Progress Towards Hotfire of a Student-Built Liquid Bipropellant Rocket Engine

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Tartarus, **founded in 2017, is a student liquid rocketry team formed as a project under the Space Hardware Club (SHC) at the University of Alabama in Huntsville (UAH). At the beginning of its lifecycle, the project's goal was to develop a liquid-fueled rocket capable of reaching 30,000 feet at Spaceport America Cup. Then in Spring of 2023, the team held a hotfire TRR for the engine developed for said rocket. The feedback provided at the review revealed many shortcomings and issues with the engine which ultimately led to a total rescope of the project going into Fall of 2023.**

Since then, the current mission of *Tartarus* is to develop design tools and a reliable testbed for long-term engine development and testing. This shall be achieved with the team's workhorse engine "Prometheus." The engine is rated to 280 pounds of thrust utilizing an ethanol and liquid oxygen propellant mixture. The engine will be tested on the team's custom mobile test stand (MTS) which underwent a critical design review (CDR) on January 17th, 2025. The test stand has been designed to be installed on a trailer for easy setup and breakdown to facilitate quick engine testing. As of now, the team has begun assembly on the stand and the engine. The team has also been developing a new in-house control system which shall undergo a critical design review of its own in early February.

In order to facilitate this level of development, the project's management has managed to make connections with industry and other student liquid rocketry teams while also utilizing new tools such as a work breakdown structure (WBS) and a product breakdown structure (PBS) to keep the team on track. In this paper, the authors shall detail the current progress the team has made towards their hotfire. Topics included are the engine, the test stand, the control system, safety tools, and management tools. As of now, the team is well on its way to achieving the hotfire date of May 9, 2025.

I. Introduction

Tartarus is a student-led, liquid rocketry research and development project at the University of Alabama in Huntsville. The project is part of the Space Hardware Club within the university. The purpose of the project is to provide opportunities for hands-on experience in developing small-scale liquid rocket propulsion systems. Since 2023, the team has been hard at work developing a custom mobile test stand, a custom control system, a verification engine known as *Prometheus,* and more. This paper will serve as an overview of the project's structure, the various subsystems created within the project, and managerial/safety tools used to help facilitate the project's operation.

II. Project Overview

When rescoped in 2023, the project's operation lifecycle was divided into three phases. The goal of Phase 1 is for the team to design, analyze, manufacture, and hotfire a testbed engine. The engine will verify the design skills of the team and the various models and programs created to develop it. The engine test will also verify the successful operation of the team's long-term mobile test stand that is intended for use in future engine tests. This engine shall never see a flight vehicle. Once Phase 1 is complete, the team will move forward into Phase 2, or the ongoing experimentation phase. Here, the team will experiment with various new engine designs. New design choices can include new methods of cooling, new engine materials, increased thrust capabilities, and more. This phase, effectively, does not have an end and is intended to be the mainstay of the project. Phase 3 would occur parallel to

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Phase 2 once the team has developed confidence in their design skills. The goal of Phase 3 is to compete in the liquid rocket division in Spaceport America Cup. The team could participate alone or in collaboration with another project in the Space Hardware Club. Regardless of the outcome of the previous point, the team would develop a liquid-fueled rocket with a custom payload. This competition could be participated in multiple times, so the team could improve and increase the complexity of their design. With all of this said, the team is nearing the completion of Phase 1. The verification engine, also known as *Prometheus*, is set to fire during the four day testing period of May 9-12 of this year.

In order to complete such a difficult task, the project members are split into four separate subteams: propulsion, fluid, controls, and systems engineering and operations. The propulsion subteam is responsible for designing and modeling the team's engines. This subteam makes use of programs such as Matlab, Ansys, and Openfoam for simulation purposes. The Fluids subteam is responsible for designing, manufacturing, and testing the ground support equipment. This subteam is currently developing the project's Mobile Test Stand which shall be discussed later. The Controls subteam is responsible for recording and controlling data and electronics on the test system, including wiring, designing, and integrating all necessary electronic components. The Systems Engineering and Operations subteam is the team's managerial team responsible for assisting upper management with project timeline, scheduling, and safety analysis. Figure 1, shown below, is a flowchart of the project's hierarchy with each of the previously mentioned subteams.

As mentioned earlier, *Tartarus* is currently in Phase 1 of its lifecycle. The engine that will be used to verify the team's designing models is called *Prometheus.* The hotfire of the engine will also be a collective test of the team's mobile Test Stand and custom control system. The details regarding each of the previously mentioned subsystems are shown below in the next three sections. The first of these sections is the *Prometheus* engine and igniter.

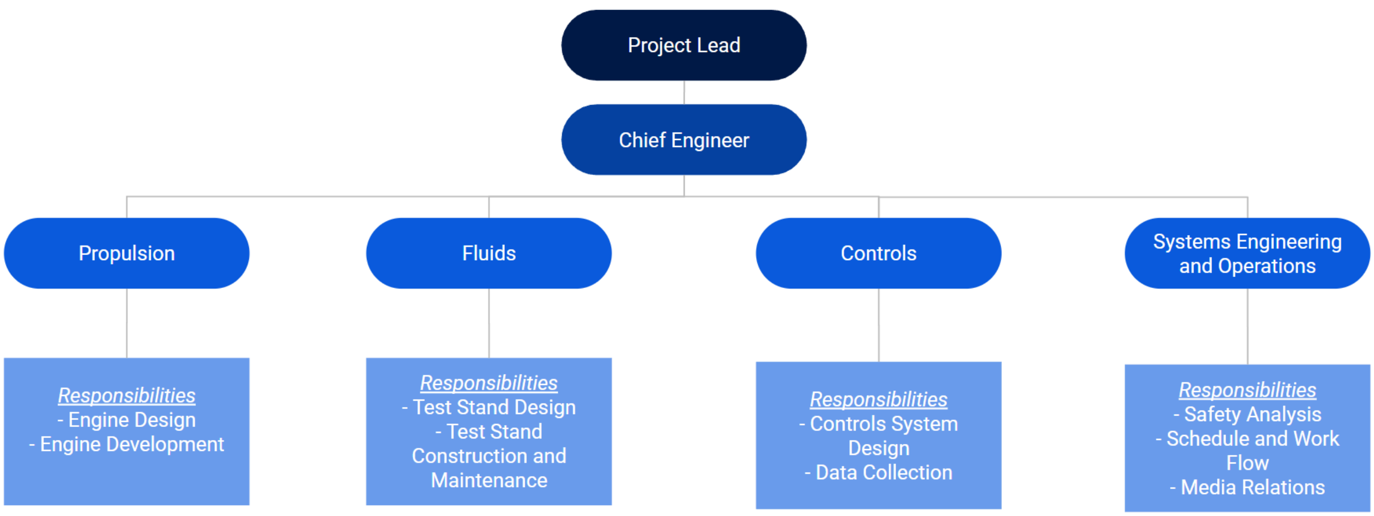

Fig. 1 ***Tartarus* Team Hierarchy**

III. Propulsion Developments

A. *Prometheus* Engine

The *Prometheus* engine is a low-efficiency, low-thrust verification piece. It is designed to be underpowered on purpose to make sure that our new test stand does not encounter any excessive forces during firing on its first test. *Prometheus* being underpowered also ensures that the engine can be fired multiple times reliably. The team plans to test this engine multiple times; therefore, it is paramount to assure that the engine can be fired safely without the need to repair it. Now, on to the engine's specifications.

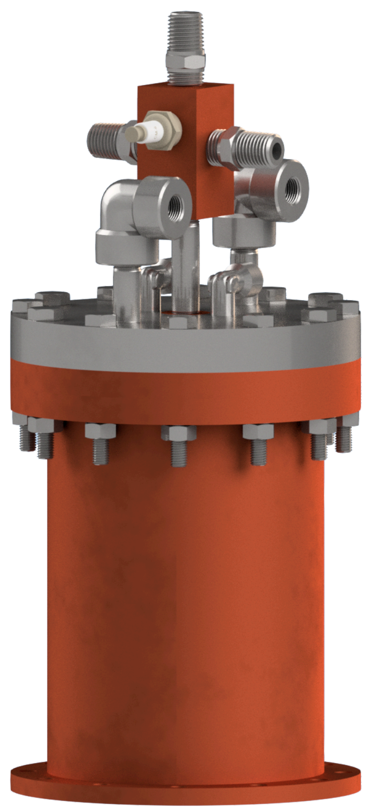

Fig. 2 *Prometheus* Engine Model

The propellant mixture being used in *Prometheus* is denatured ethanol and liquid oxygen. This propellant mixture was chosen due to the familiarity of the propellants in industry. It is a very common propellant mixture used by other student teams. This engine is rated to produce around 280 pounds of thrust with a specific impulse of 212 seconds. The oxygen/fuel ratio is set to 1.4 with a chamber pressure of around 278 psi. The nozzle is made out of copper 110 as well as the bottom half of the injector. The top half of the injector is stainless steel 303. The engine is cooled via an ethanol boundary layer sprayed at the walls of the nozzle. The copper nozzle also assists in cooling with its high thermal conductivity.

The injector, as mentioned before, is made up of two halves: the top half being stainless steel 303 and the bottom half being copper 110. The bottom half was chosen to be copper to avoid any hotspots that might occur during combustion. The injector consists of 8 oxygen and 8 fuel orifices in an unlike doublet configuration. Along with this are 16 boundary layer cooling orifices aimed at the wall of the nozzle. A cutaway of the injector can be seen in figure 3.

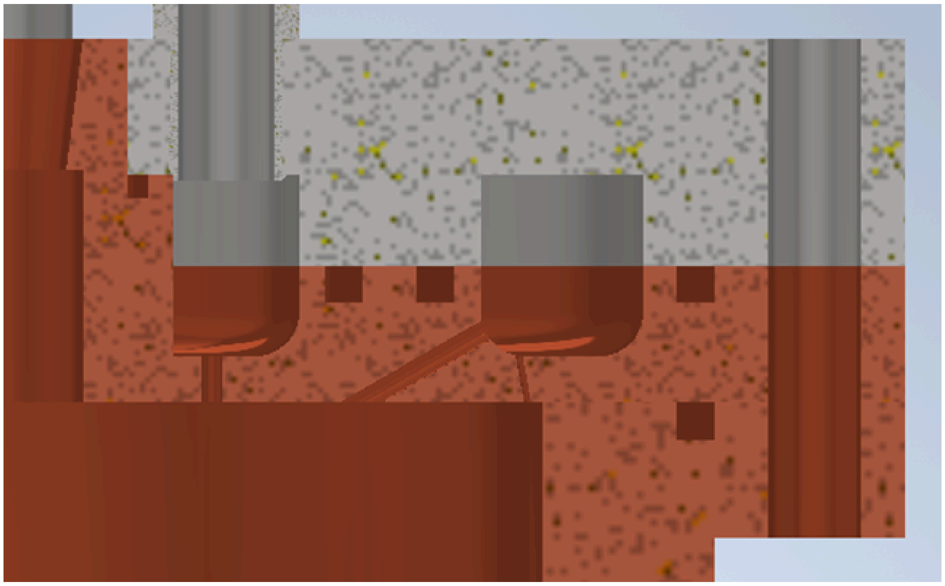

Fig. 3 ***Prometheus* Injector Cutaway**

B. Engine Igniter

To ignite the engine, the team decided to design a propane and oxygen fueled torch igniter. A torch igniter was chosen over a solid-fuelled igniter due to its reusability and the fact that it reduces the chances of a hard-start. As seen in figure 1, the igniter is placed on top of the injector. This way, the ignition flame reaches the primed propellants at the first moment of mixing instead of further down the nozzle. This way, the propellants will not ignite beyond the combustion chamber, preventing an engine-destroying hard-start. Another factor that is convenient is the ease of preparing the igniter for multiple firings. Instead of having to replace a solid charge, the team can just replace the propane and oxygen tanks that fuel the igniter. These tanks last about three ignitions and only need to be closed after firing is complete. The igniter is designed to create an ignition flame of around 1500 degrees Kelvin. The model and prototype can be seen in figures 4 and 5 shown below.

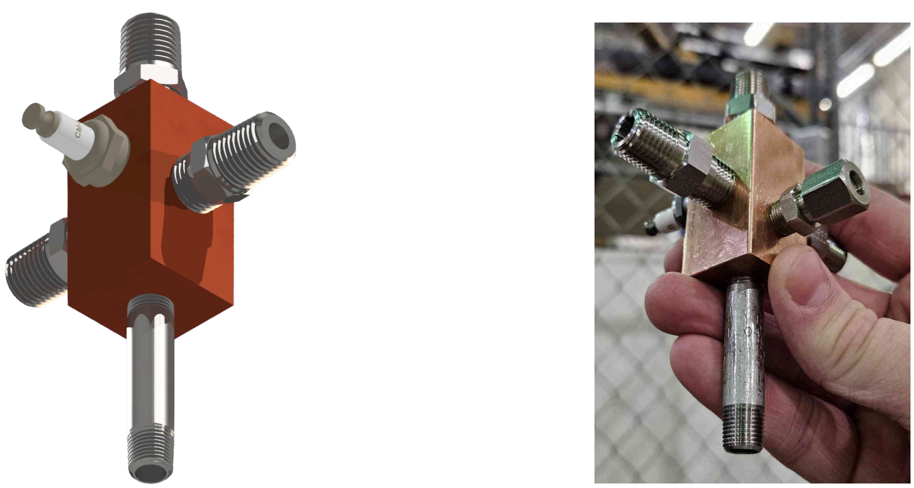

Fig. 4 & 5 Igniter Model and Prototype

IV. Fluid System Developments

A. Fluid System Overview

The Mobile Test Stand (MTS) is the team's custom test stand designed for quick setup and operation. Due to the complexity of a liquid rocket fluid system, the team decided to avoid unnecessarily long setup times by designing the fluid system inside of a trailer. This way, the team can drive to a test site, setup, test, and leave all within one day. The test stand is designed to be easily expandable as well. All of the fluid equipment is rated to an operating pressure of 1000 psi even though *Prometheus* only operates at 415 psi. This way, the team does not have to rebuild the test stand each time they want to test. Below in figure 6 is the render of the entire system. Each subsystem will be discussed separately in the following sections.

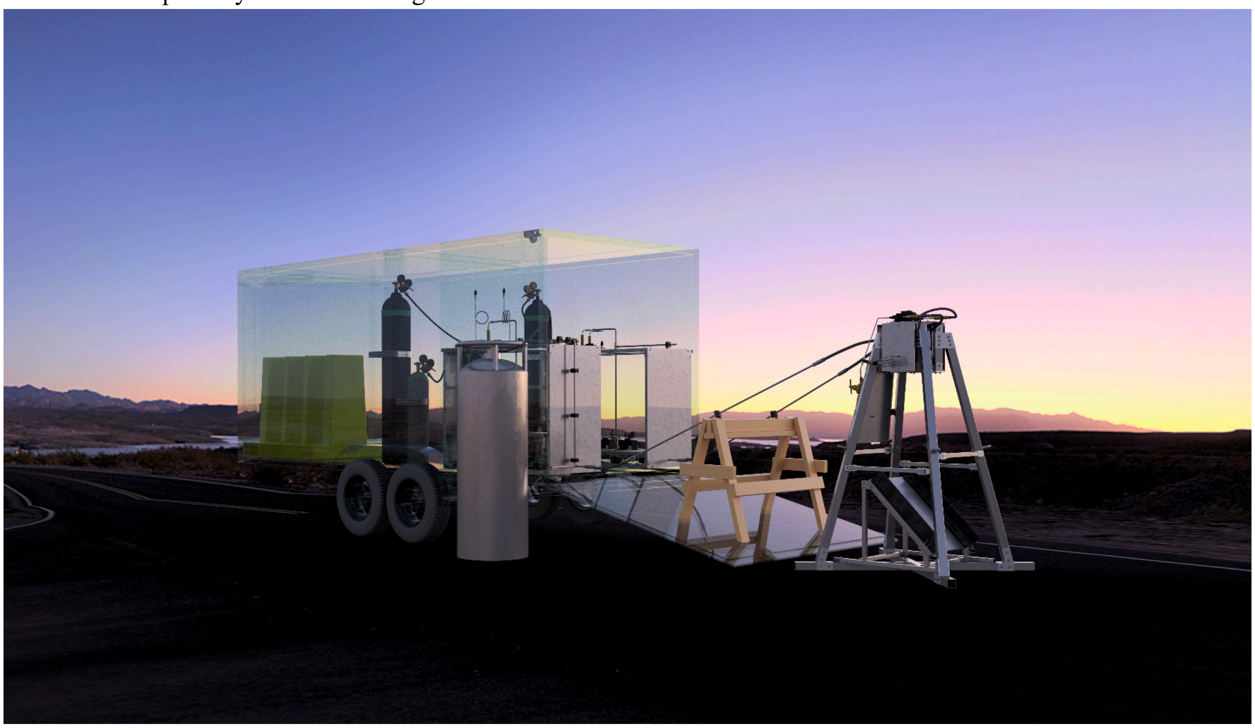

Fig. 6 Mobile Test Stand

B. Ethanol Cabinet

The first cabinet in the MTS is the ethanol/fuel cabinet. This cabinet houses all the required plumbing to store, pressurize, and flow the engine's fuel. The fluid equipment on this cabinet is not rated for cryogenic fluids or temperatures. Attached to this cabinet is the system's muscle pressure panel which provides 100 psi of nitrogen to the pneumatic actuators placed throughout the system. The muscle pressure is loaded via a small air compressor which pumps air into an accumulator tank on the cabinet. In case of an overpressure event, the cabinet houses a blowdown panel which vents at 750 psi which saves the rest of the equipment from damage. For *Prometheus,* the run panel, also on the cabinet, pressurizes the ethanol to 415 psi. It also houses a venturimeter which measures the fuel flow. Below, in figure 7, is a render of the fully-assembled cabinet.

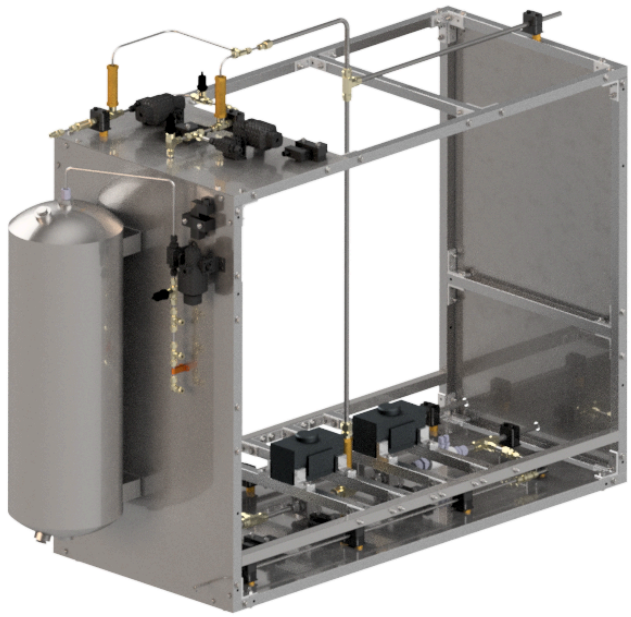

Fig. 7 Fuel Cabinet

C. LOx Cabinet

The liquid oxygen/oxidizer cabinet is much like the fuel cabinet in its construction. It has most of the same hardware, except for that it is rated to operate at cryogenic temperatures. On this cabinet is the purge system which empties the lines of any fuel remaining after a test. The LOx cabinet has the same overpressure contingencies as the fuel cabinet discussed above. Below in figure 8 is the render of the LOx cabinet.

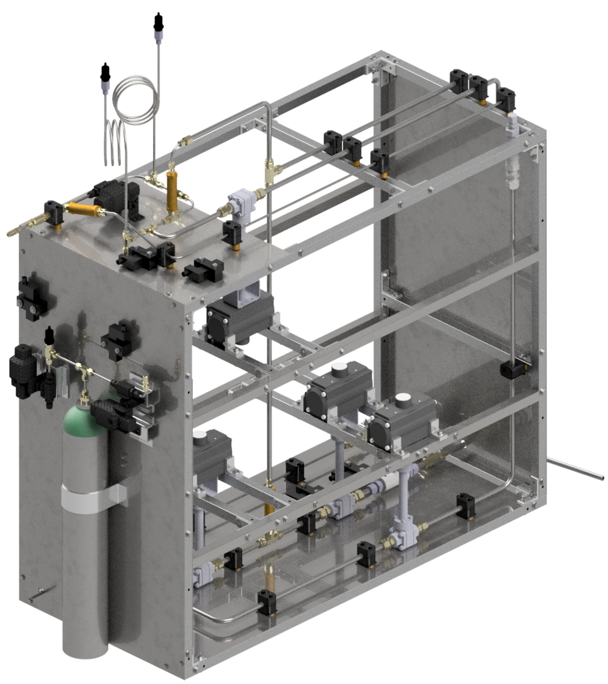

Fig. 8 Oxidizer Cabinet

D. Engine Thrust Structure

To make sure that the engine is stable during firing, the team has designed an engine thrust structure. This structure is generally simple. It is rated to withstand an upward thrust of 1000 pounds. This is also where the igniter's propellant tanks are to be mounted. The engine thrust structure tethers to the ground with steel cables to ensure that it does not move. On the engine housing are two load cells. This is how the team plans on measuring the thrust created by the engine. The engine is also mounted on linear tracks in order to allow the engine to move slightly in the direction of the load cells. In figure 9, shown below, is the render of the thrust structure.

Fig. 9 Engine Thrust Structure

V. Control System Developments

For the control system, the Controls subteam has designed a brand-new custom control system. In order to operate the MTS successfully, the team must be able to remotely actuate valves, read pressures and temperatures, and remotely abort the system in case of an emergency. To achieve this, the subteam has created custom command control and instrumentation (CCI) boards that can receive all the necessary data required to run the fluid system. It can receive pressure and temperature data and display it on a custom user interface. The control system will also be able to communicate over long distances due to the safety radius the team is enforcing. Overall, the control system should be easy to use, reliable, and simple to expand for future uses.

VI. Schedule and Management Tools

A. Establishing Requirements

Established previously, the target date for our Hot-Fire is May 10th, 2025. Ensuring that a small team of student engineers reach such an auspicious goal requires detailed attention to the development of the project timeline. At a minimum, the system needs a few preliminary tests both to ensure operator familiarization with the SOP for the system and establish system verification and validation. The tests selected to meet these requirements were as follows: System Controls Test, Low Pressure Leak Test, Water Flow Test, High Pressure Water Test, Cryogenic Wet

Dress, Hot Fire. The last 3 of which will require a Test Readiness Review to ensure safe operation and serve as a verification of our safety assurances and SOPs.

As the project is student run and operated the realities of the schedule of a student place a barrier on the accuracy of a projected schedule and hinder the permanent establishment of a timeline prior to project initiation. In order to handle the variability of the student schedule *Tartarus* utilizes a Rolling Wave Schedule management plan. With higher level logistics and general timeline block associated for the long term goals of the project, and a higher fidelity plan outlining the current project goals needed to reach the next stage of the project campaign.

To differentiate between what is considered long and short term deliverables for the project, the delimiter of one month is used as a marker. All deliverables which take place after that marker are considered higher-level and only certain aspects of them are specified out. Items which fall under these categories at the time of this paper are: Water Flow Tests, High Pressure Water Test, Cryogenic Wet Dress, and Hot Fire. The planning and logistics for these tests are the major focus until they are within the purview of the state of the project. A requirement for these higher level objectives is establishing a two week buffer period following Test Readiness Review circulation and a formality presentation the week in between. This deadline ensures that cushion time is built into the product timeline and that operation of the relevant tests are outlined prior to the initialization of the testing process and operator training.

All items within the project timeline which are expected to be completed within the next month from the current date are specified out in a combined effort between the project management. The current items within this classification are our Controls Critical Design Review (CDR), Fabrication of the Mobile Test Stand, and Creation of the Standard Operating Procedures for our Ignitor Test, Venturimeter Development Tests, Systems Control Tests, Leak Test, and Water Flow test. The creation of a high fidelity plan for manufacturing and assembly of the Mobile Test Stand and the Controls is primarily doctored through the use of our system management documentation and are updated by project management and leadership.

B. Gantt Charts

In order to organize the higher level system deadlines, the use of project gantt charts for General Deliverables, Fabrication, and Testing are utilized. The General Deliverables outline the overarching system deadlines for maintaining the timeline. These dates are populated based upon other Management tools and are linked together using a manipulation of the Google Sheets cross sheet communication allowing for automatic updating. It serves as the best case scenario timeline and is a marker to be compared with regarding the rest of system development and progression. The Fabrication Gantt chart serves as a visual representation of current required steps for manufacturing of the Mobile Test Stand. It is automatically populated by the respective Responsible Engineers for each system through use of a Google Form which houses all data regarding the manufacturing request. These tasks are assigned to a member of the relevant subteam and then completed either during the general workday for the team, or the subteam workday lead by the relevant Subteam lead. The Testing Gantt Chart is the most hands-on document of the three. It is a live document that tracks all relevant information and dates regarding the development and circulation of Tests, Testing documentation and Presentations, and other relevant design updates that could affect the project. It has the requirement of being updated at a minimum of once a week based upon the communication between project management leadership on the status of the important milestones of the project. Its goal is not to inherently have a wealth of information regarding the project, but to show the relative time distance between deliverables as accurate to the current workflow and progression.

C. Product Breakdown Structure (PBS)

In order to manage the physical components of the project, as well as provide a preliminary mapping of safety states, a PBS is utilized containing all components of the system that will be used. This branch diagram contains all the naming conventions used throughout the project and provides a roadmap for the classification of systems/subsystems within the design. It exists in two forms: poster PBS and live PBS. The poster PBS is a poster containing only the components of the system, and it serves as a visual checklist for the assembly and manufacturing of the MTS. It will be printed out and hung in the work area for the project. The live PBS is a changing document which is populated by members of the Systems Engineering Subteam and is meant to change with the fluid system and have color coordinated documentation which describes the safety state and tolerance of any given component.

D. Work Breakdown Structure (WBS)

In order to organize the tasking, design, development, and testing throughout the team, at the highest level of fidelity of the project the WBS contains the individual required tasks necessary for the current stage of the project. It is populated by Subteam leads and project management to have the necessary next task for each member. When utilized correctly, it reduces the time required to organize workflow for multiple members on a team, as they can instead of asking and waiting for instruction can simply refer to the WBS for tasking. It is linked to all Gantt Charts in some capacity and is the step-by-step guide for the average member of the team needed to complete work towards the completion of the project purview. For future implementation, to ensure maximum understanding of the current state of lower level tasks, weekly automatic updates regarding the state of tasks will be emailed to the subteam lead responsible for that portion of the WBS.

VII. Safety Tools

A. Safety Analysis Scope

Liquid rocketry is an inherently dangerous field of engineering research and development. The increased hazards and risks associated with the nature of the liquid rocket engine testing environment warrant more stringent analysis of failures. In order to adequately understand the possible hazards present, the effects of these hazards, and the risk possible failures may have, a system was developed within Tartarus to help document and quantify this information. These safety tools are based on existing industry standard practices, adapted to the university student use case. There are several reasons that industry standard tools need to be adjusted for use on a student team. The primary limitation the student team environment brings is the frequent turnover of students graduating, as well as a limited timeline due to students being full time with classes. This means that these tools need to be simplified to be usable by most students as well as be implemented effectively without causing major timeline slip. The primary tools that Tartarus uses in their safety plan consist of: preliminary hazard identification and analysis, failure modes and effects analysis, and operating procedures. These all work in conjunction with standard rules and safety practices for testing such as PPE requirements and known best practices. There's two main categories of safety, system safety and process safety. System safety analysis physical hardware on a design level to analyze failure and hazards that components within a system can cause. Process safety covers procedures, environmental hazards, personnel safety, and any possible risks associated with operating or building the hardware.

B. System Safety Analysis

A critical new system that has been implemented into the Tartarus design work flow is the inclusion of system safety analysis. This analysis is conducted to verify the safety and risk of any designed for use hardware systems. System safety analysis uses a workflow of hazard analysis, FMEA, and risk analysis to individually review each critical component in a system to assess its possible impact and likelihood of failure, and determine whether a certain component is safe for use within a system. The outline of the system safety analysis workflow is shown in figure 10.

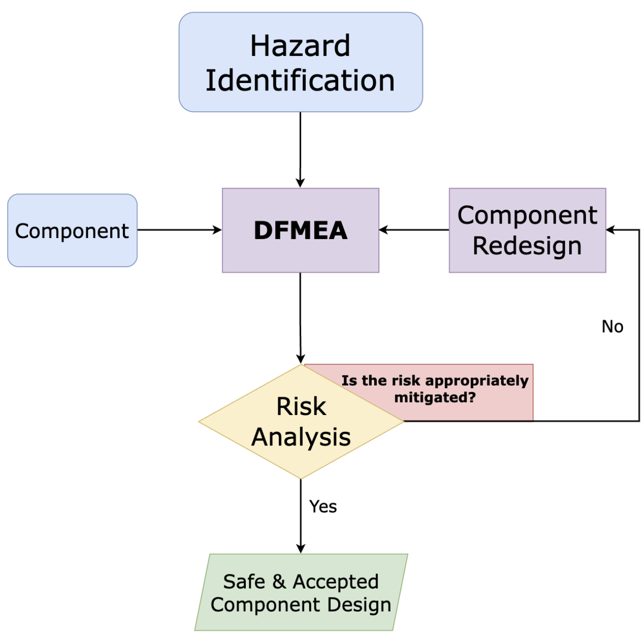

Figure 10. System Safety Analysis Workflow

The system safety analysis behind with preliminary hazard analysis. This step takes a high level overview and assesses all possible hazards that could be present within the system. The definition of a hazard used for this analysis is a potential source of harm or damage. Substances, events, or circumstances can constitute hazards when their nature would potentially allow them to cause damage to health, life, property, or any other interest of value. This includes things like slips and trips, fires, pressure loss, and many others. This step is done to help whoever is conducting the analysis in identifying possible effects of a component failure, as well as assess the risk of the hazard occurring.

The next step in the system safety analysis is the DFMEA (Design Failure Modes and Effects Analysis). This tool is used to analyze every critical component within a system. A critical component is identified as a part with a unique use within the system. This covers components like valves, tanks, and specific structural components, but not every individual fastener. This truncated analysis is done in order to ensure that FMEA worksheets can be made in a timely and effective manner. The FMEA worksheets are based on industry standard formats for FMEA review (FMEA worksheet). The worksheet contains documentation that is in line with used system engineering tools like a PBS in order to effectively track the integration of the component within the system. Every critical component has its own specific FMEA worksheet with multiple failure modes on it. In order to avoid possible bias in the FMEA of a component, the owner of the worksheet cannot be the owner of the designed system. The worksheet is shown in figure 11.

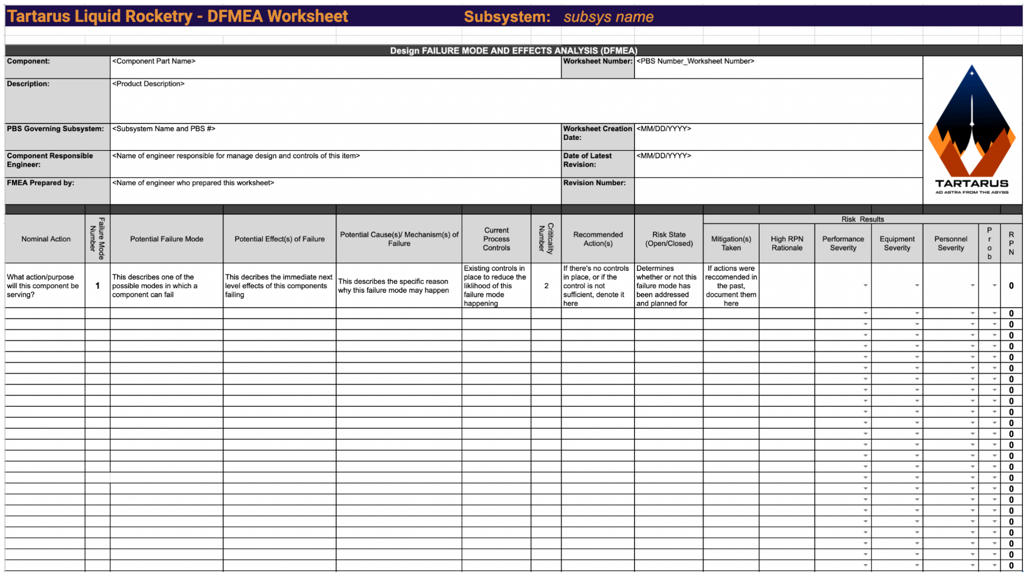

Fig. 11 DFMEA Worksheet

The final step of the System Safety Analysis is the use of risk analysis to assess the likelihood and severity of a failure mode within each worksheet. This step is conducted when each failure mode is entered into a FMEA worksheet. The risk analysis uses a standard risk matrix template, provided by NASA, multiplying an assigned probability and severity of a risk occurring giving a final RPN (risk priority number). The probability and severity values are assigned on a range of 1 to 3. These values are truncated to 3 instead of the traditional 5, as the fidelity of reliability data obtained in a student is more limited than the rigorous testing and sampling that can be done in an industrial setting to properly obtain failure probability values. If the RPN falls below 3, the existing mitigations are considered safe and accepted. If the RPN falls within 3 or 4, the component is referred back to the design owner to see if additional mitigations can be put in place to reduce the RPN. If no more practical mitigations can be put in place the design is sent to the Chief Engineer for final review and acceptance of the risk number, and the justification for acceptance documented in the FMEA worksheet.. If the RPN is 6 or greater, the risk is deemed too high and the component must be fully re-designed or replaced until the risk is reduced to an acceptable level. The main goal of this process is to get an additional set of eyes on a component's design to ensure that there are no oversights in the consequences of its possible failure.

Once the component design has gone through FMEA and risk analysis, mitigations may have to be put in place. Mitigations are either design or process steps that can be taken to ensure that the probability of severity of a risk occurring are reduced. This process is repeated until an acceptable RPN is obtained. Once an acceptable RPN has been obtained the component design is considered safe for use within the system.

C. Process Safety

The process safety within Tartarus takes the form of rules, training, and procedure to reduce the likelihood and severity of risk. Testing operations are often the place with the highest risk, and thus an extensive test preparation packet is included for all major tests the MTS must go through. The TPP is a repository of all relevant information needed for a test, including designs, FMEA worksheets, and a thorough standard operating procedure.

The standard operating procedures for Tartarus are a thorough method of ensuring that risks caused by operator error are reduced. SOPs written for tests will include clear operator roles and their responsibilities to maintain a strict hierarchy in tests. The procedure itself is broken down into every individual action an operator must execute during a test, like which exact valve needs to be opened or sensor read. Before any test is conducted a full walkthrough and dry run is conducted with all the operators to gain familiarity with the procedure before it is used.

Another form of process safety used to reduce human error is extensive training for anyone using equipment. This includes a high pressure bottle safety training and checkout procedure, which ensures that someone who is familiar with commodity bottles is always responsible for the use of them during an operation. In addition to that, multiple operators and managers will have CPR and First Aid training. Any operators that will be assigned to cryogenic loading will undergo a cryogenic safety training program before any cryogenics are handled.

The implementation of stringent process safety steps like this help reduce any possible mishaps from occurring due to a lack of knowledge or a miscommunication between personnel. This combined with System Safety Analysis greatly helps in ensuring that the team has put thorough effort into understanding the true possibilities and outcomes of mistakes or failures, better preparing the team for anomalies and helping reduce risk.

VIII. Industry and Student Connections

Throughout the lifetime of the project, we have made new contacts that have greatly assisted in our progression. The first of these connections is the line of communication developed with the *Yellow Jacket Space Program* (YJSP) of Georgia Tech University. After meeting in Spring 2024, we have since created a channel in which we can discuss topics like design changes and more. This makes getting feedback a lot faster as we do not have to solely rely on communicating with industry professionals. Due to the low number of local student liquid rocketry teams in Alabama, having YJSP as a reliable contact has proven to be invaluable.

The second of our connections is a company called *Alloy Valves and Controls* or AVCO. AVCO is an industry supplier of liquid oxygen-rated valves and other fluid hardware. They have sold valves to SpaceX and Blue Origin while also providing to student teams like ourselves and YJSP. In the summer of 2024, they reached out seeking to support us by providing either low-cost or free LOx valves. This donation will save us thousands of dollars in industry cryogenic fluid equipment and we are grateful for their support.

IX. Conclusion

As of this paper's creation, the team is in the middle of assembling the mobile test stand. More specifically, the team has just finished assembling the fuel fluid frame. Work that is expected in the upcoming months include preparing logistic information to present on test readiness reviews, machining the *Prometheus* engine, assembling the control system, and performing subsystem verification tests. There is still a lot of work to be done on the system before it is ready to be fired; however, the team is confident that they will hit their target hotfire date.

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