Investigation of Ignition Systems for an 800 lbf Thrust Bipropellant Engine

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The objective of this paper is to develop an ignition system for a student-built 800 lb thrust bipropellant rocket engine. Different ignition methods demonstrate different features, including reliability, ease of implementation, reusability, and efficiency. In this paper, a brief survey is conducted to discuss the pros and cons of candidate systems. Ignition system requirements for the current effort are specified by considering cost, space, and practical concerns. Subsequently, an in-depth discussion on some of the ignition systems is presented. Finally, two ignition systems are recommended in this project. The first method is to use a pyrotechnic ignition source, which leads to a cheap, simple, and reliable solution. The other method is based on a torch-style spark plug igniter to light the liquids as they enter the chamber. This reusable approach requires a more complicated design. Both identified approaches will be explored for the hot-fire test.

I. Introduction

With three years of design and construction, the Space Hardware Club (SHC) at the University Of Alabama in Huntsville has made significant progress on the liquid bipropellant rocket development called the Tartarus project. The goal of the Tartarus project is to compete in the 2021 Spaceport America Cup in the undergraduate Hybrid/Liquid division. A bipropellant liquid concept was adopted to use ethane as fuel and nitrous oxide as an oxidizer for propulsion. In order to prepare the final launch, a hot-fire ground test is required for the rocket engine. The ignition system is essential to enable a successful launch, but the team has not fully mapped out which type of ignition system it will use for both the tests and the launch. Currently, the working idea is to try a pyrotechnic ignition system, but it has not been determined if that is the best system for the engine the team is building. In this paper we review the different ignition systems used in modern propulsion and determine which is the best fit for project Tartarus. In order to determine and understand which ignition systems are viable and which ones are the best design for the project, it is important to have an understanding of the rocket and it's design, as well as the requirements for the competition.

Fig. 1 Current rocket design

The rocket has an outer diameter of about 6.125 inches and a length of 15 feet. It has a dry weight of just under 88 lb and a wet weight of 132 lb. The engine itself is capable of putting out about 810 lbf of thrust, giving it a large Thrust to weight ratio that will lift it to its minimum required altitude of 30,000 feet, as set by the competition guidelines. This means that the rocket does not possess a second stage, meaning that there is no need for any multistage technology and that any igniter design that is used only needs to be used once at ground level. If the ignitor can be detached or blown away, the rocket will not need to carry less weight to altitude. At this point in the

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project, the engine is partially built. A baseline injector is ready for hot-fire testing in late march. The project's current injector uses 3 zones of fuel injection (Fig. 2). Zone 1, marked in blue, is the primary injection zone which creates the impingement point with the oxidizer that is pushed out the middle. The two propellants mix here to create most of the thrust. The other 2 zones are intended to both mix with any stray oxidiser that does not already ignite and to act as cooling, both of which help avoid damage to the engine. The holes are very small, with zone 2 and 3 sharing a minimum size of .018 inches.[1]

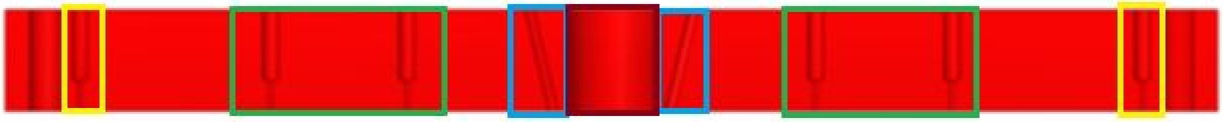

Fig 2. Injector plate cross-section[1]

As the main body of the engine has not been built, there is time for improvement and alteration to the design for different types of ignition systems. The baseline injector and workhorse engine chamber (Fig. 3) have already undergone water-flow testing and hot-fire testing will begin soon to ensure that the engine is firing correctly and that the current injector design is good enough to move forward with the rocket. Because of this, any ignition systems that would need to be built in to the injector or elsewhere in the fluid system must only require minor alterations to the overall design; otherwise the whole injector will need to be redesigned, a process that is not only time consuming but also could invalidate past testing, bringing the project backwards. As such, ignition systems that do not require modifying the injector are preferred.

Fig. 3 Rocket engine cross-section, injector faceplate in red[1]

Tartarus is a student run club project. The organization has limited funding and lacks the advanced machinery a business or better funded organization might have access to. Ignition methods cannot be considered that require a large degree of complexity, specialized machining and design that tends to be expensive. Knowing these criteria, some ignition systems are likely more fitting for project Tartarus.

II. Hypergolic Ignition Systems

Hypergolic propellants are convenient, reliable, and relatively simple to use for ignition. Hypergolics are defined as two substances that ignite spontaneously when brought into contact with each other. This quality is highly useful for many different types of missions, as it means that no ignition system is needed as long as the rocket delivers both fuels to the combustion chamber successfully, there is no risk of ignition failure [3]. This quality also reduces the chance of a hard start, which is what happens when too much propellant pools in the engine due to a delay in ignition. When ignition eventually happens, the buildup causes a small explosion that can damage the engine and prevent successful flight. Hypergolics cause no delay, thus avoiding this problem. The following section describes ways to implement hypergolics into a rocket.

A. Hypergolic fuels

With hypergolic propellants, the mixing of the fuel by the injector becomes the ignition system. There are many prior examples of this approach being successfully used[2]. Hydrazine, which is one of the more popular hypergolic fuels, has been employed in many missions, including the Titan II missions [2], which used some of the largest quantity of hypergolics in any United States spacecraft. These types of propellants are also effectively used in reaction control systems. Some are even capable of being used as a monopropellant if treated properly. Hydrazine in particular has a high specific impulse when used for propulsion, can be stored in a stable manner, and is not a cryogenic fuel, meaning it requires less temperature control.

However, hypergolic fuels are not without their dangers, and in fact are some of the most dangerous fuels and oxidisers commonly used in propulsion. Most hypergolic fuels are extremely ignition prone, as they not only ignite with other traditional hypergolic oxidizers, but they are very likely to ignite when in contact with weak oxidizers and can explode on contact with strong oxidisers. This means these fuels must only be handled in very controlled environments. Hydrazine in particular is dangerous due to its mostly smokeless and colorless flame, meaning it can be hard to identify if a fire has started. The hypergolic oxidizers, on the other hand (specifically N2O4, Nitrogen Tetroxide) are not technically ignitiable. However, when added to many ignitable materials, including common construction materials such as wood, these can cause ignition and increase the rate of combustion of any flame they come into contact with by adding oxygen. Besides their individual properties, both types of hypergolics are highly toxic, as N2O4 can react with the skin to create nitric and nitrous acid, which can cause severe tissue damage. If the vapors are inhaled, it can lead to severe lung damage and even death. Hydrazine on the other hand can cause severe chemical burns and is considered a carcinogen [2].

Because of the above factors, hypergolics are incredibly dangerous, and very specific safety measures should be put in place if using large amounts. The Tartarus team, being a student run club with limited resources and facilities, realized early on that it could not reasonably meet these safety measures and establish a closed environment. In the event of a leak, there would not be sufficient measures in place to successfully prevent the dangerous fire caused by the fuels and the team does not have the protection gear advisable for handling large quantities of these fuels. Due to these restrictions, the team decided against using hypergolic fuels as the primary propellant.

B. Hypergolic injection

Instead of using hypergolic as the main propellant, a small amount of it could be worked into a small ignition device mounted in the injector or combustion chamber. This could either be an oxidising hypergolic that reacts with ethane or a hypergolic fuel to react with the nitrous oxide. This delivery could be done in several ways. In early German V2 engines hypergolic ignition agents were delivered from the bottom of the rocket by inserting tubes through the nozzle and into the combustion chamber[3]. Besides the obvious problems that were covered in the last section, this method would require an awkward structure that would have to be quite compact given the size of the Tartarus engine. In addition, upon successfully igniting the engine for a test, these tubes would get heavily damaged and would have to be rebuilt, wasting money on the parts and time on the fabrication. Mounting them to the rocket structure would alleviate these problems. This also opens up the opportunities for more complex flight mechanics, as it means you can ignite the engine again provided you have fuel left and have extra ignition fluid. A similar system is used in many modern rocket engines, including SpaceX's Merlin 2 engine. The problem with using such a system in the Tartarus's rocket is that it adds a lot of inert weight and requires an additional tank and onboard fluids system, increasing complexity for very little gain. While this method is useful for modern large scale rockets which need to reignite multiple times, it serves very little purpose in our application.

C. Hypergolic Slugs

Considering the problems discussed with using hypergolic fuels as primary propellant and adding a full fluids system just to handle ignition, there is only one reasonable remaining way to use hypergolics - hypergolic slugs. Put simply, a hypergolic slug is a small cartridge filled with a propellant that is hypergolic to one of the main propellants but not the other. The cartridge is mounted somewhere in the final propellant lines of the system which it isn't hypergolic to. Two burst diaphragms are placed at either end to contain the slug[3]. When the system activates and fuel starts running, the diaphragms will burst from the pressure. This allows mixing the fuel with the hypergolic, and then when the fuel mix and oxidizer meet in the combustion chambers the hypergolic formula will start ignition. The flame will be sustained by the normal propellant mixing. This is likely the safest method to use hypergolics, as once they are in the cartridges there is less risk in handling them. In most of the diagrams and examples found during our research, the most common types of these were fuel hypergolics that would ignite when mixed with oxidizer, and a common location of these cartridges was embedded in the injector itself (Fig. 4).

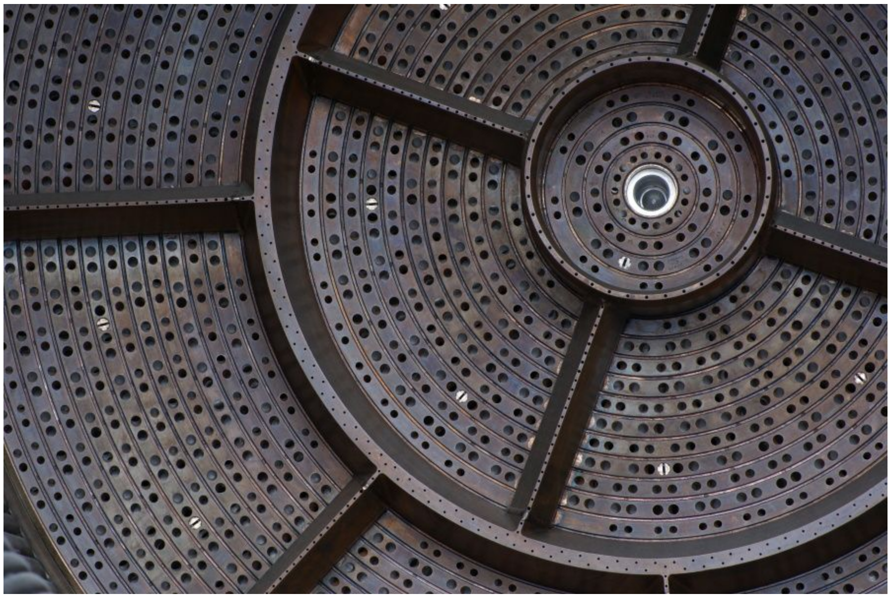

Fig. 4 F-1 Engine with hypergolic cartridges. Cartridges are the white circles that look like screws [4]

Because of the small design of our injector holes, a hypergolic slug system would not be effective. However, a system where the cartridge is mounted farther up the fluids system could potentially work. There is not enough information at this stage of research to know if the spreading out of the hypergolic by the injector would lower it's effectiveness at igniting the engine. Further testing would have to be carried out. This testing would also require a redesign of the test panel, which could take a lot of time away from testing our engine and would certainly not be done before the first hot-fire test. In addition, the remaining safety precautions for hypergolics will likely prevent the team from using these in the foreseeable future.

III. Catalysts and Nitrous Decomposition

Nitrous Oxide has properties which give a unique option for engine ignition. Once it reaches a certain temperature, the propellant will decompose into its components of nitrogen and oxygen and release enough energy to ignite surrounding propellants. This temperature is normally higher than the temperature the oxidizer would reach unless already in contact with a flame. However, if a catalyst was introduced to the system to reduce the activation energy of the propellant, the nitrous oxide could be led to decompose on command and give off the heat required to ignite the fuel-oxidizer flame [8]. The main problem with this system comes with finding a way to catalyze the decomposition reaction. A research team has previously demonstrated the possibility of using a catalyst system to ignite a Nitrous-Propane engine, which could easily be converted to an ethane system as well. However, the system wasn't simple, and it wasn't very reliable either (mostly due to its developmental nature) [6]. The added weight of a system to light an engine with nitrous decomposition, combined with the technical challenge of implementing the system, make this method not worth further consideration.

IV. Recommendation One: Pyrotechnics

Pyrotechnic igniters are, in the simplest sense, electronically activated explosives. Designed to burn slowly, these igniters make a flame that burns hot enough and lasts long enough to cause the propellant in the ignition chamber to ignite. These igniters are located in the combustion chamber and are activated by the signal to an electric pyrogen to begin to burn. There are generally multiple units aimed radially outwards from the igniter to get better heat distribution. These igniters are placed into the combustion chamber either by mounting them to the injector plate, or by inserting them into the chamber from the bottom (see fig. 6) and suspending them there with a piece of wood. This awkward support structure is generally blown away by the force of the engine once combustion starts. In modern rocket propulsion, pyrotechnic igniters don't scale up well and are mostly obsolete. They are also one-time use and unable to support repeat starts. If they are supported from the bottom, they also run the risk of damaging the thin walled nozzle of the engine, posing a great risk. These ignitors also struggle to function in the cryogenic conditions used for fuels like liquid oxygen and liquid hydrogen, leading to delayed ignitions or even duds. This can waste time or cause a hard start and risk damaging the engine [3].

The project Tartarus engine is small scale, meaning it doesn't have room for anything too big, and the combustion chamber is small and heat is delivered to only one place. The Tartarus engine only needs to ignite once. Therefore, the limitations of pyrotechnic igniters are inconsequential to the project. For our application, the easiest method to use this igniter would simply be to mount it to a support structure in the combustion chamber. The injector doesn't need to be modified and when the structure will be blown away when the engine ignites. This eliminates the weight of the ignition system , increasing the final rocket launch thrust to weight ratio. This is likely the overall best and simplest solution for the Tartarus ignition system

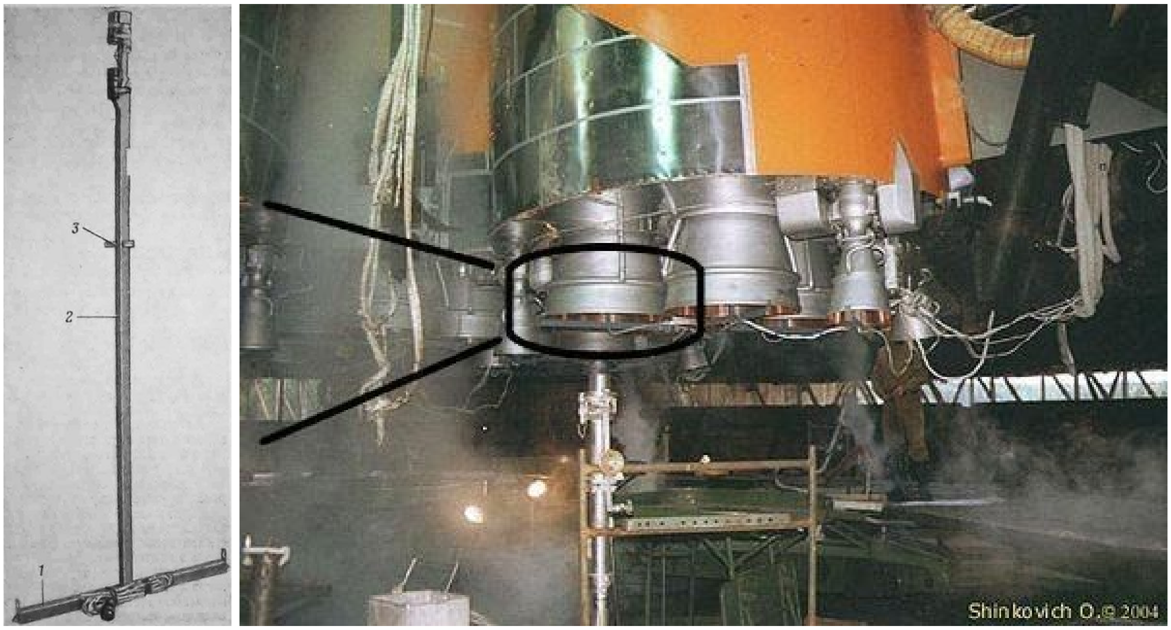

Figure 5 The ignition system on the Soyuz uses a pyrotechnic igniter (left image) mounted in the combustion chamber by a support structure attached to the Nozzle (circled in the right image) [5]

V. Recommendation Two: Spark Plug Igniters

Traditional spark plug igniters involve a spark plug located inside the combustion chamber, which creates an arc of electricity used to ignite the propellants upon flowing into the combustion chamber. This simple system can be very effective if implemented properly. However, it has some serious drawbacks, especially on larger engines. An engine starts better when the spark is placed in a perfect place where the propellant mixture will light evenly across the entire injector face upon startup. If the propellants light unevenly, combustion instability can become a problem, leading to lowered efficiency or even a damaged engine. In other cases, the engine may not even light at all simply because the area affected by the spark didn't have any fuel (or oxidizer) due to uneven mixing [3]. One of these systems could be useful for small maneuvering engines which have to be relit often. This system would need some modification to make it useful for a main engine.

A torch-style spark plug igniter is a variation of a standard spark plug igniter which fixes some of the problems. The spark plug is placed in a small chamber off of the main combustion chamber. In order to ignite the main engine, small amounts of propellant are pumped into the offshoot chamber and are then ignited by the spark plug, creating the initial flame. The flame of that reaction then runs into the main chamber, proceeding to ignite the initial propellants as they enter the chamber. Often the flame is left running after initial engine ignition, giving the system its blowtorch-like behavior. Depending on the fluid characteristics of the engine, it can be left running only a short time [7], or even throughout the duration of the engine's operation. The torch typically runs very fuel-rich, making the combustion less heated and allowing the torch-chamber walls to go without cooling [3]. This system greatly improves upon a standard spark plug igniter, as the sustained flame of the small chamber has a much easier time lighting the flame of the main chamber.

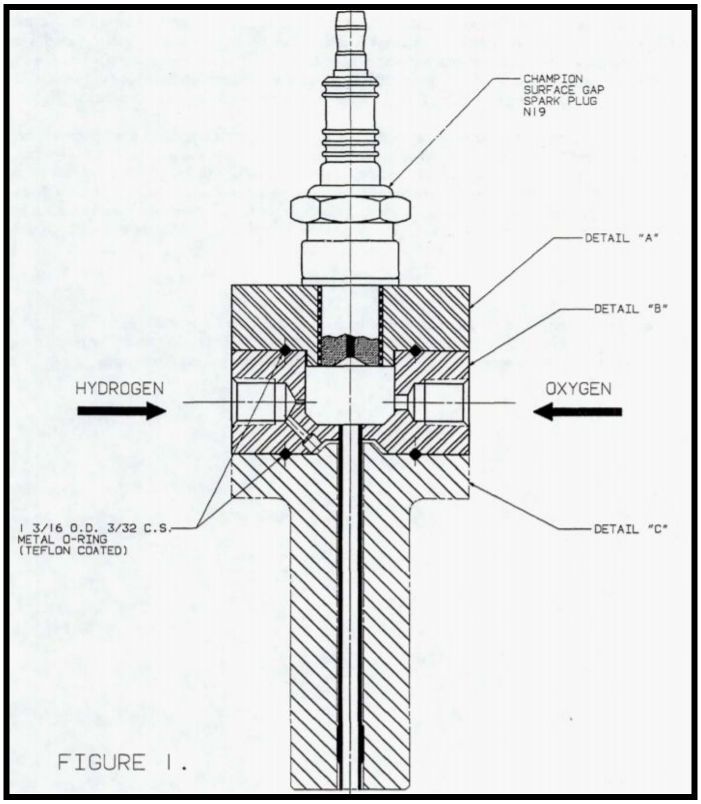

Fig. 6 A Hydrogen-Oxygen torch igniter. The Propellants are pumped in through the inputs into the small chamber, where they're lit by the spark plug on the top. The lit propellants flame into the combustion chamber through the bottom output. [7]

One of the greatest benefits of using a torch-style igniter would be its reusability. It would be more difficult to implement than a pyrotechnic stick, and would require the engine's piping and injector to be set up specifically to accommodate its presence. However, the ignition chamber could potentially go through a hundred uses before refurbishment [7] (possibly less due to the engine's propellant choice). Additionally, using a torch igniter could give the injector performance advantages over the current setup. However, any design which would require a redesign of the injector would likely not be worth the trouble, and the addition of the piping necessary to support the ignitor would also require a redesign. Despite this, if it was found to be feasible for a nitrous-ethane engine, the torch ignitor could be a great solution for our application.

VI. Conclusion

Having examined the project Tartarus rocket and looked over many of the commonly used ignition systems we can propose the best choices for our ignition system. The hypergolic systems are far too dangerous and the catalytic methods are complex and potentially unreliable. The two best choices are using either pyrotechnic systems or a torch-style igniter. Pyrotechnics can be designed to not add to weight, are simple, and mostly reliable. The changes to the injector and piping system necessary for a torch-style igniter would require too much of a change at this stage in the project to make it feasible to change the engine's layout. While the benefits of a spark plug's reusability would likely be attractive in a long-term project, our engine is only likely to be fired a handful of times. Torch style igniters provide the benefit of being reusable and can make testing and flying the rocket easier. The short-term nature of the project and the already complex nature of the rocket make simpler and faster methods more attractive. Weighing the benefits for the project suggests the pyrotechnic systems are most ideal. ., and, The project could use the torch-style ignition for testing in the future, however for the competition it is ideal to use a pyrotechnic igniter.

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References

[1] Perry, M., Hicks, R. D., Copeland, O., Bower, A. J., Biaglow, J., Russell, K., and Bennett, T., "Design and Testing of a Self-Pressurizing Liquid Propelled Rocket," 2018 AIAA Joint Propulsion Conference, Aug. 2018.
[2] Nufer, B., "Hypergolic Propellants: The Handling Hazards and Lessons Learned from Use," https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100042352.pdf
[3] Huzel, D. K., and Huang, D. H., Design of liquid propellant rocket engines, Washington: Scientific and Technical Information Office, National Aeronautics and Space Administration, 1971.
[4] F-1 Engine Injector Available: http://heroicrelics.org/info/f-1/f-1-injector.html.
[5] Zak, A., "Russia Lights It's Rockets With a Giant Match," Popular Mechanics Available: https://www.popularmechanics.com/space/rockets/a19966/russia-actually-lights-it-rockets-with-a-giant-match/.
[6] Tyll, J., Herdy, R., "The Nitrous Oxide - Propane Rocket Engine," AIAA 2001-3258, August 2001.
[7] Repas, G., "Hydrogen-Oxygen Torch Ignitor," NASA Technical Memorandum 106493, March 1994, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19940022921.pdf.
[8] Wilson, M., Eilers, S., and Whitmore, S., "Catalytic Decomposition of Nitrous Oxide Monopropellant for Hybrid Motor Re-Ignition," AIAA 2012-4305, July 2012, https://arc.aiaa.org/doi/pdf/10.2514/6.2012-4305.