Investigation of a Lightweight Oxidizer Delivery System for a Hybrid Rocket

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The Multi-disciplinary University of Colorado Hybrid Student Rocket Project is a multi-year student-led effort to develop a 300 lb_f thrust hybrid rocket motor capable of delivering a 1 lb_m payload to 15,000 ft altitude by burning Hydroxyl-terminated polybutadeine solid fuel and liquid nitrous oxide oxidizer. Specifically, an investigation will be made into the design of a pressure-fed oxidizer delivery system (which consists of a liquid oxidizer tank, feed-line and injection system) as an integral component in the functionality of this hybrid rocket and the success of the multi-year project. This investigation will focus on achieving and maintaining an oxidizer delivery system mass flow rate high enough to provide a consistent thrust of 300 lb_f. Additionally, the entire oxidizer delivery system will be designed to keep the oxidizer in a liquid state until it reaches the combustion chamber. The system design will provide weight savings in order to increase the final thrust to weight ratio of the rocket significantly enough to reach high altitude. This paper will also cover improvements to the oxidizer delivery system with regard to these design criteria which will include increasing the injection area, adding a flow regulator, and integrating tandem commercial off-the-shelf carbon fiber composite tanks. Together, these components are scheduled for integration with the final hybrid rocket motor design whose assembly will culminate in both an oxidizer flow test and a static test fire in March of 2008.

Nomenclature

lb_f = Force in pounds
lb_m = Mass in pounds
C_d = Discharge coefficient
$\dot{m}_{ox}$ = Mass flow rate of oxidizer
A = Injector total hole area
Δp = Pressure change
ρ = Density
v = Flow Velocity

I. Introduction

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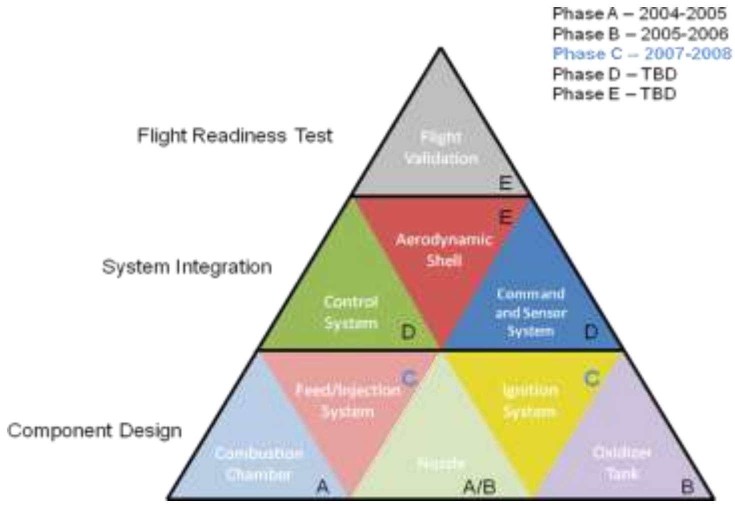


Figure 1. Revised Phased Structure for the MaCH-SR1 Senior Project[2]

HE history of the Multi-Disciplinary University of Colorado Hybrid Student Rocket (MaCH-SR1) began with a senior project proposal by a team of undergraduate students in 2001. The proposed project involved the development of a rocket capable of delivering a 10 lb research payload to low Earth orbit approximately 100 miles above the Earth's surface by 2008 through a phased multi-year process. A hybrid rocket fuel combination was chosen by the 2001-2002 team for safety reasons over rockets fueled by liquid or solid propellants. A hybrid rocket would generate thrust by igniting a solid rubber fuel, hydroxyl-terminated polybutadiene (HTPB), with the injection of a liquid oxidizer, nitrous oxide (N_2O), which was changed from liquid oxygen (LOX) in 2002[1] to reduce project complexity and cost while increasing safety. The combustion of solid fuel and liquid oxidizer acts to increase the pressure and temperature of the gases inside the chamber where the fuel is burned. These high pressure and high temperature gases then proceed to exit from the combustion chamber through a conical nozzle where they are accelerated through a compression and expansion process. The acceleration of these gases through the nozzle and out of the rocket itself generates thrust, which lifts the rocket from the ground.

As of 2008, the original objective of the MaCH-SR1 project has not been met due mostly to variations in student interest, industry sponsorship, funding, and senior project course structure, but much progress has been made with regard to the both student and faculty understanding of hybrid rocket development at the University of Colorado. For these reasons, the 2007-2008 team has decided to relax the goal of the project while proposing a new series of phases in order to continue to provide the rare, multi-disciplinary experience it offers to undergraduate students. Figure 1 shows the MaCH-SR1 project phases revised by the 2007-2008 team.

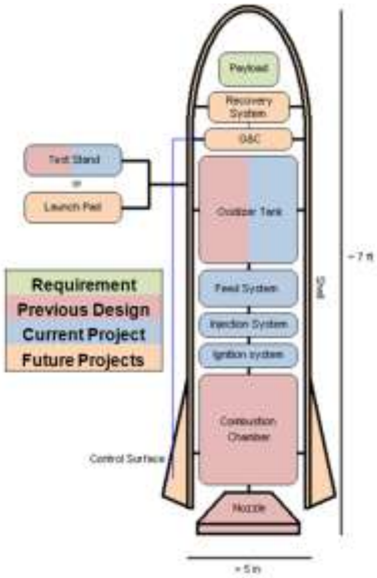


Figure 2. MaCH-SR1 Full Hybrid Rocket System[3]

The new design goal of the MaCH-SR1 project now challenges future senior project teams to deliver a 1 lb_m research payload to a 15,000 ft altitude. This change in project design goals has led to new requirements set forth by the 2007-2008 team. These project level requirements are: 1.) The motor needs to produce a minimum of 270 lb_f of thrust, with an objective thrust of 300 lb_f for a period of 15 seconds, and 2.) The full hybrid rocket system mass needs to be between 73 and 99 lb_m, with an objective goal of 84 lb_m.

As shown in Fig. 1 and highlighted in blue in Fig. 2, the N_2O feed and injection subsystems as well as the oxidizer tank subsystem selection are all under design by this year's MaCH-SR1 team. The requirements for this collection of subsystems (known as the oxidizer delivery system) are derived from both the new design goal and the resulting project level requirements. Thus, the oxidizer delivery system must be lightweight in order to provide a thrust to weight ratio high enough for the rocket to reach 15,000 ft when the rocket's flight readiness phase is reached. Additionally, the MaCH-SR1 hybrid rocket must be tested in a vertical configuration together with components of phase A and phase B in order to successfully complete what is now phase C of the project. The specific purpose of this report will be to outline the design of this lightweight oxidizer system in preparation for the flight readiness phase of the MaCH-SR1 multi-year project.

II. Oxidizer Delivery System Design

The design of the oxidizer delivery system is composed of three main subsystems: the oxidizer tank(s), the feed subsystem, and the injector subsystem. It was determined that, for this project specifically, two NOS brand N_2O tanks should be used, with commercial off-the-shelf (COTS) feed pipeline components. Also, the injector effective hole area was increased based on analytical and empirical test results. The design of these subsystems will be covered in detail within this section.

A. Injector Subsystem

1. *Overview*

The injector for the hybrid rocket should effectively introduce oxidizer into the combustion chamber while vaporizing the liquid. This is accomplished by introducing liquid oxidizer at a high velocity in very thin, straight streams aimed directly through the port hole of the solid fuel. Impinging or otherwise preventing these streams from flowing axially through the fuel port between the fuel grain is not desirable, as this can cause unstable combustion in hybrid rocket motors, as shown in Fig. 3. Also, in order to improve combustion, the boundary layer between the fuel grain and the oxidizer was designed to be very thin. With these in mind, the injector hole pattern was chosen by the 2005-2006 MaCH SR1 team to lie on the edge of the cross-pattern of the fuel port, shown in Fig. 4.

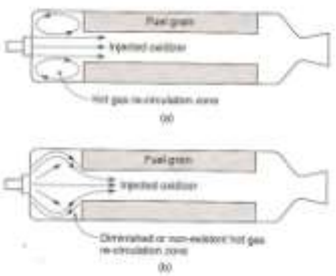


Figure 3. Hot Gas Flow Recirculation Zone Necessary for Stable Combustion[4]

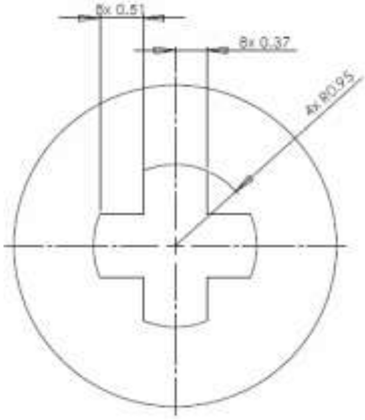


Figure 4. HTPB Fuel Grain Port Geometry[5]

2. *The Injector Discharge Coefficient*

An important parameter to the design of an injector subsystem is the discharge coefficient, C_d, which is dependant on the orifice design of the injector plate. This coefficient determines the mass flow rate of the oxidizer, $\dot{m}_{ox}$, and the velocity of the oxidizer, v, as it enters the combustion chamber, as shown in Eq. (1) and Eq. (2).

$$\dot{m}_{ox} = C_d A \sqrt{2\Delta p / \rho} \tag{1}$$

$$v = C_d \sqrt{2\Delta p / \rho} \tag{2}$$

Where A, Δp, and ρ represent the total (or effective) injector hole area, the change in pressure across the injector plate, and the density of the liquid oxidizer respectively.

Common injector discharge coefficient values are in the range of 0.6-0.9, as this provides a very high velocity for the oxidizer, leading to a high heat transfer rate. For this project, the team determined that a C_d of 0.7 would be sufficient to meet these criteria.

With C_d defined, the effective hole area required to achieve a C_d of 0.7 could then be found for any selected mass flow rate of oxidizer using Eq. (1).

3. *Injector Oxidizer Mass Flow Rate Determination*

The next step in the design process was to determine the desired oxidizer mass flow rate. This flow rate was found from an analysis of empirical data provided from the past two teams' 300 lb_f rocket motor hot fire tests [Ref. 6-7] which were conducted with closely matching rocket designs. The dependency of the thrust on the mass flow rate of the oxidizer can be assumed to be a linear relationship, as shown in Fig. 5. The R^2 value for the linear relationship was 0.99, demonstrating an accurate linear fit to the data.

From Fig. 5, it was determined that an oxidizer mass flow rate of 1.33 lb_m/s is desirable by extrapolating the trend line to 300 lb_f. Also, it is shown that a mass flow rate of 1.13 lb_m/s will provide the minimum required thrust of 270 lb_f . Using this, the design flow rate for the liquid oxidizer was chosen to be 1.33 lb_m/s.

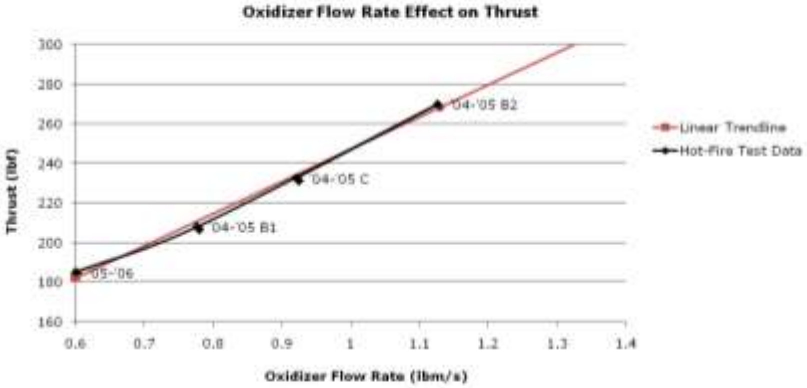
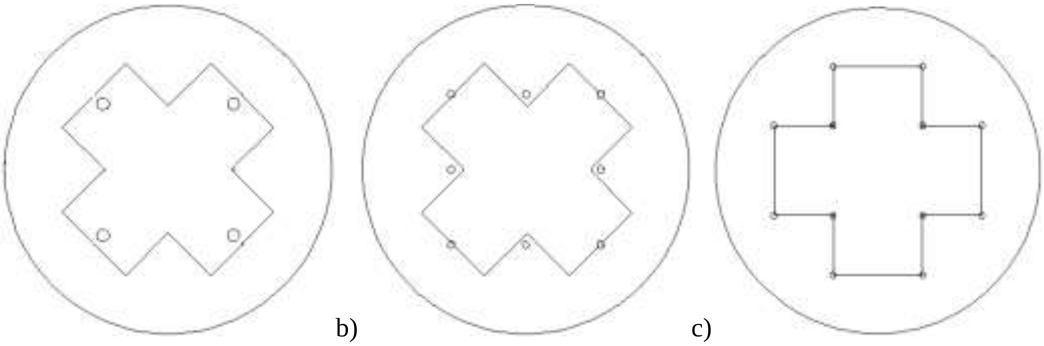


Figure 5. Empirically Determined Oxidizer Mass Flow Rate

4. Discharge Coefficient

The discharge coefficient of an injector is highly dependent on a variety of qualities of the injector plate itself, many of which are still not fully understood. Generally, the discharge coefficient is determined empirically within industry due to its complex nature with regard to fluid dynamics, so an empirical test was devised to determine how this parameter varied with different plate properties for this project.

It was determined that the most important parameters which might affect the discharge coefficient were the total effective hole area and the number of holes in the injector plate. Both of these parameters were varied with three different hole areas and three different hole numbers, leading to a 3x3 test matrix and nine acrylic test plates (see Fig. 6 for hole patterns).



a) b) c)

Figure 6. Injector Plate Hole Designs and Fuel Port Outline

Initial hole areas were determined from preliminary analysis assuming a discharge coefficient of 0.7, a combustion chamber pressure of 500 psi, an oxidizer pressure of 700 psi and a density of N_2O at room temperature. This led to an estimate of 0.029 in^2 for the total effective hole area. A further analysis accounting for various temperatures of liquid oxidizer (and therefore various densities and pressures of N_2O), but keeping a constant combustion chamber pressure of 500 psi, revealed an optimal hole area 0.023-0.031 in^3 for relevant temperatures of 60-90ºF. Below 60ºF, the oxidizer pressure became too low to maintain greater than 20% above 500 psi, a requirement that was set to ensure positive flow through the rocket without chugging. The final analysis was a blow-down model from the 2005-2006 MaCH-SR1 project[†], which was a much more accurate prediction for the behavior of the system. This code gave total injector areas of 0.022-0.035 in^2 for our desired thrust values. These results were used to set the test areas for each of the nine plates.

[†] Code credited to Richard Rieber

For the injector plate tests, water was used instead of liquid N_2O since it maintains a similar density while providing advantages in both safety and ease of use. This water was forced through each plate by a pressure differential which was measured along with the mass flow rate of water through the plates. The discharge coefficient was then found by substituting these quantities into Eq. (1) for each plate.

The apparatus used to conduct these tests was an Armfield hydraulics bench. A tube was connected to the bench, which was then connected to a 1 ½-to-3 inch diameter metal expander. This was then connected to a short 3 inch diameter female to female metal pipe adapter, which was glued in to a 2 ½-to-4 inch diameter PVC expander section. The plate was held in place by a screw-on circular cap, and a neoprene gasket was used to prevent any water leakage (see Fig. 7).

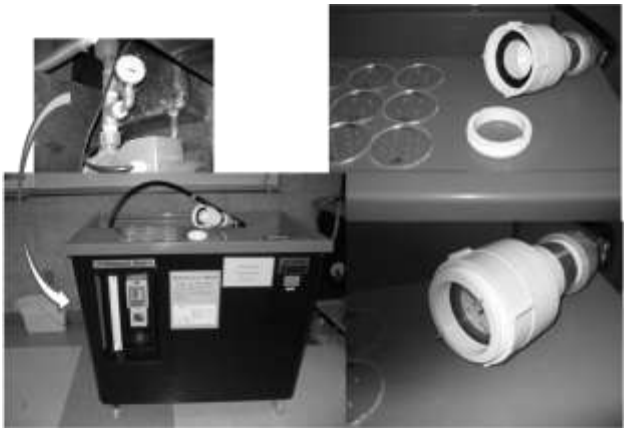


Figure 7. Injector Plate Prototype Test Setup

The pump on the hydraulics bench was used to create a pressure differential which forced the water through the injector plate. The water then filled the reservoir in the hydraulics bench as it passed through the plate. The pressure differential and the amount of water in the reservoir were measured with respect to time, using a stopwatch and video cameras for accuracy. Each test was concluded after 3-5 L of water had accumulated in the reservoir.

Table 1. Injector Plate Prototype Test Matrix

Plate Number	Drill	Diameter (in)	Holes	Ai (in^2)	Cd
#1	34	0.111	4	3.87E-02	0.41
#2	39	0.0995	4	3.11E-02	0.55
#3	44	0.086	4	2.32E-02	0.53
#4	47	0.0785	8	3.87E-02	0.47
#5	50	0.07	8	3.08E-02	0.60
#6	53	0.0595	8	2.22E-02	0.71
#7	52	0.0635	12	3.80E-02	0.52
#8	54	0.055	12	2.85E-02	0.58
#9	56	0.0469	12	2.07E-02	0.65

5. *Injector Results*

The results of the nine injector plate tests conducted using the Armfield hydraulics bench are shown in Table 1. Confidence in the discharge coefficients were determined to fall within ±0.07 based on the combined maximum measurement inaccuracies of pressure to within ±1 psi, volume of water to within ±0.05 L, and time to within ±0.1 seconds. The results show that higher C_d values were obtainable with smaller total effective hole areas, for all hole patterns. The discharge coefficient range was 0.41 to 0.71, with an average of 0.56 as summarized in the plot shown in Fig. 8.

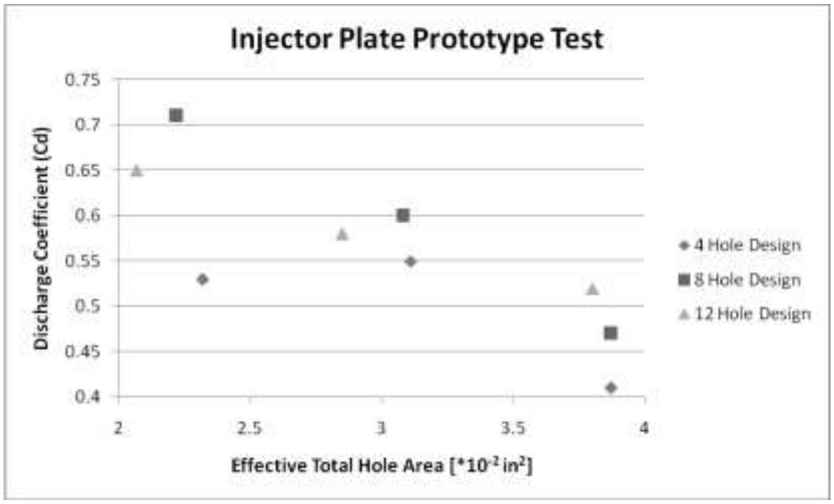


Figure 8. Plot of Injector Plate Prototype Test Results

6. *Final Injector Design*

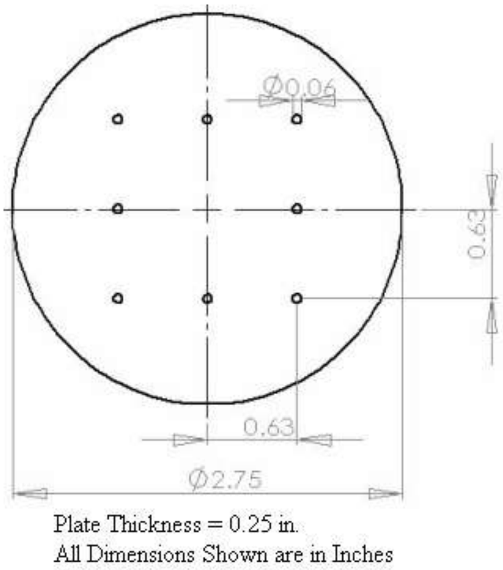


Figure 9. Injector Plate Design

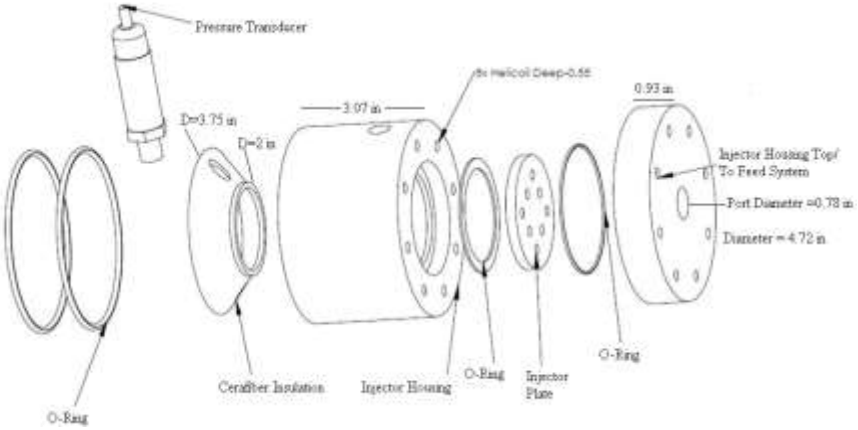


Figure 10. Injection Subsystem Assembly

After reviewing the results of the injector prototype test, the final injector plate design (see Fig. 9) was then selected with an 8-hole pattern and a total hole area of 0.0222 in^2, in order to provide the most ideal discharge coefficient of 0.71.

Also, 1/4 inch thick titanium was selected as the material from which the injector plate would be made since it provides the maximum amount of strength and minimum amount of bending under the thermal differential and pressure loads experienced by the very cold and very hot high pressure environments on both circular surfaces. Due to the hardened nature of titanium, a carbide drill bit had to be used to make the holes required to achieve a discharge coefficient of 0.71.

Finally, this plate will be integrated into the previously designed injector housing, shown in Fig 10, which will remain the same due to its rigorous design and successful testing history.

B. Oxidizer Feed and Storage Tank Subsystems

1. *Overview*

The purpose of the oxidizer tanks and feed system will involve liquid N_2O storage and transport to the injector, respectively. Although this is a relatively simple purpose, the design and integration of this system for a flight weight rocket has proven to be difficult. Neither of the past two teams has successfully integrated an upright (gravity-fed) oxidizer system, although the second one attempted to do so with a team-built oxidizer tank. This tank did not, however, meet the team's requirements, and therefore was not used. The 2007-2008 MaCH-SR1 teams' solution to this problem will involve the use of COTS parts to compose the oxidizer system. The team has also chosen to take advantage of both the self-pressurizing properties of N_2O as well as the addition of a helium (He) pressurant. The details behind this decision are shown in the next section.

2. *Investigation of Self-Pressurization Using N_2O*

The feed system will be designed to deliver oxidizer into the combustion chamber at an average mass flow rate of 1.33 lb$_m$/s, with as little variation from this value as possible. In order to accomplish this, a regulator must be used and the oxidizer must be pressurized to 1000 psi. Without these improvements the mass flow profile for an unpressurized and unregulated system would vary too greatly over time, as demonstrated by Fig. 11. Therefore, only the pressurized and regulated scenario will

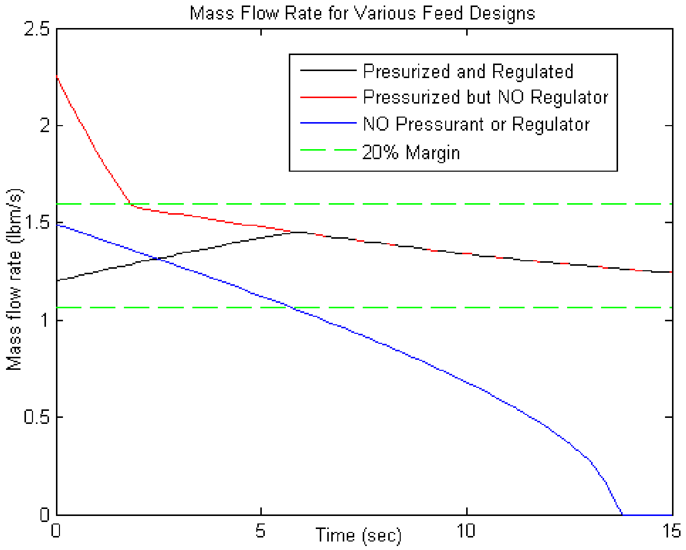


Figure 11. Mass Flow Rate

produce a consistent oxidizer flow that remains within 20% of the desired average mass flow rate.

The specific pressurized and regulated values were determined by finding conditions where the pressure drop across the plate remained above 20%, and where the average mass flow rate was exactly 1.33 lb_m/s. In order to achieve a pressure drop just over 20% at the start of the burn the regulator pressure will be set to 673 psi. With this value the corresponding initial pressure of the oxidizer must be set to 1000 psi to provide the desired mass flow conditions. The pressure drop profile across the injector plate over time (see Fig. 12) demonstrates that, with these precautions, a ΔP between 20-29% can be achieved through a burn time of 15 seconds.

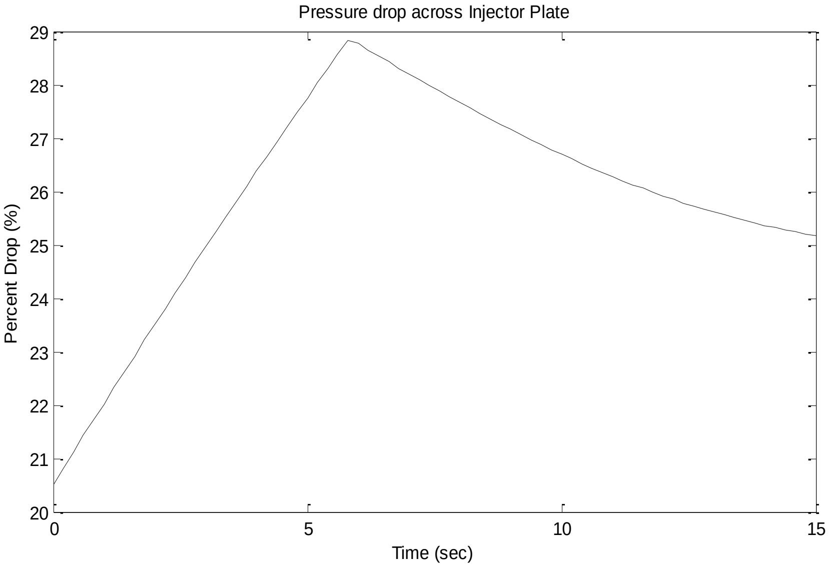


Figure 12. Pressure Drop Across Injector Plate

3. Oxidizer Tank Selection

The most difficult component to select for a flight ready rocket is the oxidizer tank due its high manufacturing cost and size requirements for a narrow rocket diameter. The 2005-2006 team attempted to solve this problem by designing and building their own composite oxidizer tank. Their method utilized a carbon fiber wrap and aluminum end fittings, and was held together by carbon fiber straps. Unfortunately, this design proved to be unsuccessful after the tank failed a pressure test. For this reason, the present team has considered alternative design options, shown in Fig. 13. The first option considered was an aluminum NOS (NOS is a brand-name that specializes in Nitrous Oxide tanks.) tank used in automobiles (see Fig. 13a). The second was also a NOS tank, but is made out of carbon fiber (see Fig. 13b). However, because of the size of this tank, two tanks would be needed. The final option was an aluminum pipe with welded end caps (see Fig. 13c).

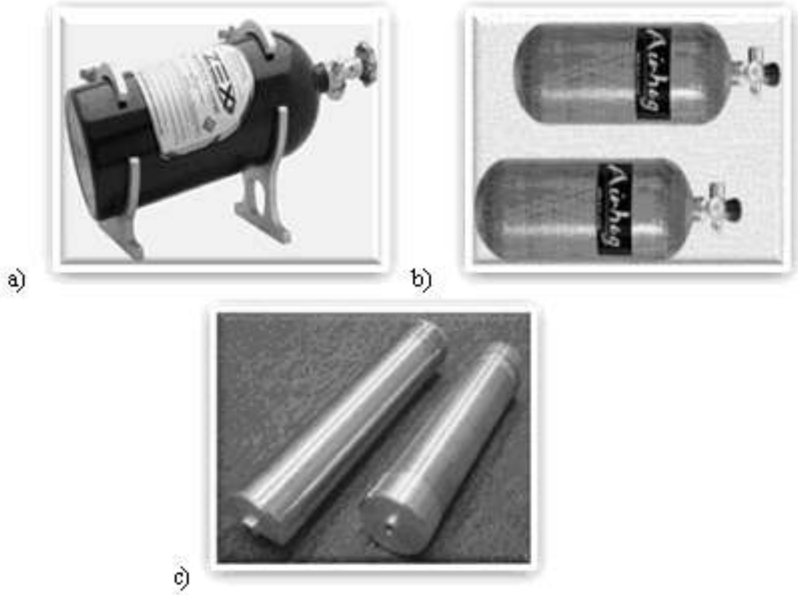


Figure 13. Oxidizer Tank Options

Table 2. Oxidizer Tank Trade Study

Specs:	(a)	(b)	(c)
Tank Mass	25.1 lb	8.75 lb	75 lb
Diameter	8 in	6.625 in	5 in
Cost	~$250	~$1100	~$500
Disadvantages	**Too wide for flight, Volume too small for nominal oxidizer**	**Stacked configuration, More complex**	**Too heavy for flight, Exceeds mass budget by 300%**
Equivalent System Mass (ESM)	**49.3 lb**	**44.7 lb**	**96 lb**
Expected Altitude	**11370 ft**	**15520 ft**	**9110 ft**

In order to select the best tank for our rocket, a trade study was performed to determine the predicted altitude allowable by each tank option. First, an equivalent system mass was determined. This value corresponds to the mass of the tank and oxidizer, as well as all the components required in order to implement each design. The two carbon fiber tanks had the smallest equivalent system mass of 44.7 lb; since an individual tank only weighs 8.75 lbs, this weight was significantly less than the other options. Using the equivalent mass the total mass for the rocket was computed for each option, as well as the predicted thrust. This total mass, combined with the rocket's diameter and assumed drag coefficient of 0.35, yielded the predicted altitudes shown in Table 2. With the requirement of a 15,000 ft altitude, the two carbon fiber tanks were the only feasible option. These carbon fiber tanks would, however, require a more complex feed system, but this was deemed to be a challenge worth undertaking by this year's team and they were selected as the oxidizer tank component for the oxidizer delivery system.

4. Final Design

The final design of the oxidizer tank storage and feed subsystems was then laid out as shown in Fig. 10. The feed subsystem design was relatively straightforward as it simply acts as a transportation system. This transportation system is required to deliver liquid nitrous oxide to the injector subsystem safely while minimizing pressure losses and providing sensor interfaces. Items shown in yellow in Fig. 10 are valves designed to control the flow of liquid nitrous oxide to the injector while items in green, blue and red are simply piping elements. Also, a parallel configuration was the only possible way it was determined that the two gray oxidizer tanks could be integrated with the feed system, as shown in Fig. 10. Finally, a turbine mass flow meter (shown in dark red) and pressure sensor (shown in dark gray) will also be integrated into the oxidizer tank and feed subsystem final design in order to provide data for performance validation after the static hot fire test is performed. Thus, the system will provide liquid nitrous oxide from the oxidizer tanks on the right side of Fig. 10 to the left side where the piping will be threaded into the injector housing.

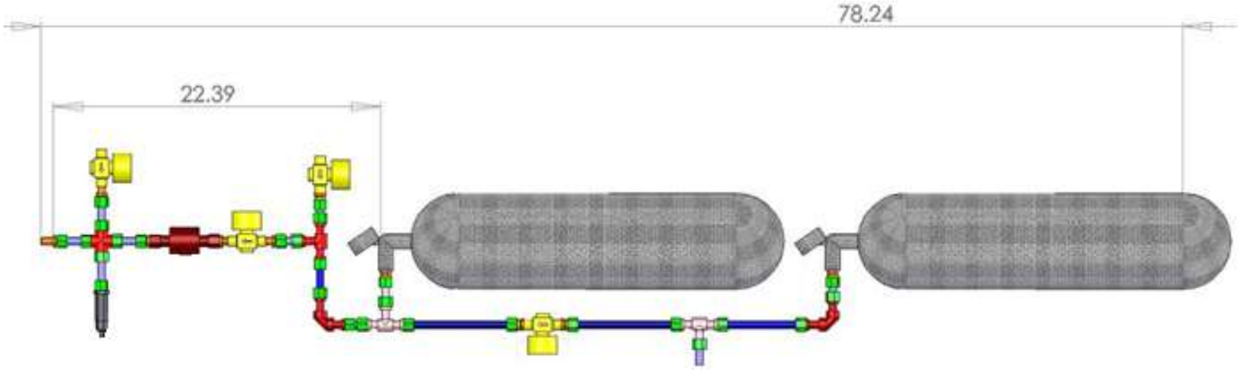


Figure 10: Feed System Final Design

III. Oxidizer Delivery System Testing

A. Purpose and Scope of Test

A test will be conducted in order to measure the pressures and flow conditions within the feed system and through the injector plate, to verify that the required flow conditions are met. This will be done by measuring the oxidizer flow rate and pressure drops across the injector plate and through the feed system.

B. Test Setup and Procedure

For the test, the initial tank pressure and regulator pressure will be set to 1200 and 673 psi respectively. These values are the theoretical desired values for proper flow conditions and will only be changed depending on the results of the experiment. This test will differ from the full rocket hot-fire test because there will be no combustion chamber and the oxidizer will flow into the atmosphere. The flow will be much faster than during the actual hot-fire test, but the data will be easily manipulated to predict hot fire performance. Three pressure transducers will give a system pressure profile, and a turbine mass flow meter will give the flow rate of the oxidizer. The oxidizer tanks and feed and injection systems will be integrated into the hot fire test stand for this test. Nitrous oxide will be used to provide accurate predictions for the behavior of the system.

IV. Conclusion

In order to design and build a flight-ready hybrid rocket motor, an effective and flight-weight oxidizer system must be designed and integrated. The 2005-2006 MaCH-SR1 team attempted to build their own liner-less composite oxidizer tank, but it failed their requirements for safety factor in test. Consequently, no University of Colorado MaCH-SR1 team has successfully integrated an upright, flight-weight oxidizer system into a hybrid rocket motor. The 2007-2008 MaCH-SR1 team plans to do this, creating a self-sufficient, flight-ready hybrid rocket motor. In order to reach the design height of 15000 ft with a payload of 1 lb_m, the rocket must maintain a thrust of at least 270 lb_f, with a goal of an average of 300 lb_f, of thrust for 15 seconds. It was found from past years' results that in order to attain this thrust value, the oxidizer flow rate needed to be increased. This was done by increasing the injector area and injector discharge coefficient. Next, in order to maintain this thrust for the full 15 seconds, and to maintain a very consistent thrust profile, the team decided to use a regulator along with initially pressurized oxidizer. Analyses of this design show that the flow rate of the oxidizer will stay within a 20% margin for the burn, and the pressure drop across the injector will be consistently between 20-29%, ensuring positive, stable flow of the oxidizer. Finally, the oxidizer tanks were selected for the design. This trade study took into account the equivalent system mass for several oxidizer tank options, as well as their drag and weight effects, and amount of oxidizer storage possible. From this study, it was determined that two tandem carbon fiber NOS tanks were the best option. The oxidizer system will undergo a system test in March of 2008 to determine if our goals were met with this design. It will also be used in a static hot fire test of the hybrid motor to verify our requirements. Both tests will utilize a turbine flow meter, pressure transducers and thermocouple temperature sensors to record data.

Acknowledgments

All authors would like to acknowledge the following people and corporations for their continuing contributions and support.

Faculty and Staff

Dr. Lakshmi Kantha
Dr. Dennis Akos
Dr. Robert Culp
Dr. Mahmoud Hussein
Dr. Scott Palo
Trudy Schwartz
Dr. Ryan Starkey
Dr. Hanspeter Schaub
Dr. Donna Gerren
Dr. Kamran Mohseni
Matt Rhode

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Kurt Etter
Laurren Kanner
Chris Madsen
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Alejandro Reiman-Moreno
Josh Stamps
Joel Wecker

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Kendra Kilbride
Hwapyong Ko
Jacob LaBonte
Brent Lewis
Adam McNeil
David Owen
Richard Rieber
Richard Rodriguez
Alex Romanov

2007-2008
Wes Haigh
Stacey Bagg
Jared Santistevan
Robert Wuest
Leon Slavkin
Richard Bell
Brad Crittenden

Industry Sponsors

Lockheed Martin Space Systems Company Denver, CO - Engineering Propulsion Lab (EPL)
Nick Patzer - Test Engineer
John Carey - Design/Test Engineer
Don Grissom - Ordinance
TY Meusberger - Design Engineer
Doug Banning - Ordinance
Dean Lenz - Lab Manager

Sartomer Inc.

Chris Ellor
Titanium Metal Supply, San Diego, CA
Walsh & Associates (Rhodia Inc. Supplier)

University Sponsors
University of Colorado Engineering Excellence Fund (EEF) Organization
University of Colorado Undergraduate Research Opportunities (UROP) Organization
University of Colorado Aerospace Department

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