Midterm Report

MECH 490 -Team 22

Presented by:

Ahlem Lamara - 40132900
Breno Coscarreli – 40032369
Gabriel Colucci - 40093424
Hania Fazal - 40111699
Yousra Hadi - 40074889
Zachary Bélanger – 27468180

Supervisor:

Dr. Charles Basenga Kiyanda

Presented to:

Dr. Ashok Kaushal
Dr. Farrah Fayyaz

Friday November 11th, 2022

Table of Contents

List of figures

List of tables

1. Introduction

Detonations move around the circle of an annular combustion chamber in a rotating detonation engine (RDE). Supersonic combustion waves are produced by detonations. The RDE cycle must be maintained in non-premixed engines by thoroughly combining the fuel and oxidizer before use. Typically, the fuel and oxidizer are injected axially into the annulus either separately (non-premixed) or simultaneously (premixed). The wave (or waves) rotates around the combustor and only reaches a certain axial distance before devouring the continuously supplied reactants.

While it comes to maintaining detonation waves when the fuel and the oxidizer are in a liquid condition, the theory underlying detonation waves is difficult to apply in practice. It is often challenging for an RDE to explode and create detonation waves when a fuel contains more carbon atoms, such as propane. Unfortunately, since they need extremely low temperatures to remain liquid, the two reactants that detonate most readily are hydrogen/oxygen and acetylene/oxygen. The research team eventually came to the decision to use ethylene and nitrous oxide as the final reactants to power the RDE since they could easily liquify at high temperatures, i.e., between 0 and 20 C, before detonating.

In a nutshell, the project's goal is to store the propellants in liquid form and use them in an experimental engine to turn them into gas. The reactants should stay liquid for at least 1 hour at a temperature of 40 °C in the surrounding air under totally sunlit conditions.

2. Problem Statement

The project's main objective is to develop and construct an injection system that will use the detonations of ethylene (C2H4) and nitrous oxide (N2O) in the annular combustion chamber. These reactants must first be kept in liquid form, or in cryogenic storage, in order to transform into gases that may be injected to cause detonations. Thermodynamics could be used to develop a potential solution, which might involve a pressure-fed cycle with a pre-burner that partially burns fuel and oxidizers to increase temperature and induce the phase change, or it might involve another mechanism that, with more investigation, could be used to transition a liquid into a gas. For the sake of simplicity, a turbo pump would not be incorporated into the design, and the tanks would be made to fit within a rocket. Additionally, working with N2O necessitates safety precautions, so a dead volume in the flow path would be considered in addition to the propellants remaining in liquid form while being in the tanks for at least an hour under sunny conditions with an ambient air temperature of 40 degrees Celsius.

The capstone team's goal is to develop the injection system based on the aforementioned premises while considering a potential rocket design in which it might be used. The nose cone and RDE engine, however, would not be created for the project. Thus, the finished product would include a design for a phase change mechanism of the cryogenic fluids that would further change into gases once they reached the injector for the RDE while acting in accordance with the aforementioned constraints when placed in a hypothetical rocket design incorporating a rotating detonation engine.

3. Design

3.1. Pre-burner Design

One way to achieve a phase change in our liquid propellants is to use a pre-burner. A pre-burner creates the phase change by adding heat into the system by combusting a small mass of fuel and oxidizer before injection into the engine. While the RDE requires completely gasified reactants to function, the combustion in a pre-burner can be induced by simply atomizing the liquid reactants and providing an initial source of energy to start the reaction. Combustion achieved, the energy stored in the reactant's bonds is dissipated into the remaining fuel and oxidizer to induce the phase change.

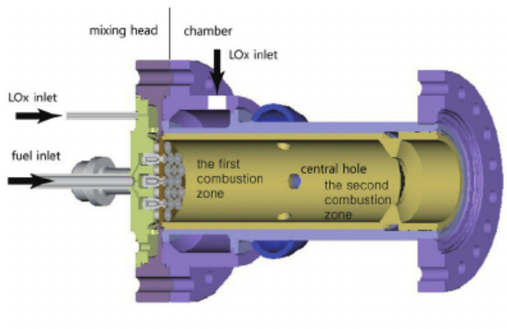


Figure 1: Pre-burner [1]

3.1.1. Swagelok Oxidizer-Rich Pre-burner

This Swagelok (ultra-torr) pre-burner is an oxidizer-rich one, where small amounts of fuel (approximately 4%) and around 75% of oxidizer are taken from their respective feed line and are sent to a combustion chamber. In this combustion chamber, the resulting products are sent back into a tube that is located around the fuel and oxidizer feed lines to heat them up, and therefore gasify the propellants not used in the pre-burner.

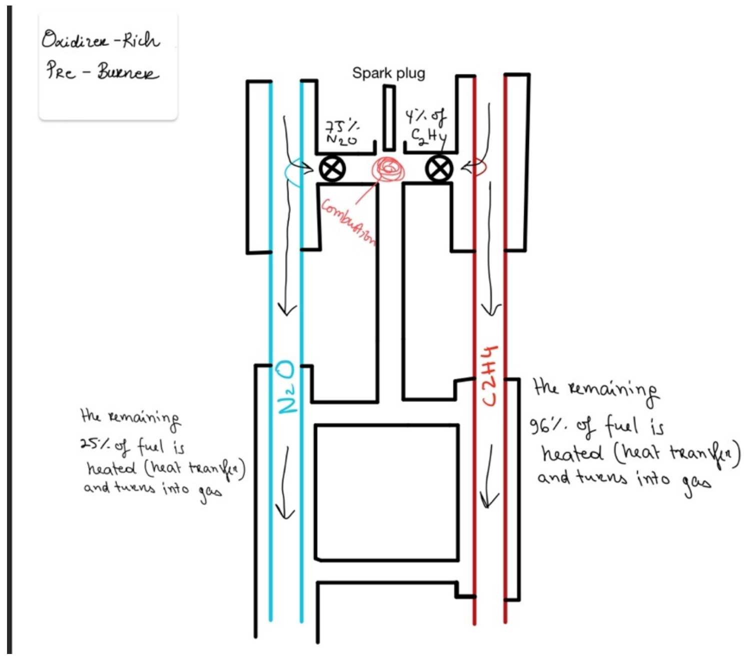


Figure 2: Pre-burner preliminary design

3.1.2. Stoichiometry and combustion reaction

The fuel and oxidizer used in the RDE engine are ethylene (C2H4) and nitrous oxide (N2O) respectively. The combustion required for a pre-burner uses a reaction of the two in the following form:

$$C_2H_4 + 6N_2O \rightarrow 6N_2 + 2H_2O + 2CO_2$$

$$\text{Mixture ratio } O/F_{\ stoic} = \frac{m_o}{m_f} = \frac{6(44.01)}{28.05} = 9.4$$

Table 1: Combustion Data

Parameter	Value
Combustion Pressure	60 Bar
O/F stoichiometric	9.4

Oxidizer (N2O) mass flow rate	0.90397453 kg/s
Fuel (C2H4) mass flow rate	0.09602547 kg/s
O/F Oxidizer-Rich	18.75
Flame temperature	366.73 K

Detailed calculations made for the flame temperature of the oxidizer-rich pre-burner can be found in *Appendix G*.

3.2. Design criteria

The injection system must perform the phase change of both propellants from liquid to gas. The outlet pressure must be greater than 5 bar. It must fit within a diameter of 6 to 10 inches so it can be installed in a rocket at a later date. The injection system must be lightweight, any opportunities for weight-savings must be taken, the target is under 5 kilograms. The design must be easily manufactured, and capable of being disassembled. For those reasons, Ultra-Torr fittings are used throughout the system. To understand the design criteria for the pre-burner in more detail, an evaluation of the T-S diagram for Ethylene and Nitrous Oxide is required. The paths drawn onto the T-S diagrams have two stages, the first is the constant pressure phase, this happens when the liquid moves through the pre-burner. The second stage starts from when the fluid leaves the pre-burner and is sent to the engine, this stage is assumed to be constant enthalpy. All the data collected from both TS diagrams is included in *Appendix F*.

3.3. Design matrix

For the phase change system, 3 pre-burners design options were suggested.

Design 1: Exhaust Pre-burner

In the first design, a stochiometric combustion will take place in the Ultra-torr cross fitting. Then, the combustion products will travel through a long pipe to heat up the fuel and oxidizer lines. Before the engine inlet, the combustion products will flow out through an exhaust pipe and will not enter the engine.

Design 2: Single Mixing Channel Pre-Burner

This is the chosen design. The combustion will take place inside the cross fitting; however, it does not have to be stochiometric. The combustion product is expected to travel through a heat transfer region but will then mix with either the fuel or oxidizer.

Design 3: Double mixing channel Pre-Burner

This last design is very similar to the exhaust pre-burner option. The combustion has to be stochiometric, however the exhaust gas will have to mix with the fuel and oxidizer lines for a maximum heat transfer. Both lines will have an equal quantity of combustion products.

Please refer to *Appendix E: Design Selection* to understand the design selection process.

3.4. Engineering Analysis

Principles of heat transfer, thermodynamics, and fluids will be applied to design the injection system at each stage. These principles will help us determine calculations that can be used for inputs into python script that will allow us to iterate our design. Some of the assumptions that have been made for our initial calculations are the following. Heat transfer is steady; it will not change with time. Heat transfer is one-dimensional, there is thermal symmetry about the centerline of the tube and no variation in the axial direction, and thus $T=T(r)$. Thermal conductivity is constant. There is no heat generation. The flame temperature is constant along each section of the pipe; in reality the heat transfer calculation will be dimensionless so that it can be applied at various sections of the injection system. At each stage, the temperature of the combusted mixture is expected to decrease. The following calculations are only to derive an initial relationship of heat transfer between the hot mixture and the propellant lines that will be heated. Loses from the hot mixture to its outer walls and ambient air is neglected since we are assuming the wall thickness and insulation around the exterior will decrease these losses sufficiently.

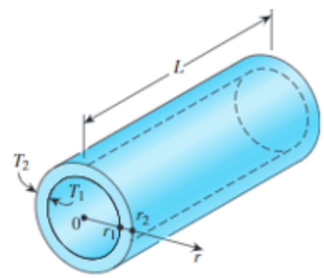


Figure 3: Tube Geometry [10]

See *Appendix G* for the calculations.

As you noticed the required length of piping to heat the propellants into a gas are extremely small. Please do not allow these initial calculations to mislead you. Those lengths are only calculated to prove that using heat from a pre burner is capable of sufficiently heating an inner tube so that the fluids inside of it change from a liquid to a gas. In reality, the outer temperature will be less than the flame temperature, causing an increasing in the length required for phase change. This ideal scenario calculated above used copper with a thin wall for the inner tubing. The injector will use a less thermally conductive metal and thicker wall which both will increase the length required.

In addition to the reduction of heat of the hot mixture as it flows along the tubing due to the heat exchange with the cooler propellants, there will be heat losses due to friction. Some of the calculations required to determine the losses in temperature due to friction will be written in the following section. These following formulations will be added to the python script to provide a more accurate model of the system.

See *Appendix G* for Fanno flow formulas.

3.5. Computed Aided Design (CAD)

Please refer to the *Appendix C* for the injection system CAD assembly, and drawings of the components.

3.6. Bill of Materials

Please refer to the *Appendix J* for the bill of materials (BOM).

3.7. Design Validation Diagram

Please refer to *Appendix D* for the Design Validation Diagram.

3.8. Cost Analysis

The Capstone Design Committee provides an 800$ budget for the design, building, and testing of the capstone project. For this project, the 800 $ will mainly be used for building the Phase change system. As for the tanks and testing equipment, most will be covered by Dr. Kiyanda since he stated that he would buy the feed tanks, give us access to his laboratories (Hall and EV lab) and the testing equipment.

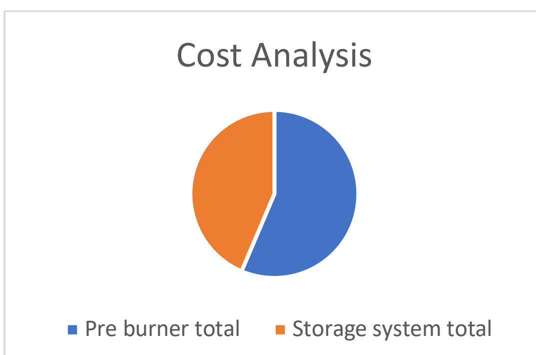


Figure 4: Cost Analysis Chart

As shown on the pie chart in Figure 4, the pre burner and the storage system material costs are almost equivalent. Although the pre-burner system is slightly more costly, the storage system requires more components especially safety components. The most expensive component on the

BOM are the solenoid valves which cost 1250 $ each. Considering that the test setup in place in the hall lab already contains solenoid valves, new purchase might not be necessary. Similarly, to the solenoid valves, many of the safety components might have already been purchased therefore the calculated subtotal of 6902.97 $ might not be the actual cost. A list of already available components will be compiled before ordering any new material.

For the storage system, a double ended cylinder would have been preferred as it would ease the installation of a dip-tube and the thermocouple. However due to its very high price of 1243.51$ [7], 99$ commercial cylinders from "Certified Cylinders" seem to be a better option. For the feed tank, the price for ethylene cylinders is known to be 14$/kg and therefore is 182 $ per 44 cf cylinder. However, for nitrous oxide, the cylinder equipped with a dip tube will cost around 450$. A more detailed quote has been requested.

4. Propellant Feed System

In order to deliver the propellants from the tanks into the combustion chamber of the engine at the appropriate mass flow rate and pressure, a liquid rocket engine needs a propellant feed system [5]. The following components are required to construct a propellant feed system:

- Tanks, whether they hold propellant or pressurized gas.
- Feed Lines, which are mainly composed of piping and tubing.
- Numerous valve types, including ball valves, check valves, control valves, solenoidal valves, and so on.
- Pre-burner (made of Swagelok's Ultra torr fittings)
- Sensors to monitor the feed.

4.1. Piping and Instrumentation (P&ID)

Our current project currently has two setups for piping and instrumentation which we need to be able to visualize. The piping from the feed tanks, bought with gas in them, to our run tanks, bought empty, as well as the piping for our testing.

See *Appendix H* for Piping & Instrumentation Diagrams.

5. Cryogenic Storage System

The cryogenic storage system consists of the following components: Feed tanks, run tanks, and Freezer. The feed tanks are the commercially bought gas cylinders which would be utilized to supply the run tanks with the gas to then liquefy them. The run tanks are the cylinders which would be utilized to run the experiment and store the liquified gas transferred from the feed tanks. The run tanks would be held at a constant volume and would be kept at a constant temperature of -10 degrees Celsius inside a freezer. The freezer is serving as the lab-grade insulation for the run tanks holding the mild cryogenics at a fixed temperature to ensure they are kept as liquids.

5.1. Piping and Instrumentation

See *Appendix H* for Piping & Instrumentation Diagrams.

5.2. Feed tanks

For our feed system, two 44 CF commercial cylinders filled with ethylene and nitrous oxide will be utilized. The ethylene gas service is supplied by “Air Liquide”, however since this company does not manufacture Nitrous Oxide cylinders with a dip tubes, another supplier’s service will be solicitated. Dr. Kiyanda already has an agreement with “Air Liquid” for his lab gas cylinders, all purchase requests will be sent by Dr. Kiyanda. For the Nitrous Oxide, “Linde” is the potential supplier as it is the only know company that supplies Nitrous oxide tanks with dip-tubes.

The feed tanks will be connected to the run tanks which will be placed inside a freezer. Before reaching the run tank, ethylene must pass through a set of copper coil tubes that will serve as a heat exchanger inside the freezer for the liquefaction to take place. However, for Nitrous oxide, no heat exchanger in required since a dip tube will be used to extract the liquid nitrous oxide in the cylinder. As slight drop in pressure in expect while using the dip tube, however since Nitrous oxide in a self-pressurizing gas, its cylinder service pressure will be conserved. For both substances, the phase change from gas to liquid is only possible if the pressure is kept constant, therefore a low flow rate should be achieved at the closest point to the feed tank.

Tank Specifications

The specifications of these tanks are as follow:

Table 2: Feed Tank specifications

Specifications	Ethylene	Nitrous oxide
Size	44 CF	44 CF
state	Gas	Mixture in the tank
Gas type	Pure	Pure
Service Pressure	1200 PSI	750 PSI
Weight of the gas	13.6 Kg	29.3 Kg
Dip-tube equipped	no	yes
Outlet fitting	CGA-	CGA-

5.2.1. Fittings

Both feed cylinders are expected to a CGA outlet type fitting, therefore it is important to add an CGA to NPT adapter as all other components will be connected using an NPT Swagelok. The component that will be added at the end of the cylinder are a needle valve, a check valve, a pressure regulator, another check valve right and right before the inlet of the heat exchanger, a thermocouple. The following devices will be connected using Swagelok Tee and straight fittings. A needle valve will be added to the system as it eases the flow control. Knowing that to liquefy the fuel and oxidizer, both will have to be fed at a very slow rate for pressure conservation, a needle valve is needed to accurately control the flow.

5.3. Run Tanks

Our preference for the run tanks would have been a double ended cylinder as this would allow us to extract liquid from the bottom of our tanks while hopefully avoiding the creation of a mixed phase flow immediately out of the tank, however the cost of these tanks is prohibitively expensive, and we will therefore use single ended cylinders. To be able to extract liquid from these tanks while potentially pressurizing them with a gas such as nitrogen during testing we will need to create a custom fitting which has both a dip-tube and a secondary channel for gas in parallel. For our testing the run tanks will actually be upside down and the dip-tube and second parallel channel will have inverted roles, dip-tube for gas inlet and secondary channel for liquid extraction. Using this method, we hope to imitate the double ended cylinder and extract liquid from the bottom thus avoiding mixed phase flow.

5.3.1. Tank Specifications

Our current tank selection for our testing purposes, which will be called "run tanks" in this report, are two 20 CF high pressure steel cylinders with the following specifications:

Table 3: Run Tank specifications

Specifications	
Size	20 CF
Service Pressure	2234 PSI
Water Volume	3.6 L
Diameter	133mm
Height	375mm
Outlet fitting	¾" - 14NGT

5.4. Tank Refrigeration

The run tanks are to be placed in the freezer and are required to be kept at approximately -10 degrees Celsius. The selection of this temperature is due to the recommended temperature range being up to -18 degrees Celsius [2]. The storage of mild cryogenic is kept inside the freezer since cryogenic requires special insulation around the tanks to keep them at a low temperature. Cryogenic tanks are usually thermally insulated; porous external insulation layers must be sealed to prevent moisture from being condensed inside the insulation layer [3]. Since the setup is done in a lab setting, the freezers would thus act as insulation and ensure that the tanks are kept and stored at a low temperature to ensure a liquid form.

It is to be noted that outside of the freezers, the feed tanks would be placed to supply the run tanks placed inside the freezer to ensure that the gas from the feed tanks is liquified. After emptying out the tanks with liquid, what would be left is cold gas. For refilling this tank now filled with cold gas, the gas at ambient temperature from the feed tanks would push the cold gas until the pressure matches and the continuous addition of ambient gas would warm up the tank a bit, but it would eventually liquefy while staying inside the freezer.

5.4.1. User Interface Panel

The user interface panel would be an extension attached to the freezer since it would serve the purpose of visualizing the pressure and temperature readings along with having a Raspberry Pi for data acquisition, LEDs, a camera, and an alarm system to monitor the tanks placed inside the freezer to always obtain a live feed. An alarm system would be instated on the panel to indicate if ever the tanks are left unattended for more than 6 hours and fluid remains in the bottle. The placement of the user interface panel would be between the lid and above the chest freezer to facilitate the readings without opening the lid to facilitate a constant temperature inside the freezer.

5.4.2. Mounting stand

The tanks would be mounted vertically in the freezer in a cage-like configuration utilizing an 80/20 T-slotted frame.

Figure 5: T-slotted 80/20 frame for mounting panel [4]

The mounting panel would be assembled so that the run tanks are able to stand with the required valves to be able to slide the frame in and out of the freezer easily.

5.4.3. Validation

The liquification process of the gases would be validated first with CO_2 tanks. The process is done by taking metal cylinders which are double ended with a ½" NPT fitting. At room temperature, CO_2 has a pressure of around 60 bars. The sample cylinder should be filled to its 3000-psi rating and fed at 60 psi (4 bars). When placed in the freezer with a pressure gauge, it would allow it to cool down at constant volume; at around 20 bars. This process would start to partially liquefy. It would expand isentropically and release pieces of ice at the bottom near the exit. A frost line should be present, which should allow to determine the pressure and distance from the frost line's height.

Purchasing a CO_2 bottle with a dip tube is another option for relieving the pressure. The liquid which would be removed from the bottom may be utilized to fill the sample cylinder that would later be frozen. The frost line should now be close to the top. Next, once the liquid and gas sides from both ends of the cylinders are open, the frost line could be measured. If it does freeze, it can be validated measuring how much CO2 causes ice to develop. This process of ice formation from the CO2 tanks are important since this liquification process can validify whether the ethylene and nitrous oxide bottles would be able to liquify.

6. Project Schedule

Please refer to *Appendix B* for the Gantt Chart.

7. Preliminary Test and Safety Procedures

For the proper and safe operation of the RDE injection system we require a properly designed propellant, oxidizer fuel system and a dedicated testing location. The facility serves two purposes: it provides safe housing for all necessary equipment, both dangerous and expensive items and it serves to protect the users from any unwanted. For these purposes, to be fulfilled completely, a list of required safety protocols needs to be compiled. The RDE testing facility (REF) safety requirements are divided into 6 sub sections and are still being developed as our systems is still subjected to change.

1. Detailed REF layout
2. Detailed design and construction of propellant supply system
3. Control and data acquisition system integration
4. System operation protocols with fail safe states for every system
5. Safety and explosive hazard assessment
6. Purge procedures

The storage of the cryogenics would entail many safety procedures followed by appropriate training to be able to run the experiment.

Preliminary safety calculations for CO_2 tests can be found in *Appendix G.*

8. Future work that remains to be completed

- Write Python script
- Thermal and structural simulations
- Finalize tubes and fittings dimensions
- Purchase components: fittings, tanks, valves, piping, freezer…
- Manufacture components: drill holes in tubing and fittings.
- Assemble and Manufacture User Interface Panel
- Assemble mounting panel
- Liquify CO2
- Test with CO2
- Liquify propellants
- Test with propellants

9. Conclusion

This paper demonstrates that an oxidizer-rich pre-burner is designed using Swagelok's ultra torr fittings to achieve a phase change of the ethylene and nitrous oxide before injection into the Rotating Detonation Engine (RDE). The analysis presented elaborates on the feasibility and offers an overview of the design of the pre-burner along with a more detailed analysis of the cryogenic storage system. Further analysis and validation are necessary before commencing the testing phase of the project.

10. References

[1] "(PDF) Design of Cooling Channels of Preburners for Small Liquid Rocket Engines with Computational Flow and Heat Transfer Analysis," *ResearchGate*, 2022, doi: 10.5140\/JASS.2011.28.3.233.

[2] "What temperature should your fridge and freezer be?" [Online]. Available: https://blog.bestbuy.ca/appliances/major-appliances/what-temperature-should-your-fridge-and-freezer-be. [Accessed: 7-Nov-2022].

[3] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*. Hoboken, NJ: John Wiley & Sons, Inc, 2017.

[4] "1010," *80/20 Inc.* [Online]. Available: https://8020.net/1010.html. [Accessed: 7-Nov-2022].

[5] J. Targonski, "Introduction into Propellant Feed Systems LPL Crash Course Lecture Series USC Viterbi School of Engineering," 2017. Accessed: Oct. 10, 2022. [Online]. Available: https://static1.squarespace.com/static/5c639f2e11f78440d05623e3/t/5c709bbafa0d600773ac9f69/1550883773599/LCCLS+Introduction+into+Propellant+Feed+Systems-compressed.pdf

[6] A. Hollings, "DARPA's new missile hints at truly game-changing technology," *Sandboxx*, Jul. 26, 2022. https://www.sandboxx.us/blog/darpas-new-missile-hints-at-truly-game-changing-technology/ (accessed Nov. 11, 2022).

[7] "Double-Ended Cylinders | Sample Cylinders | All Products | Swagelok," *Swagelok.com*, 2022. https://products.swagelok.com/en/all-products/sample-cylinders/double-ended-cylinders/c/1001?clp=true (accessed Nov. 11, 2022).

[8] Hollings, A. (2022, July 26). *DARPA's new missile hints at truly game-changing technology*. Sandboxx. Retrieved November 11, 2022, from https://www.sandboxx.us/blog/darpas-new-missile-hints-at-truly-game-changing-technology/

[9] "Was federal spending on the space race justified?," *Bill of Rights Institute*. [Online]. Available: https://billofrightsinstitute.org/activities/was-federal-spending-on-the-space-race-justified. [Accessed: 11-Nov-2022].

[10] Cengel, Y. A., & Ghajar, A. J. (2014). *Heat and mass transfer: Fundamentals and applications* (5th ed.). McGraw-Hill Professional.

Appendix A: ELSEE Analysis

The Rotating Detonation Engine (RDE) is compelling not only for research purposes as mentioned in the purpose for the capstone project but to many industries namely, space and transportation due to the potential it possesses to be lighter than existing jet engines, it offers a higher power output, increased range, and better fuel efficiency.

This premise raises the question of whether the implication of space exploration and advances in its technology is ethical and whether its moral imperative is pertinent for humans to be able to extract resources for its development. The question of ethics is related to how safe developing such technology is in a civilized society. Furthermore, whether development is perceived with a positive connotation. Regarding ethics, the safety of those involved and those utilizing and benefiting from this technology is crucial to consider. Recently, worries about pollution have risen over time. Meanwhile, human-made junk is all over the Earth's outer atmosphere. This biological and environmental contamination raises the question of whether it is moral to develop such a technology which could paradoxically harm humans and the environment more than bringing forth a positive connotation.

Furthermore, the research and development of a rotating detonation engine integrated into a rocket would also affect the fiscal policies along with the cost and benefit for development for space exploration instilled in place. By monopolizing space exploration, the government crowded out private sources and established, through a government contracting process cursed with overbilling, prices for space exploration supplies and services far beyond the reach of the private sector [9] This phenomenon is a challenge and poses a controversy as the public opinion can be biased as public tax cuts dedicated to space development is not appreciated by every individual.

That is, it can be perceived as redundant when many problems related to unemployment, poverty, and inequality in the distribution of resources are still prevalent and present on Earth.

Another key point to consider is the legal aspect this type of technology involves. In fact, in Canada, all model rocketry is governed by Transport Canada through the Canadian Aeronautical Regulations, Sections 101.07 Subsection 1 and 602.43 through .45. No licenses or permits are required to participate in model rocketry. Motors are regulated by the Explosives Regulatory Division, of Natural Resources Canada through the Explosives Act. One must be at least 12 years of age to purchase and use model rocket engines without adult supervision. The Canadian Model Rocketry Safety Code should be followed. In this case safety is also closely related to the legal aspect. Many of the required certification such as the ones required to handle explosive, and the rocket motors are not mandatory but ensures proper use of the equipment. For example, our team decided to follow the Space Concordia training to better be equipped for the testing phase of this project, however since none of us are part of Space Concordia, an NDA was signed. Although there are no real regulation or licence required for building a model rocket; ensuring our own safety, safety of other and protecting private information are stated by the Canadian law.

The Defense Advanced Research Projects Agency (DARPA) recently unveiled a new high-speed missile program focused on a propulsion system, known as a rotation detonation engine (RDE). This technology can also be used to power the Navy’s surface vessels, it can provide better power production, more range, and reduce costs of fuel. The US Air Force Research Laboratory and the University of Centra Florida have built and tested the first engines in 2020. Since then, Pratt and Whitney and a few other companies have launched their own programs. RDE technology is enabling entrepreneurial persons to innovate this field.

The objective of the DARPA program is to have a mass-producible, low-cost, high-supersonic, long-range weapon for air-to-ground strike in an anti-access/area denial (A2AD) environment. Military experts believe that this type of missile would be most effective against China's 1,000-mile area denial bubble. China possesses many anti-ships weapon systems along their shoreline which prevents carriers from getting close enough for US fighter jets to reach their shores since they can only travel 650 miles. With RDE missiles, US carriers can stay out of harm's way of the anti-ship weapons since the fighter jets can travel a longer distance and the missiles can be launched from a further distance. There are many ethical concerns related to extended range weapon systems. The first that comes to mind is the chances of hitting an unintended target, this is always present no matter the accuracy of the system.

Another reason to launch this program is the current cost of the missiles used for launching from the air, those hypersonic missiles cost as much as $106 million each. The RDE promises to achieve the same results for a much lower price. RDE will allow a more economical way to manufacture missiles. It is also predicted that RDEs can increase the warship's thrust by 10% and reduce fuel consumption by 25%, for an estimated savings of $400-500 million per year. Regarding the environmental aspect, most of the US Navy's fleet runs on marine diesel fuel, it was estimated that they used 86 million barrels of diesel in 2016… the RDE can replace those diesel engines, allowing them to switch to cleaner fuels [8].

Regarding the stakeholders of the DARPA RDE program, there is the US Airforce who will be using this technology, there is the US Government and taxpayers who will fund the project. The firms who are submitting proposals are also stakeholders, they will build the RDE systems. The universities who are developing technology must also be considered since they are the ones who are proving the RDE capabilities. Finally, I would like to add that the environment is also a stakeholder, in the interest of future generations, all efforts to reduce pollutants should be made. The environment is our holding company. If it goes out of business, we all go out of business.

The environment concerns surrounding this project can be summarized by the works of Prakhar Jindal et all. Where he summarises the negatives aspects of rockets in our environment. The literature surrounding the environmental aspects are not yet very know since rocket lunches are rare and only a hand full on countries do them. This creates a barrier for research to be conducted since rockets are highly classified engineering works.

Appendix B: Gantt Chart

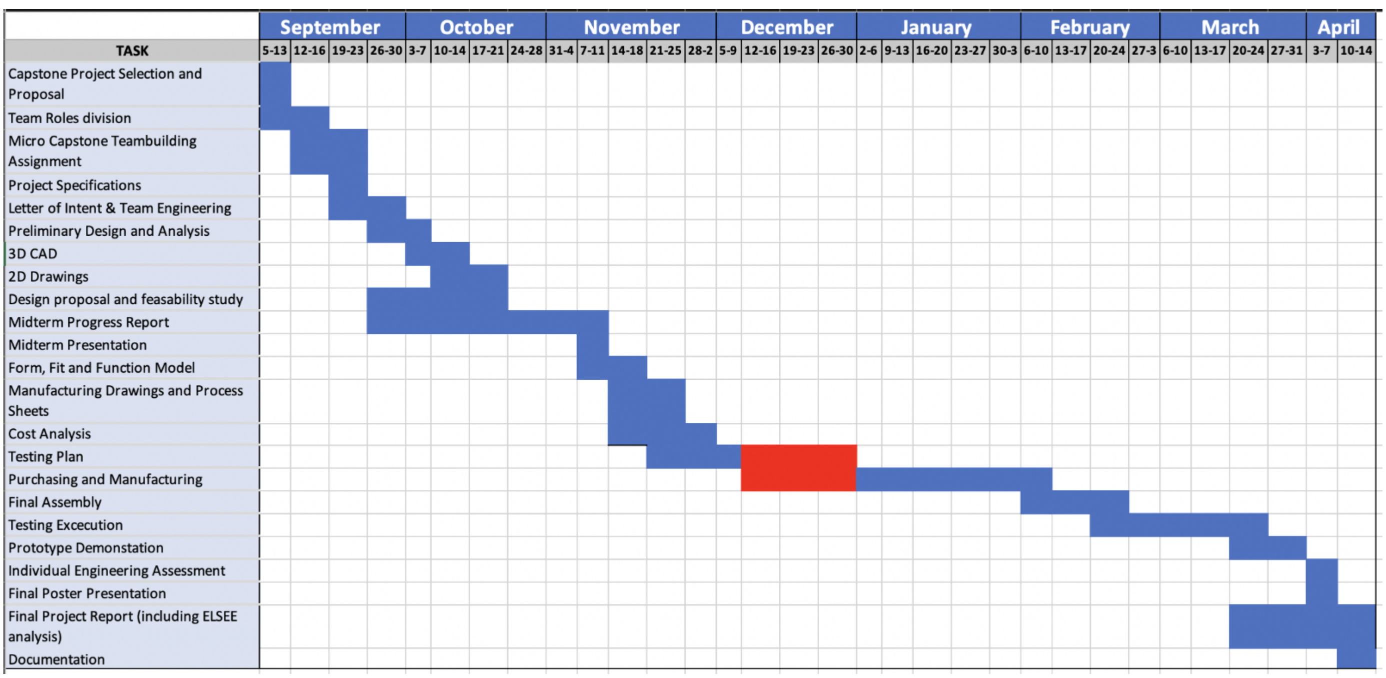


Figure 6: Gantt Chart

Appendix C: Preliminary Drawings and CAD

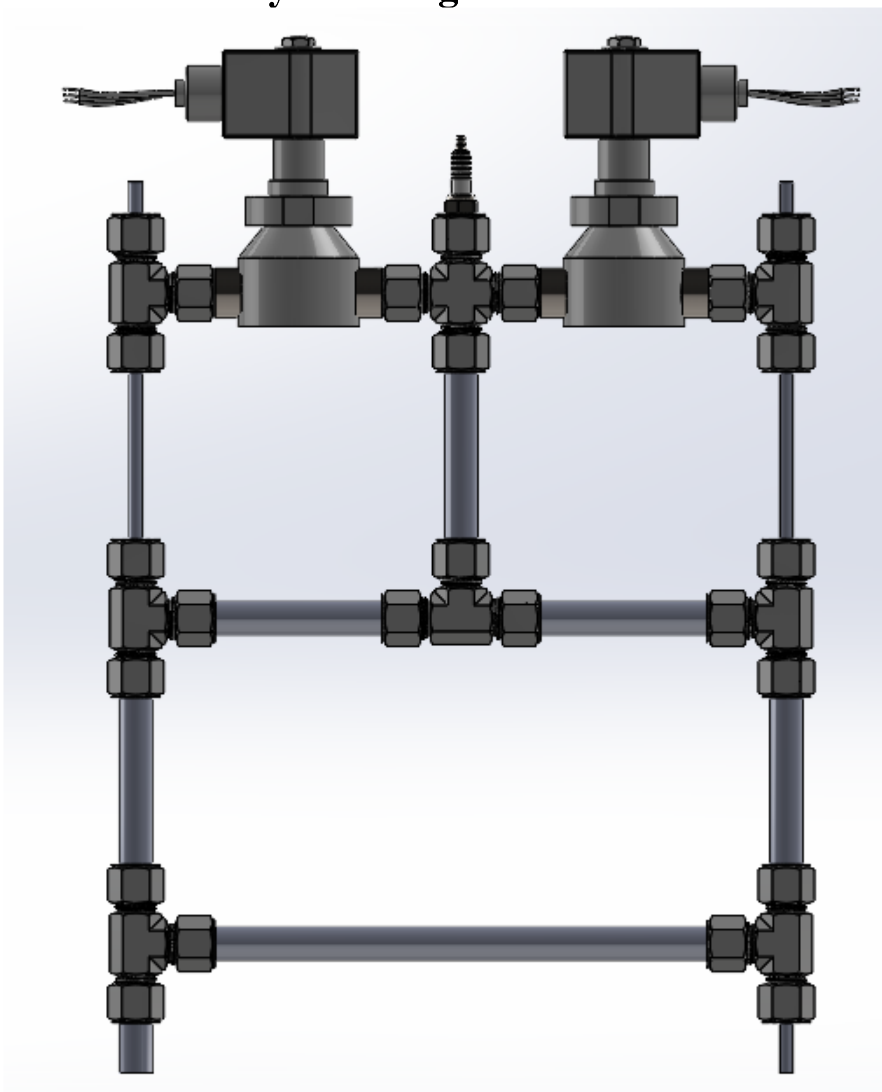
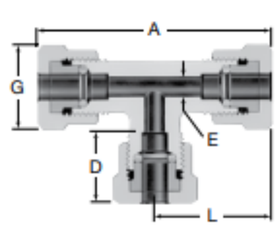


Figure 7: CAD Assembly

Union Tee



Tube OD in.	Ordering Number	Dimensions, in. (mm)				
		A	D	E	G	L
1/8	SS-2-UT-3	2.20 (55.9)	0.47 (11.9)	0.09 (2.3)	9/16	1.10 (27.9)
1/4	SS-4-UT-3	2.32 (58.9)	0.62 (15.7)	0.19 (4.8)	11/16	1.16 (29.5)
3/8	SS-6-UT-3	2.74 (69.6)	0.66 (16.8)	0.28 (7.1)	13/16	1.37 (34.8)
1/2	SS-8-UT-3	2.74 (69.6)	0.81 (20.6)	0.41 (10.4)	15/16	1.37 (34.8)
3/4	SS-12-UT-3	3.42 (86.9)	0.99 (25.1)	0.63 (16.0)	1 1/4	1.71 (43.3)
1	SS-16-UT-3	3.76 (95.5)	0.99 (25.1)	0.88 (22.4)	1 9/16	1.88 (47.8)

Figure 8: Ultra-Torr Tee Fitting

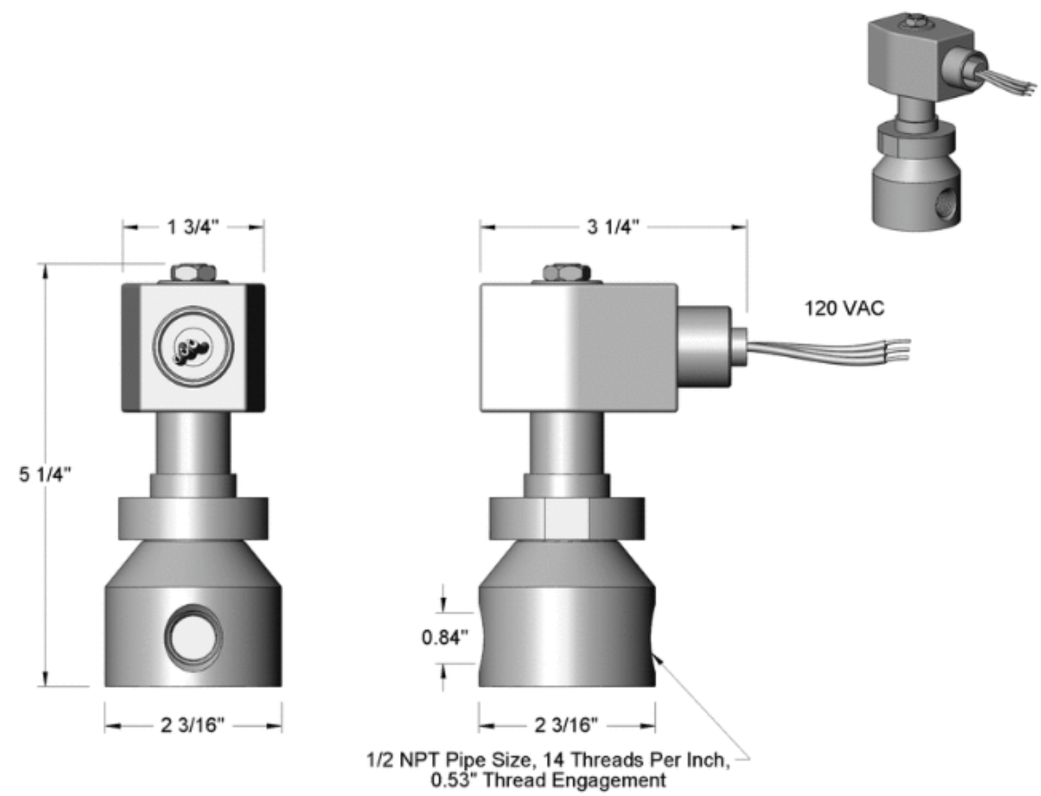


Figure 9: Solenoid Valve Fitting

Figure 10: Bosch Spark Plug

Appendix D: Design Validation Diagram

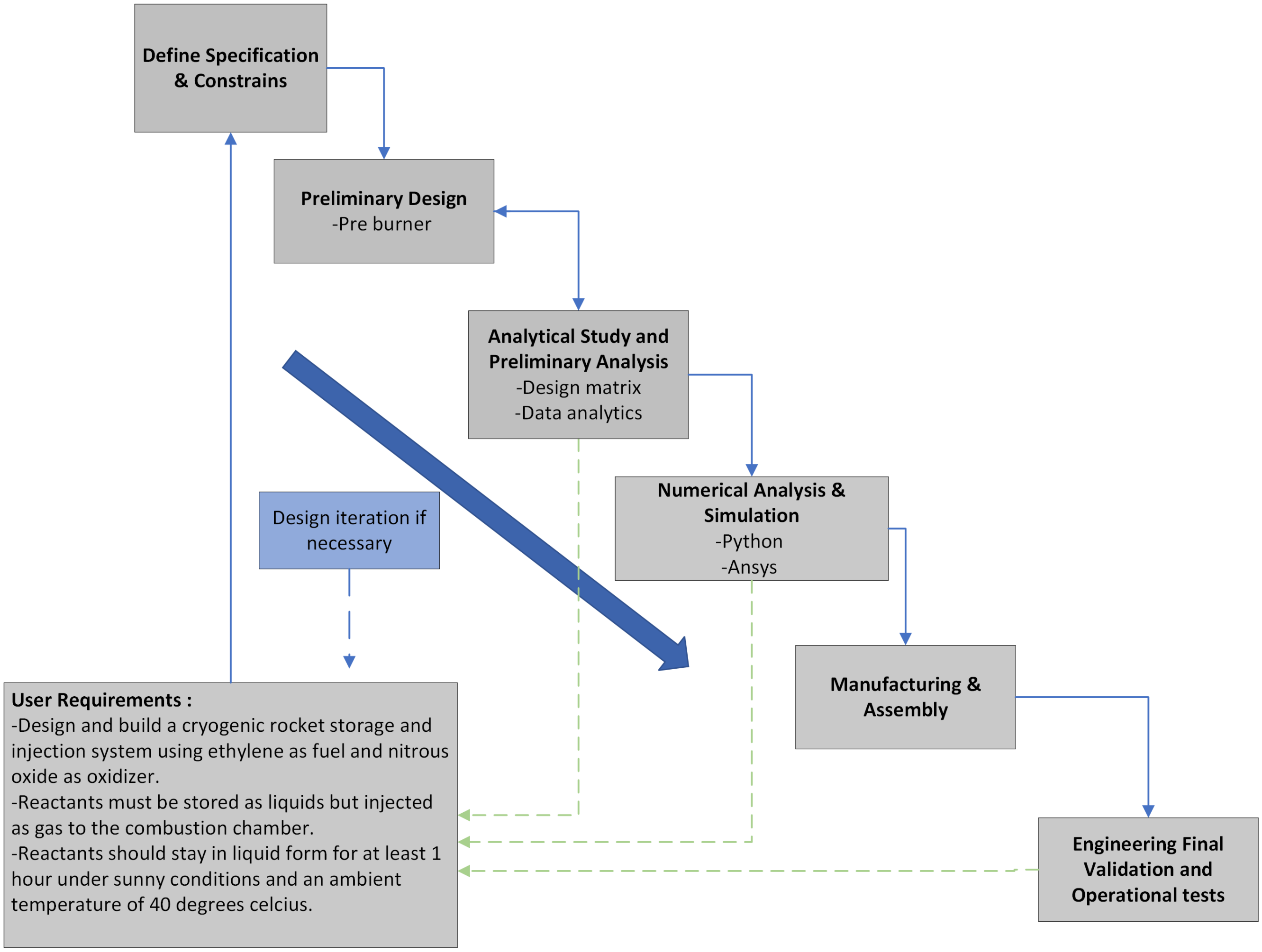


Figure 11: Design Validation Diagram

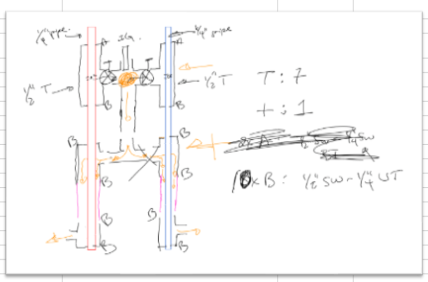
Appendix E: Design Matrix

	Categories	General							MANUFACTURABILITY			COST RISK		Engineering testing			SCORE
	Sub Criteria	Phase Change	fuel purity	applied for both ethelyne and Nitroux oxide	size	Mass	Quality	complexity of the design	Material	Time	Assembly complexity	Material Cost	OEM components	Testing methodology	Test Stand complexity	Validation	
	comment for sub criteria	can phase change be achieved from liquid to gas	ensuring constant and fluid combustion in the RDE	certainty that phase change of the two cryogenics will take place	6-10 in diameter restriction as it should fit in a rocket	to be integrated in a rocket, lightweigth component required	quality of the gas produced	number of parts to be designed. The amount of technical knowledge required.	raw material, tools and machinery availability and accessibility	labour time						Amount of analysis which can be validated	
CHECK SUM																	
515	Coarse Weight	165							100			100		150			
515	Fine Weight	100	15	10	5	5	20	10	45	40	15	60	40	60	30	60	
	percentage	0.194174757	0.029126214	0.019417476	0.009708738	0.009708738	0.038834951	0.019417476	0.087378641	0.077669903	0.029126214	0.116504854	0.077669903	0.116504854	0.058252427	0.116504854	
	Option description																
A	exhaust pre-burner	3	5	3	3	3	3	4	3	3	4	4	2	2	2	2	
B	Single mixing channel pre-burner	4	4	4	3	3	5	5	3	4	4	4	2	3	3	2	
C	double mixing channels pre-nurner	4	3	4	3	3	4	3	3	4	4	5	3	2	3	2	
	WEIGHTED SCORES																
A	exhaust pre-burner	0.582524272	0.145631068	0.116504854	0.116504854	0.116504854	0.116504854	0.155339806	0.262135922	0.087378641	0.116504854	0.466019417	0.155339806	0.233009709	0.116504854	0.233009709	3.019417476
B	Single mixing channel pre-burner	0.776699029	0.116504854	0.155339806	0.116504854	0.116504854	0.194174757	0.194174757	0.262135922	0.116504854	0.116504854	0.466019417	0.155339806	0.349514563	0.174757282	0.233009709	3.54368932
C	double mixing channels pre-nurner	0.776699029	0.087378641	0.155339806	0.116504854	0.116504854	0.155339806	0.116504854	0.262135922	0.116504854	0.116504854	0.582524272	0.233009709	0.233009709	0.174757282	0.233009709	3.475728155

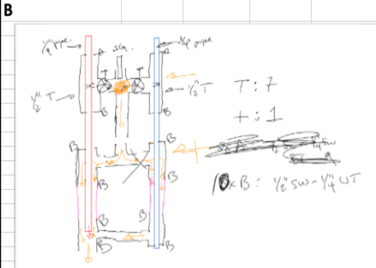
User fills in only areas highlighted colors below
Text
Entries in this row can add up to any number, weights are relative to each other

Rating system	
Not applicable	0
Very bad	1
Bad	2
Average	3
Good	4
Very good	5

A



B



C

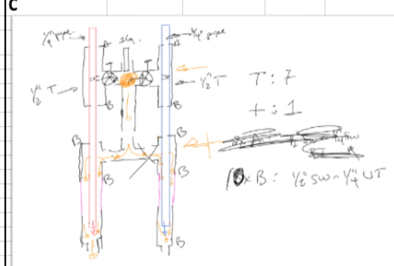


Figure 12: Design Matrix

Design Selection Table

Table 4: Design selection Table

Design option	*Advantages*	*Disadvantages*
Design 1: Exhaust Pre-burner	• Clean fuel and oxidizer feed lines with no mixing of the combustion products • Only relies on the heat transfer to change the propellants to gas. • Constant and stable combustion in the engine due to purity of the fuel and oxidizer	• Thrust and energy loss. • Strictly Stoichiometric combustion • Pressure drop in the exhaust pipes due to opening • Heat transfer through pipes might not be enough for the phase change
Design 2: Single mixing channel Pre-Burner	• Less thrust/energy loss. (Compared to design 1) • Better heat exchange with higher mass flow -more likely to have a Phase change. • Constant mass flow rate to the engine • Combustion can be fuel or oxidizer rich- better heat dissipation so it will not melt off the ultra-torr	• Length of the heat transfer pipes must be equal. • Addition of a combustion product transfer line • The oxidizer will not be pure • Possible pipe blockage at the engine inlet due to combustion products
Design 3: double mixing channel Pre-burner	• Best heat transfer since products mixed into both lines. • No mass or energy losses • Constant mass flow rate to the engine	• Difficulty ensuring separation of fuel and oxidizer lines. • Contamination of both fuel and oxidizer. • The exhaust gas lines should be designed to ensure a constant mass flow rate according to the stochiometric quantities of oxidizer and fuel – nitrous oxide should receive less combustion products than the ethylene line. • Strictly stoichiometric combustion

Appendix F: Design Criteria

Table 5: TS Diagram Data

Fuel	Ethylene C_2H_4
Oxidizer	Nitrous Oxide N_2O
Mixture ratio O/F	9.4
Combustion Chamber Pressure	100 psi / 6.9 bar
Initial Fuel Temperature	-10℃
Initial Oxidizer Temperature	-10℃
Final Fuel Temperature	-15℃ to 40℃ ($if\ no\ pressure\ loss$)
Final Oxidizer Temperature	-27℃ to 50℃ ($superheated$)
Initial Fuel Pressure	50-80 bar
Initial Oxidizer Pressure	50-70(superheated) bar
Final Fuel Pressure	> 5 bar
Final Oxidizer Pressure	> 5 bar
Initial Fuel Enthalpy	254 kJ/kg
Initial Oxidizer Enthalpy	200 kJ/kg
Final Fuel Enthalpy	582.24 kJ/kg
Final Oxidizer Enthalpy	416.61 kJ/kg

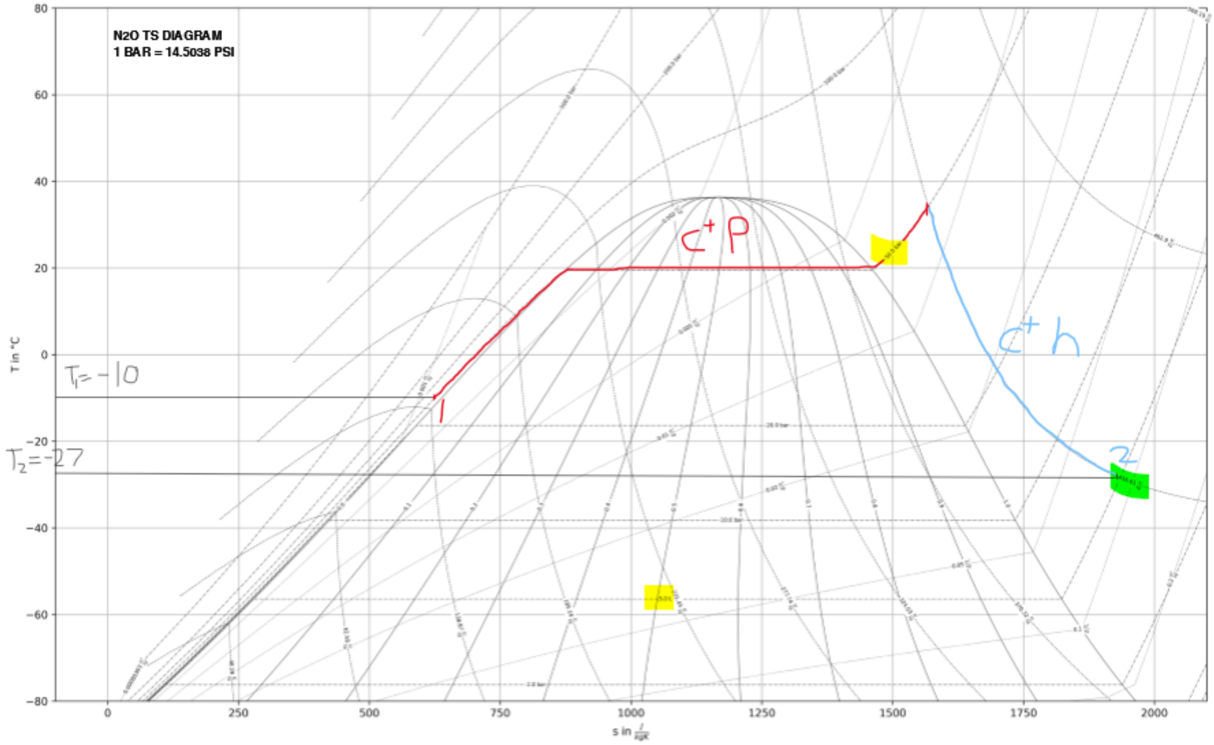


Figure 13: N2O TS Diagram

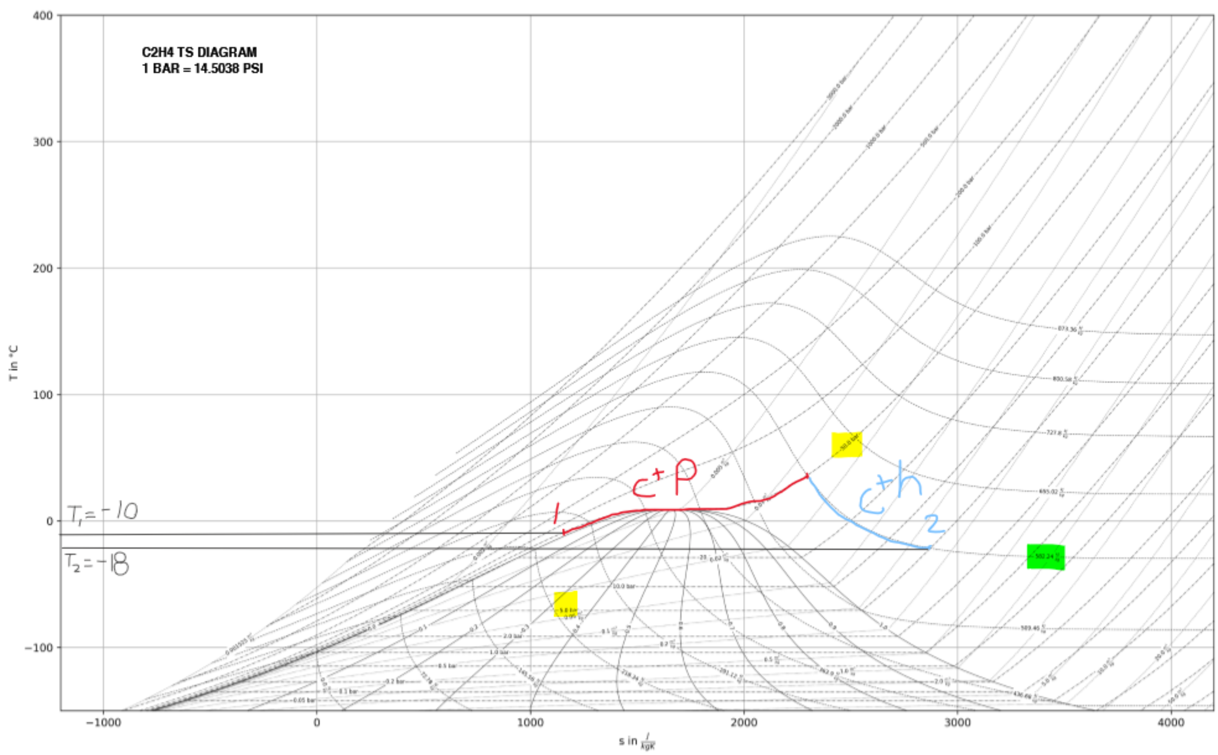


Figure 14: Ethylene TS Diagram

Appendix G: Engineering Analysis

Heat Transfer in a Pipe

L: length of pipe [m] = to be determined
r_1: inner radius [m] = 0.00559m
r_2: outer radius [m] = 0.00635m
k: thermal conducivity $\left[\frac{W}{mK}\right]$, $k_{copper} = 400\frac{W}{mK}$
T_1: inner temperature [K] = temperature of propellants = 263.15K
T_2: outer temperature [K] = temperature of combustion = 366.73K

$$\frac{d}{dr}\left(r\frac{dT}{dr}\right) = 0,$$

with boundary conditions

$$T(r_1) = T_1$$
$$T(r_2) = T_2$$

integrate with respect to r

$$r\frac{dT}{dr} = C_1$$

where C_1 is an arbitrary constant

$$\frac{dT}{dr} = \frac{C_1}{r} \text{ integrate again with respect to r}$$

$$T(r) = C_1 \ln(r) + C_2$$

now apply boundary conditions

$$C_1 \ln(r_1) + C_2 = T_1$$
$$C_1 \ln(r_2) + C_2 = T_2$$

Solve both equations simultaneously

$$C_1 = \frac{T_2 - T_1}{\ln(r_2/r_1)}, C_2 = T_1 - \frac{T_2 - T_1}{\ln(r_2/r_1)}\ln r_1$$

The variation of temperature within the pipe is determined by

$$T(r) = \frac{\ln(r/r_1)}{\ln(r_2/r_1)}(T_2 - T_1) + T_1$$

Now we can determine the rate of heat conduction through the pipe, using Fourier's law

$$\dot{Q}_{cylinder} = -kA\frac{dT}{dr} = -k(2\pi rL)\frac{C_1}{r} = -2\pi kLC_1 = 2\pi kL\frac{T_1 - T_2}{\ln(r_2/r_1)}$$

Now, if we neglect heat transfer between the outer tubing and the atmosphere, and we assume there is only heat conduction between the propellant line and the outer tubing (where the mixture is traversing), then we can equate the following heat conduction through the pipe to the gain in heat of the propellants.

$$\dot{Q}_{cylinder} = \dot{Q}_{gain}$$
$$\dot{Q}_{gain} = \dot{m}\Delta h = \dot{m}c_p\Delta T$$

We know the change in enthalpy needed for the propellants to change in phase from liquid to gas.
For Ethylene $\Delta h = 582.24 - 254 = 328.24\ kJ/kg$

For Nitrous Oxide $\Delta h = 393.46 - 150.44 = 243.02\ kJ/kg$
We know the mass flow rates of each propellant.
$\dot{m}_{ethylene} = 0.096 kg/s$
$\dot{m}_{nitrous\ oxide} = 0.903 kg/s$
We can now solve for the minimum pipe length that will cause change in phase for each propellant.
$$2\pi k L \frac{T_1 - T_2}{\ln(r_2/r_1)} = \dot{m}\Delta h$$
For Ethylene
$$2\pi(400)L \frac{263.15 - 366.73}{\ln(0.00635/0.00559)} = (0.096)(328.24)$$
$L = 0.00001543m$
For Nitrous Oxide
$$2\pi(400)L \frac{263.15 - 366.73}{\ln(0.00635/0.00559)} = (0.903)(243.02)$$
$$L = 0.01551m$$

Friction flow

$f: friction\ factor\ from\ Moody\ chart, need\ to\ know\ surface\ roughness$

$D_H = \frac{4A}{P}$ =2R: $hydraulic\ diameter$

M: Mach number

γ: ratio of specific heats

$V: velocity$

$T: temperature$

$P: pressure$

Changes in velocity due to friction over section dx
$$\frac{dV}{V} = \frac{\gamma M^2}{2(1 - M^2)} \frac{4f}{D_H} dx$$
Changes in temperature due to friction over section dx
$$\frac{dT}{T} = \frac{\gamma(\gamma - 1)M^4}{2(1 - M^2)} \frac{4f}{D_H} dx$$
Changes in pressure due to friction over section dx
$$\frac{dp}{p} = \frac{\gamma M^2[1 + (y - 1)M^2]}{2(1 - M^2)} \frac{4f}{D_H} dx$$

Adiabatic Flame Temperature

The known the molar mass of our reactants, which enables to determine mass ratio of each required to sustain a combustion. We also know the energy released from this reaction, given the starting pressure and temperature of our propellants, we can therefore determine the required amount of propellant we must combust in the pre-burner to achieve our desired ending temperature and pressure. This would be determined in the following way:

From the phase diagrams for our propellants, we know the change in enthalpy that we want to create Δh. We can now determine the heat required to cause this enthalpy change as:

$$\Delta h_{propellant}\left(\frac{kJ}{kg}\right) * Mass\ of\ propellant\ (kg) = Required\ heat(kJ)$$

From the required heat we can then determine the quantity of reactants required for the reaction to provide the desired heat as:

$$Required\ heat(kJ) \Big/ \Delta h_{reaction}\left(\frac{kJ}{kg}\right) = Mass\ of\ Reactants\ (kg)$$

Preburner Calculations + Adiabatic flame temperature

$\hookrightarrow$ max temp. that can be achieved for given reactants.

Assume

- Adiabatic process (no shaft work).
- Oxidizer-Rich mixture.

$$\underbrace{C_2H_4}_{28.05\,g/mol} + \underbrace{6N_2O}_{6(44.01)\,g/mol} \rightarrow \overbrace{6N_2}^{6(28.01)} + \overbrace{2H_2O}^{2(18.2)} + \overbrace{2CO_2}^{2(44.01)}$$

$28.05\,g/mol + 6(44.01)\,g/mol = 292.11\,g/mol$

$$O/F_{stoic} = \frac{6(44.01)}{28.05} = 9.4 = \frac{m_o}{m_f} = \frac{m_o}{1-m_o} \rightarrow m_o = 0.90397\,kg/s \;\&\; m_f = 0.09603\,kg/s$$

$\hookrightarrow$ since $m_o + m_f = 1\,kg/s$ (given by Dr. Kiyanda)

But, since we're designing an oxidizer-rich pre-burner, let's get another mixture ratio. We plan on combusting 75% of the nitrous oxidizer vs 4% of the ethylene, thus $O/F = \frac{75\%}{4\%} = 18.75$

$$18.75 = \frac{m_o}{m_f} = \frac{m_o}{1-m_o} = 1\,kg/s$$

$\rightarrow m_o = 0.94937\,kg$ (N_2O)

$\rightarrow m_f = 0.050633\,kg$ (C_2H_4)

Now, we can begin the calculation of the adiabatic flame temperature.

1) **Enthalpy of formation**

$\Delta H_{C_2H_4} = 52.28\,KJ/mol$

$\Delta H_{N_2O} = 82.05\,KJ/mol$

$\Delta H_{N_2} = 0\,KJ/mol$

$\hookrightarrow$ because free element

$\Delta H_{H_2O} = -241.8\,KJ/mol$

$\Delta H_{CO_2} = -393.5\,KJ/mol$

$\Delta H_{products} - \Delta H_{reactants} = -1815.18\,KJ$

$\rightarrow$ meaning 1815.18 KJ is the released heat.

$\rightarrow$ exothermic process.

2) $\frac{\text{Heat released}}{\text{weight of reaction}} = \frac{1815.18\,KJ}{292.11\,g} = 6.214\,KJ/g$

$\cdot Q$

3) Enthalpy Change

Reactants

C_2H_4: $h_1 = 254$ KJ/Kg
$h_2 = 582.24$ KJ/Kg

N_2O: $h_1 = 200$ KJ/Kg
$h_2 = 416.61$ KJ/Kg

$\Delta h\ C_2H_4 = h_2 - h_1$
$= 582.24 - 254 = 328.24$ KJ/Kg

$\Delta h\ N_2O = h_2 - h_1$
$= 416.61 - 200 = 216.61$ KJ/Kg

1) Required heat for C_2H_4

$328.24 \frac{KJ}{Kg} \cdot 0.05063\ Kg = 16.62$ KJ

Required heat for N_2O

$216.61 \frac{KJ}{Kg} \cdot 0.94937\ Kg = 205.64$ KJ

Total heat required for reaction:
16.22 KJ $+ 205.64$ KJ $= 222.26$ KJ $= \Delta Q$

5) Amount of Propellants required for this enthalpy change:

$$\frac{222.26\ KJ}{6.214\ KJ/g} = 35.77\ g \text{ required.}$$

Again, for $O/F = 18.75 = \frac{m_o}{m_f}$ $\qquad m_o + m_f = 35.77$ g

$$18.75 = \frac{m_o}{35.77 - m_o} \rightarrow m_o = 33.96\ g$$
$$\rightarrow m_f = 1.81\ g$$

6) Adiabatic Flame temperature:

- Pre-burner combustion is oxidizer rich, thus

$$\Delta T = \frac{\Delta H}{6cp(N_2) + 2cp(H_2O) + 2cp(CO_2)\left[\frac{m\ prod}{m\ tot}\right] + 2cp(N_2O)\left[\frac{m_o}{m_{tot_c}}\right]} \cdot m_{tot_c}$$

Cp $N_2 = 1.04$
Cp $H_2O = 1.8723$
Cp $CO_2 = 0.846$

Cp $C_2H_4 = 2$ KJ/Kg K
Cp $N_2O = 2.4$ KJ/Kg K

$m_{tot\ combustion} = 903.97\ g + 35.77\ g = 939.74\ g$
↳ after combustion for N_2

$$\Delta T = \frac{222.26 \ \mathrm{KJ/s}}{6(1.04)\left(\frac{28.01}{292.71}\right) + 2(1.8723)\left(\frac{18.2}{292.71}\right) + 2(0.846)\left(\frac{44.01}{292.11}\right)\left[\frac{35.77}{939.79}\right] + 2\left(\frac{303.975}{339.74}\right)} \cdot (0.93974)$$

$$\boxed{\begin{array}{l} \Delta T = 103.58 \ \mathrm{K} \\ \\ \text{If } T_i = 263.15 \ \mathrm{K} \ (\sim -10^{\circ}\mathrm{C}) \\ \quad T_{flame} = 366.73 \ \mathrm{K} < \text{Max temp that Ultra-Torr fittings can} \\ \qquad\qquad\qquad\qquad\qquad\quad \text{handle which is } 477.15\mathrm{K}. \end{array}}$$

Figure 15: Adiabatic Flame Temperature of the pre-burner

```python
import CoolProp.CoolProp as CP
import math
import numpy as np

fluid = 'Ethylene'

P0 = 60 #TANK PRESSURE IN BAR
T0 = -10  #TANK TEMPERATURE IN oC

density = CP.PropsSI('D', 'T', T0+273.15, 'P', P0*1e5, fluid)
H0 = CP.PropsSI('H', 'T', T0+273.15, 'P', P0*1e5, fluid)
s0 = CP.PropsSI('S', 'T', T0+273.15, 'P', P0*1e5, fluid)
phase = CP.PhaseSI('T', T0+273.15, 'P', P0*1e5, fluid)

print(f'Density C2H4: {density: .2f} kg/m^3')
print(f'Enthalpy C2H4: {H0*1e-3: .2f} kJ/kg')
print(f'Entropy C2H4: {s0*1e-3: .2f} kJ/kg.K')
print(f'Phase C2H4: {phase}')

print('--------------')

fluid = 'NitrousOxide'

P0 = 60 #TANK PRESSURE IN BAR
T0 = -10  #TANK TEMPERATURE IN oC

density = CP.PropsSI('D', 'T', T0+273.15, 'P', P0*1e5, fluid)
H0 = CP.PropsSI('H', 'T', T0+273.15, 'P', P0*1e5, fluid)
s0 = CP.PropsSI('S', 'T', T0+273.15, 'P', P0*1e5, fluid)
phase = CP.PhaseSI('T', T0+273.15, 'P', P0*1e5, fluid)

print(f'Density N2O: {density: .2f} kg/m^3')
print(f'Enthalpy N2O: {H0*1e-3: .2f} kJ/kg')
print(f'Entropy N2O: {s0*1e-3: .2f} kJ/kg.K')
print(f'Phase N2O: {phase}')
```

Figure 16: Code to get fluid properties

```
import CoolProp.CoolProp as CP
import math
from matplotlib import pyplot as plt


m_dot_target = 96.02547  #Target mass flow rate, [g/s]
fluid = "ethylene"  #Fluid
P0     = 90          #Tank pressure in bar
T0     = -10         #Tank temperature in oC
Y      = 0.80000     #Enthalpy ratio h1/h0

h0 = CP.PropsSI('H','P',P0*1e5,'T',T0+273.15,fluid)
s0 = CP.PropsSI('S','P',P0*1e5,'T',T0+273.15,fluid)

while Y<=0.99999:
  print(Y)
  h1 = Y*h0
  V1 = math.sqrt(2*(h0 - h1))
  print ('velocity = ', V1)
  try:
    c1    = CP.PropsSI('A','S',s0,'H',h1,fluid)
    M1    = V1/c1
    print('Mach number =', M1)
  except ValueError:
      print('Mach = undefined')

  rho1 = CP.PropsSI('D','S',s0,'H',h1,fluid)
  Apipe = 1e-3*m_dot_target/(rho1*V1) #m^2
  Dpipe = math.sqrt(4*Apipe/math.pi)*1000  #mm
  print('Diameter = ',Dpipe)



  Y +=0.0005

plt.plot(Dpipe,Y)
plt.grid(True)
plt.legend(['diameter'], loc='lower right')


plt.show()
```

Figure 17: Code to find pipe diameter for liquid flow

Volume expansion of CO_2 for freezer test:

Cylinder information (304L-HDF4-500):

Pressure rating: 1800psi (124 bar)

Inner volume: 500cm^3 (+-5%)

Worst case volume expansion:

1450 psi (~200 bar)

Step 1:

Assuming the CO2 tank would explode if the tank reached a bar pressure higher than the assigned 124 bar:

The initial temperature in the tank of CO2: -10ºC

Specific volume of CO_2 @ -10ºC and 200bar from online calculator:0.0009450111 m^3/kg

Taken from: https://www.carbon-dioxide-properties.com/co2tablesweb.aspx

To verify with the TS diagram:

Specific volume of CO_2 @ -10ºC and 200bar from Ts graph: ~0.001m^3/kg (a bit less so the value checks out for specific volume)

Step 2:

Density: 1/specific volume

from density calculator @ 200 bar and -10ºC density of CO_2 =1058kg/m^3

Step 3:

Determine mass of CO_2 in cylinder:

density * volume = mass,

We know that the inner volume of the tank: 500cm^3 (+-5%)

$1058kg/m^3 * 500cm^3 * (0.01m/cm)^3 = 0.529kg\ CO_2$

Step 4:

From the mass from step 3, we can calculate how much volume of CO_2 will be displaced

Specific volume of CO_2 at atmospheric pressure I.e. 1 bar and temperature (25ºC) not shown on Ts diagram. Density calculator gives 1.784kg/m^3

mass/density = volume, 0.529kg/1.784kg/m^3 = 0.30m^3 final volume of CO_2 in the room.

Appendix H: Piping & Instrumentation Diagrams

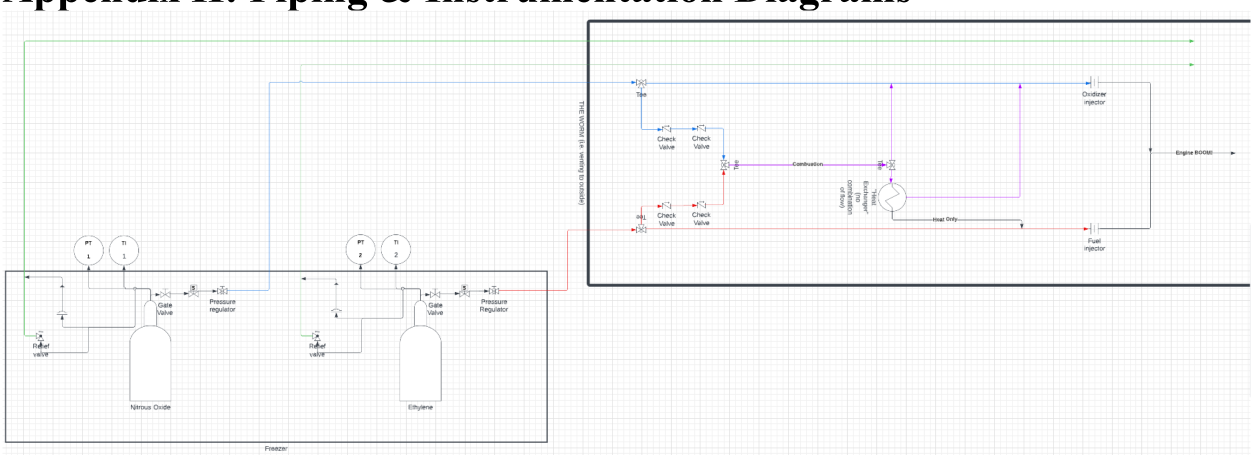


Figure 18: P&ID for our test setup

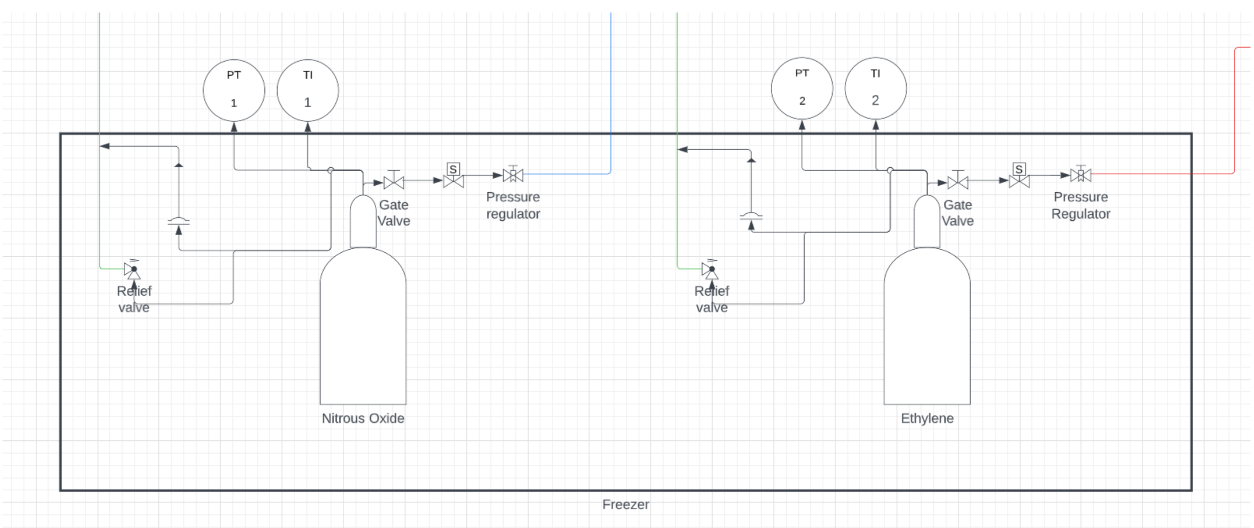


Figure 19: P&ID of the Cylinders for Tests

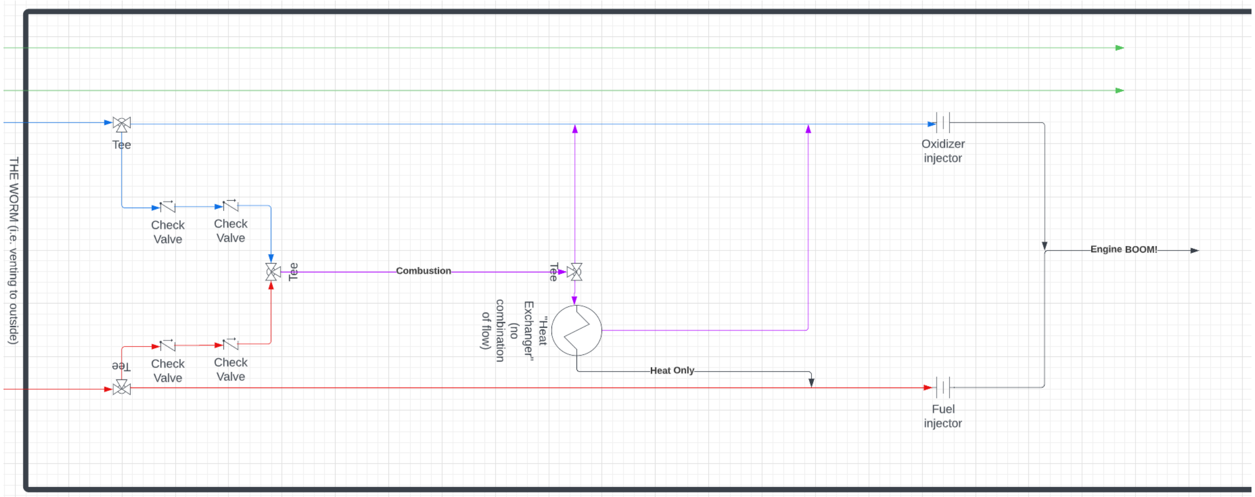


Figure 20: P&ID of the Pre-burner Test Setup

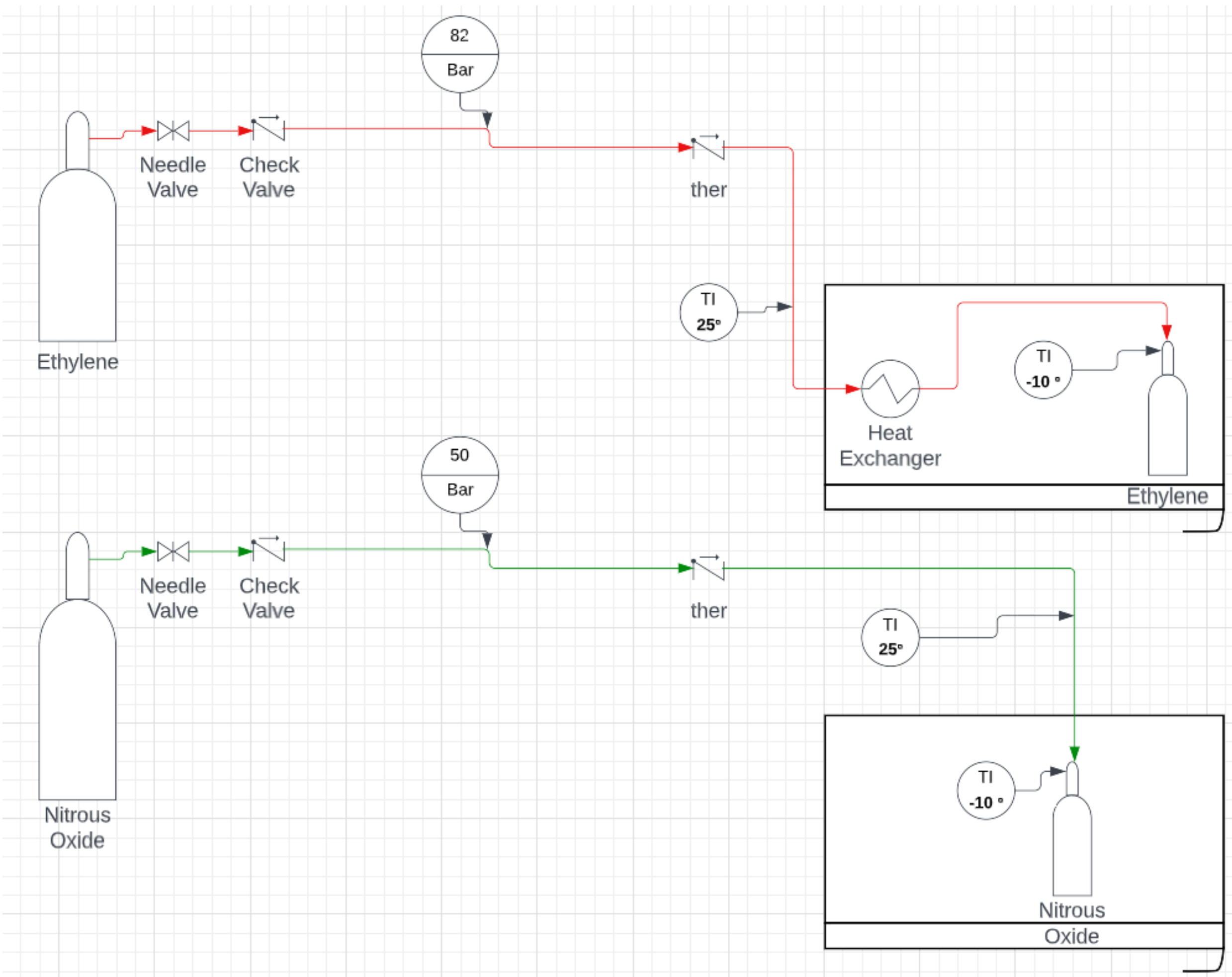


Figure 21: P&ID for Filling our Run Cylinders with Liquid

Appendix I: Safety Aspects

Leaks and spill can occur during storage, or failure of the feeding system. Substitution of the cryogenic liquid is the best method to avoid or reduce hazard. For testing, N2O will be replaced by CO2, T-S diagrams were compared for both compounds. The only noticeable difference was the critical point, the critical point for CO2 was slightly lower than N2O. Solidification of CO2 must be monitored. The pressure vessel and fittings must be designed to withstand 100 bar. For pressure fed systems, the pressure inside the storage system must be greater than the combustion chamber. Swagelok fittings are a likely candidate for our fuel distribution system since they reduce the number of potential leak points and reduce the size of the assembly.

Ethylene is categorized as a combustible asphyxiant. It is listed as a class 3 carcinogen; it is minimally toxic however it displaces oxygenated air which causes oxygen-depletion and subsequently suffocation. Nitrous oxide is a category 1 oxidizing gas, it is colorless gas stored as a liquid, it has a specific organ toxicity for single exposure. N2O is a powerful oxidizer that may explode if heated. It can also displace oxygen and cause rapid suffocation. It may also cause drowsiness or dizziness. If N2O is shocked repeatedly it can violently decompose, for that reason, dead volume must be added in the flow path.

The injectors must be designed to feed reactants at a constant mass flow rate and withstand the forces from the detonations inside the combustion chamber. Abrupt changes in the shape of components will be avoided to reduce stress concentrations. For the above reasons, all team members must pass the following EH&S trainings.

1. Workplace hazardous materials Information Session (WHMIS) (required)
2. Hazardous waste disposal for laboratory personnel (required)
3. ENCS Hands-on lab safety

4. Hazardous materials minor spill

Further to those trainings, additional courses on cryogenics will be given to all members of the team. Regarding safety factors, the following recommendations are made by D. Huzel and D.Huang in "Modern Engineering for design of liquid propellant rocket engines"[9]. The recommended safety factors are categorized into three scenarios.

Appendix J: Bill of Materials (BOM)

Table 6: Bill of materials

Item	Description	Drawing#/Part#	MNF/OEM/SPL	QTY	Material [$]
1	1/4in fuel line pipe	SS-T4-S-049-20	SWAGELOK	1	$19.80
2	1/4in oxidizer line pipe	SS-T4-S-049-20	SWAGELOK	1	$19.80
3	Ultra-Torr Fitting Tee Connector for 1/2" Tube OD	SS-8-UT-3	IMS SUPPLY	7	$1,224.93
4	Ultra-Torr Fitting Cross Connector for 1/2" Tube OD	NOT FOUND	NOT FOUND	1	$98.63
5	304 Stainless Steel Body Solenoid On/Off Valve	7902K43	MCMASTER	2	$1,250.00
6	Connector Tube (combustion products return line) SS 316	6	SWAGELOK	1	$10.70
7	Exit Outer Tube (tube that combines the fuel with the combustion products) SS 316	7	SWAGELOK	1	$5.35
8	Spark plug	SKU #256750	BOSCH	1	$8.99
9	304 Stainless Steel Body Solenoid On/Off Valve	7902K43	MCMASTER	2	$1,250.00
10	Connector to Solenoid Valve (small tubes between solenoids and Swagelok fittings) SS 316	9	SWAGELOK	4	$5.35
11	20 CF Steel Cylinders		Certified Cylinders	2	$160.00
12	Chest freezer	3846K313	Hardware store (Home Depot)	1	$300.00

13	Pressure sensors	3001C-750	MCMASTER	4	$56.60
14	Pressure relief valves	47065T101	CGV	2	$204.00
15	80/20 Framing		MCMASTER	20 ft	$97.52
16	80/20 Corner brackets	47056T236	MCMASTER	26	$205.92
17	check valves 1/2"	7746K41	MCMASTER+I23	8	$304.16
18	Needle Valves	7781K25	MCMASTER	2	$43.92
19	Bottle CGA to NPT adapter		Millipore Sigma	2	$58.00
20	Burst discs	4412T234	MCMASTER	2	$490.00
21	Pressure Regulators	4677K55	MCMASTER	2	$405.74
22	thermocouples	3856K911	MCMASTER	2	$51.56
23	Pressure Gauges		TBD	2	TBD
24	Ethylene Gas cylinder		Air Liquide	1	$182
25	Nitrous oxide cylinder with dip tube		Linde	1	$450
Total					$6902.97