be used on conventional engines. Natural gas engines however suffer from high NOx emissions mostly containing partially reacted fuel, nitrous oxide, nitrogen dioxide, and sulphur oxides. High NOx emissions can be dealt with using Exhaust Gas Recycling (EGR)), lean burn operation, development in fuel mixing and stoichiometric control technology, and a typical three way catalyst in a combination closed loop exhaust oxygen level feedback.

Natural gas safety is a very important factor, and it has been documented that no burn accidents, other injuries, or fatalities have occurred in America as a result of natural gas despite more than 500 million miles of natural gas vehicle operation. This is because of two main reasons: NG is lighter than air so it dissipates quickly in the event of an accidental spillage, and its ignition point, 1200°F, is much higher than that of gasoline, 600°F.

The analysis of the CSG industry was deemed to be very important for the overall conclusion of the project. CSG is locations within Queensland were summarised, and attainable quantities of the gas in Queensland was also researched to scope the analysis. An overview of existing natural gas distribution infrastructure was then provided followed by a cost analysis of different fuels.

From this analysis Coal Seam Gas (CSG) was found to be going through a un-precedented period of growth due to the push for alternative energy sources while development of renewable energy generation technology advances to a point where it can be widely used. In Queensland there are eight proposed coal seam gas projects worth in excess of $40 billion. These projects propose an annual gas production of 50 million tonnes of LNG from over 8600 wells piped to liquification plants in Gladstone and mostly exported. This is causing significant interest and investment in the technology, and it will provide a significant boost to employment and to the Queensland economy.

The CSG sources in Queensland Coal Seam Gas have been found to be from the Surat and Bowen basins however coal seams also exist in the Cooper, Clarence Moreton, and Galilee basins.

Natural gas consumption is expected to rise over the upcoming years mostly due to the export projects stated above, and also the continued development and consumption of natural gas domestically.

Major Queensland gas distribution pipelines have been briefly summarised and local distribution networks in Brisbane, the Gold Coast, Toowoomba, Ipswich, Dalby, Roma, Oakey, Bundaberg, Maryborough, Gladstone, Rockhampton, and Hervey Bay were identified.

The costs of natural gas production were then outlined and a costing analysis of different fuel types was conducted. Because of the different energy content per volume the fuels cannot be directly compared using the cost per litre. The energy content had to be employed to compare these fuels per contained energy volume. It was discovered that natural gas purchase was 43.41 % that of diesel per energy volume.

With this initial information the project was at a stage where further analysis required experimental fuel consumption so the focus turned to gas turbine engines. It was found that gas turbine engines operate on similar principles to conventional reciprocating engines where heat energy from the combustion process expands the working fluid. The difference however is that gas turbines change the kinetic energy of the working fluid through a constant combustion process, and then extract energy from the exhaust using a turbine. This turbine is connected to a compressor wheel which forces more air in the intake. Conventional reciprocating engines utilise the expanding working fluid in a controlled volume to move a piston.

Stationary gas turbine engines have been found to have many applications including energy generation, ship propulsion, and hovercraft propulsion. More specifically for this report stationary gas turbine engines are being used more frequently for low to medium scale co-generation projects. These projects have been most popular in remote communities, mine sites, large industrial manufacturing sites, refineries, or smelters which have particularly high electricity or heat energy demands. Most medium scale gas turbine based energy generation plants are specified and designed on a case by case basis however there are a few companies manufacturing small generic units and documenting excellent reliability data.

The thermodynamic cycles of a simple cycle gas turbine engine were outlined and it was concluded that the basic design of the model engine must allow these cycles to occur.

The first step of the design analysis stage was to set requirements and constraints to dictate the direction of the model construction stage of the project.

The design requirements were:

1. The engine must operate reliably enough to attain the desired results
2. The engine must be compact and portable
3. All manufacturing process must be conducted by myself

The design constraints were:

1. The engine must be manufactured for less than $1000 (excluding labour)
2. There must be built in safety systems to reduce risk
3. The Combustion chamber must be designed for the turbocharger

The success of this design was analysed on how well it reflected these design requirements and constraints. The first design requirement, reliability, was placed as an important factor of the finished model. Despite this upon initial testing of the model engine unfortunately the turbocharger has suffered a premature failure of the exhaust wheel and bearing. This failure has been traced to a leaking oil seal in the turbocharger which caused abnormally high lubricating oil consumption. This eventually used the 2L of oil in the reservoir and while the engine was operating the oil pump ran dry. Lubricating oil is essentially important for the bearings of a turbocharger so this failure caused significant wear on the bearing which allowed slight play in the shaft causing the exhaust wheel to come into contact with the exhaust housing damaging it.

This failure was caused by two factors. The first was the defective seals in the turbocharger, and the second was the lack of oil level monitoring built into the design. It was assumed that if the oil level was checked between every run then a monitoring system was not needed. This turned out to be un-true and the failure of the system is partially a result of that.

The second requirement, compactness and portability, was deemed important for storage and transportation reasons. This was achieved well in the design process. The frame is large and heavy enough to resist movement at full engine throttle but compact enough to be moved by one person easily.

The third and final requirement, all manufacturing work to be completed by myself, was also completed successfully with the exception of one piece. All welding and construction of the frame and combustion chamber, the wiring, and the plumbing was completed by myself as per the requirements. The oil pump bracket however was manufactured by the USQ machine shop. During the construction process it was decided that the accuracy of the belt drive and pump mount was essential for the stability of the oil supply. This could be done under the project budget allocation from the university and so would not affect the project budget. Despite this action being against one of the design requirements it was well worthwhile upon reflection.

The first specified design constraint was the model had to be manufactured for less than $1000. As specified in the costing and cutting lists earlier in chapter 6 the construction process was completed within this budget so the construction process was a success in relation to this point.

The second specified restraint was the inclusion of safety systems to minimise the risk to the operator and by standers during engine operation. Because of this an exhaust temperature monitoring device was installed to monitor the temperature of the exhaust. If the temperature rose beyond a pre-determined threshold the engine would be shut down to reduce the risk of premature failure. The lack of oil monitoring causing the previously discussed failure will be considered a safety failure due to the obvious safety concerns if the turbine was to fail at full throttle.

The testing procedure for the model set out to cover the experimental testing process and provide attained test data, and basic calculations.

The test apparatus was designed in such a way as to minimise risk to experimental operators and on-lookers by thinking about the possible causes of failure, and taking precautionary measures to minimise the risk of these occurring. In the design of the exclusion and restriction zones outlined in figure 7.1, the potential dangers to operators and on-lookers was also predicted and danger areas were outlined as a result of this. All activities were also conducted in a professional and ethical manner, and also with respect to the environment.

The experiment was carried out according to the test procedure outlined in section 7.3. During this experiment the engine was started and all measurements taken for one throttle setting. Once this period was over the oil pressure of the lubricating oil was observed to be rapidly dropping. The engine was promptly shut down however permanent damage to the turbocharger has occurred as a result of this. The turbine failure was as a result of excessively high oil consumption in the final minutes of operation most likely due to failed oil seals within the turbocharger. It was also concluded that the final model engine design did not have an oil level monitoring system built in which would have allowed the operator to monitor the oil level and potentially shut the engine down before failure. This failure has resulted in the model and testing procedure failing to meet some of the outlined requirements.

Most design requirements and restraints were achieved successfully. However when conducting the design of the model a design requirement was that ‘The engine must operate reliably enough to attain the desired results’. These required results were at a variety of throttle settings which was not fulfilled by the testing procedure. An aim of the testing procedure was also to ‘Attain the desired results’ which was also not completed. Despite this, future work on this model can repair the turbocharger and conduct further tests to attain the initially desired results.

From the obtained results however initial analysis of the data was conducted resulting in some very interesting conclusions. The thermal efficiency of the model engine was calculated to be 1.356 %. This figure is, despite appearances, a very acceptable figure for a home built model engine. Despite the relatively low thermal efficiency the calculations using results produced by this engine will still provide an accurate indication of the relative CSG fuel consumption and running cost.

The equivalent fuel consumption of CSG was then calculated, and both mass flow rate fuel consumptions were converted to volumetric fuel consumptions using the gas densities. Using table 3.2 it was observed that from the possessed data 1000L (ie. 1 m^3) of CNG costs $93.00 compared to $620.00 for 1000L of LPG. The running cost of the engine was then calculated to be $1977.80 /hour on LPG and $830.49 /hour on CNG.

These results produced a running cost saving of 58.1% for CNG over LPG. This result is an excellent conclusion for the case of CNG as an alternative fuel. 58.1% is a significant margin for saving and would produce significant saving in electricity which could be passed on to the consumer.

8.3 Conclusion

From the work conducted in this project a preliminary conclusion about CSG as an alternative fuel source would be that it is feasible.

From the background research into CSG it was discovered that there is existing distribution infrastructure which connects the gas supply with localised networks in almost every major city in Queensland. The fuel usage and proposed projects are seen to be increasing at a very high rate which will increase the distribution infrastructure by attracting investment. Further analysis of CSG showed that there are real benefits in environmental emissions, thermal efficiency, and the fuel cost per energy volume was

43.41 % for CNG compared to that of diesel. This shows significant benefits in converting to CSG, and may financially and environmentally outweigh the installation of application specific infrastructure (ie. expensive fuel pipelines to each individual site).

A model gas turbine engine has also been developed to assist in making conclusion about CSG. Despite suffering a premature failure in the early stages of the experimental process preliminary experimental data has been collected and analysed. These results produced a running cost saving of 58.1% for CNG over LPG for this style of engine. This was deemed a significant margin of saving and is an exceptionally strong argument toward CSG even without the previously said benefits.

In conclusion CSG has been found to exist in Queensland in significant and easily attainable quantities. The benefits of CSG as a fuel include significant cost saving, environmental benefits, and an increase of thermal efficiency compared to conventional fossil fuels. It has potential to significantly boost the Queensland economy over the upcoming intermediate future and create an un-precedented amount of employment and investment in infrastructure.

8.4 Future Work

Future work for the model gas turbine includes:

- Repair of the turbocharger
- Installation of an lubrication oil level monitoring system
- Conduct further experimental work to collect more data
- Experiment with different fuels (ie. liquid fuels) and an evaporator
- Conduct further tests with an intake pre heater to increase efficiency

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Appendix A – Risk Assessments

University of Southern Queensland
Risk Management Plan

http://www.usq.edu.au/hr/healthsafe/safetyproc/whsmanual/whsmanr1.htm

Date: 6 May 2010	**Faculty/Dept:** FACULTY of ENGINEERING AND SURVEYING (FoES)	**Assessment completed by:** Rhys Kirkland	**Contact No:** 0403221200
What is the task? Final assembly and wiring of gas turbine		**Location where task is being conducted:** Ground floor S-block labs	
Why is the task being conducted? Working toward the completion of my major undergraduate research project			
What are the nominal conditions?			
Personnel Facility Operator, and some or all of the following: Facility Technician(s), Experimenter(s), Visitor(s).	**Equipment** Various non-moving hand tools and a soldering iron	**Environment** Laboratory	**Other**
Briefly explain the procedure for this task (incl. Ref to other procedures) Utilise the above mentioned equipment to complete final assembly and wiring of my major project.			

Risk Register and Analysis
[ALARP = As Low As Reasonably Practicable]

Element or Sub Element/ Process Step	The Risk: What can happen and what will be the result	EXISTING CONTROLS	Risk Rating with existing controls? See next page			Is it ALARP? Yes/No	ADDITIONAL CONTROLS REQUIRED	Risk Rating with additional controls?			Is it ALARP? Yes/No	Risk Decision: Accept Transfer Treat
– List major steps or tasks in process	– Electric shock – Eye infection – Fire / explosion – Physical injury – Cut / graze – Chemical burn	List all current controls that are already in place or that will be used to undertake the task eg – List of Personal Protective Equipment (PPE) – Identify types facility, location – Existing safety measurers – Existing emergency procedures	Consequences	Likelihood	Rating		Additional controls may be required to reduce risk rating eg – Greater containment (PC2) – Additional PPE – gloves safety glasses – Specific induction / training	Consequences	Likelihood	Rating		
Soldering	Small burns from the hot soldering tip or fume inhalation.	Equipment is operated by an experienced operator. Eye protection and a respirator is worn by the operator and all personnel within a safe distance. The exhaust fan is also used.	1	E	L	Yes					Yes	
Assembly	Potential personal injury from sharp tips.	Equipment is operated by an experienced operator. Eye protection is worn by the operator and all personnel within a safe distance.	1	E	L	Yes					Yes	

Risk Treatment Schedule

Risk No	Risk	Treatment	Person Responsible for Implementation	Timetable for Implementation	Date Treatment Completed	Review of Effectiveness Effective/Not effective
1.	A small burn from the soldering iron, Fume inhalation.	Minor first aid.	The operator.	Upon occurrence.		
2.	Personal injury from a sharp object.	Minor first aid.	The operator.	Upon occurrence.		

Notes

The task should not proceed if the risk rating after the controls are implemented is still either HIGH or EXTREME or if any risk is not As Low As Reasonably Practicable (ALARP).

<u>This Risk Assessment score of Low (L) is only on the condition that all existing and additional controls are in place at the time of the task being conducted.</u>

Assessment completed by:

Name: Rhys Kirkland Signature:

Position: Equipment operator Contact No: 0403221200

Date:

Supervisor or Designated Officer

Name: Talal Yusaf Signature:

Position: Supervisor Contact No: EXT 1373

Date:

Safety Coordinator

Name: Jim Farrell Signature:

Position: Safety Officer Contact No:

Date:

University of Southern Queensland

Risk Management Plan

http://www.usq.edu.au/hr/healthsafe/safetyproc/whsmanual/whsmanr1.htm

Date: 24 May 2010	**Faculty/Dept:** FACULTY of ENGINEERING AND SURVEYING (FoES)	**Assessment completed by:** Rhys Kirkland	**Contact No:** 0403221200
What is the task? Start-up and running of model gas turbine engine to gain exhaust gas emission data		**Location where task is being conducted:** An oval far from any buildings or trees	
Why is the task being conducted? Working toward the completion of my major undergraduate research project			
What are the nominal conditions?			
Personnel Facility Operator, and some or all of the following: Facility Technician(s), Experimenter(s), Visitor(s).	**Equipment** Various non-moving hand tools, model gas turbine, fuel gas storage cylinders, garden blower for start-up, exhaust gas analyser.	**Environment** Outside	**Other**
Briefly explain the procedure for this task (incl. Ref to other procedures) Start-up model jet at a safe distance from any building to gain exhaust gas analysis data from two different fuels. An essential step in my major research project.			

Risk Register and Analysis
[ALARP = As Low As Reasonably Practicable]

Element or Sub Element/ Process Step	The Risk: What can happen and what will be the result	EXISTING CONTROLS	Risk Rating with existing controls? See next page			Is it ALARP? Yes/No	ADDITIONAL CONTROLS REQUIRED	Risk Rating with additional controls?			Is it ALARP? Yes/No	Risk Decision: Accept Transfer Treat
– List major steps or tasks in process	– Electric shock – Eye infection – Fire / explosion – Physical injury – Cut / graze – Chemical burn	List all current controls that are already in place or that will be used to undertake the task eg – List of Personal Protective Equipment (PPE) – Identify types facility, location – Existing safety measurers – Existing emergency procedures	**Consequences**	**Likelihood**	**Rating**		Additional controls may be required to reduce risk rating eg – Greater containment (PC2) – Additional PPE – gloves safety glasses – Specific induction / training	**Consequences**	**Likelihood**	**Rating**		
Obtain Fuel and move to location	• Fire/explosion • Back injury • Fume inhalation	• Fuel stored in approved cylinders • Handled outdoors (good ventilation)	3	D	M	No	• Fire extinguisher on-site • Wear safety gear	3	E	L	Yes	
Move jet to location	• Back injury	• Multiple person lift • Experience on correct lifting practices	1	E	L	Yes					Yes	
Connect all fuel lines	• Fire/explosion • Fume inhalation	• Handled outdoors (good ventilation) • Common sense	3	D	M	No	• Fire extinguisher on-site • Wear safety gear	3	E	L	Yes	
Start jet with blower	• Fire/explosion • Fume inhalation	• Good ventilation • Bystander exclusion zone	3	D	M	No	• Fire extinguisher on-site • Wear safety gear	3	E	L	Yes	

Element or Sub Element/ Process Step	The Risk: What can happen and what will be the result	EXISTING CONTROLS	Risk Rating with existing controls? See next page			Is it ALARP? Yes/No	ADDITIONAL CONTROLS REQUIRED	Risk Rating with additional controls?			Is it ALARP? Yes/No	Risk Decision: Accept Transfer Treat
Run jet for short period of time	• Fire/explosion • Engine overheat/overrun	• Good ventilation • Bystander exclusion zone • Common sense	4	D	M	No	• Fire extinguisher on-site • Wear safety gear	4	E	L	Yes	
Connect EGA & record data	• Fire/explosion • Engine overheat/overrun	• Good ventilation • Bystander exclusion zone • Common sense	3	D	M	No	• Fire extinguisher on-site • Wear safety gear	3	E	L	Yes	

Guidance Notes for review of Controls and Risk Management Plan.

When monitoring the effectiveness of **control measures**, it may be helpful to ask the following questions:

- **Have the chosen control measures been implemented as planned?**
  - Are the chosen control measures in place?
  - Are the measures being used?
  - Are the measures being used correctly?
- **Are the chosen control measures working?**
  - Have any the changes made to manage exposure to the assessed risks resulted in what was intended?
  - Has exposure to the assessed risks been eliminated or adequately reduced?
  - **Are there any new problems?**
  - Have the implemented control measures introduced any new problems?
  - Have the implemented control measures resulted in the worsening of any existing problems?

To answer these questions:

- consult with workers, supervisors and health and safety representatives;
- measure people's exposure (e.g. taking noise measurements in the case of isolation of a noise source);
- consult and monitor incident reports; and
- review safety committee meeting minutes where possible.

Set a date for the review of the **risk management process**. When reviewing, check if:

- the process that is currently in place is still valid;
- things have changed that could make the operating processes or system outdated;
- technological or other changes have affected the current workplace; and
- a different system should be used altogether.

Note: In estimating the level of risk, initially estimate the risk with existing controls and then review risk controls if risk level arising from the risks is not minimal

TABLE 1 - CONSEQUENCE

	Descriptor	Examples of Description
1	Insignificant	No injuries. Minor delays. Little financial loss. $0 - $4,999*
2	Minor	First aid required. Small spill/gas release easily contained within work area. Nil environmental impact. Financial loss $5,000 - $49,999*
3	Moderate	Medical treatment required. Large spill/gas release contained on campus with help of emergency services. Nil environmental impact. Financial loss $50,000 - $99,999*
4	Major	Extensive or multiple injuries. Hospitalisation required. Permanent severe health effects. Spill/gas release spreads outside campus area. Minimal environmental impact. Financial loss $100,000 - $250,000*
5	Catastrophic	Death of one or more people. Toxic substance or toxic gas release spreads outside campus area. Release of genetically modified organism (s) (GMO). Major environmental impact. Financial loss greater than $250,000*

* Financial loss includes direct costs eg workers compensation and property damage and indirect costs, eg impact of loss of research data and accident investigation time.

Table 2 - Probability

Level	Descriptor	Examples of Description
A	Almost certain	The event is expected to occur in most circumstances. Common or repetitive occurrence at USQ. Constant exposure to hazard. Very high probability of damage.
B	Likely	The event will probably occur in most circumstances. Known history of occurrence at USQ. Frequent exposure to hazard. High probability of damage.
C	Possible	The event could occur at some time. History of single occurrence at USQ. Regular or occasional exposure to hazard. Moderate probability of damage.
D	Unlikely	The event is not likely to occur. Known occurrence in industry. Infrequent exposure to hazard. Low probability of damage.
E	Rare	The event may occur only in exceptional circumstances. No reported occurrence globally. Rare exposure to hazard. Very low probability of damage. Requires multiple system failures.

Table 3 – Risk Rating

Probability	Consequence				
	Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
A (Almost certain)	M	H	E	E	E
B (Likely)	M	H	H	E	E
C (Possible)	L	M	H	H	H
D (Unlikely)	L	L	M	M	M
E (Rare)	L	L	L	L	L

<u>Recommended Action Guide:</u>

Abbrev	Action Level	Descriptor
E	Extreme	The proposed task or process activity MUST NOT proceed until the supervisor has reviewed the task or process design and risk controls. They must take steps to firstly eliminate the risk and if this is not possible to introduce measures to control the risk by reducing the level of risk to the lowest level achievable. In the case of an existing hazard that is identified, controls must be put in place immediately.
H	High	Urgent action is required to eliminate or reduce the foreseeable risk arising from the task or process. The supervisor must be made aware of the hazard. However, the supervisor may give special permission for staff to undertake some high risk activities provided that system of work is clearly documented, specific training has been given in the required procedure and an adequate review of the task and risk controls has been undertaken. This includes providing risk controls identified in Legislation, Australian Standards, Codes of Practice etc.* A detailed Standard Operating Procedure is required. * and monitoring of its implementation must occur to check the risk level
M	Moderate	Action to eliminate or reduce the risk is required within a specified period. The supervisor should approve all moderate risk task or process activities. A Standard Operating Procedure or Safe Work Method statement is required
L	Low	Manage by routine procedures.

*Note: These regulatory documents identify specific requirements/controls that must be implemented to reduce the risk of an individual undertaking the task to a level that the regulatory body identifies as being acceptable.

Appendix B – Oil System Specification

becktech limited

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Fluid-o-Tech TH series rotary vane pumps

The Fluid-o-Tech magnetic drive rotary vane pumps range widens with the introduction of the TH series which combines the larger flow rate (500 to 1000 l/h at 1450 rpm at 1725 rpm) with the added benefit of the magnetic coupling.

The rare earths magnet ensure high performance and perfect alignment between the pump and the motor, extending the life of the unit. The absence of friction, usually caused by the rotation of the mechanical seal against the ceramic seat, allows a more efficient operation and therefore a low power consumption.

The Rotoflow TH Series pumps offer multiple options to configure the product to the specific need of each customer. The housing is available in AISI 303 or brass. The internal components include AISI 303 rotor, carbon graphite pumping chamber and a choice of NBR, EPDM or Viton seals.

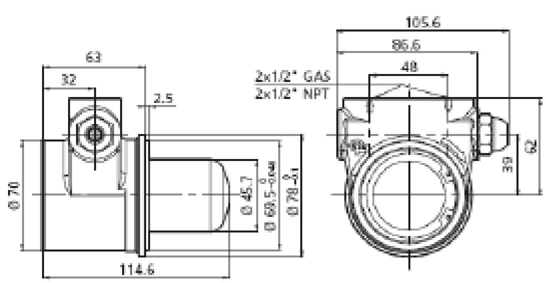
Benefits of magnetic drive

- longer service life
- no mechanical seals
- totally sealed body
- low maintenance
- less power consumption
- smooth transmission

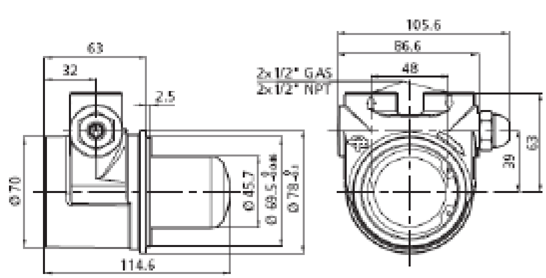
Features of the series

- 1/2" GAS or NPT threaded ports
- Built-in relief valve
- NSF listed pumps available for potable water
- Max speed: 1725 rpm
- Max system pressure: 18 bar (260 PSI)
- Max temperature: 70°C (158°F)

Technical Specification



Dimensions in mm



Dimensions in mm

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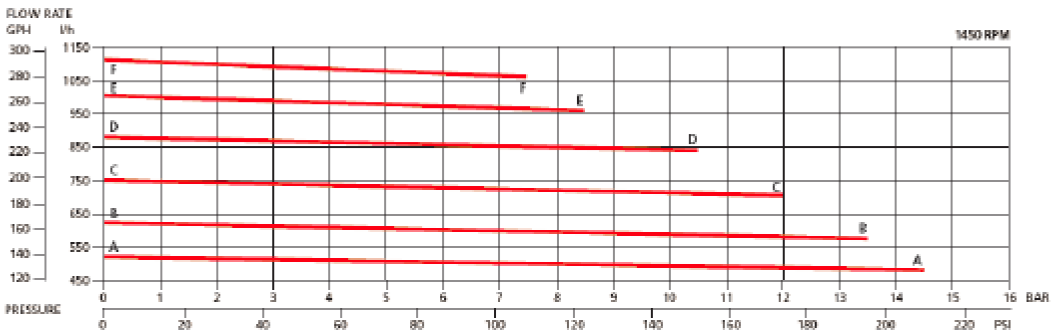
Performance Data

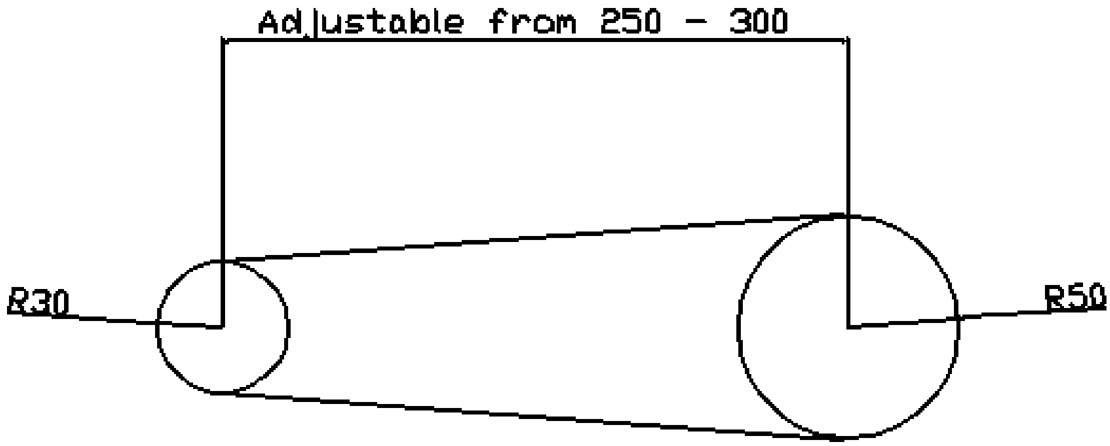
Model series	50xA	60xA	70xA	80xA	90xA	100xA
Figure	A-A	B-B	C-C	D-D	E-E	F-F

The x in the model series number designates the bypass option.

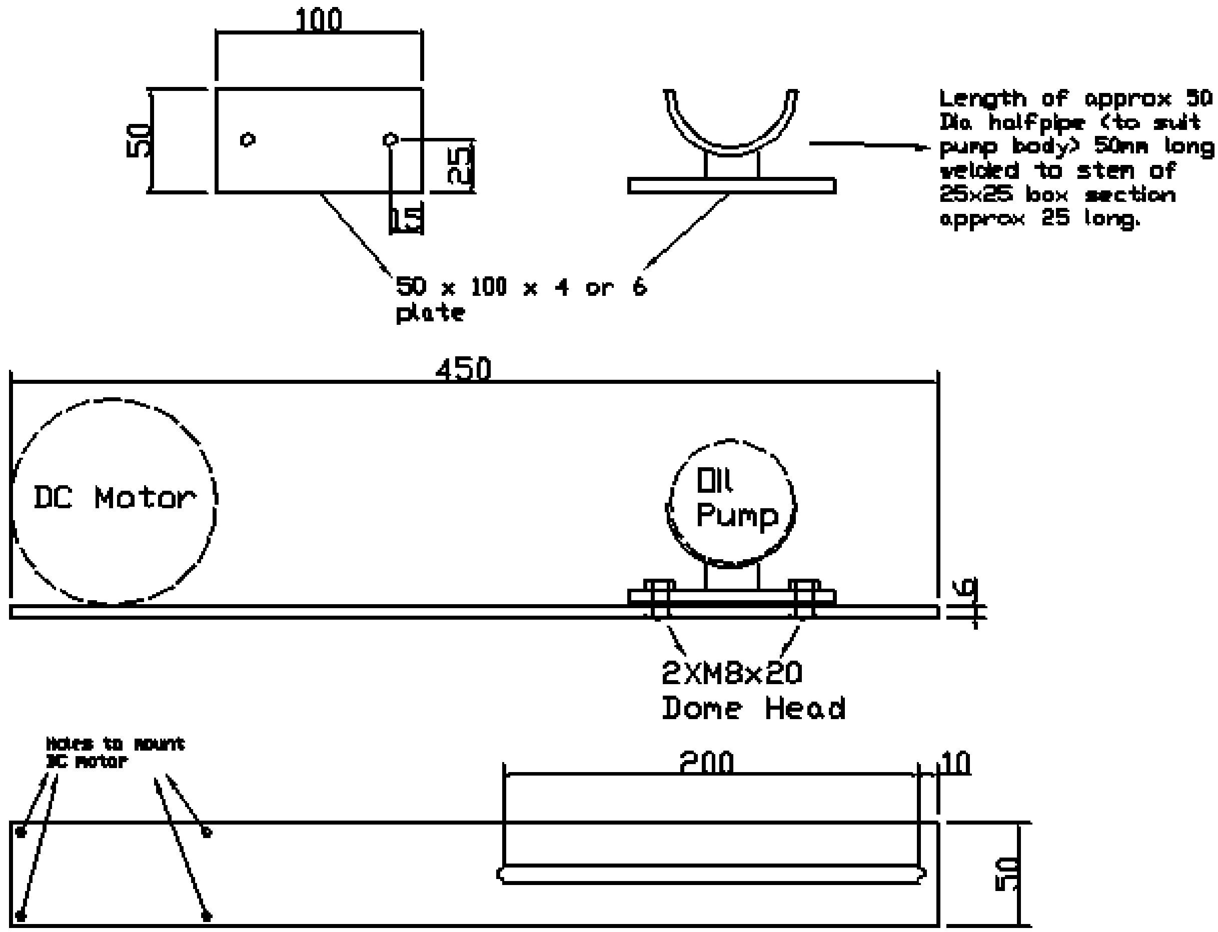


Note: Characteristics with water at 20°C and without by-pass. Use filter before pump inlet not larger than 20 microns. Pump weight: 2.1kg.

For applications involving other fluids, high temperatures, unusual processing conditions or speed higher than 1725 rpm please contact us.


Adjustable from 250 - 300
R30
R50


DC Motor
Oil
Pump

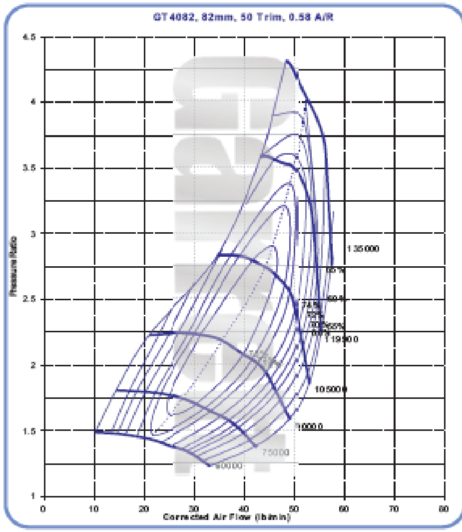

100
50
25
15
Length of approx 50 Dia halfpipe (to suit pump body) 50mm long welded to stem of 25x25 box section approx 25 long.
50 x 100 x 4 or 6 plate
450
DC Motor
Oil Pump
6
2XM8x20 Dome Head
Holes to mount DC motor
200
10
50

Appendix C – Turbocharger Specifications

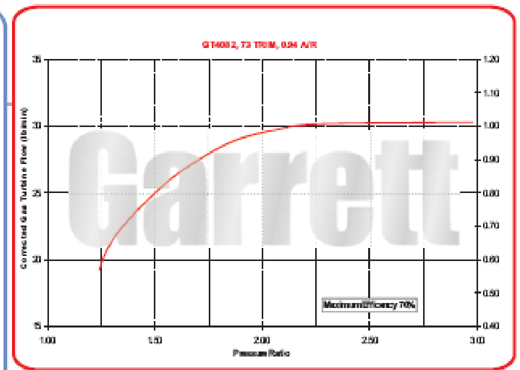
Turbochargers > GT40 Family >GT4082 - 452232-5

- Journal bearing
- Oil-cooled bearing system
- High Load Capacity GT Journal Bearing System
- High performance BCI-18 compressor and UHP turbine
- 4-bolt turbine outlet flange
- T3 turbine inlet flange

Compressor Map



Turbine Map



POWERSHIFT

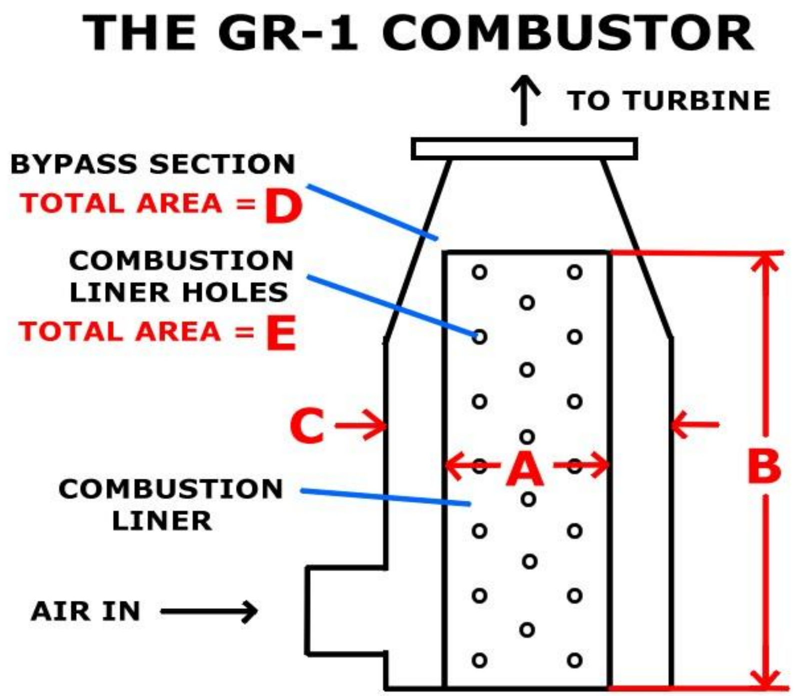
Horsepower 370 - 650
Displacement 3.5L - 5.0L

Journal bearing

GT4082		COMPRESSOR				TURBINE			
Turbo	CHRA	Wh Dia Ind	Wh Dia Exd	Trim	A/R	Wh Dia	Trim	A/R	Type
452232-5	449739-39	58.0mm	82.0mm	50	0.58	77mm	73	0.94	Free Float

Oil-cooled Bearing System

Appendix D – Combustor Formula

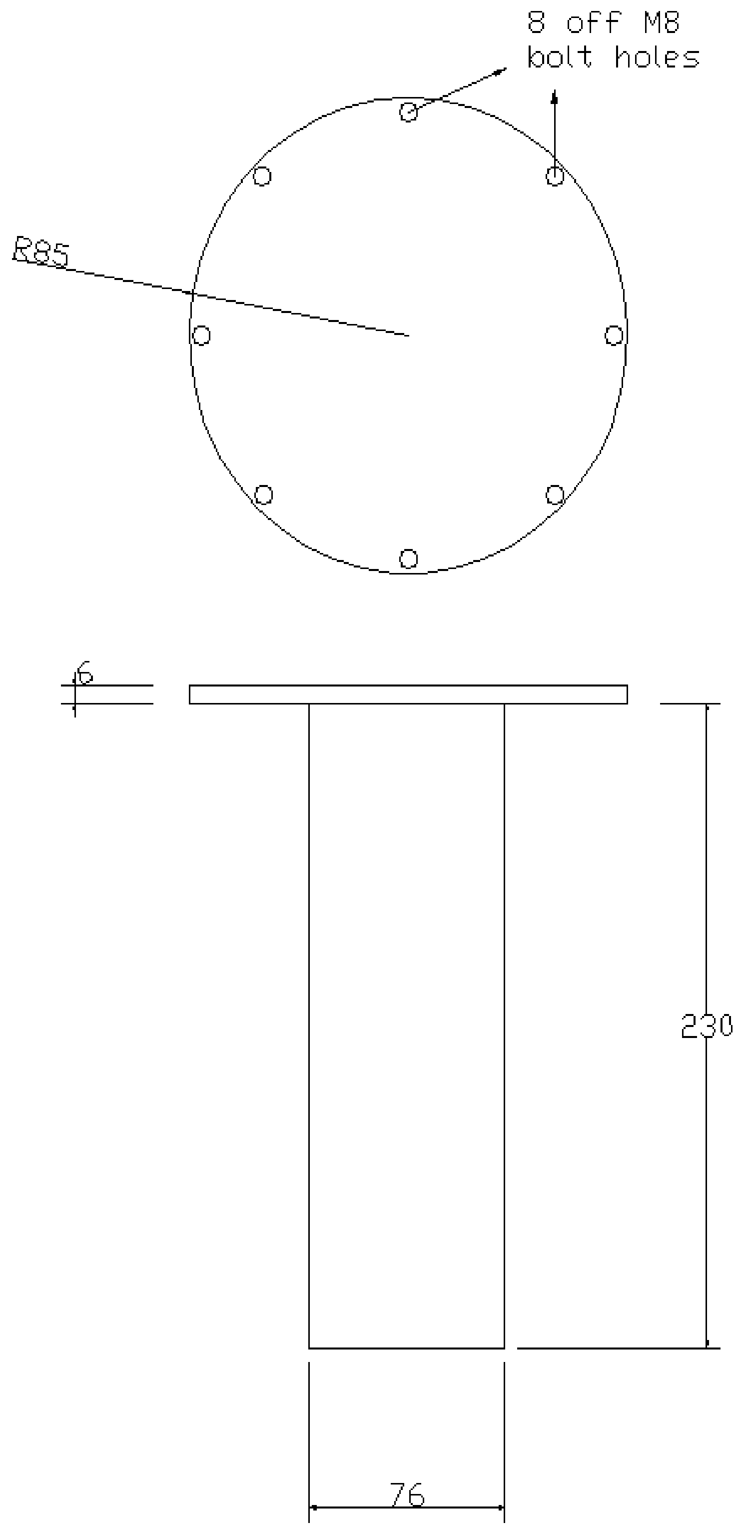


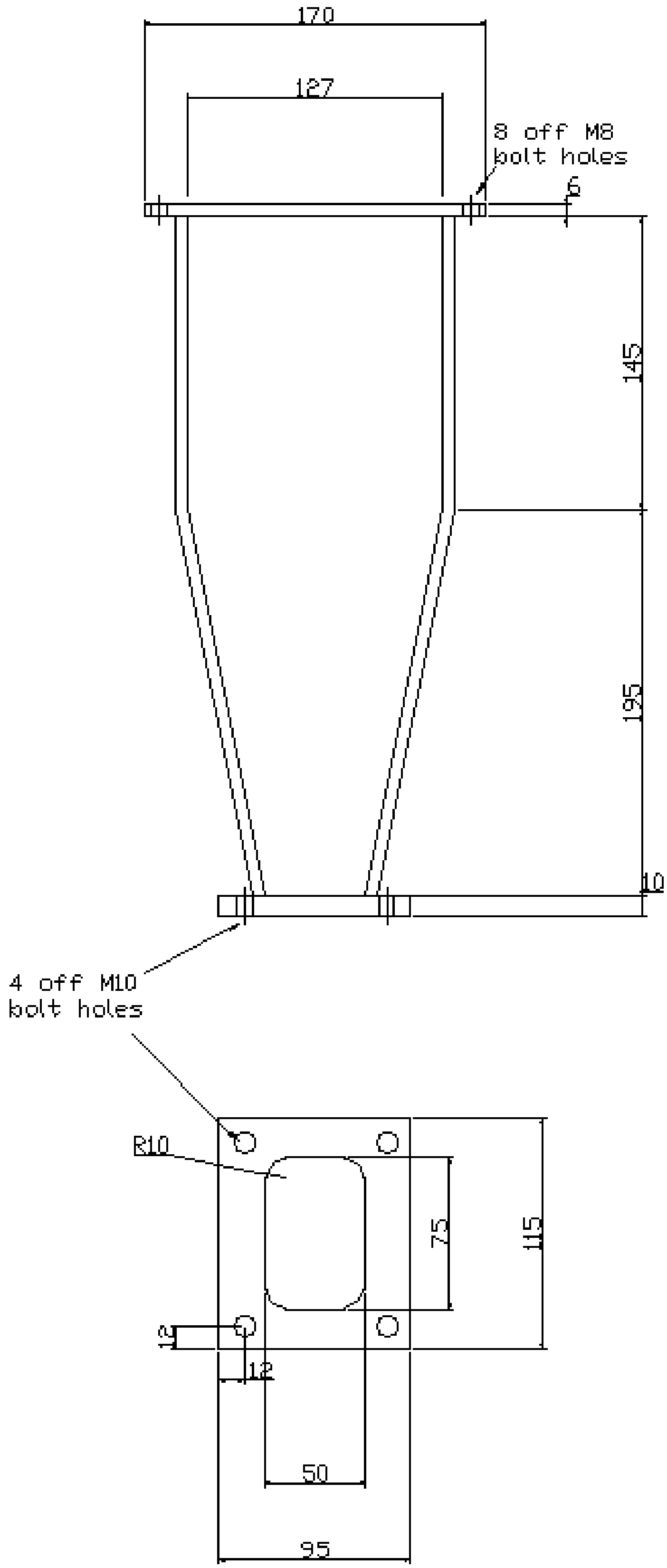
The GR-1 Combustor Formula is as follows:

The inside diameter (in cm) of the turbocharger's inducer (inlet) shall be represented by the value "I" ***** Only use centimeters not inches!!! *****

The inside diameter (in cm) of the combustion liner:	**A = 1.3 X I**
The length (in cm) of the combustion liner:	**B = 3.85 X I**
The inside diameter (in cm) of the combustion chamber:	**C = 2.1 X I**
The cross-section area (in square cm) of the bypass section:	**D = 3.6 X I**
The total area (in square cm) of the combustion liner holes:	**E = 4 X I**
The total number of holes (F) in the combustion liner:	**F = E / 0.33**
The individual size (G) of the liner holes (in square cm):	**G = E / F**

Appendix E – Combustion Chamber Construction Drawings




170
127
8 off M8
bolt holes
6
145
195
10
4 off M10
bolt holes
R10
75
115
12
12
50
95