The Design and Testing of a Gas/Liquid Rocket Engine Used to Gain the Technical and Practical Skills Required for Developing New Rocket Engines

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Abstract

Liquid fueled rocket engines are the primary system that propels rockets into orbit, to the moon, Mars and beyond. Rocket engines achieving a balance between performance, reliability and cost effectiveness, is considered by some to assist in the aim to develop cheaper access to space. This paper discusses the development of a rocket engine from design to firing with the aim to be a training tool to develop an understanding of the high standards of technical and practical skills required for rocket engine design and testing. The low powered gas/liquid rocket engine was tested in late 2006 to commission the control system. Combustion pressure and thrust data was not obtained due to faulty data input equipment and as such the engine specific impulse efficiency could not be calculated. The paper concludes by summarizing knowledge gained in this engine test. Design simplicity, a robust testing process and safe operating procedures were found to be 'best practice' for developing future rocket engines.

1. Introduction

Liquid Rocket engine technology and performance had very much evolved by the 1970s to near theoretical limits for chemical propulsion as developed by the Space Shuttle Main Engine (SSME) [1].

However liquid rocket engines are still by enlarge expensive to develop and procure encouraging the use of solid fuel booster rockets as used on the space shuttle and on the upper stages of the Delta rocket series. Today, there is an emerging privately funded space industry, mostly consisting of smaller groups such as 'Starchaser Industries'[2] and 'SpaceX [3]. These groups have identified making cheaper and simpler rocket engines as one area to reduce launch costs and are developing their own engines as part of their drive for cheaper space transportation systems.

In addition future Mars exploration [4], both manned and robotic has a clear need for small methane powered rocket engines. To this end, the author has embarked a path to explore the art of rocket engine design with the ultimate intention of developing small rocket engines and individual skills suited for the emerging market.

2. The Aim of the Rocket engine

Developing and testing rocket engines is difficult and dangerous involving hazardous fuels that can potentially explode. High standards in design, manufacturing, propellant metering, control and safety procedures are required. Minor errors can quickly lead to major catastrophic failures. As such the aim of the rocket engine described in this paper is: ‘To be a training tool to develop an understanding of the technical, practical and safety skills required for rocket engine design and testing.’

It was not intended to make an engine with a performance suitable to become a certified flight rated engine. The author hoped the engine development process would attract interested individuals who could form a core team with the skills to of develop future engines.

To this end, supporting the project aim, a set of key design principles was outlined as:

- The engine must be designed to maximize safety. Performance, while useful for understanding the testing process, is not relevant.
- Technical solutions and equipment purchased must be within the very limited budget boundaries of the author; and,
- The manufactured hardware must be adaptable and transportable as the testing location and test stand details had not been determined.

These key design principles became the guide assisting the author to identify design challenges with corresponding design choices for the engine.

3. The Design Process

Leading on from the aim and design principles the author set out a list of design challenges required to meet the engine design, construction and testing, each with a set of design choices. These design challenges and choices are listed in table 1. They provided the framework and plan for undertaking the project.

Table 1: Design Challenges and Choices.

The Design Challenge	**The Design Choices**
The engine construction	• The engine size; • The combustion chamber operating pressure; • Material selection; and, • The method of wall cooling;
Propellants	• Liquid fuels with a liquid oxidizer, requiring an ignition system; • Hypergolic fuel and oxidizer that does not require an ignition system; • A solid fuel and liquid oxidizer system; • A liquid fuel and gas oxidizer; or • A gas fuel and gas oxidizer.
Type of Injectors	• The injector hole sizes; and • The injector fuel and oxidizer hole arrangement in the engine

	head.
The Ignition system	• Ignition by using hypergolic propellants; • Adopting a spark plug; • Adopting pyrotechnic devices; and, • Adopting a hot wire.
Method of control and data acquisition	• Safe Starting, stopping and control of the engine; • Field instruments to measure thrust and engine pressure; and • Adopting computer hardware and matching software.
Engine test location	• A large location in a remote area; • A bunker nearer to the authors home; or • A smaller bunker in a not so remote area.
Engine test stand design	• A Test Stand arrangement with either the exhaust exit aimed down or horizontal; • A method of sound suppression; • A method of controlling explosions; and, • A method of measuring thrust.
Developing safe operating procedures	• Equipment testing during construction; and, • Testing procedures

Clearly the list of design choices is long with many options leading to very different outcomes. For example the propellant choice of using solid fuel with oxidizer would result in a very different engine design experience than using traditional kerosene and liquid oxygen. Some of the design choices could be resolved by referring to the 'key design principles' as a benchmark. Others required the author to exercise 'judgment' or 'preference engineering' to reach a solution. These issues are discussed below as we cover inturn each of the above 'design challenges'.

4. The Engine Construction

What physical size do we make the engine? The engine size influences the thrust and hence the size of the test stand, propellant tanks, valves and accompanying equipment. The larger the engine the greater equipment costs and the greater dangers in the event of an explosion. This inturn increases the need to find a more isolated test site location. On the other hand, it is preferable, the engine be not too small. It needed to be large enough for it to be a useful training tool and become a benchmark to compare with future engines. In particular, elements such as injectors and igniters were planed to be measured and scaled to suit different propellants and engine pressures for future engine designs.

However, the engine size was chosen for the simple reason that the thrust chamber diameter dimensions would fit in the author's lathe. This choice was determined early in the project and followed from the key design principles. The engine size adopted has a throat diameter of 60 mm and thrust chamber diameter of 120 mm. A maximum operating pressure of 10 Bar pressure was chosen as this could be provided by pressure feeding the propellants into the combustion chamber using standard 'off the shelf' industrial valves and pipe work. Assuming the propellants are kerosene and oxygen, the theoretical thrust would be 3.58 kN at sea level. Calculations for thrust are shown in the appendix. The thrust level implied a test stand size and equipment that at the time was deemed manageable by the author in terms of cost and complexity.

The thrust chamber material choices, based on other rocket engines are set out in table 2 with matching comments.

Table 2: Material choices (4) & (5)

Material	**Material Attributes**	**Design choice Comments**
Austentic (300) series Stainless Steel	• Relative low strength (250 MPa yield). • Corrosion resistant. • Used for chamber walls. • Operating temperature, 217° to 315°C.	• Requires TIG (Tungsten Arc Welding process)
Copper alloys	• Up to 800 MPA yield strength. • Used for chamber walls. • Operating temperature, 217° to 537°C.	• Expensive to purchase • Requires TIG (Tungsten Arc Welding process)
Nickel alloys (Inconel)	• Used for chamber walls. • Operating temperature, 217° to 700°C.	• Expensive to purchase • Requires TIG (Tungsten Arc Welding process)
Mild Steel	• Not corrosion resistant. • Low tensile strength at temperature.	• Simpler welding process can be brazed. • Cheap for fabrication

The author chose mild steel to keep the cost down and be compatible with the author's workshop tools and welding skills. Mild steel is considered as <u>not</u> a good choice for engines due to the issues stated in Table 2. However given that performance was not an issue in this project and that the engine may be modified many times during the testing period, it was deemed that mild steel was an appropriate choice. Adopting mild steel limited the life of the engine due to the water cooling causing corrosion in the cooling jacket.

Finally, the method of water cooling, as stated, was chosen as the coolant for safety reasons in the event of the jacket leaking. The water flow rate could be independently varied to match the heat transfer to the engine chamber walls ensuring the mild steel did not overheat. Design options for the coolant jacket construction were:

- Constructing the combustion chamber from 6 mm brazed tubes;
- Constructing the combustion chamber as a jacket with an inner and outer shell from rolled and welding sheet steel; or,
- Constructing the combustion chamber and throat from rolled and welded sheet steel and lining the inside with fibreglass for heat protection with no water cooling.

The author adopted the first option as it was assumed that later combustion chambers would be made in tubular construction form. This later proved incorrect. The last option, using a fibreglass layer for heat protection was discarded as it was viewed this was not the direction for future larger engines. Gaining experience in liquid cooling was deemed desirable at this stage.

5. Propellants

Table 1 lists propellant design choices which are now expanded in Table 3 and compared to the key design principles.

Table 3: Propellant options [6] and Comparison to the Key Design Principles

Propellant type	Fuel	Oxidizer	Comparison to the Key Design Principles
Liquid fuels + liquid oxidizer	Kerosene	Liquid oxygen	Safe handling of liquid oxygen was deemed a big undertaking combined with a first rocket engine.
	Methanol spirits	Liquid oxygen	Methanol spirits has a low boiling point and deemed likely to cause fires.
	Kerosene	Nitric acid	This combination deemed as easily doable. Nitric acid is a manageable safety hazard.
	Liquid Hydrogen	Liquid oxygen	Liquid Hydrogen and Oxygen deemed a big undertaking combined with a first rocket engine.
	Liquid Methane	Liquid oxygen	Liquid Methane not easily available at the time of engine construction
Hypergolic fuel and oxidizer	Kerosene	Nitrogen tetra-oxide (N_2O_4)	Extreme Safety hazard due to unplanned propellant mixing and potential explosions possible.
Solid fuel and liquid oxidizer	Rubber	Nitric acid	This combination deemed as easily doable. The propellants do not have the potential for high performance.
Liquid fuel and gas oxidizer	Kerosene	Gas oxygen	This combination deemed as easily doable. The propellants do not have the potential for larger engines for rockets due to gas storage limitations
Gas fuel and gas oxidizer	Gas Hydrogen	Gas oxygen	This combination deemed as easily doable. The propellants do not have the potential for larger engines for rockets due to gas storage limitations
	Gas methane (town gas)	Gas oxygen	This combination deemed as easily doable. The propellants do not have the potential for larger engines for rockets due to gas storage limitations

In summary the author considered the following direction in regard to the propellants:

- Avoid cryogenic chemicals as this required a separate training and skills to be gained in addition to operating a rocket engine;
- Avoid hypergolic chemicals as they are a potential explosive hazard if handled incorrectly;

- Avoid liquid-solid and gas-gas propellant mix as this is a specialized area with specific design issues;
- Avoid gas-gas propellant mix was as the propellant handling was regarded as too easy.

Finally, the author adopted the kerosene combined with gas oxygen option. Kerosene required a pressurized fuel tank, a useful learning experience and the gas oxygen is easily available and safe to control. Using kerosene combined with nitric acid was an attractive option but the gas oxygen as deemed safer and easier to purchase.

The next step was to consider the propellant injectors, one of the most important part of the engine performance.

6. The Type of Injectors

As stated, the injector design is a major contribution towards engine performance. The injector design choices listed in table 1 are expanded and options adopted are listed in Table 4.

Table 4: Injector design choices and adopted options.

Design Issue	**Adopted options**
The injector fuel and oxidizer hole arrangement in the engine head. The injector fuel and oxidizer holes arranged in rings machined on the engine head. OR The injector fuel and oxidizer holes clustered in groups.	The injector fuel and oxidizer holes arranged in rings machined on the engine head was deemed difficult to make and test for leaks between the fuel and oxidizer compartments. The injector fuel and oxidizer holes clustered in groups of 8 was adopted. This was a simpler design minimizing the welds between the fuel and oxidizer compartments.
The injector hole sizes	The propellant hole sizes was based on: - The kerosene injection speed into the combustion chamber was adopted at 15 m/second at 10 bar operating pressure. - The gas oxygen injection speed into the combustion chamber was adopted at 230 m/second at 10 bar operating pressure.

The propellant injector holes were clustered into groups of 8, each cluster with a Ø10 mm central hole for the gas oxygen surrounded by 3 off Ø1.5mm holes for the kerosene. A total of 24 holes provided for the kerosene as shown in Figure 1. This set up ensured a simple combustion chamber head design involving 2 compartments, one for gas oxygen and another for the kerosene. The simple design reduced the risk of propellant leaking into the wrong compartment due to faulty welding.

The injector system purpose is to mix liquid kerosene and gas oxygen. The kerosene holes did not have an impinging angle to the central oxygen holes as the cluster was to form a ‘coax element’[7] where mixing of the propellants occurs through the kerosene droplets shearing against the high speed oxygen gas flow. Coax elements commonly have the gas flow speed 10 times faster than the liquid flow speed. This approach has been adopted in the US space shuttle SSME engine [8] and the Russian NK33 [9] engine used on their N1 moon rocket.

Unfortunately, later during the engine tests, the coax element geometry was considered as not successful as the kerosene holes were located to distant form the oxygen gas holes for effective shearing action. Drilling the small kerosene holes also proved to be difficult particularly for holes less than Ø1.5 mm through the 5 mm steel head. Future engine injector holes could be made with Electrical Discharge Machinery (EDM) methods to obtain smaller and more accurate holes.

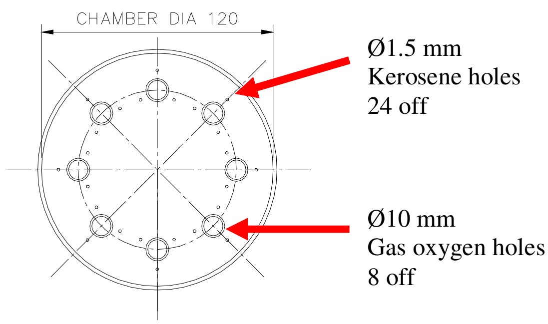

Figure 1: The engine head injector hole arrangement

After being forced through the injector holes, the propellant must be ignited to commence firing. This is covered in the next section.

7. The Ignition System

The propellant was not hypergolic and as such the engine required an igniter to commence the firing process. The ignition system was to be simple and safe as possible as per our key design principles. The ideal system would be integrated into the engine combustion chamber head.

However, there was no intention for quick repeated engine firings and hence the author chose to avoid design issues associated with an ignition system integrated into the chamber head. This implied a spark plug system was not possible. In addition the choice of using pyrotechnic devices was disregarded as they invoked new safety issues in their storage and handling.

Finally the author adopted using a 800 mm long Nickel-chromium wire coiled taped into the combustion chamber walls between the throat to the near the injectors. The wire was connected to a contactor controlled from the computer or operator. Upon ignition the wire would become hot, igniting the propellant. After a controlled ignition the hot exhaust gasses would blow the wire and cables out of the combustion chamber.

8. Method of Control and Data Acquisition

Rocket engine 'start up' and 'shut down' are processes that must be controlled. In the case of engine 'start up' the combustion chamber must not become flooded otherwise a 'hard start' or explosion could occur. In the case of 'shut down' the flame must be extinguished to avoid burn back into the combustion chamber head. As such, the engine 'start up' run and 'shut down' control was identified as a major safety issue and a nitrogen purge system attached to the kerosene head manifold was chosen to quench flame at shut down.

Huzel and Huang [10] suggest that safe start up sequence involves opening the oxygen valve first followed by opening the kerosene valve. A shut down sequence has all valves closing simultaneously.

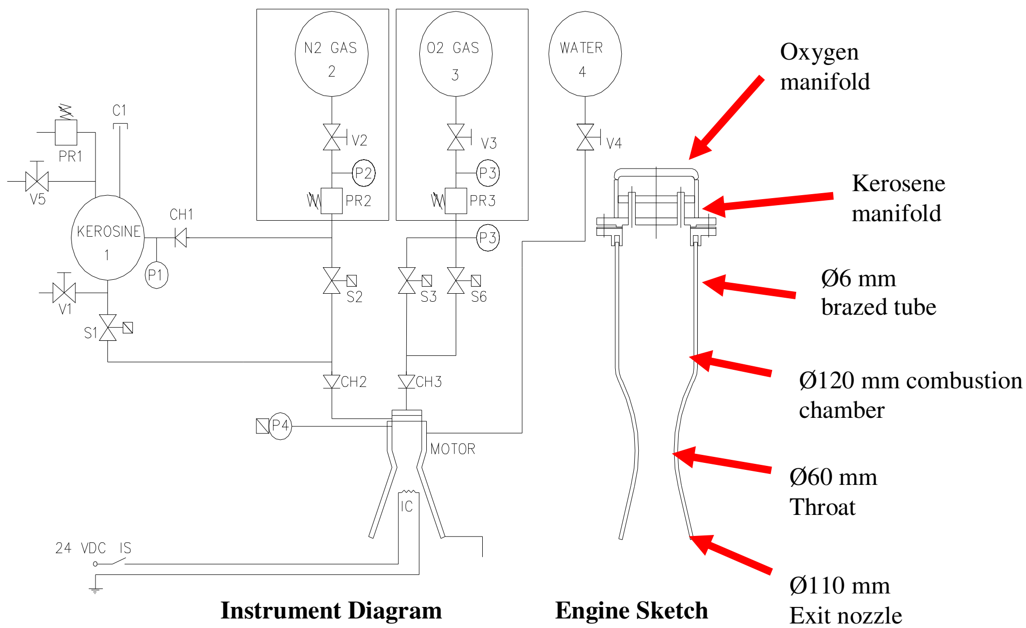

Figure 2: Instrument Diagram and Engine sketch

Refer to the instrument diagram and engine sketch in Figure 2. The valves to be controlled are:

- 1 off kerosene valve;
- 2 off gas oxygen valves. Two valves were needed to provide for the large oxygen flow rate;
- 1 off nitrogen purge valve; and
- The Nickel-chromium ignition wire.

In addition 2 analogue date inputs were available from the engine and test stand. These were:

- An analogue 4-20 mA pressure sensor on the combustion chamber to measure the engine chamber pressure; and
- An analogue 4-20 mA pressure sensor on a modified jack on the test rig to measure the engine thrust load.

The water cooling valve was controlled manually and the kerosene mass flow rate was to be calculated from dip stick measurements in the fuel tank before and after each firing. Similarly the oxygen mass flow rate was to be calculated from measuring the pressure on the oxygen bottles before and after each firing. These measurements proved difficult to obtain during the tests. The mass flow rates and the thrust load measurement are inputs to calculate the specific impulse [11] of the engine providing the engine measure of efficiency as per:

$Isp = F/(mf + mo)g$ Where: Isp = Specific impulse (seconds);
mf = Kerosene mass flow rate (kg/sec); and
mo = Oxygen mass flow rate (kg/sec)
$g = 9.81$ m/sec²

Design issues covering the combustion chamber and throat heat transfer to the walls could not be investigated with these instruments. Leading on for the instrument diagram, a start up and shut down sequence was adopted for the engine computer control system. These sequences are shown in the Figures 3 and 4 and the control display panel in Figure 5.

Note that 5 modes of operation on the control panel were made:

- The 'IDLE' mode, where the system is 'live' and run duration and valve sequence timing operating data can be input;
- The 'START' mode, where the system commences the 'start up' sequence;
- The 'RUN' mode where the system operates and monitors the engine pressure and thrust load data from analogue sensors;
- The 'STOP' mode, where the system commences the shut down sequence, initiated by the run duration timer; and,
- The 'ESTOP' mode where the system commences the shut down sequence, initiated by the operator.

No provision in the software was provided to shut down the engine if the field pressure sensor measured 'over pressure'. Fast shut down was to be provided by the operator initiating the ESTOP.

Finally the control system hardware required to be chosen. Standard Programmable Logic Computers (PLCs) could be used as in general industry work. However the author adopted a control system using Visual Basic software on a laptop. A "comms card" was required to assist communication between the laptop and a switch board in the field. The switchboard housed contactors that operated the solenoid controlled valves on the engine. The analogue input data went directly to the 'comms card'. This approach was chosen as it was considerably cheaper than the PLC option. However, as discussed later, the 'comms card' failed to read the analogue input data from the pressure sensors due to Windows and Qbasic software interface issues.

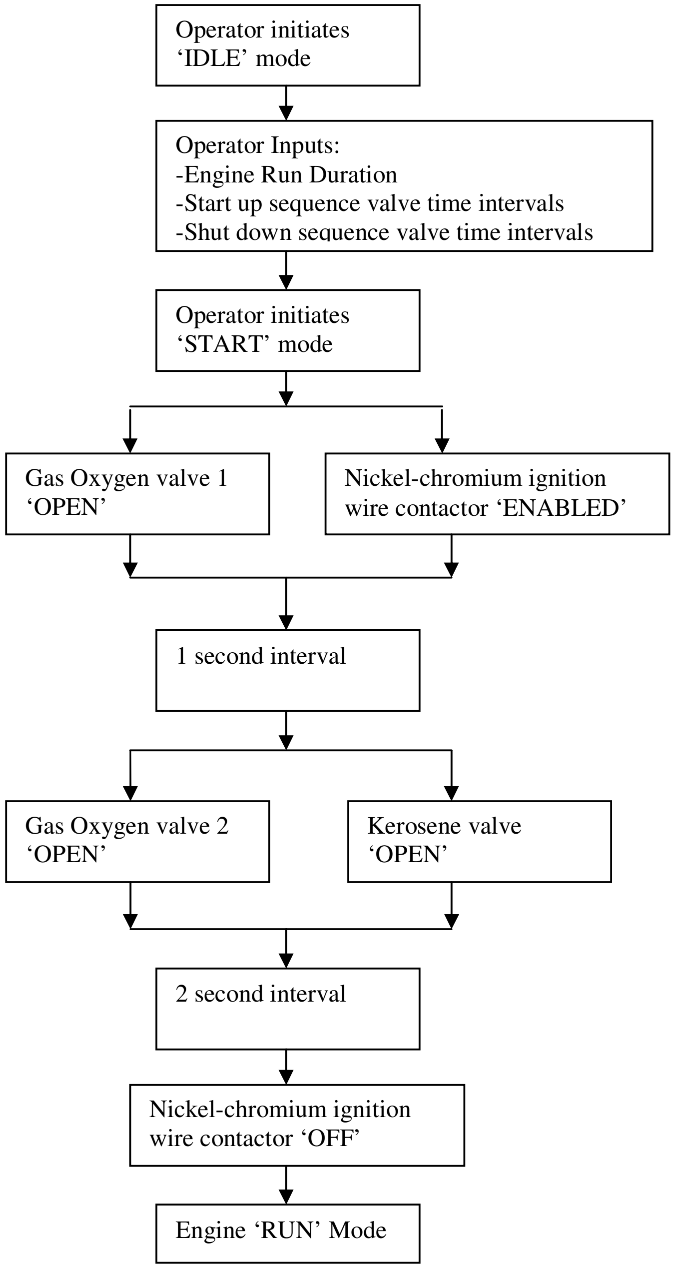

Figure 3: Engine Start Up Sequence

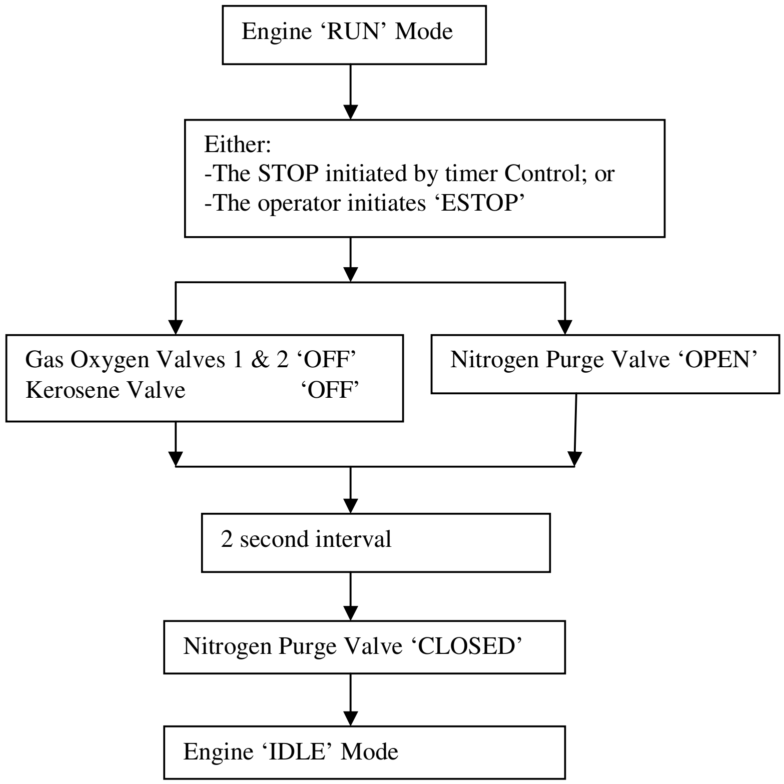

Figure 4. Process Diagram 2: Engine Shut down Sequence

Figure 5 shows the software’s control panel with displays for:

- The modes of operation, ‘IDLE’, ‘Engine START’ and ‘Engine ESTOP’, top left;
- The modes of operation GO/NOGO display, mid left;
- The valve GO/NOGO display, top right;
- The run time and sequence timing inputs, bottom left
- The engine pressure and the firing accumulated thrust data from the analogue pressure sensor, bottom right**.**

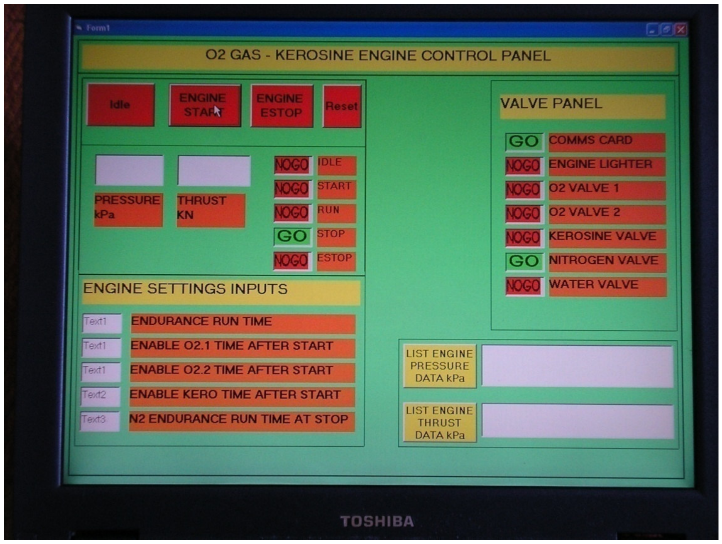

Figure 5: Visual Basic control panel

9. Engine Test Location

The next task to be resolved was to find a testing location. The preferred location was a large area distant from habitation. This would ensure safety in the case of explosions and avoid complaints due to the noise. However these areas are distant resulting in lost time due to traveling. Alternative locations nearer to habitation involve less travel time but are smaller in size.

Finally, a location was chosen in a hilly farming region 30 minutes drive from the capital city (Hobart). The test site is on the edge of a deep valley concealing it from the nearest neighbor 300 metres distant. Water is available from a nearby tank and a trench in the earth located 20 metres from the engine test stand. The operators and control station resided in the trench providing protection from possible explosions at the engine test stand.

10. Engine Test Stand Design

In brief, the test stand lay out was chosen to run the engine with the exhaust firing horizontally. A test stand with the exhaust firing up could result in kerosene flooding the oxygen compartment if the engine became flooded at start and an arrangement with the exhaust firing vertically down would require more complex steel work and foundations compared to horizontally firing. The engine was mounted on a pivoted triangular frame with a single near horizontal member to carry the engine thrust load to the ground as shown in Figure 6(a).

A single ram mounted in this member measured the engine thrust as shown is Figure 6(b). This was done by measuring the ram pressure and calculating the load from the ram cross section and hydraulic pressure. The ram, a modified jack, was preferred to an electronic load cell as it was considerably cheaper and could be easily calibrated using a pressure gauge fixed to the ram. The test stand details is shown Figure 6(b and c).

Kerosene tank,
Nitrogen pressurized

Gas Oxygen and
Nitrogen cylinders

Ram with analogue
pressure sensor

Figure 6 (a) The engine, test stand and team.

Figure 6 (b) The engine test stand ram (a modified jack) to measure thrust analogue pressure sensor located on underside.

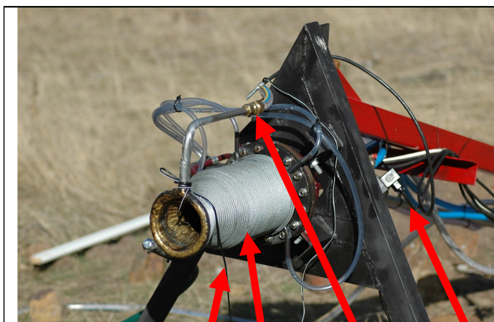

Figure 6 (c) The engine mounted on the test stand (front side)

Figure 6(d) The operators trench located 20m from the test stand

Figure 6(e): Refueling the kerosene tank, a Ø100 NB pipe, was difficult

Cable leading to
nichrome ignition
wire

Engine Pressure
chamber,
-Brazed tube walls,
-Wrapped in pre-
tensioned 5mm cable

Water inlet
for water
jacket cooling

Location of
Gas oxygen,
kerosene and gas
nitrogen valves

11. Developing Safe Operating Procedures

Developing safe operating practices is a mandatory obligation within the Occupation Health and Safety (OH&S) legislation and procedures for construction and testing were put in place. Procedures for the construction were:

- Pressure testing the combustion chamber and tube jacket to 1.5 times the operating pressure of 10 bar. This was done with water pressurized with nitrogen. The engine head fuel and oxygen compartments could not be pressure tested due to the injector holes leaking;
- Bench testing the software. This was done using the GO/NOGO indicators on the laptop operator panel as shown in Figure 5; and
- Dry commissioning the engine using gas oxygen and nitrogen instead of kerosene.

Similarly during the test runs the safety procedures were:

- Loading kerosene procedure consisted of ensuring all power is off, purging air from the tank with nitrogen and loading measured quantities of kerosene via a small port in the top of the tank and venting the excess nitrogen via a second port.
- Personnel must be in the operators trench when kerosene is loaded and the 'IDLE' command initiated on the operators panel;
- Personnel must be in the operators trench when the engine is fired;
- If the engine fails to start then the power is disabled before approaching the engine.
- A sign 'Danger, Rocket Testing in Progress' was installed on the access road to the test location when testing providing warning to non-invited visitors.

At the end of the test process additional safety procedures were deemed necessary for future testing, particularly for more powerful engines. These were;

- Provide more detailed documentation in the form of Inspection and test plans (ITPs) during the construction process;
- Install sand bags around the engine to limit the extent of possible explosions;
- Install water spays at the engine nozzle exit to minimize the noise level.
- Install CCTV to observe the engine without looking directly at it.

12. The Operating Tests

Four test runs were undertaken in September 2006. The aims of these tests were to:

- Test the control start up and shut down process;
- Test the ignition process;
- Find a workable oxygen and kerosene mixture ratio by adjusting the oxygen in-feed pressure;
- Estimate the thrust and efficiency of the engine;
- Trial safe operating procedures; and
- Test the combustion chamber sealing and water cooling system flow rate.

The tests were done at low pressure combustion chamber pressure from a kerosene in-feed pressure of 3 bars. This was done for safety reasons, testing the sealing of the combustion chamber and ensuring water exiting from the cooling jacket was without steam. Steam indicates the water is boiling in the jacket causing a loss of heat transfer capacity through the combustion chamber walls [12]. As stated the analogue pressure sensors on the combustion chamber and engine thrust ram were not operational. However the ram did have a pressure gauge which could be roughly read from a distance using binoculars.

13. Results

Three firings of 5 seconds duration (excluding the startup and shut down) and one firing of 15 seconds duration was completed. The following issues were noted:

- The Ignition system did not work on the first firing as the Nickel-chromium wire burnt out due to current overload. The wire did not have enough resistance or length for the current. A longer wire was made and the ignition system worked on subsequent tests.
- The exhaust gas did not appear to achieve supersonic speeds. Diamond shock fronts were not observed;
- The flame was observed as a fuel rich mix. The gas oxygen in-feed pressure was adjusted higher on each test to find the best mixture through observing the flame colour. Later major carbon and oil deposits on the inside chamber walls and head were noted indicating an efficient mixture ration had not been achieved
- The start up and shut down process worked very smoothly. There were no ‘hard’ starts and post shut down engine fires.
- The water connections leaked.
- The analogue load sensor data input did not work.
- Thrust shown on the ram pressure gauge was very small at nominally equivalent to 260 N thrust.
- The 15 second firing indicated the engine heat transfer characteristics and propellant feed system was stable. The water coolant temperature before and after the firing was not measured.

The efforts of the tests resulted in the following comments (refer to Figures 11):

- The fuel and oxygen may be burning at the throat causing a loss of performance. A trial of new injectors causing the kerosene to impinge on the oxygen is required to investigate better performance;
- The non return valves on the oxygen in-feed could be removed to ensure a greater oxygen delivery;
- The start up and shut down timing could be tightened up and made shorter. The valve response speed was observed in fractions of a second and did not influence the start up and shut down timing.
- The system gave us the confidence of being safe and reliable to operate;
- The oxygen flow rate was limited by the valve size; and,
- The low operating pressure for the nozzle diameter implied the exhaust gas will over expanded relative to the surrounding atmosphere causing inefficiency.

Figure 7(a) The first test, ignition failure. Un-burnt propellant blow through exhaust nozzle

Figure 7(b): The final test, a 15 second run. Note the lack of supersonic diamond shock fronts in the exhaust.

Figure 11(c) Oil and carbon deposits around the injectors.

Figure 11(d) Carbon and oil deposits in the combustion chamber.

Finally, the engine specifications resulting from the outcome of the design choices and tests for the engine are listed in Tables 5, 6 and 7.

Table 5: Expected Maximum Engine Operating Parameters

Calculated Maximum Operating Parameters (Engine operating at 10 Bar)	**Details**
Thrust in Vacuum	4.59 KN
Thrust at sea level	3.58 KN
Specific Impulse	253 second
Max Combustion chamber pressure	10 Bar
Fuel/Flow rate:	Kerosene, 0.46 kg/sec
Oxidizer/Flow rate	Oxygen gas, 1.15 kg/sec
Mixture ratio: oxygen/Fuel	2.5
Throat diameter	60 mm
Chamber diameter	120mm
Nozzle diameter	110mm
Expansion ratio: Nozzle area/Throat area	3.3

Table 5: Engine Design Choices

Construction	Details
Propellant feed method	Propellant pressure fed: Oxygen gas self fed Kerosene pressurized by nitrogen
Nitrogen purge	Nitrogen purge at the engine head kerosene manifold
Chamber construction	Thrust chamber made of 6 mm brazed mild steel tubes wrapped with pre-tensioned 5 mm wire rope.
Ignition system	Nickel-chromium wire
Control	Operated from a laptop
Operating software	'Visual basic'
Injectors	Oxygen injectors are 8 off Ø10 mm diameter holes Kerosene injectors are 3 off Ø1.5 mm holes set in parallel around the oxygen each hole.

Table 7: Actual Engine Operating Parameters

Operating Parameters during tests (Engine operated at an assumed 2.5 bar)	**Details**
Calculated Thrust at sea level	0.6 KN
Measured thrust as noted via ram pressure gauge	0.26 K N
Specific Impulse	Undetermined
Assumed Combustion chamber pressure as measured from Kerosene pressure at engine head manifold	2.5 Bar
Fuel/Flow rate: (nominal)	0.12 kg/sec
Oxidizer/Flow rate	Undetermined
Actual Mixture ratio: oxygen/Fuel	Undetermined

14. Conclusion

The rocket engine performed 4 test firings, 3 of with were successful. In particular the start up, run and shut down sequence performed well. A high confidence level in the overall system and procedures was achieved. However, the analogue data inputs failed to operate preventing and accurate thrust and chamber measurements being undertaken. In addition, for safety reasons, the initial run tests were operated at a low 3 bar pressure. The engine did not achieve its expected performance as supersonic diamonds patterns were not observed at the nozzle exit and low thrust loads were noted on the load sensor pressure gauge. This was thought to be due to:

- The lack of proper propellant mixing at the injectors. The propellant was burning at the throat. It could be argued that ignition was able to be enacted due to the large ignition Nickel-chromium wire coiled from the throat to near the injectors;
- Substantial oil and carbon deposits inside the combustion chamber indicated incorrect fuel/oxygen mixture ratio; and
- The engine operating at low pressures only resulted in the exhaust gas over expanding at the nozzle exit relative to the surrounding atmosphere causing inefficiency.

Modifications to the injectors, in particular the fuel injector holes set on an angle to enable the fuel droplets to impinge on the oxygen gas flow, would improve the propellant burning. Further tests with different operating pressures, propellant mixture settings and injector details would be required to improve the performance and efficiency of this engine.

In addition the lessons learnt from this experience were:

- Adopting the simplest engine design as possible. In particular, replacing the chamber wall tube design with an inner shell with machined channels and an outer ‘close out’ shell greatly reducing the cost and number of fabrication welds;
- Developing ITPs (Inspections & Test Plans) and more detailed safety manufacturing procedures.
- Replacing the Visual Basic software and laptop with industrial accepted software and PLC system;
- Provide sand bags around the test rig to absorb explosions and CCTV to observe the tests indirectly;

It was decided not to pursue improving the engine’s performance as the aim of the exercise in developing technical, practical and safety skills required for rocket engine design and testing’, was achieved. Instead it was decided to start on a new rocket engine where certifiable performances could be achieved.

Appendix

Calculations based on [13]

The engine calculations covered:

1 The thrust, propellant flow rate and specific impulse;
2 Combustion chamber structural stresses;
3 Propellant head loss; and
4 Heat transfer across the chamber walls.

These calculations are standard. As such, this paper will only undertake the first set of calculations. Please note these calculations have been greatly simplified.
First we consider the following inputs and assumptions:

Fuel and oxidizer		Kerosene and Oxygen
Combustion chamber pressure (absolute)	Pc	1000 Kpa
External pressure:	Pe	100 KPa
Throat diameter	Dt	60 mm
Exit Nozzle diameter and area	De/Ae	110 mm, 0.002827 m2
Combustion temperature	Tc	3500 ° K
Molecular weight of combustion products	Mc	21.9 mole
Heat Capacity at const pressure/Heat Capacity at const temperature, Cp/Cv	y	1.24
Universal gas constant	Ru	8314 J/kg/Kmole

As such we have,
Gas constant R = Ru/Mc
= 8314/21.9
= 379.63 J/kg/Kmole

Exhaust velocity Ve = (2 R Tc (y/(y-1)) x (1-(Pe/Pc)^((y-1)/y)))^0.5
= (2 x 379.63 x 3500 x (1.24/(1.24-1)) x (1-(100/1000)^((1.24-1)/1.24)))^0.5
= 2222 m/sec

The specific impulse Isp = Ve/g where g = 9.81 m/sec2
= 2222/9.81
= 226

Exhaust temperature Te = Tt x (Pe/Pt)^(y-1/y)
= 3500 x (1000/100)^(1.24-1/1.24)
= 2241 ° K

Burn't product density Roe = Pe/(R Te)
= 100 KPa/(379.63 x 2241)
= 0.117 Kg/m3

Propellant mass flow rate m = Roe Ae Ve
= 0.117 x 0.002827 x 2222
= 1.61 Kg/sec

Finally, Thrust F = m Ve
= 1.61 x 2222
= 3.58 KN

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