T512 NASA In-Space Cryogenic Propellant Storage

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NASA strives to improve space travel technology to extend the amount of time crews can remain in space on various missions. Team 512 designed a storage tank that holds the amount of fuel required for spacecraft to return to Earth from any mission destination. It maintains the temperature and pressure of fuel by reducing heat transfer into it. This reduces fuel loss and increases storage time, resulting in longer missions. The design of a prototype is necessary for testing and validation, as well as a full-scale tank that will be recommended to NASA.

The rocket fuel we are designing for is cryogenic, meaning it is in a usable, liquid state from -238°F to -460°F. Out tank protects propellant from heat transfer to sustain temperatures lower than the fluid's boiling point. This heat transfer is from conduction through connections, convection through liquids and gases, and radiation from surroundings. If the temperature exceeds the boiling point, a fluid goes through a phase change from liquid to gas. This gas causes a rise in pressure inside the tank. It is necessary to release gas to prevent the internal pressure of the tank from exceeding its limit, causing rupture. This release reduces the amount of usable fuel in the tank.

The team designed the tank by selecting ideal geometry, scale, wall thickness, supports, and insulation type. Prototype testing determines the mass flow rate of gas leaving our tank, which should be less than the rate from existing tanks. The results are compared to heat transfer calculations to predict the performance of the recommended large-scale tank. A successful tank prototype reduces the mass flow rate and does not fail during testing. Data obtained from testing should validate all design choices for both the prototype and full-scale design.

I. Nomenclature

CAD = Computer Aided Design
MLI = Multilayer Insulation
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration

II. Introduction

A. Project Description

Currently, NASA is performing research to design the most efficient cryogenic storage system to allow for longer space missions. To do this, they must design a tank that reduces heat transfer into the fluid and extends the amount of time the fluid is in a usable, liquid state. Our project aims to design and prototype a storage container to hold cryogenic propellants in space that maintains the fluid at the proper temperature and pressure by reducing heat loss into it. We have designed a full-scale tank to be recommended for use by NASA, as well as a simplified prototype that can be tested in a lab to validate our design choices.

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B. Project Objective

The objective of this project is to design a storage tank for cryogenic propellant that increases storage time, reduces fuel loss, and reduces heat transfer.

C. Key Goals

There are five main key goals to achieve for this project to be successful. They are maintaining temperature, maintaining pressure, reducing heat transfer, reducing fuel loss, and developing a prototype. Heat transfer into the tank causes the temperature of the fluid inside to rise. As the temperature exceeds the boiling point of the fluid, it will go through a phase change from a liquid to a gas. This gas causes the internal pressure of the tank to rise. To prevent the pressure from exceeding the limit of the tank, there must be a pressure relief valve. The gas that is released is fuel that is no longer usable. A prototype must be developed in order to properly test our design and validate each design choice.

D. Assumptions

Three assumptions were made to narrow the scope of the project. First, we are assuming that liquid nitrogen will be used for testing, rather than liquid hydrogen or oxygen that would be used in a full-scale tank. Liquid hydrogen is much more dangerous to test with, due to its flammability, and liquid nitrogen is what is readily available for us in the lab. Next, we are assuming the tank can withstand Earth, space, and lift-off conditions. The tank will be filled with fuel on Earth, loaded into the spacecraft, launched into space, undergo various temperatures and pressures based on positions in space, as well as reenter Earth's atmosphere. It should maintain structural integrity through each of these stages. Finally, we are assuming that we are designing for a lunar mission lasting two weeks, therefore the tank should maintain the fuel at the appropriate temperature and pressure for at least that amount of time.

III. Targets and Metrics

To define targets and metrics for this project, our team first had to define what aspects of the project are the most important to our project sponsor. Utilizing the customer's needs, we were able to define targets and metrics for the in-space cryogenic fuel storage tank. The most important critical functions for our design are to store cryogenic fluid and reduce heat transfer. Our critical targets and metrics will reflect these functions.

A. Storage

The storage function requires the tank to hold cryogenic fluid without failure, maintain internal pressure, and maintain internal temperature. Assuming a lunar mission, the goal is to accomplish these functions for a duration of two weeks. Material research was done to ensure that Stainless Steel 304 would be able to hold the cryogenic fluid for two weeks without cracking and contain the fluid at the necessary storage conditions. The internal temperature of the tank should be maintained at 77 K, which is the storage temperature of liquid nitrogen for it to remain in a liquid state. If this temperature is increased, the liquid will go through a phase change from a liquid to a gas. As more gas boils off, the internal pressure of the tank will rise. That pressure should be maintained at 15 psi, which is comparable to average conditions at sea level.

B. Insulation

In order to maintain the temperature and pressure of the cryogen, the heat transfer entering the system should be reduced. There is heat transfer from conduction through internal and external supports, radiation from surroundings, and convection through fluids. There should be less than 1% boil off of the fuel per day for the duration of a mission. The boil off of gas leaves less usable, liquid fuel, so there should still be liquid fuel after the two week projected mission.

IV. Results and Discussion

This section outlines the validation made for the design choices for the prototype for this project, as well as the relation to a recommended full-size design that will be recommended to NASA.

A. Testing Results

The following graph shows the weight of the liquid nitrogen in the inner tank in relation to time.

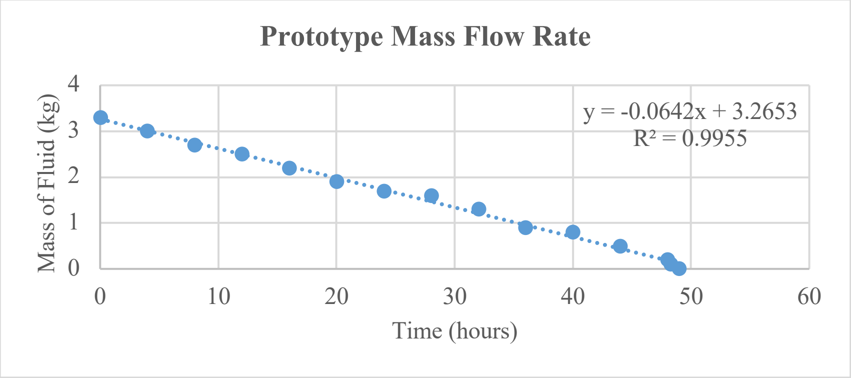

Figure 1: Prototype Mass Flow Rate

We began testing with 3.26 kg of fluid in the tank and weighed the tank with a bathroom scale every four hours until all the liquid nitrogen had been released. It took 49 hours for all the fluid to boil off, making the mass flow rate of the prototype 0.0642 kg/hr. The trend of the line is linear, meaning there is a linear relationship between mass and time. Our data is 99.55% accurate to the linear trendline, which is shown by the R^2 value on the graph.

B. Prototype Design Validation

The experimental boil off time was found to be 49 hours, and the calculated time is 48.85 hours. Comparing these results gives us an error of 0.3%, which can then be applied to a full-scale design. The targets and metrics we determined are based on a full-scale design. The bathroom scale used also has a 3% error, so a total of 6% error should be applied to the recommended design. Each mode of heat transfer into the system can be seen in the table below. This allows us to see which design components contribute to the most heat transfer, allowing us to continue to edit them to reduce the total heat transfer into the system. Changes can be made to the insulation, tank geometry, and internal and external support geometry to improve the design further.

Radiation through MLI [W]	0.21
Conduction through Fill Pipe [W]	7.33
Conduction through G-10 CR supports [W]	0.83
Total Heat Transfer Rate [W]	8.37
Mass of Fluid [kg]	3.3
Specific Heat Capacity of Liquid Nitrogen [J/kg*K]	2000
Time [hours]	48.85
Time [days]	2.04
Experimental Time [hours]	49
Calculated Time [hours]	48.85
Calculation Error [%]	0.31

Table 1: Prototype Heat Transfer Calculations

C. Full-Scale Design Validation

Using the same calculation process used for the prototype, it was determined that a full-scale tank will hold liquid hydrogen at the proper conditions for 1.14 years. We accounted for heat transfer during lift-off, while in space, and during reentry, due to our assumption that the tank will be undergoing each of these conditions. It was found that the tank would lose 7.14 kg of liquid hydrogen during lift-off and 3.61 kg during reentry to Earth's atmosphere. This left a total of 128,925.5 kg of fluid to be used in space. Applying error from prototype testing, the minimum length the tank will hold the fluid in space is 1.07 years, which is much longer than the two-week goal. It has a mass flow rate of 310.24 kg/day, which is 0.24% per day. This is lower than the 1% goal, so both the prototype and full-scale designs are successful. These values do not account for external struts that would connect the storage tank to the inside of the spacecraft, which would contribute significantly to these calculations, but this was outside the scope of our project.

The heat transfer into this system can be seen in the tables below at each stage of the rocket's movement. Again, these values can be used to alter the design choices to further reduce the total heat transfer.

	Lift-Off	**Re-Entry**
Specific Heat Capacity of Liquid Hydrogen [J/kg*K]	14,304	14,304
Total Heat Transfer Rate [W]	381,176.17	1,667,194.24
Time for Lift-off [s]	510	90
Temperature of Lift-off/Re-Entry [K]	1,922.04	2,922.04
Temperature of Fluid [K]	20	20
Change in Mass [kg]	7.14	3.61

Table 2: Full-Scale Liftoff and Reentry Calculations

	Space
Remaining Mass [kg]	128,925.5
Specific Heat Capacity of Liquid Hydrogen [J/kg*K]	14,304
Temperature of the Moon Facing the Sun [K]	400
Temperature of Fluid [K]	20
Total Heat Transfer Rate [W]	19,517.51
Storage Time [years]	1.1385 (9973.63 hours)

Table 3: Full-Scale in Space Calculations

V. Conclusion

The full-scale design that will be recommended to NASA will hold and maintain liquid hydrogen for 1.07 years accounting for error, which is much higher than the goal of two weeks. This is assuming the fuel is not being used and is only being stored in space for that period of time. The percent boil off per day for the full-scale design is 0.24%, which is less than the 1% intended target. Since both targets were met, we can consider the design successful.

A. Errors

An experimental error of 0.3% was found by comparing experimental results with calculated results. This error could be from fluctuations in the quality of the vacuum, fluctuations in surrounding conditions, and additional random and human errors. Instrumentation error was also accounted for from the pressure relief valve, which was 4%, but did not include it in the total error of our prototype, since we left the vent open throughout the duration of testing and the relief valve was never used.

B. Design Flaws

During the machining and welding process, the bottom flange warped, making it difficult to seal the outer tank to create the vacuum between the layers. Additional clamps had to be added in certain locations to create the necessary seal. If a second prototype were designed, it would be important to make thicker flanges to prevent this.

The pipe that was selected to use as the vacuum port had a diameter of 0.25 inches, which made the process of pulling the vacuum take a longer amount of time than it could have if the diameter was larger. That process took away time we could have been using to do more testing.

To make assembly and machining more simple, we added a clamp between the two tank layers to connect the fill pipe, rather than connecting the entire fill pipe in one piece. This decision was made so that we could easily disassemble and access each part of the tank if problems arose during testing. It created more problems when creating seals to pull the vacuum between the layers, since we had to create two different seals instead of the one we had initially planned for.

Sealing the inner and outer tank took many attempts, and each time, the screws in the flange had to be removed. This caused the threads in both the flange and screws to stretch, making it too difficult to screw them in. Time was spent rethreading each flange several times, again taking time away from further testing. This could have been avoided by not threading the flange and using nuts and bolts instead of screws.

Finally, the initial design included a reflective outer layer, which was not implemented into our physical prototype. That would have reduced the heat transfer further and extended the testing time.

C. Future Work

The continuing stages of this project would be further refinement of the design of our full-sized tank. The team focused more on the physical prototype than the full-scale design, so there is still more research and refinement to be done on that design. One aspect to improve is the supports that fix the inner tank to the outer tank. The research and development of the optimal geometry for these supports is pivotal to the structural integrity of the tank.

Integrating screens or display options on the full-sized tank will increase ease of use and overall safety of the full-sized tank. The displays would show the current temperature and pressure readings of the cryogenic fluid in the tank, as well as the amount of fuel remaining in the tank.

Another aspect that needs to be further researched is the external connections and ports on the tank. It is necessary to have vents, pressure relief valves, a vacuum port, and fuel inlets and outlets. Since this tank is so much larger, there are significantly more safety precautions that must be taken, meaning more relief outlets are needed in case others fail. Further research should be conducted on how to integrate these into the tanks geometry as to not take away from the pill shape or increase heat transfer too drastically. Lastly, it is important to include the heat transfer through the struts connecting the tank to the inside of the spacecraft. Current state-of-the-art struts that connect tanks to spacecrafts are responsible for most of the heat transfer to the tank. The goal is to increase cryogenic fuel hold time by reducing heat transfer, so extensive work must go into developing the most efficient struts for the full-sized design.

The next stage of the project would be to incorporate a space graded bill of materials. This would be in accordance with the standards upheld by NASA on material selection.

Finally, prototypes with similar design components as the full-sized design should be built and tested. The prototypes would be tested using liquid nitrogen, hydrogen, or oxygen. These prototypes would also be tested in different conditions such as zero gravity, liftoff, and reentry to see if they can withstand the forces they will undergo on the spacecraft. During these tests, thermal analysis would be performed on the prototype tanks to see the temperature gradients. This would show where most of the heat transfer is coming from, as well as provide information on the locations on the tanks that need improvement.

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