Preliminary Design of a 1 kN Liquid Propellant Rocket Engine Testing Platform

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ABSTRACT

This work presents a preliminary design of a liquid rocket engine test platform to support research into liquid propulsion systems and rocket engine components, including injectors, ignition systems, combustion chambers and engine cooling systems. The liquid propellants, specifically liquid oxygen and ethanol, are pressure-fed using gaseous nitrogen. The test platform supports engine thrust values up to 1 kN, as well as varying oxidizer/fuel ratios up to 4.0 and varying ethanol concentrations between 70 and 100%. The test platform will integrate with a mobile control centre, which was designed concurrently, and provides remote control of the test procedures and data acquisition of all relevant pressure, temperature, mass flow and thrust data. The propellant feed assembly can support both cold and hot fire testing campaigns and is equipped with numerous safety features including inert gas purge lines, emergency drain lines and emergency shut-down and de-pressurization procedures.

Key Words: Liquid rocket engines, liquid propulsion, test platform, LOX/ethanol.

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This work is dedicated to my late mother, Shelley Ringas.

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ABBREVIATIONS

AFRL	Air Force Research Laboratory
ASME	American Society of Mechanical Engineers
BOQ	Bill of Quantity
CAD	Computer-Aided Design
CCTV	Closed-Circuit Television
CGA	Compressed Gas Association
COTS	Commercial-Off-The-Shelf
DAQ	Data Acquisition
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
EO	Earth Observation
GOX	Gaseous Oxygen
GUI	Graphical User Interface
HD	High Definition
HTPB	Hydroxyl-terminated Polybutadiene
I/O	Input/Output
ICBM	Intercontinental Ballistic Missile
IR	Infrared Radiation
LCH_4	Liquid Methane
LEO	Low Earth Orbit
LH_2	Liquid Hydrogen
LN_2	Liquid Nitrogen
LOX	Liquid Oxygen
LPL	Liquid Propulsion Laboratory
LRE	Liquid Rocket Engine
MEO	Medium Earth Orbit
MMH	Monomethylhydrazine
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MRETS	Mobile Rocket Engine Test Stand
MTCR	Missile Technology Control Regime
NI	National Instruments
NI-DAQ	National Instruments Data Acquisition Module
NPT	National Pipe Thread
NTO	Nitrogen Tetroxide
O/F	Oxidizer/Fuel Ratio
PBAN	Polybutadiene Acrylonitrile
PCB	Printed Circuit Board
PID	Proportional-Integral-Derivative
PPE	Personal Protective Equipment
RFI	Request for Information
RFNA	Red Fuming Nitric Acid

RP-1	Rocket Propellant 1
RP-2	Rocket Propellant 2
RTD	Resistance Temperature Detector
SABS	South African National Bureau of Standards
SANS	South African National Standards
SANSA	South African National Space Agency
SIDS	Sustainable Infrastructure Development Symposium
SMART	Specific Measurable Attainable Reasonable and Time-bound
STERN	Studentische Experimentalraketen (Student Experimental Rockets)
TU Dresden	Dresden University of Technology
UCT	University of Cape Town
UDMH	Unsymmetrical Dimethylhydrazine
USB	Universal Serial Bus
USC	University of Southern California

Chapter 1

1. Introduction

This document provides a preliminary design of the propellant feed assembly for the University of Cape Town (UCT) Liquid Rocket Engine (LRE) Test Stand. The test stand will supplement the research activities at UCT's SpaceLab and once constructed will allow for the testing, verification and optimization of propulsion systems and rocket engine components, including combustion chambers, injectors, ignition systems and engine cooling systems. These activities will provide students with invaluable practical experience with liquid rocket propulsion systems and cryogenic propellants and will facilitate the design, development and realization of a student LRE sounding rocket.

1.1 Project Motivation

During the 1980s and 1990s South Africa designed, developed and tested a space launch vehicle with orbital capabilities in collaboration with Israel. The multi-stage solid rocket engine, named the RSA-3, was based on the Israeli Shavit launch vehicle and was intended to place a 330 kg surveillance satellite into low Earth orbit (LEO). The launch vehicle had two successful launches in 1989 and 1990. The RSA-3 was a precursor to the planned RSA-4 that had more than double the payload capabilities of the RSA-3 and could be used as an intercontinental ballistic missile (ICBM) or a satellite launcher for higher orbits. The principle contractor responsible for the development of the rockets, Houwteq, attempted to market the RSA-4 as a launcher for Earth observation (EO) satellites in medium Earth orbit (MEO) after the national missile programme was terminated in 1994 due to international pressure. However, the project was abandoned after a commercial South African launch vehicle was deemed unsustainable. In 1995 South Africa joined the Missile Technology Control Regime (MTCR) and all relevant technical data was retrieved from subcontractors and the rocket components and associated infrastructure were dismantled [1, 2, 3, 4].

Since then, research and development into space launch vehicles and propulsion systems within South Africa, and Africa as a whole, has been scant. The 2019 NewSpace *Africa Industry Report* noted only 2.9% of space business activities in the continent focus on propulsion systems and the report identified only one private company working in this sector, specifically DeltaV Aerospace in Cape Town, South Africa [5]. DeltaV state they are currently designing two launch vehicles; however no further details are available [6].

The South African National Space Agency (SANSA) was established in 2010 and is an active player in the local space industry. The four main programmes of the space agency are: i) Earth Observation (EO), which focusses on remote monitoring, ii) Space Engineering that develops satellites and their subsystems iii) Space Operations, which offers ground station facilities, and iv) Space Science, which performs radio-astronomy and space weather research [7]. Currently SANSA does not have any active research regarding propulsion systems or launch vehicles. However, in September 2020 SANSA issued a request for information (RFI) to industry calling for information regarding the private sector’s expertise and capabilities relevant to launch and support vehicles, business services and ground infrastructure for both orbital and sub-orbital launches [8].

The RFI came a month after it was announced that SANSA was awarded R 4.47 billion in funding to develop a Space Infrastructure Hub over the next three years as part of the Sustainable Infrastructure Development Symposium (SIDS). The Space Infrastructure Hub will include the construction of numerous EO satellites and a new ground station, an increased data segment and a new data visualization centre. In addition to the R4.47 billion funding additional budget was awarded to separate projects, including R 75 million to upgrade the Houwteq satellite testing facility [8, 9, 10]. To give some perspective on the relative size of the funding, SANSA’s parliamentary budget allocation for the 2020/2021 financial year was R 151.33 million [11]. The award of this funding will hopefully lead to a renewed focus and interest in propulsion systems within the South African space economy.

This work will promote indigenous research into liquid propulsion systems, thereby building local capacity and knowledge in the sector and assisting in the realization of a local sub-orbital launch provider in the future. Once constructed the test stand will provide both undergraduate and post-graduate students hands-on technical experience with propulsion system testing campaigns similar to those performed in industry on large scale launchers. Furthermore, the infrastructure will foster research and development of engine components as well as gas generator and turbopump designs.

1.2 Project Definition

The scope of work for this dissertation involves the development of a preliminary design of a mobile rocket engine test stand for liquid propellant engines with a thrust of up to 1 kN using liquid oxygen (LOX) and ethanol. The test stand shall be designed using commercial-off-the-shelf (COTS) components where possible and must be capable of performing both cold fire and hot fire test campaigns. The propellant feed assembly shall be a pressure-fed system where inert gas is used to pressurize the propellants. The test stand must support test durations of up to 25 seconds and pressures of up to 50 bar. The test stand must measure and record all relevant pressure, temperature, mass flow rate and thrust data, as well as video recordings of the test campaigns. The design of the combustion chamber, injector and chamber cooling system are not included in the scope of this work.

The test stand will be controlled remotely using a mobile Test Stand Control Centre, which will have automatic shut-off systems to ensure the safety of test personnel at all times. The preliminary design of the Test Stand Control Centre was performed by James Wilson at UCT’s SpaceLab and is presented in his thesis titled: “*Preliminary Design of a Test and Launch Control Centre for Liquid Propellant Rocket Engine Applications*”.

1.3 Objectives

The main objective of this thesis is to develop the preliminary design for a mobile, remote-controlled, pressure-fed test stand for liquid rocket engines with LOX and ethanol as propellants. The test stand must allow for monitoring and recording all associated data (including pressures, temperatures, mass flow rates and thrusts) and must be safe, reliable and easy to use.

The secondary objectives are listed below:

1. To support propulsion system and LRE research at UCT,
2. To provide an adjustable test stand to cater for varying engine designs, testing campaigns and support testing of gas generator designs in the future,
3. Provide functionality for upgrades to use the test stand as a mobile launch site.

Additional objectives of this work are to commence academic LRE research within South Africa and Africa through multi-stakeholder partnerships and knowledge-sharing to increase the technical capacity of young professionals in this field.

1.4 Requirements

The functional requirements of the UCT LRE Test Stand are listed below:

1. The test stand must be capable of testing engines with a thrust of up to 1 kN,
2. The test stand must be modular in design and allow for mounting rocket engines of varying designs and sizes,
3. The test stand must be able to be mounted in a standard 20 foot shipping container (internal dimensions L x W x H: 5.9 x 2.35 x 2.39 m) to ensure mobility,
4. The test stand must provide functionality for cold and hot fire test scenarios as well as all relevant tests required to commission and calibrate the test stand itself,
5. Purge and drain lines must be incorporated into the design of the test stand. The purge lines flood the rocket engine with inert gas to stop the combustion process and the drain lines allow for quick draining of the propellant tanks and supply lines when required,
6. The test stand must continuously monitor and record all relevant data and must automatically abort a test if critical values approach dangerous limits,
7. The test stand must be rated for maximum operating pressures of up to 50 bar,

8. The test stand must be able to support test durations of up to 25 seconds,
9. The test stand must be robust enough to withstand the extreme forces associated with hot fire static tests for the maximum test duration,
10. The design, fabrication and calibration of the test stand must be done in accordance with the relevant local and international standards.

The operational requirements of the UCT LRE Test Stand are listed below:

1. The test stand must interface with the Test Stand Control Centre and allow for remote operation using both Ethernet and analogue connections,
2. The test stand must use inert gas to pressurize and supply the propellants to the combustion chamber,
3. The test stand must allow for refilling of the propellant tanks without removing the tanks from the stand assembly,
4. The test stand must be safe to operate by undergraduate and post-graduate students. The safety system must include a combination of manual, remote-controlled and automatic safety features as well as an emergency shut-down procedure.

1.5 Constraints

The UCT LRE Test Stand constraints are detailed below:

1. The test stand must avoid the use of specialized, bespoke components. Instead COTS components must be incorporated wherever possible to reduce development time,
2. All valves installed on the propellant feed lines downstream of the propellant tanks must be pneumatically actuated to reduce the risk of accidental ignition or explosions,
3. The test stand design must be able to be constructed, tested and commissioned by university students using the university's facilities,
4. Components and fittings on the LOX lines need to be cleaned for oxygen use and must be constructed with compatible materials,
5. All pressure vessels must be externally verified to ensure safety.

Chapter 2

2. Literature Survey

This section provides a brief overview of LREs and their mechanics. Common oxidizers and fuels used with LREs are then discussed and compared based on their performance, toxicity and handling requirements. The propellant combinations employed in recent prominent liquid propellant engines is then presented. Thereafter, similar university LRE testing platforms are examined and compared to identify common design choices and best practices.

2.1 Liquid Rocket Engines

Rockets are generally divided into four subsystems, specifically the structural system, the payload system, the guidance system and the propulsion system. The propulsion system provides the required force to overcome Earth's gravity to propel the rocket from the surface, through the atmosphere and into space [12]. The propulsion system employs Newton's third law to achieve this – by accelerating and expelling the working fluid (the mass or particles) out of the rocket engine, a force is generated in the opposite direction, which propels the rocket. This force is referred to as the engine thrust and acts through the rocket's centre of gravity, along its length (assuming stable conditions where the rocket's centre of gravity is above its centre of pressure) [13, 14].

The propulsion system comprises three core components, namely the propellant, a method to accelerate the working fluid out of the rocket and an exit nozzle where the working fluid exits after combustion in the form of hot gases. The thrust of the engine is directly dependent on the supply of the working fluid, and will cease if this supply stops [15].

The proposed test stand is intended for use with a liquid bi-propellant rocket engine. This type of rocket uses chemical propulsion to generate thrust by converting the energy contained within the propellants to kinetic energy through chemical combustion. The two liquid chemicals, specifically the fuel and the oxidizer, are mixed together and ignited inside the combustion chamber creating exhaust gas and considerable amounts of heat. The heat causes thermodynamic expansion in the working fluid, causing it to expand and accelerate through the rocket nozzle, which generates the engine thrust [14, 15, 16].

Although liquid propulsion systems are often more complex than solid propulsion systems, they are advantageous in that they provide more control over the combustion process and the engine thrust can be actively controlled in-flight [15]. Furthermore, bi-propellant systems tend to be more efficient and exhibit higher performance values than solid propulsion systems. Liquid propulsion systems also have less onerous ground handling requirements than solid rocket engines since the system can be transported empty and the propellants can be filled prior to testing or launch. This is in contrast to the complex ground handling and storage requirements associated with solid propulsion systems due to the sensitivity of the propellant grains that contain the fuel and oxidizer combination [15].

Another advantage of liquid propulsion systems over solid systems is their repeatability – where a solid rocket engine is a single-use rocket, liquid rocket engines can be used numerous times, allowing for thorough testing and verification, as well as re-using rocket bodies. The first stage booster of SpaceX’s Falcon 9 is designed for at least ten re-uses (and up to 100 with booster refurbishments), which reduces launch costs significantly. The proposed test stand is a pressure-fed system, which uses inert gas to pressurize the propellant tanks and supply them to the combustion chamber as opposed to a blow-down system or pump driven system. The latter is commonly used on large launch vehicles to provide the required large mass flow rates [15].

One disadvantage with liquid propulsion systems is that many of the liquid propellants are both hazardous and corrosive and produce toxic exhaust fumes during combustion. As such, selection of the propellants requires a thorough trade-off analysis between thrust capability, chemical stability, handling and storage requirements, material compatibility and health hazards [15, 17].

2.1.1 Common Liquid Oxidizers

Common oxidizers include dinitrogen tetroxide (N_2O_4, commonly referred to as nitrogen tetroxide (NTO)), nitric acid (HNO_3) and LOX. NTO is popular as it can be stored indefinitely in material-compatible containers and is hypergolic with hydrazine (and its derivatives), meaning that the two will spontaneously ignite on contact. However, special storage requirements are necessary to keep NTO in its liquid phase to avoid vaporization or freezing. Furthermore, the decomposition of NTO creates highly toxic NO_2 fumes [15].

Nitric acid is hypergolic with numerous compounds, including hydrazine, amines and certain ketones. In its concentrated form, nitric acid is extremely corrosive and there are a limited number of materials suitable for storage. As such, the most common form of nitric acid is inhibited red fuming nitric acid (RFNA), which is a mixture of nitric acid, NTO and water with an inhibitor to protect the container metals, making it easier to store. Nitric acid is toxic and will result in severe burns if it comes in contact with skin. Furthermore, the evaporated fumes of nitric acid are poisonous to humans and if inhaled can result in sever pulmonary burns [15].

LOX is the most common oxidizer used in modern large-scale rocket engines as it can be used with numerous fuels, provides good performance and is non-corrosive and non-toxic.

However, LOX is a cryogenic liquid and as such requires the handling and transportation precautions associated with cryogenic liquids. Furthermore, materials and components for use with LOX must undergo rigorous cleaning to ensure all greases and organic materials are removed to avoid kindling chain reactions. Also, special care must be taken when selecting components to ensure they are oxygen compatible as most materials become combustible in 100% oxygen. As such, with LOX systems, all potential heat sources must be eliminated from the system, including heat from particle impacts, mechanical impacts, friction heating and compression heating [18]. All components must be insulated to reduce evaporation and extended storage of the oxidizer is problematic due to its cryogenic nature. Lastly, LOX can result in severe burns if it comes into contact with bare skin [15, 16].

To avoid the strict handling, storage and transport requirements associated with LOX, gaseous oxygen (GOX) can be considered. The majority of the university test stands analysed in Section 2.2 use GOX as the oxidizer as it is widely available, can be stored at ambient temperature and is inexpensive [19]. However, the decision to use GOX in place of LOX has a large impact on the performance of the rocket engine. GOX provides significantly less O_2 during combustion – LOX has an expansion ratio of 1:862, meaning that the volume of O_2 in liquid form is equivalent to 862 times the volume of O_2 in gaseous form at room temperature and normal atmospheric pressure [20].

2.1.2 Common Liquid Rocket Fuels

There are numerous options available for selection as the rocket fuel, but the most common fuels include hydrazine, liquid hydrogen and hydrocarbon-based fuels. Hydrazine (N_2H_4) is hypergolic with NTO and nitric acid. This toxic and carcinogenic propellant is relatively unstable and exhibits a high freezing point. As such it requires specialized heating systems in its application. Furthermore, its vapours can ignite spontaneously with air and the fuel reacts with numerous materials including copper. Two common derivatives of hydrazine used as storable liquid fuels are monomethylhydrazine (MMH, formula: $CH_3(N)NH_2$) and unsymmetrical dimthylhydrazine (UDMH, formula: $H_2NN(CH_3)_2$) as they are more stable than hydrazine and the latter is more resistant to shock impact and blast waves [15, 16].

Liquid hydrogen (LH_2) is widely used as fuel in large rocket engines as it offers a high specific impulse and is non-corrosive and non-toxic. However, it is a cryogenic liquid and as such requires specific storage and handling precautions. Also its low boiling point of 20 K (the lowest of all rocket fuels) translates to increased insulation requirements to minimize evaporation resulting in flammable hydrogen gas. Additionally, due to its extreme cold temperature, all common liquids and gasses solidify in the cryogenic fuel, which can cause blockages in the propellant feed assembly and as such special cleaning procedures are required. Furthermore, due to its low density it requires large, bulky storage tanks [15, 16].

When compared with other fuels, hydrocarbon-based fuels are generally less costly, more readily available, and less onerous to handle, transport and store. Also, their higher densities correlate to smaller propellant tanks. However, one major disadvantage with these fuels is that they produce less thrust than other fuels given the same oxidizer [15]. Hydrocarbon-based fuels are derived from natural gas and petroleum. Liquid methane (LCH_4) is a common cryogenic fuel derived from natural gas. Although being chemically stable and non-corrosive with most materials, it is extremely flammable and can explode if mixed with strong oxidizers. Liquid methane is incompatible with halogenated and fluorinated compounds and requires specific storing and handling conditions associated with cryogenic liquids [21, 22].

This is in contrast to petroleum-based fuels, such as ethanol, gasoline and kerosene (including refined kerosene fuels like rocket propellant RP-1 and RP-2) that can be stored at ambient temperatures. These fuels are non-corrosive, non-hypergolic and chemically stable; however they are highly flammable and may react violently with strong acids. The fuels and their combustion products are non-toxic and the safety risks associated with accidental contact with these fuels are less severe than other fuels. RP-1 is a derivative of petroleum that has an H/C ratio of 1.953 and is often used in launch stages due to its low toxicity, high density and moderate performance. One benefit specific to ethanol is that it can be diluted with water to vary its combustion properties [23, 24, 25, 26, 27, 16].

An important characteristic used to evaluate the performance of propellant combinations is specific impulse, I_{sp}. The specific impulse, with dimensional units of seconds, is a measure of the amount of thrust produced by a propellant relative to its mass and as such provides an indication of how efficiently the energy content of the propellants can be converted into thrust [14, 16]. The specific impulse is related to the effective exhaust velocity and thrust of a rocket engine, which is discussed in detail in Section 3.1.1. Table 2-1 provides information on the performance of common liquid propellant combinations.

Table 2-1: Theoretical Performance of Common Liquid Rocket Propellants [15, 28].

Oxidizer	Fuel	O/F Mixture Ratio	Chamber Temp (K)	Chamber C^* (m/s)	I_{sp} (s)
Liquid Oxygen	Ethanol (75%)	1.29	3167	1643	264
	Ethanol (95%)	1.49	3314	1698	269
	RP-1	2.24	3571	1774	285
	UDMH	1.65	3594	1864	310
	Liquid Methane	3.00	3526	1853	311
	Hydrazine	0.90	3404	1892	313
	Liquid Hydrogen	4.02	2999	2432	390
Nitrogen Tetroxide	50% UDMH 50% Hydrazine	2.00	3372	1711	289
	MMH	2.15	3396	1747	289
	Hydrazine	1.34	3152	1782	292
Red Fuming Nitric Acid	RP-1	4.80	3230	1609	269
	50% UDMH 50% Hydrazine	2.20	3172	1701	279

Note: These values were calculated using a combustion chamber of 1000 psia (6895 kN/m^2) and a nozzle exit pressure of 14.7 psia (1 bar) and assume optimum expansion. The indicated O/F mixture ratios are for approximate maximum values of I_{sp}. C^* is the characteristic exit velocity and is independent of the nozzle.

2.1.3 Propellant Selection

The propellants chosen for the UCT LRE Test Stand are LOX for the oxidizer and ethanol for the fuel. This O/F combination offers good performance and valuable learning opportunities with relatively low safety and environmental risks. LOX was selected to ensure the test stand and associated rocket engine studies are in line with modern day heavy launch vehicles that generally use LOX, as shown in Table 2-2. Furthermore, using LOX as the oxidizer will provide future students with practical experience with cryogenic propellants.

Table 2-2: Propellant Combinations used in Prominent Rockets.

Rocket	Stage	Oxidizer	Fuel
Saturn V [29]	First	LOX	RP-1
	Second	LOX	LH_2
	Third	LOX	LH_2
Soyuz-2 [30]	Boosters	LOX	RG-1*
	First	LOX	RG-1
	Second	LOX	RG-1
	Upper Stage	NTO	UDMH
Ariane 5 [31]	Solid Boosters	Ammonium Perchlorate	Aluminium & HTPB**
	Core Stage	LOX	LH_2
	Upper Stage ***	LOX	LH_2
Atlas V [32]	Solid Boosters	Ammonium Perchlorate	Aluminium & HTPB
	Main Engine	LOX	RP-1
	Upper Stage	LOX	LH_2
Ariane 6 [33]	Solid Boosters	Ammonium Perchlorate	Aluminium & HTPB
	First Stage	LOX	LH_2
	Second Stage	LOX	LH_2
Space Launch System (SLS) [34]	Solid Boosters	Ammonium Perchlorate	PBAN****
	First Stage	LOX	LH_2
	Second Stage	LOX	LH_2
Falcon 9 [35]	First Stage	Subcooled LOX	RP-1
	Second Stage	LOX	RP-1
Falcon Heavy [35]	Boosters	Subcooled LOX	RP-1
	First Stage	LOX	RP-1
	Second Stage	LOX	RP-1
Starship [36]	First Stage	Subcooled LOX	Subcooled LCH_4
	Second Stage	LOX	Subcooled LCH_4
New Glenn [37]	First Stage	LOX	LCH_4
	Upper Stage	LOX	LH_2

* RG-1 is a Russian hydrocarbon-based rocket fuel similar to RP-1

** HTPB = Hydroxyl-terminated polybutadiene

*** The second stage on the original Ariane 5 G rocket used NTO/MMH

**** PBAN = Polybutadiene Acrylonitrile

Ethanol was selected as the LRE fuel as it is non-corrosive and non-toxic and offers a moderately high thrust output. Ethanol is easy to source and requires less onerous handling and storage precautions associated with some of the other fuels. Additional benefits of ethanol are that it is a renewable fuel created from the fermentation of organic material and that its combustion does not produce any toxic compounds [15]. As such, it is often referred to as a “green” fuel. The combustion reaction of ethanol is shown below:

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O \tag{2.1}$$

2.2 Similar University Rocket Testing Platforms

This section provides an analysis of similar university LRE test stands, specifically the University of Southern California’s Water-Flow Test Stand and the Hydra test stand, California State Polytechnic University Pomona’s Mobile Rocket Engine Test Stand (MRETS), Luleå University of Technology’s liquid propellant rocket engine test stand and the Technical University of Dresden’s SMART Rockets test stand. Thereafter a comparison of the various test benches is offered and key design points identified from the assessment are discussed.

2.2.1 Water-Flow Test Stand

Established in 2015, the University of Southern California (USC) Liquid Propulsion Laboratory (LPL) has developed and manufactured four liquid bi-propellant rocket engines, namely the 2.2 kN Blue Steel engine, the identical 3.3 kN engines Jessie and James, and the 10 kN engine Balerion. The propellants for the Blue Steel, Jessie and James engines are kerosene and GOX, whereas the Balerion engine runs on Kerosene and LOX [38]. To assist with the development and verification of the rocket engines, LPL developed two test platforms, the mobile LRE test bench Hydra (discussed in Section 2.2.2) and the Water-Flow Test Stand. The Water-Flow Test Stand was developed to increase the infrastructure within the laboratory and provide a rapid, accurate and reliable testing platform for evaluating LRE components. Design of the test stand commenced in June 2017 and the test stand was operational by July 2018 [38].

The objective of the Water-Flow Test Stand is to provide quantitative and qualitative data on fluid system components, including flow coefficients, injector spray formations and flow distribution within regenerative cooling jackets. To achieve this, the liquid propellants are replaced with distilled water, which is pressurized using gaseous nitrogen and has equivalent mass flow rates based on the original propellant [38]. Analysis of the Water-Flow Test Stand can provide key insights regarding propellant pressurization and cold fire test objectives.

The maximum total mass flow rate of the system is 5 kg/s, however to allow for varying O/F ratios and accommodate larger engines, each feed line can provide flow rates up to 4 kg/s.

The Water-Flow Test Stand can support test pressures between 2 and 20 bar [38]. A schematic of the test stand is shown in Figure 2-1. The two propellant lines are identical.

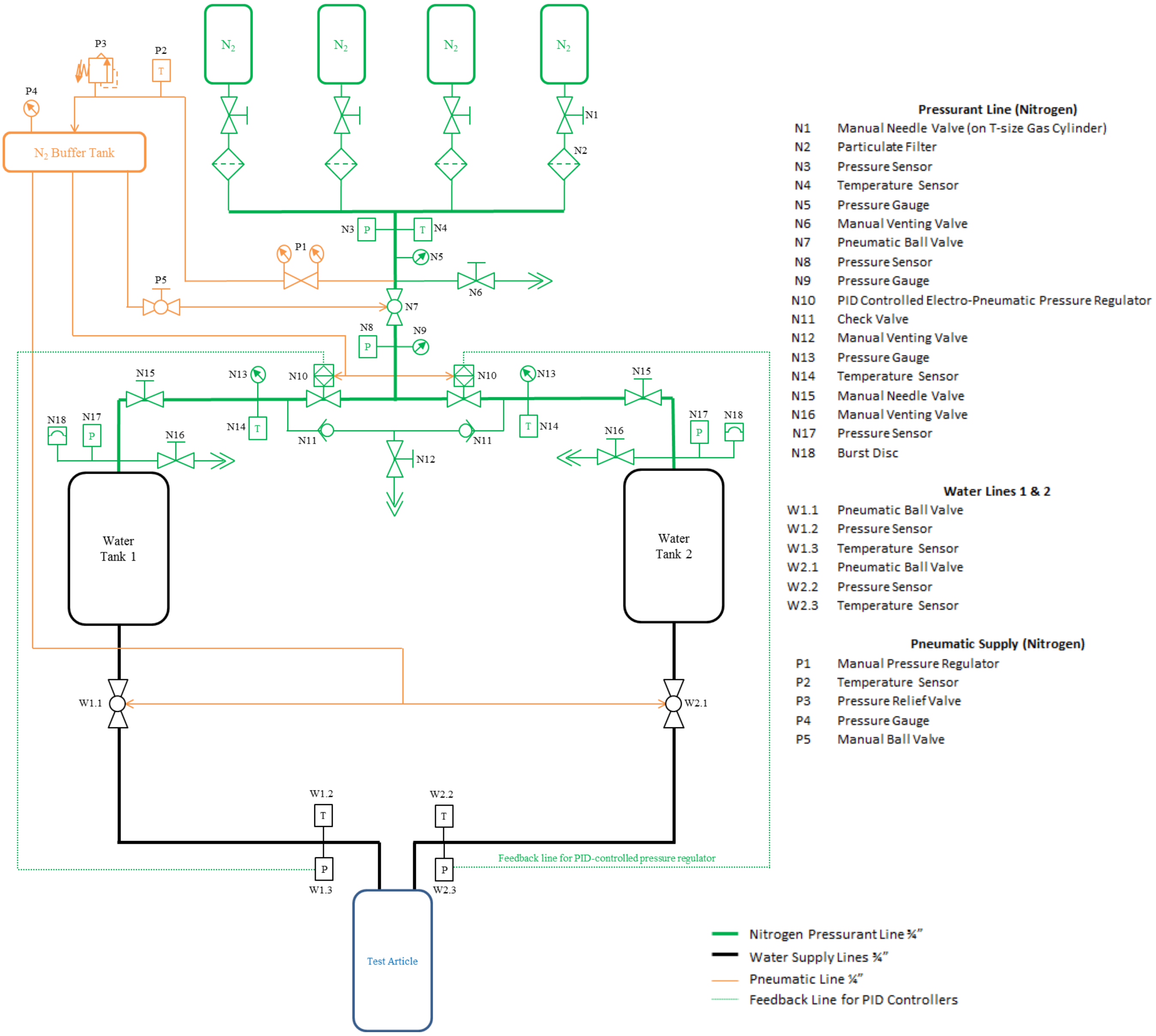


Figure 2-1: Schematic of LPL's Water-Flow Test Stand redrawn from [38].

The system is pressurized using four T-sized nitrogen gas cylinders with their own particulate filter (Item N2, see Figure 2-1), which are joined to a common line using a ¾ inch manifold. A take-off from the nitrogen line passes nitrogen through a manual pressure regulator (P1) to a buffer tank that serves as the pneumatic supply. A pneumatic ball valve (N7) is used to isolate the nitrogen supply if needed and is controlled by operating the respective manual ball valve (P5). The pneumatic ball valve (N7) will fail closed in the case of a loss of pneumatics pressure thereby isolating the downstream components from the pressurizing system.

Additional manual ball valves used for venting and de-pressurizing the system are installed on the supply line upstream of the pressure regulators (Valve N6) and on the downstream supply lines (Valve N12). The two venting valves positioned above the water tanks (N16) are located at the highest point of the system and are employed when pressure testing the system using water to identify potential leaks.

The nitrogen supply to the two water tanks is controlled using two proportional-integral-derivative (PID) controlled electro-pneumatic pressure regulators (N10) that vary the incoming nitrogen pressure based on the measured pressure at the test article (W1.3 and W2.3). The electro-pneumatic pressure regulators used in the system were oversized and as such manual needle valves (N15) were required on each pressurant line to restrict the nitrogen flow [38]. Each water tank is equipped with a rupture disc (N18) as a safety measure to prevent the tanks from bursting as a result of accidental over-pressurization.

The supply of the pressurized water to the test article is controlled by the two pneumatic ball valves (W1.1 and W2.1). These valves fail closed, so that in the event of a power loss the water supply to the test article is interrupted. The nitrogen supply lines and the water supply lines are constructed from ¾ inch stainless steel piping.

The ratings of the various pressure and temperature sensors included in the system are depicted in Table 2-3. A collector tank is located below the test article to collect the expelled water. Four S-Beam type load cells are installed underneath the water collector and are connected with bridge compensation to form the load cell module. The mass flow through the test article is calculated using the water collector weight before and after the test [38].

Table 2-3: Transducers Installed on LPL's Water-Flow Test Stand [38].

Sensor	Purpose	Range
Pressure Transducers		
N3	Monitor nitrogen supply pressure	0 – 345 bar, 0 – 5 V
N8	Measure pressure before regulators	0 – 345 bar, 0 – 5 V
N17	Measure water tank pressures	0 – 70 bar, 0 – 5 V
W1.3 & W2.3	Monitor water supply line pressures to test article	0 – 34 bar, 0 – 5 V
Temperature Transducers		
N4	Measure nitrogen supply temperature	T-type thermocouple
N14	Measure nitrogen temperatures after regulators	T-type thermocouple
W1.2 & W2.2	Measure water supply line temperatures	T-type thermocouple

The system is controlled using LabVIEW software along with a National Instruments data acquisition (NI-DAQ) system that collates the data from the various transducers and controls the active elements in the system, specifically the electro-pneumatic pressure regulators (controlled using analogue outputs between 1 and 5 V) and the valves (controlled using metal-oxide-semiconductor field-effect transistors (MOSFETs) that are switched using digital output signals) [38].

Testing and verification of the test stand revealed numerous challenges with tuning the PID controller, even after the manual needle valves (N15) were included in the system. The sudden change in pressure associated with opening the water supply valves (W1.1 and W2.1) results in a drop in the output pressure of the PID-controlled regulators. Moreover, turbulence in the collector tank results in noise in the load cell measurements. This can be overcome by incorporating a diffuser to distribute the flow out of the injector and baffles in the water collector tank to prevent wave formation [38]. However, in spite of these challenges, the test stand does provide a reliable and accurate method for conducting cold flow tests of articles as demonstrated in [38] where the results of a 30 minute cold flow test of the injector for the James rocket are presented and the flow coefficient of the injector was measured to an accuracy of 0.4%.

2.2.2 HYDRA

The other test stand developed and manufactured by USC’s LPL is the mobile liquid engine test stand named Hydra (see Figure 2-2). The test stand is designed for use with a liquid fuel and pressurized gaseous oxidizer to enable testing of USCs kerosene/GOX rocket engines. The test stand is mobile and is transported using a trailer. The substructure is constructed using welded stainless steel square tubing and transfers the engine thrust to the structure or ground at the test site by either being bolted to a vertical I-beam or to the test site floor. [39]

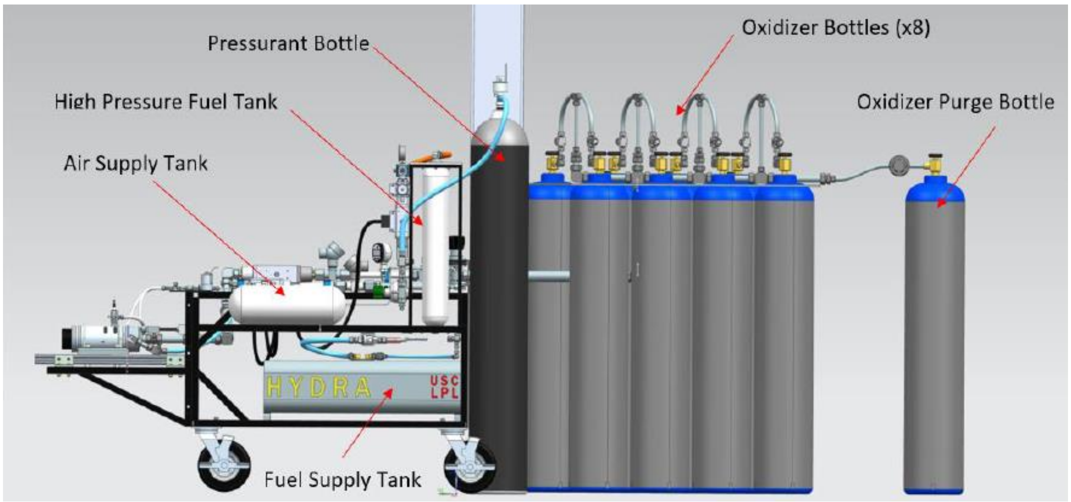


Figure 2-2: CAD Render of Hydra Test Bench [39].

Hydra was designed to use non-cryogenic propellants to reduce the complexity and cost of the test stand. Similarly, the test stand is not designed to operate with highly corrosive propellants. The propellant feed assembly is constructed using smooth-bore seamless 316 stainless steel piping and flexible hoses along with National Pipe Thread (NPT) and Swagelok fittings. The diameters of the lines were decided using the Darcy-Wiesbach equation along with a trade-off analysis between costs and head loss [39].

Supply of the liquid fuel is controlled using pressurized nitrogen. The fuel is stored in the fuel tank and a pump assembly is used to fill the 3.7 litre fuel pressure vessel before firing. The oxidizer is provided with up to eight GOX cylinders connected in parallel to meet the high flow rates required by the engine. The design ensures the propellant supply lines can be drained, purged and primed independently [39]. Figure 2-3 depicts the schematic of the test stand.

Pressurization System

Fuel pressurization is achieved using a commercially available gaseous nitrogen cylinder with an outlet pressure of 200 bar controlled with a manual valve (Item N1, Figure 2-3). The cylinder is connected to an analog pressure gauge (N2) before passing through a particulate filter (N3). The pressure gauge (N2) is a safety mechanism allowing operators to quickly confirm the line is de-pressurized before disconnecting the gas cylinder.

The supply pressure is reduced using a manual single stage pressure regulator (N6) that has a variable outlet pressure between 0 and 140 bar. Temperature and pressure sensors (N4, N5, N7, N8) are installed either side of the pressure regulator to confirm its performance.

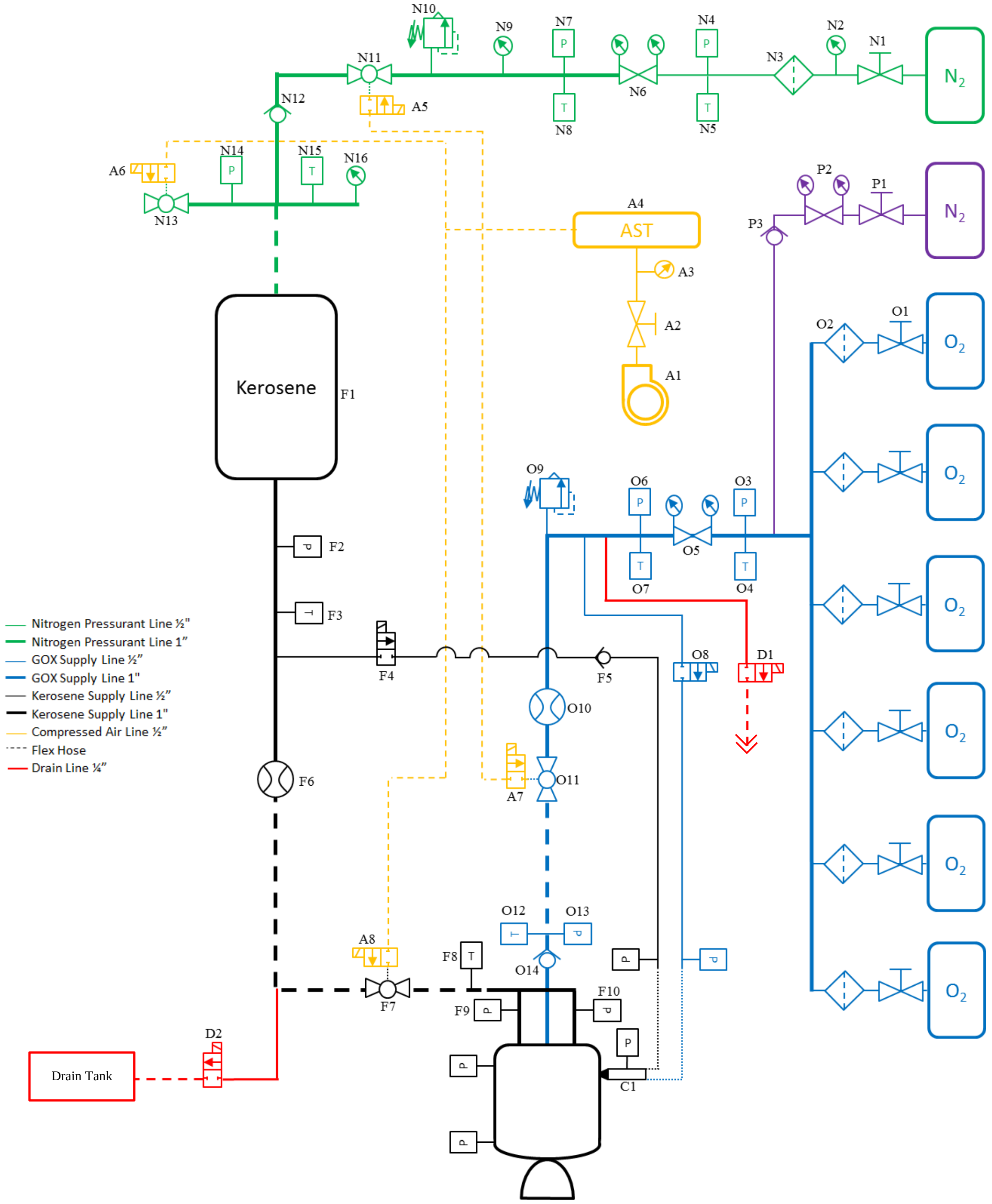
As part of the safety system, a pressure relief valve and burst disc assembly (N10) are connected to the pressurant supply line. The pressure relief valve will reduce the line pressure if the pressure regulator is accidentally set higher than the allowable set pressure and then re-seat itself once the pressure is lowered to within acceptable limits. The burst disc will rupture if there is an extreme build-up of pressure, venting the gas with a high flow rate and adds redundancy to the safety system in case the relief valve fails [39].

The valve that controls the fuel pressurization process is a normally closed pneumatic ball valve (N11), which is remotely operated using a solenoid valve (A5) that manages the supply of compressed air to the pneumatic valve. The ball valve (N11) is designed to open slowly but shut quickly, to avoid slamming the fuel with a column of gas. The nitrogen then passes through a check valve (N12) before being connected to the fuel tank manifold.

The tank manifold houses a pressure sensor (N14), a temperature sensor (N15), a pressure gauge (N16) and a pneumatic ball valve (N13). The pneumatic ball valve is another safety element of the system. It is a normally open, spring-return pneumatic valve that must remain closed during pressurization and testing. Should the system lose power during operation, this valve will spring open thereby de-pressurizing the fuel tank.

Fuel Supply Line

Pressurized fuel flows from the stainless steel fuel tank (F1) to the combustion chamber of the engine, with a smaller diameter tap-off line used to provide fuel to the ignitor (C1). Pressure and temperature data are measured using sensors (F2 and F3) connected at the outlet of the fuel tank. The fuel supply to the injector is controlled using a normally closed solenoid valve (F4) and a check valve (F5) prevents any back-flow along the ignitor tap-off line. The volumetric flow rate of the fuel is measured using a turbine-type flow meter (F6) located before the main fuel control valve (F7). This is a pneumatic ball valve operated by the normally closed solenoid valve (A8) on the compressed air supply line. The fuel supply line is then connected to the combustion chamber using a flexible hose.



Pressurant Line (Nitrogen)

N1	Manual Needle Valve (on Gas Cylinder)
N2	Pressure Gauge
N3	Particulate Filter
N4	Pressure Sensor
N5	Temperature Sensor
N6	Single Stage Manual Pressure Regulator
N7	Pressure Sensor
N8	Temperature Sensor
N9	Pressure Gauge
N10	Pressure Relief Valve & Burst Disc Assembly
N11	Normally Closed Pneumatic Ball Valve
N12	Check Valve
N13	Normally Open Pneumatic Ball Valve
N14	Pressure Sensor
N15	Temperature Sensor
N16	Pressure Gauge

Fuel Line (Kerosene)

F1	Stainless Steel Fuel Tank
F2	Pressure Sensor
F3	Temperature Sensor
F4	Normally Closed Solenoid Valve
F5	Check Valve
F6	Turbine Flow Meter
F7	Normally Closed Pneumatic Ball Valve
F8	Temperature Sensor
F9	Pressure Sensor
F10	Pressure Sensor

Oxidizer Line (Gaseous Oxygen)

O1	Manual Needle Valve (on Gas Cylinder)
O2	Particulate Filter
O3	Pressure Sensor
O4	Temperature Sensor
O4	Temperature Sensor
O5	Single Stage Manual Pressure Regulator
O6	Pressure Sensor
O7	Temperature Sensor
O8	Normally Closed Solenoid Valve
O9	Pressure Relief Valve & Burst Disc Assembly
O10	Turbine Flow Meter
O11	Normally Closed Pneumatic Ball Valve
O12	Temperature Sensor
O13	Pressure Sensor
O14	Check Valve

Purge Line (Gaseous Nitrogen)

P1	Manual Needle Valve (on Gas Bottle)
P2	Single Stage Manual Pressure Regulator
P3	Check Valve

Drain Line (Also used for Priming)

D1	Normally Closed Solenoid Valve
D2	Normally Closed Solenoid Valve

Pneumatic Supply (Compressed Air)

A1	Air Compressor
A2	Manual Gate Valve
A3	Pressure Gauge
A4	Air Supply Buffer Tank
A5	Normally Closed Solenoid Valve
A6	Normally Closed Solenoid Valve
A7	Normally Closed Solenoid Valve
A8	Normally Closed Solenoid Valve

Combustion Chamber

C1	Ignitor

Figure 2-3: Schematic of Hydra Liquid Rocket Engine Test Stand redrawn from [39].

The combustion chamber configuration depicted in Figure 2-3 includes a manifold that splits the fuel injection in two different locations. The pressure and temperature of the fuel are measured just before the combustion chamber using transducers (F8, F9 and F10).

Oxidizer Supply Line

Hydra allows for up to eight GOX cylinders to be connected to the system using a manifold. Each cylinder has its own manual valve (O1) and is equipped with a particulate filter (O2) to prevent any contaminants from entering the supply line. The pressure of the oxidizer is reduced using a manual single stage pressure regulator (O5) and temperature and pressure sensors (O3, O4, O6, O7) monitor data either side of the device. A tap-off line is then connected to the oxidizer line to provide oxygen to the ignitor, controlled using a normally closed solenoid valve (O8).

Similar to the fuel supply line, a pressure relief valve and burst disc assembly (O9) is installed on the oxidizer supply line to protect downstream components from over-pressurization. A turbine-type flow meter (O10) is located before the oxidizer main control valve (O11) to measure the volumetric flow rate during testing. The main control valve for the oxidizer is a pneumatic normally closed ball valve. The valve is controlled indirectly using a solenoid valve (A7) installed on the compressed air supply line.

The oxidizer supply line is then connected to the combustion chamber using a flexible hose. Temperature and pressure data are monitored using relevant transducers (O12 and O13) and a check valve (O14) prevents any backflow from the test article.

Purge and Drain Lines

The oxidizer supply line can be purged using low pressure inert gas at any time to stop combustion in the combustion chamber. This is achieved using a dedicated nitrogen cylinder connected to the oxidizer supply line just after the oxidizer supply manifold. The purge line consists of a manual valve (P1), a pressure regulator (P2) and a check valve (P3).

Although there is no purge functionality on the fuel supply line, there is a drain system that can be used to divert fuel away from the combustion chamber to a collection tank. The drain line connects to the fuel supply line just before the main fuel control valve and is controlled using a normally closed solenoid valve (D2). A similar drain system is also installed on the oxidizer supply line, which vents the gaseous oxygen to the atmosphere when the normally closed solenoid valve (D1) is activated. The drain systems are also used to prime each of the propellant feed lines before firing [39].

Pneumatic Supply

The pneumatic supply system comprises a commercially available air compressor (A1) and a buffer tank (A4). The buffer tank ensures there is sufficient capacity to fulfill the high flow rate requirements of the pneumatic valves and is pressurized intermittently by the air compressor. A manual gate valve (A2) must be opened to allow compressed air into the buffer tank and an analog pressure gauge (A3) is used to confirm the pressure of the compressed air within the tank. Compressed air is provided to the pneumatically operated valves using flexible hose and remotely operated solenoid valves. The solenoid valve controls the pneumatic supply to the respective pneumatic valve, which in turn pressurizes the valve stem and turns the ball inside the valve accordingly.

Control System

The DAQ system, control electronics and power supply unit are housed in an enclosure integrated into the chassis of the test stand complete with dust and water-proof connectors to allow for interfacing with the various sensors and control elements. Additional threaded and bayoneted locking features are used with the sensor connectors to ensure the connections do not work loose from the vibrations during testing. Engine ignition is achieved using a spark plug ignitor supplied with tapped-off propellants or alternatively an e-match assembly positioned near the engine's combustion chamber. Thrust is measured using a load cell installed on the engine mounting plate [39].

The test bench is controlled using software written in LabVIEW installed on a computer located inside a bunker during testing. The LabVIEW software has three different panels, the first is used to set all the relevant parameters (including maximum and minimum pressure limits, the test duration, and the ignition sequence timing), the second user-interface panel is dedicated to testing and verifying the test bench itself, and the third panel is used to operate actual test fires. Communication between the computer and the test stand is achieved using a 30 metre long universal serial bus (USB) cable allowing for two-way communications [39].

The performance of the Hydra liquid rocket engine test bench has been verified and the stand was used to perform two successful hot fire tests, the first was for the Blue Steel engine on the 2nd of December 2017 and the second was with the Jessie engine in June 2018 [39].

2.2.3 MRETS

Students at California State Polytechnic University Pomona are aiming to be the first university to send a payload to space. To this end, the Cal Poly Pomona Liquid Rocket Lab has assembled three teams, the Launch Vehicle team, the Engine team and the Mobile Rocket Engine Test Stand (MRETS) team consisting of students from the mechanical, aerospace, electrical and software engineering departments [40].

MRETS was developed to assist in engine development, testing and verification and will record key engine data, including thrust versus time, combustion chamber pressure and combustion chamber wall temperatures to confirm flight readiness. Figure 2-4 shows an annotated render of the MRETS final design.

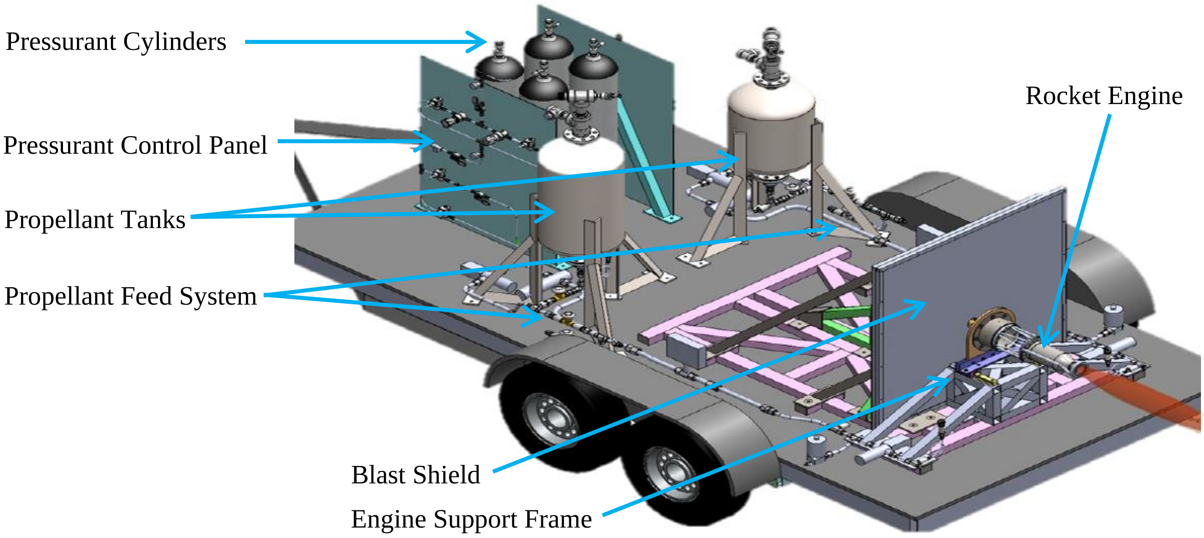


Figure 2-4: Render of the Mobile Rocket Engine Test Stand (MRETS) [40].

MRETS is designed to operate with liquid methane as the fuel and LOX for the oxidizer and can test engines with a thrust of up to 22.2 kN [40]. The propellants are supplied to the engine using a pressure-fed system that uses four K-type nitrogen cylinders to pressurize the propellants. Figure 2-5 shows a schematic of the propellant feed assembly and was derived from the system overview contained in [40]. Since both the fuel and the oxidizer are cryogenic liquids, the two propellant feed lines are identical. The propellant feed assembly is constructed using stainless steel piping of varying diameters and was designed and manufactured in consultation with a Californian engineering firm, Exquadrum [40].

Pressurization System

The nitrogen supply is split into two identical lines, which are housed on the pressurant control panels (see Figure 2-4). As a safety feature, three manual ball valves (Item N1, N5 and N8, see Figure 2-5) are installed on each pressurant line and must be opened manually before firing. During normal operation, nitrogen flows through a high-pressure manual pressure regulator (N2) with an output pressure of approximately 25 bar. Two normally closed solenoid valves (N3 and N7) are located after the pressure regulator. These valves are operated remotely using the test stand control software and control the supply of high-pressure nitrogen to the propellant tanks.

A 40 micron Swagelok particulate filter (N9) is used to remove any contaminants from the pressurant supply before it is connected to the propellant tanks using a flexible hose. Each propellant tank is equipped with a safety assembly that comprises a venting valve (N10), pressure relief valve (N11), analogue pressure gauge (N12) and a burst disc (N13) to avoid over-pressurization. The venting valve is a cryogenically-rated normally closed solenoid valve that allows for exhausting gas when refilling the tanks [40].

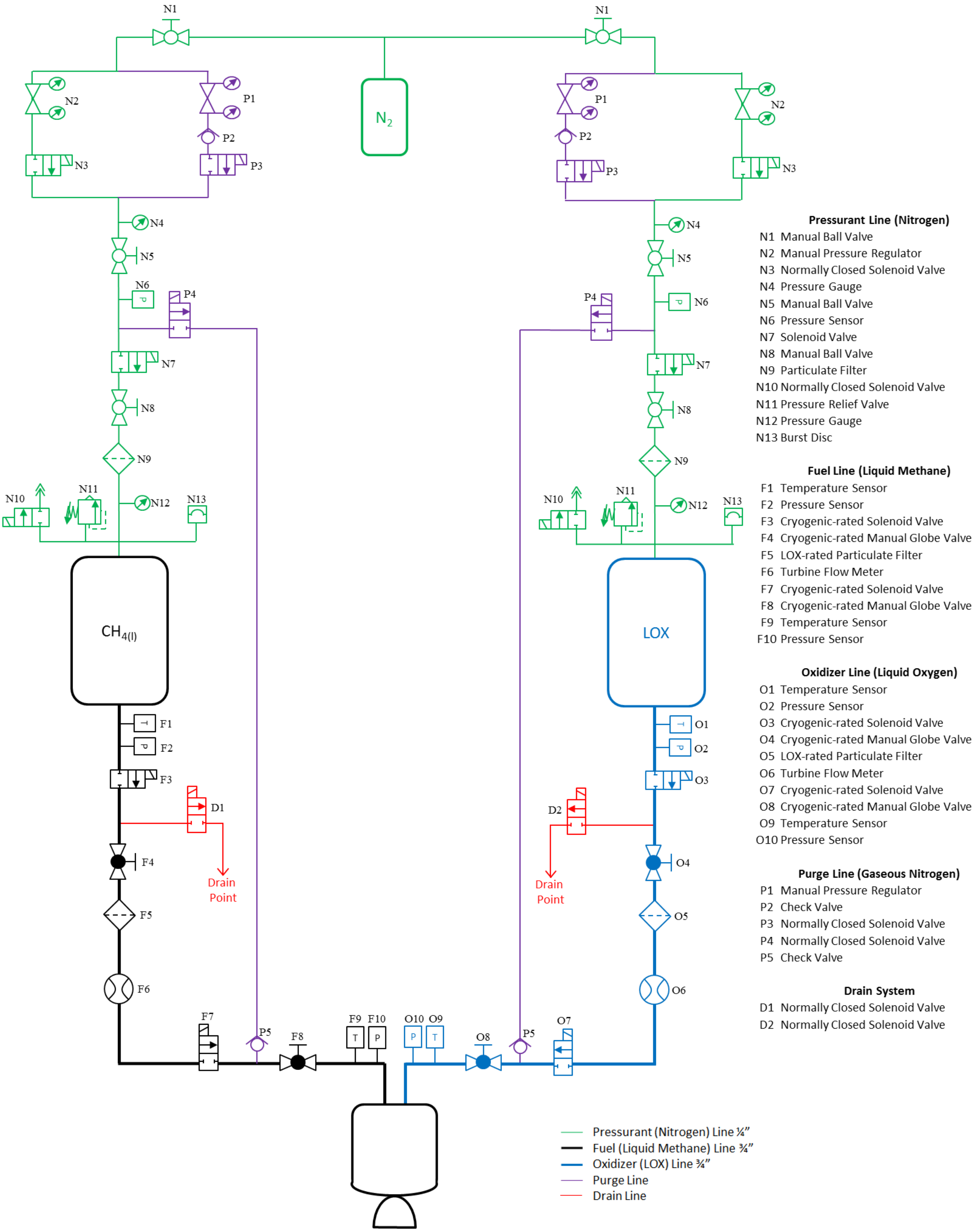


Figure 2-5: Schematic of MRETS derived from [40].

Fuel Supply Line

The liquid methane fuel is stored in an American Society of Mechanical Engineers (ASME) approved stainless steel pressure vessel. The fuel flow is controlled using a collection of cryogenic-rated manual globe valves and solenoid valves to direct the flow to the combustion chamber or the low-point drain [40].

Temperature and pressure sensors (F1 and F2) record data at the tank outlet. A normally closed cryogenically-rated solenoid valve (F3) is located before the take-off to the low-point drain. After the drain connection, the fuel supply line has a manual globe valve (F4) and a Swagelok 20 micron cryogenic-rated particulate filter (F5). A turbine flow meter (F6) is then located along the line to measure the fuel volumetric flow rate. The FML 250 Liquid Flow Monitors from Universal Flow Meters were selected as they are rated for cryogenic applications and constructed using stainless steel [40].

The main fuel valve is a normally closed solenoid valve (F7) located just before a manual globe valve (F8) that must be opened prior to testing. Temperature and pressure data at the end of the fuel line are recorded using appropriate sensors (F9 and F10) where the line is connected to the combustion chamber using a flexible hose.

Oxidizer Supply Line

Since both the fuel and oxidizer are cryogenic liquids, the supply lines are identical. To reduce expenditure the MRETS team acquired previously used cryogenic solenoid valves from Norton Sales Inc, who sell used rocket hardware. The valves were cleaned for use with LOX and their performance verified by conducting extensive tests using liquid nitrogen. As such, although the two propellant lines are identical, some of the solenoid valves, fittings and flow coefficients of the solenoid valves differ [40].

Purge and Drain Lines

The purge line is used to flood the combustion chamber with low-pressure nitrogen to stop the combustion process. A loop on the pressurant control panel (see Figure 2-4) houses the control elements for the purge line. It consists of a manual single stage pressure regulator with a 3.4 bar outlet pressure (P1), a check valve (P2) to protect the low pressure regulator during test firing and two normally closed solenoid valves (P3 and P4). The purge line is activated when P3 and P4 are opened, resulting in nitrogen flowing through the purge line. The purge line connects to the propellant feed lines after the main propellant solenoid valve (F7 and O7) to by-pass the flow meters as they are not rated for use with gas media [40]. A check valve (P5) is located just before this connection point to prevent propellant from entering the purge line.

A drain system is installed on each propellant feed line. It is connected before the first manual globe valve (F4 and O4) on the propellant lines and is controlled using a normally closed solenoid valve (D1 and D2). When these valves are opened, the propellants are re-directed through the drain system into collection tanks. Since the propellants are both liquids, the connection points of the drain lines are made at the lowest geometric points in the propellant feed assembly to avoid trapping propellant in the lines [40].

Control System

The control software for MRETS was implemented using LabVIEW while the data acquisition is achieved using a National Instruments' myRIO embedded input output (I/O) controller. Communication between the LabVIEW software and the myRIO controller is achieved using either an Ethernet cable or a long distance wireless system. Digital output signals from the myRIO device activate solenoid relays to control the solenoid valves from the LabVIEW software [40].

Thrust measurements are performed using a thrust rod assembly to translate the force to a load cell. Temperature measurements are achieved using 30 Type-K thermocouples secured using Kapton tape. To reduce the cost of the pressure transducers, the pressure sensors used in the propellant feed assembly are not rated for cryogenic applications. As such, a "pig-tail" configuration is used that employs a short segment of pipe with a calculated length to alter the cryogenic liquid until it is in an acceptable condition to interact with the pressure sensor. Flow rates are determined by analyzing the digital pulses emitted by the flow meters [40].

MRETS has been used to test components of the Bronco One launch vehicle, which is designed to reach an apogee greater than 6 km. In June 2020 it was announced that California State Polytechnic University Pomona would receive US$ 2.5 million for the Liquid Rocket Lab as part of an educational partnership agreement between the Air Force Research Laboratory (AFRL) and the university. Over 200 graduate students have contributed to the Liquid Rocket Lab projects since its inception [41].

2.2.4 Luleå University of Technology

The Luleå University of Technology in Sweden offers a master's programme in space engineering. Recent work completed by their post-graduate students offers a preliminary design of a small-scale LRE test stand for academic purposes [17]. The propellant combination of ethanol and GOX was selected after a trade-off analysis between performance and safety was completed. The design of the Luleå University of Technology test bench, which is based on similar designs found in [19] and [42], can test rocket engines with a force up to 1 kN. A schematic of the test bench is presented in Figure 2-6 and is redrawn from [17].

Pressurization System

The test stand uses GOX as the oxidizer and as such the pressurization system is only required to pressurize the fuel tank and supply line. A 20 litre, 200 bar gaseous nitrogen tank serves as the pressurant [17]. A manual valve (Item F1, see Figure 2-6) is used to de-pressurize and vent the section of the line upstream of the pressure regulator assembly (N3) after testing.

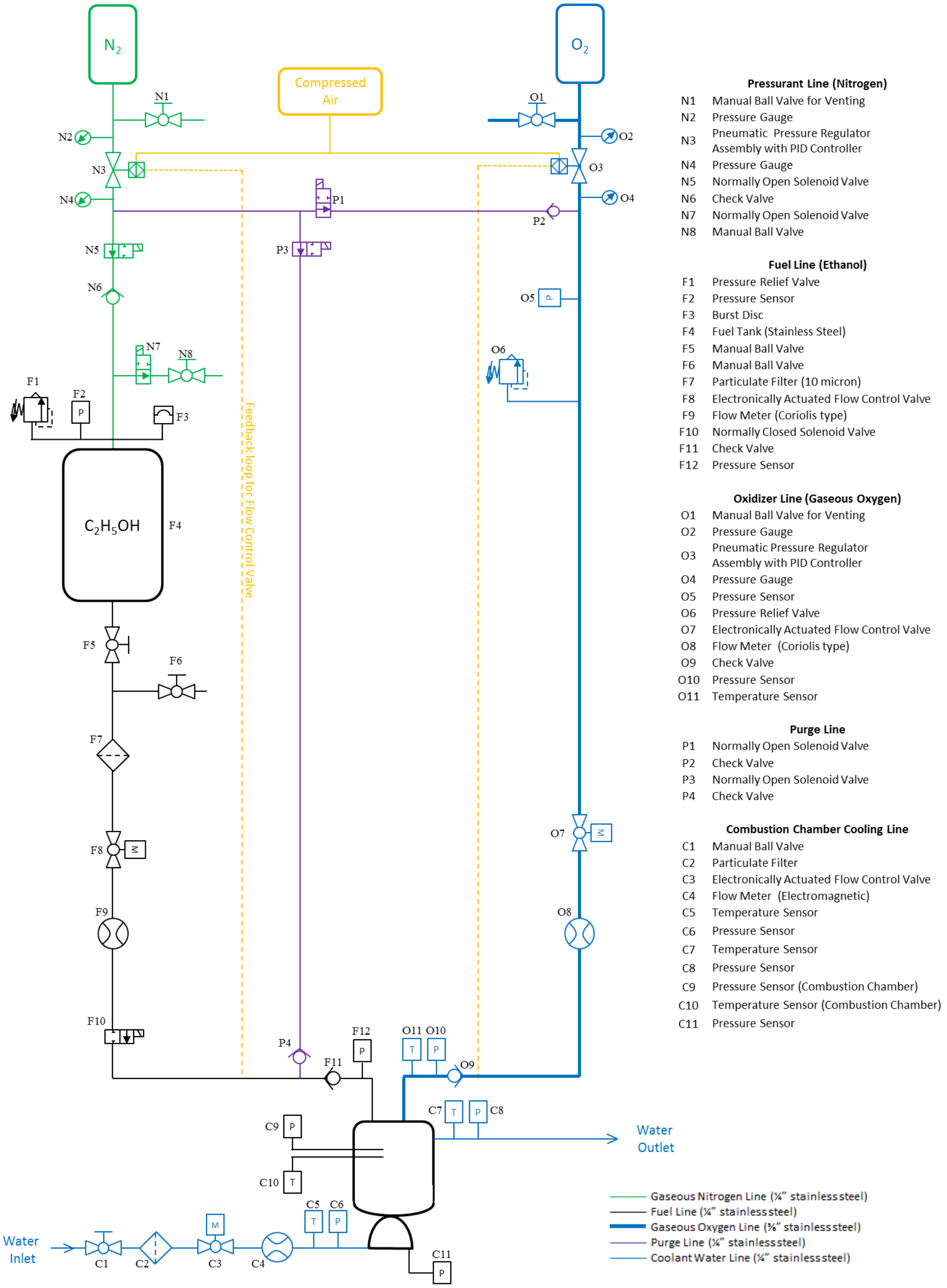


Figure 2-6: Schematic of Luleå University of Technology's Liquid Rocket Engine Test Bench redrawn from [17].

The analogue pressure gauge (N2) is used to confirm that the line is not under pressure when disconnecting the nitrogen cylinder. The pressure regulator assembly (N3) consists of three parts: i) a pneumatically actuated control valve that decreases the pressure, ii) a PID controller that automatically regulates the output pressure based on continuous downstream pressure measurements, and iii) a pressure sensor and transmitter mounted downstream of the control valve that measures the pressure and sends a proportional signal to the PID controller. The pneumatic supply for the pressure regulator assembly is provided using compressed air.

A normally open solenoid valve (N5) and a check valve (N6) are then located on the pressurant line, followed by a normally open solenoid valve (N7) and manual ball valve (N8) situated on an off-take on the pressurant line. The solenoid valves are used to remotely operate the pressurization system during testing and the check valve prevents any back-flow along the pressurant line. The manual ball valve is used to fill the fuel tank (with the solenoid valve N7 kept open). The manual ball valve is opened before testing so that in the case of a loss of power, the two solenoid valves will fail open and the pressurant will be vented [17].

Fuel Supply Line

The fuel tank (F4) has a volume of 20 litres and is constructed from stainless steel. It is equipped with two ports on the top and one on the bottom. The top side of the tank is equipped with a pressure relief valve (F1), a pressure sensor (F2) and a burst disc assembly (F3). The pressure relief valve is designed to prevent the fuel tank from bursting from accidental over-pressurization and the burst disc is included to ensure redundancy should the relief valve fail [17].

The fuel supply line connects to the bottom of the fuel tank. Two manual ball valves (F5 and F6) are located near the connection point. The first manual valve (F5) is included to facilitate testing of the downstream components along the fuel supply line during commissioning. The other manual valve (F6) is located on a tee-off line and is used to drain the fuel line if required. A 10 micron particulate filter (F7) is located after the tee-off to remove any contaminants and debris that may block the injector [17].

The main fuel control valve (F8) is an electronically and remotely actuated flow control valve of the characterized seat control type. The electric actuator is sized according to the required valve torque and receives positioning inputs from an electronic positioner mounted on the valve. The electronic positioner is controlled using a microcontroller and provides calibrating, monitoring and diagnostic functionality [17].

Located after the main fuel control valve are a Coriolis-type flow meter (F9) and a normally closed solenoid valve (F10). The Proline Promass F 300 Coriolis Flow Meter measures the fuel mass flow rate [17]. The solenoid valve is included as a safety feature and will fail closed in a power failure, thereby shutting off the fuel supply to the combustion chamber. Lastly, a check valve (F11) and a pressure sensor (F12) are located at the end of the fuel supply line before it connects to the combustion chamber.

Oxidizer Supply Line

GOX is the selected oxidizer for the test stand and is provided using a 50 litre, 200 bar pressurized cylinder [17]. Similar to the pressurant line, a manual ball valve (O1) is used for venting the section of the oxidizer line upstream of the pressure regulator assembly (O3). Nearby manual pressure gauges (O2 and O4) are used to confirm the functioning of the pressure regulator as well as ensuring the line is de-pressurized before disconnecting the oxygen cylinder. The pressure regulator assembly is identical to that on the pressurant line and consists of a pneumatically activated control valve, a PID controller and a pressure sensor located downstream near the connection to the combustion chamber.

A pressure sensor (O5) is used to monitor the oxidizer pressure downstream of the pressure regulator. A pressure relief device (O6) is included on the oxidizer line to protect the components from accidental over-pressurization. The main oxidizer control valve (O7) is an electronically actuated flow control valve (of the characterized seat control type) and is operated remotely to control oxidizer flow to the combustion chamber. The oxidizer mass flow rate is measured using a flow meter (O8), specifically the Proline Promass F 300 Coriolis Flow Meter. The flow meter is cleaned for oxygen use and is constructed from stainless steel and its wetted parts from Alloy C22 (an alloy of Nickel, Chromium, Molybdenum and Tungsten) due to its resistance to oxidizing media [17].

A check valve (O9) is located at the end of the oxidizer line where it connects to the combustion chamber to prevent any back-flow and pressure and temperature data are monitored using sensors at this location (O10 and O11).

Purge Line

The purge line uses nitrogen from an off-take of the pressurant supply line to flood the propellant feed lines to the combustion chamber when required. The oxidizer purge line is connected just after the pressure regulator assembly (O3) and is controlled using a normally open solenoid valve (P1). The fuel purge line is operated using a normally open solenoid valve (P3) and connects just before the fuel line connection to the combustion chamber. Check valves (P2 and P4) are installed at the end of both purge lines to ensure the flow is in only one direction. The solenoid valves used to control the purge lines are normally open to ensure that in the event of a power loss, they will fail open and automatically purge the propellant feed assembly.

Combustion Chamber Cooling System

To prevent potential damage from the intense heat generated by the combustion process and to allow for longer test durations, a steady-state water cooling system is included in the test stand design [17]. The combustion chamber will be encapsulated in a concentric cooling jacket and water coolant will flow in the annular space between the two structures.

The coolant water is provided from an external source at 5 bar pressure and is connected to the cooling line, which is constructed from ¼ inch stainless steel piping. The cooling line consists of a manual ball valve (C1), a particulate filter (C2), an electrically actuated flow control valve (C3), a flow meter (C4) and temperature and pressure sensors (C5, C6, C7, C8) located either side of the cooling jacket. The manual ball valve is used to isolate the cooling line from the water supply to test the downstream components' functionality. It is followed by a particulate filter (identical to the one used on the fuel supply line) to remove contaminants and any debris that may be present in the coolant water supply. Remote control of the cooling system is achieved using the electrically actuated flow control valve and the mass flow rate of the coolant water is measured using an electromagnetic flowmeter (specifically the Proline Promag H 300 Electromagnetic Flowmeter) [17].

Control System

The electrical interface for the test stand has not yet been designed; however it is recommended that the EtherTRAK-2 I/O Module is used for data acquisition as it has sufficient analog and digital I/O ports. A total of 15 analog inputs are required for the nine pressure sensors, three flow meters and three temperature sensors. Eight analog outputs are required to control the flow control and solenoid valves [17].

All the pressure sensors are piezo-resistive pressure transducers, except for the two located on the combustion chamber, which are stainless steel piezo-electric pressure sensors that are accurate under high vibrations. The sensors will be connected to the combustion chamber using open ended tubes of a sufficient length to ensure the temperatures are reduced to within the operating range of the sensors. Temperature detecting immersion type probes will be used to monitor temperature data. For monitoring the temperatures within the combustion chamber a high precision infrared radiation (IR) camera is recommended. Thrust measurements are performed using a strain gauge load cell installed on the top of the engine mount [17].

Ignition is achieved using a hot-source ignition system, namely a 12 V oil-filled ignition coil that creates a spark between two wires where a gasoline-soaked piece of cotton is mounted. The control software for the test stand has not been developed, but it is recommended that LabVIEW is used to create the control software [17].

2.2.5 SMART Rockets

Under the German Aerospace Center (DLR) STERN (an abbreviation of “Studentische Experimentalraketen” or “Student Experimental Rockets”) programme, the Dresden University of Technology (TU Dresden) designed and developed a 500 N ethanol / LOX sounding rocket (see Figure 2-7) under the project name SMART Rockets (which is an acronym for Specific, Measurable, Attainable, Reasonable and Time-bound Rockets). The motivation for selecting liquid propellants as identified by the SMART Rockets team is three fold: i) to align the propellants of the sounding rocket with common modern day launchers, ii) to provide students with experience working with cryogenic propellants, and iii) ethanol can be diluted with water, allowing for increased control over the combustion process [43].

As part of the project a test bench was developed, constructed and validated to facilitate verification and optimization of the complex propulsion system. Setup of TU Dresden's rocket engine test bench commenced in September 2012 and was operational by December 2013, with the assistance of two full-time doctoral students. The first open combustion test campaign occurred in July 2014, which commenced a rigorous and thorough verification campaign of the rocket engine as well as optimization of the injector and combustion chamber designs, consisting of more than 122 tests across eight campaigns [43, 44].

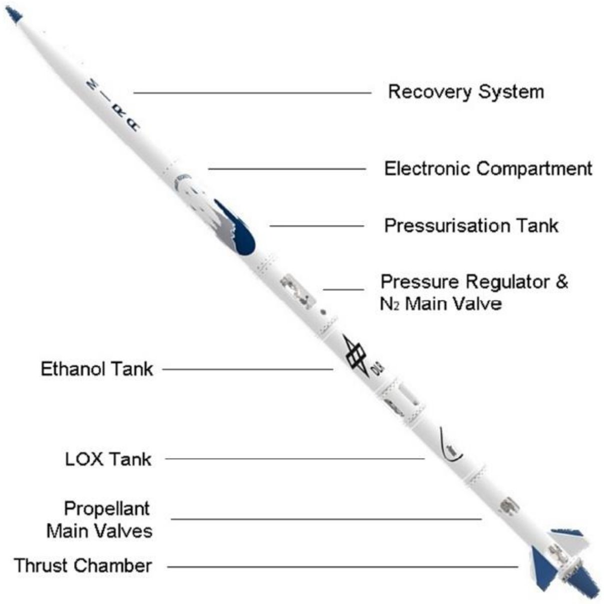


Figure 2-7: MIRA Rocket Developed by TU Dresden.

The SMART Rockets test bench is comprised of the propellant feed lines, the pressurant line, the control box and sensors, an engine rack and the control computer [45]. A schematic of the test bench is presented in Figure 2-8. The propellant lines are ½ inch copper tubing, while the pressurant and purge lines use ¼ inch tubing. Copper tubing was selected over stainless steel piping as it allows for easier on-site modifications. The propellant containers are commercially sourced aluminium tanks suitable for cryogenic liquids that were modified in the university workshop to provide connectors on the top and bottom of each tank [45].

Pressurization System

The manual pressure regulator (Item N1, see Figure 2-8) on the nitrogen supply cylinder is used to regulate the pressure from 200 bar to 40 bar. The nitrogen supply cylinder is equipped with a particulate filter (N2) and a manual control valve (N3). A manual venting valve (N4) is used to de-pressurize the nitrogen supply lines after testing and a pressure relief valve (N5) protects the downstream components from accidental over-pressurization.

The nitrogen supply is then split in two lines that are connected to the propellant tanks. The pressure is measured at this location using a pressure sensor (N6), and then the pressure of each line is stepped down from 40 bar to 25 bar by a manual pressure regulator (N7 and N9). Each pressurant line to the propellant tanks is equipped with its own normally closed solenoid valve (N8 and N10), which are operated remotely to control propellant pressurization. An off-take from the nitrogen line is passed through a manual pressure regulator (N11) that further reduces the pressure from 40 bar to 6 bar for low-pressure applications, specifically purging and the pneumatic supply [45].

Fuel Supply Line

A multi-point adaptor fabricated by the university is installed above the fuel pressurization tank. The adaptor houses a filling port (F1), a pressure sensor (F2), a connection point for the pressurant line with a check valve (F3) to prevent backflow, an analogue pressure gauge (F4) and a pressure relief valve (F5). The pressure relief valve has a manual release that can be used to vent gases while filling the tank.

Pressurized fuel will flow from the bottom of the tank to the combustion chamber along the fuel supply line. A 440 micron particulate filter (F6) is located after the tank to remove any potential contaminants and debris in the fuel. This is followed by a flow meter (F7) and a manual ball valve (F8) that must be manually opened prior to testing. The main fuel control valve (F9) is operated remotely during firing and is a normally closed pneumatic valve. No solenoid or electrically actuated valves are used along the propellant feed lines to reduce the risk of an explosion or catastrophic failure [45]. A check valve (F10) is located after the main fuel valve along with a pressure sensor (F11) to measure and record the fuel pressure entering the combustion chamber. An additional check valve (F12) is located at the connection point to the combustion chamber to prevent any back-flow along the propellant lines in the case of a test misfire.

Oxidizer Supply Line

The oxidizer supply line is similar to the fuel supply line, however since LOX is cryogenic, there are some notable changes. Connected to the multi-point adaptor installed on top of the oxidizer tank are: a pressure relief valve (O1), a pressure sensor (O2), a connection port to the pressurant line with a check valve (O3), an analogue pressure gauge (O4), a burst disc (O5) and a manual venting valve (O6) used during the filling procedure.

The oxidizer supply line is connected to the bottom of the tank. Temperature data are recorded at two points along the line using Type-K thermocouples (O7 and O9), and a tee-off with a manual valve (O8) is located below the tank for refilling. A cryogenically-rated, oxygen cleaned 250 micron particulate filter (O9) eliminates any contaminants in the oxidizer before a Coriolis-type flow meter (O11) measures the volumetric and mass flow rates. The main oxidizer control valve is a normally closed pneumatic valve (O12) that is operated remotely to control the oxidizer flow. Check valves are installed after the main valve and just before the connection to the combustion chamber (O13 and O15 respectively). The oxidizer pressure is recorded at the end of the propellant feed line using a pressure sensor (O14).

Purge and Drain Lines

The purge lines on the SMART Rockets test bench are ¼ inch copper tubes and flood the combustion chamber with low-pressure nitrogen when activated. As previously mentioned, a take-off from the nitrogen supply line is passed through a manual pressure regulator (N11) and is split into four lines using a manifold – two lines for the pneumatic supply to the main propellant valves and two lines for the purge lines. Each purge line is controlled using a normally closed solenoid valve (P1 and P2). One line is connected to the fuel supply line and the other to the oxidizer supply line, just before the combustion chamber. A check valve (P3 and P4) is installed at each connection point to prevent any back-flow in the purge lines.

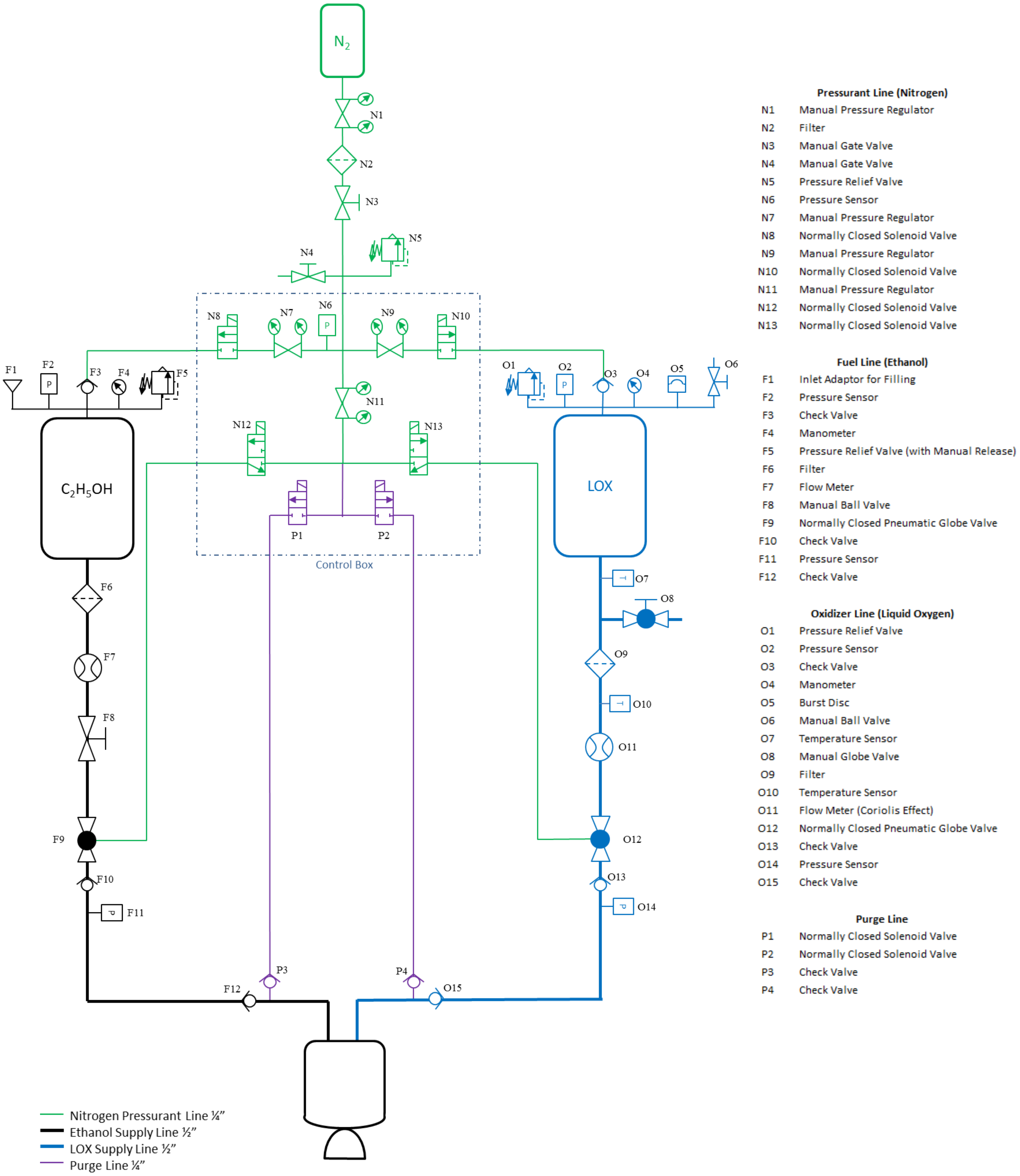


Figure 2-8: Schematic of SMART Rockets Test Bench redrawn from [45].

A schematic of the SMART Rockets test stand emergency drain system is contained in Figure 2-9. The emergency drain system is a critical safety element of the test stand and is used to divert the propellants away from the combustion chamber to collection tanks (Item D13 and D14, Figure 2-9) and de-pressurize the propellant tanks. Due to the key nature of the emergency drain system, the system must be entirely redundant and reliable. As such, it is operated using a combination of manual and pneumatic valves. The pneumatic supply can be manually switched between nitrogen and compressed air (D1) using a manual valve (D2) to ensure redundancy. A pressure relief device (D3) is installed to avoid accidental over-pressurization and an additional manual valve (D4) is used to prime the system [46].

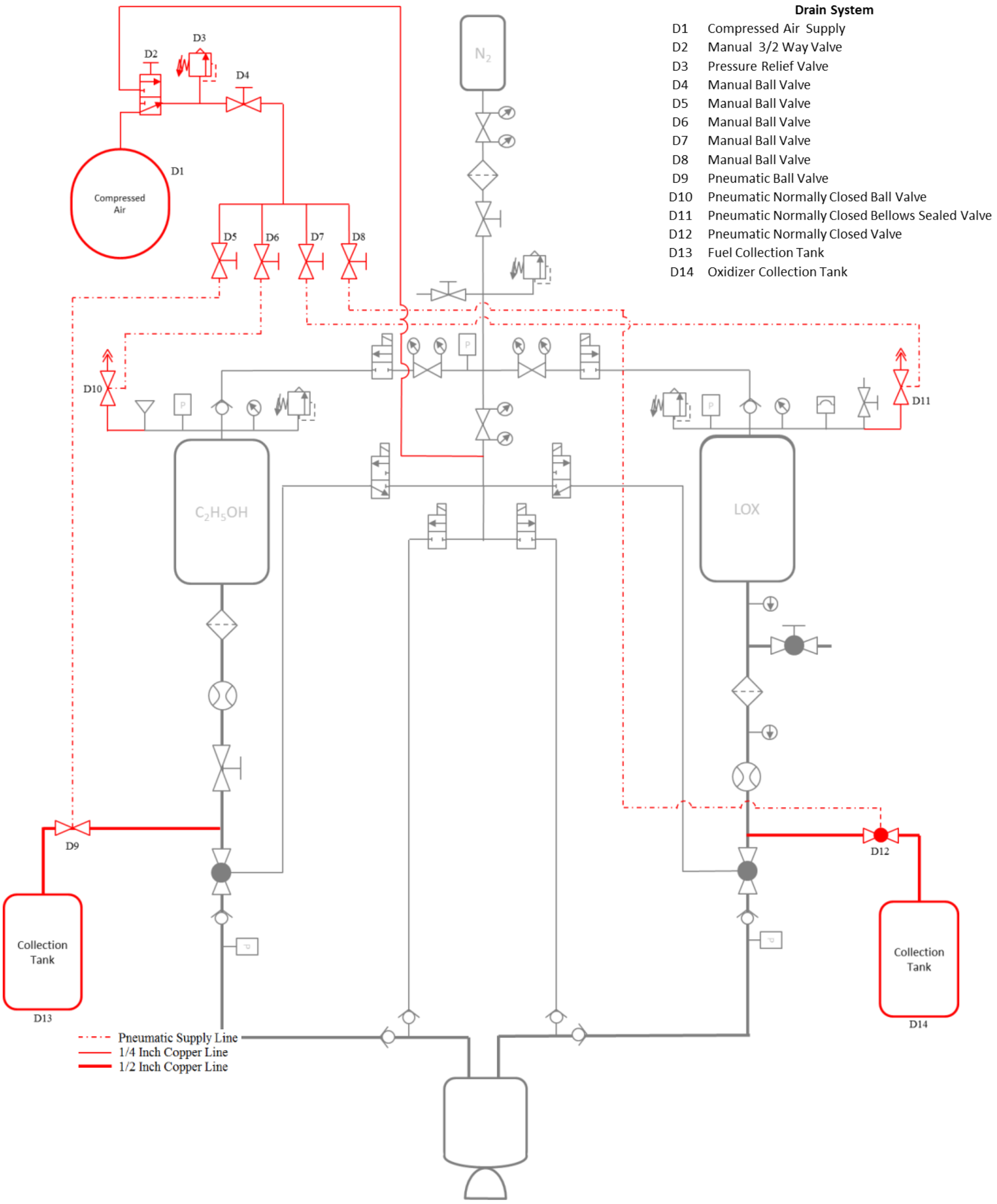


Figure 2-9: Emergency Drain System of SMART Rockets Test Stand redrawn from [46].

The manual valves (D5-8) are used to manually operate the corresponding pneumatic valve (D9-12), as per the following [46]:

- Opening D5 operates the pneumatic valve D9 to divert the ethanol supply to the fuel collection tank,
- Opening D6 operates the pneumatic valve D10 to de-pressurize the fuel tank,
- Opening D7 operates the pneumatic valve D11 to de-pressurize the oxidizer tank, and
- Opening D8 operates the pneumatic valve D12 to divert the LOX supply to the oxidizer collection tank.

Control System

The control system comprises the various sensors and DAQ system, the test stand control software and a control box (indicated in Figure 2-8). The control box is the interface between the electrical and mechanical parts of the test stand. It houses the power supply unit, the printed circuit board (PCB) used to collate the data from the sensors, and the relays used to control the solenoid valves [45]. The relays are triggered by an incoming digital high-signal that switches a transistor thereby applying a voltage to the relay. The relay in turn switches an according voltage and opens the respective solenoid valve. The control software was developed using LabVIEW and will automatically intervene if certain measurements fall outside of the defined safety limits [45].

Thrust measurements are achieved using a load cell installed underneath the engine support structure. Using lever principles, the load cell can be used to measure engines with a thrust between 100 and 3,000 N. The engine support structure allows for mounting of the injector, the combustion chamber and the ignition system. A reusable ignitor using propane and oxygen was developed by the university for the test stand. The ignitor has a central mixing chamber and is ignited using a spark plug controlled by the test stand software [45, 43].

2.2.6 Comparison and Findings

Table 2-4 contains a comparison of the key elements of the five university LRE test stands reviewed in the literature survey.

Table 2-4: Comparison of Similar University Liquid Rocket Engine Test Stands.

Characteristic	**Test Stand**				
	Water-Flow Test Stand	**Hydra**	**MRETS**	**Luleå**	**SMART Rockets**
Oxidizer/Fuel	Water / Water	GOX / Kerosene	LOX / Liquid Methane	GOX / Ethanol	LOX / Ethanol
Max Engine Thrust (N)	Not Specified	4,450	22,200	1,000	3,000
Control Software	LabVIEW	LabVIEW	LabVIEW	LabVIEW	LabVIEW
Pressure Regulation	Active PID Controller	Manual Regulator	Manual Regulator	Active PID Controller	Manual Regulator
Thrust Measurement	NA*	Load Cell on Engine Mount	Load Cell with Thrust Rod	Load Cell on Engine Mount	Load Cell with Levered Frame
Ignition System	NA*	Not Specified	Tapped-off Propellants & E-Match	Oil-filled Ignition Coil	Propane & Oxygen with Spark Plug
Main Propellant Valve Actuation	Pneumatic (Nitrogen)	Pneumatic (Compressed Air)	Cryogenic Solenoid Valves	Electronically Actuated	Pneumatic (Nitrogen)

*The Water-Flow Test Stand only performs cold fire tests.

Analysis of the aforementioned test stand designs reveals the following salient points and design principles that must inform the design of the UCT LRE Test Stand:

1. Particulate filters are required to remove contaminants and debris from the system and are located on the pressurant supply and after the propellant tanks,
2. Manual valves should be incorporated into the pressurant and propellant lines as part of the safety system and are opened before testing. The test bench designs generally use ball valves for gaseous and liquid media and globe valves for cryogenic liquids,
3. Solenoid valves allow for safe, reliable and fast-acting control of media flow,
4. Valves used to control the pressurant supply must open slowly (but shut quickly) to avoid slamming the propellants inside the tank with a column of gas,
5. Pressure relief devices and burst discs are required on the pressurized vessels to avoid damage or injury from accidental over-pressurization,
6. Venting valves are required on pressurized subsystems to allow for de-pressurization after testing or in an emergency shut-down,
7. Valves on the propellant tanks allow for venting of gases when refilling the tanks,
8. Propellant tanks can be equipped with multi-point adaptors to allow for additional connections,

9. Similarly, manifolds can be used to connect numerous gas cylinders in parallel,

10. Drain, purge and emergency shut-off systems are a critical part of the safety system,

11. Drain connections on propellant lines carrying liquids need to be located at the geometrical lowest point of the system to avoid propellant entrapment,

12. GOX and gaseous nitrogen can be vented to the atmosphere, whereas any drained fuels must be drained to a collector tank,

13. The safety system must return the test bench to a safe state in the event of a power failure and the control software must automatically shut-down the test stand if any readings approach unsafe limits,

14. Check valves ensure safe operation of the propellant feed assembly by limiting the flow in only one direction,

15. Main control valves for the propellants should ideally be pneumatically actuated to reduce the risk of sparks and/or explosions. Solenoid valves can be used to toggle the pneumatic supply to the main control valves and can be located in a safe location,

16. The pneumatic supply system is generally a low-pressure (between 3 and 7 bar). gaseous nitrogen or compressed air system. A buffer tank may be required to ensure the pneumatic supply system has sufficient capacity to meet the high-flow requirements of the pneumatic valves,

17. Active pressure regulation using PID controllers presents specific challenges relating to tuning and control. Also, the incorporation of such controllers results in the test stand having a different design to potential flight models of the rocket,

18. Cryogenically-rated pressure sensors can be costly. To overcome this, “pig-tail” connectors can be employed to allow for the use of non-cryogenic sensors,

19. Similarly, pressure sensors used at the combustion chamber can be connected using open-ended tubes of a sufficient distance to ensure the temperature in the location of the sensor is reduced to within the sensor’s operating range,

20. The most common temperature sensors utilized in the test stands are Type-K thermocouples, but PT 100 platinum temperature sensors can also be used,

21. Special attention is required for oxygen components to ensure material compatibility with the oxidizer. Furthermore, all components used with GOX or LOX must be cleaned for oxygen use to reduce the risk of combustion.

Chapter 3

3. Relevant Rocket Theory and Calculations

This chapter discusses the relevant rocket theory applicable to the UCT LRE Test Stand and presents the necessary calculations pertaining to the design thereof. It does not include theory and equations relating to the combustion chamber or the injector as these are outside the scope of work. All equations are taken from [15] unless stated otherwise.

3.1 Rocket Theory

3.1.1 Thrust and Velocity Theory

The total thrust (F_T) generated by the combustion chamber, in *N*, is given by:

$$F_T = \dot{m} v_e + (p_e - p_a) A_e \tag{3.1}$$

where $\dot{m}$ (in $kg\ s^{-1}$) is the total propellant mass flow rate and v_e is the average exit velocity (in ms^{-1}). The nozzle exit pressure and ambient pressure are indicated by p_e and p_a respectively and are measured in Pa. A_e is the cross-section area of the nozzle in m^2.

The ambient pressure is a function of the altitude above sea level h in *m*, as described in Equation 3.2 [47]:

$$p_a = 101{,}325(1 - 2.25577 \times 10^{-5} \times h)^{5.25588} \tag{3.2}$$

The average nozzle exit velocity is dependent on the propellant characteristics, the chamber pressure and the chamber temperature and is calculated as follows:

$$v_e = \sqrt{2RT_c \left(\frac{k}{k-1}\right)\left(1 - \left(\frac{p_e}{p_c}\right)^{(k-1)/k}\right)} \tag{3.3}$$

R is the gas constant of the working fluid with units $Jkg^{-1}K^{-1}$ and T_c is the temperature of the combustion chamber in K. The ratio of the specific heats of the oxidizer and fuel is denoted using k and is dimensionless. The chamber pressure is given in Pa and is denoted p_c.

The effective exhaust velocity, c, which is defined as the average mass-equivalent velocity of the propellant as it is ejected from the rocket is given in ms^{-1} and is calculated by dividing the total thrust by the total propellant mass flow rate:

$$c = \frac{F_T}{\dot{m}} = c^* \times C_F \tag{3.4}$$

As shown in Equation 3.4, the effective exhaust velocity is also equal to the product of the characteristic velocity, c^*, and the thrust coefficient C_F. The characteristic velocity is an engine parameter indicative of its efficiency and is given in ms^{-1}. The thrust coefficient provides information on how well the nozzle converts the latent utility of the propellants into thrust and depends on the physical characteristics of the nozzle and the chamber pressure.

As previously mentioned, another important parameter used to evaluate the performance of an engine is specific impulse (I_{sp}), which is measured in s and indicates the thrust generated by a rocket per unit of propellant:

$$I_{sp} = \frac{F_T}{g_0 \dot{m}} \tag{3.5}$$

where g_0 is the acceleration of gravity at sea level and is equal to $9.81\ ms^{-2}$.

3.1.2 Mass Flow Rate Theory

The propellant mixture ratio, r, is defined as the ratio of the oxidizer and fuel mass flow rates, and is written as:

$$r = \frac{\dot{m}_o}{\dot{m}_f} \tag{3.6}$$

where $\dot{m}_o$ and $\dot{m}_f$ are the oxidizer and fuel mass flow rates respectively in kgs^{-1}.

The total mass flow rate is the sum of the two propellant flow rates as shown below:

$$\dot{m} = \dot{m}_o + \dot{m}_f \tag{3.7}$$

It follows then that the fuel mass flow rate can be determined using the propellant mixture ratio and the total mass flow rate, as shown in Equation 3.8:

$$\dot{m}_f = \frac{\dot{m}}{1+r} \tag{3.8}$$

Note that the total mass flow rate can also be determined using the following equation [48]:

$$\dot{m} = \frac{A_t p_c}{\sqrt{T_c}} \left(\frac{k+1}{2}\right)^{-\frac{k+1}{2(k-1)}} \left(\sqrt{\frac{k}{R}}\right) \tag{3.9}$$

where A_t is the nozzle throat cross-sectional area in m^2 and can be described as:

$$A_t = \frac{F_T}{p_c C_F} \tag{3.10}$$

To determine the volumetric flow rate of the oxidizer or fuel required to meet a specific mass flow rate, the density of the propellant is required, as shown below:

$$\dot{V}_o = \frac{\dot{m}_o}{\rho_o} \tag{3.11}$$

$$\dot{V}_f = \frac{\dot{m}_f}{\rho_f} \tag{3.12}$$

where $\dot{V}$ is the volumetric flow rates (in m^3s^{-1}), ρ is the propellant density (in kgm^{-3}) and the subscripts *o* and *f* are used to indicate the oxidizer and fuel respectively.

The required volume of propellant for a given test duration (*Time* in *s*) can be calculated by multiplying the volumetric flow rate with the test duration, as shown below:

$$V = \dot{V} \times Time \tag{3.13}$$

Dynamic similarity states that two liquids with equal Reynolds numbers will exhibit identical steady-state flow properties. Cold fire test campaigns leverage this principle to use liquid nitrogen (LN_2) or distilled water to simulate the oxidizer and fuel [38]. The Reynolds number, R_e, in a tube is dependent on the tube diameter, *d* in *m*, and the dynamic viscosity, μ, of the fluid and the fluids mass flow rate, and is written as [38]:

$$R_e = \frac{4\dot{m}}{\pi d \mu} \tag{3.14}$$

To account for differences in viscosity, the mass flow rate of the replacement fluid (denoted using the subscript *repl.*) must be scaled accordingly to ensure the Reynolds numbers are equal.

This is done using Equation 3.15, where the original fluid is denoted using the subscript *original* [38]:

$$\dot{m}_{repl.} = \dot{m}_{original} \frac{\mu_{repl.}}{\mu_{original}} \tag{3.15}$$

3.2 Preliminary Design Calculations

3.2.1 Oxidizer and Fuel Mass Flow Rates

This section details the calculations performed as part of the preliminary design to determine initial design parameters, such as expected mass flow rates and required propellant volumes.

As a starting point to determine the required mass flow rates of the propellants for the UCT LRE Test Stand, the mass flow rates used in similar test stands were assessed, as shown in Table 3-1. These values are then increased according to the expected propellant mixture ratios and design factors to determine the expected maximum mass flow rates.

Table 3-1: Mass Flow Rates of Similar Test Stands.

Characteristic	**Test Stand**	
	SMART Rockets [44]	**Luleå UT** [17]
Oxidizer:	LOX	GOX
Fuel:	Ethanol	Ethanol
Thrust (N):	500	1,000
Total Mass Flow (kg/s):	0.250	0.447
Fuel Mass Flow (kg/s):	0.125	0.194
Ox. Mass Flow (kg/s):	0.125	0.253
O/F Ratio:	1.0	1.3
Chamber Pressure (bar):	15	15
Chamber Temperature (K):	2,750	3,030
Exhaust Velocity (m/s):	2,010*	2,236*
Specific Impulse (s):	205*	228*

* Calculated

It is important to note that assuming optimum expansion of the working fluid (i.e. assuming ideal gas laws), the ambient pressure, p_a, and nozzle exit pressure, p_e, are equal [15]. As such, Equation 3.1 simplifies to:

$$F_T = \dot{m} v_e \tag{3.16}$$

It is clear from the above equation that the total thrust of the rocket engine is directly proportional to the total mass flow rate and the nozzle exit velocity. As such, doubling either of these values will result in twice the thrust. The nozzle exit velocity is a function of the chemical properties of the propellants and the characteristics of the combustion chamber. As such, to determine the required mass flow rates for the 1.0 kN UCT LRE Test Stand, one can double the values indicated for the 0.5 kN SMART Rockets test stand, as shown below:

$$\dot{m}_{o,expected} = 2 \times 0.125 = 0.250\ kg/s \tag{3.17}$$

$$\dot{m}_{f,expected} = 2 \times 0.125 = 0.250\ kg/s \tag{3.18}$$

These mass flow rates assume a propellant mixture ratio of 1. However, literature indicates that the optimum propellant mixture ratio for oxygen/ethanol engines is between 1.3 and 1.6 depending on the ethanol concentration [49]. As such, the oxidizer mass flow rate must be increased to cater for differing mixture ratios:

$$\dot{m}_{o,max} = \dot{m}_{o,expected} \times r_{max} = 0.250 \times 1.6 = 0.400\ kg/s \tag{3.19}$$

To ensure the test bench has capacity for various engines and to account for unforeseen losses, the maximum flow rates are increased by a factor of 50%. For simplicity, the maximum fuel mass flow rate for the UCT LRE Test Stand is set at same value as the maximum oxidizer mass flow rate, as shown in Equation 3.20.

$$\dot{m}_{o,max} = \dot{m}_{f,max} = 0.600\ kg/s \tag{3.20}$$

3.2.2 Propellant Volume Requirements

The volumetric flow rate (in *l/s*) of the fuel and oxidizer is dependent on the fluid density (as taken from [45, 49]) and is determined using Equations 3.11 and 3.12. The total required volume (in *l*) of the propellants is then determined using Equation 3.13, with a maximum test duration of 25 seconds. The calculations are performed for three different concentrations of ethanol, namely 70%, 85% and 100% using the expected mass flow rate of 0.250 kg/s as well as the maximum mass flow rate of 0.600 kg/s. The results are presented in Table 3-2.

Table 3-2: Volumetric Flow Rates and Propellant Volumes for the UCT LRE Test Stand.

Fluid	**Density (kg/m^3)**	**Expected Mass Flow Rate:** $\dot{m}_o = \dot{m}_f = 0.25$ kg/s		**Maximum Mass Flow Rate:** $\dot{m}_o = \dot{m}_f = 0.60$ kg/s	
		Volume Flow Rate (l/s)	**Total Propellant Volume (l)**	**Volume Flow Rate (l/s)**	**Total Propellant Volume (l)**
70% Ethanol	885	0.282	7.06	0.678	16.95
85% Ethanol	845	0.296	7.40	0.710	17.75
100% Ethanol	789	0.317	7.92	0.760	19.01
LOX (93 K, 20 bar)	1130	0.221	5.53	0.531	13.27

It is clear from the above that the maximum propellant volumes required for a 25 second duration test fire are 13.27 litres of LOX and 19.01 litres of ethanol (if pure ethanol is used). These values are used to determine the minimum size requirements of the test stand propellant tanks. The minimum tank sizes are shown below, however it should be noted that larger tanks will allow for a greater volume of propellants, which translates to longer test durations:

- Minimum Oxidizer Tank Size:	15 litres
- Minimum Fuel Tank Size:	20 litres

It is necessary to ensure that the propellant tanks also have sufficient capacity to cater for cold fire tests of the same duration. During cold fire tests, distilled water is used to replicate the fuel and LN_2 is used to replicate LOX (see Section 5.2 for more details on the cold fire testing campaigns). The calculations are repeated for these liquids, with equivalent mass flow rates calculated using Equation 3.15 based on the dynamic viscosities taken from [50] and [51]. The results are presented in Table 3-3.

Table 3-3: Volumetric Flow Rates and Propellant Volumes for Cold Fire Liquids for the UCT LRE Test Stand.

Characteristic	**Fluid**	
Replacement Fluid:	Distilled Water	Liquid Nitrogen
Density (kg/m^3)	998	804
Dynamic Viscosity of Replacement Fluid (cP)	0.890	0.152
Dynamic Viscosity of Original Fluid (cP)	1.095	0.195
Equivalent Mass Flow Rate (kg/s) for 0.25 kg/s	0.203	0.195
Volume Flow Rate (l/s)	0.204	0.242
Total Volume Required (l)	5.090	6.059
Equivalent Mass Flow Rate (kg/s) for 0.60 kg/s	0.488	0.468
Volume Flow Rate (l/s)	0.489	0.582
Total Volume Required (l)	12.216	14.543

It is clear from the above that the previously calculated minimum fuel tank capacity is sufficient to accommodate the required volumes of the replacement liquids during cold fire tests. However, to simplify the manufacturing requirements, the capacity of both the fuel and oxidizer tanks is set at 20 litres, as shown below:

- Final Oxidizer Tank Size:	20 litres
- Final Fuel Tank Size:	20 litres

With these propellant volumes and mass flow rates the test stand can support various O/F mixture values up to 4.0 using varying ethanol concentrations (between 70 and 100%) for the full test duration of 25 seconds.

Chapter 4

4. Test Platform Design

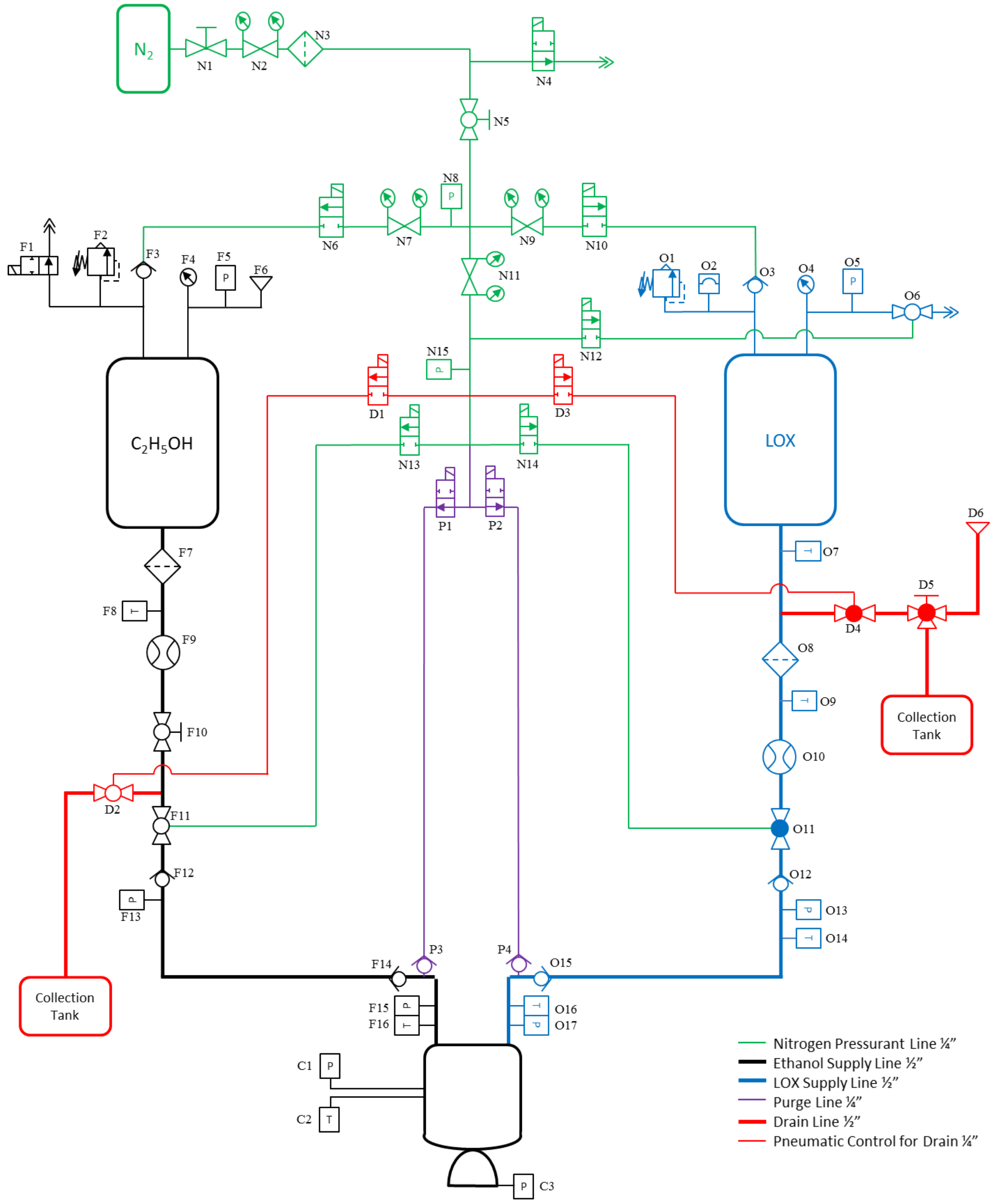
This section details the preliminary design of the UCT LRE Test Stand, with a specific focus on the propellant feed assembly. An overview of the Test Stand Control Centre is then provided based on the preliminary design in [52]. The structural support system, injector and the combustion chamber are then discussed briefly along with suggestions on their development.

4.1 Propellant Feed Assembly

The preliminary design of the UCT LRE Test Stand propellant assembly is depicted in Figure 4-1. The pressurant lines, pneumatic supply lines and the purge lines are constructed using ¼ inch copper tubing, while the fuel supply, oxidizer supply and drain lines are ½ inch copper tubing. The piping assembly can be constructed using copper or stainless steel tubing, however copper was selected as the material of choice as it is easier to machine. The design is a pressure fed system that uses gaseous nitrogen to pressurize the propellants and supply them to the combustion chamber at the required mass flow rates. The gaseous nitrogen is supplied using a commercially available nitrogen cylinder with a 200 bar pressure. A pressure reduced tap-off from the supply is used in the purge lines and for the pneumatic supply of the test stand. The design uses easily available COTS components for all valves, filters, regulators and burst disc assemblies, however the injector, combustion chamber and propellant tanks will need to be designed and fabricated specifically for this application.

4.1.1 Pressurization System

The manual valve (see Item N1, Figure 4-1) on the nitrogen cylinder is used to toggle the nitrogen supply. The manual pressure regulator (N2) and the particulate filter (N3) are also part of the cylinder assembly. The output pressure of the regulator is set to 40 bar and the particulate filter removes any potential debris or contaminants from the pressurant. A normally open solenoid valve (N4) is connected to an off-take of the nitrogen supply line and is used to de-pressurize the line before disconnecting the nitrogen cylinder or in an emergency shut-down. A normally open valve is selected to ensure the line is de-pressurized and vented to the atmosphere in the event of a power failure. A manual ball valve (N5) is then positioned on the nitrogen supply line and must be opened before testing commences. The supply line is then split into three separate lines: the fuel pressurization line, the oxidizer



	Pressurant Line (Nitrogen)
N1	Manual Needle Valve (on Gas Cylinder)
N2	Pressure Regulator (on Gas Cylinder)
N3	Particulate Filter (on Gas Cylinder)
N4	Normally Open Solenoid Valve
N5	Manual Ball Valve
N6	Normally Closed Solenoid Valve
N7	Pressure Regulator (25 bar output)
N8	Pressure Sensor
N9	Pressure Regulator (25 bar output)
N10	Normally Closed Solenoid Valve
N11	Pressure Regulator (6 bar output)
N12	Normally Closed Solenoid Valve
N13	Normally Closed Solenoid Valve
N14	Normally Closed Solenoid Valve
N15	Pressure Sensor

	Fuel Line (Ethanol)
F1	Normally Open Solenoid Valve
F2	Pressure Relief Valve
F3	Check Valve
F4	Pressure Gauge
F5	Pressure Sensor
F6	Filling Adaptor
F7	Particulate Filter
F8	Temperature Sensor
F9	Flow Meter (Turbine-type)
F10	Manual Ball Valve
F11	Normally Closed Pneumatic Ball Valve
F12	Check Valve
F13	Pressure Sensor
F14	Check Valve

	Oxidizer Line (LOX)
O1	Pressure Relief Valve
O2	Burst Disc
O3	Check Valve
O4	Pressure Gauge
O5	Pressure Sensor
O6	Normally Open Pneumatic Ball Valve
O7	Temperature Sensor
O8	Particulate Filter
O9	Temperature Sensor
O10	Flow Meter (Turbine-type)
O11	Normally Closed Pneumatic Globe Valve
O12	Check Valve
O13	Pressure Sensor
O14	Temperature Sensor
O15	Check Valve
O16	Temperature Sensor
O17	Pressure Sensor

	Purge Line
P1	Normally Open Solenoid Valve
P2	Normally Open Solenoid Valve
P3	Check Valve
P4	Check Valve

	Drain Line
D1	Normally Closed Solenoid Valve
D2	Normally Open Pneumatic Ball Valve
D3	Normally Closed Solenoid Valve
D4	Normally Open Pneumatic Globe Valve
D5	Manual 3/2 Pneumatic Globe Valve
D6	Filling Adaptor

	Combustion Chamber
C1	Pressure Sensor
C2	Temperature Sensor
C3	Pressure Sensor

Figure 4-1: UCT LRE Test Stand Propellant Assembly Schematic.

oxidizer pressurization line and a low-pressure line that is used for purging and pneumatics. A pressure sensor (N8) is installed at this location to allow for remote monitoring of the nitrogen pressure.

A normally closed solenoid valve (N6 and N10) and a manual pressure regulator (N7 and N9) are installed on each of the pressurization lines to the propellant tanks. There is a dedicated regulator on each line to allow for independent pressurization of the fuel and oxidizer tanks, although both regulators will be set at an output pressure of 25 bar for initial tests (but may be increased to 35 bar depending on the mass flow rates). The solenoid valve (N6) is used to start or stop the fuel tank pressurization remotely, while valve N10 controls the oxidizer tank pressurization. These valves are normally closed valves to ensure that if there is a loss of power, the tank pressurization is automatically terminated.

The low-pressure nitrogen tap-off is used to control the pneumatic valves along the propellant assembly and for purging. A manual pressure regulator (N11) reduces the pressure from 40 to 6 bar for these applications and is monitored with a dedicated sensor (N15). The pneumatic valves are controlled remotely using solenoid valves (N12, N13 and N14) operated by the test stand control software. These solenoid valves are all normally closed so that if power is lost the pneumatic supply is ceased and the pneumatic valves will return to their natural state, which is either normally open or normally closed depending on the valves function. Pneumatic valves used in the drain system or to vent pressures are normally open, while those used to control the flow of the propellants to the combustion chamber are normally closed to ensure the test stand is automatically returned to a safe state if there is a power failure.

4.1.2 Propellant Tanks

The propellant tanks will be purchased locally and will be constructed from stainless steel or aluminium. The tanks will have an expected operating pressure between 25 and 35 bar, however they must be rated for a maximum pressure of 100 bar for safety. The fuel and oxidizer tanks are identical and are specified with two ports located at the top and one port at the bottom of each tank.

The top two ports will house the safety equipment (specifically the pressure relief valves and burst disc assemblies), the pressure sensors and the connection to the pressurization line. On the fuel tank a filling port is also included on the top of the tank. If required, multi-point adaptors can be used to ensure all components can be connected safely and securely. The bottom port will be connected to the propellant supply lines that connect to the combustion chamber.

In Section 3.2.2, the minimum required volume of the propellant tanks was calculated to be 20 litres. The tanks must be approved for use by the South African Bureau of Standards (SABS) or similar Approved Inspection Authority (AIA) in accordance with South African National Standard (SANS) 347:2019 *Categorization and Conformity Assessment Criteria for All Pressure Equipment* [53].

4.1.3 Fuel Supply

A normally open solenoid valve (F1) is located on top of the fuel tank to allow for remote de-pressurization of the tank. This valve must be actively kept closed by the Test Stand Control Centre during tank pressurization and testing. If there is a loss of power the valve will return to its normally open state to vent the nitrogen pressurant to atmosphere and de-pressurize the fuel tank. Also located on top of the tank is a pressure relief valve (F2), a manual pressure gauge (F4), a pressure sensor (F5) and a filling port (F6). A check valve (F3) is located at the nitrogen line connection to ensure unidirectional flow and the pressure relief valve is used to prevent over-pressurization of the vessel.

The pressurized fuel will flow out the bottom of the tank through the ½ inch fuel supply line to the combustion chamber. A 20 micron particulate filter (F7) is located after the tank along with a temperature sensor (F8). A turbine-type flow meter (F9) is used to monitor the volumetric flow rate, which is used to calculate the fuel mass flow rate in the control software.

The main fuel control valve is a normally closed pneumatic ball valve (F11) controlled using the solenoid valve (N13) on its pneumatic supply line. A normally closed valve is specified for the main fuel control valve to ensure that in the event of a power failure the fuel flow to the combustion chamber is automatically ceased.

A check valve is located after the main fuel control valve (F12) and another before the fuel supply line connects to the combustion chamber (F14) to prevent any backflow towards the fuel tank. Pressure and temperature data are monitored at the connection to the combustion chamber using sensors (F15 and F16), while the pressure sensor (F13) monitors the pressure just after the main fuel control valve.

4.1.4 Oxidizer Supply

All components installed on the oxidizer tank and supply line must be rated for cryogenic application and cleaned for oxygen use (as per the Compressed Gas Association (CGA) G-4.1 *Cleaning of Equipment for Oxygen Services* 2018 standard [54]). Furthermore, the oxidizer tank, the ½ inch piping and all components on the oxidizer supply line must be sufficiently insulated to reduce evaporation of the LOX.

The one port on top of the oxidizer tank is used to connect a pressure relief device (O1), a burst disc assembly (O2) and the nitrogen pressurant connection with a check valve (O3). Connected to the other port is a manual pressure gauge (O4), a pressure sensor (O5) and a normally open pneumatic ball valve (O6). The pressure relief valve is used to prevent over-pressurization and will vent gas as the pressure inside the tank increases due to evaporation of the LOX. The burst disc is included to allow for rapid de-pressurization of the tank should the pressure relief device malfunction or fail. The pneumatic valve acts as a venting valve and is used to de-pressurize the tank remotely by controlling the solenoid valve (N12). In the case of a power failure, the solenoid valve will fail closed thereby removing the pneumatic supply to the venting valve, which will in turn return to its naturally open state and de-pressurize the tank. The venting valve is pneumatic as its location is in an oxygen rich environment and any electrically actuated valves pose a safety risk in such environments.

A temperature sensor (O7) is used to monitor the LOX temperature as it exits the tank. A cryogenically-rated, cleaned for oxygen use 20 micron filter (O8) is employed to remove any debris or contaminants from the oxidizer that could potentially block the injector in the combustion chamber and result in unsafe conditions. An additional temperature sensor (O9) is located before the Coriolis-type flow meter (O10).

The main oxidizer control valve (O11) is a normally closed pneumatic globe valve. A globe valve is specified over a ball valve as per the recommendations in certain literature that raise concerns with LOX possibly becoming trapped inside a ball valve resulting in potentially unsafe conditions [40]. The main oxidizer control valve is controlled remotely using the solenoid valve (N14) on its pneumatic supply line. In the event of a loss of power, the valve will return to its normally closed state and shut off the flow of LOX to the combustion chamber. A check valve (O12), a pressure sensor (O13) and a temperature sensor (O14) are situated just after the main oxidizer control valve as well as at the connection of the oxidizer supply line to the combustion chamber (O15, O16 and O17 respectively).

4.1.5 Purge System

The purge system consists of two separate ¼ inch lines connected to the low-pressure nitrogen supply. One line is connected to the fuel supply line at its connection point to the combustion chamber and the other is connected to the oxidizer line in a similar location. The purge line is used to flood the combustion chamber with nitrogen to terminate a test when required. Normally open solenoid valves (P1 and P2) are used to control the purge lines to ensure that if there is a power failure the combustion chamber is automatically purged. Check valves (P3 and P4) are located at the end of the purge lines to ensure they do not interfere with the functioning of the test stand during normal operation.

4.1.6 Drain System

The drain system is used to divert the propellants away from the combustion chamber to dedicated collection tanks in the case of an emergency or if a test needs to be ended prematurely. The drain system uses pneumatic valves since no electrically actuated valves are allowed on the propellant supply lines as per the design philosophy. The piping in the drain system is constructed using ½ inch piping and ¼ inch piping is used for the pneumatic supply. The drain system is designed to ensure that if there is an unexpected loss of power, the propellants will drain automatically to separate tanks.

The drain line on the fuel supply line is connected just before the main fuel control valve. A normally open pneumatic ball valve (D2) is used to control the draining of the fuel line and must be actively kept closed during testing. It is controlled using the normally closed solenoid valve (D1) on its pneumatic supply. The combination of a normally closed solenoid valve and normally open pneumatic valve ensure that if power is lost unexpectedly, the fuel line and tank are immediately drained.

The drain line on the oxidizer line is slightly more complex as it also provides functionality for refilling the oxidizer tank (which is done from below the tank). This is achieved using a three port, two way manual pneumatic globe valve (D5) that is used to connect either the filling port (D6) or the drain tank to the oxidizer line using a ½ inch tube connected before the particulate filter (O8) as shown in Figure 4-2. A normally open pneumatic globe valve (D4) is located on the tube, near the connection to the oxidizer supply line. The pneumatic valve is controlled by operating the normally closed solenoid valve (D3). Before testing, the manual globe valve is set to the drain connection to ensure the system can be drained in an emergency if needed. The pneumatic valve (D4) is actively kept closed during testing and is opened to drain the oxidizer to the collection tank when required.

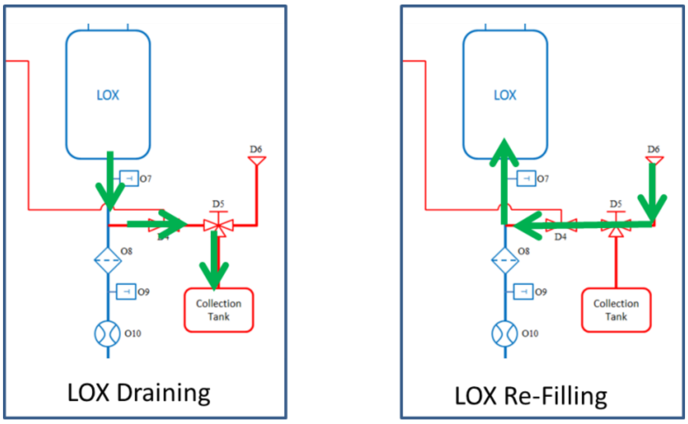


Figure 4-2: LOX Draining and LOX Refilling on the UCT LRE Test Stand.

LOX refilling is done as follows: i) set the manual valve (D5) to the refill connection, ii) open the pneumatic valve (D4) using the relevant solenoid valve (N12), iii) open the pneumatic venting valve (O6) on top of the LOX tank, iv) commence oxidizer refill procedure.

4.2 Control System

The data acquisition and control system has been designed by James Wilson, a post-graduate student at UCT's SpaceLab in his thesis titled "Preliminary Design of a Test and Launch Control Centre for Liquid Propellant Rocket Engine Applications" [52].

The control system consists of the control software installed on a Windows laptop, two Arduino Due microprocessors, a power supply unit, the measurement elements and the valve and ignition control subsystems. The control software is developed using Makerplot, which is an affordable graphical plotting and DAQ software. Data acquisition and active control is achieved using two Arduino Due microprocessors located on the test stand. Communication between the remote control software and the microprocessors is performed using an Ethernet cable and two dedicated analogue lines to control the ignition system and purge lines independently [52]. Figure 4-3 provides an overview of the Test Stand Control Centre for the UCT LRE Test Stand.

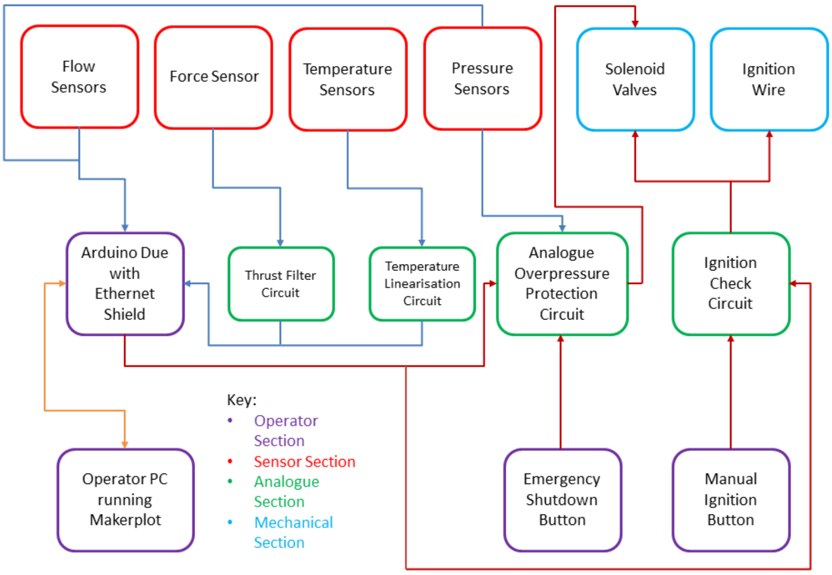


Figure 4-3: Overview of Control System for the UCT LRE Test Stand [52].

An example of the graphical user interface (GUI) of the control software developed in Makerplot is depicted in Figure 4-4. Note that the on-screen schematic is a simplified example based on the Water-Flow Test Stand and does not represent the propellant feed assembly of the UCT LRE Test Stand.

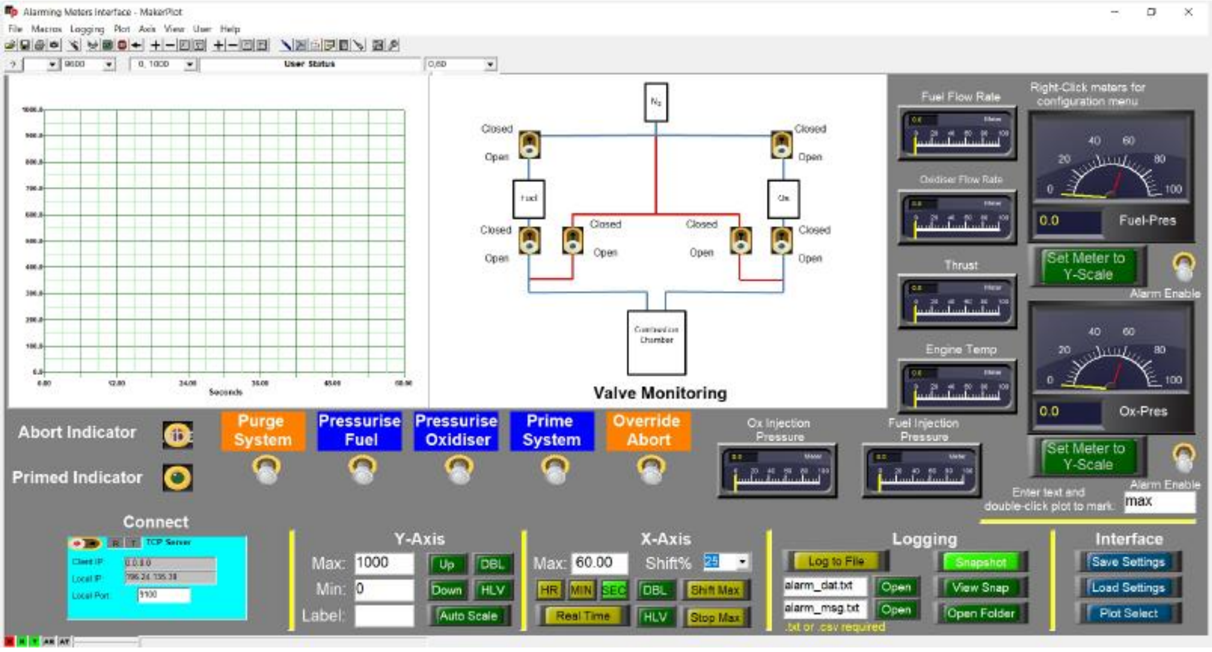


Figure 4-4: Graphical User Interface developed for the UCT LRE Test Stand [52].

4.2.1 Measurement Systems

This section details the various measurement systems included in the UCT LRE Test Stand and their integration with the DAQ system, namely: the pressure sensors, temperature sensors, flow meters, thrust sensors, vibration transducers and closed-circuit television (CCTV) cameras. Schematics of the associated interfacing and control circuits are contained in Appendix A.

Pressure Sensors

Common electronic pressure sensors generate either a proportional voltage or proportional current signal, generated by the movement of the sensor's internal diaphragm connected to a strain gauge [52]. The sensors are sized according to the expected operating pressures and temperatures at their location on the propellant feed assembly. Circuits for interfacing with pressure sensors of both operational types have been developed and tested and are depicted in Figure A-1 and A-2 of Appendix A.

Temperature Sensors

Temperature transducers commonly used in rocket engine applications are resistance temperature detectors (RTDs) and thermocouples due to their large operational ranges. Generally, RTDs offer more accurate measurements; however they require additional compensation and interfacing circuitry when compared to thermocouples. As such, Type-K thermocouples are specified as the temperature sensors for the UCT LRE Test Stand. Type-K thermocouples have an operational range of -200 to 1200 °C and can be secured using Kapton tape [52].

The thermocouples contain a junction of different metals that generates a small emf based on the temperature. This emf needs to be amplified and compensated. This is achieved using the Analog Devices AD8495 thermocouple amplifier. The associated circuit design required for accurate temperature measurements using Type-K thermocouples is contained in Figure A-3 of Appendix A. Due to the high temperatures it is not possible to measure the temperature inside the combustion chamber during a test, rather the internal chamber pressure is inferred based on temperature measurements on the external surface [52].

Mass Flow Measurement

The recommended flow meter on the fuel supply line is a stainless steel turbine-type meter, capable of measuring the continuous volume flow and transmitting it to the control software. The volume flow of the fuel is then converted into a mass flow by the control software using the fuel density. Turbine flow meters are one of the least expensive meter types, however because they use in-line sensing elements that impede flow they have an associated pressure drop. Furthermore, they often have requirements of the piping upstream and downstream of the meter, specifically that there can be no bends or pipe specials within a certain distance either side of the flow meter. However, the pressure drop is not significant enough to interfere with the delivery of the fuel to the combustion chamber and the piping requirements of the meter can be easily accounted for in the piping train [52, 55]. Although ethanol is non-corrosive, care must be taken when selecting the flow meter materials to ensure material compatibility, especially with the seals and wetted parts. The fuel will have an operating temperature equal to ambient temperature and an expected operating pressure of between 25 and 35 bar.

The flow meter selected to measure the oxidizer mass flow rate has additional requirements. Firstly, the operating temperature range of the meter must be capable of withstanding the cryogenic LOX temperature of approximately -183° C. Furthermore, the materials of the meter must be compatible with LOX and cleaned for use with oxygen since the high concentration of oxygen in the oxidizer makes metals more susceptible to combustion and at high temperatures most materials (metallic and non-metallic) will combust in 100% oxygen [18]. As such it is imperative to not only ensure material compatibility and oxygen cleaning (to remove potential combustibles), but also to eliminate all possible heat sources. Heat sources include localized heating caused by particles with high velocities impacting with a material, localized heating caused by mechanical impact inside of valve bodies, friction heating and compression heating associated with rapid compression [18, 56].

Common flow measurement techniques for LOX are indirect techniques that do not use in-line elements, such as Coriolis-type flow meters, Venturi tubes (or differential pressure flow meters) and orifice-type flow meters. Coriolis-type flow meters are beneficial in that they can measure mass flow directly with great accuracy however; they are costly and are not suitable for very large mass flow rates. Turbine-type flow meters developed specifically for LOX use are available and provide good accuracies, but generally only measure volumetric flow rates [57, 58]. The MRETS Test Stand uses the turbine-type FML 250 Liquid Flow Meter for measuring liquid methane and LOX, while both the SMART Rockets test stand and the Luleå University of Technology test stand use Coriolis-type flow meters [40, 45, 17]. It is recommended that a cryogenic Coriolis-type flow meter is used on the UCT LRE Test Stand as it can measure volumetric and mass flow rates as well as fluid density [52].

Thrust Measurement

The thrust generated by the rocket engine in a hot fire test is recorded with a load cell comprised of numerous strain gauges connected using a Wheatstone bridge. The load cell will have a minimum rating of 100 kg and can be installed at the engine mount or underneath the engine mount support structure. The latter option is advantageous in that simple lever principles can be employed to allow for measurements of larger rocket engines should they be required. The output signal from the load cell is passed through a differential amplifier (such as the Analog Devices AD623) before being sent to the microprocessor [52]. The circuit schematic for ensuring accurate, precise measurements with the load cell is depicted in Figure A-4 of Appendix A.

Vibration Measurements

The structural support structure of the test stand will be designed with a specific mechanical frequency bandwidth to avoid potential failures as a result of resonance, although it is expected that this will be negligible due to the relatively low thrust values associated with the test stand. Nevertheless, since the test stand is designed for use within the university, monitoring the vibrations within the test stand during a hot fire test will provide educational value. Vibration measurements can be performed using a sensitive three-axis accelerometer, such as the Analog Devices ADXL325 unit, which has a pre-filtered bandwidth of 1600 Hz. If required, a low-pass filter can be included in the circuit to reduce the noise levels. The accelerometers are fairly affordable and as such multiple units can be installed at various locations around the test stand structure [52].

Closed-Circuit Television Cameras

The preliminary design of the control centre for UCT’s LRE Test Stand recommends the inclusion of high definition (HD) Ethernet-enabled CCTV cameras for real-time visual verification of the pressures indicated on the manual pressure gauges situated on the propellant tanks [52]. An additional HD camera should be installed in a location some distance away from the test stand to transmit and record the rocket exhaust plume during hot fire tests.

4.2.2 Control Elements

The solenoid valves are controlled using appropriately sized relays to ensure the current requirements of the valves are met [52]. If required, solid state relays can be used, which have no moving parts and offer increased longevity.

The ignition system recommended in [52] is a small length of Nichrome wire covered in ethanol-soaked cotton wool placed inside the combustion chamber before testing. When current flows through the Nichrome wire, it heats up rapidly causing the ethanol-soaked cotton wool to ignite. The timing of the ignition sequence must be accurately controlled by the control system. This can be achieved by using hard-coded delays in the control software, coupled with verifications of the pressures and mass flow rates in the fuel and oxidizer supply lines. Ignition is activated using a manual push-button and will only commence if the conditions are safe. This will avoid a hard start, which occurs when there is too much fuel in the combustion chamber and can result in an explosion [52]. To successfully activate the ignition system a sufficient amount of oxygen must be present in the combustion chamber.

4.3 Structural Support System

As defined in Requirement #2 and #3 (see Section 1.4), the test stand must have a modular design capable of mounting various engine designs and must fit inside a standard 20 foot shipping container. It is proposed to instead construct the test stand on a flat-bed trailer, similar to the MRETS test stand (see Figure 2-4), to allow for easy transportation. The support structure will be mounted to the trailer and will comprise an engine mount structure, a load cell support structure and a strongback frame constructed using welded steel tubing. The engine mount structure provides different mounting positions to support varying rocket engine designs. The load cell support structure is used to house the load cell for accurate thrust measurements and transfers the load from the engine through the load cell to the strongback. The design of the load cell support structure should allow for testing of engines with different thrust capacities by employing basic lever principles. The strongback in turn transfers the thrust to the ground at the test site and has capability to be installed against a vertical steel I-beam or directly to the ground using removable steel legs fastened to the ground [40]. Static structural analyses must be performed to confirm the structure is capable of withstanding the forces and stresses during test fires without deforming or buckling, as per Requirement #9.

It is also recommended that a blast shield is incorporated into the test stand design to protect the propellant feed assembly and propellant tanks from damage arising from a potential engine misfire. The MRETS team designed a blast shield using Kevlar armor paneling after conducting a study on the puncture prevention capabilities, melting points, densities and minimum thicknesses of various materials [40]. However, since the thrusts associated with the UCT LRE Test Stand are an order of magnitude smaller than MRETS, a dedicated blast shield design is not required. Rather, it is recommended that a temporary blast shield is constructed on site using water-filled containers or sand bags stacked to a sufficient height located between the combustion chamber and the propellant feed assembly.

4.4 Injector and Combustion Chamber

To realize hot fire tests, an injector and a combustion chamber must be designed and constructed. The injector mixes and atomizes the oxidizer and fuel to ensure complete combustion within the chamber and decouples the propellant feed assembly from the vibrations of the combustion chamber during firing. There are numerous different injector types, however coaxial swirl injectors are the most commonly used injectors in LREs due to their efficient atomization, good mixing properties, throttleability and combustion stability margins [59, 60].

The Luleå University of Technology test bench proposes a brass conical spray injector (since their stand has only one liquid propellant) and a copper combustion chamber complete with a stainless steel cooling jacket and water cooling system [17]. The SMART Rockets project designed and manufactured a coaxial swirl injector with an adjustable oxidizer nozzle recess for use on their test stand [60]. They also developed a modular test combustion chamber to facilitate studies of rocket engines with different characteristic lengths. It is constructed using a copper inlay and a steel cooling jacket that uses water to provide chamber cooling and consists of three different segments (one nozzle segment and two chamber segments with different lengths) [59].

It is recommended that a brass coaxial swirl injector and a copper combustion chamber (complete with a water cooling system and steel jacket) are investigated for use with the UCT LRE Test Stand. Thorough static-thermal and static-mechanical analyses using ANSYS must be performed to determine the number of cycles the chamber can withstand before failing.

Chapter 5

5. Testing Campaigns

This chapter details the necessary tests and procedures to commission, verify and characterize the UCT LRE Test Stand. Thereafter the cold and hot fire test campaigns are discussed and a hot fire test procedure is presented.

5.1 Test Platform Verification

To commission the test stand and verify its safety and performance, an extensive testing and validation campaign must be performed. First, the performance of the individual components is validated and all sensors are calibrated and verified. Once the propellant feed assembly is constructed, hydrostatic pressure tests and gas leak tests are performed to ensure the system is safe to operate. Thereafter, characterization of the feed assembly lines and the injector are performed as well as functional testing of the control system. The propellant feed assembly can be isolated into smaller sections by closing the relevant valves to assist with the pressure and leak tests.

5.1.1 Hydrostatic Pressure Tests

Hydrostatic pressure testing is performed to identify leaks and confirm the system can maintain and hold the expected operating pressures during normal operation. It is a requirement in both the SANS 347:2019 *Categorization and Conformity Assessment Criteria for All Pressure Equipment* and ASME B313.3 – 2020 *Process Piping* standards. The testing procedure will be a modified proof pressure test and involves filling the propellant feed assembly with an incompressible fluid and using a hydrostatic pump to pressurize the system for a specified duration [39].

The test pressure is set at 150% of the operating pressure and is monitored for the test duration. Any drop in pressure during the test is indicative of a leak where pressure is escaping. Leaks are identified via visual inspection and dyes can be added to the testing fluid to aid in this regard. If a leak is identified, then the system is de-pressurized, the relative component is tightened and the pressure test is repeated. The pressure tests are performed in an increasing staged approach where each stage has a pressure equal to one fifth of the final test pressure [39, 61].

Deionized water must be used for the hydrostatic pressure tests instead of hydraulic fluids or oils. An incompressible fluid is used to ensure that any failures will have a relatively small amount of energy compared to a compressible gas and will result in minimal damage.

The SABS-approved propellant tanks will be pressure tested by the tank manufacturer and must be issued with the relevant certification. It is recommended that an external service provider is contracted to assist with the hydrostatic pressure tests of the test stand. *Foxolution* is a Cape Town based company that can assist in this regard as well as provide oxygen cleaning services [62].

5.1.2 Gas Leak Testing using Gaseous Nitrogen

After successful hydrostatic pressure testing, the propellant feed assembly must be tested for leaks using gaseous nitrogen [39]. Leak testing is similar to hydrostatic pressure testing, except instead of filling the test article with an incompressible fluid, gaseous nitrogen is used as it is a smaller particulate medium and can thus find smaller leaks [63]. The leak test is also conducted in a staged manner, where the first phase uses the lowest test pressure. If no leaks are identified over the specified period, generally five minutes, then the pressure is increased to the next stage. The pressure increase is equal to one fifth of the maximum test pressure, which is equal to 110% of the design operating pressure [39, 64]. Leaks can be identified using hand-held nitrogen detectors or by visual inspection using soapy water around each fitting or component [64]. The leak test is passed when there are no leaks at the maximum test pressure. After a successful leak test, it is recommended to “torque stripe” all fittings. “Torque striping’ involves applying a bright strip of lacquer or paint across a bolt and its adjoining structure after it is tightened to allow for easy visual identification of any loosening or shifts [39].

5.1.3 Propellant Feed Assembly Characterization

To determine the output settings of the manual pressure regulators on the fuel and oxidizer supply lines it is necessary to determine the pressure drop of each line. To do this, the pressure drop of the injector and the combustion chamber must be known. The combustion chamber pressure will only be known once the chamber is designed, however it is assumed to be 15 bar, as per [15, 16, 45].

To ascertain the injector pressure drop, the injector is connected to the propellant feed assembly and single flow cold fire tests are performed with replacement liquids. The flow coefficient, C_v, of the injector is calculated using Equation 5.1 [65] and averaged from repeated tests [39]:

$$q = N_1 C_v \sqrt{\frac{\Delta p}{G_f}} \tag{5.1}$$

where q is the flow rate, N_1 is a numerical constant based on the desired units (equal to 14.42 for flow rates in *l/min* and pressure in *bar*), C_v is the flow coefficient, Δp is the pressure drop across the injector (equal to the inlet pressure minus the outlet pressure) and G_f is the specific gravity of the fluid [65].

Once the pressure drop on the fuel and oxidizer side of the injector is known, the pressure drop of each line can be measured to determine the pressure regulator settings. This is done by replacing the injector from the assembly with a needle valve to represent the pressure drop over the rocket engine during firing. The pressure drop over the needle valve is set to equal the pressure drop of the injector plus the designed combustion chamber pressure. The C_v of the needle valve is calculated using the curves provided by the valve supplier. The outlet pressure of the regulator is found when the operational flow rates match the design flow rates and the pressure drop over the needle valve is equal to the rocket engine pressure drop [39].

5.2 Cold Fire Test Campaigns

As mentioned previously, cold fire test campaigns use replacement fluids to characterize and optimize the injector and confirm the mass flow rates of the system. The first set of cold fire tests are single flow tests, meaning that the fuel-side of the injector and the oxidizer-side are tested independently. The cold fire fuel tests use distilled water as the replacement fluid for ethanol and record the mass flow rate and injector pressure for extended test durations. The cold fire oxidizer tests are first performed using distilled water and thereafter using liquid nitrogen as the replacement fluid for LOX. Once acceptable performance and mass flow rates of the injector have been realized using single flow tests, the injector is tested using ethanol and liquid nitrogen to confirm there is no throttling effect when both fluids are present [59]. The cold fire tests are used to confirm the mixing and atomization of the oxidizer and fuel, as well as the performance and spray angle of the injector. Tests with liquid nitrogen can also be used to give an indication of the pre-cooling requirements of the LOX line. Pre-cooling of the oxidizer supply line is required to reduce vapor build up within the cryogenic fluid, which negatively impacts the combustion process and engine performance [59].

5.3 Hot Fire Test Campaigns

Hot fire test campaigns use the intended liquid propellants (i.e. ethanol and LOX) in the rocket engine, which are ignited to perform static combustion tests. Open combustion tests are usually performed first to validate the injector performance, investigate the relationship between tank pressures, injector pressure drop and mass flow rates, and experiment with different mixture ratios. Open combustion chamber tests are performed with only the injector and injector plate connected to the test stand and the combustion chamber is omitted. This allows for visual observation and analysis of the combustion properties using different injector parameters and propellant mixture ratios [59]. An example of an open combustion test from the SMART Rockets programme showing near optimal combustion is shown in Figure 5-1. The blue flame indicates stable combustion of the LOX close to the injector plate, while the remaining ethanol combusts further away from the injector. This is beneficial as the ethanol provides film cooling within the combustion chamber [59]. Open combustion tests can also be used to confirm the time delays used in the ignition sequence to ensure a hard-start is avoided and test and validate the ignition system [39, 44]. Flame tubes can be added to open combustion tests to perform investigations into material suitability for potential chamber materials [44].

Figure 5-1: Open Combustion Test Fire from SMART Rockets Programme [59].

After the design mass flow rates and propellant mixture ratio are achieved and the injector, ignition system and ignition sequence are verified, static fire tests can commence. Static hot fire tests are performed with the injector assembly and combustion chamber connected to the test stand to evaluate the rocket engine’s performance with different system parameters (such as O/F ratios, ethanol concentrations and varying injector properties). These tests allow for thrust-versus time and thrust-versus-tank-pressure graphs to be obtained.

5.4 Testing Procedures

Detailed testing procedures are required to ensure the safe operation of the test stand. Specific procedures must be developed and verified once the test stand is constructed, including: transportation, test stand establishment (along with a pre-fire checklist), propellant refilling, system priming, line pre-cooling, combustion test preparation, combustion test, emergency abort and post-fire procedures. A preliminary overview of the operations required before and during a hot fire test is offered in this section and is based on [15], [17] and [39].

Before a new test can be started at the test site, the following steps are required:

- Unload all parts of the system not fixed to the test stand, including the gaseous nitrogen cylinders and drain collection tanks,
- Bolt the test stand to the ground or vertical steel I-beam at the test site,
- Ensure all manual valves are in their correct starting positions,
- Perform a thorough visual inspection of all the components of the propellant feed assembly, paying special attention to the torque stripes on each component,
- Mount all CCTV cameras,
- Connect the emergency drain system,
- Connect the nitrogen cylinder to the propellant feed assembly,

- Construct temporary blast shield using sand bags or water-filled containers,
- Connect the power supply unit and verify communication with the DAQ and Test Stand Control Centre,
- Perform system functionality tests to verify the performance of all valves,
- Ensure the rocket engine is securely connected to the engine mount,
- Setup the combustion chamber cooling system if applicable,
- Connect the fuel and oxidizer supply lines to the rocket engine,
- Prime the propellant feed assembly with gaseous nitrogen to ensure the plumbing is emptied of any air or residual propellants,
- Assemble the ignition system, and
- Set the outlet pressures of the manual pressure regulators to the correct values (assume 25 bar for intial tests).

5.4.1 Combustion Test Preparation Procedure

Preparation for a hot fire test involves priming the fuel supply line and LOX supply line, filling the propellant tanks and priming the ignition system. The steps are shown below:

1. Set the manual valve on the LOX drain (Item D5, see Figure 4-1) to the drain connection.
2. Open the manual valves on the nitrogen pressurant supply line (N5) and the fuel supply line (F10).
3. Use the control software to close the nitrogen venting valve (N4).
4. Set the nitrogen output pressure on the manual pressure regulator (N2) to 40 bar and start the nitrogen supply by opening the manual valve on the cylinder (N1).
5. Verify with the control software that the reading on the nitrogen supply manifold pressure sensor (N8) is 40 bar. The system is now pressurized up until the two solenoid valves on the propellant pressurant lines (N6 and N10).
6. To prime the fuel supply line, the control software will:
    a. Close the fuel tank venting valve (F1),
    b. Close the pneumatic fuel drain valve (D2) by opening solenoid valve D1,
    c. Open the fuel pressurant control valve (N6), thereby filling the fuel tank with gaseous nitrogen,
    d. Verify the pressure within the fuel tank is at 25 bar using pressure sensor F5.
    e. Confirm the pressure downstream of the main fuel control valve (F11) is at ambient pressure to confirm the valve provides a perfect seal when closed,
    f. Open the main fuel control valve (F11) by opening solenoid valve N13.
    g. Gaseous nitrogen will now flow through the full length of the fuel supply line and evacuate any air trapped in the system.
    h. After ten seconds the line is deemed sufficiently cleaned, and the control software will start shutting off the valves sequentially in reverse order, i.e. first close the main fuel control valve (F11), then close the fuel pressurant control valve (N6).

    i. The venting valve on the fuel tank (F1) is then opened to vent the nitrogen inside the tank. The valve is closed again once the pressure has reduced to ambient pressure.

7. The software will prime the LOX supply line in a similar manner, as shown below:
    a. Close the LOX tank venting valve (O6) by opening solenoid valve N12,
    b. Close the LOX drain valve (D4) by opening solenoid valve D3,
    c. Open the LOX pressurant control valve (N10), thereby filling the LOX tank with gaseous nitrogen,
    d. Confirm the pressure within the LOX tank using pressure sensor O5,
    e. Confirm the pressure downstream of the main LOX control valve (O11) is at ambient pressure to verify the valve is sealed closed,
    f. Open the main LOX control valve (O11) by opening solenoid valve N14,
    g. Gaseous nitrogen will now flow through the full length of the LOX supply line.
    h. After ten seconds the line is deemed sufficiently cleaned and the control software will start shutting off the valves in the reverse order i.e. close the main LOX control valve (O11), then close the LOX pressurant control valve (N10).
    i. The venting valve on the LOX tank (O6) is then opened to vent the nitrogen inside the tank. The valve is closed again once the pressure has reduced to ambient pressure.
8. The propellant supply lines are now primed and any air evacuated. The propellant tanks can now be filled while the main propellant control valves (F11 and O11) are kept closed. The fuel tank is filled first to reduce vapor formation in the LOX tank. The venting valves are kept open while the tanks are filled to allow the residual nitrogen inside the tanks to escape. Ensure that the manual drain valve on the LOX drain (D5) is set back to the drain connection after filling the LOX tank.
9. After the tanks are filled, the last step in preparing the test stand for firing is priming the ignition assembly. This involves disconnecting the ignition assembly and soaking the cotton on the assembly in 100% ethanol. The ignition assembly is then reconnected to the control cables and mounted inside the combustion chamber.
10. The test stand is now primed and ready to perform a test fire. All personnel must vacate the test area and relocate to the control centre.

5.4.2 Combustion Test Procedure

11. Close the fuel drain valve (D2) and the LOX drain valve (D4).
12. Close the venting valve on the fuel tank (F1) and on the LOX tank (O6).
13. Open the fuel pressurant control valve (N6) and the LOX pressurant control valve (N10) and monitor the tank pressures until they reach the desired operating pressure.
14. Confirm that the flow meters indicate no flow and that there is no change in pressure downstream of the main propellant control valves to confirm they are closed correctly.

15. Use the control software to commence the combustion test, which will carry out the following steps using previously determined time delays:
    a. Open the main LOX control valve (O11) to introduce oxygen into the combustion chamber,
    b. Use the ignition assembly to start burning the cotton,
    c. Open the main fuel control valve (F11) to introduce fuel into the combustion chamber
16. The combustion test is now underway and the control software will monitor and record all relevant data including video, mass flow, pressure, temperature, and thrust data. Combustion will continue until the test is ended in one of the following ways:
    a. The test continues until all the fuel is consumed. The combustion process will be automatically extinguished by the gaseous nitrogen flowing through the fuel/oxidizer supply line. Thereafter the control software will close the main propellant control valves (F11 and O11).
    b. The operator ends the test at a specific time using the control software, which in turn simultaneously stops the flow of fuel and oxidizer to the combustion chamber (by closing the main control valves F11 and O11) and purges the combustion chamber with gaseous nitrogen (by opening solenoid valves P1 and P2).
    c. An emergency abort is triggered either by test personnel or automatically by the control software if any of the measurements exceed the safety limits.
17. Divert remaining propellants to the drain collection tanks by opening D2 and D4.
18. Once all propellants are drained, D2 and D4 are closed and the main propellant control valves (F11 and O11) are opened to purge the entire feed assembly with gaseous nitrogen for a given duration after which F11 and O11 are closed.
19. The fuel and LOX pressurant control valves (N6 and N10) are then closed.
20. The manual valve on the nitrogen cylinder is then used to shut off the nitrogen supply.
21. The propellant tanks are de-pressurized using their venting valves (F1 and O6).
22. The venting valve on the nitrogen supply line (N4) is then opened to de-pressurize the nitrogen supply line.

5.4.3 Emergency Abort Procedure

The emergency abort procedure can be activated manually or automatically by the control software if the sensors indicate unsafe conditions, and is shown below:

- Purge the combustion chamber by opening the purge control valves (P1 and P2),
- Stop the flow of fuel and oxidizer to the engine by closing the main propellant control valves (F11 and O11),
- Drain the propellants by opening the drain valves (D2 and D4),
- De-pressurize the propellant tanks by opening the venting valves (F1 and O6), and
- Stop the supply of pressurant by closing the fuel and LOX pressurant control valves (N6 and N10).

Chapter 6

6. Discussion and Conclusion

The primary objective to develop a preliminary design for a mobile, remote-controlled, pressure-fed test stand for rocket engines with LOX and ethanol as propellants, has been achieved. The design is informed by safety considerations and relevant best-practices, which were identified through a thorough examination of similar university LRE test stands and applicable literature and standards.

6.1 Evaluation of the Preliminary Design

The preliminary design of the UCT LRE Test Stand is in accordance with all the identified technical requirements, as discussed below:

1. The test stand can support rocket engine thrusts up to 1 kN.
2. A modular design is realized that is suitable for use with engines of varying designs.
3. The test stand can be mounted inside a standard 20 foot container, however it is recommended that a flat-bed trailer is instead employed for the test stand housing structure as it is more easily transported.
4. The preliminary design has functionality for both cold and hot fire tests. Furthermore, all procedures required to commission and verify the test stand have been identified.
5. The preliminary design includes purge lines that can be remotely activated to flood the combustion chamber with gaseous nitrogen to terminate a test on demand. Emergency drain lines have also been implemented that divert the propellants away from the chamber to separate collection tanks.
6. The test stand provides transducers to measure and record all relevant data including pressures, temperatures, mass flow rate and thrust data. In addition, the design includes infrastructure for an auto-abort procedure, which is activated manually or automatically if any of the readings approach dangerous values. The abort procedure simultaneously shuts off the propellant supply to the combustion chamber, drains the propellant supply lines, de-pressurizes the propellant tanks and purges the chamber.
7. The test stand is capable of withstanding maximum operating pressures of 50 bar and additional safety components are included in the preliminary design to avoid bursts or damage resulting from accidental over-pressurization.
8. The test stand can support test durations of up to 25 seconds. Longer test durations can also be supported, but with reduced mass flow rates.

9. Requirement #9 is applicable to the structural support system of the test stand and states it must be able to withstand the forces and vibrations associated with a hot fire test for the maximum test duration. This is not applicable at this stage, however the analyses required to ensure compliance with this requirement have been identified.
10. The last requirement states that the design, fabrication and calibration of the test stand must be done in accordance with all relevant local and international standards. The relevant requirements of SANS 472:2019 and ASME B313.3 – 2020 have been identified where applicable to the preliminary design.

In addition to the functional requirements, the preliminary design of the test stand meets all of the project's operational requirements, specifically: i) the test stand interfaces with the Test Stand Control Centre using Ethernet protocols to allow remote control, ii) it uses an inert gas (nitrogen) to pressurize the system and feed the propellants to the combustion chamber, iii) the design includes infrastructure to refill the propellant tanks without removing them from the feed assembly, and iv) the design has a robust, tiered safety system comprising both hardware and software elements operated using a combination of manual, remote-controlled and automatic prompts and as such is deemed safe to use by undergraduate and post-graduate students with the correct training and adherence to the relevant safe operating procedures.

Lastly, the preliminary design is evaluated to determine its compliance with the project constraints. The first constraint requires that where possible the propellant feed assembly must use COTS components. All the valves, regulators, burst discs, pressure relief devices and sensors (pressure, temperature, flow meters and load cells) are COTS components that can be easily sourced. However, the propellant tanks must be designed and manufactured by a SABS-approved pressure vessel supplier. Similarly, the coaxial swirl injector, the combustion chamber and its cooling jacket are not COTS components and will need to be researched and designed by post-graduate students.

The second constraint specified that the propellant feed assembly cannot use any electrically actuated valves downstream of the propellant tanks. The preliminary design ensures compliance with this by using pneumatically actuated valves in these locations. The design ensures that the majority of the test stand can be constructed, tested and commissioned by university students using the university's facilities and is therefore in line with the third project constraint.

The fourth constraint mandates that all components for use on the LOX line are cleaned for oxygen use and are constructed with compatible materials. This has been specified in the preliminary design and a provider of oxygen cleaning services located close to the university has been identified. The final project constraint requires that the pressure vessels are externally certified to ensure safety. The design ensures this constraint is met by stipulating the propellant tanks must be manufactured and certified by a SABS-approved pressure-vessel manufacturer.

6.2 Realization of the Test Platform

Once constructed, the UCT LRE Test Stand will meet the secondary project objectives by supporting research in LREs and propulsion systems at UCT. The preliminary design caters for future modifications to support studying gas generator designs and realize a mobile launch platform. As such, once built, the test stand will increase the technical capacity of young professionals in South Africa in the field of liquid propulsion systems. This impact can be extended to Africa through knowledge-sharing platforms and student exchange programmes.

Numerous steps must be completed to construct, commission and verify the UCT LRE Test Stand, including:

1. Perform a critical design review and verification of the preliminary design.
2. Identify a suitable flat-bed trailer to use as the test stand housing structure.
3. Design the structural support system based on the trailer dimensions. Perform all necessary structural analyses and simulations to verify the structure will withstand the forces and vibrations associated with a full length static test fire.
4. Finalize the physical design and layout of the test stand and develop a three dimensional model using a computer-aided design (CAD) package, such as SolidWorks.
5. Specify all the propellant feed assembly components ensuring material compatibility and compliance with system pressures and temperatures.
6. Develop a bill of quantities (BOQ) and component list of all parts indicated in the design, including the piping, fittings, structural elements and consumables.
7. Identify suppliers for all of the necessary components and compile a budget estimate.
8. Engage with a pressure-vessel manufacturer and furnish them with the tank design and specifications so they can manufacture and certify the propellant tanks.
9. Purchase all of the required components and materials.
10. Send all the LOX components to be cleaned for oxygen use.
11. Calibrate all sensors using the work-bench verifications identified in the preliminary design of the Test Stand Control Centre [52].
12. Test all valves and flow components using replacement liquids (components on the fuel line will be tested with distilled water in place of ethanol and those on the oxidizer line will be tested with liquid nitrogen instead of LOX).
13. Implement the Test Stand Control Centre software and test the DAQ and control system with the relevant components.
14. Install the structural support system on the trailer and construct the test stand.
15. Integrate the Test Stand Control Centre with the test stand.
16. Perform a full system functional test using the Test Stand Control Centre.
17. Commission the test stand by performing the required hydrostatic pressure tests and gas leak inspection tests.

In addition to the above, the test stand combustion chamber and injector must be researched, designed and developed concurrently by post-graduate students. Adequate resources will need to be allocated to the project to ensure its successful completion, including monetary and human resources. It is estimated that the test stand can be completed with six full time master's students and two full time doctoral candidates supplemented with additional assistance from undergraduate students. The undergraduate students can be included in the project by establishing a student rocketry club at the university or by integrating certain aspects of the project into the courses of the relevant engineering undergraduate courses. Safe operating procedures (as identified in Section 5.3) must be developed and evaluated iteratively while the test stand is being constructed to ensure the safety of all parties involved at all stages of the development process.

6.3 Future Work

Once the UCT LRE Test Stand is commissioned and operational, it will facilitate novel and contemporary research into liquid propulsion systems and rocket engines. Future aspirational objectives relevant to the test stand are mentioned below:

- Establish multi-stakeholder partnerships with other South African universities to promote knowledge and resource sharing to build local capacity in rocket engines and potential launch systems.
- Establish a South African Student Liquid Rocket Engine research group with a mission to develop student sounding rockets for use in scientific research.
- Extend the functionality of the UCT LRE Test Stand to support research into turbopump designs and gas generator systems for LREs.
- Upgrade the UCT LRE Test Stand and Control Centre to increase its capabilities to realize a mobile launch centre for liquid propellant sounding rockets.

6.4 Conclusion

A preliminary design for a pressure-fed liquid propellant rocket engine test stand, named the UCT LRE Test Stand, has been presented. The designed test stand is intended for use with LOX/ethanol engines with thrust values up to 1 kN and supports both cold and hot fire testing campaigns. In conjunction to this work, a Test Stand Control Centre has been designed, which interfaces with the test stand and allows for complete remote-control and acquisition of all temperature, pressure, mass flow rate and thrust data. The design ensures a mobile, modular test stand that can support O/F mixture ratios up to 4.0, varying ethanol concentrations between 70 and 100% and rocket engines of various designs. Included in the design is a redundant safety system comprised of pressure relief devices, burst discs, venting valves, purge lines, drain lines and an automatic abort procedure.

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Appendix A

Sensor Interfacing Circuits

This appendix contains schematics of the circuits required to interface the various test stand sensors with the microprocessors in the Test and Launch Control Centre as detailed in [52].

A.1 Pressure Sensors

Figure A-1 shows the interfacing circuit for pressure sensors that output a proportional current relative to the measured pressure, whereas Figure A-2 shows the circuit for proportional voltage pressure sensors.

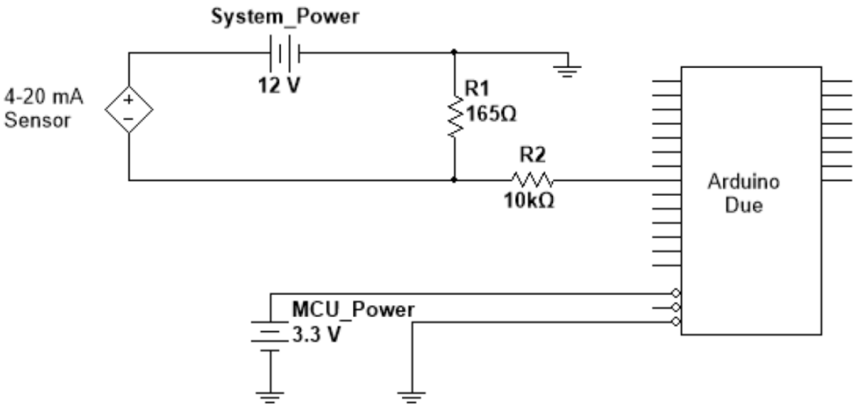

Figure A-1: Interfacing Circuit for a Proportional Current Type Pressure Sensor (4 – 20 mA) [52].

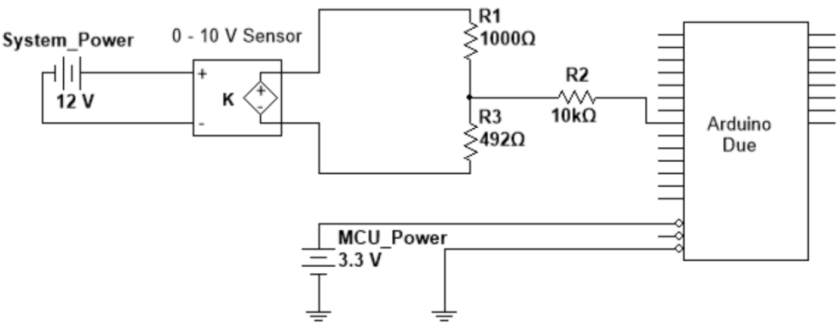

Figure A-2: Interfacing Circuit for a Proportional Voltage Type Pressure Sensor (0 – 10 V) [52].

A.2 Temperature Sensors

Figure A-3 depicts the interfacing circuit for a Type-K thermocouple with signal correction and amplification performed using an Analog Devices AD8495 thermocouple amplifier.

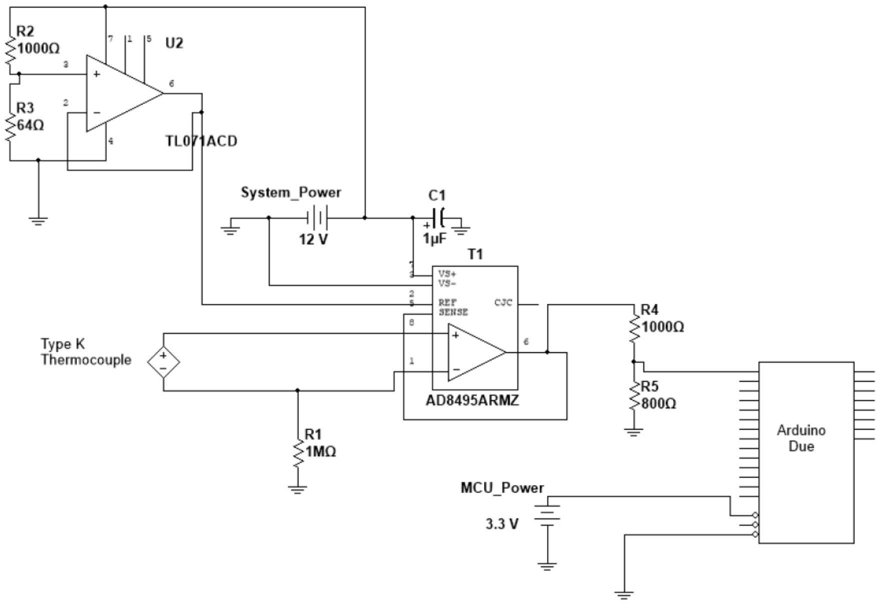

Figure A-3: Interfacing Circuit for a Type-K Thermocouple with Correction and Amplification [52].

A.3 Thrust Sensors

Figure A-4 shows the schematic of the circuit required to amplify the output from the load cell (using the AD623 differential amplifier from Analog Devices) used for thrust measurements and interface it with the microcontroller.

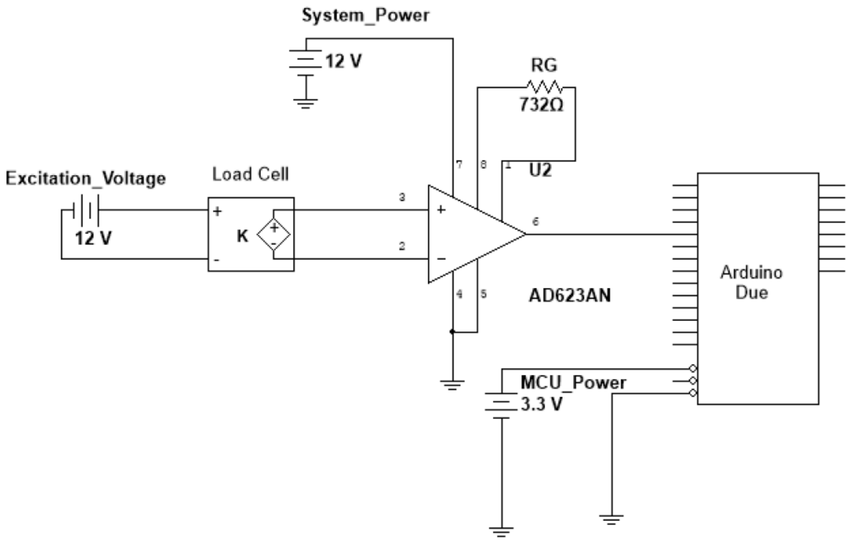

Figure A-4: Amplification and Interfacing Circuit for the Load Cell used for Thrust Measurement [52].