Update on the Student Development of a Liquid Bipropellant Rocket Engine

Elias Perez[1], Michael Johns[2] and Jeffery Reeves[3]
The University of Alabama in Huntsville, Huntsville, Alabama 35805, USA

Founded in 2017 as a part of The Space Hardware Club at The University of Alabama in Huntsville, The Tartarus project started as a student-led endeavor to launch a nitrous oxide and ethane fueled rocket to 30,000 feet to compete in the Spaceport America Cup. Since then, the team has made many changes in design, scope, and mission, and this paper will serve as an update on the team's progress as well as give detailed explanations on the changes that the team has made to its plans and scope and why these changes were made. Many factors impacted the projects previous design, and after the team decided to rescope in spring 2023, the parts of the project that were impacted the most include the team's propellant choice, the design of the engine and injector, the design of the test stand, and the overall scope of the team. The team has abandoned the goal of being a Spaceport America Cup team in favor of being a team dedicated to the research of liquid propulsion systems. With that change of scope, the team has also adopted a three phase plan to slowly ramp up production and testing of liquid propulsion systems, in hope to more gently ease the team into testing of these devices and to create a strong foundation of knowledge to build off of as the team expands and goes through its generational cycle.

I. Introduction

The Space Hardware Club at The University of Alabama in Huntsville is a student organization dedicated to giving students the opportunity to be involved with hands-on hardware and software engineering experience through participation in various aerospace related projects. The club currently has 14 projects spread across 5 different programs: Autosat, Balloonsat, Outreach, Rocketry, and Spaceflight. Tartarus is one of the projects under the Rocketry Program, with the goal of providing experience in the realm of liquid bipropellant propulsion. The Tartarus project was founded in 2017 and originally was intended to be a Spaceport America Cup team, planning to launch a liquid rocket in the 30,000'-student researched and designed category of the competition. Since then, the project has gone through many different phases and leadership cycles, and the project has changed significantly since its conception.

In the spring of 2023, the team underwent a significant rescope following years of struggling to meet objectives. The rescope aimed to correct all the problems that were causing the team to have difficulty moving forward in their plans, and this paper will go into significant detail about all the major changes that were made during this rescope and the reasoning behind making these changes.

II. Project Constraints

As a student project, there are several unique constraints placed on the team that create specific challenges as compared to commercial, government, and amateur rocketry programs. The constraints that we face can be narrowed down to regulatory constraints and technical constraints. As an entity of UAH, we adhere to university set rules and regulations, focused on upholding safety of personnel and hardware. As a student led project, we also face technical

[1] Undergraduate, Mechanical and Aerospace Engineering Dept, erp0009@uah.edu, Student Member, 1401368
[2] Undergraduate, Mechanical and Aerospace Engineering Dept, mjj0027@uah.edu, Student Member, 1424694
[3] Undergraduate, Mechanical and Aerospace Engineering Dept, jgr0018@uah.edu, Student Member, 1424709

challenges surrounding our knowledge and experience base. The combined constraints create weird challenges for the team to deal with, and these constraints have a great influence on the team's design choices.

Propellant logistics are one of the constraints that have had the greatest influence on our design choices. We have to follow the safety and handling procedures that are set by the university, and with certain propellants we face issues with complying with these set regulations. This specifically impacts our choice towards propellants that would require significant conditioning to use; for example, hydrogen peroxide is near impossible to procure on the consumer market in a high enough concentration to use for propulsion purposes, so university teams must turn to distilling it into higher concentrations, which creates regulatory and logistical nightmares. We also must think about where we are able to store our propellant, which in our case is in the UAH machine shop, so our propellants need to be stable at STP, or if we have cryogens, they can only be stored short term as we do not have access to long term cryogenic storage.

We also face general constraints related to manpower and knowledge base. As a university team, we are constantly gaining and losing members, and our leadership team turns over every 2-3 years, so we constantly must deal with the pass down of knowledge from our senior members to younger ones as the senior's graduate. As a team composed solely of students, we also lack a great amount of insight that is gained from industry experience, which is commonly brought up at any design reviews when we present our work to seasoned industry professionals.

The team also faces significant constraints related to our budget. We are incredibly grateful to be supported by the Alabama Space Grant Consortium, who provides the club with a majority of its budget, in conjunction with the UAH College of Engineering and the UAH College of Science. Going through a severe redesign, however, is incredibly expensive, especially when we must buy cryogenic hardware and PPE. Because of this we are having to find ways to cut costs without sacrificing system reliability and safety, and we are also having to rely on external donors to be able to afford things in time to meet our set deadlines.

All these factors put external pressure on the team that greatly influences the design of our system, and this will be seen throughout the remainder of this paper. This causes us to make some decisions that may seem counterintuitive, but we have to make sacrifices on things like performance in favor of safety or budget.

III. Propellant Selection

When the team decided to rescope in the spring of 2023, one of the biggest driving factors was the difficulties we were having with working with nitrous oxide. Nitrous oxide had originally been selected as our oxidizer in 2017 because of its self-pressurizing properties. Nitrous has a relatively high vapor pressure, and the idea was that on an actual rocket, the oxidizer would not need to have any internal gas ullage to push it out of the tank, which would simplify the design and reduce weight of the vehicle. This came with a lot of costs however, and many of them were not seen until much later in the design process. The temperament of nitrous oxide was the greater problem, as its recorded tendency to decompose even under ideal conditions was something that we could just not make work with our safety requirements. To comply with the necessary safety requirements, we would have had to build the system to a factor of safety that we could not do with our budget constraints, and there was a lot of things that we just could not figure out knowledge wise, as there is not very much research done with nitrous oxide and what we could find was mostly 1960s and 1970s era research.

Taking these problems into consideration, we decided that the path forward that gave us the highest chance of making it to a hot fire test would be to change propellants. Looking at a new combination of propellants, we decided that they needed to be decently performing, non-toxic, require no special processing, be easy to store, transport and procure, are compatible with most of the components we already own, and that they have good cooling properties.

For our fuel choice, considering the above characteristics, we considered kerosene, isopropyl alcohol, denatured ethanol, non-denatured ethanol, and ethane. We immediately eliminated ethane because it has less than ideal cooling characteristics. We eliminated kerosene because of its messiness and because it creates some toxic combustion byproducts. Isopropyl alcohol was eliminated due to its toxicity, and we initially eliminated denatured ethanol in favor of non-denatured, as we thought the additives in denatured would affect combustion performance, but after discussions with industry professionals we decided to go with denatured ethanol as it would be cheaper and easier to procure. We decided that this would be a well-rounded choice for our fuel that would be easy to buy and store, cheap, and perform pretty well.

For our oxidizer choice, we considered nitrous oxide, liquid oxygen, and hydrogen peroxide. Nitrous oxide was immediately eliminated for all the reasons already discussed. Hydrogen peroxide was eliminated because it is difficult to procure in high concentration or requires special processing to distill into concentrations high enough to be used, leaving us with liquid oxygen as our oxidizer.

This choice came with its own set of drawbacks, however. Primarily, dealing with cryogens is a large challenge, but it's one that is incredibly documented. One of our biggest deciding factors to go with liquid oxygen was the fact that nearly every university liquid propulsion program uses liquid oxygen as their oxidizer, and they are all happy and willing to share information to help out other university teams. It is a challenge, but it is one that we know a university level team is capable of overcoming. Another drawback of using liquid oxygen is that we must ensure cleanliness of our system to prevent any ox fires, and as of the creation of this paper we are actively developing the ox cleaning procedures, however, the cleaning procedures are risks associated with fluid system contamination are much less severe when compared to the decomposition that occurs when nitrous oxide encounters debris.

Switching propellants has been a change to the team that has greatly impacted the future work of the team. While it appears to be a bit of a step backward to have to completely redesign the system to work with a new propellant combination, we spent 4 years working to overcome the challenges presented by our previous propellants, and since making the choice to change, we have already surpassed the amount the progress we made in those 4 years. Despite the challenges we are destined to encounter with cryogens, we feel that we have a strong network of individuals who can help us with all challenges we may face, and we are now in a much better position to make it to static firing our engine.

IV. Engine Redesign

Because we changed our propellants, it is natural that we would have to redesign our engine to accommodate them, however, there were many more considerations we wanted to make while we were redesigning our engine. Our previous engine was designed to make around 600 lbf of thrust, which is an incredibly high thrust class for a student team's first engine. The engine also consisted of poor performing materials, and the injector design gave poor combustion performance and was incredibly difficult to model. With our new design, we wanted an engine that was lower thrust but still efficient, made of materials that had better thermal characteristics, and that used a simpler injector design.

The redesign that we settled on was a 200-250 lbf thrust engine with a copper combustion chamber and nozzle, and a stainless-steel injector. The injector was simplified to use unlike impinging orifices with an outer ring of fuel film cooling. This simplified the manifolding and would create a better combustion zone with less chance of having recirculation causing hotspots on the injector face. The dynamics of this injector are also much easier to model and predict as compared to the previous design, and this gives us much more confidence in our models.

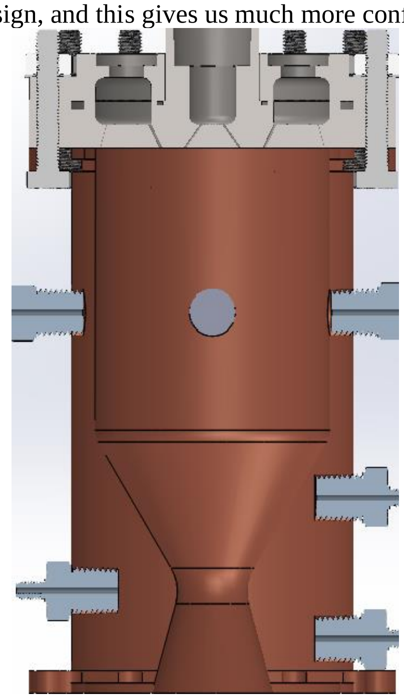

Fig. 1 Cutaway view of new engine assembly.

Another problem we faced with the previous engine was the inability to directly measure thrust. It was capable of taking pressure and temperature measurements in the combustion chamber and along the nozzle but had no way of directly measuring thrust. In our new system, the engine is designed to be mounted to a low friction sled, combined with multiple s-block strain gauge force measurement sensors so that we could get a direct thrust measurement. These will be able to give us accurate measurements of thrust and will allow us to validate all of our theoretical models, giving us confidence in the performance of future systems we design with those models. This sled will also be able to scale up with larger engines, as the strain gauges can measure up to 600 lbs of force, and if needed they can be replaced with stronger ones for fairly low cost.

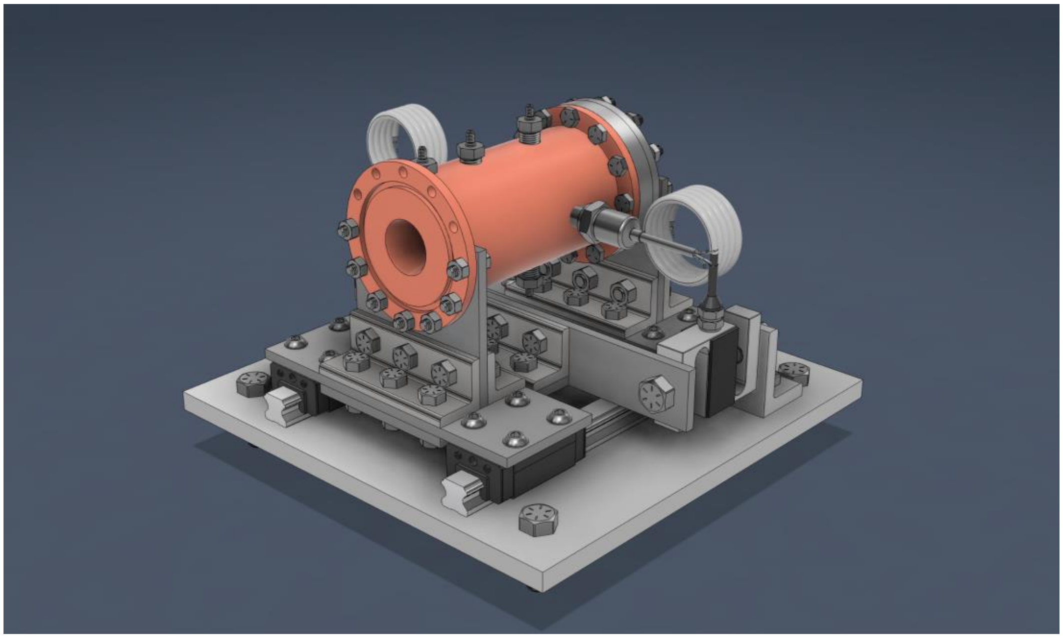

Fig. 2 CAD model of the engine assembly on the thrust sled.

The final engine system that needed to be changed was the ignition system. Originally, our ignitor was a neon sign transformer, and the leads would be routed through the nozzle, inside the combustion chamber and the arc would be used to light a cluster of cannon fuse which would give us about a 4 second window in which we could light our engine. This system was incredibly unreliable, gave us a very short ignition window, and we had a very hard time modeling it and could not prove with absolute certainty that it would provide enough energy light our propellants, which is also party due to our previous propellants requiring a lot of energy to start combustion. With our new design, we have decided to implement a gas torch igniter mounted centrally in our injector. This ignition system will be extremely reliable, has a much longer, almost indefinite, burning time, and it can be easily modeled and proven to provide enough energy to start combustion.

Ultimately, with our new engine design, we are going for a much more reasonable, reliable, and easy to develop and test engine. This engine will act as a much better first step into liquid propulsion testing and will give the team a good foundation to build upon in the future.

V. Test Stand Redesign

In parallel to changing our propellants, we also had to investigate changing our fluid system. Prior to the rescope, our test stand was made of one large station that had the run tanks and the engine, and two propellant loading stands that were connected via six 30 feet lines made of six-foot segments of tubing. Because of this, every time we moved the test stand from where it was stored in the UAH shop to outside the shop where we had our testing area, we had to disconnect and reconnect all these lines, which led to fittings getting stripped and gave us constant leaks in our system. We also had to completely disassemble the entire control system every time it was moved, which led to wires and instruments constantly being damaged. It also was a very long and tedious process to set everything up, and we lost about 5 hours every day we wanted to test due to assembly and cleanup. This led us to want to design a test stand that did not require any disassembly or reassembly for transport, and also one that was designed with simplicity and safety in mind, as our previous system was also much more complex than it needed to be.

With these design considerations in mind, we explored two possible options for our new test stand. Both options were based on the idea of a mobile test stand, where the test stand was completely built onto a trailer. Our two designs differed in what kind of trailer we used. The first one we looked at was an uncovered, flatbed trailer, where our propellant tanks would be mounted on top of it near the tongue of the trailer, and the engine would be at the back pointed behind it. This design had the pro of being lighter and cheaper, but we decided not to go with it because it gave no protection to the components inside. The other design utilized an enclosed trailer, where the entire fluid and control system are contained within the trailer. This is the design we ultimately decided to go with.

Having our entire system built within an enclosed space has a large number of advantages. There is practically no assembly or disassembly required when moving the trailer, and because everything is internal to the trailer there is no risk of weather damage to any fluid or control system components. To make our fluid system work, the team designed a two-piece internal frame structure, shown below as Figure 3. This frame will be mounted directly to the bottom frame of the trailer in order to give it the greatest possible stability. The first piece of the structure is the engine test frame, and it is designed to be the primary structuring handling the forces of the engine. The other piece is the fluid system frame, and it is designed to hold the propellant tanks, the nitrogen muscle pressure bottles, and the components of the fluid system.

Fig. 3 Cut away view of trailer showing internal support frame.

One problem that we had to face with using a trailer was that we did not want to keep our bulk propellant storage tanks in close proximity to each other inside the trailer. To combat this problem, we developed two propellant fill carts, which utilize two separate carts that we put our bulk propellant storage containers into. These carts are kept separate from each other, and during fill operations each of these carts is rolled up to the trailer one at a time, and the run tanks are filled through quick disconnect fittings located on the outside wall of the trailer. This ensures that no personnel must enter the trailer during testing operations.

This redesign of the fluid system and test stand has greatly improved our ability to perform tests and has greatly expanded the number of the testing locations we can utilize, as all that is required is somewhere we can drive the trailer to. This has significantly shortened our SOP, greatly reduced the number of people we need on our red team and is just a generally simpler and safer system as compared to our old fluid system and test stand. This new test stand has also been designed to scale up as the project does and can accommodate up to a 500 lbf thrust engine with no modification, and larger engines with small amounts of reinforcement.

VI. Project Scope

The original scope of the project, as mentioned earlier, was to design, build and then fly a liquid bipropellant rocket in the Spaceport America Cups 30,000-foot, student researched and developed class. This mission was an extremely lofty goal for a team with no prior experience with liquid propulsion or previous participation in the Spaceport America Cup. One of the biggest challenges we faced prior to the rescope was being able to support multiple subteams around all the required areas. We simply did not have the manpower to work on development and testing of a propulsion system, development of a vehicle, and the development of an avionics and guidance system. The scope of all those combined things was too large for a single team to support, and so the team decided that it would be a better fit for the team to narrow down our scope. We wanted to focus on the main thing that made our team unique: liquid propulsion. Our new scope abandons the idea of having an entire launch vehicle, and now we are solely involved in the design, development and testing of liquid propulsion systems. We do this with the hope of creating a team with a strong understanding of liquid propulsion and plenty of experience with propulsion system testing. Using their knowledge, this team would then be able to support other teams, such as by providing a tested and proven liquid propulsion system to another rocket team planning to compete in Spaceport America Cup.

With this change of scope, the team also wants to take a turn toward being more involved in research. Once the team has a solid foundation, we plan on exploring the design, development, and testing of more novel propulsion systems, and we hope that this will enable us to perform more elaborate research in the realm of liquid propulsion, specifically research that can be applicable to other university level propulsion teams.

VII. Three Step Plan

As a part of our change in scope, the team has developed a three-step plan to help us ramp up toward our ultimate goals. The first phase of this three-step plan is the development phase, where the team is working on the development of our design methods, development procedures, and testing procedures. This phase is effectively our way of dipping our toes into the world of liquid propulsion. This phase involves the development of the aforementioned demonstrator engine and the development of our design, development, testing and safety procedures. During this time, we are putting a huge focus on documentation, documenting every step of the design process and the reasoning behind every design decision we make. By doing this, we are effectively creating a "how to make liquid engines" document that will be able to be referenced by every future member of the team, and thus is helping us minimize the amount of knowledge lost with every generation of the project. This phase ultimately sets the foundation for all the team's activities moving forward.

The second phase of the project is going to be a phase of continuous repeated design, development, and testing of liquid propulsion systems. This is the phase where we intend to do the majority of the research, and using the foundation set by phase 1, the team will be able to rapidly design, build, and then test different engines. We expect the team to be able to get on an annual cycle of design, development, and testing, with a new propulsion system developed and tested every year. The intent is for this phase to last indefinitely, and that the cycle of design, build, and test will continue for the remainder of the project's lifetime.

The third phase of the project will either act as a break from phase two or will act in parallel in phase two. With phase three, the team wants to return to the goal of flying in the Spaceport America Cup, and to do this the team is hoping to be able to work with another team at the university that is planning on entering the Spaceport America Cup in the solid propulsion category. The hope is for that team to gain experience with the design and development of the vehicle and avionics systems, and in a few years' time, when they have a proven airframe and avionics system and we have a proven propulsion system, we can mate the two together and have a functioning liquid propulsion powered rocket. Our current timeline for this is about five years in the future, but that is very dependent on our team's progress and the progress of the other team. After this phase is completed by a successful flight of a liquid rocket, the team would then return to the ongoing efforts of phase two.

We think that this three-phase plan will help the team take things one step at a time, which will lead to more consistent progress and will allow us to develop a strong foundation before taking on any huge challenges. One of our biggest prior challenges was trying to accomplish too many objectives at once, so we believe that this is the best solution to break our progress into smaller steppingstones that will allow us to actually make progress and see the growth and development of our team.

VIII. Near Future Plans

Currently, the team is working toward our Critical Design Review which we have planned for May of 2024. Prior to that review, we are planning to conduct a cold flow test of our injector which will most importantly allow us to determine the discharge coefficients of our orifices to improve our models, as well as a test of our torch ignitor. Both these tests will give us valuable data to support our CDR. After our CDR, through the summer, we plan on procurement of our trailer and all other needed parts, and the construction of the mobile test stand. In fall of 2024, we plan on going through a series of leak checks and high-pressure tests on the system, culminating into a wet dress rehearsal of a static fire in late November. Then, the team plans on beginning static fire operations in spring of 2025, starting with a short, 2 second duration static and working up incrementally to a 10 second, full duration burn test.

IX. Long Term Vision

This change of scope is also intended to open opportunities for undergraduate and graduate students at The University of Alabama in Huntsville to gain hands-on engineering experience with liquid propulsion systems. Generally, opportunities to participate in liquid propulsion at the university level are highly competitive and these projects are generally led by faculty or all graduate students. Our team is proud to be completely student led and to be completely open to any and every person who is interested in joining the team. The team wants to provide any student with opportunities to get industry level experience for no cost, helping to develop a more experienced and developed workforce straight out of their undergraduate education. The team already has a long history of members being hired by the most prestigious and competitive aerospace companies before their graduation, and we hope to continue and expand this trend. Most of all, we want to give students the opportunity to take part in something that is meaningful to them. All the members of the Tartarus team are here because we share a passion for rockets and spacecraft and being able to work on the development of our own engine, with the goal of one day being able to create our own smoke and fire.

X. Conclusion

The Tartarus team has faced significant challenges since its creation, but since the rescope we made in spring of 2023 the future of the team has never seemed brighter. It was not easy for the team to decide to scrap all of the hardware he had developed for our prior designs, but it was something that was necessary for the team to do to be able to move forward. The designs we have now chosen are designs that we are extremely confident in and we have used all the lessons learned from previous mistakes to design this new system. Now, the team has record membership and high morale, and we have never been more likely to achieve the goals we have set for ourselves. The Tartarus team is an incredibly unique team, and it faces incredibly unique challenges, but all the members of the team are incredibly driven to accomplish any goal and work through any challenge. All team members share a passion for the realm of liquid propulsion, and it takes a very dedicated individual to sacrifice their weekends and free time to working on a project like this, while being a full-time student. We are excited for the future and can't wait to be able to share the results of our tests in the future.

Acknowledgments

The Tartarus team would like to firstly thank the Alabama Space Grant Consortium for their longtime and generous support of Tartarus and the Space Hardware Club as a whole. Without their support, the club would not be able to do any of the amazing things that they do. The team would also like to thank Blue Origin for their sponsorship of the team in 2024. The team also thanks their Faculty Advisor, Dr. Gang Wang, as well as the many faculty members and industry professionals who have supported the team along the way, including Dr. Richard Tantaris, Mr. Scott Claflin, Dr. David Lineberry, Mr. Preston Jones, Mr. Jim Turner, and Mr. Pravin Aggarwal.