Valve Selection Considerations for a Student Liquid Bipropellant Rocket

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The liquid bipropellant rocket team "Tartarus" at the University of Alabama in Huntsville is developing an 800lb thrust Nitrous Oxide-Ethane engine. The project began in 2017 and launch is planned for June 2021 at the Spaceport America Cup in New Mexico. The current valves have presented issues with the opening force and are larger than the rocket's expected diameter. These valves are also borrowed and will need to be returned after the first static fire. There is a need for entirely new valves designed specifically for our rocket. The need for normally closed, remotely actuable valves that operate in the required temperature and pressure range (up to 1000psi) has significantly limited the available options. This paper contains a review of the team's current valve setup and specifications, as well as the process of evaluating various options for the new valves. Initial findings indicated that a pneumatic pilot actuated ball valve will likely be the team's best option.

I. Introduction

The Intercollegiate Rocketry Engineering Competition at the Spaceport America Cup is an annual rocketry competition held in late June in New Mexico. Rockets at the competition have target altitudes ranging from 10,000 to 30,000 feet. In Summer 2017, The University of Alabama in Huntsville's Space Hardware Club formed a team to design and build a liquid bipropellant rocket to take to the competition. The original team decided on an 800lbf thrust nitrous oxide-ethane engine hoping to fly to 30,000 feet. After cold flow tests in Spring 2019, and re-naming the team "Tartarus" in Fall 2019, the team is hoping to have its first static fire in March 2020.

Major static fire preparations began in September 2019 with the start of construction of the test stand (Fig. 2). If the static fire test is successful, Tartarus is planning on taking the rocket to the competition in Summer 2021. The current model of the rocket is shown in Fig. 1. The rocket is planned to be 15 to 16 feet tall with an outer diameter of 6 to 6.125 inches. The rocket will carry a 8lb payload. The teal and yellow segments of the figure below are the payload and recovery sections. The red and blue segments are the fuel and oxidizer tanks, respectively.

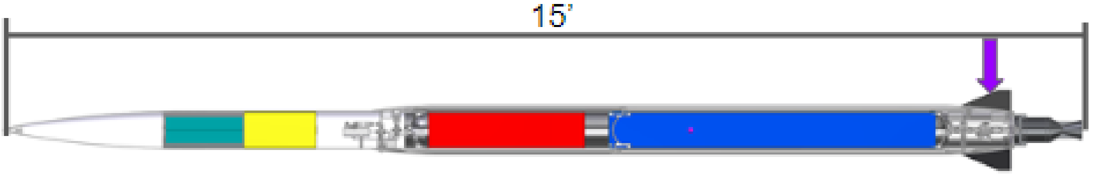

Figure 1. Current Rocket Model

The two ball valves currently used are borrowed and will need to be returned following the first successful static fire test of the injector and engine. The approximate location of the run valves is indicated by the purple arrow in figure 1. Although the team expects to be primarily in a design phase for the Summer and the start of the Fall 2020 semester, the team will soon need new valves for further testing. Team Tartarus has a limited number of valves currently available and may need to purchase new valves to replace the borrowed ones.

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II. Current Run Valve Requirements

A. Current Run Valves

The team is currently using two pneumatically actuated ball valves with the air pilot coming from a single solenoid valve. The two valves (See fig. 3) were loaned to Tartarus with the air pilot lines already installed. As the valves were already connected to each other, the team had to consider them a single unit during design and stand construction. They take up a space measuring at least 7x8x7 inches and weigh at least 5kg. If it were determined to be necessary, the width of this setup could be decreased by no more than 1 inch by moving the valves closer together. The nitrous side diameter is ½ inch while the ethane side diameter is ⅜ inch.

The team had originally planned to do static fire with the propellant tanks that were already designed for the rocket, however they cracked during pressure testing last year. The final fluid system design and tank location may change. The valve specifications may correspondingly evolve.

Figure 2. Static Fire Test Stand and Vehicle Panel

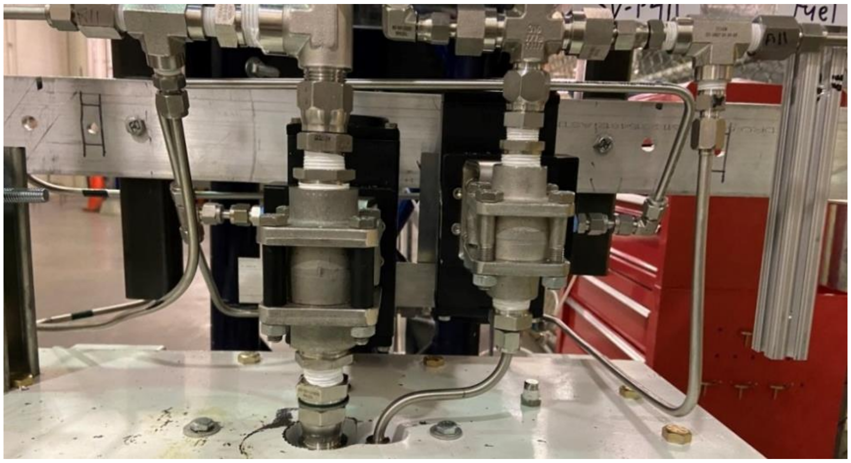

Figure 3. Current Run Valves

B. Valve Design and Operational Concerns

The team expects a mass budget of 2kg for the valves, significantly under the 5kg estimate for the current valves. The rocket is expected to have a diameter of 6 inches, meaning even just one of the two current valves would likely be a challenge to fit into the rocket. The valves need to be remotely actuable, most likely by pneumatic or electric means. The expected system pressure is around 800psi, and there are 1000psi burst disks on both the ethane and nitrous oxide lines. The lowest temperature that is expected to affect the valves is -70F. Based on the current injector design, a flow of 0.5 US gallons per minute through the valves is required. In order to prevent unexpected release of propellant, the run valves are normally closed and safed in the event of power loss or pilot pressure loss. For testing and eventual firing, the run valves are only toggled twice within one run of the test procedure.

Later this semester the team will perform the first high pressure integration test. While the team does not expect to encounter opening torque problems in the high pressure tests, the test will confirm whether or not this will be an additional factor to take into account for the new valves.

III. Analysis of Available Valve Types

A. Overview

Various valve designs were reviewed and characterized by advantages and disadvantages. Several common valve types were excluded for clearly being inappropriate for our application. All information about the various valves is from *Design of Liquid Propellant Rocket Engines*[1].

Butterfly valves (Fig. 4) open and close using a rotating disk in an otherwise straight and unobstructed flow path. The rotation of the flat disk means that butterfly valves are much more likely to encounter opening and closing problems while under pressure. The disk stays in the flow path when the valve is open. This can cause instability in the downstream flow. The section of the model in figure 4 for the operator and the handle would look different on the team's valves as Tartarus is using pneumatic or electric actuation, not manual.

Ball valves (Fig. 4) use a sphere with a hole through the middle instead of a flat disk. Unlike butterfly valves, ball valves do not obstruct the flow path while open. The spherical shape also allows the valves to easily open and close while under pressure. Ball valves are best on rockets when the ball diameter is under 3 inches. Larger ball valves are likely to have a disproportionately high weight when compared to other valve types of the same fitting or tubing size.

Based on most requirements, the choice is less likely to be the following, however they have uses elsewhere in Tartarus's fluid systems. Poppet valves are designed to be normally closed and pneumatically actuated. Because the flow path turns, poppet valves often lead to a large drop in pressure. Poppet valves would not be appropriate for our application due to the pressure drop. Tartarus currently uses solenoid poppet valves to give pilot pressure to existing ball valves on ground systems. Needle valves require multiple full rotations to fully open or close. They take a significant time to open and close. Any pneumatic or electric actuation design for needle valves would likely be expensive and relatively large. , therefore are rarely available with any low cost or small sized actuation option and are not practical for the run valves as they take a significant amount of time to open and close. Tartarus uses needle valves as part of the manual pre-fill procedure where it may be necessary to partially limit the flow through the valve.

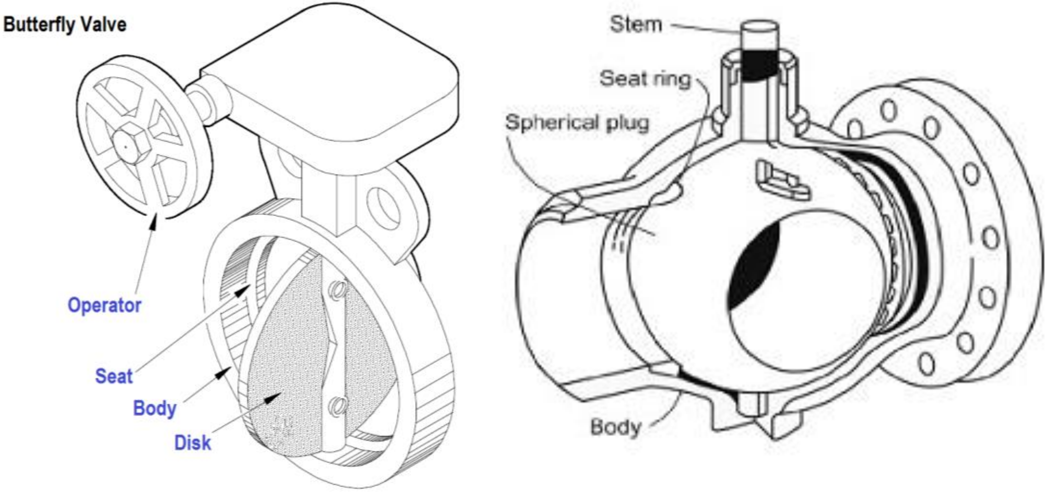

Figure 4. Labelled models of a butterfly valve(left)[3] and ball valve (right)[4]

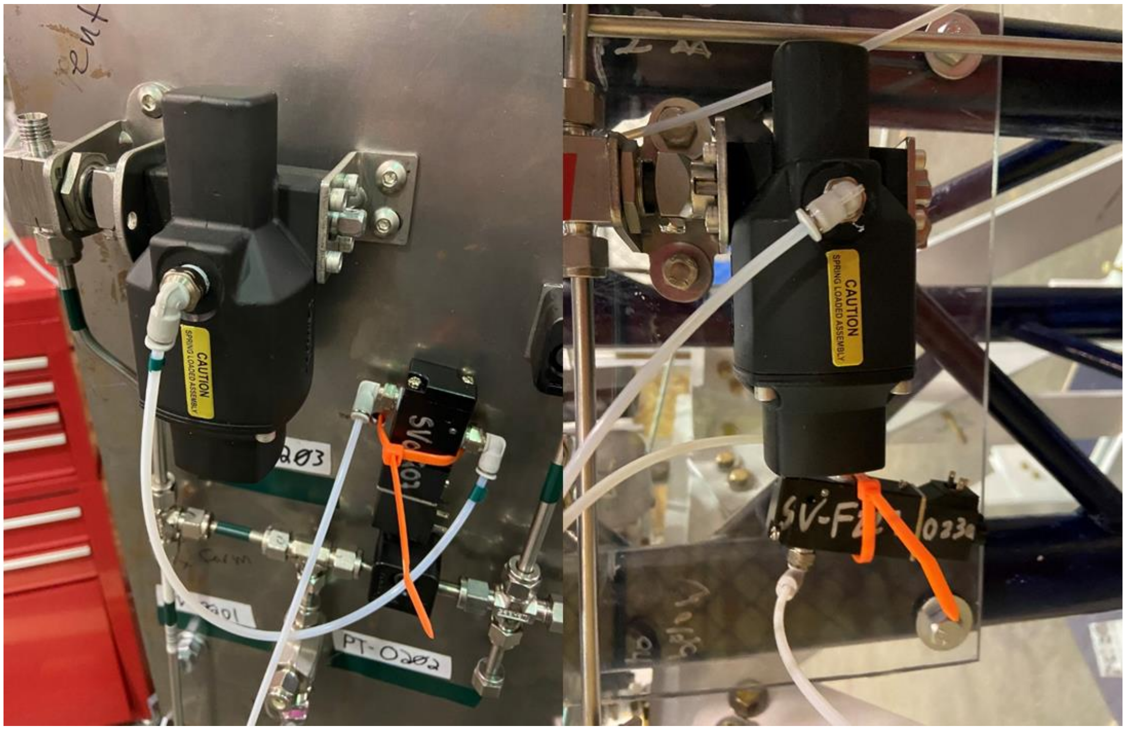

Figure 5. Two examples of currently installed GSE Valves

B. Best Pneumatic Options for Run Valve Application

Based on the above information, ball valves seem to be the best choice for our application. At least ten pneumatically actuated ball valves are already used on ground support equipment. These GSE valves have not created any issues so far in testing preceding static fire. The team recently became aware of the fact that only 8 of the 10 GSE valves were necessary for the current fluid systems design due to two of the valves being used as redundant vent valves. An installed GSE valve is shown in Fig. 5. The main concern for using these two extra GSE valves as run valves is that they are ¼ inch, and the current run valves are ⅜ inch and ½ inch. This size difference may destabilize flow through the valves. Valve catalogs on Swagelok[4]-the manufacturer of the GSE valves- indicate that the ¼ inch and 3/8 inch ball valves can be swapped without purchasing another actuator. The team likely will not be able to determine if this will be a problem until the vehicle propellant tanks are replaced.

C. Providing Pilot Pressure to Pneumatic Valves

In the event that the team chooses to continue to use pneumatically actuated valves for the run valves, the team must determine how to provide pilot pressure to the valves once the rocket has left the ground. Based on the current rocket model (Fig. 1), a segment only around 1 foot tall would be available for storing an inert gas for pilot pressure. A small nitrogen or carbon dioxide canisters, similar to those used in paintball and airsoft, could provide the pilot pressure. Most commercial off the shelf industrial application canisters or cylinders seem to not be smaller than 12 inches, which would complicate the search process for an appropriate size canister.

During a recent low-pressure integration test, the team discovered that the solenoids controlling pilot pressure to the GSE valves would leak during and shortly after pilot pressure was activated. This leaking could be mitigated by a team member placing a temporary cap over the solenoid's third hole until pilot lines had been fully pressurized. Additionally, the polyethylene tubing used to connect a solenoid to its respective pneumatic valve frequently has small leaks at connection points. Both these sources of leaking could present significant problems once pilot pressure is no longer applied from a large nitrogen cylinder.

Figure 6 illustrates a potential solution to providing pilot pressure to run valves from an on-board tank. All sections of the two propellant lines have been intentionally excluded from the figure both to save space and because no sections except the run valves are affected by this addition. The solid black line represents the frame of the rocket.

Valve 01 will either be a manual ball valve or a solenoid valve depending on how this addition would fit into the team's fill and launch procedure. The valve would likely only be manual if the decision was made to have a launch team member remove the polyethylene line between it and the rocket instead of having it removed by the same umbilical release that is being planned for the propellant fill lines.

Check valve 02 may be replaced with a solenoid and vent valve 05 may be removed if either the manual valve option is chosen for valve 01 or a vent is located on the farm panel in a location that the pilot fill system could vent through before the fill line is released. The pressure transducer will allow to team to confirm when the tank is full and if there is any leaking.

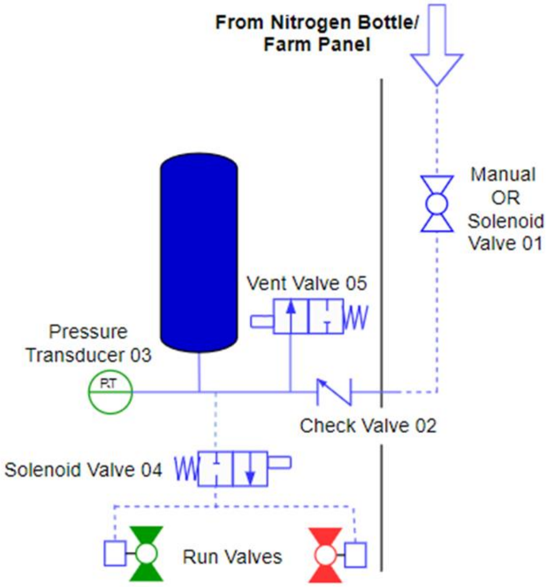

Figure 6. Potential Pilot Pressure Fill System

D. **Electric Actuation**

If the team is unable to provide pilot pressure for pneumatic valves, electric actuation will most likely be the best option. The team had previously attempted electric actuation with a different set of valves. The servo used, a Hitec HS-M7990TH, has a maximum torque of 500~611 oz-in. This attempt failed to effectively transfer torque through a linkage bar from the motor to valve. The valves that were used in this test are not currently in use on any Tartarus fluid systems. The team moved to the current run valves following the failure of this test. According to valve selection guide[5] from the manufacturer of the GSE valves, their required opening torque is 512 oz-in. If electric actuation is pursued, the team will likely need either a higher torque motor, or must find valves with lower opening torques. As Tartarus still has access to both the servo and the extra GSE valves, the team may be able to test the opening time this semester before the decision to make extra purchases is made. The servo the team used for the first attempt at electric actuation cost $176.

IV. Conclusion

The team's decision between either pneumatic or electric actuation of ball valves will most likely be determined by the available space inside the rocket body near the valves. Electric actuation is more likely to present technical issues with opening torque. Although the primary challenge with pneumatic actuation would be fitting the necessary components into the rocket, it has the benefit that its components have more freedom to move around. The servo would need to be in a specific location next to the run valves. Once team Tartarus has more time for less urgent tests following static fire, testing needs to be done regarding the rate of pilot pressure leaking as well as the viability of using currently available servo and valve combinations.

Acknowledgments

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