UK RACE TO SPACE

Draft Engine Documentation 2024

Cranfield University

CranSEDS Propulsion Team 23-24

D.R.A.K.E.

Development and Research of Advanced Kinetic Engines

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Contents

List of Figures

List of Tables

Acknowledgments

We would like to express our deepest thanks and gratitude to all the people who helped shape this design work and report:

A big thanks to Professor Antonios Tsourdos, Head of the Autonomous and Cyber-Physical Systems Centre, Cranfield University and the Centre for Autonomous and Cyberphysical Systems, Cranfield University, for financially supporting the team for manufacturing and supervision costs. Without their help, the team wouldn't have succeeded.

To David Thompson and the manufacturing team at the Test facility of Cranfield University for helping us in manufacturing and making the process as smooth as possible.

To all our mentors, Adam Baker, Ryan Chatfield and Triyan Al Patora who have gone above and beyond to aid the project. They have consistently provided a friendly and concise yet greatly effective mentorship, employing their knowledge, skills and experiences to help us in our design and manufacturing phase.

And, to the Race to Space competition team for organizing this contest, giving us the unique opportunity to grow and gain an amazing experience.

To our sponsors, CranSEDS, School of Aerospace, Transport and Manufacturing and the Cranfield Student's Association, for their financial support and technical backing.

To the ASE course professors from the School of Aerospace, Transport and Manufacturing, Cranfield University, for their technical guidance and constructive suggestions.

To the tireless committee team at CranSEDS and Cranfield Student's Association, who helped in the facilitation of our requests and encouraged the team to propel through the dark clouds.

To Gregor Arbuckle for his help in designing the team's logo.

And to the passion and drive within all of the team members to learn, explore and embark on this journey and always keep pushing their limits.

1. Introduction

1.1 History and background of engine development at the university

CranSEDS is Cranfield University's local chapter of UKSEDS and is comprised of students interested in space exploration. The association promotes students' practical learning in the space sector by organising several competitions in the field of rocketry, robotics, and satellite design. The Propulsion team was a continuation of the Hybrid Rocket Motor Test Stand project that was completed last year by Triyan. As a continuation of that project this years propulsion team set out to streamline the process for designing a hybrid rocket engine, increase the thrust of last years engine and optimise a hybrid rocket engine for Race2Space. The plan for the future of the team is to use the information gathered from this engine and the avenues of testing opened up by this years team to begin development of a liquid bi-propellant engine.

Figure 1.1: Team Logos: Old (left) and New (right). Source: Own.

This project has the objective of fostering interest and developing students' skills in the field of space propulsion as well as giving the opportunity to future CranSEDS students to work on rocket motor projects. Another objective for this project is to provide an enrichment ground for the Cranfield students, and potentially other university students, to develop their research projects and thesis with the help of the Hybrid engine built by the team. Originally started in 2020, the long-term goals of the project are to integrate the hybrid motor into a rocket and move on to the development of liquid engines.

The work done by the 22-23 team has paved the way for rocket engine development here at Cranfield University. The information and equipment that they left behind has facilitated the smooth and rapid development of this years engine. Our task was to refine the development cycle that started 3 years ago with HRMTS and develop an engine that would not only excel at Race2Space but could also be tested on campus.

1.2 Engine type

The team has a plan to build a Small Horizontal Hybrid Engine with a mean thrust of 535 N using liquid oxidiser propellant as Nitrous Oxide and solid fuel propellant as HDPE (High-Density Poly-Ethylene) Grain case. The following report describes the initial design and operation plan of the team and the next steps that the team needs to take for designing, manufacturing, testing and validating the Hybrid Engine before presenting the engine at the Race to Space competition in July 2024.

1.3 Current sponsors and funding

The team's sponsors have been mentioned in the list below. They have been utterly helpful in aiding the team to develop the engine and mould the members into better engineers. The sponsors have aided the team with technical support for the Hybrid engine, financial support and support for developing the managerial and Systems model for the project.

Table 1.1: List of Project Sponsors

Sponsor	**Assistance type**
Centre for Autonomous and Cyber-Physical Systems, Cranfield University	Financial Support
School of Aerospace, Transport and Manufacturing	Financial Support, Technical Support
CranSEDS	Financial Support
Cranfield University Test Facility	Technical Support

The team is actively looking for sponsors to aid the team in refining our project design and, with time, develop the project team to take up the task of building Cranfield University's 1st Student team-built Hybrid and Liquid Engine. The funding and current budget of the project has been tabulated below. The table indicates the overview of the budget allocation between various sub-systems and the overall estimated cost of the project at this stage. A general margin of 20 percent has been used for sub-systems and as an overhead cost.

2. Project Management

2.1 Assigned Roles and Team Roster

2.2 Team roles and Responsibilities

The team has been sub-divided into 6 sub-systems which work in concordance with each other to develop their sub-system to an optimal level while ensuring proper integration between every sub-system to yield an efficient system of a working Hybrid Engine. The members of the team and their respective roles have been attached herewith.

Table 2.1: Team members and their roles

Name	**Role**	**Email ID**	**Course**
Noah Buttrey	Project Manager; Technical Lead	noah.buttrey.762@cranfield.ac.uk	ASE
Rodrigo Irisarri	Emeritus Project Manager	r.irisarrimuelas.306@cranfield.ac.uk	ASE
Alex Shufflebothm	Systems Lead	alex.shufflebotham.993@cranfield.ac.uk	ASE
Noah Buttrey	CAD and Manufacturing Lead	As above	ASE
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Aarya Kulkarni	FEA Lead	aarya.kulkarni.724@cranfield.ac.uk	TPP
Himanshu Manoj Gaur	Liner Lead	himanshumanoj.gaur.729@cranfield.ac.uk	TPP
Karthigeyan Sakthikumar	Feed system and Control Lead	k.sakthikumar.722@cranfield.ac.uk	ASE
Alex Shufflebotham	Electronics Lead	As above	ASE

* ASE: Astronautics and Space Engineering; * ACE: Aerospace Computational Engneering; * TTP: Thermal Power and Propulsion;

For the Work Package Distribution, the team attempted to classify the work without any major interdependency; however, overlaps between the works packages can't be avoided, and the team took it as an affirmation of the collaborative work the members need to put in for the system as a whole.

2.3 Stakeholder Map

The stakeholders are anyone internally or externally involved with the organisation and project and have an impact based on the project's output. As a crucial exercise to start any project, it is a good practice to envision them, to realise the areas in which they can be categorised and their interest in the project. Being reminded of them through the project can help raise a positive outcome and identify any negative impact early on. The stakeholder classification has been highlighted in figure 2.1.

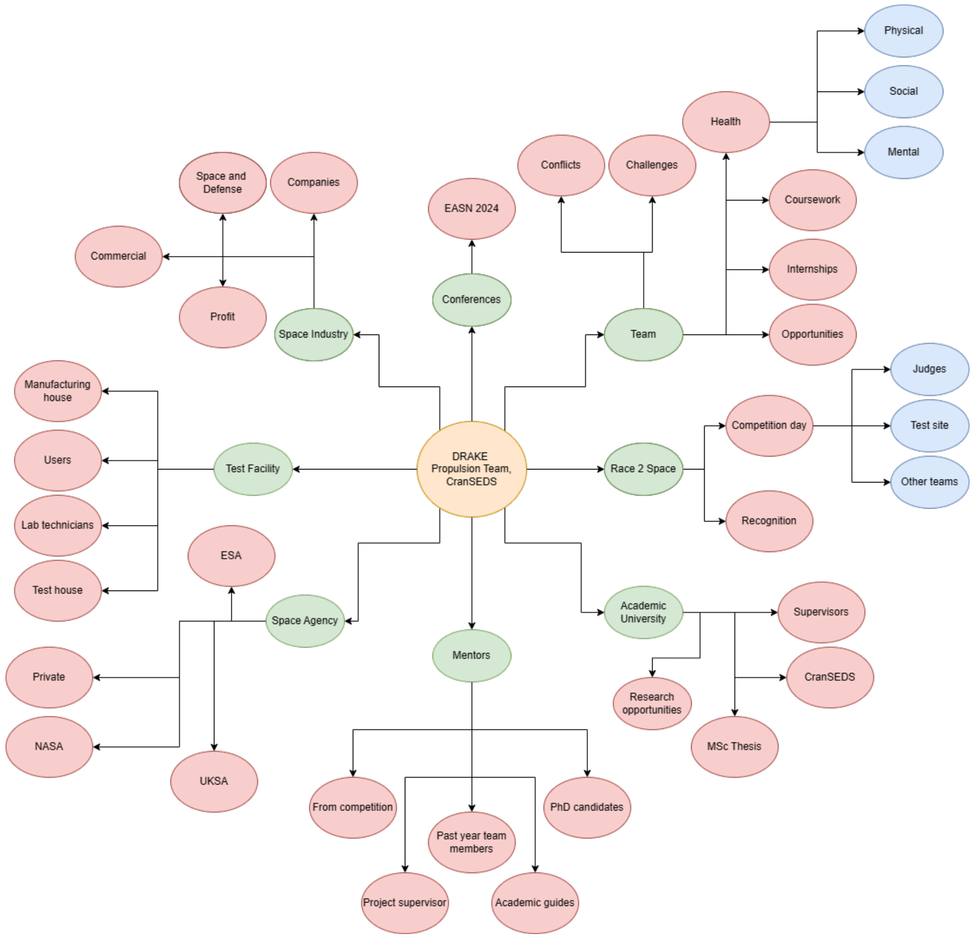

Figure 2.1: Stakeholders Map. Source: Own.

2.4 Work Package Breakdown Structure

The **Work Breakdown Structure** (WBS) is a visual, hierarchical and deliverable-oriented deconstruction of a project. This tool arranges and breaks down the project scope by displaying all deliverables into work packages. By doing this, it is easier to track and monitor the tasks that each subsystem is performing. It also assists in scheduling and keeping track of the schedule done in the Gantt Chart **??**. The work breakdown overview for the team is shown in 2.2. A **stakeholders map** is also detailed in 2.3.

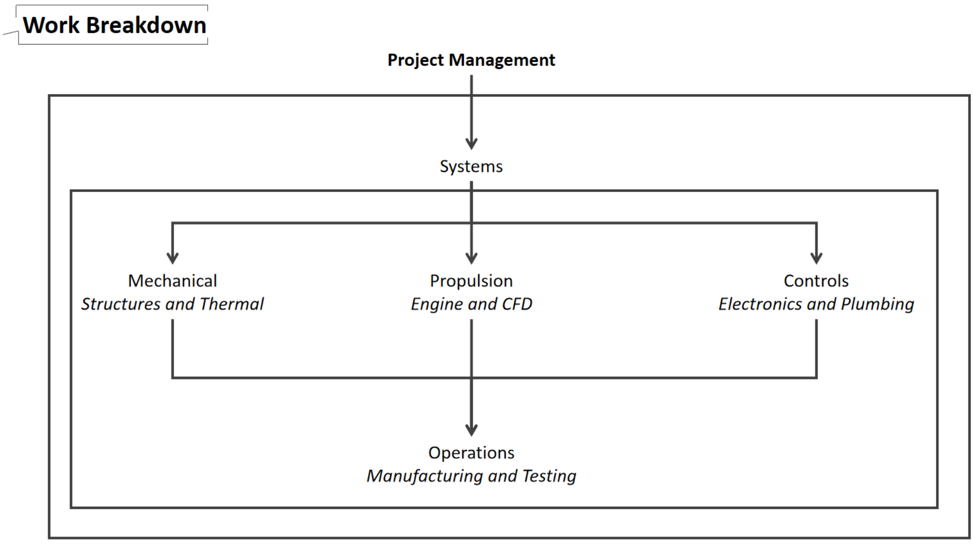

Figure 2.2: Project Work Breakdown Overview. Source: Own.

2.5 Preliminary Budget

The current status of the cost budget is shown in 2.2 below. This depicts the total cost for component and material procurement, manufacturing and covering staff costs for each sub-system.

Table 2.2: Cost Budget and Acquisitions

Subsystem	Net Cost (£)	Acquired (£)	To be raised (£)
Propulsion	232.61	232.61	0
Structures	205	205	0
Manufacturing and Supervision	2824.18	2824.18	0
Feed Line System	132.20	132.20	0
Data Acquisition System	10	10	0
Sponsorships	2824.18	2824.18	0

2.6 Project Risks, COSHH and Mitigations

At the start of the project and through its duration before firing, risks were identified by each subsystem and for the whole system. These risks were accompanied by a separate COSHH assessment for the propellants. Several strategies were implemented to reduce their likelihood of occurrence. These have since been closely monitored, and an updated status table has been presented in Appendix 11.6.

2.7 Project Plan

The use of a **Gantt chart** here facilitates the preliminary scheduling for the entire project. This tool depicts a graphical representation of activities and deliverables against time. It is a simple and efficient way of overseeing the status of the project. While it may seem like a big chunk of project work time, this was also put in place to allow for a buffer in case more work of assembly, integration and testing was required. The **full Gantt chart** elaborated for this project is depicted in Appendix **??**.

2.8 Team Management

Weekly meetings were held for the whole team for general updates and discussions, in which the designs were finalised and the project plan was updated. Microsoft Teams continued to be used to track time spent and store all data.

The workload and timings of the student courses meant that some of these meetings between teams could not be held, and this placed stress on completing team deadlines. **Work meetings** of more than 2 hours were added to the weekly schedule to dedicate time to the tasks and ensure they were achieved. The benefit of this meant communication to make design choices between sub-systems could be done quickly in person, saving time and building team rapport.

As the project continued, some members chose to leave due to other commitments. Because of this, WP tasks were reallotted and shared by the rest of the team. The team was encouraged to engage with the Race to Space and their assigned mentors.

3. Requirements

The top-level requirements set out by the team for the project are as shown below. From these requirements, all sub-systems derived their requirements and designed the system to satisfy all the sub-system and top-level requirements while keeping the design simple and easy to manufacture, assemble and test.

Table 3.1: Top-Level Requirements for the Project (DR-1XXX)

ID	**Parameter**	**Requirements**	**Traceability**
DR-1001	Thrust	The Engine shall be designed to deliver a thrust of no less than 500 N	
DR-1002	Burn Time	The burn time shall be greater than 15 seconds	
DR-1003	Propellants	The liquid propellant used shall be Nitrous Oxide	AEL-J1 Nitrous Oxide Test-Rig IC
DR-1004	Ignition System	The engine shall be ignited using an external fuse wire to create sparks in the combustion chamber	
DR-1005	Mass flow rate	The mass flow rate of propellants shall be lower than 2.3 kg/sec (Nitrous Oxide)	AEL-J1 Nitrous Oxide Test-Rig ICD
HY-1006	Feed Pressure	The feed line shall be able to hold pressures up to 80 bars.	AEL-J1 Nitrous Oxide Test-Rig ICD
HY-1007	Chamber Pressure	The chamber pressure for the complete fire sequence shall be lower than 51 bars (Nitrous Oxide Vapor Pressure)	
HY-1008	Mounting bracket	The mounting bracket shall provide support in all 3 axes from the experienced loads	

4. Propellants

A combination of solid fuel and liquid oxidiser was selected as the propellants for the hybrid engine, as it provides a safe alternative during manufacturing. The fuel and oxidiser themselves only react and combust when at high temperatures, which makes it an ideal configuration to be applied by the student team for a small-scale hybrid engine project and work on its research aspects.

This section comprises of the propellant selection for the liquid oxidizer, solid fuel.

The purging gas selected for the engine is Nitrogen gas, and the pre-charge will be performed using liquid oxygen gas at low pressures, providing an oxygen-rich environment inside the combustion chamber.

4.1 Liquid Oxidiser

The liquid oxidiser is required to be non-reactive. However, it shall only react with the solid fuel at high temperatures ensuring safety during the assembling and setup phase. The propellant used shall be a standard propellant issued to be used by the university, testing facility and international standards. These requirements with other parameters will be used to trade off the alternatives for the final selection. The selected alternatives are Nitrous oxide (N_2O), Isopropyl Alcohol (IPA) and liquid Oxygen (LOx).

The table 4.2 summarises the trade study performed. While the rubrics used for preparing the trade-off table have been presented in table 4.1.

Table 4.1: Assembly and Equipment level requirements Source: Own.

Requirement ID	**Statement**
Number	**Description**
Weighting Rubric	
1	Low priority
2	Medium priority
3	High priority
Scoring Rubric	
1	<20 % of the desired value
2	20-40 % of desired value
3	40-60 % of desired value
4	60-80 % of desired value
5	80-100 % of desired value

NOTE: Desired value can be maximum achievable or minimum achievable or according to a set standard.

Table 4.2: Liquid Oxidiser propellant selection trade study

Alternative	Availability	Simplicity	Reactivity	Oxidising potential	Stability	Compatibility with the fuel	Vapour Pressure	Temperature sensitivity	Safety	Feasibilty	Total (110)
Weights	2	1	3	2	2	3	3	1	3	2	
N_2O	4	4	4	5	3	5	5	2	5	4	**95**
LOx	3	5	5	4	2	5	2	1	2	3	**72**
IPA	5	4	2	3	5	5	3	5	4	5	**87**

So the final selection for the liquid oxidiser for the hybrid engine is **nitrous oxide** (N_2O).

The N_2O will be kept in a liquid state for the combustion to have a better performance. The average mixture ratio O/F is fixed at 6.1. This value was determined via calculations from the software RPA (Rocket Propulsion Analysis) at a nominal pressure in the combustion chamber of 3.7 MPa.

4.2 Solid Fuel

The solid fuel that needs to be selected for the hybrid engine shall be readily available, easily manufacturable, non-reactive in the atmosphere, shall not have explosive properties when reacting with the liquid oxidizer, and shall be feasible to procure. These parameters, along with the requirement on the engine performance of sustaining a 500 N producing engine for more than 15 seconds and the combustion products shall not be harmful, makes it really constricted on the alternatives that can be considered for use as the solid fuel.

In-depth research work was performed by the previous year's team, which has been used as the baseline for the current propellant selection. The general consensus was to select a plastic that can easily be manufactured and will react with nitrous oxide at high temperatures to sustain the combustion of the hybrid engine.

After many discussions and iterations, the final selection for solid fuel was made to be **high density polyethylene (HDPE)**.

The products obtained after the combustion are CO_2, N_2O, and N_2. HDPE is readily available, feasible and easily manufacturable. As its main application is in thermosetting plastics, it is non-reactive. However, nitrous oxide is able to corrode and break down the polymer to its constituent monomers and react with the hydrocarbon monomer for successful combustion. This makes it a great choice for the current design.

The thermochemical reaction is presented in detail in the design calculation section 6.3.

Acrylonitrile butadiene (ABS) and polylactic acid (PLA) were also among the top contenders, in lieu of their properties of 3D printing. However, they were unable to satisfy the system requirement of providing a minimum of 500 N thrust. And so, the final selection for the solid fuel is **HDPE**.

5. Detailed Design

The current design of the Hybrid Engine has been inspired by the old design of the previous year's team. The design methodology was a small combustion chamber with axial support from the L-shaped engine mount at the back and 2 planar supports positioning the chamber horizontally to the ground. Their baseline design concept has been carried over to this year, with modifications made at the interfaces of components, new requirements and manufacturing constraints. The requirements on propellants used are that they shall comply with safety standards in place at the university's test facility and shall be available during the race to space competition. So, liquid nitrous oxide (N_2O) is used as the oxidiser, and HDPE (high-density Polyethylene) is used as the fuel, which will be milled into the desired shape with one circular port. The target firing time is over 15 seconds, and the expected peak thrust output is 535 N. For the ignition process, the chamber will be pre-charged with liquid oxygen (LOx) at low pressures, followed by spark ignition, which will be achieved remotely by igniting a fuse which enters the combustion chamber through the nozzle. Gaseous nitrogen (N_2) will be used to purge the system after each firing. The feeding system incorporates multiple safety features, such as valve isolation between the tanks and the chamber.

The final design of the Hybrid Engine on the ICD Bench is shown in figure 5.1. The engineering drawings for the component parts have been attached in Appendix 11.1.

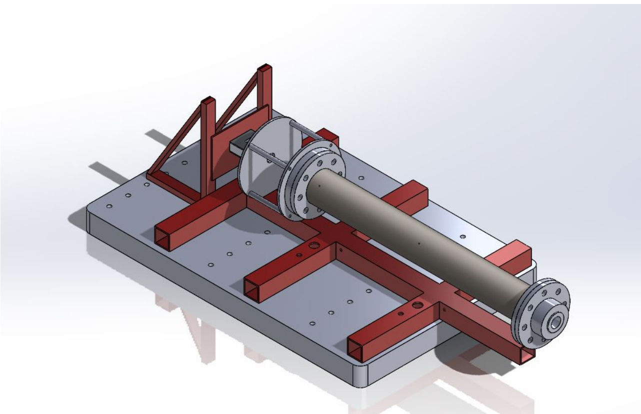

Figure 5.1: Hybrid Engine Assembly on the ICD Bench. Source: Own.

5.1 Engine Design

The drawings of the hybrid motor combustion chamber and its components are attached in appendix 11.1.

The section view of the combustion chamber with components is shown in figure 5.2. It comprises an injector plate with 10 injector holes of 1 mm for propellant atomization. It is followed by the combustion casing locked in on both edges with a welded flange and an inner layering of the engine cork liner. Following is the Graphite nozzle inside the nozzle casing with a welded flange over it to hold it within the combustion chamber casing environment.

The material used for the components is generally heat-treated Mild Steel. Further discussion on the material selection can be found in the section 5.5.

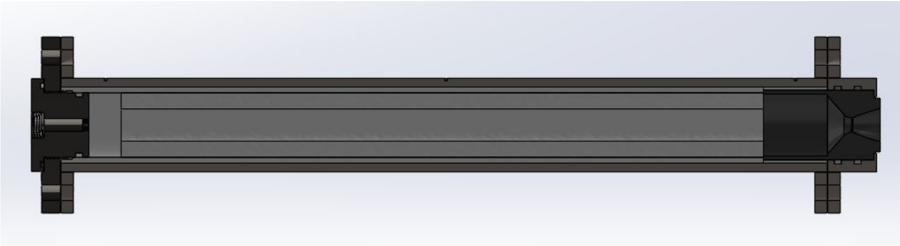

Figure 5.2: Engine Chamber Cross Sectional View. Source: Own.

To calculate the hoop stress in a chamber (thin wall pressure vessel), the following equation is used:

$$\sigma_\theta = \frac{P \cdot D_m}{2 \cdot t} \tag{5.1}$$

The calculations for the thin wall stress, along with the description for the math used, have been shown in the section 6.7.

5.1.1 Fuel Grain and Combustion Casing Geometry

As a circular bore produces a progressive-regressive thrust curve, it is the chosen geometry for the fuel grain. For initial trials, a circular bore is selected for simple geometry and easy production. The team needs to discuss with the manufacturer the perspective of different cross-sectional configurations for the solid fuel grain, such as star shape, annular shape, and others, as they provide better performance and consistent burn rate [2] [3]. To keep the initial testing straightforward, a circular bored configuration is selected, as shown in figure 5.3. The fuel grain and steel combustion chamber casing are separated by a 5 mm thick layer of insulation made out of off-shelf cork. Further assembly is discussed in Chapter 9

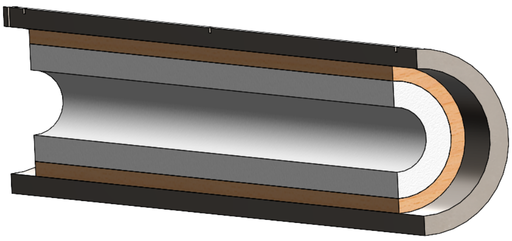

Figure 5.3: Fuel Grain geometry inside the combustion chamber. Source: Own.

The interface holding the combustion chamber over the test stand is held by 2 ring clamp systems, which are in turn mounted on Steel plates attached and fixed to the Test Stand. The design of the ring clamp system is depicted in figure **??**. To assess the deformation and maximum stress associated with this holding configuration, and other components of structures, a detailed FEA was performed for all components.

The combustion casing has been evaluated for structural performance through Finite Element Analysis (FEA). The resulting deformation and induced stress are indicated in figure 5.4. The analysis result showcases the maximum stress in the worst-case scenario of maximum thrust, with the worst temperature and vibrations modelled in the software.

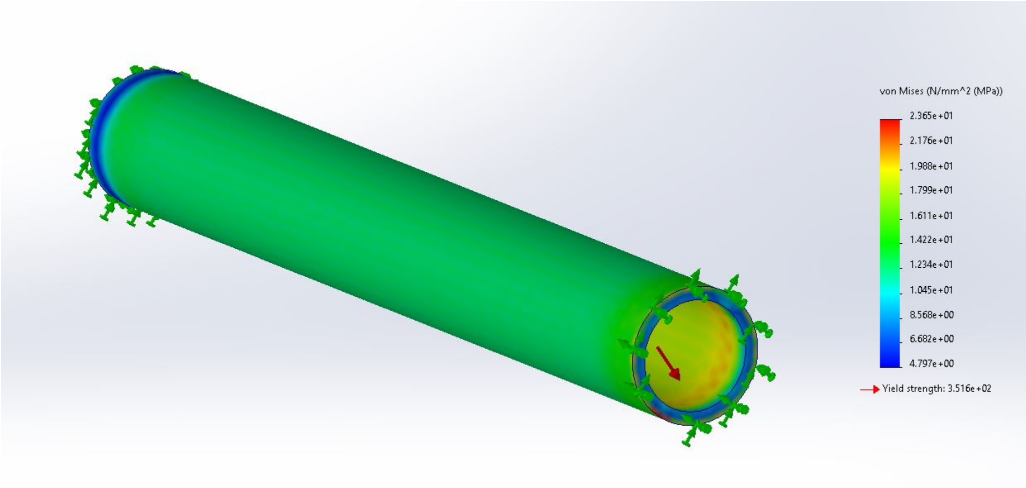

Figure 5.4: FEA results of combustion chamber steel casing: Max. Stress: 23.65 MPa (FOS: 14.9). Source: Own.

5.2 Propulsion Design

This section describes the design of the propulsion system of the motor. All the tasks performed are presented in the sections: Motor Sizing, Injector, Nozzle Design, Ignition Mechanism and Thrust Adapter.

5.2.1 Modelling, Simulation and Grain Dimensions

The objective of the project is to design, build and test a highly efficient hybrid rocket motor that runs for an extended period of time. Therefore, our main aim is to maximize specific impulse and prolong burn time.

Considering the available resources, the scope of the project is focused into developing an engine considering:

- A minimum specific impulse of 200 s
- A minimum burning time of 15 s
- The propellants are: N20 and HDPE

5.2.2 Combustion and Chemical Equilibrium

The motor modelled burns a combination of liquid nitrous oxide at saturation conditions and High-density polyethylene (HDPE). For this analysis, the equilibrium gas-chemistry code Chemical Equilibrium with Applications (CEA) was used to model the combustion products. The CEA code was developed at NASA Glenn Research Center and has been successfully applied for the analysis of rocket combustion, detonation, and flow across nonadiabatic shock waves. The code posits chemical reactions across the shock wave and then minimizes the Gibbs free energy to reach thermodynamic and transport properties at chemical equilibrium. The CEA code has extensive internal libraries for gas thermodynamic and transport properties including standard and nonstandard temperature and pressure conditions. The propellants have been defined as follows:

Reactant	T0 (K)	Hf (kJ/mol)	Mw (g/mol)
N20	298	81.6	44.01
HDPE	288	-28.18	14 (mol of CH2)

Table 5.1: Properties of selected propellants

Parameters such as the characteristic velocity, combustion temperature, specific heat ratio and molecular weight have been computed for pressures ranging from 10 to 40 bar and for O/F ratios ranging from 4 to 9. Additionally, a combustion efficiency of 85% has been included on the characteristic velocity, c*. These curves have been then fed into a MATLAB script to be used when integrating the model.

As can be seen below, the maximum specific impulse for this propellant combination is around 240s for an OF ratio of 6.1. Therefore, the engine's grain geometry has been designed to burn around this point.

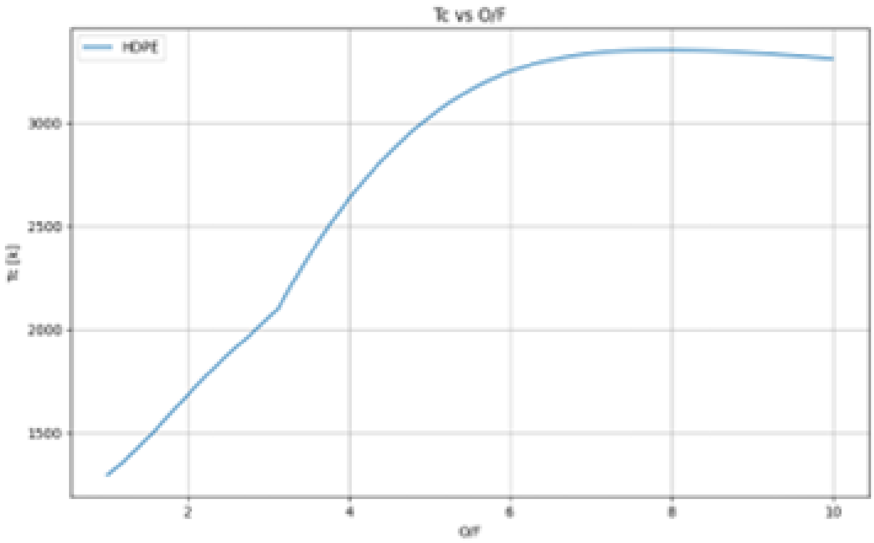

Figure 5.5: Matlab graph of combustion temperature vs O/F ratio Source: Own.

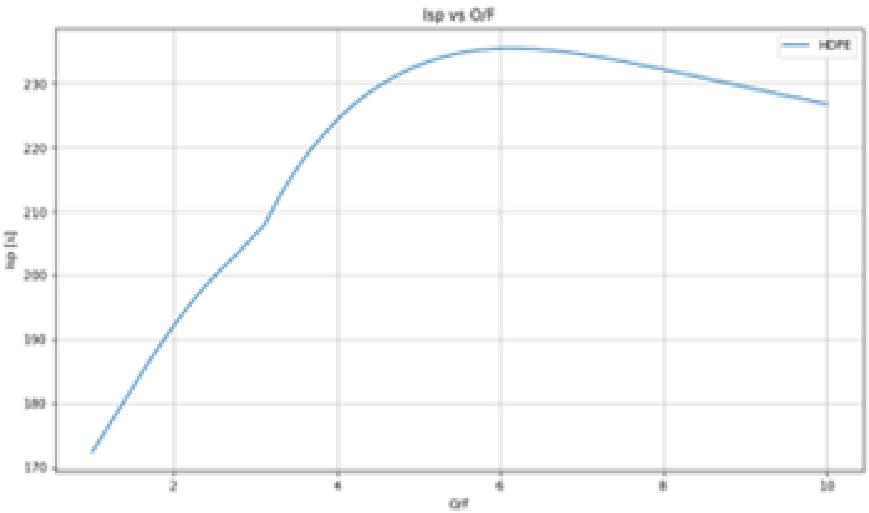

Figure 5.6: Matlab graph of ISP vs O/F ratio Source: Own.

5.2.3 Fuel Regression Model

Sutton and Biblarz (Rocket Propulsion Elements, p. 599) outline the basic structure of the enthalpy-balance regression rate model used for this analysis. For nonmetallized (or low radiation) hybrid combustion, fuel surface regression has been shown to be a function of turbulent boundary-layer heat transfer in a variety of studies. Therefore, for this model, it is assumed that a turbulent flame zone close to the fuel surface dominates combustion in hybrid rocket motors. Boundary-layer mixing creates a region in which oxidizer flow from the centre of the motor combustion port mixes with vaporizing solid fuel leaving the fuel wall. Close to the fuel wall is the flame zone, where the combustion of fuel and oxidizer primarily takes place. Heat transfer from this zone to the solid fuel grain drives the regression rate behaviour of the hybrid rocket motor. Hence, the fuel regression rate for a nonmetallized propellant can be written as:

$$\dot{r} = a(G_o)^n \tag{5.2}$$

where a and n are two empirically fitted constants which, for an N2O/HDPE engine, are found to be (Doran 2007):

- a = 0.248
- n = 0.55

Table 1: Ballistic Coefficients of Three Fuels with N_2O

Fuel	a*	n*
HDPE	0.248	0.331
PMMA	0.284	0.335
HTPB	0.417	0.347

* To be used when $\dot{r}$ is in mm/s and G_{ox} is in g/cm²-s.

Figure 5.7: Image of Table [1] from Doran 2007 Source: Doran 2007.

5.2.4 Internal Ballistics Model

As the fuel begins to burn, the combustion process produces high-temperature gases that escape through the nozzle throat. Assuming the nozzle throat chokes immediately, the generated gases cannot escape as fast as they are produced, and pressure within the fuel chamber builds. Using the ideal gas law to rewrite density in terms of chamber pressure and temperature, the differential equation that rules chamber pressure can be written as:

$$\frac{\partial p_c}{\partial t} = \frac{RT_c}{V_c}(\dot{m_f} + \dot{m_o} - \dot{m_{noz}}) - \frac{p_c}{V_c}\frac{\partial V_c}{\partial t} \tag{5.3}$$

where the mass flow rates are:

$$\dot{m_o} = C_D A_{inj}\sqrt{2p_o(p_{tank} - p_c)} \tag{5.4}$$

$$\dot{m_f} = \rho_p \frac{\partial V_c}{\partial t} \tag{5.5}$$

$$\dot{m_{noz}} = \frac{p_c A_t}{c^*} \tag{5.6}$$

and where the progression of the volume can be obtained from the regression rate as:

$$\frac{\partial V_c}{\partial t} = 2\pi L_p r \frac{\partial r}{\partial t} \tag{5.7}$$

Parameter	Value
Number of injection ports	10
Injection port diameter	1 mm
Discharge coefficient	0.45
Nitrous Oxide tank pressure	55 bar

Table 5.2: Injector dimensions. Source: own.

where the wall regression rate has been introduced before and can be written as:

$$\frac{\partial r}{\partial t} = a(\frac{\dot{m}_o}{\pi r^2})^n \tag{5.8}$$

5.2.5 Performance Parameters

After solving the system of partial differential equations presented above, the following set of equations is used to compute the expected performance of the engine as well as the optimum expansion ratio.

- Thrust coefficient (adapted nozzle, p = pa)

$$C_T = \Gamma(\gamma)\sqrt{\frac{2\gamma}{\gamma-1}(1-(\frac{p_a}{P_c})^{\frac{\gamma-1}{\gamma}})} \tag{5.9}$$

- Optimum expansion ratio

$$\epsilon_{opt} = \frac{A_e}{A_t} = \frac{\Gamma(\gamma)}{(\frac{p_a}{p_c})^{\frac{1}{\gamma}}\sqrt{\frac{2\gamma}{\gamma-1}(1-(\frac{p_a}{P_c})^{\frac{\gamma-1}{\gamma}})}} \tag{5.10}$$

- Thrust

$$T = p_c A_t C_T \tag{5.11}$$

- Specific Impulse

$$I_{sp} = c^* C_T \tag{5.12}$$

5.2.6 Grain and Injector Dimensions

Using the model presented above, the geometry of the engine has been optimised to achieve maximum performance while maintaining a high degree of modularity. In this sense, the geometry of the injector as well as the grain can be found in the following tables. The number of ports and the port diameter have been selected to enhance the atomisation of the oxidiser particles while ensuring that enough oxidiser is fed into the combustion chamber at the desired O/F. In addition, small injection holes are known to generate more turbulence inside the chamber, thus enhancing the fuel regression rate. Also, the discharge coefficient has been taken from literature, from a similar-sized injector. Lastly, the nitrous tank pressure has been selected at 55 bar, as a large pressure difference is desired to avoid combustion instabilities and "chugging". In this context, Delft's DARE team developed a similar hybrid rocket using the same tank pressure. Regarding the pre-chamber length, a L/D ratio of 0.5 was used for optimal vaporisation of the oxidiser. In addition, the fuel grain length has been selected in order to maintain the chosen O/F ratio at the simulated regression rate. Lastly, the post-chamber length is known to have a significant effect on the engine's performance, as the unburned fuel has the chance to react in this region before reaching the nozzle. In this context, an L/D ratio ranging between 0.5 and 1.0 is known to be enough to provide the additional residence time required to combust the remaining fuel.

Parameter	Value
Pre-chamber length	25 mm
Fuel grain length	500 mm
Fuel grain initial port diameter	25 mm
Fuel grain final port diameter	50 mm
Post-chamber length	50 mm

Table 5.3: Fuel grain dimensions. Source: own.

5.2.7 Expected Performance

The internal ballistics model has been implemented into a MATLAB script and integrated over the burning time. In order to remain conservative regarding the performance expectations, a combustion efficiency of 85% has been applied, similar to the one utilised by Delft's DARE team. It is also worth noting that the following simulation has been carried out using an 11 mm throat and 55 bars of N2O tank pressure.

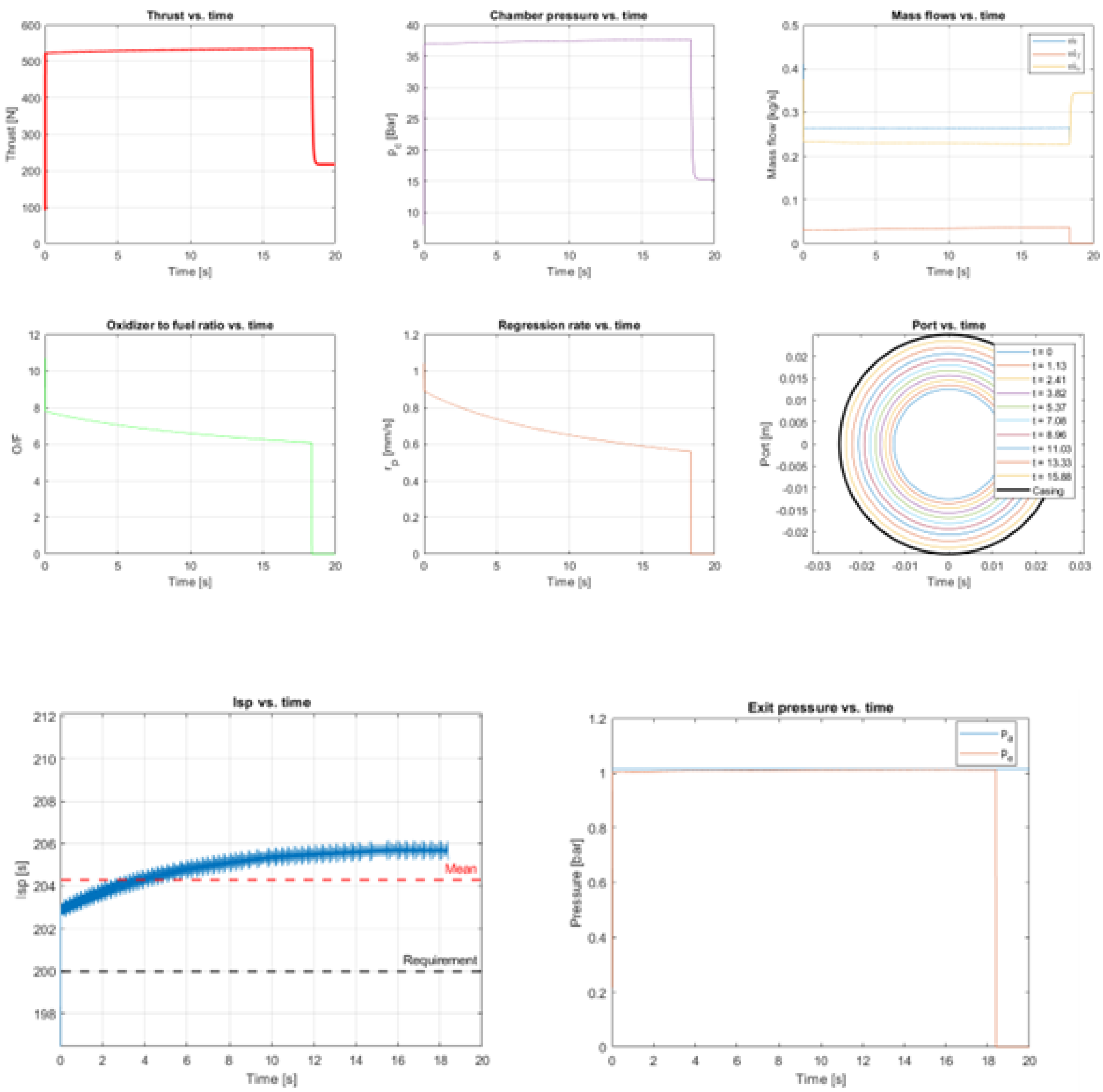

Figure 5.8: Matlab graphs of performance. Source: own.

5.2.8 Performance values

Table 5.4: Performance results from MATLAB

Initial Conditions	**Value**	**Units**
Burn time	18.23	s
Oxidiser to fuel ratio	6.1	
Thrust	535	N
Chamber pressure	37	bar
Exit pressure	1	bar
Specific impulse	204.26	m s^{-1}
Total mass flow rate	0.282	kg s^{-1}
Regression rate	$1.84 \cdot 10^{-3}$	m s^{-1}
Initial steps for the sizing		
Throat area	$9.5 \cdot 10^{-5}$	m^2
Throat diameter	$11 \cdot 10^{-3}$	m
Expansion ratio	5.21	
Exit area	$49.56 \cdot 10^{-5}$	m^2
Exit diameter	$25.12 \cdot 10^{-2}$	m
Mass Data		
Fuel mass flow rate	0.04	kg s^{-1}
Oxidiser mass flow rate	0.242	kg s^{-1}
Fuel mass	0.714	kg
Sizing		
Port diameter	$2.5 \cdot 10^{-2}$	m
Fuel grain length	0.5	m
Final Port diameter Chamber	$5 \cdot 10^{-2}$	m
Post-Comb. Chamber length	$5 \cdot 10^{-2}$	m
Pre-Comb. Chamber length	$2.5 \cdot 10^{-2}$	m
From Simulations		
Characteristic velocity, C^*	5277.8	m s^{-1}
Stabilized chamber temperature	3107	K

5.2.9 Injector

The main purpose of the injector is to inject and atomize the oxidiser flow into the combustion chamber. The amount of oxidiser flow required is the one that allows the O/F ratio of 6.1 to be maintained. The injector shall be able to create a shower of small droplets of liquid oxidizer, which would be vaporised into the combustion chamber and, with its high flow pressure, be able to erode the fuel grain and combust.

The final design of the injector is depicted in figure 5.9

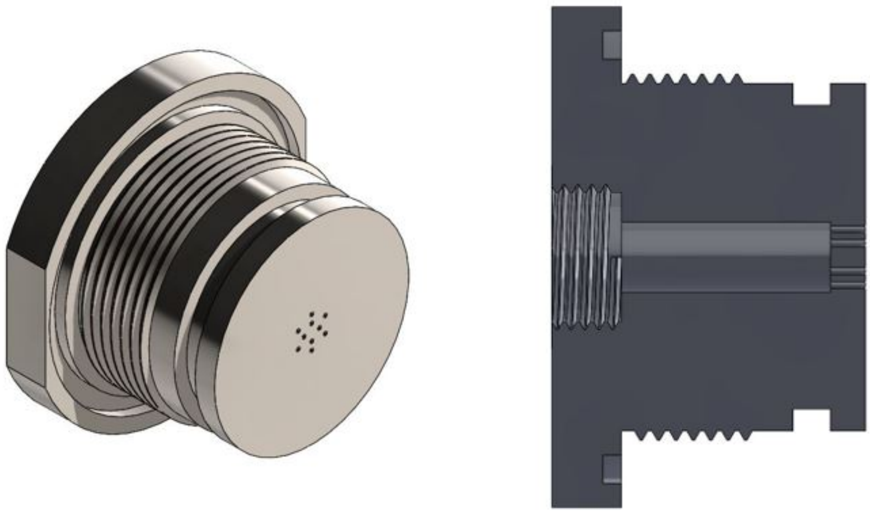

Figure 5.9: Designed Injector: Isometric View (left), Cross-Sectional View (right). Source: Own.

The main inputs to determine the design of the injectors are the properties of the oxidiser at the inlet of the injector (equal to the properties at the outlet of the feeding system), the pressure in the combustion chamber, and the mass flow of the oxidiser. And the outputs will be the number of holes and the diameter necessary to satisfy the requirements.

For simplicity's sake, the design of the injector follows a **showerhead axial injector** style. That means that the injector is a plate with several holes, all of them with the same diameter and drilled axially to the plate.

The diameter of each hole is set as 1 mm. This value is in accordance with the general rule to avoid diameters higher than 1.5 mm [4] while keeping a realistic view of its manufacturing.

The input values are shown in Table 5.5

Table 5.5: Input values to determine the number of holes on the injector plate.

Parameters	**Values**
Oxidiser mass flow rate	0.242 kg/s
Injector hole diameter	1.0 mm
Oxidiser density	822.2 kg/m3

It is necessary to determine both the pressure drop across the injector and the discharge coefficient (C_d). The pressure drop can be regulated/adjusted by the feeding system reducing the pressure from its maximum value. As the discharge coefficient depends on the operational conditions and the quality of the manufactured holes, this value only can be estimated until the injector is physically tested. For the current case, it has been estimated to be 0.8. The values of the discharge coefficient follow the indications seen in [5].

It is observed that for a wide range of C_d values and pressure drops, the optimal number of holes is 10: 4 holes at a circular radius of 2 mm and the other 6 at a radius of 4 mm. The complete calculations have been developed and described in the next chapter's section 6.5.

The injector plate has been evaluated for structural performance through Finite Element Analysis (FEA). The resulting deformation and induced stress are indicated in figure 5.10. The analysis result showcases the maximum stress in the worst-case scenario of maximum thrust.

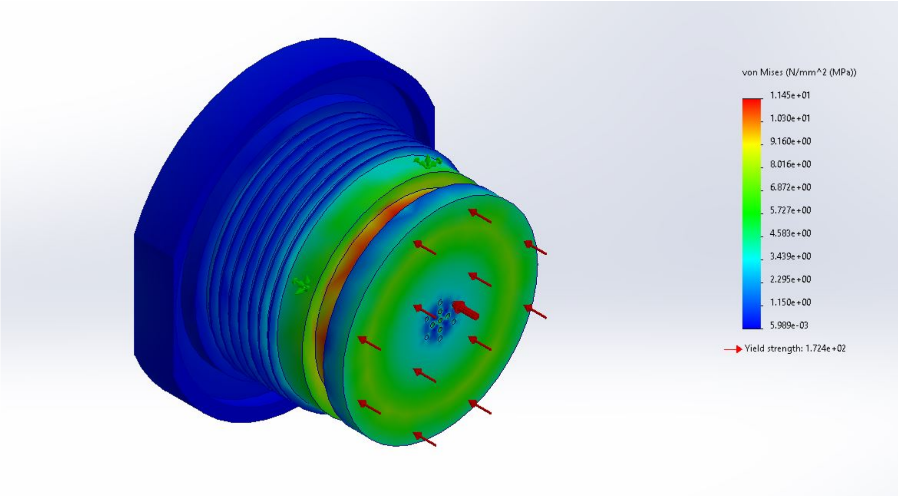

Figure 5.10: FEA results of injector plate of stainless steel: Max. Stress: 11.45 MPa (FOS: 15.1). Source: Own.

A similar analysis was performed on the injector flange that holds the injector plate and makes up the injector sub-assembly. The results have been displayed in figure 5.11.

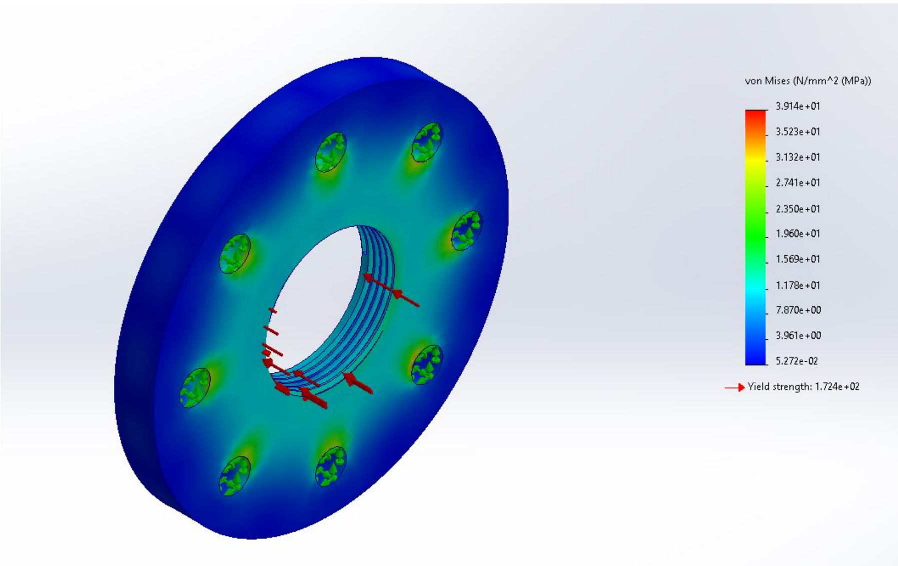

Figure 5.11: FEA results of injector flange of stainless steel: Max. Stress: 39.14 MPa (FOS: 4.4). Source: Own.

5.2.10 Nozzle Design

This section outlines the design of the Rao bell nozzle. The area ratio selected between the throat and the exit is 5.2. Based on the calculations shown in the section 6.2, the design for the nozzle was prepared, and the final design is depicted in figure 5.12.

Figure 5.12: Graphite Nozzle Design: Isometric View (left), Cross-Sectional View. Source: Own.

The performance of graphite nozzles greatly increases with less oxidation (controlled manually). Graphite has moderate resistance to cracks generated due to thermal stresses. Fibre-reinforced plastic nozzles show less erosion but are costly to manufacture [1]. The datasheet for the graphite material used has been attached in appendix 11.2.1.

The Rao nozzle is the simplest bell nozzle to design. It is relatively easy to fabricate and most suitable for small nozzles due to its simplicity.

Using the equation:

$$L_n = 0.85 \frac{(\epsilon - 1) R_t}{\tan 15} \tag{5.13}$$

The Length of the bell is calculated to be **22.4 mm**.

The graphite nozzle and the nozzle casing have been evaluated for structural performance through Finite Element Analysis (FEA). The resulting induced stress is indicated in figure 5.13 for the graphite nozzle and in figure 5.14 for the steel nozzle casing. The analysis result showcases the maximum stress in the worst-case scenario of maximum thrust.

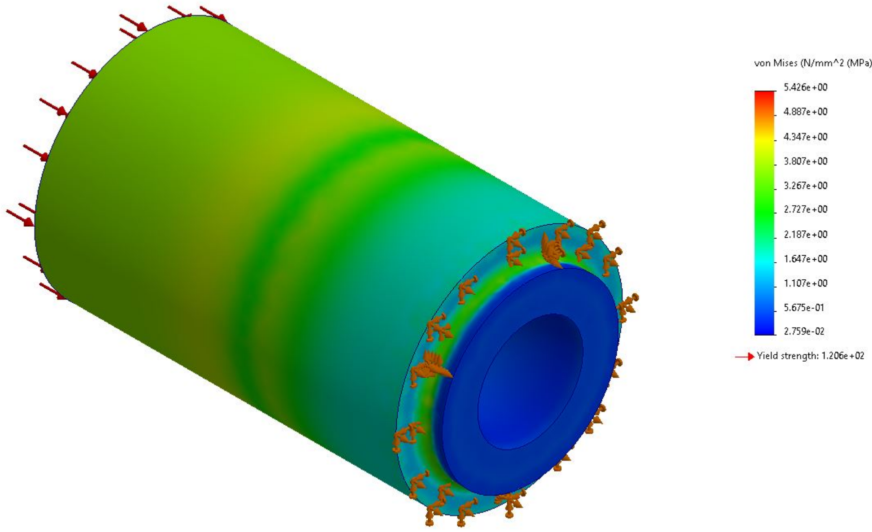

Figure 5.13: FEA results of the graphite bell nozzle: Max. Stress: 5.4 MPa (FOS: 22.2). Source: Own.

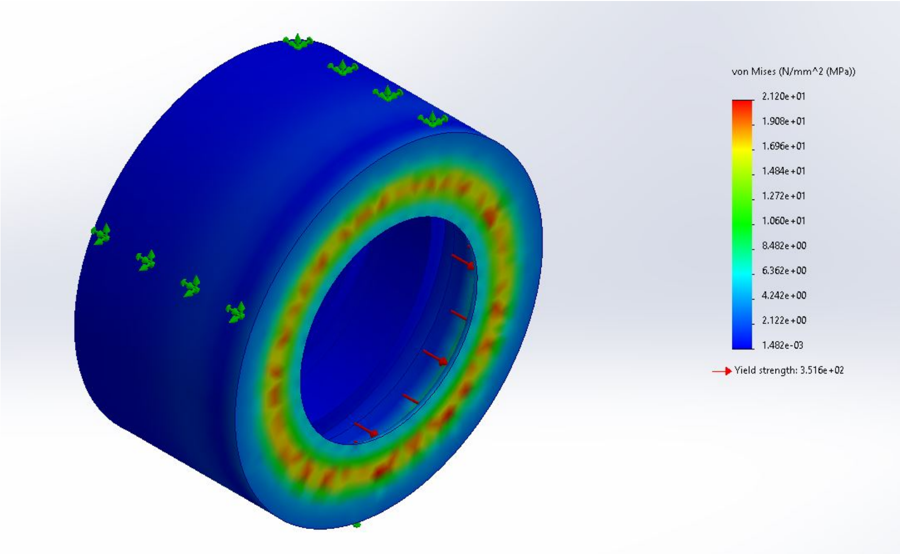

Figure 5.14: FEA results of steel nozzle casing: Max. Stress: 21.2 MPa (FOS: 16.6). Source: Own.

5.2.11 Ignition Mechanism

A 15 kV DC High Voltage Arc Ignitor ($\approx$ 100 cm^2) will be placed close to the nozzle next to the rocket stand. The arc will ignite a long fuse ($\approx$ 1 m), which will enter via the nozzle exit and go through the nozzle until it reaches the pre-combustor chamber. The fuse will be lighted wirelessly from a safe distance via the arc ignitor using an Arduino circuit. A rough schematic for this system is depicted in figure 5.15 [1].

The spark is assumed to be hot enough to ignite the fuel-air mixture. The fuse shall be able to carry the spark successfully up to the point of ignition. The electric arc generated shall ignite the fuse.

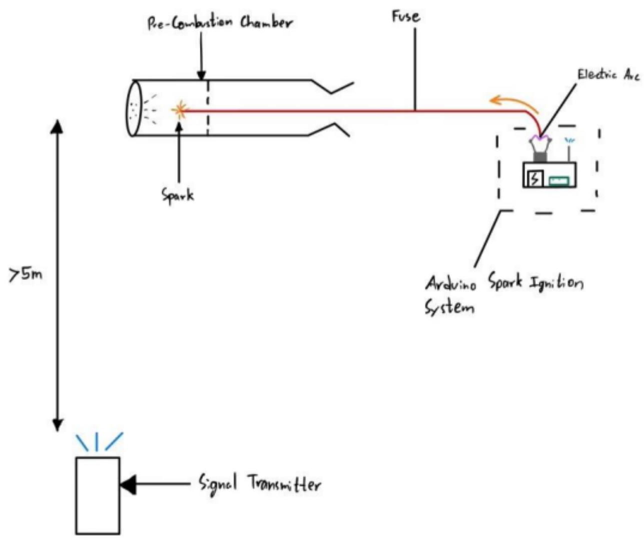

Figure 5.15: Schematic of Ignition System. Source: Own. [1]

5.2.12 Thrust Adapter Assembly

The purpose of the thrust adapter is to transfer the thrust force to the load cell. This adapter is needed to provide a central port for supplying the liquid propellants into the injector plate while still providing axial support and strength. The assembly has 2 end plates, one connected to the chamber flange and the other connected to the load cell. These plates are attached by 4 tie rods. The material for this whole assembly is Mild Steel.

The critical buckling of the struts is given by Euler's Buckling formula: [1]

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{{L_e}^2} \tag{5.14}$$

where L_e is the effective length, equal to half the length of the strut, E is the elastic modulus of steel, and I is the Moment of Inertia.

The cross-sectional moment of inertia for rods with a circular cross-section is given by:

$$I = \frac{\pi \cdot d^4}{64} \tag{5.15}$$

Using this method, the critical buckling load is calculated to be 2337 kN. The maximum load each strut is expected to experience is 1500/4 = 375 N. Each strut will experience maximum stress of 9.4 MPa. Mild steel with a yield strength of 250 MPa provides a high factor of safety.

The circular plate is directly bolted to the load cell and thus has the highest risk of bending. An appropriate thickness for the plate is determined to be 5 mm by performing structural analyses.

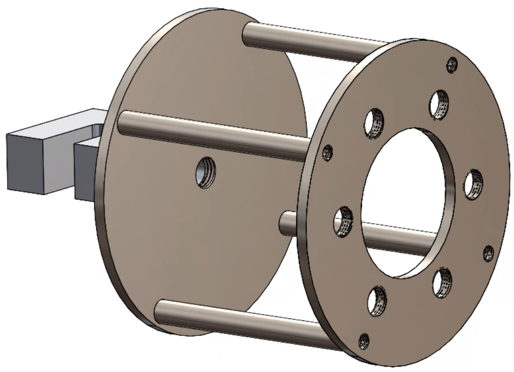

Figure 5.16: Thruster Assembly (The rectangular section in the back is the S-type Load cell). Source: Own.

5.3 Feed System Design

The feed system designed for the hybrid engine is simple in comparison to a Liquid bipropellant engine. There are 3 components for which the feed line system needs to be developed.

For the Hybrid engine, we need only one propellant to be supplied by the feed line, which is Nitrous Oxide from a pressurized tank to the injector plate of the combustion chamber.

However, in real test firing, Nitrous oxide does not ignite easily at lower temperatures due to its low affinity to break down to its constituent species and release oxygen which will combust the compound. Therefore, a small amount of oxygen is required as a precharge to create an oxygen-rich environment for a fast pace ignition. Once ignited, nitrous oxide at the already high temperature is able to break down to release oxygen and sustain the combustion for its entirety without any more aid from the oxygen source.

For clearing out the feed line and the combustion chamber line before the pre-charge or ignition and after the end of the firing, the system needs to be purged with a non-reactive gas that will flush out any group of particles that haven't been fully combusted and are in the chamber, which may stand as a hazard afterwards. For this purpose, we use Nitrogen gas from a highly pressurized tank. As this purge gas acts as a safety net for the whole system that can flush out the other 2 gases in case of a leak or emergency failure, the pressure for nitrogen is kept the highest.

A schematic for the feed system was prepared by the team and verified by the on-site technicians for the design's viability and safety. This has been depicted in figure 5.17.

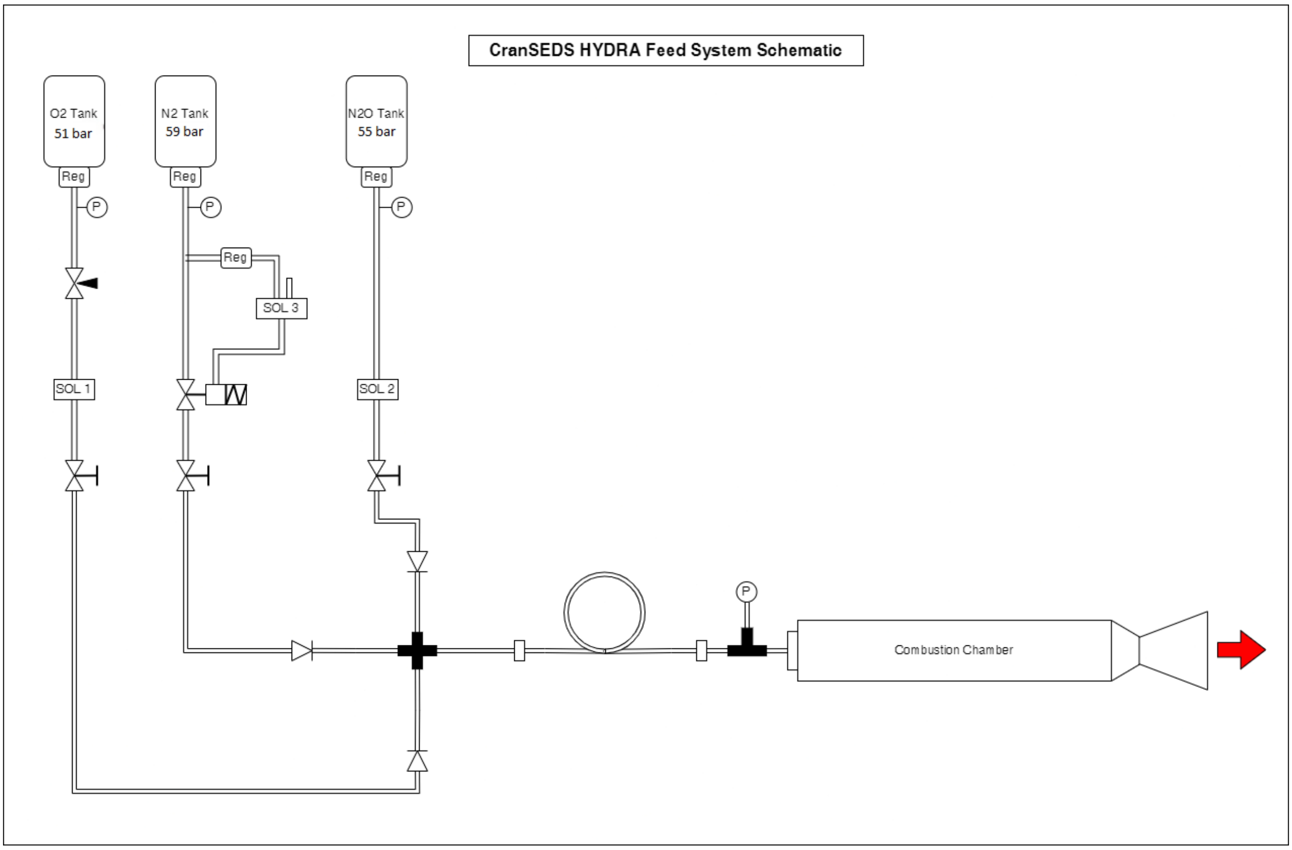

Figure 5.17: Feed System Schematic. Source: Own.

Note: The circular loop represents a bendable pipeline taking all the deformation loads from the chamber firing and saving the metal pipes and other feed components.

- The feed line sub-system consists of 3 lines from the Nitrous oxide tank, Nitrogen tank and Oxygen tank.
- As to fulfil the need for a flame restrictor on the nitrous oxide line, the design was updated after talks with BOC Ltd. (British-based multinational industrial gas company) and the university technicians to incorporate a separate run tank between the main nitrous oxide tank and the combustion chamber.
- So, the main nitrous oxide tank is regulated to let about 4.5 litres in the run tank. This connection is manual and performed before commencing the test firing.
- This run tank is directly connected to the combustion chamber using pressure actuated valve, which is triggered by a separate line of nitrogen gas with a solenoid valve to trigger the pressure-actuated valve. The valve on this line is normally closed.
- A similar configuration is used for the Nitrogen purge line as well. The pressure-actuated valve is triggered by flowing nitrogen gas through it. This valve is normally open to purge the whole system in case anything goes sideways and the power supply is cut off.
- The oxygen line is at low pressure, just for recharging, and hence incorporates only a normally closed solenoid valve.
- The nitrous oxide tank, run tank, and oxygen tank also have a burst valve for safety reasons.

- The 3 gas lines merge onto a 4-way connector, feeding into the combustion chamber through the outside of the injector plate. The connection has been designed according to the specifications given in the ICD document ([6]) by the Race to Space competition.

5.3.1 Valves

As can be observed from the schematic shown above, each feed line has 3 separate valve configurations, that is,

- **Manual stop valves** to control the flow of the pressurant inside the feed line (Note that this valve is separate from the regulator used just after the tank).
- **Solenoid valves**, which will be actuated using the control system from the control room to regulate and initiate the chemical flow when required.
  Note that the solenoid valve used for Nitrogen gas is Normally open configuration, while the other 2 are Normally closed configuration. This ensures in the case of electrical failure; the valves will close off the Oxygen and Nitrous oxide while purging the whole system with Nitrogen gas.
- **Non-return valves**, as the pressure flow of Nitrogen is higher than the other 2, we need to avoid any backflow in the feed lines, and all the component gases flow into the combustion chamber.
- Nitrogen being at very high pressure is sought out to be employed using 2 feed valves, one of which is a **3-way solenoid valve**, and the other is a **2-way solenoid valve**. This valve configuration reduces the load on a single valve and strengthens the system from any imminent failure.
- As for the feed lines, the team made a design choice for using a 3/8 inch steel pipe, which can be employed for highly pressured liquids which will be used in the coming years by the team. And they provide ample performance for the current design case.
- The feed system needs to be validated by a physical leak test, which is planned to be performed before the competition. Further details regarding the same can be found in the Manufacturing section.

5.3.2 Controls and DAQ Electronics

The controls encompass the electronic circuit inside a control box, controlling the feed line sub-system to perform the hot fire testing, and the data acquisition system on-board the test stand.

The control box is sub-divided into 2 separate circuits, controlled using a toggle switch. The 1st switch activates manual control, where all the control inputs for the feed system, including oxidiser feed, purging, pre-charge, ignition and run-through, are performed annually by the personnel from the control room. The 2nd switch initiates a circuit which automates the complete fire sequence. And this circuit uses an Arduino board which will be used to control the sensors and actuators remotely from a safe distance of the control room, monitor the pressure in the oxidiser tank and combustion chamber, measure thrust output via load cells in the thrust adapter and provide data used for validation of the CFD simulations. The control box circuit is described in figures 5.18 and 5.19, while the integration is discussed in the engine setup chapter 9.

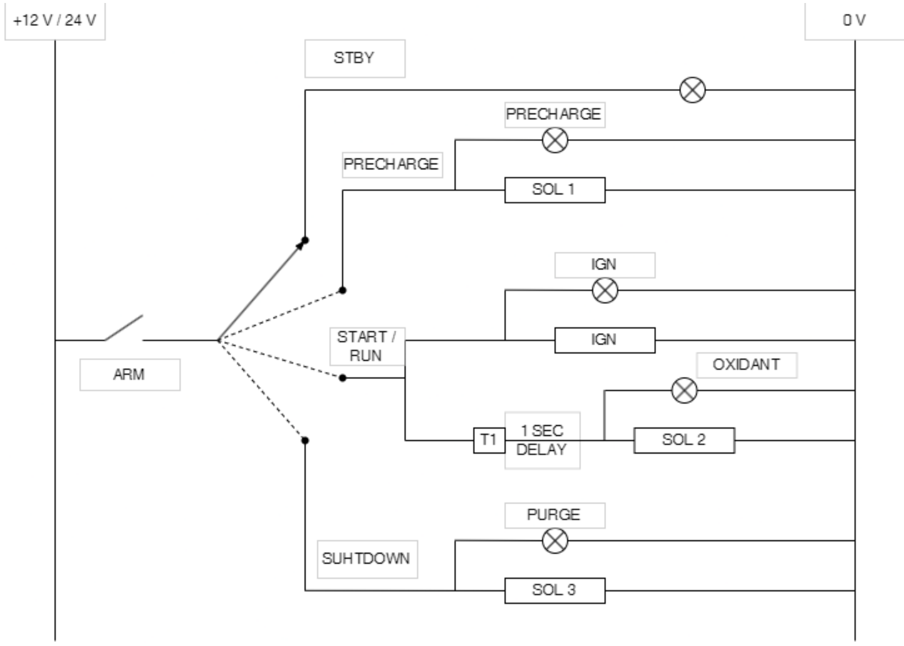

Figure 5.18: Control Box setup schematic. Source: Own.

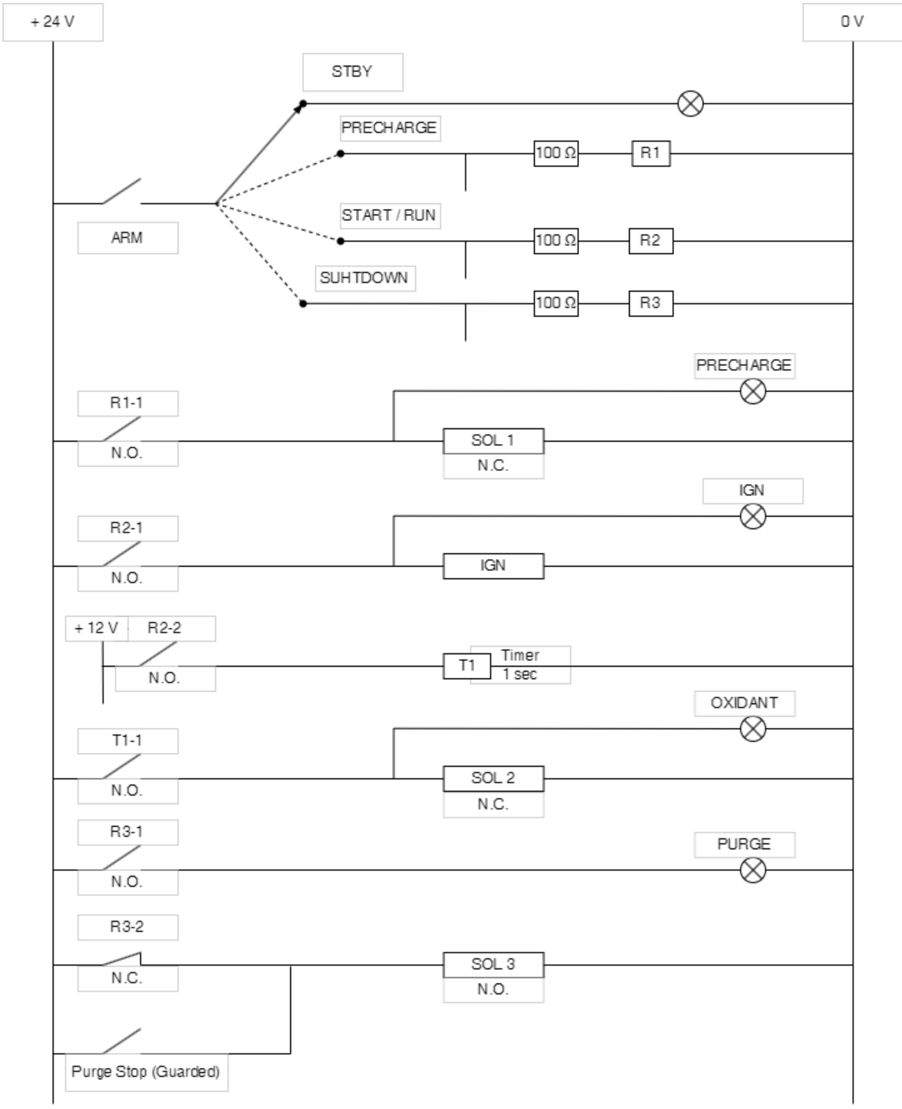

Figure 5.19: Control Box setup schematic. Source: Own.

The Data acquisition system consists of the sensors employed over the engine test stand to measure the performance and characteristics of the test firing. The sensors used, and the parameter measured within this sub-system are:

- Engine Thrust: S block Load cell
- Internal combustion chamber pressure: Pressure transducer
- Fuel line pressure: Pressure transducer
- Temperature of the nozzle and combustion chamber casing: K-type thermocouple

There are 3 thermocouples on the casing, which sits in a groove which is not through. That means the internal environment of the system is preserved, and the readings of the thermocouples are the measurement of internal temperature after conduction through the steel casing. The thermocouples have their independent readers, which will be used for the testing. The thermocouples draw power from the LiPo battery.

The pressure transducer used to measure the feed line pressure is directly connected to the line using a tee connector, which is then passed through the injector inside the combustion chamber.

While the pressure transducer for measuring the internal combustion chamber pressure is mounted on top of the combustion chamber next to the injector flange, which covers a through hole going inside the combustion chamber. This hole will help in measuring the internal chamber pressure throughout the firing, depicted in figure **??**.

The pressure transducers have independent connections with their readers and draw power from the AC voltage regulator.

The load cell measures the thrust produced during the firing. The S block load cell used is Tedea Huntleigh 615, with a capacity of 100 kg measurement. However, the readings obtained in terms of mV are very small, which cannot be read by Arduino. For that, a load cell amplifier needs to be used. It was decided to use HX711, as it is the most reliable, most commonly used, and industrially acceptable amplifier for load cells. This helps the Arduino board to read the signals and plot the thrust graph for the firing.

The Arduino board, load cell circuit, and thermocouples draw power from the LiPo battery. Based on the power budget (Appendix 11.4.4), the battery to be used was selected as an 11.1 V 1500 mAh LiPo battery. However, the Arduino operates at 5 V, which requires a step-down voltage converter to be placed between the battery and the Arduino Uno. LM 2596 was selected to be used as the step-down converter, owing to the previous experience of using it and its performance. The complete data acquisition circuit is presented in figure 5.20. The code for the load cell Arduino circuit is attached in appendix 11.4.

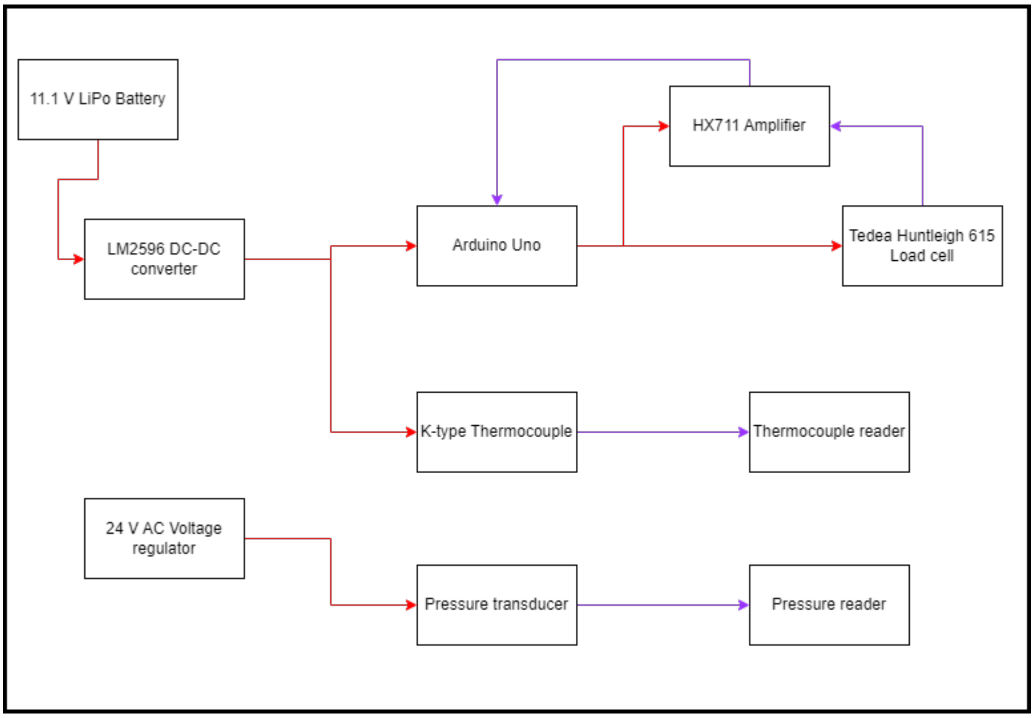

Figure 5.20: Data acquisition sub-system circuit schematic diagram. Source: Own.

An image of the load cell DAQ setup is shown in chapter 8, in figure 8.5.

5.4 Engine Mount

5.4.1 Test Stand

The objective of the Engine mount is to provide support and fixture capability to the main combustion chamber and carry the loads transmitted from the engine firing without any failure-causing deformation. The final design for the engine mount has been shown in figure 5.21.

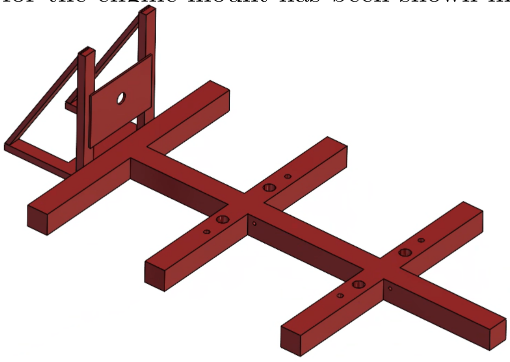

Figure 5.21: Test Stand. Source: Own.

For this, the design began with an L-shape configuration, where a thrust assembly provides axial support to the combustion chamber and carries the transmitted loads from the firing to the structure mount.

While the lower end, horizontal to the ground, ran across the length of the combustion chamber and provided mounting points for support plates, on which the chamber rests and attains a horizontal alignment with the bench.

From these interface criteria, the mount needs to connect to the steel bench as described in the ICD document ([6]). This has been depicted in figure 5.22. The loads transmitted from the chamber firing and due to gravity are to be carried by the Engine mount and passed on to the Test house bench provided by the competition. According to the ICD, the connection will be accomplished using M10 bolts with standard pitch. Therefore, the Engine mount has been designed with boreholes of 10 mm diameter. For the estimation of the number of bolt holes, the bolts should be in pairs so as to avoid any Yaw movement of the structure after assembly.

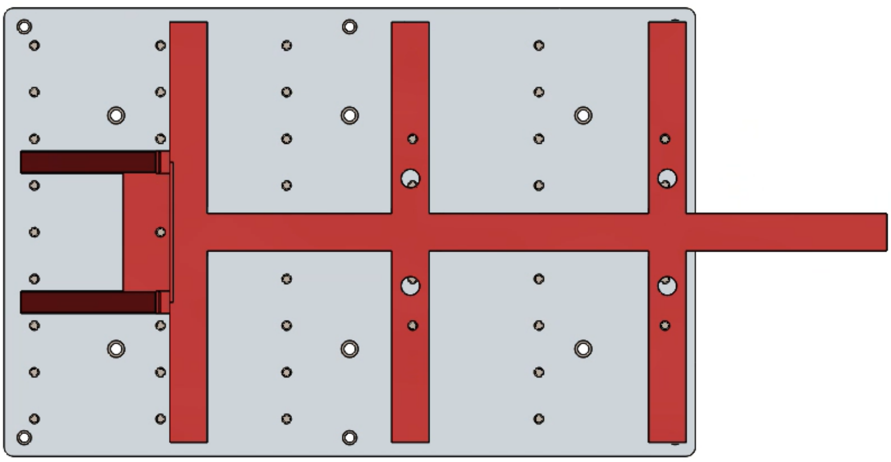

Figure 5.22: Test Stand on the ICD Bench. Source: Own.

Note: The Image of the Test Stand (figure 5.22) has 4 bigger holes (M20) which do not align with the holes of the ICD bench. Those are the bolt holes we have used for the test bench available at our university's test facility. This will be modified to adapt to the interface as provided in the ICD document.

The mount has bars in the lateral direction to provide roll stability, and the bolt holes are drilled at the sides of the chamber length symmetrically.

The cross-sectional shape used for the mount is square with a 3 mm thickness. The material used for the mount is stainless steel. The team was able to manufacture the engine mount and successfully tested it for another engine of 1.5 kN, justifying that the structure and design for the engine mount are safe and have sufficient structural strength.

The test bench has been evaluated for structural performance through Finite Element Analysis (FEA). The resulting deformation and induced stress are indicated in figure 5.23. The analysis result showcases the maximum stress in the worst-case scenario of maximum thrust. The iterations for FEA started with 2 bolts and for the worst loading scenario. Although safe, the team decided to add 3 more bolts for additional safety. Hence, a 5-bolt configuration was selected, with 4 bolt holes on the side arms and 1 bolt along the centre beam of the bench.

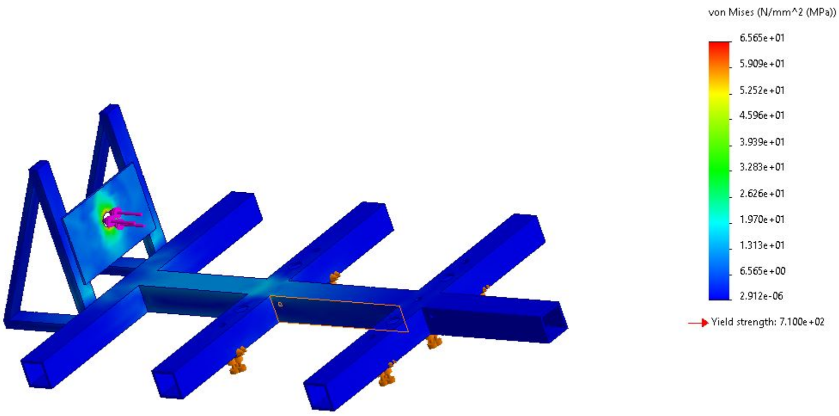

Figure 5.23: FEA results of the engine test stand: Max. Stress: 65.65 MPa (FOS: 10.8). Source: Own.

5.5 Material Selection

The material selected for the combustion chamber, welded flanges and nozzle housing is Mild Steel due to its high enough material strength, low cost and easy machining. Mild Steel, however, poses the risk of corrosion, this is why the injector and injector flange are made using Stainless steel. Plus, Stainless steel has a higher yield strength, providing a better factor of safety. On the downside, the cost of stainless steel is higher than mild steel. So the team made a design choice to use mostly mild steel instead of stainless steel.

For the nozzle, which will experience peak temperatures (enough to melt steel), graphite material (DuraGraph, appendix 11.2.1) was selected.

While for the insulation between the fuel grain and steel casing is a 5 mm thick layer of cork Tufnol with very low thermal conductivity, ease in manufacturing and lightweight.

5.6 Cooling Plan and Thermal Analyses

As it stands, the design incorporates a 5mm thick insulating layer of Tufnol to isolate the internal combustion chamber and grain case from the steel cylinder casing and the external environment. The insulating material has very low thermal conductivity and, thus, for a burn time of 10 seconds, will not conduct high enough heat to melt the steel casing.

However, this needs to be validated and correctly estimated. For this reason, the team used RPA software to study the thermal response of the developed engine. The results are indicative of the stable state when the temperature and flow stabilize, not for 10 seconds, and thus the values obtained are extremely higher than the ones which will be experienced in the actual testing of the engine. The results showed that the maximum temperature occurs at the nozzle throat, as expected, while the average combustion chamber temperature at the stabilized state will be about 2100 K. These results, being at the stabilized state, do not include thermal insulation from the tufnol layer between the fuel grain and steel casing. Hence, a better model needs to be developed to estimate an accurate temperature profile for the engine. The team is working on this front and will elaborate on the research work in the final Engine document.

The melting point of mild steel is 1620 K, which makes the material unsuitable to be used.

However, the current scenario runs for less than 10 seconds, and the repetitive tests are planned to be performed with enough time intervals for the system to cool down. This consideration, along with the cost consideration, led the team to select Mild Steel for the design.

However, the material will be subjected to high loads from thermal cycling, which needs to be assessed and analysed. For this, thermos-structural analyses were performed to simulate the material component for the worst thermal cycling and loading altogether to see if the Mild steel can hold or not.

In order to achieve the required 18-second burn time simulated additives have been researched by the team. Coating such as DOWSIL 93-104 is being looked into as they are no longer export-restricted in the UK and could provide a longer ablative period for the liner.

6. Design Calculations

6.1 Combustion Chamber Length

For the Steel Casing available with us, Outer Diameter, $OD_{cc} = 73.03mm$
Inner Diameter, $ID_{cc} = 59.01mm$
Thickness, $t_{cc} = 7.01mm$

Post Combustion Chamber length, $L_{postcc} = OD_g = 50mm$
Pre Combustion Chamber Length, $L_{precc} = OD_g/2 = 25mm$
Minimum Required Combustion Chamber Length, $L_{req.cc} = L_f + L_{precc} + L_{postcc} = 575mm \sim 600mm$

6.2 Nozzle Shape

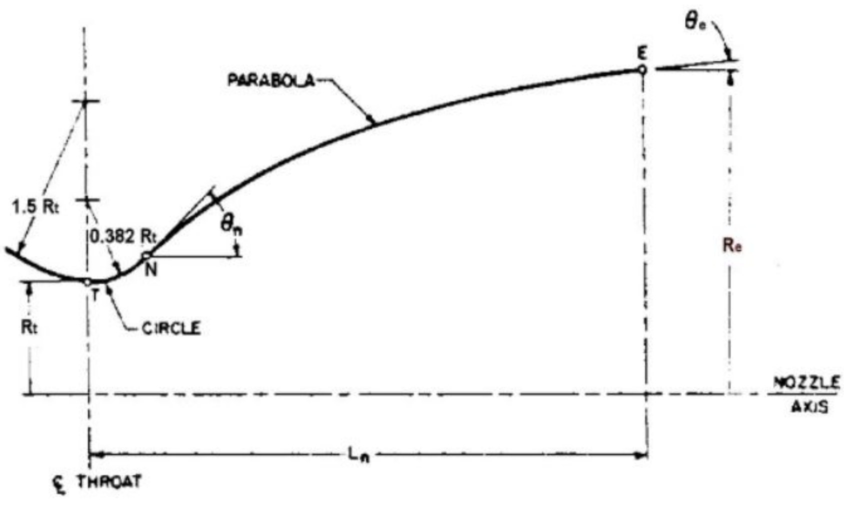

Figure 6.1: Design method of a Rao nozzle. Source: Own.

$R_t = 5.5mm$

$\epsilon = 5.2$

$$R_e = \sqrt{\epsilon} R_t \tag{6.1}$$

$R_e = 12.6mm$

$$L_n = 0.85(\frac{(\sqrt{\epsilon} - 1)R_t}{tan15}) \tag{6.2}$$

$L_n = 22.4mm$

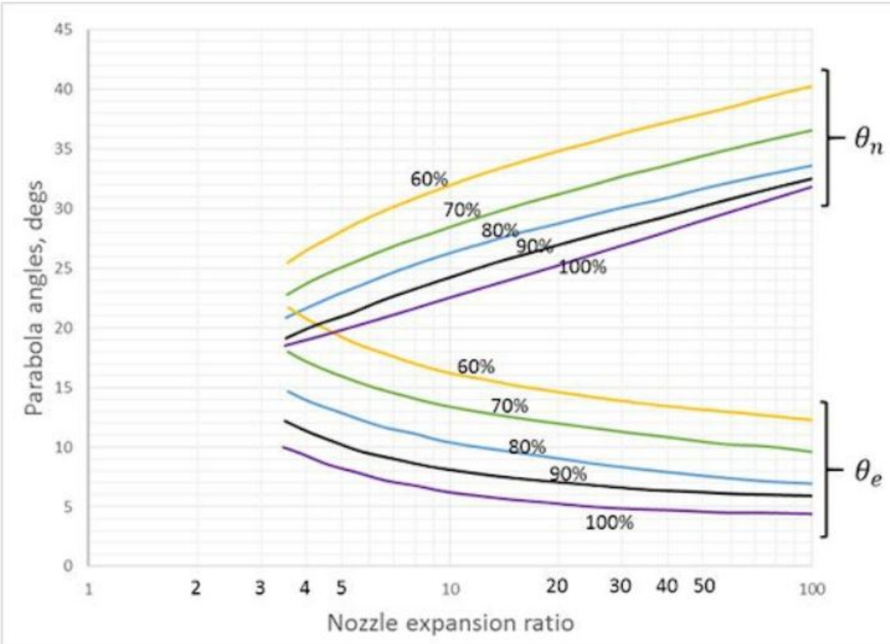

Figure 6.2: Design method of a Rao nozzle. Source: Own.

$\theta_n = 23$

$\theta_e = 11$

6.3 Thermochemistry for combustion reaction

The combustion reaction occurring between liquid nitrous oxide and solid HDPE fuel results in 3 products from 100% combustion, carbon dioxide, water vapour and nitrogen. This has been represented in the reaction given in equation 6.3.

$$2\ (C_2H_4)_n\ +\ 2\ (N_2O)\ \rightleftharpoons\ 2\ CO_2\ +\ n\ H_2O\ +\ N_2\ +\ \Delta \tag{6.3}$$

The "n" in the reaction signifies the number of molecules in a single polymer chain of HDPE.
The initial reaction mass of HDPE is 119.118 grams, and N_2O is 905.3 grams.
HDPE is a polynomial of carbon and hydrogen molecule monomers. So, the molecular mass of HDPE can be calculated from the available data of its constituent components, i.e., carbon and hydrogen.
Carbon has 12 grams/mol, and hydrogen has 1 gram/mol. Calculating for HDPE's molecular mass,

$$m_{HDPE} = n \cdot [2(12) + 4(1)]\ grams/mol = 28n\ grams/mol \tag{6.4}$$

Similarly, molecular mass for N_2O is,

$$m_{N_2O} = 14 \cdot 2 + 16\ grams/mol = 44\ grams/mol \tag{6.5}$$

Now, to calculate the moles consumed in the chemical reaction,

$$Moles_{N_2O} = N_{N_2O} = \frac{905.3}{44} = 20.575mol \tag{6.6}$$

This provides the number of moles that are produced in the reaction when it is 100% complete. The number of moles produced per species are:

- Carbon dioxide: 20.58 mol
- Water vapour: 8.50 mol
- Nitrogen: 10.29 mol

Now, to calculate the enthalpy of all the reactants and products, Enthalpy of formation of carbon dioxide at 298.15 K, $\Delta H_f(CO_2)$ = -393.5 kJ/mol Enthalpy of formation of water vapour at 298.15 K, $\Delta H_f(H_2O)$ = -285.82 kJ/mol Enthalpy of formation of nitrogen at 298.15 K, $\Delta H_f(N_2)$ = 0 kJ/mol Enthalpy of reduction of nitrous oxide at 298.15 K, $\Delta H_{red}(N_2O)$ = -82.05 kJ/mol Enthalpy of combustion of HDPE is a 2-part enthalpy, enthalpy of polymerization and enthalpy of combustion of a single monomer. This is described in equation 6.7.

$$\Delta H_{comb}(HDPE) = \Delta H_{poly}(HDPE) + \Delta H_{comb}(C_2H_4) \tag{6.7}$$

$$\Delta H_{comb}(HDPE) = (-100\ kJ/mol) + (-651.28 kJ/mol) = -751.28 kJ/mol \tag{6.8}$$

The above enthalpies will be used to calculate the overall enthalpy of the reaction as follows,

$$\Delta H_{reaction} = 2\,\Delta H_f(CO_2) + n\,\Delta H_f(H_2O) + \Delta H_f(N_2) - 2\,\Delta H_{comb}(HDPE) - 2\,\Delta H_{red}(N_2O) \tag{6.9}$$

$$\Delta H_{reaction} = 308.02 kJ/mol \tag{6.10}$$

Now, using the enthalpy values and number of moles, we can calculate the dissipated heat using the formula,

$$Q_{reaction} = \Delta H_{reaction} \cdot N_{HDPE} \tag{6.11}$$

This dissipated heat can be equated to the amount of heat carried by the 3 reaction products with the formula,

$$Q_{reaction} = n \cdot C_{p,eq.} \cdot dT \tag{6.12}$$

Here, $C_{p,eq.}$ represents the equivalent specific heat of the reaction products at constant pressure. This can be calculated as,

$$C_{p,eq.} = \frac{N_{CO_2} \cdot C_{p,CO_2} \ + \ N_{H_2O} \cdot C_{p,H_2O} \ + \ N_{N_2} \cdot C_{p,N_2}}{N_{CO_2} \ + \ N_{H_2O} \ + \ N_{N_2}} \tag{6.13}$$

Putting in the values,

$$C_{p,eq.} = \frac{N_{CO_2} \cdot 0.849\ J/gK \ + \ N_{H_2O} \cdot 4.186\ J/gK \ + \ N_{N_2} \cdot 1.04\ J/gK}{N_{CO_2} \ + \ N_{H_2O} \ + \ N_{N_2}} = 1.72\ J/gK \tag{6.14}$$

Now equating both the equations of dissipative heat, the temperature gradient can be calculated as,

$$dT_{reaction} = \frac{Q_{reaction}}{C_{p,eq.}} = \frac{\Delta H_{reaction} \cdot N_{HDPE}}{C_{p,eq.}} = 761.039K \tag{6.15}$$

Considering the initial ambient temperature is 298.15 K, the final temperature when the reaction is exhausted can be calculated as

$$T_{f_{reaction}} = dT_{reaction} \ - \ T_{ambient} = 1059.19K \tag{6.16}$$

Now, the temperature within the combustion chamber increases exponentially, which can be represented as

$$T_{CC} = T_A \cdot e^{B \cdot t} \tag{6.17}$$

where T_A is the temperature constant, B is the temperature exponential rate constant, and t is the time in seconds.

And the regression rate calculated in section **??** is 0.872 grams/sec.

The calculation made in the previous section for the time until complete exhaustion of the HDPE solid fuel is 6.25 seconds, and the final temperature calculation made in this section aids in estimating the values for the constants of equation 6.17.

The exponential rate constant has the inverse value to the oxidizer flux rate constant used for the regression rate, representing the exact same combustion property of fuel material exhaustion but with an increment factor rather than a reduction (regression).

From this, T_A can be calculated by integrating equation 6.17 as

$$dT_{CC} = T_A \cdot e^{\frac{t}{0.763}} \cdot dt \tag{6.18}$$

$$\int_{298.15}^{1059.19} dT_{CC} = T_A \cdot \int_0^{6.25} e^{\frac{t}{0.763}}\, dt \tag{6.19}$$

$$761.04K = \frac{T_A \cdot [e^{\frac{6.25}{0.763}} - e^{\frac{0}{0.763}}]}{0.763} = T_A \cdot 4729.478 \tag{6.20}$$

The value of T_A obtained is 0.161 K. The obtained graph of the exponential rise in temperature is displayed in figure 6.3. The graph has been developed using the Matlab tool, and the code is attached in appendix 11.3.

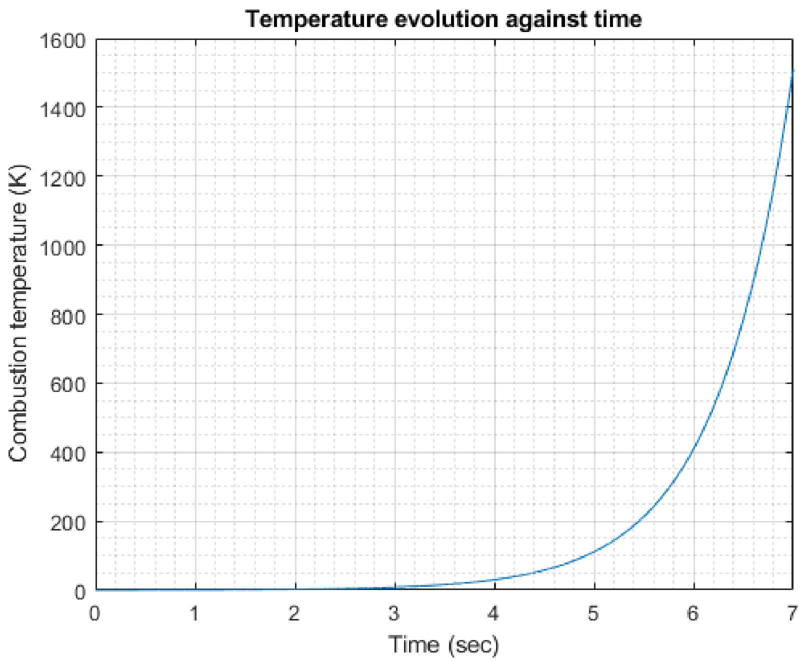

Figure 6.3: Exponential rate graph for temperature with time

6.4 Pressure Drop

6.4.1 Feed Line Pressure Drop

Oxidiser mass flow rate, $m^{\cdot} = 0.242kgs^{-2}$
Oxidiser Density, $\rho_{ox} = 822.2kgm^{-3}$
Dynamic Viscosity of Nitrous Oxide of Saturated Gas at $15^{o}C$, $\nu = 0.016mNs/m^2$
Flow Velocity,

$$v = \frac{m_{ox}^{\cdot}}{\rho_{ox} \cdot A_{pipe}} = 0.85ms^{-1} \tag{6.21}$$

Reynold's Number,

$$R = \frac{\rho_{ox} \cdot v \cdot ID_{pipe}}{\nu} = 722 \tag{6.22}$$

Darcy Friction Factor, $f_{darcy} = 0.04$
Feed Pipe maximum estimated length, $l_{pipe} = 2m$
A half-inch pipe is planned to be used for the feed system.
Combustion Chamber Pipe Inner Diameter, $ID_{pipe} = 20.99mm$ [7]
And, thickness for standard pipe, $t_{pipe} = 2.24mm$ [7]
So, Combustion Chamber Pipe Inner Diameter, $ID_{pipe} = OD_{pipe} - 2t_{pipe} = 16.51mm$
Frictional Pressure Drop,

$$dP_{feed} = f_{darcy} \cdot \frac{l_{pipe}}{ID_{pipe}} \cdot \rho_{ox} \cdot \frac{v^2}{2} = 1.44bars \tag{6.23}$$

6.4.2 Injector Pressure Drop

Mass flow rate, $m^{\cdot} = 0.246kgs^{-2}$
The general value of the Coefficient of Discharge for Nitrous Oxide, $C_d = 0.8$
(Historical Data) Diameter of Injector, $d_{inj} = 1mm$
Area of Injetor, $A_{inj} = 7.854 \cdot 10^{-7}m^2$
Density of Nitrous Oxide, $\rho_{ox} = 822.2kgm^{-3}$
Number of Injector holes, n = 10.
Using the modified Bernoulli's equation for a single-phase incompressible fluid, we have [8] [9]

$$m^{\cdot} = Q \cdot \rho = C_d \cdot A_{inj} \cdot \sqrt{\frac{2 \cdot dP_{inj} \cdot \rho_{ox}}{1 - (\frac{A_{inj}}{A_1})^2}} \tag{6.24}$$

where A_1 is the upstream cross-sectional area, i.e., the area of the inlet side of the injector, which is $A_1 = 7.85 \cdot 10^{-5}$. Also, $A << A_1$. Rearranging the equation above and substituting the values, we get the value of pressure drop for total n = 10 holes as

$$0.246 = 0.8 \cdot 10 \cdot 7.854 \cdot 10^{-7} \cdot \sqrt{\frac{2 \cdot dP_{inj} \cdot 822.2}{1 - (\frac{7.854 \cdot 10^{-7}}{7.85 \cdot 10^{-5}})^2}} \tag{6.25}$$

And so, the Overall Injector Pressure Drop, $dP_{overallinj} = 0.9321MPa = 9.321\ bars$

From the above 2 sections, we get the overall pressure drop as,

$$dP_{overall} = dP_{overallinj} + dP_{feed} = 10.76\ bars \tag{6.26}$$

The target chamber pressure is 37 bars. Therefore, the pressure regulator on top of the Nitrous oxide tank shall regulate the flow at $P = 33.5 + dP_{overall} = 47.76\ bars$.

However, as can be seen in the feed system diagram (figure 5.17), the pressure for the Nitrous oxide tank is taken as 55 bars. This is due to the practical experience of our team members using similar setups.

6.5 Injector Design

6.5.1 Injector Sizing

To calculate the injector size, the basic design shall be defined.

The injector is a single bolt configuration with injector holes in the configuration of showerhead injection.

The values used from other sections for determining injector sizing are, Maximum operating pressure of combustion chamber, $CC_{max.op.} = 55$ MPa, Number of injector bolts, $n_i = 1$, The inner diameter of the combustion chamber, $CC_{ID} = 0.059$ m.

These can be used to calculate the maximum axial force on the combustion chamber as,

$$F_{A,max.op.} = CC_{max.op.} \cdot \frac{\pi \cdot {CC_{ID}}^2}{4} = 15036.84\ N \tag{6.27}$$

The selected material is stainless steel with a proof load of 600 MPa. This will be used to calculate the maximum applicable axial force on the injector.

The maximum applicable axial force was calculated as,

$$Axial\ force = 600 \cdot 10^6\ Pa \cdot \frac{\pi \cdot 0.05^2}{4}\ m^2 = 1.18 \cdot 10^6\ N \tag{6.28}$$

And the factor of safety is calculated as,

$$FoS = \frac{Axial\ force}{F_{A,max.op.}} = \frac{1.18 \cdot 10^6\ N}{15036.84\ N} = 78\ >\ 20 \tag{6.29}$$

6.6 Flange Sizing

From the previous sections, we know the values for:
outer diameter of combustion chamber = 73.03 mm,
bolt size = M12,
Washer diameter = 24 mm.

$$\text{Flange inner diameter, } ID_f = CC_{OD} = 73.03mm \tag{6.30}$$

Assuming a weld bead of 4mm the flange outer diameter can be calculated as,

$$OD_f = ID_f + 2(washer\ diameter + 2(weld\ bead)) \tag{6.31}$$

$$OD_f = ID_f + 2 \cdot (2(4) + 24) = 137.03\ mm \tag{6.32}$$

The number of bolts used is 8. This leads to an equal hole spacing as,

$$\text{Hole spacing} = \frac{360^o}{8} = 45^o \tag{6.33}$$

6.7 Chamber thin wall stress calculations

Longitudinal Stress:

$$\sigma_L = \frac{P_{chamber} \cdot r_{chamber}}{2 \cdot t} = 9.7MPa \tag{6.34}$$

Cicumferential / Hoop Stress:

$$\sigma_h = 2 \cdot \sigma_L = 19.3MPa \tag{6.35}$$

Shear Stress: Shear Stress occurs as In-plane stress and Out-of-plane stress. The value for the current case, however, remains the same.

$$\sigma_s = \frac{\sigma_L}{2} = 4.85MPa \tag{6.36}$$

Overall Stress and FOS: Calculating the overall stress from the above 3 defined stresses, we get,

$$\sigma_{total} = \sqrt{{\sigma_h}^2 + {\sigma_L}^2 + {\sigma_s}^2} = 22.138MPa \tag{6.37}$$

The Yield Strength of Mild Steel is 250 MPa, which gives a Factor of Safety value as, FOS = 11.3

7. CFD Simulations

Computational fluid dynamics (CFD) simulations are performed on the nozzle to evaluate the performance of the hybrid engine subjected to high temperatures and pressure multi-phase flow. The target set for the simulations is to model the solver as close to the real world with multiple phases of the propellants, with varying pressure and temperatures for the first 6.5 seconds of the burn. The flow is steady state showcasing the evolution of combustion and engine characteristics for the burn time of the developed engine.

7.1 Methodology

As part of its CFD software, Ansys has the ability to approximately solve Navier-Stokes' equations to analyze complex fluid dynamics problems with a high degree of accuracy. The software was utilized to determine the performance aspects of the nozzle under various flow and boundary conditions, in addition to providing a variety of turbulence models to compute turbulent flow.

7.1.1 Step 1: Modelling the geometry

In Solidworks, the nozzle was designed in two dimensions and then imported into Ansys Fluent Design Modeller for editing. The geometry was designed using simple tools such as sketching and plane surface creation. To facilitate the meshing process, after the geometry has been transferred to the Design modeller, it is divided into different sections. After importing the geometry to the ANSYS design modeller, the further process of named selection is performed. As shown in figure 7.1, the geometry is divided in half so that it will be easier to compute and because the other half which will produce similar results.

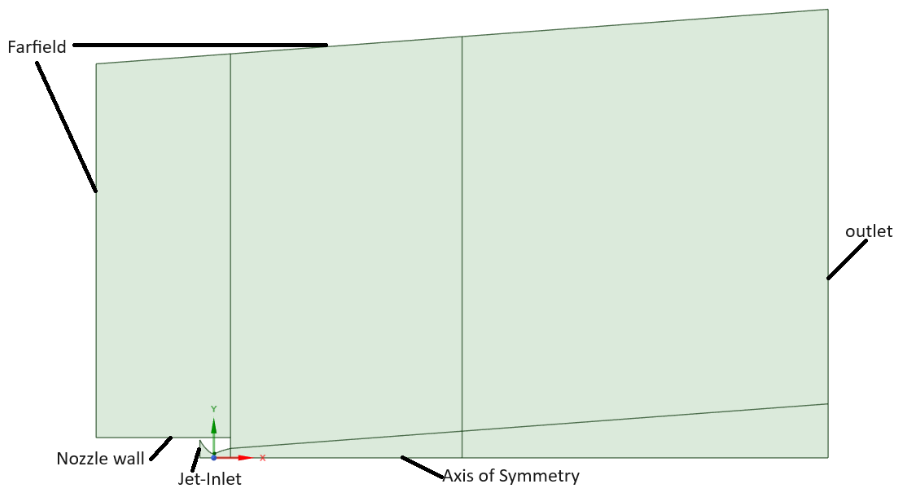

Figure 7.1: Model geometry for CFD simulation of the engine nozzle. Source: Own.

7.1.2 Step 2: Meshing

Among the most important process is meshing the developed geometry. A mesh refers to a discretization of geometry into small elements, which can be either structured or non-structured. The significance of performing this process lies in computing the flow equations at the nodes of each equation. In order to achieve close to accurate simulation results, high-quality structured meshes have to be used. It was especially important to divide the nozzle curve part into a number of sections before meshing to ensure a structured mesh along the curve while maintaining orthogonality, skewness, and aspect ratio. The following subsections show the meshing operations performed, the overall meshing visual, and the meshing along the nozzle curve.

Skewness

Based on ideal element-type angles, Skewness is a measure of element quality. A minimum angle may also be defined as the angle between the vectors from each node and the opposing mid-side, as well as the angle between the two adjacent mid-sides of each element's nodes. As one of the primary properties of the Measures of finite element mesh, skewness is determined by the degree of closeness a face or cell is to ideal (i.e., equilateral or equiangular). The closer it is to zero, the better it is.

Aspect Ratio

As the name suggests, the aspect ratio describes the relationship between an element's largest and smallest characteristic dimensions. As a result of large aspect ratios, the finite element representation becomes more inaccurate, and the convergence of Finite Element Solutions suffers. A one-value aspect ratio is ideal but cannot always be maintained.

Orthogonal Quality

Orthogonal quality refers to the angle between the vector that connects two mesh nodes (or control volumes) (s) and the normal vector for each integration point surface (n) associated with those nodes.

Figure 7.2 shows the final meshing of the allowable nozzle flow region.

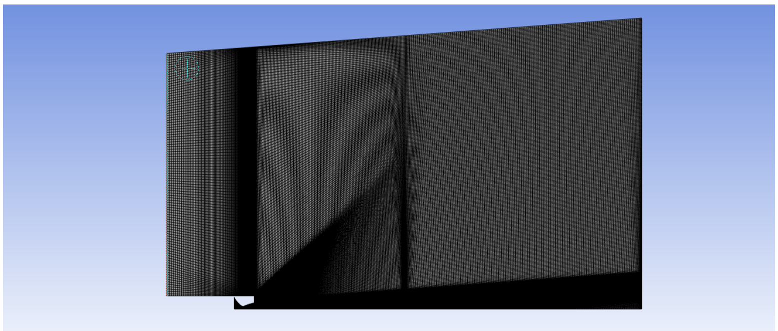

Figure 7.2: Meshed geometry for CFD simulation of the engine nozzle. Source: Own.

7.1.3 Step 3: Setting boundary conditions

The boundary conditions were set to the domain according to the preferences. They are enlisted below:

1. Farfield
2. JetInlet
3. Nozzle wall
4. Outlet
5. Axis of Symmetry

7.1.4 Step 4: Solver pre-processing (Setup)

The next step is to setup the solvent parameters to initialise the simulation. This involves setting parameters in such a way that yields the expected solution for the problem setup. The parameters include physics models, material properties, boundary conditions, reference values, solution methods, solution controls, and solution initialization settings.

- A pressure-based solver is used along with the realisable $k - \epsilon$ turbulence model which contains an alternative formulation to resolve turbulent viscosity. An exact equation for the transport of mean-square vorticity fluctuation has been derived from a modified transport equation. The energy equation was activated in order to allow heat transfer to occur. This solver and turbulence model combination yields more accurate results when compared to a density-based solver.
- The problem is simulated to be a steady state, which is defined by characteristics that do not change with time and are assumed to have been reached after a long period of time.
- Since the mesh created was 2D, the axisymmetric option was chosen in 2D space settings. The central axis has been created in the nozzle geometry. This method only requires simulating fluid behaviour in one two-dimensional plane, thereby saving time and computational power.
- Some values for initialization: total gauge pressure for inlet is 3801325 Pa and temperature of 3000 K.
- As a flow material, N_2O has been selected. For density settings, the ideal gas has been chosen. Furthermore, a constant viscosity has been set for the compressible flow.

- Later, the pressure inlet, far field, and pressure outlet boundary conditions were determined. To calculate the selected oxidizer flow, the cell zone was made into nitrous oxide material. The pressure inlet was initially given conditions from the combustion chamber, such as temperature and pressure, while the pressure outlet was set to atmospheric conditions. The symmetric boundary was chosen as the axis since it defines the partition between the other half of the nozzle.

- Initial solution methods: include the Roe-FDS flux type, which splits the fluxes in accordance with their corresponding flux method eigenvalues. In spatial discretization, the initial gradient setting is set to be Least Square Cells Based, and the flow and modified turbulent viscosity are set to be Second Order Upwind. It is recommended that users use this flux type for most simulations.

- A standard initialization method has been selected for initialization, as well as the initial values have been computed from the inlet of the nozzle before initialization. A converged solution is reached in 3000 iterations.

7.2 Results

The obtained results are tabulated with pressure, velocity, and temperature values, taken from the report definitions, in table **??**. The values are recorded for every 100 iterations.

The contour results obtained for the nozzle flow for a 2D centre planar flow are highlighted in figures 7.3 for density contour, 7.4 for pressure contour, 7.6 for velocity contour, and 7.5 for temperature contour.

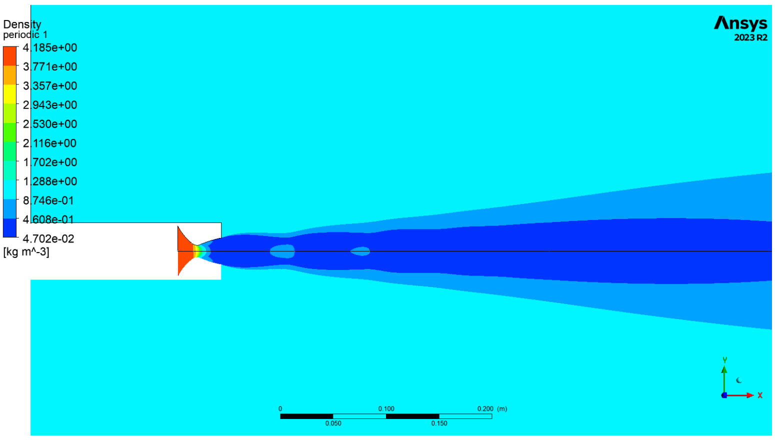

Figure 7.3: Obtained results for CFD simulation of the engine nozzle: Density contour. Source: Own.

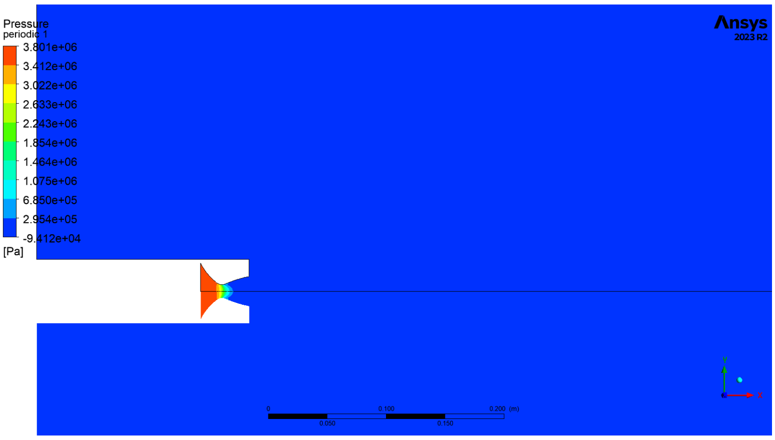

Figure 7.4: Obtained results for CFD simulation of the engine nozzle: Pressure contour. Source: Own.

The temperature and pressure both increase at first and then start decreasing after the throat section in the nozzle. The pressure shows a drastic change in the value after the combustion crosses the throat part.

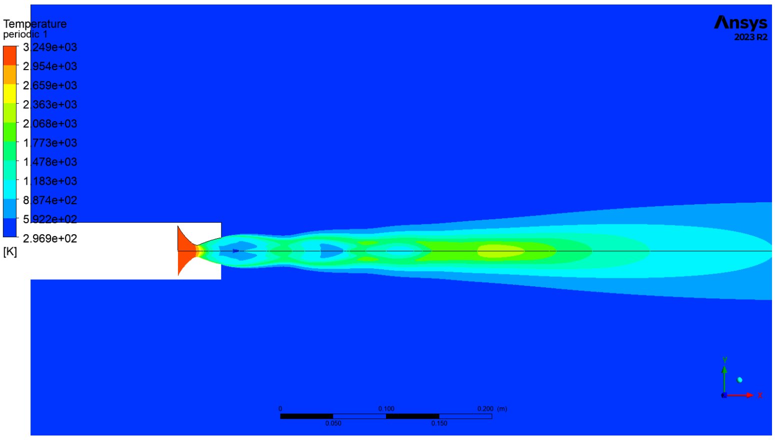

Figure 7.5: Obtained results for CFD simulation of the engine nozzle: Temperature contour. Source: Own.

On the other side, the velocity starts from a lower value and reaches a higher value after going through the throat of the nozzle.

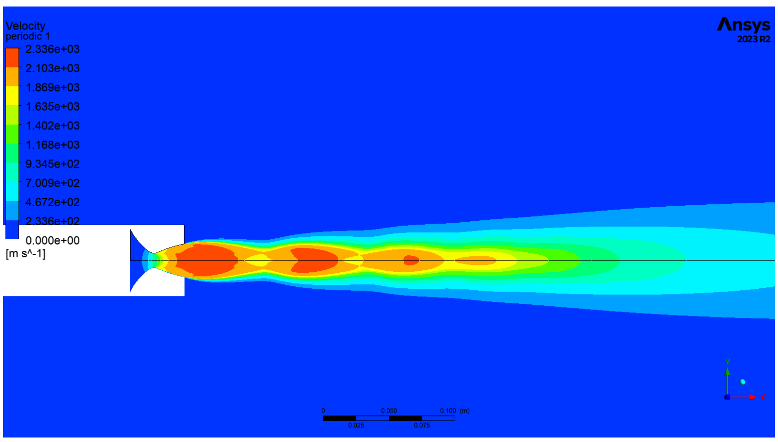

Figure 7.6: Obtained results for CFD simulation of the engine nozzle: Velocity contour. Source: Own.

7.3 Future Work

Further work requires performing a simulation of the combustion chamber. Due to the need of using chemical species transport models, which requires the selection of premixed combustion options, it is difficult to compute the combustion chamber in two dimensions. To select the fuel and oxidizer for the hybrid rocket motor, a three-dimensional model must be used. For a proper understanding of the combustion distribution within the chamber, it is necessary to conduct a 3-D simulation of the combustion chamber, which will provide us with the necessary values to compare with the theoretical and experimental values derived from the computation. A 3D modelling of the combustion chamber and injector assembly is also currently under work. The next step should be the assembly of the injector and nozzle. Future work can also focus on simulating a transient model to achieve a better correlation with real-world testing. The transient response will aid in correctly determining the evolution of temperature, pressure, chemical reaction, and flow characteristics of the hybrid engine.

8. Manufacturing

8.1 Timeline and lead time overview

1. **Procurement of steel:** Based on the verified engineering drawings, the manufacturing team was able to place an order for the required billets with the help of the test facility team. The procured material was cleaned, de-rusted, and the outer layers chipped off. These billets are not ready to be machined to the desired components.

2. **Test stand:** The Test Stand has already been manufactured by the team with M10 bolt holes.

Figure 8.1: Manufactured test stand. Source: Own.

3. **Combustion chamber:** The manufacturing of the combustion chamber is underway. The end flanges will be welded onto the casing, and the chamber shall be pressure tested.

4. **Injector plate and flange:** The Injector plate with the tapped hole for fitting in the feed line end and the 1 mm holes for injection of oxidiser into the combustion chamber is being manufactured, along with its flange, onto which the main injector plate will be fastened using external male threads on the injector plate.

5. **Fuel grain block and cork liner sub-assembly:** The fuel grain block has been purchased and upon arrival will be cut into 3 parts and drilled to achieve the desired grain geometry.

   The cork liner is a little more than 1 mm thick, allowing to use of 5 cork liner sheets overlapped on the fuel grain that fits inside the combustion chamber.

   The bond adhesive will be spread out between the fuel grain and the cork liner sheets. To hold it in position until the adhesive is cured, 3D-printed fixtures will be used for this purpose.

6. **Thruster assembly:** The thruster assembly with its front and back plate and the 4 mid connectors have been manufactured by the test facility manufacturing team based on the team's

design. The design for the threads was updated to address the inevitable gap during the fastening of components using bolts and optimized to remove any unwanted gaps between the threads of the components. A separate connector bushing was designed, analyzed, and 3D printed to provide fitting to the bolt connection between the thruster assembly and the load cell. The material has been tested through brute force of pulling.

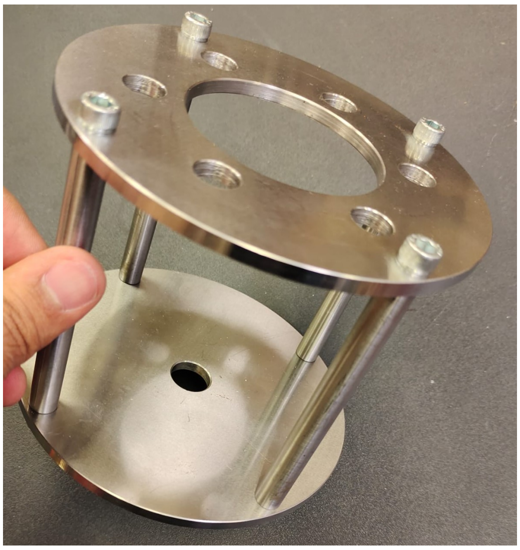

Figure 8.2: Manufactured and assembled thruster assembly. Source: Own.

7. **Support assembly:** The Support plates consist of 2 parts - Ring clamps and bend support plates. To conserve the cost of manufacturing, the mild steel sheet was procured separately, and the sheet metal machining, including cutting, bending, drilling, and fitting, was performed completely by the team.

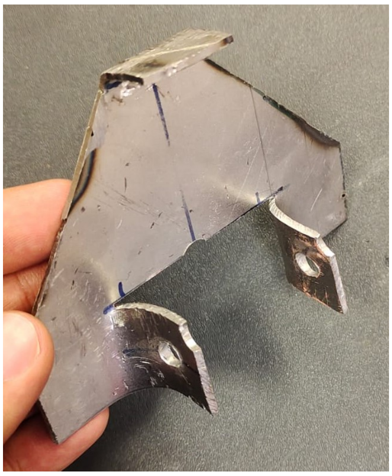

Figure 8.3: Manufactured bend support plate. Source: Own.

This setup was tested with the combustion chamber for correct alignment through the length of the combustion chamber and tested with brute pull force.

8. **Graphite nozzle:** The graphite nozzle is being manufactured and delivered to the team from external manufacturers.

9. **Nozzle casing:** The nozzle casing is being manufactured and modified for correct fitting with the manufactured and procured graphite nozzle.

10. **Feed line system:** The components for the feed system have been procured, and the cutting of steel pipes, joining with the adapters and valves, and the overall fitting has been initiated and

is planned to be completed by May. This includes the connection to the 3 different tanks to the combustion chamber, the connection between the main oxidiser tank and the run tank, and the safety nets for the system. This will be tested thoroughly with the help of cold flow testing for the whole feed line system to check for any leaks or potential failures that will be reinforced.

11. **Controls and data acquisition system:** The Control Box has been assembled, integrated and tested by the test facility's supervision team and the student team. The control box will be in the safe operating room in the test house. This will be connected with a long tether for the power supply in the facility.

    The Data Acquisition system has been developed and tested in 3 separate circuits by the student team separately that are, Load cell circuit, Thermocouple circuit, and Pressure transducer circuit. The connections are made and soldered to the component electronics, which will be housed inside a 3D-printed box fixed onto the nearby test bed tower. This sub-system will be assembled with the rest of the whole ensemble during the final assembly and integration of the system in the test house. This is further discussed in the next chapter on Engine Setup 9.

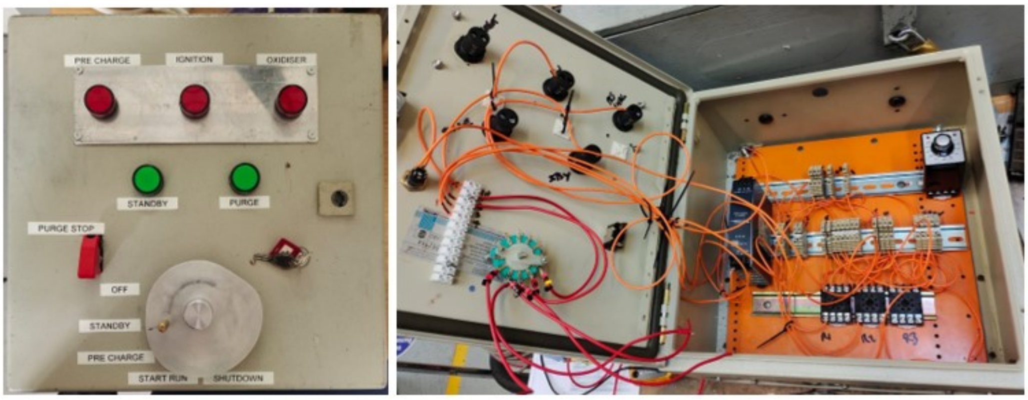

Figure 8.4: Assembled control box. Source: Own.

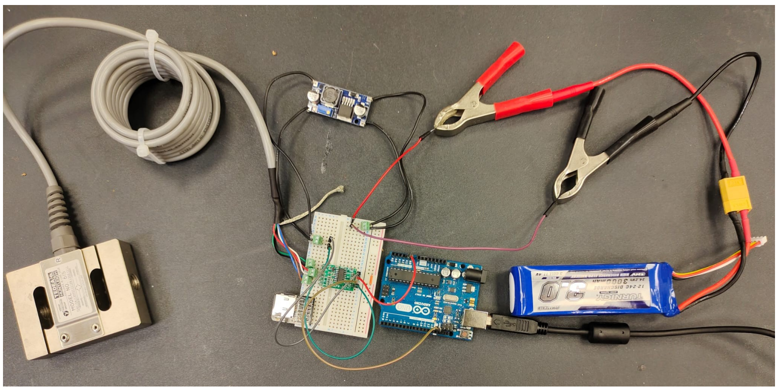

Figure 8.5: Assembled data acquisition system for the load cell. Source: Own.

12. **Off-the-shelf components used:** The team decided to use some components directly as OEM parts. They are –

    - O-rings
    - Engine liner
    - Gasket
    - Bolts and fasteners
    - Electronics and Feed system (except for length cut of pipes)

13. **Assembly and integration:** The assembly will be performed by the members and the test facility supervision team. The assembly and integration is a long process that starts with the

manufacturing phase for interface compatibility of the designed components and checking for the tolerance relations for the interacting components. This has been covered in-depth in the next chapter on Engine setup 9.

8.2 Manufacturers used

The manufacturing for the main combustion chamber assembly is primarily conducted by the manufacturing department and workers of the Cranfield University Test facility, with the guidance of the design team.

The structural assembly of the engine and the fuel sub-assembly is conducted in a separate area. The final assembly and integration of the test stand, controls and electronics, and the feed line system are being performed at the Test house by the team.

For the nozzle, Erodex Ltd. firm has been employed for the CNC machining of the graphite Rao bell nozzle. The graphite was integrated with the engine in the initial phase during the fitting of the nozzle in the steel nozzle casing for the structure sub-assembly integration. The fitting was performed by the university's manufacturing team by varying the tolerance of the nozzle casing to ensure tolerance fit for the nozzle sub-assembly.

The fuel blocks of 500 mm in length will be divided into 3 sections for ease of machining for boring through the billet on a lathe machine. At the same time, the assembly of fuel blocks, cork liner, and adhesive will be conducted by the team.

The Test stand was initially manufactured by the test facility manufacturing team in 2022. However, it has been modified for this year to make it compatible with the Race to Space ICD document specified interface by the team.

The feed line pipe cutting, joining and assembling are being carried out by both the team with the assistance of the supervision team at Cranfield's Test facility.

9. Engine Setup and Hot-Fire Sequence

9.1 Engine Integration

The assembly, integration and testing (AIT) phase of the project will begin in May 2024. This temporary assembly will aid in aligning the self-manufactured bending support plates onto the test stand. Once performed, the structural part of the test stand is complete. The images taken during last year's setup phase have been attached in Appendix 11.5. The section is sub-divided into 3 categories:

9.1.1 Engine Structure

- The injector houses an axial O-ring creating a seal between the injector and the injector flange. The injector also houses a radial O-ring that seals to the liner. The graphite nozzle is pushed inside the nozzle casing with 2 radial O-rings.
- The combustion chamber sub-assembly consists of 2 end flanges welded on the ends of the combustion chamber casing and the solid fuel with its lining inside the casing.
- The liner is of cork, hardened by a special cork adhesive and hardener solvent. This mixture is spread out on one side of the linear, which is folded on the solid fuel bars. This is put in place using 3D-printed fixtures to hold it in place until the adhesive is cured. Once cured, the fuel block sub-assembly is ready to be assembled with the system.
- The nozzle sub-assembly and the injector sub-assembly are connected to the combustion chamber sub-assembly with solid fuel and liner inside of it.

9.1.2 Feed Line System

- The feed line sub-system consists of 3 lines coming from the Nitrous oxide tank, Nitrogen tank and Oxygen tank.
- As to fulfil the need for a flame restrictor on the nitrous oxide line, the design was updated after talks with BOC and the university technicians to incorporate a separate run tank between the main nitrous oxide tank and the combustion chamber.
- So, the main nitrous oxide tank is regulated to let about 4.5 litres in the run tank. This connection is manual and performed before commencing the test firing.
- This run tank is directly connected to the combustion chamber using pressure actuated valve, which is triggered by a separate line of nitrogen gas with a solenoid valve to trigger the pressure-actuated valve. The valve on this line is normally closed.

- A similar configuration is used for the Nitrogen purge line as well. The pressure-actuated valve is triggered by flowing nitrogen gas through it. This valve is normally open to purge the whole system in case anything goes sideways and the power supply is cut off.
- The oxygen line is at low pressure, just for recharging, and hence incorporates only a normally closed solenoid valve.
- The nitrous oxide tank, run tank, and oxygen tank also have a burst valve for safety reasons.
- The 3 gas lines merge onto a 4-way connector, feeding into the combustion chamber through the outside of the injector plate. The connection has been designed according to the specifications given in the ICD document ([6]) by the Race to Space competition.
- The feed system overview schematic is described in figure 5.17.

9.1.3 Controls and DAQ System

- The control box is one of the most crucial components for the test firing, and its assembly of it shall adhere to strict and precise arrangements.
- The electrical parts are put in the available big control box connected to the electrical AC supply regulator. These are, in turn, connected to the switches mounted on the top face of the box, with their connecting ports below the box lid to make internal connections. It shall be ensured that the wiring is done, keeping frequent opening and closing of the box lid.
- The control box has a 4-way switch to actuate one of the 4 sub-circuits according to the test firing sequence. These phases are: Standby, Pre-charge, Start/Run, and Shutdown. They will, in turn, allow their respective circuit to be operational, and the firing sequence can be correctly continued.
- The schematics of the control box are shown in figures 5.18 and 5.19. The assembled control box is displayed in figure 9.1.

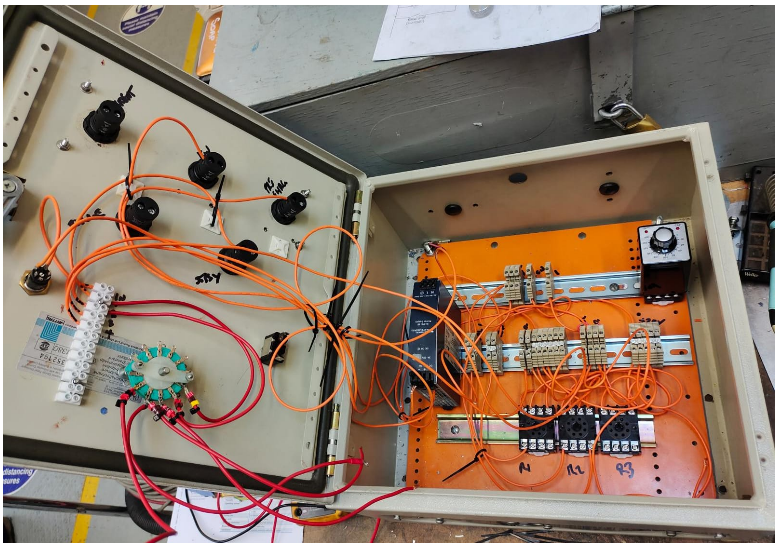

Figure 9.1: Assembled Control Box. Source: Own.

- For the data acquisition system, the red-designed slots and positions are correctly manufactured and ready to be placed.

- The load cell is fastened and acts as the connection between the combustion chamber assembly and test stand, acting as the thrust carrier.
- The thermocouples are sealed inside their respective slots using high-grade silicone sealant.
- The pressure transducers are screwed down to the tee connector for the feed line and the adapter on top of the combustion chamber's end flange.
- Although the electrical connections were made separately for testing the circuit, it is rewired with long wires to mount the data loggers and Arduino board on the adjacent tower. This process took a little bit of on-site work with long wires cutting into place.

9.2 Manufacturing: Test-Firing Procedure and Operations

A preliminary procedure for the hot test-firing was developed so the operators follow the correct procedure in a checklist manner, and safety is ensured.

9.2.1 Combustion Sequence Overview

The combustion chamber casing is separated from the bottom injector plate attached using bolts. The combustion chamber is closed and properly sealed with different components (Injector coin, nozzle, ceramic coating inside) intact using retainer rings, gasket, and sealants. The whole assembly is then fixed to the test table. The following subsections discuss the assembly, maintenance, safety, and test preparations.

9.2.2 Assembly and maintenance

Fuel Preparation

Procedure:

1. Take the 3 part machined solid blocks of HDPE, all of which are 166.7 mm long, and the cork liner.
2. The cork liner is 5 mm thick, so at least 4 layers will be required to fix the fuel inside the combustion chamber. Cut the cork such that it only completes one whole revolution around the fuel blocks.
3. The cork liners will be 548 mm long, encompassing the solid fuel part of 500 mm and the pre-combustion chamber length.
4. The liner and the fuel blocks will be fixed into position using industrial-grade adhesive mixed with a hardener. This will fix the blocks relative to the liner sheets and fix the liner sheets with each other. This also aids in hardening the soft cork liner to provide structural rigidity.
5. Wait until the adhesive in this liner and fuel block assembly is cured.
6. Now spread a very small amount of adhesive into the combustion chamber when starting to put the fuel block in the chamber.
7. While fastening the injector plate on one side of the combustion chamber, pass on the fuel and liner block through the nozzle side. The adhesive layer will bind the cork liner to the combustion chamber, thus fixing its position.

Chamber Assembly

Prerequisites: Fuel Preparation Procedure 9.2.2.
Procedure:

1. Ensure the horizontally stable position of the combustion chamber.
2. Attach the nozzle sub-assembly to the end of the combustion chamber.
3. Once the prerequisites are fulfilled, and the combustion chamber is assembled, connect it with the thruster assembly and the load cell, which will then complete the single-line assembly.
4. Put the 2 ring clamps around the combustion chamber and tighten them until the chamber is fixed and collinear with the lower straight bar of the test stand.
5. Now take this to the site and the test bench, where the stand needs to be bolted down tightly.
6. Place the screws two by two in opposite positions. Tighten without reaching the stop. Once they are all positioned and tightened, give the last torque adjustment to all of them two by two in opposite positions.
7. Connect the 1/2 inch BSP parallel connection between the feed line output and the injector mouth.
8. From the assembled circuit for the load cell, connect the 6 wires from the load cell to the board and secure the electronics in position on the tower.
9. Screw in both the pressure transducers and plug their output into their respective data loggers.
10. Use silicone sealant to fix the 3 thermocouples on the combustion chamber and the nozzle. Wait until it's cured. (Do this step earlier so there will not be a need to wait at the test site. Possibly 8 hours prior.)
11. With the assembly completed, the safety and inspection phase can be initiated.

9.2.3 Safety Checks

Prerequisites: None; can be done at any time.
Procedure:

1. Ensure N2O Tank charged to > ((min pressure))
2. Check N2 Tank charged to > ((min pressure & 5 bar > N2O tank pressure))
3. Check PI and PX coherent
4. With Feed Sys Manual Isolation Vv SHUT, set Feed Sys EAV to OPEN and check OPEN; SHUT EAV and check SHUT
5. With Purge Sys Manual Isolation Vv SHUT, set EAV to OPEN and check OPEN; SHUT EAV and check SHUT

9.2.4 Run System

Prerequisites:

1. PXX Safety Checks
2. PXX Fuel Preparation
3. Suitably qualified and experienced personnel on hand at the firing site
4. University Fire Safety notified
5. Area cleared and marked to reduce risk to bystanders
6. All teams give the OK on their systems to the Run Coordinator
7. Fire extinguishers on hand

Procedure:

1. Ensure Feed Sys EAV SHUT and Purge Sys EAV SHUT
2. Ensure N2O tank Feed Vv SHUT
3. Check N2O tank pressure ((ok))
4. Check N2 tank pressure ((ok))
5. Assemble Arduino circuit with arc-ignitor
6. Insert SIM Card in the circuit board
7. Mount the Assembly adjacent to the pre-combustion chamber
8. Place the wire fuse inside the arc ignitor
9. OPEN N2O tank Manual Isolation Vv and OPEN N2 tank Manual Isolation Vv
10. Evacuate firing chamber
11. Initiate ignition via Text Message: "Fire"
12. OPEN Feed Sys EAV
    motor runs
13. SHUT Feed Sys EAV
14. OPEN Purge Sys EAV
    run purge
15. SHUT Purge Sys EAV
16. Check fire out
17. Ventilate firing chamber (if indoors; open doors); safe to re-enter
18. SHUT Purge Sys and Feed Sys Manual Isolation Vvs
19. Remove the SD card from Arduino and disassemble the circuit.
20. Note down final N2O and N2 tank pressures

10. Outreach

For the academic year 2023-24, CranSEDS society outreach activities are managed by two dedicated outreach officers and volunteers from the society's members. Majority of outreach is concerned with STEM engagement and promotion for young students, this year's activities are detailed as below.

In January 2024, CranSEDS attended the KS3 Student Climate Change Summit at the University of Bedfordshire as one of the industry and academia based exhibitors, and a workshop lead on the topic of space sustainability. 164 students from 17 schools were in attendance to learn about projects that contribute to sustainability or tackle climate change. CranSEDS projects were showcased on this theme, such as the SDC cubesats for wildfire detection and monitoring, in-orbit servicing applications for space debris, and solar UAV detection of arctic ice-caps.

CranSEDS have also been involved in mentoring a team from Mill Hill County High School that are participating in the 2024 UK CanSat Competition organised by UK's European Space Education Resources Office (ESERO-UK).

The newly established CranSEDS Solar UAV Research Project works with A-Level computer science students from the Girl's Day School Trust (GDST) Space Technology Diploma as part of their outreach work. The goal is to upskill computer science students for space technology and engineering ventures.

(a) Space sustainability workshop

(b) NSSC stall

(c) Engineering lead Noah

Figure 10.1: Outreach photos

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[2] Guobiao Cai, Hao Zhu, Dalin Rao, and Hui Tian. Optimal design of hybrid rocket motor powered vehicle for suborbital flight. *Aerospace Science and Technology, Volume 25*, 2013.

[3] Francesca Heeg, Lukas Kilzer, Robin Seitz, and Enrico Stoll. Design and test of a student hybrid rocket engine with an external carbon fiber composite structure. *Aerospace, Volume 7*, 2020.

[4] Richard M. Newland. *The science and design of the hybrid rocket.* Lulu.com, 2017.

[5] Jungpyo Lee, Artur Elias De Morais Bertoldi, Artem Andrianov, Renato Alves Borges, Carlos Alberto Gurgel Veras, Simone Battistini, Takakazu Morita, and Patrick Hendrick. Role of precombustion chamber design in feed-system coupled instabilities of hybrid rockets. *Journal of Propulsion and Power (JPP), Volume 36, Issue 6*, 2020.

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[7] Engineering Toolbox. Pipes - nominal wall thickness, 2008.

[8] Benjamin S. Waxman, Jonah E. Zimmerman, Brian J. Cantwell, and Gregory G. Zilliac. Mass flow rate and isolation characteristics of injectors for use with self-pressurizing oxidizers in hybrid rockets. *American Institute of Aeronautics and Astronautics*, 2013.

[9] RIT Launch Initiative Hybrid Rocket. Injector design process, injector, propulsion, engine specifications, 2018.

11. Appendices

11.1 Engineering Drawings

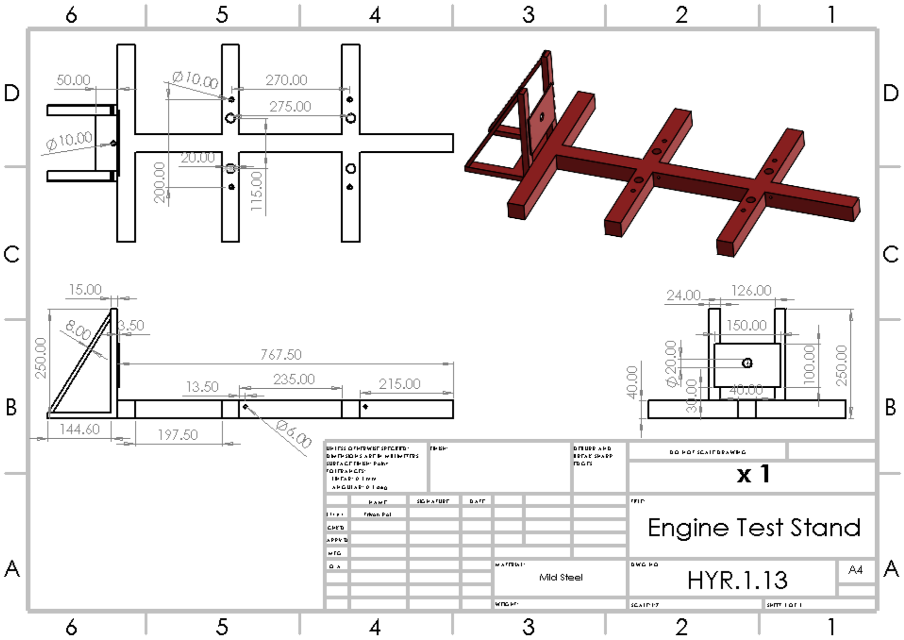

Figure 11.1: Engine Test Stand. Source: Own.

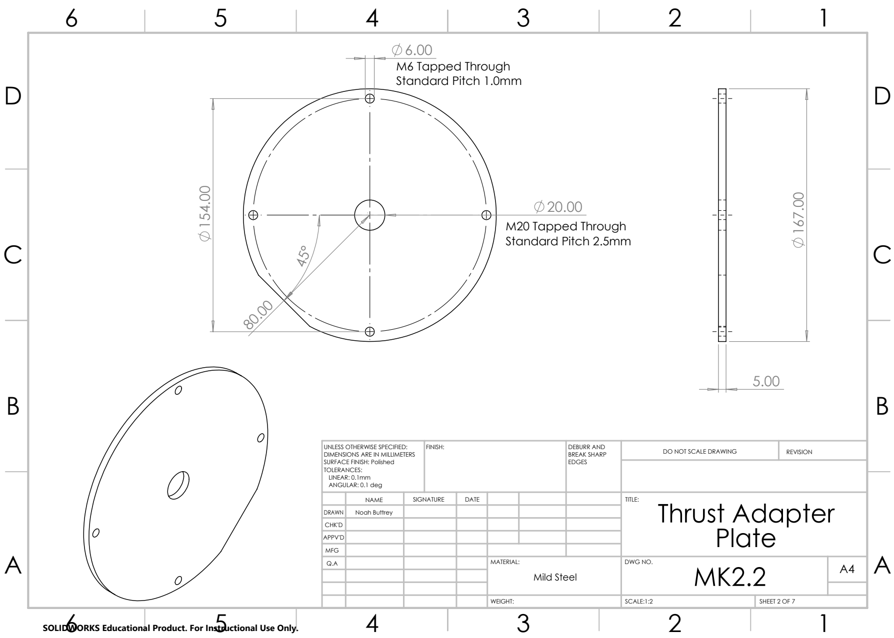

Figure 11.2: Thrust Adapter Rear Plate. Source: Own.

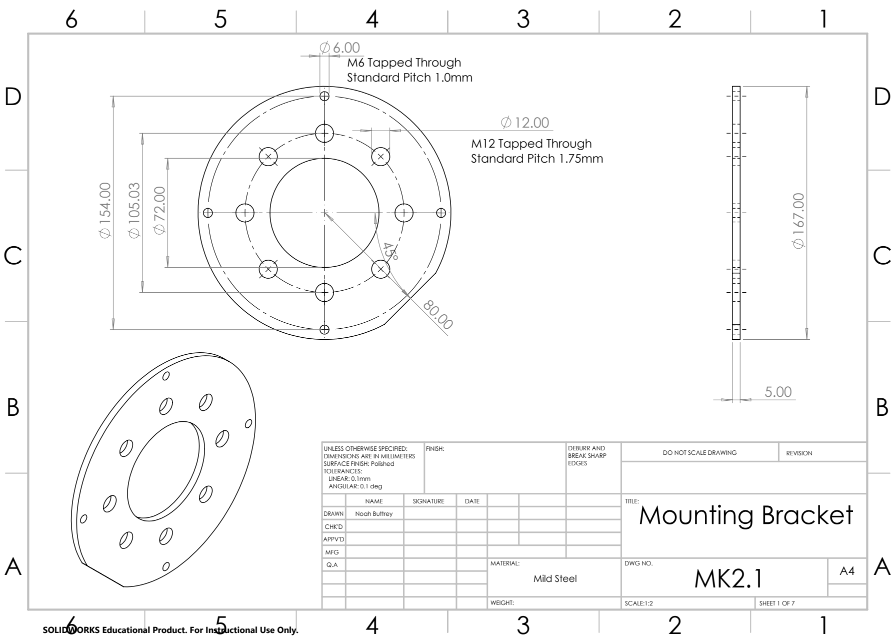

Figure 11.3: Thrust Adapter Front Plate. Source: Own.

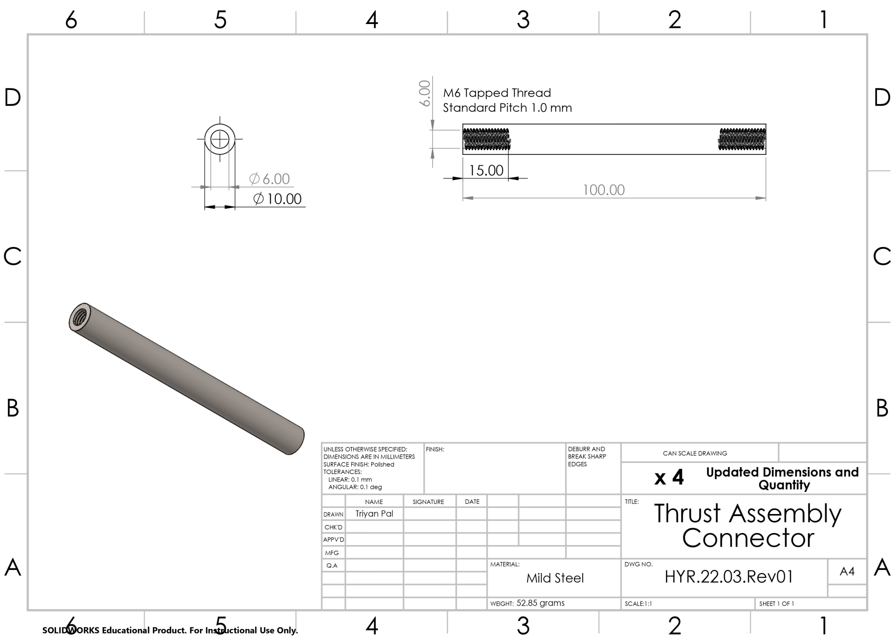

Figure 11.4: Thrust Adapter Connecting Tie rods. Source: Own.

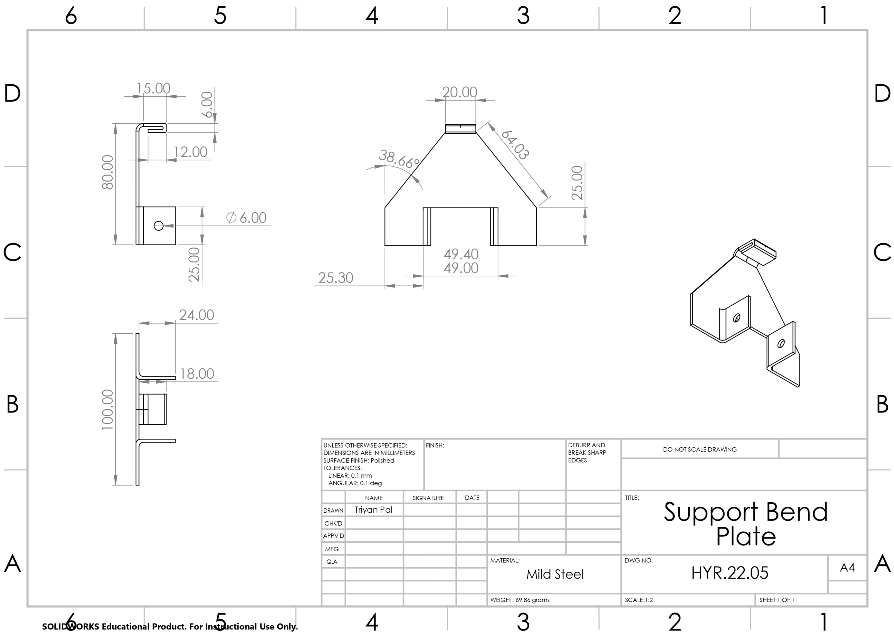

Figure 11.5: Engine Chamber Ring Clamp System Support Plates. Source: Own.

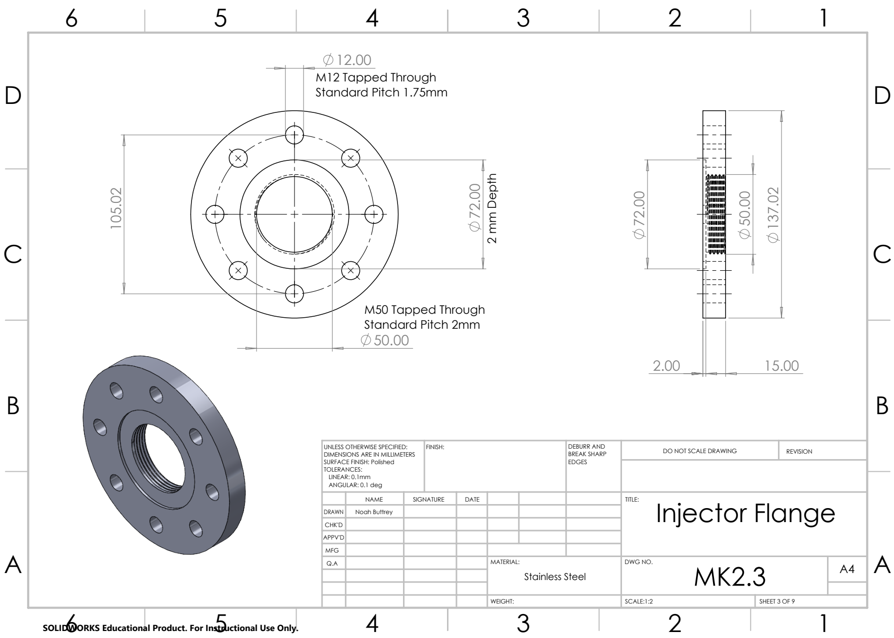

Figure 11.6: Engine Injector Flange. Source: Own.

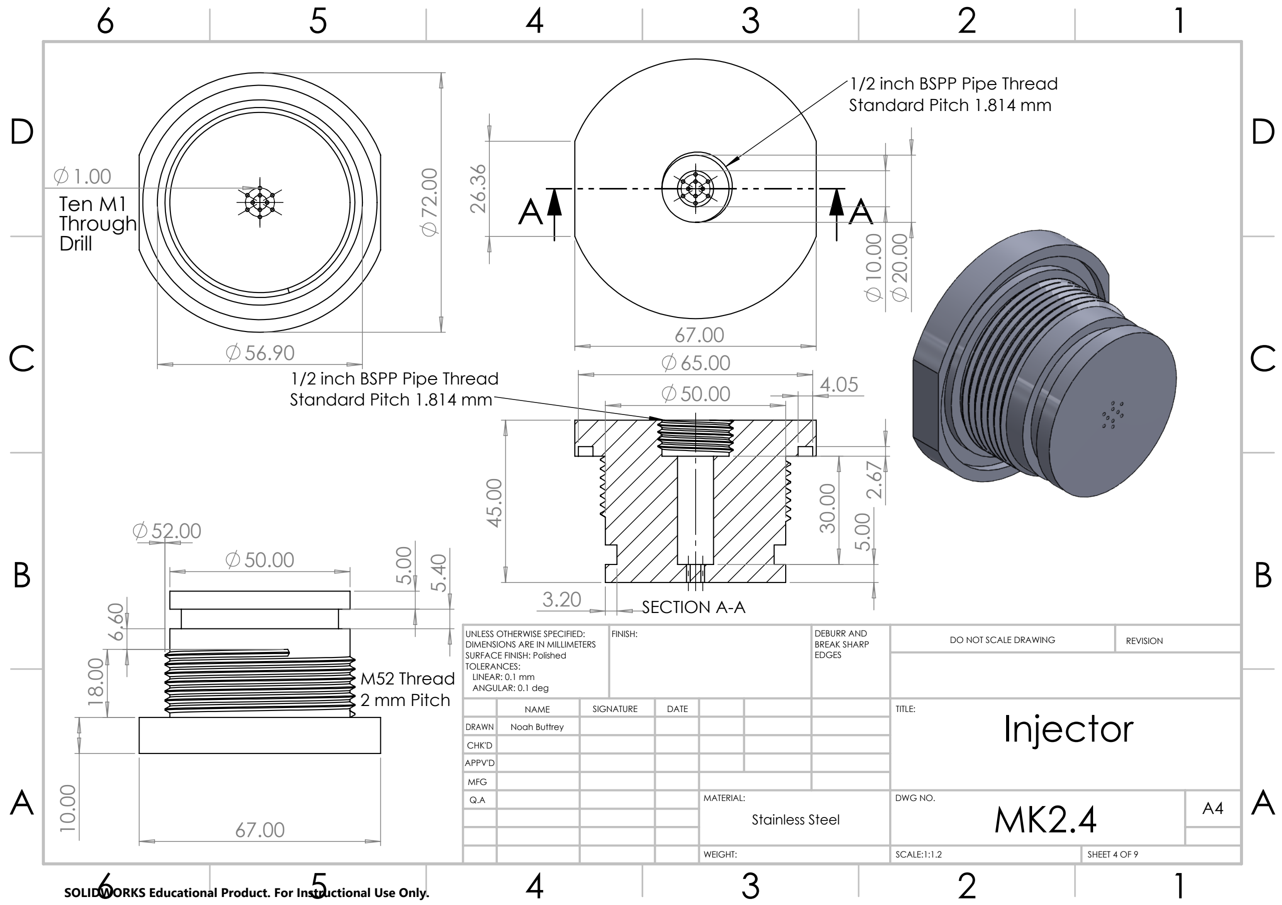

Figure 11.7: Engine Injector Plate. Source: Own.

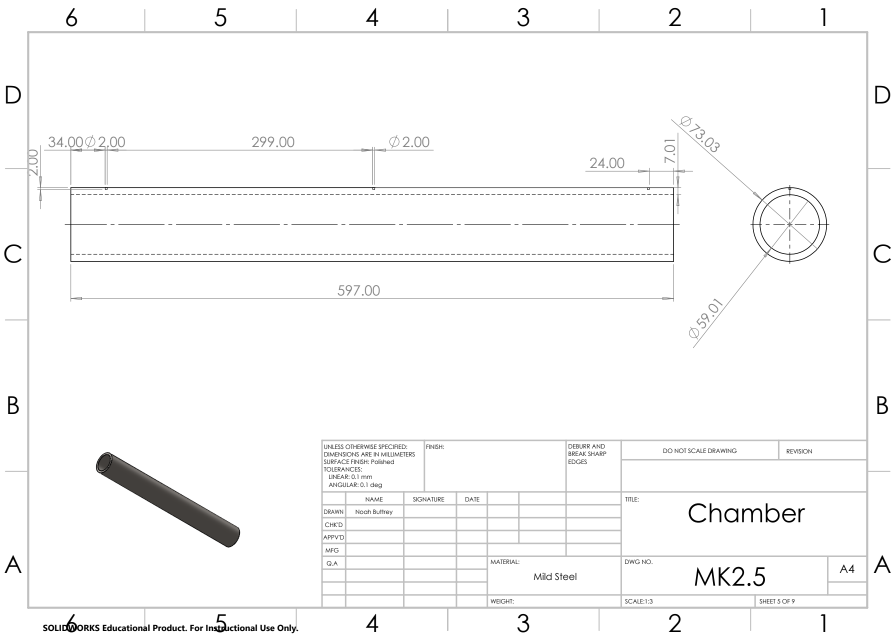

Figure 11.8: Combustion Chamber Casing. Source: Own.

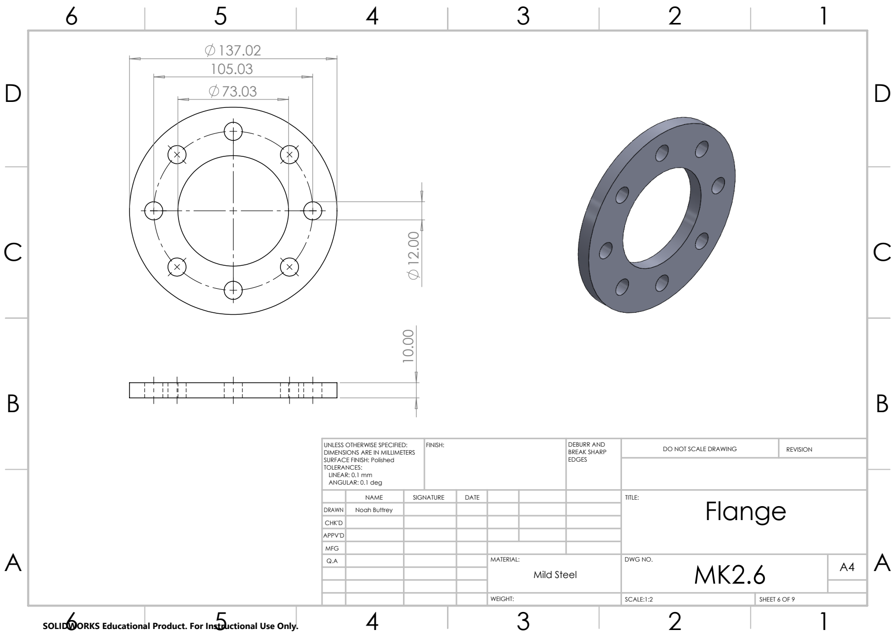

Figure 11.9: Combustion Chamber Casing End Flanges. Source: Own.

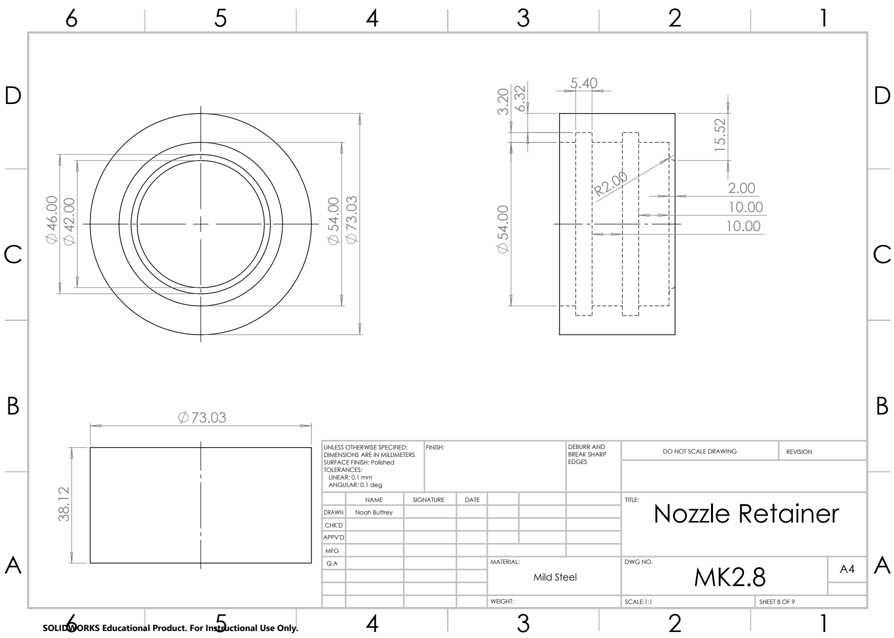

Figure 11.10: Metal Nozzle Casing. Source: Own.

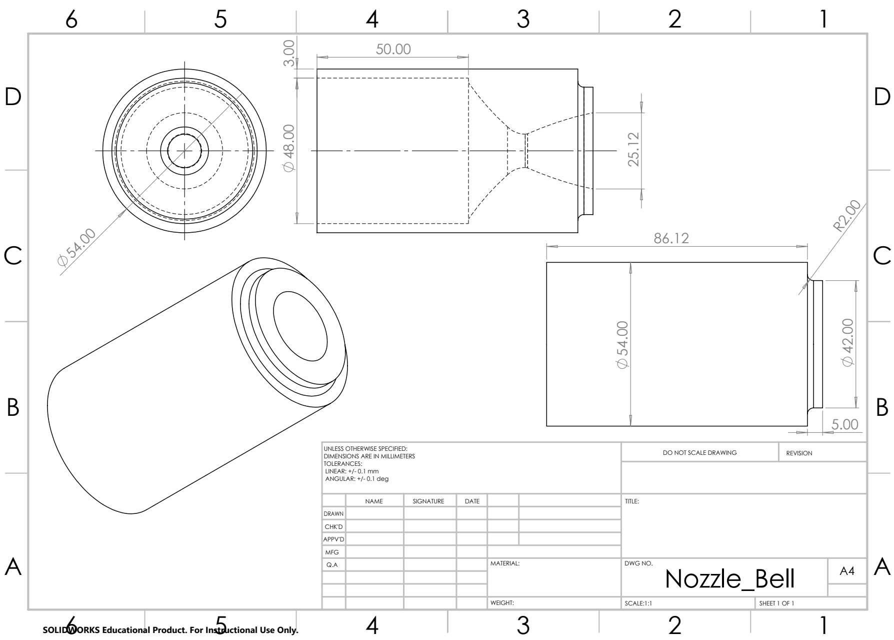

Figure 11.11: Graphite Nozzle. Source: Own.

11.2 Material Datasheets

11.2.1 Graphite Datasheet

THE LEADING EDGE

DATA SHEET
ISSUE 1 | 27-JUL-18

DURAGRAPH® 150

Typical Property	Test Standard	Unit	Value
Average Grain Size	ISO 13320	µm	10
Bulk Density	DIN IEC 60413 / 204	g/cm^3	1.83
Open Porosity	DIN 66133	Vol.%	10
Medium Pore Size	DIN66133	µm	1.8
Permeability (Air at 20°C)	DIN 51935	cm^2/s	0.06
Rockwell Hardness $HR_{10/100}$	DIN IEC 60413 / 303		90
Specific Electrical Resistivity	DIN IEC 60413 / 402	µΩm	13
Flexural Strength	DIN IEC 60413 / 501	MPa	60
Compressive Strength	DIN 51910	MPa	130
Young's Modulus	DIN 51915	MPa	11.5×10^3
Thermal Expansion (20- 200°C)	DIN 51909	K^{-1}	4.2×10^{-6}
Thermal Conductivity (20°C)	DIN 51908	$Wm^{-1}K^{-1}$	105
Ash Content	DIN 51903	ppm	20

*Value might be changed due to material size

Erodex (UK) Limited, Tipper Industrial Estate, Park Road, Halesowen, West Midlands B63 2RH
TEL: +44 (0)1384 892011 FAX: +44 (0)1384 897162 Email: sales@erodex.com
www.erodex.com

11.3 Temperature Graph Matlab Code

Listing 11.1: Temperature exponential graph calculation code. Source: Own.

```
% This code is a property of HRMTS CranSEDS 2022-2023 team.
% Author: Triyan Pal Arora
% Date: 3rd June 2023

% This line marks the start of the code for deriving the temperature
% evolution with respect to time using its exponential function derived in
% section 5.5: Thermochemistry in the final document report.

T_a = 0.161; % Temperature constant
e=2.71; % Napier's constant
t=0:0.001:7; % timestep definition
T_cc = T_a*(e.^(t/0.763)); % Exponential temperature evolution equation

% Plotting the temperature against time for the equation,
figure
plot(t,T_cc)
hold on
grid on
grid minor
xlabel('Time (sec)')
ylabel('Combustion temperature (K)')
title('Temperature evolution against time')
hold off

% This line marks the end of the code.
```

11.4 Load cell DAQ Arduino code

11.4.1 Load cell calibration code

Listing 11.2: Load cell calibration Arduino code. Source: Rui Santos Random Nerd Tutorials website.

```
/*
  Rui Santos
  Complete project details at https://RandomNerdTutorials.com/arduino-load-cell-hx711/

  Permission is hereby granted, free of charge, to any person obtaining a copy
  of this software and associated documentation files.

  The above copyright notice and this permission notice shall be included in all
  copies or substantial portions of the Software.
*/

// Calibrating the load cell
#include <HX711.h>

// HX711 circuit wiring
const int LOADCELL_DOUT_PIN = 2;
const int LOADCELL_SCK_PIN = 3;

HX711 scale;

void setup() {
  Serial.begin(19200);
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
}

void loop() {

  if (scale.is_ready()) {
    scale.set_scale();
    Serial.println("Tare... remove any weights from the scale.");
    delay(5000);
    scale.tare();
    Serial.println("Tare done...");
    Serial.println("Place a known weight on the scale...");
    delay(5000);
    long reading = scale.get_units(10);

    double known_weight = 0.5294; // in kilograms
    double g = 9.806;
    double newtons = known_weight*g; //force in newtons

    Serial.print("Force in Newtons: ");
    Serial.println(newtons,7);
```

```
    Serial.print("Result: ");
    Serial.print("Reading: ");
    Serial.println(reading);
    Serial.print("Calibration Factor: ");
    Serial.println(newtons/reading,7); // this is the calibration factor to use in the force measurement program
    //-0.000224 seems to work across different weights
  }
  else {
    Serial.println("HX711 not found.");
  }
  delay(1000);
}
```

11.4.2 Load cell execution code

Listing 11.3: Load cell execution Arduino code. Source: Bogdan Necula Random Nerd Tutorials website 2018.

```
/**
 * Complete project details at https://RandomNerdTutorials.com/arduino-
    load-cell-hx711/
 *
 * HX711 library for Arduino - example file
 * https://github.com/bogde/HX711
 *
 * MIT License
 * (c) 2018 Bogdan Necula
 *
**/

#include <Arduino.h>
#include "HX711.h"

// HX711 circuit wiring
const int LOADCELL_DOUT_PIN = 2;
const int LOADCELL_SCK_PIN = 3;

HX711 scale;

void setup() {
  Serial.begin(19200);
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  scale.set_scale();
  Serial.println("Remove weights from scale");
  delay(5000);
  scale.tare();
  Serial.println("Tare complete - starting measurement in 3 s");
  delay(3000);

}

void loop() {
  float calibration_factor = -0.000224; //calculated by placing several
     known weights on scale and measuring reading
  //result is given in Newtons
  float time = millis()/1000.0 - 8.0; //also print time since program
     start

  Serial.print(time,3);
  Serial.print(", ");
  Serial.println(scale.get_units()*calibration_factor, 5);

  delay(100);
}
```

11.4.3 Propellant Budget

Table 11.1: Propellant Budget

Propellant	Physical state	Volume used (litres)	Storage pressure (bars)
Nitrous Oxide	Pressurized liquid	4.5	55
High density Polyethylene	Solid	0.71	1
Liquid Oxygen	Pressurized liquid	0.6	50
Nitrogen	Gas	5.5	60

11.4.4 Power Budget

Table 11.2: Electrical Power Budget

Component	Quan.	Operating voltage (V)	Operating current (mA)	Power (W)	Duration (sec)	Net power
Load cell	1	10.00	13.40	0.13	10.00	0.13
HX711	1	5.50	1.80	0.01	10.00	0.01
Arduino Uno	1	5.00	200.00	1.00	10.00	1.00
Step down transformer	1	5.00	0.00	0.00	10.00	0.00
Pressure transducer	2	10.00	20.00	0.20	10.00	0.40
Thermo-couple	3	0.06	5.00	0.00	10.00	0.00
Control box	1	24.00	5000.00	120.00	15.00	120.00
Margin	**20%**					24.31
Total						**145.85**

Power Source	Description	Net Voltage (V)	Nominal Current (A)	Delivered Power (W)	Required Capacity (mAh)
Battery	11.1 V 1500 mAh LiPo battery	11.10	2.35	26.09	6.53
AC supply	24 V voltage generator	24.00	5.00	120.00	20.83
Total		**35.10**		**146.09**	**27.36**

11.5 Engine Test Setup

Figure 11.12: Welding on the combustion chamber and end flange connection. Source: Own.

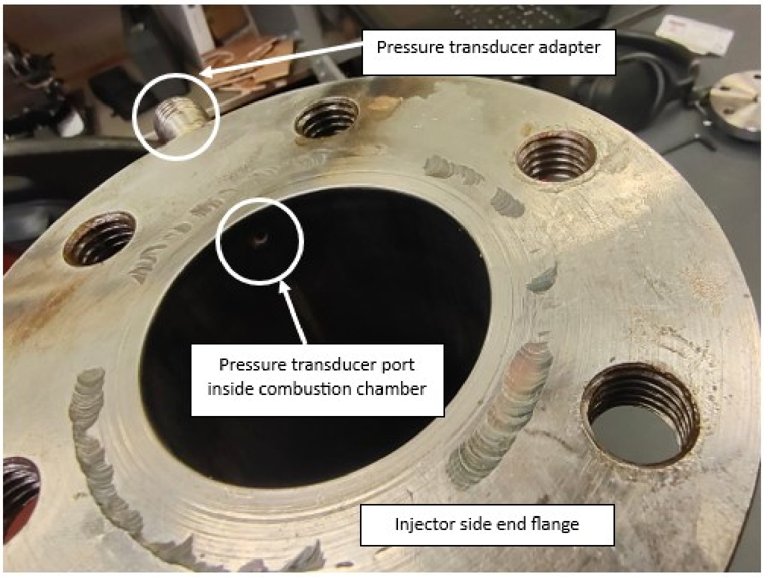

Figure 11.13: Internal hole for pressure transducer to measure internal combustion chamber pressure. Source: Own.

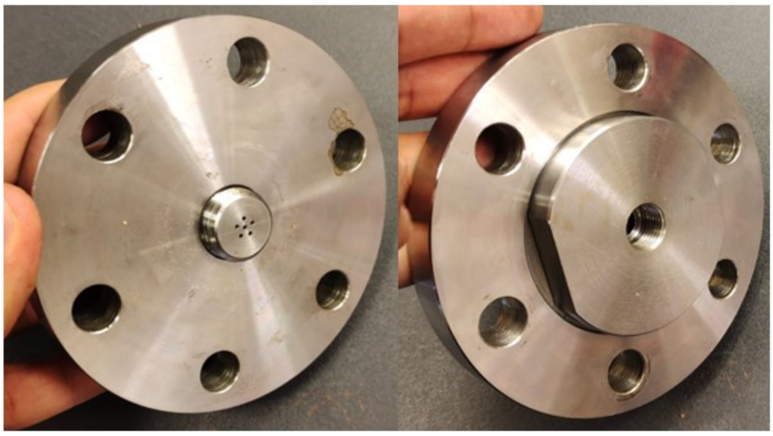

Figure 11.14: Injector plate assembly. Source: Own.

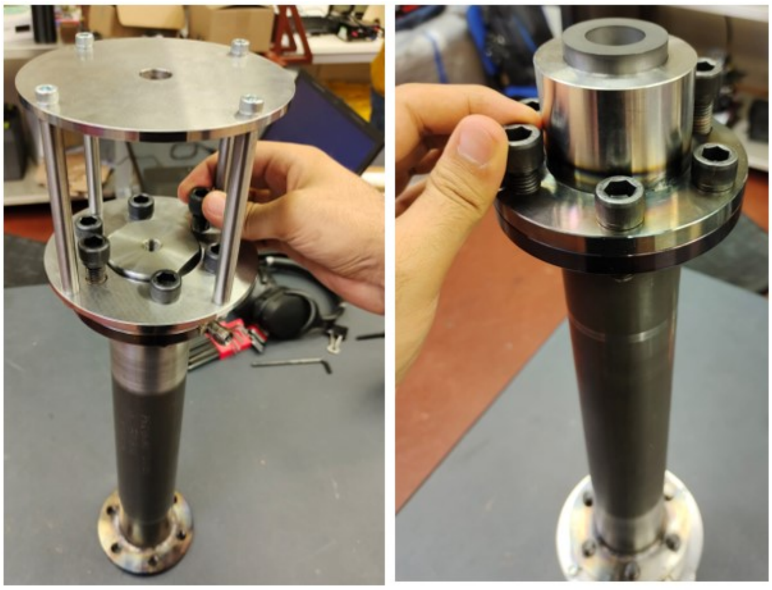

Figure 11.15: Line assembly of the combustion chamber. Source: Own.

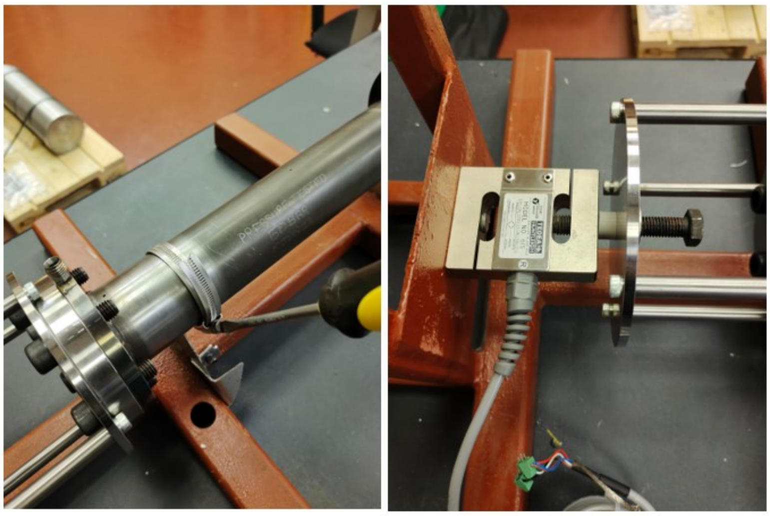

Figure 11.16: Structural assembly of the engine setup. Source: Own.

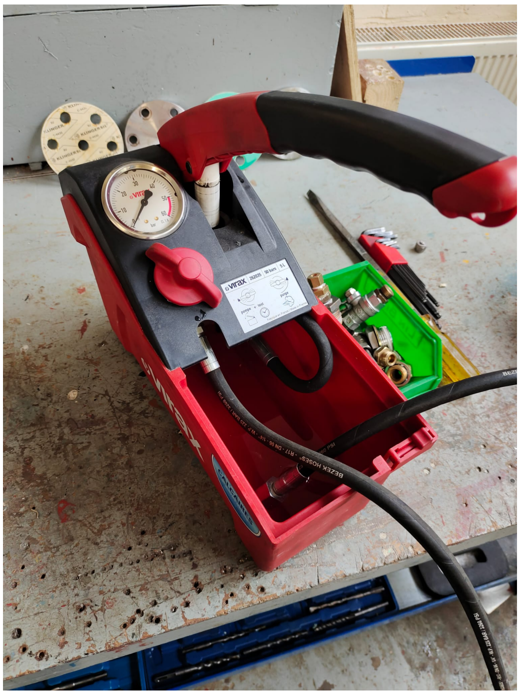

Figure 11.17: Pressure testing machine for the combustion chamber. Source: Own.

Figure 11.18: Etching on combustion chamber after passing the pressure test. Source: Own.

11.6 Risk Assessment

The table below displays all the identified risks for the project made initially at the PDR phase. The team is responsible,'/ and the current status of the action taken is updated at this stage. If the status is marked as "Closed", then it is no longer considered an issue. If the status is marked as "Open", then the risk mitigation action is still in effect and will carry on further on into the project.

The Pareto diagram illustrates the risks in order of their importance. The accumulated risk helps to show the most important tasks from the lesser ones. Typically, 80% and below are considered tasks of less importance. With this, more dedication was given to mitigating high-importance risks.

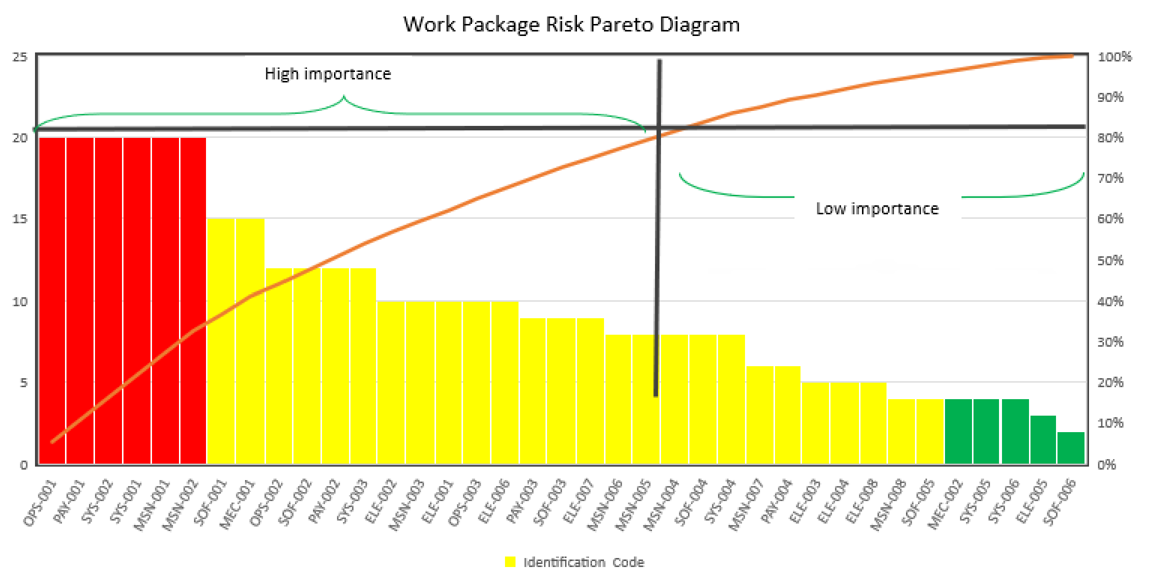

Figure 11.19: Pareto diagram. Source: Own.

11.6.1 Risk Assessment

Risk Assessment Form

CU-SHE-FORM-3.01

V4.0

Risk Assessment Number:	1 of 1	**Title:**	H.Y.D.R.A. Hybrid Rocket Engine, CranSEDS 2022-2023 v2.0	
Task/Activity assessed:	Hot Fire Rocket Engine Test			
Name/job role of people consulted during assessment:	Project Supervisor, Project Mentors, Test Site Manager, Health and Safety Officer	Date of Assessment	11th June 2023	
Acknowledgements, Sign off and Authorisation				
	Acknowledgement	**Name**	**Signature**	**Date**
Risk Assessor:	By signing this risk assessment, I acknowledge my responsibility as the Risk Assessor for conducting this risk assessment in accordance with CU-HAS-PROC-3.01, Risk Assessment Procedure.	Triyan Pal Arora, Project Manager		11th June 2023
Checked by:	By signing this risk assessment, I acknowledge my responsibility as the checker for this risk assessment in accordance with CU-HAS-PROC-3.01, Risk Assessment Procedure.	Dr Adam Baker, Visiting Fellow, Space Propulsion		
Authorising Person:	By signing the risk assessment, I acknowledge my responsibility as the Line manager/Supervisor for reviewing and approving this risk assessment and communicating controls and any additional controls to staff/students (as appropriate).	Scott Booden, Test Site Manager		

Tasks/Operational steps/Sub tasks/Events:		**Significant hazards** • What could happen and why?	**Who is affected and how** • Who might be hurt? • How bad could it reasonably be?		**What are your existing controls?** (Reference all Safe Systems of Work (SSOW), Standard Operating Procedures (SOP) and Emergency Procedures)	**Existing Risk Rating** (**C**onsequence x **L**ikelihood = Total)			**Are additional controls needed? Y/N** (If Yes, RAMP required)
						C	**L**	**TOTAL**	
1	*Stored gas pressure vessel failure (e.g., where filling run-tanks with high pressurise fluids (Nitrous Oxide, Oxygen, and Nitrogen)).*	The tank connector, feed line or the tanks themselves could either become disconnected or rupture due to over pressurisation.	Operators (students/staff)	Minor injury due to filling line pipe disconnecting during filling. Possibility of tanks rupturing due to over pressurisation. Blast effects, possible - shrapnel.	• The maximum expected operating pressure (MEOP) of the system is significantly less than the maximum allowable tank pressures (60 Bar maximum working pressure to be held within the 207 Bar rated run tanks – safety factor of 3.45x MEOP). • To prevent the tanks from over pressurisation, each feed line shall contain a burst disk rated to 130 Bar. • All tanks used during firing shall undergo a hydrostatic pressure test prior to use, alongside being new and certified for use. • All feed system components are rated sufficiently in excess (227 Bar) of the 130 Bar burst disk setting. • A nitrogen pressurisation leak test shall be conducted using soapy water to ensure all feed system connections are reliable and secure. • Filling shall be done in a well-ventilated area. • All stored gas cylinders to be secured when not being transferred to avoid unintentional shock loads. • Eye protection must be worn during filling operations. • The run tank employed shall have a maximum allowable pressure of 200 bars. • The run tank shall incorporate dip tube and proper external connection to secure the gas in the tanks properly.	5	1	5	N
2	*Electrical Fire in test house 11 when preparing to test fire or during/after firing.*	Control system short circuiting, cable melting or being exposed to extreme engine temperatures, causing an electrical fire.	Operators (students/staff)	Could cause the generation of asphyxiate gas (e.g., CO/CO_2). The fire could reach the propellant tanks which could heat	• Ensure the test house is well ventilated. • All operators shall wear fire protection lab coats and have water and CO_2 fire extinguishers readily available. • A metal blast shield shall be mounted to the tank stand to deflect any excess heat from the engine. • The tank stand, containing the electrical equipment shall be located besides the engine as opposed to	3	2	6	Fire blankets (for an electrical fire) and multiple buckets of water (for a chemical

		Engine failure exposing tank stand to excess heat.		them to a sufficient temperature to cause over pressurisation and compromise their structural integrity.	behind the engine, to reduce the risk of failure if the engine's injector were to fail. • All wires selected have been selected to withstand the maximum likely current expected, reducing the risk of wires melting. • Tanks have burst disks rated to 130 Bar, so if the tank were to heat excessively and over pressurise, this would rupture first and release its contents, as opposed to rupturing the tanks. To reduce the risk of the tank contents encouraging the fire during such an event, the tanks shall only be filled to a maximum of 3 Litres. • All test operations shall be conducted 10 m away from the engine, behind a blast-proof shield, in a well-ventilated room. • If the fire becomes uncontrollable, all operators shall evacuate the test site and gather in the test site car park. Calling the fire brigade for assistance.				fire) shall be located and easily accessible around the engine test bench.
3	*Engine dismounting from test stand during firing.*	Engine plume may be directed towards the tank stand and/or the control room (containing the operators).	Operators (students/staff)	Potential to cause damage to test site equipment and burn to personnel. Hearing and eyesight damage is also possible.	• All test operations shall be conducted 10m away from the engine, behind a blast-proof shield, in a well-ventilated room. Significantly reducing the risk to operators. • The control system has an integrated emergency stop button, which, as indicated in the SOP, shall be pressed if such an event were to occur. • The engine is safely secured to the test stand using jubilee clips and straps, preventing significant lateral movements.	3	2	6	N
4	*Flashback from the engine to the feed system tanks.*	Could cause an internal feed system fire which may result in tank rupture and/or an uncontrollable fire.	Operators (students/staff)	Fire injury to personnel and damage to equipment. Feed line or valve failure / possible ignition / shrapnel.	• All test operations shall be conducted 10m away from the engine, behind a blast-proof shield, in a well-ventilated room. • A positive pressure difference of at least 10 Bar across the injector (i.e., between the feed system and the engine's combustion chamber) shall be maintained throughout the burn, with the injector acting as a check valve reducing the risk to operators by preventing any pressure oscillations causing reverse flow into feed lines.	4	2	8	N

5	*Power cut during firing.*	Engine becomes uncontrollable from the remote-control unit.	Operators (students/staff)	The engine may burn for longer than desired, increasing the risk of engine failure and overheating the surrounding test stand area.	• All solenoid valves selected are designed to fail-shut. Thus, preventing the flow of oxidiser/fuel to the engine and stopping the combustion process. • The Nitrogen purge line has normally open valves, to allow the whole system to be purged and extinguished with the high pressure nitrogen.	2	2	4	N
6	*Electric shock.*	Electrocution of an operator from the 230 VAC power supplies.	Operators (students/staff)	A double insulated wiring connection may become exposed and contact personnel resulting in burns and/or a cardiac arrest.	• The control system is designed to be 12VDC (within the control room) and 24VDC (by the engine) power systems, using step-down transformers to ensure a safe operating voltage. • The wiring within the control room is insulated by the control box and the box is grounded to the floor of the control room. • The more exposed 230VAC cable on the tank stand is covered to reduce the risk of contact when live.	4	1	4	N
7	*Gas tank's toppling.*	Physical impact and/or dangerously expelling combustion fluids.	Operators (students/staff)	Nearby persons may endure a high energy impact resulting in significant physical harm if a tank connector were to break-off a tank.	• The tanks shall be secured to their places using multiple sandbags and keeping them far from the thrust trail of the engine. • The feed line will incorporate a plastic tube before the feed line goes to the injector. This plastic tube will carry the thrust deviations and protects from transference of big loads to the steel pipes and the tanks. • All operators will remain at least 10m away from the engine during firing and behind a blast proof shield. Operators must wear safety boots during preparation and testing.	3	1	3	N
8	*Personnel contact with hot parts post firing.*	Heat damage to skin	Operators (students/staff)	Minor injury from burns	• Warning signs and barriers to be put in place immediately pre-firing • Operators only to approach engine after ambient temperature achieved – determined visually and using thermal hand sensors. • Operators to use heat-resistant protective gloves when handling hardware post-burn	3	1	3	N
9	*Combustion after firing terminates*	External heating of rocket engine chamber.	Operators (students/staff)	Cosmetic damage to motor, burns to operators	• Ensure equipment is clean, no loose, potentially flammable items within range of motor plume. • Purge each feed line and the engine with nitrogen gas after every burn.	2	2	4	N

	eg from fuel slivers.			inspecting after firing.	• CO_2 and dry powder fire extinguisher(s) to be available during test fire – can be used to extinguish any post-test burning.				
10	*Upstream leakage of gas: N_2O / O_2 / N_2 - during loading / ignition / hot fire / purge.*	High pressure gas leak: fire and / or asphyxiant.	Operators (students/staff)	Minor injury from ejected gas Damage to instrumentation and feed system	• Low pressure gas test of plumbing (10 Bar) – *balance* between pressure required for MEOP + safety factor hydraulic test, and risk from high pressure gas in event of a mechanical failure. • PPE (full face masks and fire-retardant suits) to be worn during loading. • All operator staff to be remote (min 10m and behind a blast proof shield) during firing. • All plumbing connections double checked for leaks with soapy water.	3	2	6	Hydraulic cold flow test of fully assembled plumbing, from tanks to injector.
11	*Burn through of engine chamber*	Burn the internal side of the casing, melt it, and deform the surface. Causes corrosion of the metal during cool down after the burn out.	Operators (students/staff)	Cosmetic damage to motor, minor burns to operators inspecting after firing, damage to the casing making it prone to failure.	• The chamber casing will be painted to protect from corrosion, and completely covered with a thick layer (5 mm) of cork liner to protect from the combustion of the engine. • The thickness of the casing is 6 mm to protect from any burn through. Thicker metal makes it difficult for conductive heat transfer within the 6.5 seconds burn	2	2	4	N
12	*Nozzle failure*	Nozzle breaks, the exhaust flow is deviated, due to cracked nozzle, creating unresolved loads on structure. blocks the combustion chamber outflow, makes it a high pressurized and high temperature gas cylinder, with explosive potential.	Operators (students/staff)	Potential to cause damage to test site equipment, may damage the engine setup, may cause a big explosion.	• The nozzle is tested through simulations for higher than worst loading. • The graphite nozzle sits on nozzle casing with 2 compressive radial O-rings, creating sealed outer zone. • The fitting of nozzle and nozzle casing is tolerance fit of 0.1 mm, making it difficult to break and create a space pocket in the combustion chamber.	4	2	8	N
13	*Nozzle blockage and overpressure of chamber*	Blocks the combustion chamber, makes it a high pressurized and high temperature gas cylinder, with explosive potential.	Operators (students/staff)	Potential to cause damage to test site equipment, may damage the engine setup, may cause a big explosion	• If the nozzle is blocked and/or the chamber is overpressured, the rear end of the nozzle casing with 2 mm of steel layer fails and pops out the graphite nozzle. This releases the internal overpressure and saves crucial components from damaging.	4	2	8	N
14	*Overpressure of*	High pressure of 33.5 bars, but low velocity	Operators	Potential harm to equipment, any	• The thickness of combustion chamber is considered with a big margin to be 6 mm.	4	1	4	N

	combustion chamber	causes pressure builds up, which may crack/ rupture the chamber.	(students/staff)	personnel standing close, or in unsafe manner	• The chamber has been water pressure tested up to 50 bars as pre-requisite tests.				
15	*Structural failure due to vibrations, heat and thrust loads*	The test stand, structure or any interface can fail due to vibrational loads, heat loads, and thrust loads	Operators (students/staff)	Potential harm to equipment, any personnel standing close, or in unsafe manner	• The design of components has been thoroughly tested against possible worst thrust loads, heat loads, and vibrational loads. A minimum of 1.5 factor of safety was targeted and achieved, at every component and interface.	3	2	6	N
16	*Malfunctioning or failure of feed line component (valves, regulators)*	Valves and regulators malfunction due to unexpected pressure load, internal mechanical failure, or electrical failure	Operators (students/staff)	The leakage of N_2O may concentrate the surrounding atmosphere and make it hazardous. O_2 leak may lead to fire explosion.	• The feed line components are checked for valid certifications before putting in all together. • The valves and regulators will be tested during the cold flow test to ensure no leaks or failure occurrence. • The components will be sealed with Teflon tape and copper thread locker to eliminate any sliver of opening and ensure tight connections at all the interfaces.	4	2	8	N
17	*Leakage from feed line pipes*	Feed line pipe connections not tight enough, the pipes used are of low quality, causing cracks due to high pressured flow.	Operators (students/staff)	The leakage of N_2O may concentrate the surrounding atmosphere and make it hazardous. O_2 leak may lead to fire explosion.	• The feed line pipes are 3/8 in steel Swagelok pressure fluid pipes. They cross the threshold limit established through calculations. Valid certifications for the pipes is checked. • The feed pipes will be tested during the cold flow test to ensure no leaks or failure occurrence. • The pipes will be sealed with Teflon tape and copper thread locker to eliminate any sliver of opening and ensure tight connections at all the interfaces.	4	1	4	N
18	*Improper assembly, misalignment*	May lead to gaps in interfaces, weakening the structure, single point failures, the exhaust plume will not be in the anticipated direction	Operators (students/staff)	Potential harm to structure, if not enclosed, the exhaust plume can pollute the surroundings	• The assembly is checked for correct alignment using handset inclinometer at each step of the assembly and integration. The fixtures prepared aid in correctly aligning the line assembly onto the test stand for correct alignment for the plume. • The setup will be tested during cold flow test to ensure proper alignment has been achieved. • The structure is capable enough to take unanticipated loads with a safety factor of 1.5	3	2	6	N
19	*Ignition failure or delayed ignition*	Uncontrolled propellant buildup or incomplete combustion. Affects the recorded engine performance. The	Operators (students/staff)	Incomplete combustion means intermittent species (CO, NO,	• The ignition will be tested before the actual test firing. The burning of the Nichrome wire (28 AWG) will be measured, with the required distance to keep the controls behind the blast cover.	3	2	6	N

		required voltage for ignition is a potential danger.		NOx) existing in the exhaust which will be harmful to personnel	• The required voltage may be potentially dangerous and will always be shielded. • The data acquisition system shall have enough storage to allow for no or bad readings, which will be removed in post processing of the obtained results. This will be corelated with the firing through the camera feed.				
20	*Noise, shockwave, or acoustic hazard during firing*	The noise and acoustic hazard are inevitable in test firing. Acoustic vibrations may shake components in surrounding, like tanks, cameras, sensor placement	Operators (students/staff)	Large noise may be harmful to human ears. May cause nearby equipment to shake due to acoustic vibrations	• The tanks and cameras will be fixed in place of sandbags. • The tower containing the electronics will be shielded by a wooden board to protect from shock waves and any kind of explosion. • The operators shall always wear headphones. • The sensor readings may have jitters, which can be removed in post processing of the obtained results. • The test facility area will be alerted before the testing. The area will be blocked from any outsider to enter.	2	3	6	N
21	*After-firing Exhaust*	The exhaust after test firing may contain unburnt combustion products (like CO, NO, NOx) which are dangerous to humans, and may ract with equipment.	Operators (students/staff)	Potential to cause damage to test site equipment. Hazardous to humans and nearby personnel.	• To clear up the surroundings from large exhaust concentration, electric fans will be used kept at sufficient distance to avoid any hazardous reaction of the unburnt particles in the exhaust. • The purging through nitrogen gas will be extended to ensure safety. • The setup will be placed near to the outside gate of the test house to keep the system in an open atmosphere. • The area will be kept closed for a certain pre-determined time to ensure the exhaust is completely dissipated and there's no chance of harm from the exhaust to the personnel or equipment anymore.	3	3	9	N

		PERSONAL PROTECTIVE EQUIPMENT (PPE):										
		☒	☐	☒	☒	☐	☒	☐	☐	☒	☐	☐

For every item of PPE required, specify the type and other relevant information below:

- 1 x LABORATORY COAT (PER OPERATOR)
- 1 x SAFETY GLASSES (PER OPERATOR)
- 1 x SAFETY GLOVES (PER OPERATOR)
- 1 x SAFETY HEADPHONES (PER OPERATOR)
- 1 x SAFETY BOOTS (PER OPERATOR)

		Type	Other relevant information *e.g material, level of protection, etc.*

Emergency Planning Arrangements relating to operations/event

		In event of emergency ring x 2222 or 01234 752999. For an ambulance ring 999, then direct the ambulance to the test site.

Risk Rating Matrix

RISK MATRIX					
Consequence **Likelihood**	Negligible (1)	Minor (2)	Medium (3)	Major (4)	Severe (5)
Almost Certain (5)	5	10	15	20	25
Likely (4)	4	8	12	16	20
Possible (3)	3	6	9	12	15
Unlikely (2)	2	4	6	8	10
Very Unlikely (1)	1	2	3	4	5

Rating	Interpretation	Authorisation
≤ 6 = Low Risk	Acceptable but ensure that controls are maintained	Line Manager or equivalent
8 -12 = Medium Risk	Adequate but look to improve if reasonably practicable	Line Manager or equivalent
15 – 25 = Unacceptable Risk	STOP activity and make immediate improvements	PVC School/Director of PSU

CONSEQUENCE (considered WITH controls in place)		
5	Severe	• Fatality (ies) • Severe or chronic illnesses or permanent life changing impact
4	Major	• Injury such as fracture of bones, dislocation, or acute ill health e.g. occupational asthma, occupational dermatitis
3	Medium	• An injury that requires first aid treatment and subsequent treatment by health care professional • No lost time illnesses and no chronic/acute health effects
2	Minor	• An injury that requires basic first aid treatment such as administering a plaster, individual able to continue at work e.g. minor cuts, bruising, abrasions, strains or sprains
1	Negligible	• Superficial or no physical injury or health effects

LIKELIHOOD (considered WITH controls in place)		
5	Almost Certain	• Will occur/greater than a likelihood of 1 in 1(yr)
4	Likely	• Known to occur/probably occurs most circumstances/No greater than a likelihood of 1 in every 10
3	Possible	• Might occur /no greater than a likelihood of 1 in 1000
2	Unlikely	• Not likely/could occur at some time/no greater than a likelihood of 1 in 10,000
1	Very Unlikely	• May only occur in exceptional circumstances/no greater than a likelihood of 1 in 100,000

11.6.2 COSHH Assessment for Nitrous Oxide

The COSHH assessment stands for the Control of Substances Hazardous to Health. A COSHH assessment concentrates on the hazards and risks of hazardous substances in your workplace.

Since the oxygen and nitrogen to be used are already available in the test facility of the university, the existing COSHH assessments for the gases are used. However, the nitrous oxide, which needs to be bought this year, requires an individual-specific COSHH assessment to be bought and used for the hybrid engine test firing. This assessment is a 2-page document attached in this section, as described hereon.

Standard COSHH Assessment

STANDARD COSHH ASSESSMENT *This form is only to be used after completing the COSHH flow chart in Appendix A.*	**Ref. No:**	**Date:**
	HY23-03 Rev.00	05.06.2023

TASK / PROCESS / ACTIVITY/LOCATION: *What will be done? Where and when will this work be carried out?*
Gases will be used at various stages of firing procedure for a hybrid rocket engine firing on a horizontal test bed, during feed line fill, ignition, combustion, and purging the system.

PERSONS EXPOSED:						
Staff	☒	Students	☒	Visitors	☐	Other (specify):

HAZARDOUS SUBSTANCES: *What will be used? What is the materials physical form? (e.g. powder, dust, granular, liquid, solution, gas)*
Nitrous oxide – pressurized gas To be used as oxidiser in a hybrid engine with high density polyethylene as the solid fuel.

STOCK QUANTITY: *What is the quantity of the stocksubstance container?*	**PROCESS QUANTITY:** *What is the quantity used in the process?*	**FREQUENCY:**	**DURATION:**
Nitrous Oxide: Type W tank (to be bought from BOC)	*10% margin considered* Nitrous Oxide: 1.2 litres per hot test firing	Process quantity used once per firing (4 planned hot firings in June)	Less than or up to 8 seconds

HAZARD CLASSIFICATION:

Physical			Health			Environment
☐	☒	☒	☒	☐	☐	☐

ROUTES OF EXPOSURE:									
Eye Contact	☒	Skin Contact	☒	Inhalation	☒	Ingestion	☐	Injection	☐

Specific storage requirements:
Consider chemical incompatibility, segregation, etc.

All gases stored in separate pressurized containers with following pressure ratings:

- Nitrous oxide: 44.5 bars (Main engine oxidiser)

All containers should be stored upright and kept at moderate temperatures.

Containers shall be kept away from open flames or other sources of ignition.

Valve operation shall avoid any abrupt closure or opening, eliminating any chance of shock propagation through the feed line.

In lieu of pressure decay during combustion, the supply tank shall maintain a minimum pressure of 4 bars eliminating risk of combustion instability.

Pressurized Nitrogen (already available in test facility at Cranfield University) will be used as a purge gas for the whole system.

PERSONAL PROTECTIVE EQUIPMENT (PPE):						
☒	☒	☒	☒	☐	☒	☒

For every item of PPE required, specify the type and other relevant information below:	
Type	**Other relevant information** *(e.g material, level of protection, etc.)*
Eye protection	Eye goggles required at minimum, if possible face masks should be worn when handling highly pressurized gases.
Clothing	Long sleeved clothing should be worn when handling pressurized gases. Shorts should not be worn.

Are additional controls required?	No ☒ Yes ☐ If yes, complete RAMP (Appendix D).

EMERGENCY PRECAUTIONS	
Eyes:	Nitrous Oxide – Remove contact lenses if any, rinse eyes with warm water for several minutes, seek medical attention.
Inhalation:	Nitrous Oxide – Remove exposed person from contaminated area immediately, move to fresh air andseek medical attention.
Skin:	Nitrous Oxide – Immediately submerse the affected body part in warm water, soak it in for a while and remove the exposed person from the area.
Ingestion:	N/A
Spill:	N/A
Fire:	Extinguish using Water, powder, foam, CO_2 (oxidising element, apply as required by burning material)

Risk Rating Severity of potential harm x Likelihood of exposure = Total	**S**[8]	**L**[9]	**Total**[10]
	3	**3**	**9 (Moderate Risk)**

AUTHORISATION			
Assessor:	Triyan Pal Arora	Date:	05.06.2023
Reviewer:		Date:	
Authoriser:		Date:	

8. See Appendix G for severity definitions and scoring. Severity should be based on information including the worst case illness.
9. See Appendix G for likelihood definitions and scoring. Likelihood should be based on how likely ill health is to occur. Good existing controls will reduce the likelihood.
10. The total existing risk rating is determined by Severity x Likelihood. See Appendix H.