Reaction Control System

ME 461 SENIOR CAPSTONE FINAL REPORT

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Abstract

The Boston University Rocket Propulsion Group was in need of a custom RCS system that utilizes the already onboard pressurant of Nitrogen (which we will use as propellant) to terminate the roll of their Quasar rocket upon re-entry into the atmosphere. The purpose of this is to mitigate as much risk as possible in deploying the recovery system. The Reaction Control System we have designed and fabricated consists of force coupled, 3-D printed nozzles mounted to a 7” tall ring section of the rocket. The internal piping consists of a regulator to control the output from the source tank and two solenoid valves which control each nozzle couple. This low thrust, long duration burn system is capable of providing enough thrust to cancel a roll rate in a given window of the rocket’s trajectory.

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Design Problem Statement

The Boston University Rocket Propulsion Group requires roll control to stabilize their Mk IV Quasar rocket on ascent and to de-spin the rocket for atmospheric re-entry. No such system is available for selection due to the complex nature and customization of the vehicle. As a result, a system that can provide these functions is sought out to be designed and fabricated. A full Project Proposal can be found in Appendix 1.
Background and Benchmarking

As various members of this project team are also members of the Boston University Rocket Propulsion Group, we have been aware of their own ongoing project and its needs for nearly a year. BURPG is working with several other universities to collectively build a large sounding rocket that will be launched in the later part of August 2014 with payloads and flight computers on board for these universities’ research. Over time they determined that one of the many components they required was a RCS (Reaction Control System) that would be used to control the stabilization rotation of the rocket during ascent, and later on completely de-spin the rocket once it had reached its operation altitude in preparation for re-entry into the denser region of the atmosphere.

As this system would require the design of nozzles to provide the required thrust, we were tasked as aerospace concentrator seniors. In short order, our team had been contracted to design and manufacture this system. Typical Reaction Control Systems are sets of thrusters firing a variety of unburnt fuel or compressed gas which are assembled in pairs to form arrays. These arrays can be fired in tandem to control the roll, pitch, and yaw of the spacecraft, or to translate the spacecraft. RCS’s of this type have been used since nearly the beginnings of space exploration in the 1950’s. Since our customer only wants to spin and de-spin a rocket as per the requirement, our system only needs to control the roll of the rocket.

As such, we have decided to not use standard arrays that allow for movement and rotation in three directions and instead use the type of system used to maintain the rotation of “spinning” spacecraft and missile systems. That is, the RCS will contain two pair of thrusters on the surface of the cylindrical rocket body; one set for clockwise rotation and another for counterclockwise rotation.
# Customer Requirements

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<th>Weight</th>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Must withstand 15 G’s, Design for 40 G’s</td>
<td>Compliant</td>
</tr>
<tr>
<td>2</td>
<td>Must de-spin rocket from 6 Hz to zero spin in 3 seconds</td>
<td>Not compliant</td>
</tr>
<tr>
<td>3</td>
<td>Must use on board Nitrogen</td>
<td>Compliant</td>
</tr>
<tr>
<td>4</td>
<td>Nominal Roll Rate on Ascent: 4 Hz</td>
<td>Compliant</td>
</tr>
<tr>
<td>5</td>
<td>Nominal Altitude for activation: 60,000 ft.</td>
<td>Compliant</td>
</tr>
<tr>
<td>6</td>
<td>Budget: $780</td>
<td>Compliant</td>
</tr>
<tr>
<td>7</td>
<td>Must be complete and ready for integration by next fall (originally April 5th)</td>
<td>In progress</td>
</tr>
<tr>
<td>8</td>
<td>Mass of Ring 2.9lbs, we are left with 3.1lbs (6lbs total)</td>
<td>Not Compliant</td>
</tr>
</tbody>
</table>

*Table 1: Customer Requirement compliancy chart*
The requirements of the RCS include the customer requirements as set by the BU rocket and the engineering requirements. The system has to be able to withstand 15 G’s of force during flight however it is designed for 40 G’s. The connections points are built to withstand such a force. The most important requirement is that the RCS must de-spin the rocket from 6 Hz to zero spin in 3 seconds. This is what drives the design portion of the system. To de-spin the rocket the system will be using the nitrogen on board the rocket as the monopropellant. The nominal roll rate on ascent on ascent will be 4 Hz meaning the RCS will activate when the rocket is spinning at 4 Hz and this is to be handled by the sensor system. In addition the sensor system will know that the nominal altitude for activation is 60,000 ft. The budget available is $780. Originally the system was supposed to be complete and ready for integration by April 5th and the RCS was designed with the requirement in mind. However the rocket team’s deadline was pushed continually pushed back until it was determined that the rocket would not be launched this year but instead next fall. A physical requirement is that the system has to be less than 3.1 lbs however this is not a hard requirement and not one that has been met.
As can be seen in the functional decomposition graph, on the first level the RCS must reduce the pressure that is being fed from the nitrogen tank. Calculations have been (and will later be shown) done to determine the ideal pressure for the RCS to operate. To reduce the pressure of the nitrogen to the desired pressure a mechanical pressure reducing valve will be used, as shown in the 2\textsuperscript{nd} level of the chart. In addition, gas must be transported to the exit of the nozzle for the system to work and this will be accomplished by the piping. Lastly, the RCS must expel the gas to achieve de-spin. To control when the gas will be expelled, a solenoid valve is opened and closed by the sensor system. The gas that is expelled also has to be accelerated and expanded and this is accomplished by the design of the nozzles that the solenoid valves feed into.
Engineering Specifications and Relevant Basic Physics

The physical requirements imposed on the RCS include volume, weight, power, pressure, and most importantly roll rate. The volume is constrained by the housing of the system which is a cylinder with a 7.75 inch inner diameter and 7 inch height. The target weight is to be less than 5 pounds, however this is not a hard requirement and one in fact that is not met with the system currently at 6.6 pounds. There is a power requirement of 12 volts to power the two solenoid valves to be used in the system. The RCS will be accessing an onboard pressurant tank which will initially be at 4500psi. After the burn of the main engine and subsequent activation of the RCS system, we will be dealing with around 2100 psi regulated down to 300psi. Through moment calculations and simulations it was determined that 300 psi is required to control flow per nozzle. The driving requirement of the RCS is a required terminate roll rate of 6 Hertz in 3-5 seconds. The torque that is needed by the system was calculated based on this requirement as follows:

\[
\tau = l \frac{d\omega}{dt} = 3502.12 \text{ lbf} \cdot \text{s}^2 \cdot \text{ft} \cdot \frac{6\text{Hz} \cdot 2\pi}{3s} = 44008.94 \text{lbf} \cdot \text{in}^2 = 9.5 \text{lbf} \cdot \text{ft}
\]

(Equation 1)

In addition, the system must be able to withstand 15-40 G’s of acceleration which in all cases is tested using FEA analysis assistance from the solidworks CAD program.
Housing

The housing is designed to contain the RCS system in a 4” tall section of the rocket. It must overlap with adjoining sections via 1.5” tall coupler. We are allowed to use the total volume of the 7”

Figure 3: RCS Housing Design

Our design includes 4 ports for mounting thruster, a thinned area in the middle to reduce the weight, and the 2 requested couplers to attach to adjoining sections of the rocket.
Nozzle Design

Compressible Flow Theory

Compressible flow deals with the analysis of fluids that exhibit significant changes in density with changes in pressure. The effects of compressibility become significant at when a fluid’s velocity relative to a given reference frame approaches and exceeds the speed of sound in the fluid. The measure of the velocity as it pertains to compressible flow is called the Mach number and is defined as the ratio of velocity to the speed of sound in the fluid. When the Mach number exceeds 1, the fluid exhibits acoustic shock waves. The fluid will also exhibit different characteristics when undergoing compression and expansion, called choked flow.

The Mach Number

The Mach number is the ratio of velocity to the speed of sound in the fluid.

\[
M = \frac{v}{a}
\]

(Equation 2)

The speed of sound, \( a \), is defined as:

\[
a = \sqrt{\gamma RT} = \sqrt{\gamma \frac{P}{\rho}}
\]

(Equation 3)

Where \( \gamma \) is the ratio of specific heats for the fluid, \( R \) is the specific gas constant of the fluid, \( T \) is the fluid temperature, \( P \) is the fluid pressure, and \( \rho \) is the fluid density. It can be seen in equation above that the ideal gas law applies.

Isentropic Flow

Isentropic means “constant entropy”. Isentropic processes are adiabatic and reversible, allowing for no head addition or loss, and no dissipative effects such as friction. In the study of compressible flow, this assumption is often held to simplify the mathematical modeling, with the exception that the isentropic assumption is not held across shock. Fig 3 shows a list of equations used under isentropic flow conditions. The identifiers “total” and “sonic” refer to conditions at a mach number of \( M=0 \) and \( M=1 \).
respectively. This chart also includes the equation for a supersonic nozzle area ratio (equation 9), which we will use later on.

![Isentropic Flow Chart](image)

**Figure 4: Isentropic flow equations**

Shockwaves and expansion fans

As flow changes from subsonic to supersonic, a shockwave is generated and isentropic conditions no longer apply across the shock. Shocks are also generated when supersonic flow contacts new surfaces and when it becomes subsonic again. There are two main types of shocks, normal and oblique. A normal shock occurs perpendicular to a supersonic body, and an oblique shock occurs at an angle. If there is no contact with the body, like in a duct flow, or if there the body contacted is normal to the flow, a normal shock will occur. If a supersonic flow encounters a body at an angle, if two shocks within a flow interact at an angle, or if a flow exits a duct at a pressure lower than the ambient pressure, an oblique shock will occur. An expansion fan is the opposite of an oblique shock. Instead of a sudden compression, an expansion fan is the result of a sudden expansion of the flow around an angle. An expansion fan will occur as a supersonic flow passes a surface angled away from the flow, or if a flow exits a duct at a pressure higher than the ambient pressure.

The flow changes across a normal shock can be described by the equations listed in Fig 5.
Choked Flow

A duct flow can be “choked” to achieve supersonic flow conditions. This is incredibly useful in the design of nozzles, as a key feature of supersonic flow is that unlike subsonic duct flows, which lose velocity as they expand, supersonic flows gain velocity as they expand. Choked flow is defined by a pressure decrease according to the following equation:

$$\frac{p^*}{p} = \left(\frac{2}{\gamma + 1}\right)^\frac{\gamma}{\gamma - 1}$$

\[\text{(Equation 4)}\]

Where \(p\) is upstream pressure and \(p^*\) is the critical pressure.

If the downstream pressure falls below \(p^*\), supersonic flow is achieved. In a choked flow, the smallest diameter of the duct is called the throat. The flow at this point will always be \(M=1\). Expansion of choked flow is characterized by the expansion ratio, \(\frac{A}{A'}\) or \(\epsilon\) (fig 6 or fig *). This ratio will be important to designing our nozzles.
15

Figure 6: Equations for choked mass flow and expansion ratio

Nozzle Theory

Our nozzles are based on the Rao bell nozzle design. This is the optimal bell nozzle design. It was developed by G.V.R. Rao in 1960. Since our nozzles must mount in a cylindrical rocket, we must modify the nozzles to become what are called “scarfed” nozzles. We also developed but were unable to test a different nozzle design based on a combination of a Rao bell nozzle and a curved tube. We were hoping that this nozzle would perform comparatively with the scarfed bell nozzle, but were unable to test and did not generate simulation data for this design.

Rao Bell Nozzle

The Rao Bell Nozzle is described by the equations listed in fig 6. Nozzle throat diameters are specified and exit plane diameters are determined using the expansion ratio equation in fig 5. This parameter along with the length scale is used to find the parabolic section entry and exit angles, and throat diameter is varied to generate nozzles with different thrusts and flow rates. Typically, optimal bell nozzles are very long which can be problematic in some applications. The nozzle can be shortened by a percentage of its full length for a small performance loss.

As an example, the Virgin Galactic SpaceShipTwo uses a 20% bell nozzle which is very short compared to a typical 100% bell nozzle. This very short nozzle allows for SpaceShipTwo to easily land without worry of scraping the nozzle on the ground and reduces risk of damage during landing due to the moment applied by the weight of the nozzle.
Approximate Optimization Approach

• Near throat region composed of two spherical sections
  – before throat: \( R_1/R_\ell = 1.5 \)
  – after throat and up to N: \( R_1/R_\ell = 0.382 \)
  – N given by \( x_N = R_1 \sin \alpha \) \( y_N = R_\ell + R_1 (1 - \cos \alpha) \)
• Parabola (after N) with slope matched at N
  \( y' = P x' + Q + (S x' + T)^{\frac{1}{2}} \)
  – 4 unknowns: \( P, Q, S, T \)

4 boundary conditions:
1) \( x_N = y_N = 0 \)
2) \( x'_N = L - x_N \) \( y'_N = \sqrt{\varepsilon \, R_\ell - y_N} \)
3) \( \partial y_N = \text{supplied (e.g., Rao)} \)
4) \( \partial y'_N = \text{supplied (e.g., Rao)} \)

Figure 7: Rao Bell Optimization Contour

Approximate Optimization Approach

• Output of approach is "optimal" contour given
  – \( \varepsilon \)
  – acceptable length \( L \) (shorter \( \Rightarrow \) larger divergence \( \theta_e \))
• Typically \( L \) is specified relative to length of conical nozzle with \( \alpha = 15^\circ \)
  \[ L = f(\%)(\frac{R_\ell}{\tan 15^\circ}) \left\{ \sqrt{\varepsilon} - 1 + 1.5 \left( \frac{1}{\cos 15^\circ} - 1 \right) \right\} \]

Figure 8: Rao Bell Optimization Length

AE6450 Rocket Propulsion
We should note that in our modeling, we did not determine the equation of the parabolic section according to the given equation $y' = Px' + Q + \sqrt{Ss'} + T$ and the boundary conditions listed in fig 6. As it turns out, the parameters in this equation are incredibly difficult to solve for analytically. After many attempts to solve for the parameters, we instead used SolidWorks to generate a spline curve that connects the two points $x$ and $y$ and is tangent to the angles specified in fig 8. Though we cannot confirm that it is a true parabolic section, the curve appears to fit exactly what we need and any error is negligible. The performance increase of a full length bell nozzle over a comparable conical nozzle is only about 1%. There is a great increase in relative performance as a bell nozzle is shortened compared to a shortened conical nozzle, though as we’ll see, our design allows for us to use 100% length bell nozzles.

In designing a nozzle we must consider how the expansion ratio affects the flow out of the nozzle. A low expansion ratio will result in under expanded flow, causing oblique shocks at the exit plane of the nozzle. A high expansion ratio will result in over expanded flow, causing a normal shock to occur inside the nozzle followed by the formation of shock diamonds outside of the nozzle. A fully expanded flow will have a normal shock exactly at the exit plane, and is desired. It is important to remember that the flow is driven by a pressure gradient, and these pressure gradient changes as a rocket ascends due to decreasing atmospheric pressure. Overexpanded flow is more desirable than underexpanded flow and occurs at altitudes higher than fully expanded flow. Underexpanded can potentially be damaging to the
nozzle and should be avoided as much as possible. Thus, it is best to design the nozzle to be fully expanded at the lowest altitude we plan to fire it at.

The driving pressure gradient is very important to determining how much force we need out of the nozzle. From repeated simulation, we decided to use an inlet pressure of 300psi, which will be discussed in the simulations section. The nozzles we generated from the design conditions and the 300psi inlet pressure are shown in fig 9.

<table>
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<tr>
<th>Nozzle Design Data</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<td>alpha deg</td>
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<td>15</td>
<td>15</td>
<td>15</td>
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<td>0.125</td>
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<td>R_u in</td>
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<td>R_d in</td>
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<tr>
<td>A_t in2</td>
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<td>0.04909</td>
<td>0.07069</td>
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<td>A_e in2</td>
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<td>0.7854</td>
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<td>expansion ratio n/a</td>
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<td>16.43</td>
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<td>L in</td>
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</tr>
<tr>
<td>theta_e deg</td>
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<td>5</td>
<td>5</td>
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</table>

*Parabolic Section Interpolated in SolidWorks*

Figure 10: Design data for 4 Rao Bell Nozzles

**Scarfed Bell Nozzle**

A scarfed nozzle is a nozzle that is cut such that flow exits through a surface different from the nozzle’s specified exit plane. Scarfed nozzles have many applications, especially on vehicles that experience atmospheric flight during their mission. Nozzles that stick out from a rocket’s side can be a large source of drag during atmospheric flight and should be contoured to the rocket’s body. Scarfed nozzles were used in the space shuttle’s RCS system as shown in fig 10.
Though scarfed bell nozzles are not uncommon, there is very little information on them publicly available. Most textbooks on rocket propulsion systems will mention scarfed nozzles and show that the thrust from a scarfed nozzle will be angled more towards the removed section of the nozzle as shown in fig 11, but how large this angle will be and how it is affected is not often discussed.

There is, however, one study done by NASA in 1979 that gives useful information on the efficiency loss for 2 different types of scarfed nozzles. One of these nozzles (analytical scarfed nozzle (a) fig 12) is similar to our design and can be used to give an estimate of our expected efficiency loss. Since we are only using this as a rough estimate, we will ignore that our nozzles are not cut along a plane like the
nozzles in the NASA study. It can be seen in fig 13 that the maximum efficiency loss is about 3% for the LOX-LH₂ and the maximum loss occurs at the original exit plane ($e_2$). Though there is data for a chamber pressure of 300psi, we must be wary of this data. This data is for the LOX-LH₂ combustion at a 300psi chamber pressure. We are not using a combustive system. It is possible that we will have a larger efficiency loss due to this difference, however without comparative data, we cannot know. We will assume that we will have a loss of 2%-3% from scarfing.

Figure 13: NASA Scarfed Bell Nozzle Study

Figure 14: NASA Scarfed Bell Nozzle Study, efficiency vs relative cross sectional area
**Nozzle Layout**

Our nozzle layout is determined by a few factors; they must produce a force couple (180 degree radial symmetry about rocket axis), they must be as close to tangent to the rocket body as possible, and they must have enough material covering the sides of the bell to prevent any damage or leakage.

A cross section of our nozzle layout with nozzle C (fig 10) can be seen in fig 14.

![Figure 15: Scarfed Nozzle Layout](image)

**Swept Half-Bell Nozzle**

We had a novel idea for a design that we wanted to test against the scarfed bell nozzle, but we were never able to test it. A preliminary design of this nozzle is shown in fig 15. Please note that this is not a proper convergent-divergent nozzle. It is only an illustration to show the intended contour of the nozzle.
The swept nozzle is an interesting concept that is very difficult to produce. However with the advent of 3D printing, this design is now much easier to manufacture and could be made and tested on a small scale.

The swept half-bell has some potential benefits and drawback when compared to the scarfed bell nozzle.

Benefits:

- Thinner exit area allows for flow to be more uniformly directed
- Sweeping allows for flow to be more tangential to the rocket body

Drawbacks:

- Smaller exit area allows for poorer expansion of flow
- Curved nozzle will suffer losses that a linear nozzle will not
- Curved nozzle may experience internal oblique shocks

We cannot be certain if the benefits will outweigh the drawbacks, and though we were unable to test these nozzles, we remain interested in them and may develop them in to a personal project for one or more of our team members.

**Nozzle Manufacturing**

We decided to 3D print our nozzle on the Objet 3D printer in BU EPIC. 3D printing allows for fast production of complex geometries that are difficult or impossible to machine. The object uses ABS plastic which is cured with UV light. The plastic is quite strong and not prone to cracking, which is useful for our application. Our one concern that we were unable to test is the potential for the plastic to crack at very low temperatures.
SolidWorks Models

Single Scarfed Bell Nozzle

For our early modeling, we wanted to be able to print a pair of nozzles that would generate a force couple for testing. We printed pairs of single nozzles for this initial testing. The nozzles slip in to the ports in the nozzle housing. Among the problems with this design is that the individual nozzles could not be easily attached to the RCS housing in a way that would withstand the thrust produced.

![Single Scarfed Bell Nozzle Models](image)

*Figure 17: Single Scarfed Bell Nozzle Model*

Double Scarfed Bell Nozzle

The double scarfed bell nozzle combines two nozzles in to one unit that can be mounted to the housing with ¼-20 screws. When mounted with these screws, it is capable of withstanding the forces produced during operation. It is our final nozzle design.

![Double Scarfed Bell Nozzle Models](image)

*Figure 18: Double Scarfed Bell Nozzle*
Test Bell Nozzle

Due to the low thrust of our final nozzle, we designed and tested a linear version of the D nozzle to try to get a better thrust reading. We have not yet tested this nozzle.

![Test Nozzle Cutaway](image)

**Figure 19: Test Nozzle Cutaway**

Nozzle Simulation

Our simulations are done in AeroRocket Nozzle 3.7. All of our simulations are solved for with the classical gas dynamics method, which uses the equations listed in the compressible flow theory section and figures (fig 1-3). Nozzle 3.7 is also used to determine if our nozzle is properly expanded at our design altitude of 60,000 ft.

AeroRocket Nozzle 3.7

More information on the use and functionality of Nozzle can be found at [http://aerorocket.com/Nozzle/Nozzle.html](http://aerorocket.com/Nozzle/Nozzle.html).
Flow Modeling

Figure 20: Nozzle Input Table

Figure 21: Nozzle Output Table

Shockwave Modeling

We want to have fully expanded flow in our nozzles at our design altitude. Iterative modeling of the shockwaves shows how close we are to our target design. In fig 22, the shock angle $\theta$ is less than $1^\circ$, indicating that we are at our target design.
Simulation Results

Table 2 shows the inputs, outputs, and some calculations related to the nozzles. The section “Data for nozzle sim inputs” is the same as the table in fig 20. The Required Torque, Exit Plane Angle, and Required Thrust fields are calculated using the same method as shown in the “Engineering Specifications and Relevant Basic Physics” section. The Thrust, Mass flow rate, and Isp fields are outputs from the simulation. Fully expanded? Shows if the nozzle meets our target design.
<table>
<thead>
<tr>
<th>Nozzle</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
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<td>Type</td>
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<td>Entrance Pressure</td>
<td>psi</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Back Pressure</td>
<td>psi</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cp/Cv</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>R</td>
<td>255457.733</td>
<td>255457.733</td>
<td>255457.733</td>
<td>255457.733</td>
</tr>
<tr>
<td>Length + Throat Location</td>
<td>in</td>
<td>1.635782731</td>
<td>1.797257072</td>
<td>2.113348486</td>
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<tr>
<td>Throat Diameter</td>
<td>in</td>
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<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>Throat Location</td>
<td>in</td>
<td>0.1399</td>
<td>0.1398</td>
<td>0.1244</td>
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<tr>
<td>Upstream Throat Radius</td>
<td>in</td>
<td>0.165</td>
<td>0.1875</td>
<td>0.225</td>
</tr>
<tr>
<td>Downstream Throat Radius</td>
<td>in</td>
<td>0.04202</td>
<td>0.04775</td>
<td>0.0573</td>
</tr>
<tr>
<td>Theta_n</td>
<td>degrees</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Exit Diameter</td>
<td>in</td>
<td>0.9</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>Required Torque</td>
<td>ft*lbf</td>
<td>9.49</td>
<td>9.49</td>
<td>9.49</td>
</tr>
<tr>
<td>Exit Plane Angle</td>
<td>degrees</td>
<td>34</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>Required Thrust</td>
<td>lbf</td>
<td>16.55</td>
<td>16.96</td>
<td>17.18</td>
</tr>
<tr>
<td>Thrust</td>
<td>lbf</td>
<td>18.525</td>
<td>23.919</td>
<td>34.444</td>
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<tr>
<td>Mass flow rate</td>
<td>lbm/s</td>
<td>0.257</td>
<td>0.39</td>
<td>0.562</td>
</tr>
<tr>
<td>Isp</td>
<td>s</td>
<td>72.2</td>
<td>61.3</td>
<td>61.3</td>
</tr>
<tr>
<td>Thrust/Required Thrust</td>
<td></td>
<td>1.119197556</td>
<td>1.410181414</td>
<td>2.004640592</td>
</tr>
<tr>
<td>Fully Explanded?</td>
<td></td>
<td>Fully Expanded</td>
<td>Fully Expanded</td>
<td>Fully Expanded</td>
</tr>
</tbody>
</table>

*Table 2: NOZZLE Simulation Results*
Evolution of Project

Basics

From the very conception of the project, it was known that we would be following a well-established design. Rather than re-invent the wheel, we decided to extrapolate our design on the RCS systems currently in use by governmental and commercial space agencies around the world. While most in-use RCS systems are a set of many small thrusters that allow the spacecraft to be both translated and rotated in any combination of XYZ space, the specifications given by our customer only require us to control the roll of the rocket during ascent. This in turn led to our initial design.

![Figure 23: Overview of First Design](image)

We began by simply designing four nozzles, organized in two force couple pairs, to be placed in the RCS ring, flush with the outer surface of the ring. The curvature of this surface required the nozzles to be cut along the curved plane, creating a set of four scarfed nozzles. These nozzles are connected
internally via piping to a pair of solenoids, which in turn are connected to a single pressure regulator that provides a consistent 300 psi to the system from the Nitrogen (N$_2$) tank that acts as the propellant for the RCS. The solenoids are also connected through a board to the rocket’s existing computer system, which controls when the force couples are activated.

![BRAINSTORMING - MORPHOLOGY](image)

Since the design was easy to set up the basics for, it became clear that the main challenge to be presented to us was to design the nozzles themselves such that they provide the proper thrust to de-spin the rocket in the specified time. To this end, there was a large amount of simulation, CAD design, testing, additional simulation and redesign, retesting and building done to achieve nozzles that provide the performance required.
The very first step was to receive data from the customer on the physical dimensions and properties of the rocket as a whole. This data was fed into a spreadsheet (Figure 23) along with the rotation and de-spin specifications to determine the force couple required to meet said specifications, and the horizontal thrust the nozzles must provide.

![Figure 25: Calculation of Required Torque and Force](image)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment Torque Requirements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T=ldw/dt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable Name</td>
<td>Symbol</td>
<td>Value</td>
<td>Units</td>
<td></td>
</tr>
<tr>
<td>Z Axis Moment of Inertia</td>
<td>lzz</td>
<td>3502.12</td>
<td>lbm*in^2</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>t</td>
<td>20 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational Rate</td>
<td>wr</td>
<td>6 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle of Propellant Ejection</td>
<td>theta</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Moment Arm</td>
<td>arm</td>
<td>4.15 inch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Calculations**

<table>
<thead>
<tr>
<th>Torque</th>
<th>6601.34 lbm*in^2/s^2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.42 lbf*ft</td>
</tr>
<tr>
<td>Horizontal Force</td>
<td>4.12 lbf</td>
</tr>
<tr>
<td>Total Force</td>
<td>4.86 lbf</td>
</tr>
<tr>
<td>Total Force per Nozzle</td>
<td>2.43 lbf</td>
</tr>
</tbody>
</table>
Figure 26: Simulation of Nozzle Design in NOZZLE suite
Following this, we then moved on to using the NOZZLE program (Figure 24), developed by AeroRocket\textsuperscript{8}. This software suite allows for the input of nozzle parameters (length, throat diameter, exit diameter, species of fluid, shape of nozzle, and more) to simulate how a given design of nozzle will perform at various altitudes. This software was chosen as it is a common package in industry, and has been shown to be reliable by them for a long time. Starting from a scarfed version of the standard Rao Bell Nozzle, we then iterated through designs until we reached four candidate designs that both provided the necessary thrust and met the physical space limitations placed by the specifications. Said designs were shown to our customer, and with their approval design work continued.
Internal Workings

With the most demanding segment of the design completed, we moved on to designing the internal workings of the RCS, starting with the pressure regulator. From the nozzle simulation data (Figure 25), it was determined that the inlet pressure of the nozzle must be 300 psi. As such, we searched for a pressure regulator that can regulate from a tank pressure range of 4500 psi to 2100 psi down to the requirement, and do so without fluctuations in the outlet pressure. After much research, talks with more knowledgeable engineers, quotes and discussions with manufacturers, it was discovered that the Ninja Pro SLP Series Tank Pressure Regulator for paintball guns met our needs at reasonable cost.
That completed, the solenoids were the next thing to be selected. With the knowledge of the line pressure and the planned binary operation of each force couple, further research was done, and the McMaster Carr #5077T144 Solenoids were chosen and ordered. After that had been set, the next step was to design the printed circuit board that would be used to amplify and regulate the operation signals received from the onboard computer for use by the solenoids. As the solenoids support ideal binary behavior (current on causes full activation, current off fully closes the valve), a fairly simple design (Figure 9) was completed. The main issues was choosing the appropriate resistors and transistors to both allow for the use of “Active/In Use” LEDs on the RCS and allow the incoming signal to be amplified to the 12 V that runs the solenoids, respectively.

As none of the team are Electrical Engineers or were particularly skilled in Circuit Theory, we collaborated with an expert, one Dean Alexander De Carli from the Rocketry Team, to complete the design, which was ordered from the ExpressPCB company. The final schematic labels the +12V power supply that powers solenoid activation, the input signal port from the onboard computer, the signal ports (SA-B) were the leads of the solenoid are to be attached, transistors T1 and T2 that amplify the control signal, resistors R1-3 that form the voltage amplifiers, diodes D1 – D3 that light up when board or solenoid is in use, and the ground port for all the above. The completed board will be mounted on the
underside of the bulkhead dividing the RCS section from the nose cone, and will be powered by a dedicated 12V LiPo batter that will mounted to the same.

Figure 31: Final PCB Design
Piping

Figure 32: Final Piping CAD

The last of the internal workings of the design was the piping specification. The main consideration taken was the creation of a piping layout (of \( \frac{3}{8} \)" aluminum pipe) that fits within the given space without containing turns so sharp that significant head loss would not occur. In addition, the \( \frac{3}{8} \) inch outer diameter pipe was chosen because it was the smallest size that the accessible pipe bending tools could bend. The pressure drop across one line of pipe was calculated using a spreadsheet provided by Professor Frank DiBella. The inputs for this spreadsheet are pressure, temperature, fluid density, fluid viscosity, fluid flow, pipe diameter, and number of fittings in line. It was determined that along one line of pipe there is a pressure drop of 32.8 psi. While it would be ideal to have no pressure drop, this is not a substantial amount and satisfactory for the design.
Testing

Test Setup

In order to obtain data for the thrust provided by the RCS a test setup was fabricated that uses an S-load cell as the data acquisition unit. The thrust of the system pushes against the load cell and registers as data. The load cell was connected to a DAQ board in a Boston University lab and LabView was used to interpret the incoming data. A LabView program was made that recorded in 3 second intervals with a 5 Hz cutoff frequency. To calibrate the setup, independent masses were hung from the load cell and then interpreted in Excel to obtain calibration data.

Test Stand – Design Concept

Ultimately, we want to determine torque applied to the rocket, as well as thrust from each of the nozzles. To achieve this, we designed a system which measures linear force applied tangentially to the RCS unit. With the load cell mounted to measure force tangential to the housing, we do not need to account for the difference in the moment arms applied by the nozzles and the load cell, simplifying our analysis.
We had a total of four tests completed with our original design. The first two tests were run and gave correct results, but analysis showed that total thrust achieved by our nozzle was constant at a given value. Upon review of our rig, we found that the bolt that connects the load cell to the rig had been over tightened, which effectively gave a pre-stressed setup. The results from these two tests were ignored. After correcting the issue we ran another two rounds of tests, which gave more reasonable data. We discovered, however, that we still had an offset that could not be accounted for in our physical rig. With this system, we determined that our nozzles were giving an average of 1.1 lbf. Due to the unquantified error, we sought more consultation with Rocket Team member Drew Kelley, who assisted us in reconfiguring our Data Acquisition Board and data capture software to give more precise results.
This final set of results was found to give precise results, and showed that our nozzle system gave an average thrust of 0.2 lbf with the Ninja regulator called for in the design. This was much less than the expected 1.12 lbf of thrust at sea level. This result in turn meant that the design would de-spin the rocket in about 15 seconds instead of the 6 seconds required. After investigation into the cause, we found that there were two major shortcomings. The first was that our chosen design of nozzle required a significantly higher mass flow rate than what our pressure regulator was capable of providing. The second was that the chosen stock of pipe has an internal diameter smaller than the throat of the nozzles, which caused the flow to choke too early and not provide the flow parameters expected at the nozzle exit. We decided to pursue a different pressure regulator at this point.
Current State of Project

General-Purpose Diaphragm-Sensing, Pressure-Reducing Regulators (KPR Series)

The KPR series is a compact regulator with excellent accuracy, sensitivity, and set-point pressure stability.

Features
- Convoluted, nonperforated diaphragm
- Metal-to-metal diaphragm seal
- Low internal volume
- Two-piece cap design provides linear load on the diaphragm seal
- High-flow, dual-gauze type filter positively retained in inlet port

Technical Data

Maximum Inlet Pressure
- 3600 psig (248 bar)
- 6000 psig (413 bar) with PEEK seat

Pressure Control Ranges
- 0 to 10 psig (0.08 bar) through 0 to 500 psig (34.4 bar)

Flow Coefficient (Cv)
- 0.06 and 0.20
  - See page 41 for flow graphs.
- 0.02 and 0.50 also available

<table>
<thead>
<tr>
<th>Flow Coefficient (Cv)</th>
<th>Pressure Control Range</th>
<th>Supply Pressure Effect, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 100 psig (6.8 bar)</td>
<td>250 psig (17.2 bar) and Higher</td>
</tr>
<tr>
<td>0.02</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>0.08</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.20</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>0.50</td>
<td>2.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Maximum Operating Temperature
- 176°F (80°C) with PCTFE seat
- 392°F (200°C) with PEEK seat
- 212°F (100°C) with PEEK seat and maximum inlet pressure greater than 3600 psig (248 bar)

Weight
- 2.4 lb (1.1 kg)

Ports
- 1/4 in. female NPT inlet, outlet, and gauge ports (all body materials)
- 1/4 in. tube butt weld inlet, outlet, and gauge ports (316 SS body material only)
- 1/4 in. VCR® inlet, outlet, and gauge ports (316 SS body material only)

Figure 37: Final Pressure Regulator

10
With this the redesign process began. The first step was to more carefully choose a pressure regulator, which was ultimately a simpler task than we had imagined (as such information was easy to find once we were looking for it). A new order was placed, and focus changed to the nozzles. They were redesigned such that the narrowest point in the system would again be at the throat. After this only minor changes were needed for the piping, and soon our second design was finished. Due to a thirty day manufacturing and shipping lead-in for the new pressure regulator\textsuperscript{1}, the final build of the RCS will not be available until the end of May, but upon discussion with our customer, it was learned that their own deadline for the finished rocket was pushed back, which in turn allowed for an extension of our project. Further, it was decided that the first build of the RCS would be sufficient for all testing purposes until then.

\textbf{Figure 38: Final Nozzle Design}

1
Additional

Though not directly related to our design process, there was an additional incident that occurred between our team and the customer. During the start of the first round of nozzle testing, the communication between our team and the customers greatly slowed down, which caused the customers to make assumptions on our progress. About two weeks later, the customers contacted us, angry at the lack of information and taking it as evidence that our team had made no progress at all. After heated discussion, the issue was de-escalated and resolved. The Rocketry Team was informed of all progress up to then, and the two teams worked much more closely from then on. While have little concrete effect on the project, the argument caused time to be lost on both times and caused some (thankfully short lived) strife between the teams, but it did ultimately increase our communication.
Market and Benefit Analysis

As with nearly all project and products, the cost and benefit of the final product to both the customer and the firm providing the product/service is something that is of enormous import. The clearest part of this is easily the Market Analysis. The majority of RCS systems are meant to provide translation and rotation in three dimensions, while our design provides only rotation about one axis. As this is a very specialized piece of equipment that is made to very nonstandard specifications, it is not something that can be easily adapted to other cases. At best, the Rocketry Team will keep the design for their own use and modify it for later iterations of sounding rocket design, or possibly for other universities rocketry teams of similar design. As such, we will likely not have more than 1-2 dozen customers, and that only if we manage to become a key player in the market. This in turn means that we are very unlikely to ever make back our investment, and that we should not pursue the selling of our design to others.

Project cost incurred by the design and construction team (i.e., us) was well below our given budget at the end. All teams that were completing a project for ME461 were given a budget of $400 to pay for all expenditures. However, all teams were also allowed and encouraged to procure outside funding, be it from a company sponsor, an organization on campus, or private donators. In our case, we were additional funding from our customers, the Boston University Rocketry Team, in the amount of $750. From our total budget of $1150 we purchased all of our ordered parts and stock for us to fabricate parts ourselves in the Tinker and EPIC labs. These ultimately included ¼” aluminum piping, flaring tools, adapters, pressure regulators, solenoids, printed circuit board, batteries, and miscellaneous nuts, screws, and etc. A full bill of materials is included in Appendix 2.

All custom parts needed for the design, with the exception of the PCB, were hand machined by the team, whose labor was donated to our cause. All off the shelf parts were ordered. These factors combined led to a total expenditure of $606.24, broken up into $373.37 from the Capstone Budget and $232.87 from the Rocket Team contribution. As we had no budget targets to meet other than our limit, we are at liberty to say that we are under budget, with about 47% of our budget remaining. Given that our project that is never met to compete with commercially available RCS, it is not fair to compare the costs of our designs with their prices. Despite this, we are proud to say that our system is only a fraction of the approximately $100,000 that the system used on the space shuttle costs.
Conclusions and Recommendations

On the whole, we feel that the project was done well, but not to the fullest of our ability. As we originally had a deadline of April 5th, we had to rush somewhat on our first design, which led to us purchasing and using the first components found that met our specifications without doing in depth due diligence analysis on them. This led to the failure of our original design and precipitated the need for a re-design. With the delays and changes in schedule of our customer, the project deadline was extended to mid-May, and we suddenly had the time to do our in depth analysis and complete the ordering of parts for our second and final design that does meet the customer specifications.

Reflecting upon this path, we can see that we did at the end have appropriate time to have completed a successful design the first time if we had done our due diligence and not rushed on it for our ultimate moot deadline. This is the only change we would have made to our design process. Despite this, we did deliver a working (if non-ideal) design at the time asked for, and are now providing a design that meets the original specs to our customers.

At this point we have largely laid out our plans for delivering a system that meets the original specifications. Within the next few days we will be placing the order for our new pressure regulator that will provide adequate flow for our nozzle design. This will take around thirty days to be delivered to us. In the meantime we plan to continue testing with a linear nozzle to remove some complication from our setup, and therefore reduce error sources. We will also be completing integration with the flight computer of the rocket and possibly be getting a dedicated pressurant tank for our RCS. After the regulator arrives we will finish integration and allow our customers to continue with their hot fire tests. All work should be done by the first few days of June, and will be ready for hand over after that. Throughout it all we will be taking more care to do proper due diligence and analyze all our results fully.

Appendices

1. Project Proposal
2. Bill of Materials
3. Test Stand Design Drawings
4. Load Cell Data Sheet
5. Load Cell Calibration
References

6. http://books.google.com/books?id=pFktw0GYSX8C&pg=PT124&lpg=PT124&dq=scarfed+rocket+nozzle&source=bl&ots=FBC3giYN8V&sig=d0_p7PFLiOwtAW0Tv1wRACrgy44&hl=en&sa=X&ei=S-lhU63WPKvksAT56IGYAw&ved=0CEYQ6AEwBg#v=onepage&q=scarfed%20rocket%20nozzle&f=false
10. After contacting the manufacturer Swagelok, we learned that no express orders are possible, and any order for the chosen pressure regulator will take at least 30 days from the date the order is placed until the shipment would arrive.
11. http://www.nasa.gov/centers/kennedy/about/information/shuttle_faq.html#1