Colorado State University - Aries IV

Team 104 Project Technical Report for the 2018 IREC

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The CSU Aries IV rocket will compete in the 10,000 foot - SRAD hybrid/liquid category of the Intercollegiate Rocket Engineering Competition. The propulsion system is composed of a liquid motor that uses nitrous oxide and ethanol as its propellants. The aerostructure is student-manufactured out of fiberglass composites with an Aeromat core for added strength. In order to successfully recover the rocket, a dual deployment recovery system is integrated into the rocket where a drogue parachute will deploy at apogee and the main parachute will deploy at 1,000 feet above the ground. The scientific payload will collect four atmospheric samples at various altitudes during descent, which will then be delivered to the Atmospheric Sciences Department at Colorado State University. Lastly, to strive for both innovation and excellence in targeting apogee, the rocket will employ an active flight control system in the form of air-braking flaps that will deploy if the onboard algorithm determines that the rocket will overshoot the 10,000 foot goal.

Nomenclature

A^*	=	Nozzle Throat Area
Ac	=	Cross-sectional Area of Orifice
Ae	=	Nozzle Exit Area
Cd	=	Orifice Discharge Coefficient
CFD	=	Computational Fluid Dynamics
CG	=	Center of Gravity
DOF	=	Degree(s) of Freedom
F	=	Thrust
FDM	=	Fused Deposition Modeling, a type of additive manufacturing

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FEA = Finite Element Analysis
I/O = Input and Output (of signals, data, etc)
Mdot = Mass Flow Rate
Me = Exit Mach Number
PCB = Printed Circuit Board
Pe = Exit Pressure
Po = Ambient Pressure
Pt, Tt = Tank Pressure
R = Universal Gas Constant

I. Introduction

The Aries IV rocket team originated as a senior design project for the Mechanical Engineering Department at Colorado State University (CSU). The primary faculty advisor of the team was Dr. Stephen Guzik with Dr. Anthony Marchese as the secondary faculty advisor. Dr. Guzik provided guidance and suggestions for the electronic systems as well as the aerodynamic structures. Dr. Marchese was responsible for mentoring and assisting those in charge of the liquid propulsion system. Other major advisors to the Aries IV team included Mr. Edward Wranosky, who allowed the team to conduct flight tests through his rocketry memberships and motor donations, and Mr. Iman Babazadeh, who led the CSU Aries III team last year and continued on to mentor this year's team.

This year's team of fourteen students were divided into four subteams: propulsion, airframe, control systems, and payload & recovery. For leadership structure, Taylor Morton was the overall team project manager, Danielle Fassold was the Financial Officer, Colum Ashlin was the propulsion team lead, Evan Feldmann was the airframe team lead, Nate Keisling was the control systems team lead, and Austin Funke was the payload & recovery team lead. These six students would meet once a week to make executive decisions concerning the rocket, and to better ensure the successful integration of all the subsystems. The entire team would also meet once a week with the advisors to discuss progress made and weekly future goals for each subteam.

The CSU Aries IV rocket will compete in the 10,000 foot - SRAD hybrid/liquid category of the Intercollegiate Rocket Engineering Competition. The propulsion system is composed of a liquid motor that uses nitrous oxide and ethanol as its propellants. The aerostructure is student-manufactured out of fiberglass composites with an Aeromat core for added strength. In order to successfully recover the rocket, a dual deployment recovery system is integrated into the rocket where a streamer will deploy at apogee and the main parachute will deploy at 1,000 feet above the ground. The scientific payload will collect four atmospheric samples at various altitudes during descent, which will then be delivered to the Atmospheric Sciences Department at Colorado State University. Lastly, to strive for both innovation and excellence in targeting apogee, the rocket will employ an active flight control system in the form of air-braking flaps that will deploy if the onboard feedback control algorithm determines that the rocket will overshoot the 10,000 foot target apogee.

II. System Architecture Overview

The Aries IV rocket is comprised of three main sections: the nose cone, the upper airframe, and the lower airframe. The experimental payload is located inside the nose cone in order to minimize space and to increase flight stability. The recovery system is housed in the upper airframe section, which is comprised of avionics, two pistons, the main parachute, and a drogue streamer. Inside the lower airframe section is the flight controls electronics bay and the propulsion system. The propulsion system is a liquid motor with a nitrous oxide tank, an internal concentric ethanol tank, slide check valves, and a combustion chamber. The fins are attached to the bottom part of this section, as well as a boat tail to minimize base pressure drag. This entire assembly can be seen in Figure 1.

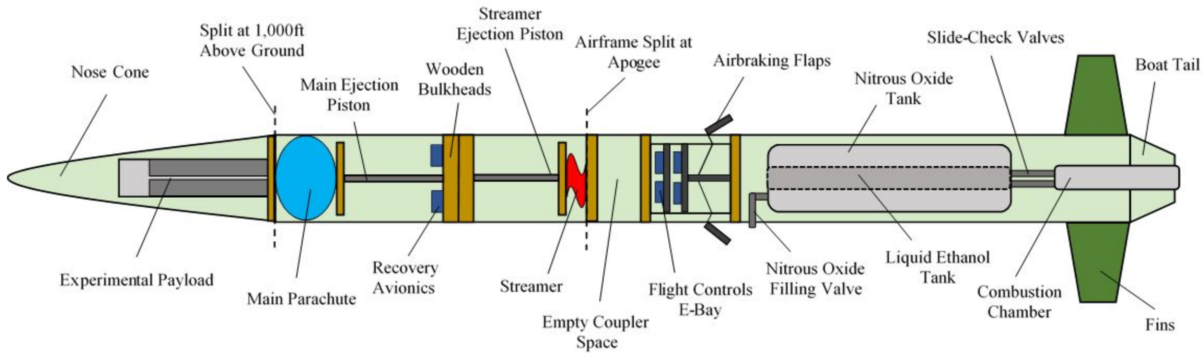


Figure 1. Aries IV system architecture overview.

A. Propulsion Subsystem

This year's team has analyzed the 2017 design and learned from the events during competition to optimize and improve the new engine seen in Figure 2. The propellant tanks and combustion chamber have been separated into two different components and custom plumbing lines have been added between them. This acts as a damper to the overall system to avoid resonance frequencies, as well as limit the amount of propellant exposed to the combustion chamber in case of catastrophic failure during the burn.

The most cost effective and accessible fuel and oxidizer options for the team to use in a liquid propellant rocket are ethanol fuel and nitrous oxide oxidizer. Due to the pressure and temperature at which nitrous oxide vaporizes, the oxidizer is self-pressurizing. In this system, it doubles as the driving force for both the oxidizer and fuel to get to the combustion chamber. This eliminates the need for expensive and bulky turbopumps or pressure vessels filled with inert gases that act as a hindrance at the scale the Aries IV will operate. The most space and mass efficient way to store the propellant was by storing ethanol in a coaxially mounted tank inside the larger nitrous oxide tank. This way the pressure differential between the ethanol and nitrous tanks is insignificant, allowing the ethanol tube to be very thin and decreasing the engines overall weight.

In order to transfer the fuel and oxidizer to the combustion chamber, custom slide check valves (SCVs) were made. The liquid motor utilized two SCVs, one for the fuel and one for the oxidizer. Each SCV allows the pressurized liquid in the propellant tanks to flow through and into the combustion chamber once initiated by an actuator mechanism. This mechanism works by blocking the path for the SCVs to open. It is clamped shut using a pyrobolt. When it is time for the SCVs to open, the charge in the pyrobolt is set off, causing it to fracture. At this time, two springs push the actuator out of the way of the SCVs and allow the pressure upstream to force the valves to open. At ignition, the actuator is released resulting in the flow of propellant through the SCVs and into the combustion chamber.

Moments before initiating the flow of liquid propellant, a hockey puck sized cylinder of solid rocket propellant, a "preheater", is ignited inside the combustion chamber. The preheater serves as an ignition source to the liquid propellant as it is introduced to the combustion chamber. Nitrous oxide and ethanol are non-hypergolic and do not combust when contacted under normal conditions. Therefore, it is necessary to prime the combustion chamber with a very hot and energetic flame to successfully begin combusting the propellant. This year's propulsion system utilized hand mixed preheaters made from ammonium perchlorate (AP), copper oxide, and aluminum powder to bring the combustion chamber temperature up to as high as 2,600℉. The third fuel component of the tribrid motor comes into play here in the form of HTPB. This HTPB is a form of solid fuel and lines the combustion chamber to aid in ignition, help maintain combustion, and protect the chamber walls by ablating away rather than conducting heat after liquid fuel and oxidizer enter the combustion chamber.

After preheater ignition and just before entering the combustion chamber, the oxidizer and fuel travel through an injector that makes up the top of the chamber. The injector serves to mix the fuel and oxidizer before combustion. This year's design incorporated a pintle style injector to induce impinging flow and ensure efficient mixing of propellants to quickly achieve full combustion in the chamber. The exhaust produced from combustion will be accelerated through an insulated graphite converging-diverging nozzle, producing approximately 450 pounds of initial thrust to propel the rocket at a speed that will stabilize the rocket's flight. The entirety of the burn will produce on average 425 lbs of thrust for approximately 10.2 seconds. The total impulse of around 4,335 lb-s is enough to propel the 115 lb rocket to its desired apogee of 10,000 ft.

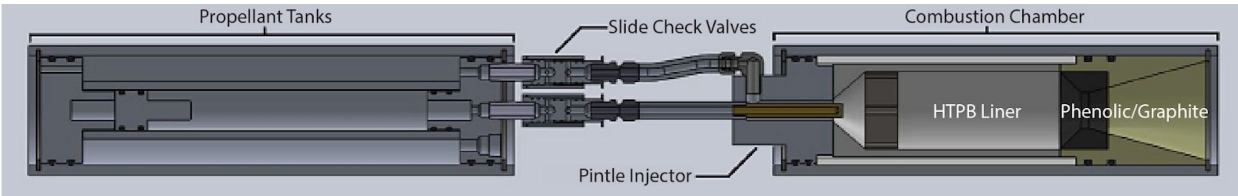


Figure 2. CAD modeling of the propulsion system.

B. Aero-structures Subsystem

The aero-structure subsystem of the Aries IV rocket is composed of four main components: The nose cone, fuselage, boat tail, and internal bulkheads. The outer structure of the rocket can be seen in Figure 3. The nose cone and boat tail were manufactured out of layered 6 ounce S-glass fiberglass. The fuselage was manufactured out of sandwich panels consisting of an AeroMat core surrounded by a layer of 6 ounce S-glass fiberglass. Internal bulkheads were manufactured out of plywood.

Figure 3. CAD model of the Aries IV rocket.

The nose cone was created to follow a Von Karman Tangent-Ogive profile which reduces drag force optimally at transonic flight speeds. Layered fiberglass was used to reduce the overall weight of the rocket. The nose cone was covered with a light-weight body filler to create a smooth surface finish.

The fuselage is the main body of the rocket, used to contain the internal components. The fuselage was manufactured out of fiberglass and Aeromat to reduce weight and provide structural integrity. Helius composite software was used to confirm that the fuselage construction could withstand fight forces. Through the analysis, the theoretical overall instability stress was given as 1248 psi, as shown in Figure 4. After consulting the propulsion and recovery subteams, it was apparent that the force from takeoff would be the largest that the rocket would see from all aspects of flight and recovery. An estimate of 550 pounds force would be the maximum force on the airframe in the axial direction. Based on Helius analysis, the team felt confident that the composite airframe would not succumb to flight forces.

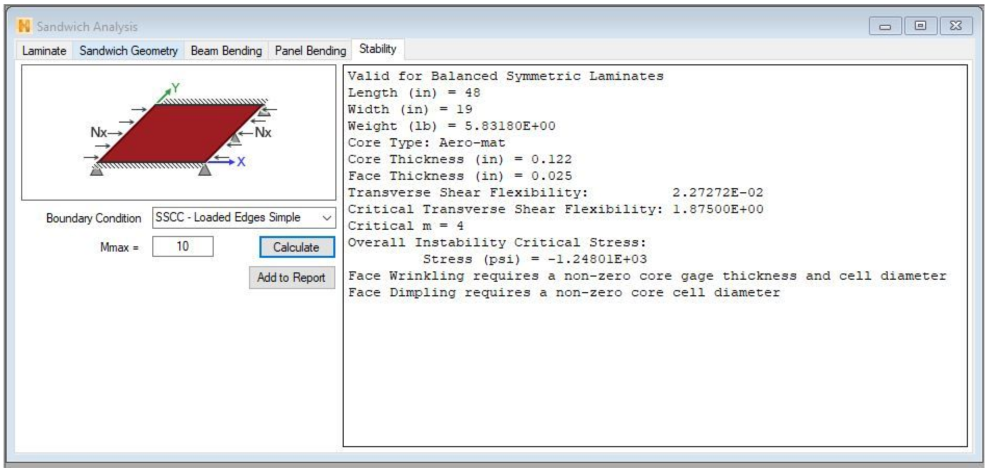


Figure 4. Helius stress results.

A boat tail was added to the bottom of the rocket to reduce drag force on the rocket. A three-dimensional CFD analysis was conducted to understand how much the drag force was reduced. In order to lessen the computational cost, a ½ section of the entire outer-rocket geometry was used through symmetry. The flaps from the flight control system were deployed at 45 degrees for this simulation. Only farfield flow was used; no boundary condition of thrust from the motor was assigned. Velocity contours of the bottom portion of the rocket, with and without a boat tail, are seen below in Figures 5 and 6.

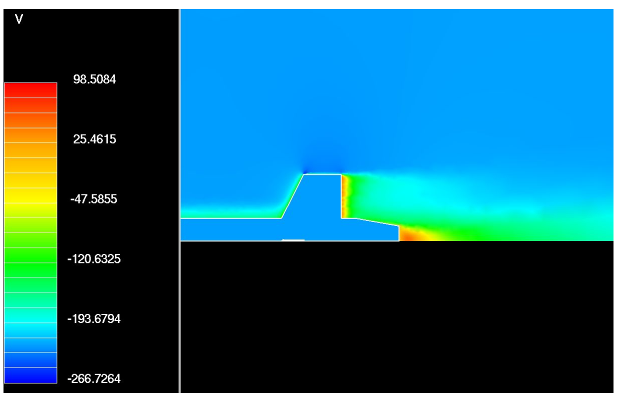


Figure 5. Velocity (m/s) with the boat tail.

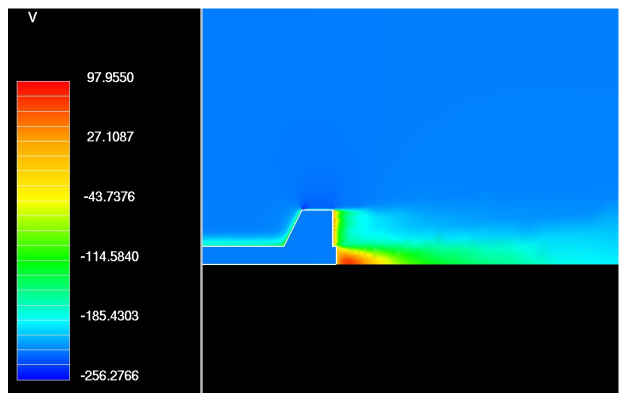


Figure 6. Velocity (m/s) with no boat tail.

Visually, the boat tail is causing a delay in flow separation at the base of the rocket. It is this delay that reduces the pressure drag at the base of the rocket. The total drag force for the rocket with the boat tail is 141 lbf, while the total drag on the rocket with no boat tail is 160 lbf. So, the addition of the boat tail reduces overall drag on the rocket by almost 20 lbf. This amount is significant enough to justify having the boat tail.

The bulkheads are internal wooden rings used to center and separate internal components, transfer force to the airframe, and provide internal rigidity. The bulkheads are of a two-part design, which allow for 10-32 bolts to placed inside with square nuts (Figure 7).

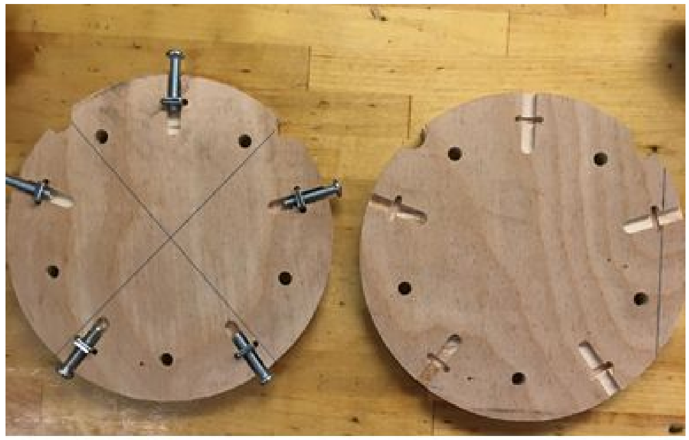


Figure 7. 2-Part Bulkhead with 10-24 bolts and square nuts.

A major consideration for these parts was how many bolts should be placed in the bulkhead in order to successfully transfer force from the motor to the fuselage without failure. A few different calculations were made for each small scale rocket due to different motor configurations. This analysis focused on the full scale rocket nearing 450-550 pounds of thrust. Basic force analysis was used (Figure 8). Every failure mode was analyzed including wood glue failure, bolt shear, plywood delamination, and composite panel failure.

$$\sigma = k_t \cdot \left(\frac{F_{thrust} \cdot SF}{N \left(A_t \right)} \right) \qquad k_t := 2.4$$

From Juvinall Textbook,transverse hole with uni-axial loading

$$N := k_t \cdot \left(\frac{F_{thrust} \cdot SF}{\sigma_{cs\_test} \cdot A_t} \right) = 30.346$$

5 bulkheads with 8 bolts each, give us 40 total bolts

Figure 8. Bulkhead force analysis.

The calculations show that fiberglass would fail before all other modes. Using this analysis, the total number of bolts needed to transfer force without failure could be calculated. There would need to be at least 31 10-32 bolts to complete this task. In the current configuration there are 5 bulkheads that could be outfitted with bolts. Simple math dictates that 5 bulkheads with 8 bolts each would provide enough support to successfully transfer force without failure.

C. Recovery Subsystem

Deployment mechanisms for the recovery system make use of RRC-2+ and RRC-3 altimeter systems to manage the actuation of two pistons. These altimeter systems rely on barometric pressure sensors to determine the altitude of the rocket and deliver the required power to each ignite independently wired electronic matches in the ejection pistons. These systems are independently powered to mitigate the possibility of recovery system failure. As either or both of the installed e-matches ignites, so too does a measured black powder charge inside the piston. The resulting force from the pistons on the packed parachutes and bulkheads cause the shear pins holding portions of airframe together to break, allowing for the deployment of the parachutes.

The two pistons are arranged such that they are situated to eject in opposite directions while sharing an electronics mounting solution. The first piston ejects at apogee to deploy a streamer. The second piston ejects at 1000 ft to deploy the main parachute. The main parachute was constructed with a square shaped cross section and a cross sectional area of 86.5 square feet (Figure 9). This square design achieves an experimental drag coefficient of 1.98.

Figure 9. Main parachute in operation.

Using the cross sectional area of the piston on which the black powder exerts an upwards pressure (0.98 in^2), it has been determined that a charge of approximately 1.5 grams of 3F black powder is sufficient to produce just over 10 ksi of pressure on the shear pins in the airframe, ensuring reliable deployment of the recovery system. This figure requires substantial testing- too little powder fails to break the shear pins and eject the parachute, while too much powder risks structural damage to the bulkheads.

D. Payload Subsystem

The technical objective of this payload is to collect air samples into four evacuated chambers at distinct altitudes during the descent of the rocket. Each chamber is composed of a mild steel square tube with welded end caps, a Schrader valve (to draw vacuum when assembled), and a solenoid to regulate air flow into the chamber. An onboard barometric altimeter tracks the rocket's ascent and records the altitude above ground level at which apogee is achieved. At this moment, the solenoid controlling flow of air into the first of the four evacuated chambers actuates temporarily, allowing air to fill the chamber before the chamber is resealed. The next chamber fills at 75% of the rocket's maximum altitude, using the apogee recorded earlier in the flight. The final two chambers fill at 50% and 25% of maximum altitude respectively, providing air from several altitudes to be examined on the ground. Once on the ground, it is relatively trivial to test each sample for CO_2 and CH_4 concentrations and to better model and understand the mixing of these gases in the atmosphere. The full assembly is CubeSAT compliant (4U), and is shown in Figure 10 below.

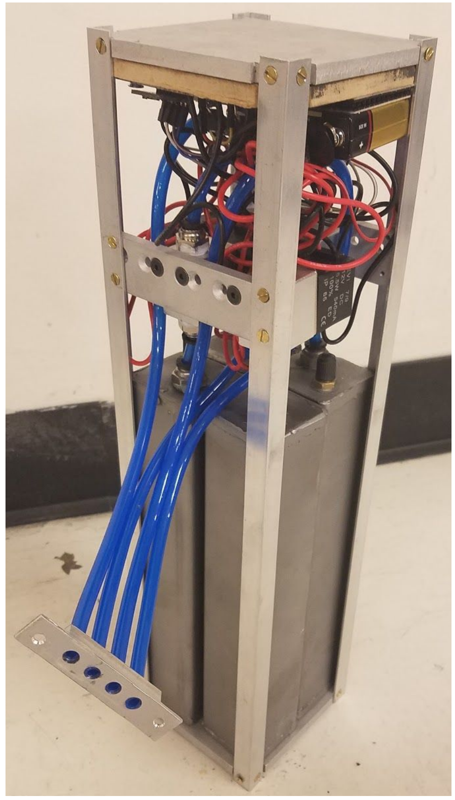


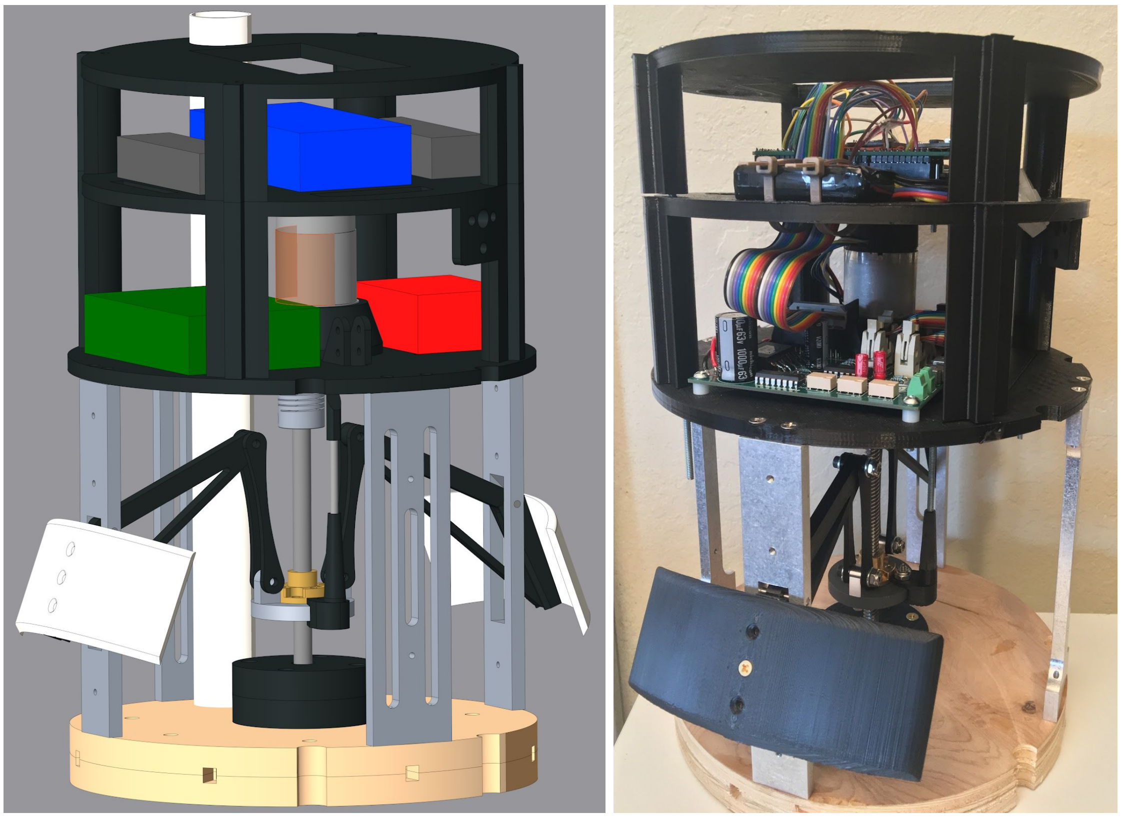
Figure 10. Fully assembled air sampling payload unit.

This payload is comprised of several off the shelf components, as well as several components (primarily on the chassis and collection chambers) which required machining. The barometric altimeter used is a BMP-280 from Adafruit. It relays altitude data to an Arduino Uno, which regulates actuation of four 12V solenoid valves using TIP120 mosfets. Power is supplied from a 9V battery attached to the payload chassis. The air sample chambers are made up of 1.75"*1.75" mild steel square tubing (0.062" wall), with 1/4" steel plates MIG welded to both ends. The top of each chamber includes a Schrader valve and 6mm hose attachment. A short length of the 6mm hose extends to a corresponding solenoid valve directly above. Hose extends from the other side of the solenoid, permitting sampled air to flow directly into the chamber. The chassis of the payload is comprised of three ¼" thick milled 6061 aluminum plates, four 3/8" aluminum l-profile angle bar segments, and two segments of 6061 aluminum bars. The plates are drilled and tapped (#4-40) in the corners in order to match with countersunk holes drilled in the angle bars, which together form a 40cm*10cm*10cm frame. Two aluminum bars have been milled to length, aligned and countersunk to hold the solenoids securely in place.

E. Flight Controls Subsystem

Because of the difficulty of metering exact and consistent launch specifications for propellant temperature, mass, and pressure, especially for the wildly different climates and altitudes of northern Colorado versus southern New Mexico, it was recognized that some method of affecting the flight path of Aries IV would be required to consistently and competitively achieve the 10,000 foot apogee. In order to focus on this apogee objective and to widen the performance margin of Aries IV's liquid motor by nearly 20%, an air-braking module is included just above the propellant tanks, near the CG of the vehicle. This enables the motor to be oversized so that it can safely underperform and still carry the rocket to 10,000 feet, but can also overperform and the excess energy can be dissipated by the air-braking module.

This module, weighing only 4 pounds and shown below in Figure 11, contains a robust single-actuator mechanism tied to two air-braking flaps with a total aerodynamic area of about 50 square inches. The avionics on board include a barometric altimeter, a 9-DOF Inertial Measurement Unit (accelerometer, gyroscope, and magnetometer), and a data collection SD card. This suite of electronics is attached via a robust shield to an Arduino Mega which runs the flight code and controls the air-braking flaps through an Ion Motion Roboclaw, a motor controller capable a treating a DC motor and encoder like a positional servo using a tuned internal PID control algorithm. Finally, a custom-designed PCB provides signal conditioning, I/O, power conditioning, and a robust and analog failsafe system. The overall system structure can be seen in Figure 12.



a) **b)**

Figure 11. Completed air-braking module.

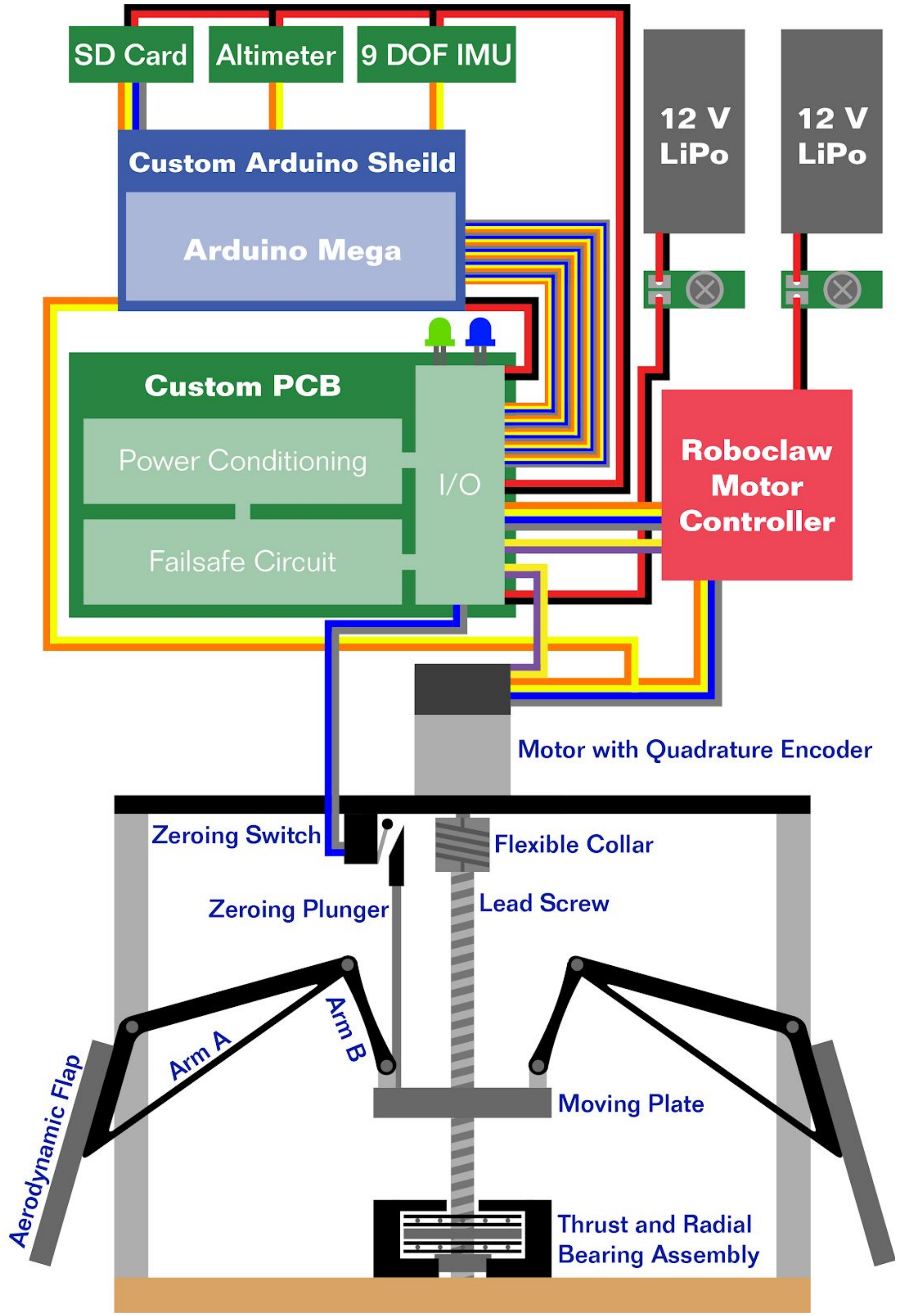


Figure 12. Overall controls system diagram.

Designed to integrate into the airframe as easily as possible, the control system is a single, self-contained 13 inch long module. Once aligned inside Aries IV, it is fastened rigidly to the airframe with multiple external machine screws. Extensive FEA was utilized during the design of the module in order to use the lightest possible material in every application. This lead to the use of nearly a dozen distinct materials including aluminum, stainless steel, brass, PVC, nylon, acetyl, plywood, carbon fiber composites, and extensive use of additive manufacturing, specifically FDM with ABS and PETg plastics for all of the avionics support platters and even several major mechanical components, such as the flap arms and linkages as well as the bearing case. ABS was selected for simple parts where ease of printing, strength, and surface finish were major concerns and for parts designed to be finished with more traditional manufacturing techniques. PETg was used for parts where minimal warping and maximum dimensional accuracy were required, such as the large, flat avionics platters and the flap arms. Aluminum and steel were selected in places where dimensional accuracy and strength were of greatest concern. The main structural columns that support the avionics, attach the module to the airframe, and carry all of the aerodynamic and actuation forces are precision machined from cold-rolled 6061 aluminum bar stock and carry a ⅛ inch stainless steel axle on which the flap arms pivot to extend the flaps. To design these columns and the mechanical linkages they support, an upper end value for aerodynamic force needed to be established. By considering the standard equation for dynamic pressure with an over-estimated drag coefficient of 1.5, apparent flap area of 12 by 15 centimeters, air density of 1 kg/m^3, and a vehicle velocity of 275 m/s (Mach 0.8), this upper estimation for aerodynamic force is about 900 Newtons per flap, or about 200 pounds per flap. While quite a bit more than expected, FEA showed that the low profile and lightweight aluminum design with ⅛ inch stainless steel axle would deflect less than 0.01 inches and maintained an overall safety factor of at least 1.8, as seen below in Figure 13.

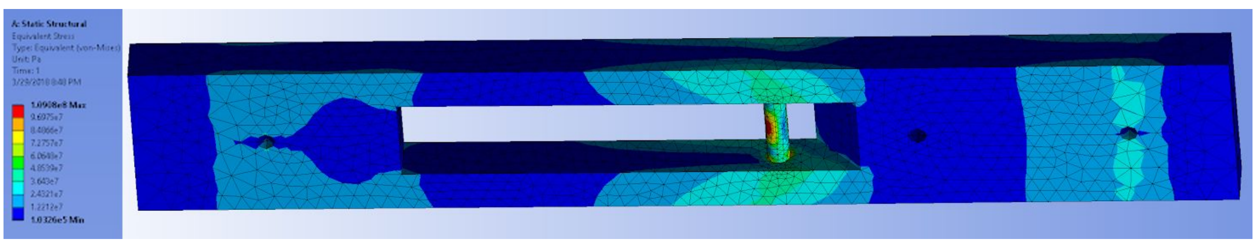


Figure 13. Finite element analysis of stress on flap support column and axle.

Driving this mechanism, the Arduino runs a suite of code over 1,600 lines long and contains a great deal of clever and efficient solutions to a wide variety of problems. One such solution is a triggering mechanism that accurately determines the state of the flight of the rocket. By knowing what stage of the flight the rocket is in, the code can more efficiently implement only the sections of code required for that stage of flight, such as the apogee prediction algorithm which uses sensor data to predict the rocket's final apogee. This piece of software feeds the Ion Motion motor controller responsible for actuating the flaps and slowing the rocket. The flow charts below in Figure 14 highlight a simplified version of the logic used in the overall structure of the program and of the launch-detection subroutine. This logic supports the ultimate *modus operandi* of the flight code- the control algorithm. The cornerstone of this algorithm is a simple yet effective apogee prediction approximation developed with example data as well as flight data. This apogee prediction is based on the simple kinematic equations for parabolic flight with constant deceleration run through a scaling function to accommodate for the decrease in overall drag as the rocket slows down. This predicted apogee is compared to the desired apogee and fed into a closed-loop PID control algorithm which actively adjusts the angle of the flaps throughout the unpowered ascent in order to close the gap between the predicted apogee and the target apogee.

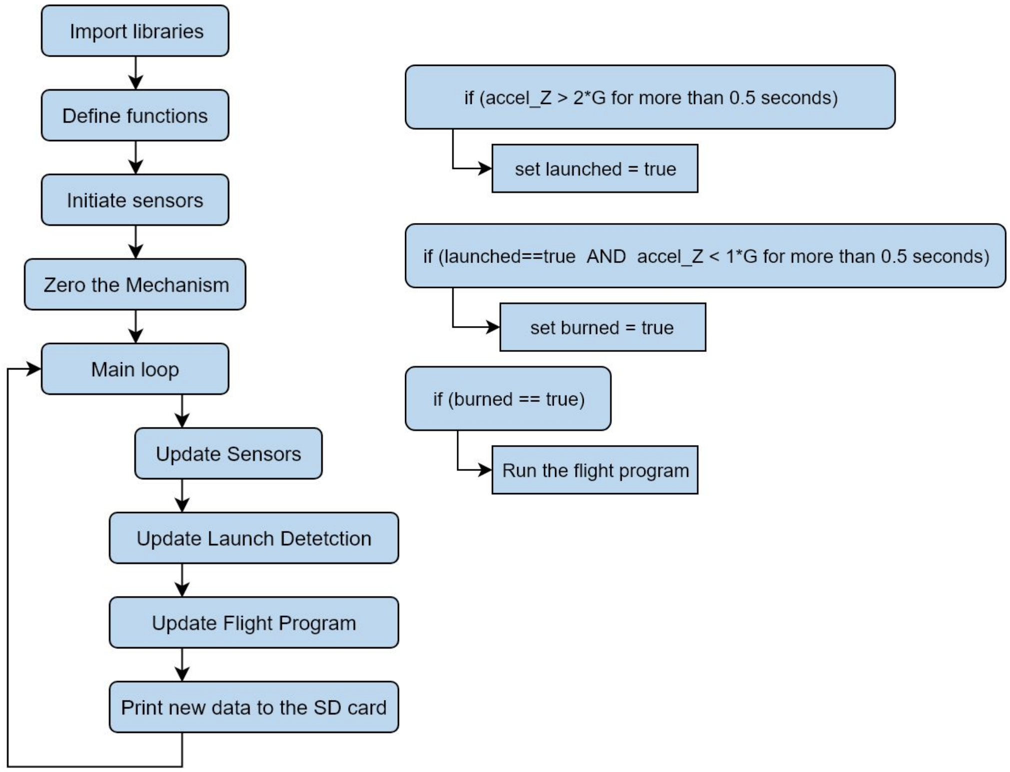


Figure 14. Simplified logic outline.

In terms of safety, the module has been designed from the ground up to be highly robust physically, electronically and logically. On a basic level, the entirety of Aries IV has been laid out specifically to place the air-braking flaps at or behind the CG, meaning that, theoretically, symmetrically deployed air-brakes should only make the rocket *more* stable in flight. That being said, there is extensive logic that monitors the behavior of the vehicle, including a check for flight orientation. These potential fail states are ultimately handled by the custom PCB which contains a highly effective and incredibly simple failsafe system. This system is based around relays and a retriggerable monostable multivibrator or "one-shot". The failsafe functions by monitoring the health of the Arduino with the one-shot. The arduino must send a pulse to the one-shot at least twice a second or the one-shot will trip and trigger the failsafe relay, which disconnects the motor controller from the motor and switches the motor over to -12V straight from a backup battery, causing the motor to reverse at full speed until the mechanism is fully collapsed and hits it's zeroing switch, which then disconnects the failsafe board. This method is not only 100% analog but highly simple and robust. It protects the system against detected failures, such as a departure from the flight path, a sensor failure, or a motor controller failure. It also protects the system against less detectable failures, like a loss of main power, Arduino brown-outs, the Arduino hanging or failing, or even the physical destruction of any of the electronics including physical destruction affecting any of the other components on the failsafe board. These considerations make Aries IV's control system one of the most fail-resistant parts of the overall rocket design. This failsafe system can be seen along the bottom right of the custom PCB designed by the Flight Controls Team and shown below in Figure 15.

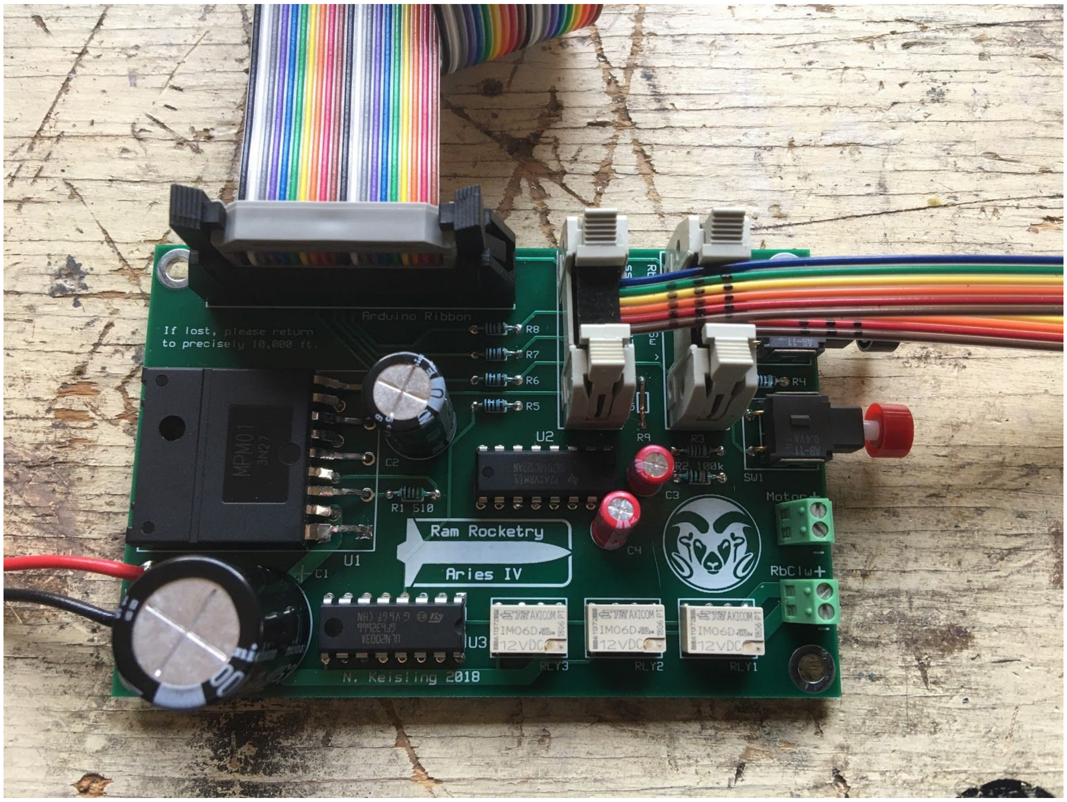


Figure 16. Custom PCB with signal/power conditioning and mechanism failsafe.

III. Mission Concept of Operations Overview

The seven stages that the Aries IV rocket will proceed through are standby, ignition, liftoff, ascent, apogee, descent, and landing. The overall launch and flight procedure can be seen below in Figure 17.

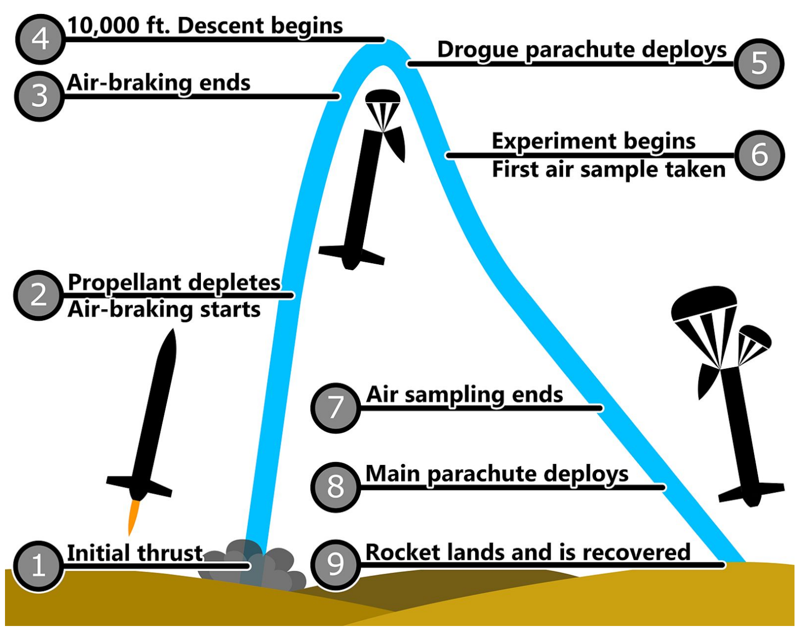


Figure 17. Stages of Aries IV flight.

A. Standby

During standby, the Aries IV rocket is resting vertically on the launch rail supported by launch lugs that are backed by hardpoints on the inside of the airframe. The altimeters of both the recovery system and the control systems are activated and calibrated at this time. A feedback noise will sound to indicate the successful arming of these systems. The final step of this phase is to fill the nitrous tank with liquid nitrous to an approximate pressure of 700 psi.

B. Ignition

Once the nitrous tank is at 700 psi, the rocket is now in the ignition phase. The filling valve is then remotely disconnected using a signal sent to a pyrovalve. Another remote signal is sent to the e-matches which will ignite the pre-heater grain inside the combustion chamber. During the most energetic part of this burn, the nitrous oxide and the ethanol are released from their respective tanks into the combustion chamber using pyrovalves.

C. Liftoff

Directed by the launch lugs and propelled by the combustion of the liquid motor, the rocket moves straight upward on the launch rail, achieving a speed of 58.5 ft/s by the time it clears the launch rail. Due diligence is being implemented to ensure an end-of-launch-rail stability of at least 1.75.

D. Ascent with Thrust

Ascent begins the moment the rocket fully leaves the launch stand. The liquid motor will burn for 10.2 seconds, producing on average 426 lbs of thrust through its liquid phase, and reach a maximum velocity of Mach 0.68 . All airframe components are connected during the entirety of the ascent.

E. Controlled Ascent

The rocket will then coast for 19 seconds. If the onboard flight control algorithm determines that the rocket will overshoot the 10,000 foot target apogee, the air-braking flaps will deploy to slow the rocket down. This system includes a robust, analog failsafe capable of retracting the air-braking flaps in less than 1 second. The flaps will retract at apogee and remain closed for the duration of the rocket's descent.

F. Apogee

At an apogee of 10,000 feet, the RRC3 altimeter (barometric pressure-based) will send a current to the e-matches, igniting the black powder inside the piston, pushing the nose cone off of rocket, and then deploying a streamer, ensuring a rapid yet controlled descent.

G. Descent

As the rocket descends, the payload will collect air samples at several altitudes beginning with the apogee of the rocket's flight. The remaining air samples are conducted at 75%, 50% and 25% of the maximum flight altitude above ground level. When the rocket is 1,000 feet above the ground, the RRC3 altimeter will send a current to the e-matches, igniting the black powder inside the piston, separate the top section of the airframe from the middle section, and then deploy the main parachute.

H. Landing

The rocket will softly land at a velocity between 15-25 ft/s. The landing range will vary based on wind conditions, but the total flight time is projected to be roughly 2 minutes and 15 seconds, so launching into the wind is advisable to prevent excessive horizontal drift.

IV. Conclusions and Lessons Learned

The propulsion team has had an exciting year developing a reliable liquid propulsion system. The system has several features that not only are safer than last years design, but also have shown significantly better performance. Many difficult problems were identified and solved in a unique and customizable way. Unfortunately, there are not many components available on the market that can just be bought and put into a rocket. Through some clever thinking, and countless trial and error, simple yet robust solutions have been found to solve every issue faced this year. It is a great experience having to troubleshoot many of these problems and not have an immediate solution available, or even an ideal solution available. Next year, the propulsion team should scale the system so it is capable of taking the Aries V to 30,000 feet. The team should either then develop a special rocket, intended to go as high as possible for scientific and experimental reasons at the competition, or begin developing a liquid oxygen (LOX) rocket engine. This system would require a pump or a separate chamber of inert gas to drive the propellants into the combustion chamber. LOX requires a lot of new hardware, such as cryogenic equipment, but is a much more commonly used oxidizer in industrial rocketry. With development of a LOX engine, CSU would stand out above all else in student-driven rocket development and innovation.

The airframe sub-team of CSU designed and manufactured the fuselage, nose cone, boat tail, internal bulkheads all while overseeing and ensuring the integration of all subsystems. The fuselage constructed out of fiberglass with an AeroMat core, and the fiberglass nose cone and boat tail will be sufficient to achieve our goal to reach 10,000 feet and withstand even the harshest of recovery situations. Some recommendations for next year's IREC Team would be: Begin learning about composites (materials, manufacturing, etc.) as early as possible, practice both fiberglass hand-layups and resin infusions prior to attempting to make the airframe parts, use unidirectional fibers to tailor known forces and reduce weight, sit in on composites lectures and attend SAMPE events, conduct weekly meetings with the project manager and the subteam leads for cohesive integration.

The goal of the payload team is to design and build a functional experiment apparatus in a robust chassis and a reliable and effective recovery system that meets all objectives and constraints of the IREC competition. The payload will be competitive through its scientific merit with the air intake experiment. The recovery system employs a dual-deployment system that is robust and will ensure that the rocket lands in a recoverable state. A major lesson learned for next year's team is to test using the actual airframe section and nose cone that will be flying in the launch. Repeated tests of this nature will provide great confidence for the actual launch.

For the Flight Control Systems Team, this year has been considered, overall, an incredible success. Despite losing everything in December and having to change course for simplicity, the team settled on a solution that was, ultimately, better in every way and even managed to produce a 6" prototype *and* the 8" competition module in about three months. That being said, the air-braking module has been an expensive and heavy solution to the problem of widening the liquid motor's performance margin. It is the recommendation of this year's Flight Control Systems Team that next year's team investigate integrating payload, recovery, and avionics into a single universal, efficient, and highly redundant system and work closely with Propulsion to investigate using motor throttling as the primary form of altitude control, a method we believe will be lighter, less expensive, easier to ground test, and more relevant to industry.

Appendix

A. System Weights, Measures, and Performance Data

Table 1. 3rd progress report.

		Spaceport America Cup Intercollegiate Rocket Engineering Competition Entry Form & Progress Update								
Color Key			SRAD = Student Researched and Designed							v18.1
Must be completed accurately at all time. These fields mostly pertain to team identifying information and the highest-level technical information.										

Should always be completed "to the team's best knowledge" , but is expected to vary with increasing accuracy / fidelity throughout the project.

May not be known until later in the project but should be completed ASAP, and must be completed accurately in the final progress report.

Date Submitted:	5/24/2018		
		Country:	United States of America
Team ID:	104	State or Province:	Colorado
	* You will receive your Team ID after you submit your 1st project entry form.		State or Province is for US and Canada

Team Information

Rocket/Project Name:	Aries IV	
Student Organization Name	Ram Rocketry	
College or University Name:	Colorado State University	
Preferred Informal Name:		
Organization Type:	Senior Project	
Project Start Date	8/21/2017	*Projects are not limited on how many years they take*
Category:	10k – SRAD – Hybrid/Liquid & Other	

Member	Name	Email	Phone
Student Lead	Taylor Morton	tmorton915@gmail.com	720-548-7275
Alt. Student Lead	Danielle Fassold	dfassold@rams.colostate.edu	303-489-7511
Faculty Advisor	Dr. Anthony Marchese	anthony.marchese@colostate.edu	970-491-2328
Alt. Faculty Adviser	Dr. Stephen Guzik	stephen.guzik@colostate.edu	970-491-4682

For Mailing Awards:

Payable To:	Anthony Marchese
Address Line 1:	104 Scott Bioengineering Building
Address Line 2:	Colorado State University
Address Line 3:	Fort Collins, CO 80523-1374
Address Line 4:	
Address Line 5:	

Demographic Data

STEM Outreach Events

This is all members working with your project including those not attending the event. This will help ESRA and Spaceport America promote the event and get more sponsorships and grants to help the teams and improve the event.						Rivendell Elementary School Bottle Rocket Collaboration Project - teach elementary students about the science behind rockets, build and launch bottle rockets with the students
Number of team members						
High School	0		Male	12		
Undergrad	14		Female	2		
Masters	0		Veterans	0		
PhD	0		NAR or Tripoli	1		
Just a reminder the you are not required to have a NAR, Tripoli member on your team. If your country has an equivelant organization to NAR or Tripoli, you can cant them in the NAR or Tripoli box. CAR from Canada is an example.						

Rocket Information

Overall rocket parameters:

	Measurement	Additional Comments (Optional)
Airframe Length (inches):	204	
Airframe Diameter (inches):	8.25	
Fin-span (inches):	28	Including airframe diameter
Vehicle weight (pounds):	86	
Propellent weight (pounds):	20	
Payload weight (pounds):	9	
Liftoff weight (pounds):	115	
Number of stages:	1	
Strap-on Booster Cluster:	No	
Propulsion Type:	Liquid	
Propulsion Manufacturer:	Student-built	
Kinetic Energy Dart:	No	

Propulsion Systems: (Stage: Manufacturer, Motor, Letter Class, Total Impulse)

1st Stage: Liquid, 15 lb Nitrous Oxide and 5 lb Ethanol, N Class, 19000 Ns		
Total Impulse of all Motors:	19000	(Ns)

Predicted Flight Data and Analysis

The following stats should be calculated using rocket trajectory software or by hand.

Pro Tip: Reference the Barrowman Equations, know what they are, and know how to use them.

	Measurement	Additional Comments (Optional)
Launch Rail:	Team-Provided	
Rail Length (feet):	20	
Liftoff Thrust-Weight Ratio:	4.2	
Launch Rail Departure Velocity (feet/second):	59	
Minimum Static Margin During Boost:	1.75	
Maximum Acceleration (G):	5	
Maximum Velocity (feet/second):	710	
Target Apogee (feet AGL):	10K	
Predicted Apogee (feet AGL):	10,832	

Payload Information

Payload Description:

Our team will be flying a functional payload this year. The payload will collect air samples using evacuated chambers approximately every 2,500 vertical feet after apogee and monitor airborne particulate concentrations over the duration of the rocket's decent. These samples can be tested on the ground to determine concentrations of certain greenhouse gases, particularly methane. This will help determine how GHG's are distributed throughout the atmosphere and if predictive models can assume these gases are well mixed. The payload will remain inside the airframe and not require an independent recovery system. The dimensions of the payload are 10cm x 10cm base, 40cm long. The approximate weight of the payload is 9.0 lbs.

Recovery Information

Our rocket will be using a dual deployment recovery system. The rocket will come down as one connected mass using the same recovery system. At apogee (about 10,000 feet) a streamer will deploy out of the middle of the rocket attached to the propulsion tube; the ejection force breaks the rocket into 2 roughly equal halves. When the rocket reaches 1000 feet, the main parachute will deploy from between the nose cone and adjacent body tube to slow the rocket to its final descent speed of around 17.5ft/s. This dual recovery system relies on two pistons each filled with a measured amount of black powder and 2 electronic matches to deploy recovery systems and break the airframe. Prior to piston actuation, shear pins hold the airframe together ensuring stable flight until recovery systems deploy. The recovery system is controlled by two barometric dual-deploy altimeters purchased from Missile Works (RRC3 and RRC2+ boards). The RRC3 board is considered the main board with the other running fully independently in parallel as a redundant backup. These boards control the electronic matches which set off the pistons at the appropriate event altitudes.

Planned Tests

* Please keep brief

Date	Type	Description	Status	Comments
11/25/17	Ground	1st validation test of grid fin controls	Major Issues	Did not meet testing requirements
12/2/17	In-Flight	1st small-scale test launch - Solid	Major Issues	Hosted by Northern Colorado Rocketry - ascent successful, but parachute did not deploy
12/2/17	In-Flight	Controls perturbation test	Major Issues	Fins flew static, then all hardware was lost in the recovery crash
1/15/18	Ground	Recovery system integration testing	Minor Issues	Parachute did not fully leave airframe
1/27/18	Ground	Recovery system integration testing	Minor Issues	Parachute again did not fully leave airframe
1/29/18	Ground	Airframe compression test	Successful	Composite cross-section withstood sufficient amount of compression force

2/3/18	In-Flight	Recovery system and parachute test launch	Major Issues	The launch just testing recovery system was not pursued any further
2/10/18	Ground	1st small-scale liquid motor static fire	Major Issues	The preheater did not ignite
2/14/18	Ground	Small-scale liquid motor static fire	Minor Issues	Achieved combustion but nitrous lasted significantly longer
2/17/18	Ground	Small-scale liquid motor static fire	Minor Issues	Achieved combustion once more and the ethanol lasted longer, but a significant change is necessary
2/14/18	Ground	Air-Brake mechanical failure testing	TBD	
2/22/18	Ground	Small-scale liquid motor static fire	Major Issues	The slide checks actuated before they were supposed to but the ethanol and nitrous flow rates equalized
2/23/18	Ground	Small-scale liquid motor static fire	Major Issues	The slide check actuator did not move when supposed to
2/24/18	Ground	Small-scale liquid motor static fire	Major Issues	The slide check actuator did not move when supposed to
2/24/18	Ground	Recovery system integration testing	Successful	Parachute was testing with flight ready airframe and nose cone. Parachute was ejected everytime and optimal powder amount was determined
3/2/18	Ground	Small-scale liquid motor static fire	Major Issues	The slide check actuator did not move when supposed to
3/3/18	Ground	Small-scale liquid motor static fire	Major Issues	The slide check actuator did not move when supposed to
3/3/18	In-Flight	2nd Small-Scale Test Launch	Major Issues	Cancelled due to red flag fire warnings
3/8/18	Ground	Small-scale liquid motor static fire	Minor Issues	The slide check actuator did not move when supposed to
3/9/18	Ground	Small-scale liquid motor static fire	Minor Issues	The slide check actuator did not move when supposed to

3/14/18	Ground	Small-scale liquid motor static fire	Minor Issues	The slide check actuator did not move when supposed to
3/15/18	Ground	Small-scale liquid motor static fire	Minor Issues	The slide check actuator did not move when supposed to
3/16/18	Ground	Small-scale liquid motor static fire	Minor Issues	The slide check actuator did not move when supposed to
3/19/18	Ground	Small-scale liquid motor static fire	Major Issues	Slide checks actuated but the ethanol extinguished preheater
3/20/18	Ground	Small-scale liquid motor static fire	Major Issues	Slide checks actuated but the ethanol extinguished preheater, this time the engine hard started several times
3/21/18	Ground	Small-scale liquid motor static fire	Major Issues	Slide checks actuated but the ethanol extinguished preheater
3/22/18	Ground	Small-scale liquid motor static fire	Major Issues	Slide checks actuated but the ethanol extinguished preheater
3/23/18	Ground	Small-scale liquid motor static fire	Successful	Total burn was stable combustion
3/24/18	Ground	Small-scale liquid motor static fire	Successful	Total burn was stable combustion
3/25/18	Ground	Small-scale liquid motor static fire	Successful	Total burn was stable combustion
3/26/18	Ground	Small-scale liquid motor static fire	Successful	Total burn was stable combustion
4/1/18	Ground	Dual-recovery system integration testing	Successful	
4/5/18	Ground	Small-scale liquid motor static fire	Successful	Total burn was stable combustion
4/15/18	Ground	Small-scale liquid motor static fire	Successful	Total burn was stable combustion
5/5/18	In-Fligh t	Medium-scale test launch with dual deployment	Successful	
5/8/18	Ground	1st Full-scale liquid motor static fire	Major Issues	Engine hardstarted and the combustion chamber exploded
5/20/18	Ground	2nd Full-scale liquid motor static fire	TBD	Total burn was stable combustion

Any other pertinent information:
Our team has decided to move away from active grid fin controls in favor of a more simple solution that can be more robustly designed and tested. The rocket will fly static planar fins. The team will instead employ an air-brake system built into a single-unit avionics/mechanicals bay immediately above the motor, such that the aerodynamic surfaces act at or below the empty CG to encourage minimal disturbance under air-braking. This system will be designed with multiple levels of failsafes including robust mechanical lockout and automatic return-to-zero under most failure conditions, including loss of power. This system is designed to predict the apogee of the rocket and utilize a feedback control algorithm to apply air-braking and precisely hit the target 10,000 foot apogee. In terms of launch rail stability, the team is applying due diligence to ensure that the rocket is stable even though it is leaving the launch rail at 59 ft/s. To prove stability, documentation will be provided at the launch site to show a minimum rocket stability of 1.75, which is slightly higher than the minimum required by IREC.

B. Project Test Reports

<u>Recovery System Testing</u>

Prior to each previous launch, the recovery pistons have been fitted into the airframe and wired for testing. For each test, E-matches are installed into the pistons along with a measured charge of black powder (starting with a very small amount and gradually increasing the charge until a satisfactory test result is achieved). A folded parachute is loaded above the installed piston. The adjacent section of airframe is then installed (by way of coupler), and held in place by three #6-32 nylon shear pins. This assembly is fired outside using an ignition controller from a safe distance, as shown in Figure 18 below. Once the amount of black powder necessary to eject the parachutes has been determined, the test is repeated at least 3 times to ensure that the results are repeatable.

Figure 18. Recovery piston testing.

The square parachute design has also been tested for resilience and effectiveness. In order to demonstrate that the parachute manufacturing technique is strong enough to survive flight conditions, the parachute was attached to the trailer hitch of a pickup truck and driven down an airstrip at speeds exceeding the projected descent rate of the rocket. The seams of the parachute were intact, as were all shroud line attachment points. Data was extrapolated from on board sensors during test flights to analyze the parachute's performance. To ensure the recovery systems would function regardless of power losses to onboard altimeters, a secondary altimeter has been installed in parallel.

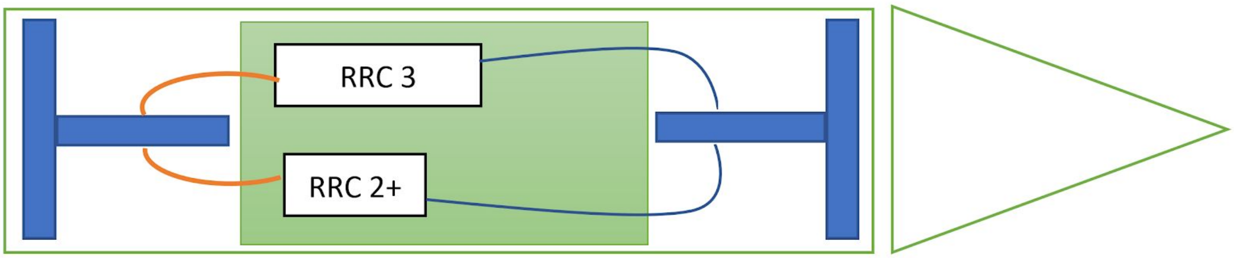


Figure 19. Redundancy of recovery electronics.

<u>Combustion Chamber Pressure Testing</u>

The combustion chamber has been constructed out of 0.25" thick 6061-T6 Aluminum, and the expected operating pressure of the chamber is 400 psi. The SRAD combustion chamber has been hydrostatically tested up to 1,000 psi without complications. This gives the combustion chamber a safety factor of > 2.5. This year's team elected to add extra mass to this chamber in the name of safety after last year's motor experienced a catastrophic failure.

<u>Liquid Propulsion System Tanking Testing</u>

During the initial static hot-fire testing, the loading and unloading procedure of propellants was tested. The ethanol fuel is initially loaded into the tanks, and the nitrous oxide oxidizer is loaded while the motor is in a "launch-configuration".

After loading the motor with both components of the propellant, the unloading procedure is simple. First disconnect the wires to the preheater and short them to ensure no random static charge can ignite the preheater. Then open SCVS connected to the fuel and oxidizer tanks to release the propellant to the ambient environment. Unfortunately, this unloading system has been tested multiple times during static hot-fire tests where a different failure mode were experience before ignition. As a redundant system, there is also a solenoid valve connected to the oxidizer tank to release the nitrous oxide if needed.

Static Hot-Fire Testing

To date, there have been six successful small scale static hot-fire tests of the motor that will be used in the competition, as well as one successful full scale test. These were conducted to achieve a greater understanding of thrust curves and give a baseline to scale up from. There are currently 4 full scale static hot-fire tests on the schedule before the competition to ensure the full scale motor both behaves as expected and is consistent with its output thrust curve. Figure 21 lists all of the recorded thrust data throughout each of the small scale hot-fire tests.

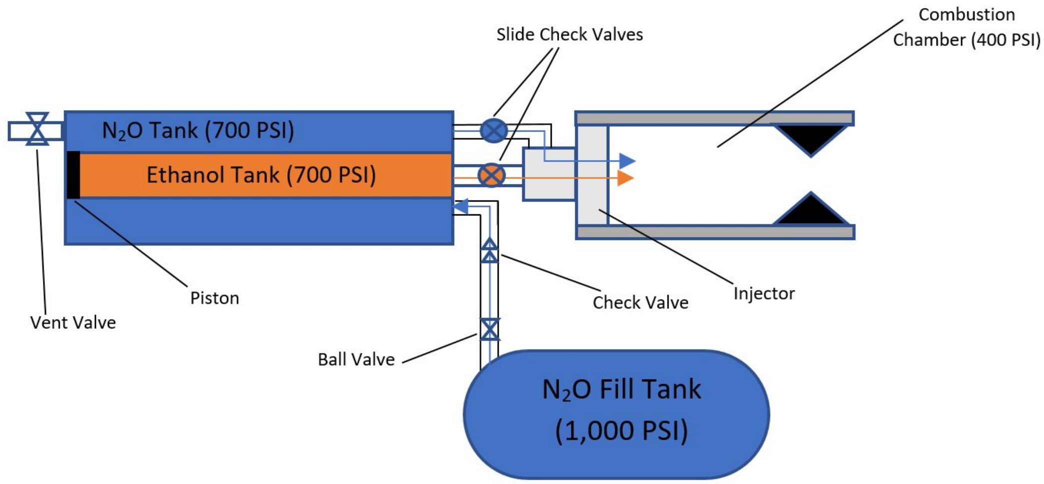


Figure 20. Fluid circuit diagram.

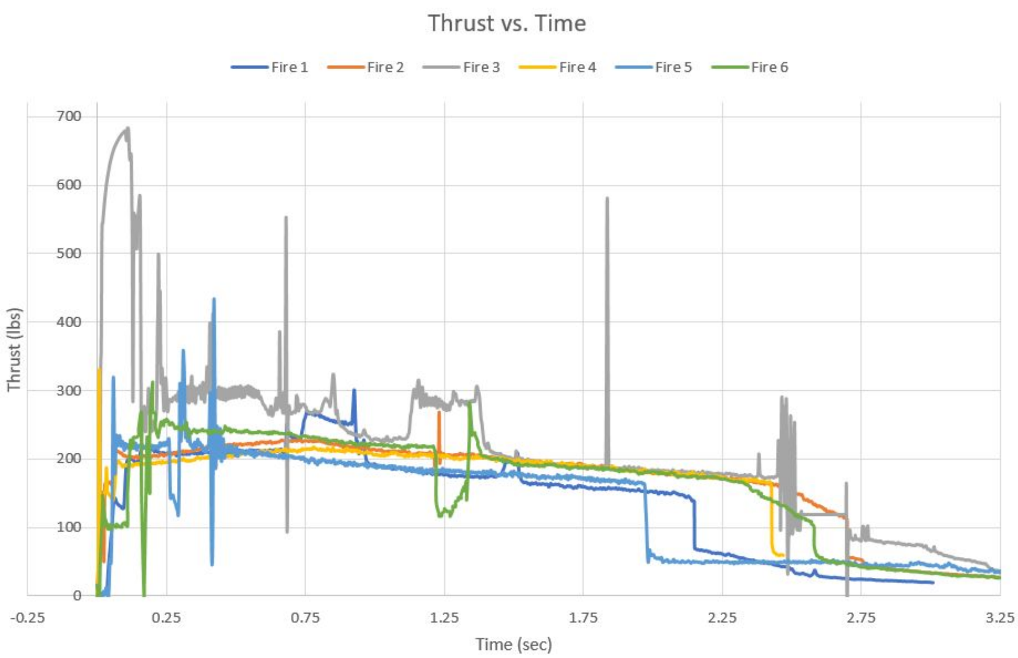


Figure 21. Small scale hot-fire tests.

The numbers from these tests were used to scale up to the final sized motor. These burns produced a typical total impulse range of 450 - 500 lb-s, so there was a baseline to scale up from while designing the full scale motor. An impulse of 4,040 lb-s is necessary to carry the Aries IV rocket to its 10,000 ft mark, so the full scale propellant tanks are scaled up ust over 8 times in volume. Of course the thrust is increased to double the thrust output in order to keep a stable flight throughout the burn. The thrust curve from the first full scale motor test can be seen in Figure 22. A very conservative approach is being taken to scale up the motor because of concerns about explosions, so the thrust numbers are lower than what the final motor will produce. Throughout the next 4 hot-fire tests, the magnitude of the thrust output will be optimized for competition.

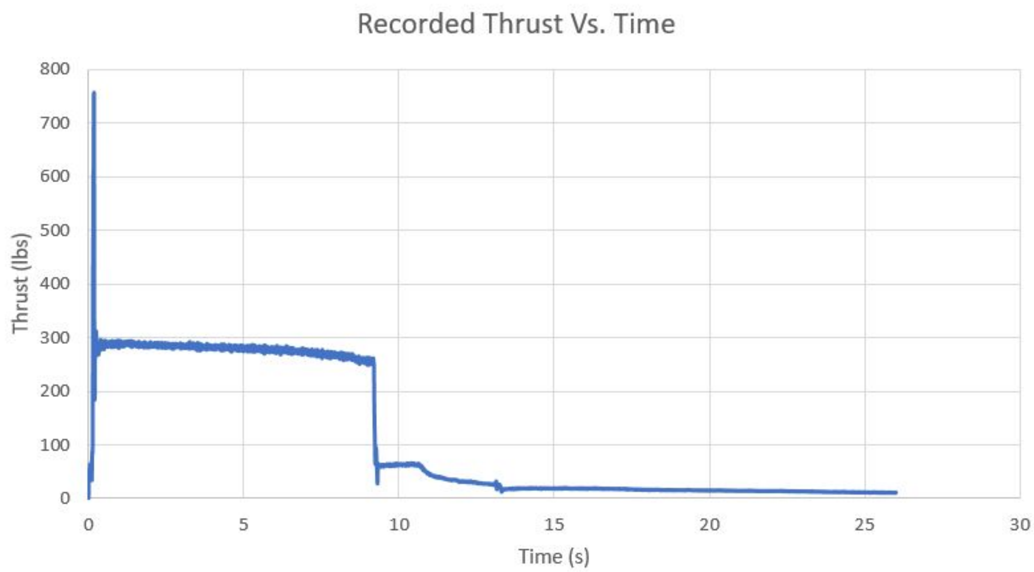


Figure 22. Full scale static hot-fire test.

Pressure Vessel Testing

After careful analysis of the engines' various pressure vessels, hydrostatic pressure tests were conducted to ensure each vessel could withstand its intended operating pressure with a safety factor of 2. These tests were conducted on individual components as well as on the whole assembled system. This allowed the ability to test the SCV actuator device and ensure that it functioned as intended.

Aero-structure Compression Testing

To determine how many layers of fiberglass were necessary for the fuselage, compression tests were performed. Three small sections of fuselage were prepared with 1, 2, and 3 layers of fiberglass on each side of an AeroMat core. This gave fuselage sections with 2, 4, and 6 total layers of fiberglass. Samples were tested in the CSU Smash lab. Each sample was placed in a hydraulic press and compressed until yield (Figure 23). The graphs of the results can be seen in Figures 24-26. It was found that 2 layers of fiberglass yielded at 4500 lbs, 4 layers yielded at 7400 lbs, and 6 layers yielded at 10700 lbs. The compressive forces expected on the fuselage during flight is 550 lbs. This means the 2 layers of fiberglass with an AeroMat core is sufficient for the fuselage of the Aries IV rocket.

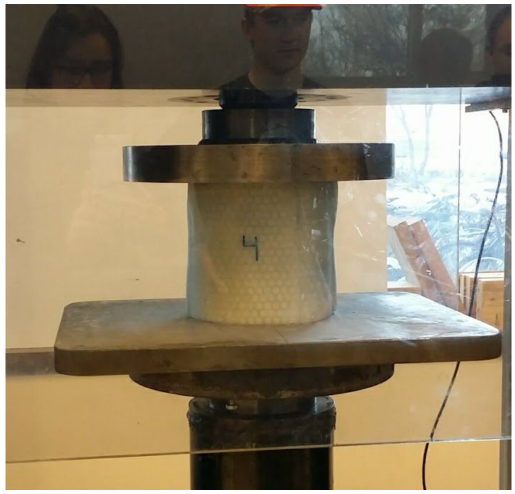


Figure 23. Compression testing of airframe cross-section.

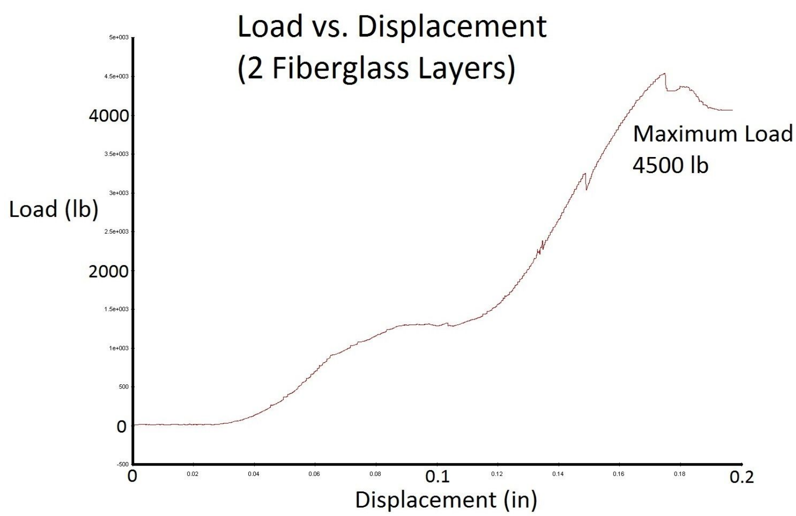


Figure 24. Compression test plot.

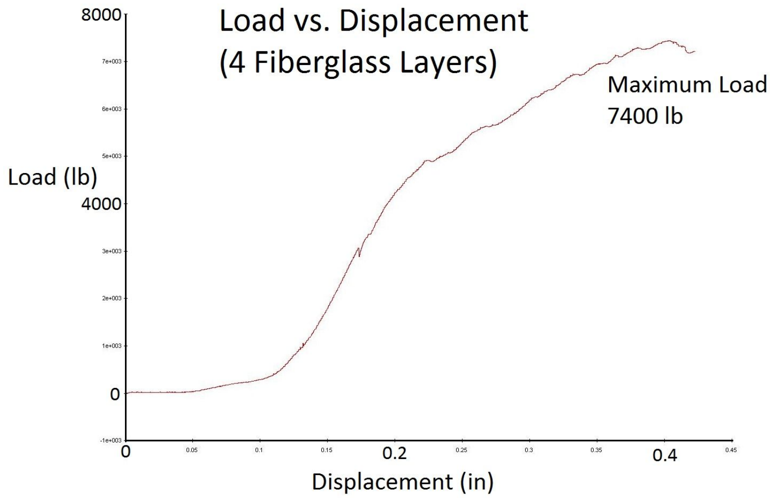


Figure 25. Compression test plot.

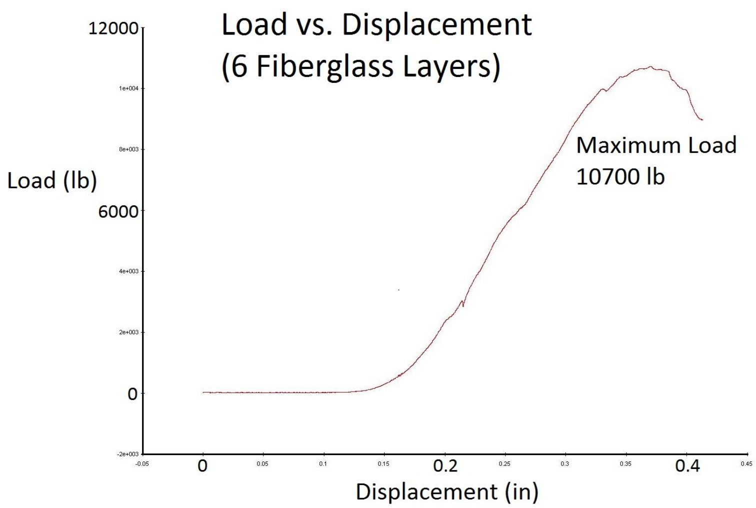
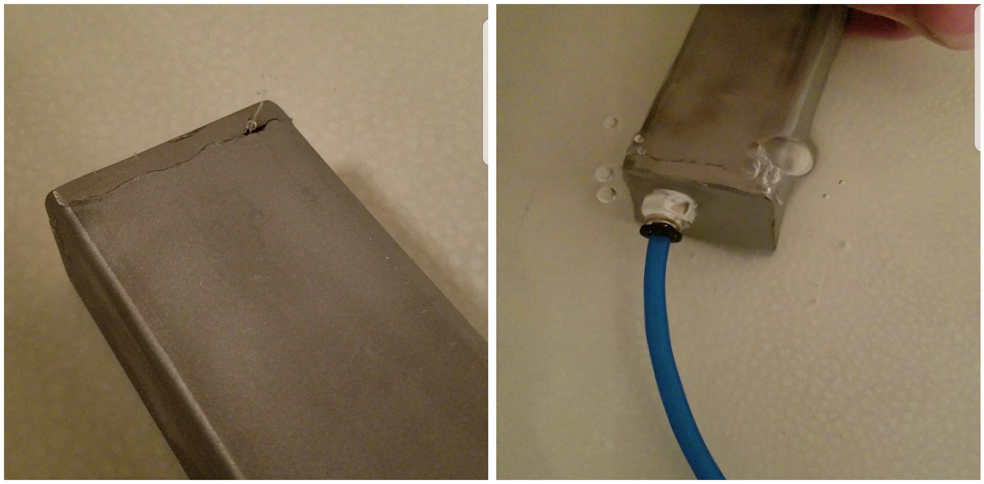


Figure 26. Compression test plot.

Payload Testing

The air collection chambers were tested for airtight seals after the caps were welded in place. To achieve this, the air hose going to the top of each chamber was attached to a bicycle pump and the chamber was submerged in water. 25 psi was pumped into each chamber to easily identify leaks, which were then rewelded and sealed. The formation of bubbles can be seen in Figure 27.



a) b)

Figure 27. Payload chamber seal tests.

To demonstrate the functionality of the solenoids and their controller, a set of altimeter data was fed into the controller unit. This "dummy" data was the altimeter data logged from a previous small scale launch. As this data was fed into the controller unit, each of the solenoids actuated in sequence.

<u>Flight Control System Testing</u>

In order to test the failsafe system, extensive torture testing of the system was done on the ground in a bench setting. This testing involved running test code while violently shaking the module, pulling and tugging on wires, removing batteries, resetting the Arduino, removing on-board ribbon cables, and other aggressive and even destructive actions in order to confirm that the failsafe board will still be able to function even in destructive situations with compounding failures. The only failures the failsafe board is not able to mitigate is mechanical destruction of the mechanism and loss of backup power to the failsafe board.

In order to develop an effective apogee prediction and control algorithm, theoretical data would not be enough. A smaller 6" air-braking module was flown and the full 8" module was also flown on small scale launches to roughly 4,000 feet on small solid motors. The data from one of these flight tests can be seen below in Figure 26. The most interesting thing to note is the unusual acceleration seen in the barometric altimeter data timed with when the flaps begin to deploy for their 5 second drag test. It is believed this is caused by the low pressure zone behind the flaps sucking air out of the airframe, causing a low pressure zone inside. This issue has been mitigated by allowing for more airflow into the mechanical section of the module and by better isolating the mechanical half of the module from the avionics bay.

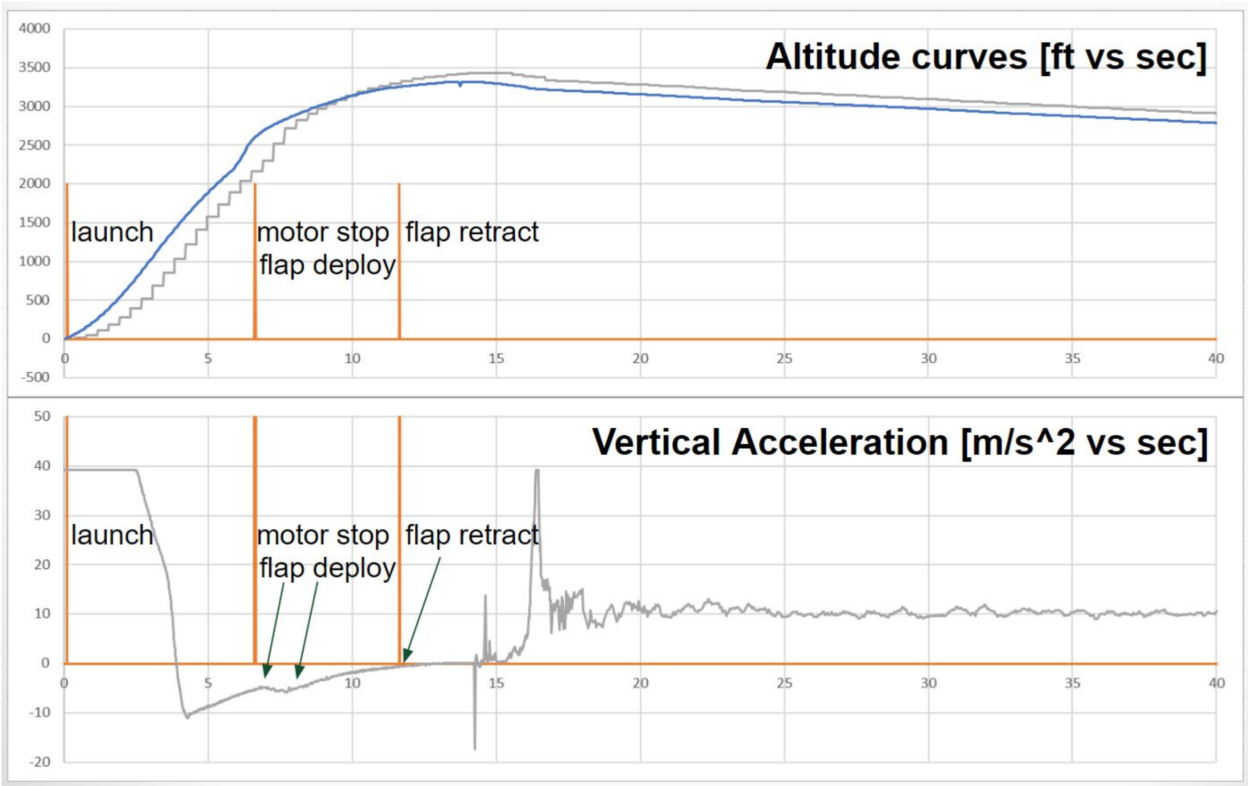


Figure 28. Altitude and vertical acceleration plots from test launch.

C. Hazard Analysis

Table 2. Hazard analysis.

Material	Transportation / Storage	Handling	Mitigation
4F Black Powder	The black powder will be stored in a plastic bottle inside of green ammunition box. This ammunition box will be kept out of the sun in a cool place and strapped down when transporting.	Safety glasses must be worn at all times while dealing with black powder. Powder will be kept away from heat/flame sources. All Ematches used to ignite squib charges will be shorted before becoming in contact with charges.	Black powder charges will be added after all other possible work has been completed to the rocket. No more personnel than is necessary will be present when loading black powder.
Ethanol	Ethanol will be stored in commercial 5 gallon jugs in a cool place and will be strapped down when transporting.	Nitrile gloves and safety glasses will be worn while handling the ethanol. The ethanol will be kept away from heat/flame sources.	The ethanol will only be taken out when the motor is being fueled and not until all other motor assembly procedures have been completed. Funnels will be implemented to aid in pouring the ethanol. In the event of unloading ethanol, the ethanol will

			be unloaded separately from the oxidizer.
Nitrous Oxide	The nitrous oxide will be kept in a DOT rated tank and chained to the inside of the trailers walls while in the vertical position. A hand cart with a support chain will be used when handling the tank. A minimum of two people will handle the tank at any given time.	Safety glasses must be worn while opening and closing the oxidizer tank values. The tank will be strapped down when filling.	Three pressure valves in series will be used when filling rocket motor on the launch rail. The global valve on the oxidizer tank will be opened first, then the second ball valve will initiate flow of oxidizer into the propellant tank. A solenoid driven valve will be used to close the fill line when the motor is full, at which point, the second ball valve will be shut off, followed by the oxidizer tank global valve.
Stability at the end of launch rail	N/A	N/A	Due diligence for a stability of no less than 1.75 will be taken and provided in the form of documentation

D. Risk Assessment

Table 3. Risk assessment.

<table>
<tr><th>Risk</th><th>Possible Causes</th><th>Risk of Mishap and Rationale</th><th>Mitigation Approach</th><th>Risk of Injury after Mitigation</th></tr>
<tr><td rowspan="3">Liquid-propellant motor explodes during launch with blast or flying debris causing injury</td><td>Propellant tanks or combustion chamber become overpressurized and fail</td><td rowspan="3">Medium: student-built motor with limited testing methods</td><td rowspan="2">Only necessary personnel present when filling motor and monitoring pressure</td><td rowspan="3">Low</td></tr>
<tr><td>Instabilities in combustion reaction</td></tr>
<tr><td>Combustion chamber becomes overheated and fails</td><td>Use ductile non-fragmenting material for combustion chamber</td></tr>
</table>

	Inner retaining rings are unable to withstand forces and fail		Conduct hydrostatic testing of motor components with appropriate retaining rings prior to pressurizing with oxidizer	
	Nozzle becomes obstructed prior to flight		Inspect the nozzle before launch while on launch stand	
Rocket is unstable when it reaches the end of the launch rail	Thrust is insufficient to accelerate the rocket to a stable speed before leaving launch rail	Low: Verified thrust curves and significant testing.	Use only tested motor configurations with thrust curves that are known. Verify acceleration speeds and stability with OpenRocket	Low
Rocket deviates from nominal flight path, strikes personnel at high speed	Fin detaches causing the rocket to lose control	Low: fins will be secured to the airframe	Fins will be adhered and bolted both on the inside and outside of the airframe to ensure connection	Low
Recovery system fails to deploy, rocket rapidly descends and lands on personnel	Piston has insufficient force to break shear pins	Medium: substantial ground testing accounts for controllable factors	Extensive ground testing of pistons and shear pin strengths	Low
	Parachute is unable to escape from airframe		Extensive ground testing of pistons inside airframe to determine that the parachute leaves airframe	
	Electronics fail to activate	Low: redundant electronics will be used	Redundant electronics as used in test flights with failsafes are used	Low
Recovery system partially deploys, rocket rapidly descends and lands on personnel	Parachute is unable to escape from airframe	Medium: Substantial ground testing accounts for controllable factors	Extensive ground testing for piston and shear pin strengths and the ability of the parachute to deploy; redundant electronics with failsafes used	Low

E. Assembly, Preflight, and Launch Checklists

Table 4. Assembly, preflight, and launch checklist.

Step		Procedure
1		**Recovery**
	a	Clean pistons (see description below the table)
	b	Set E-Matches in place with wadding
	c	Attach piston combustion chamber
	d	Attach piston assemblies to bulkheads
	d	Connect E-Matches to recovery electronics
	f	Lubricate piston rods
	g	Place and screw in piston assembly
	h	Tie kevlar rope to all attachment points of the rocket
	i	Attach packed parachutes to kevlar line
	j	Pour measured amounts of powder into piston with wadding
	k	Slide piston rods into place
	l	Coil kevlar ropes and shroud lines, attach rubber bands, and place in rocket
	m	Attach nose cone and rest of airframe with shear pins
	n	Activate screw terminal switches when rocket is on launch rail
2		**Controls**
	a	Charge both LiPoly Batteries
	b	Confirm voltage of at least 12.4 V on each battery
	c	Install batteries into their cage, zip-tie in place
	d	Check tightness of all fasteners
	e	Install and run test code
	f	Install flight code
	g	Slide module into airframe, screw into place
	h	Affix flap adaptors and flaps with three screw each- do NOT overtighten
	i	Confirm access to screw switches and visual access to status LEDs
	j	Turn airframe over to Propulsion for final assembly of propellant tanks
	k	Once upright and on stand, enable roboclaw then Arduino screw switches
	l	Watch for proper startup sequence LED and a green "enabled" failsafe LED
	m	Module is GO if zeroing sequence completes and both LEDs turn GREEN
	n	If module fails to enable, reset arduino
3		**Payload**
	a	Attach fresh batteries to the assembly
	b	Activate electronics
	c	Secure payload into the nose cone
	d	Secure hoses and plate for flight
4		**Motor**
	a	Clean Propellant tanks (see description below the table)
	b	Install new o-rings
	c	Krytox grease o-rings
	d	Attach slide check valves
	e	Fill fuel tank with ethanol
	f	Assemble propellant tanks with bulkheads
	g	Insert liner and preheater into combustion chamber
	h	Insert nozzle into combustion chamber
	i	Assemble injector and install in combustion chamber
	j	Load squibs for pyrobolts

	k	Attach actuating mechanism to slide check valves
	l	Insert motor into airframe of the rocket.
5		**Motor Filling and Launch**
	a	Attach nitrous oxide fill hose
	b	Connect ematches for slide check valve actuating mechanism, detaching the fill hose, and lighting the preheater
	c	Set up and connect wiring to light the E-Matches (but not to the control box yet) and control solenoid release valve.
	d	Insert skewer with black powder charge into the preheater for ignition
	e	Fill the tank with nitrous oxide and retreat to a safe distance
	f	Connect the ematch wires to the control box
	g	Detach nitrous oxide fill hose with its pyrovalve
	h	Ignite preheater
	i	Fire the SCV actuating mechanism 4-5 seconds into the burn
	j	Liftoff
	k	Enjoy the flight
6		**Dis-arming/Safeing of the Motor**
	a	Detach wires connected to preheater ematch and make sure it is shorted
	b	Fire SCV mechanism allowing propellant to vent through combustion chamber with no ignition source
	c	Wait for all propellant to vent before approaching the rocket

To clean the motor components, all surfaces that come in contact with the propellant, especially the oxidizer, are excessively wiped down with brake cleaner until there is no residue left. Then the brake cleaner will be wiped off with water-wetted paper towels. Finally, the system will be dried with clean paper towels, so that no water is within the tanks. The recovery pistons are cleaned in the same manner.

F. Engineering Drawings

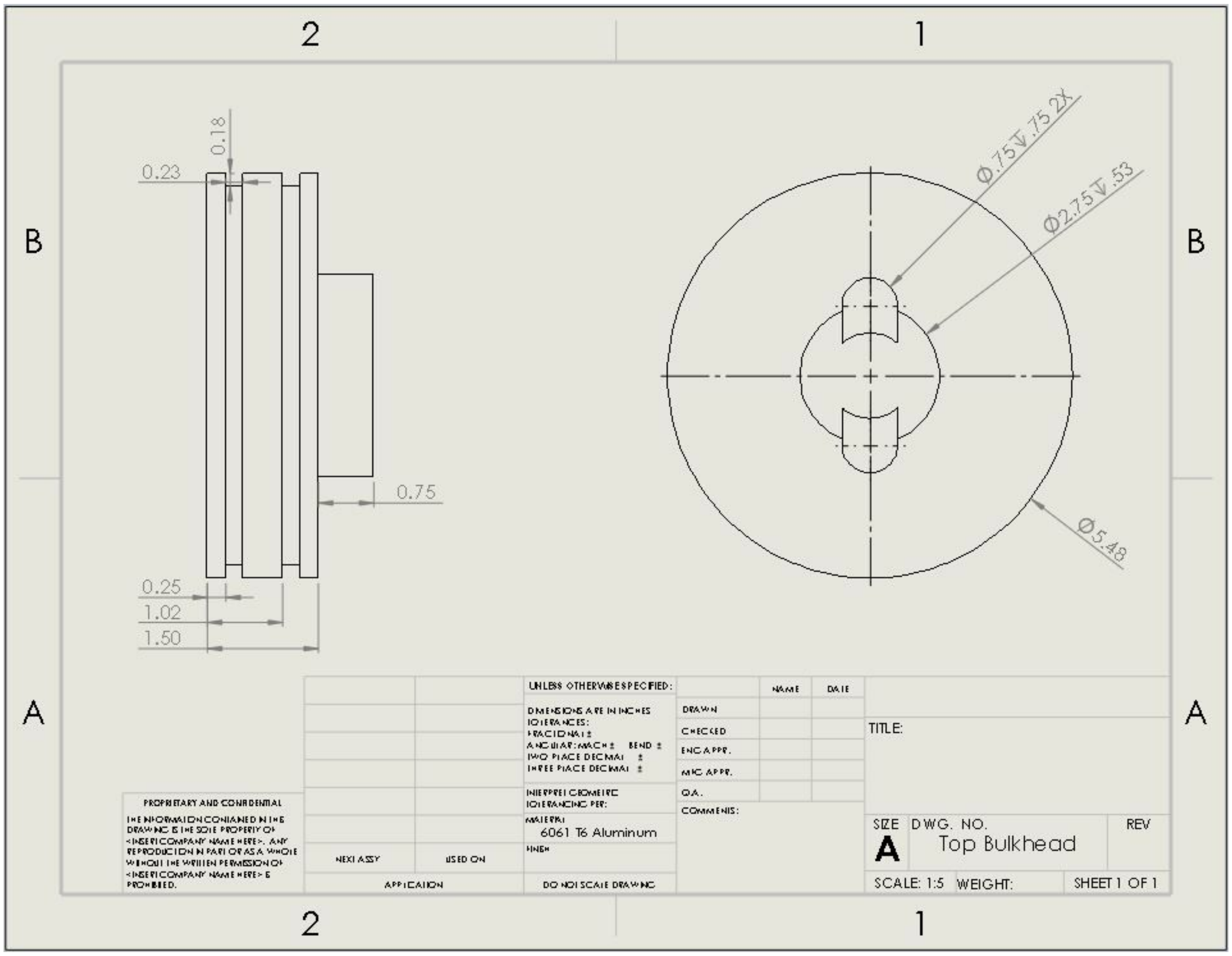


Figure 29. Engineering drawing of the motor top bulkhead.

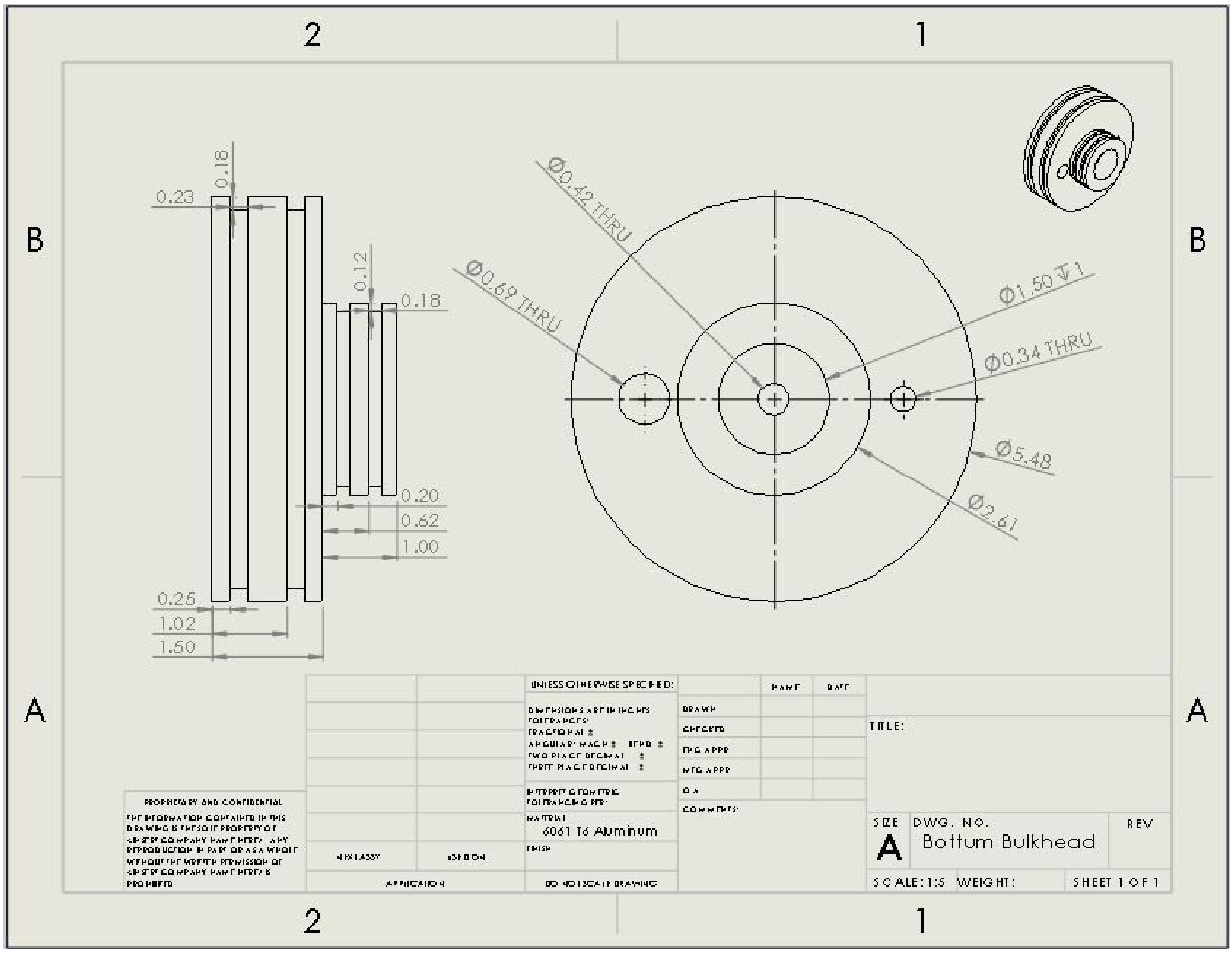


Figure 30. Engineering drawing of the motor bottom bulkhead.

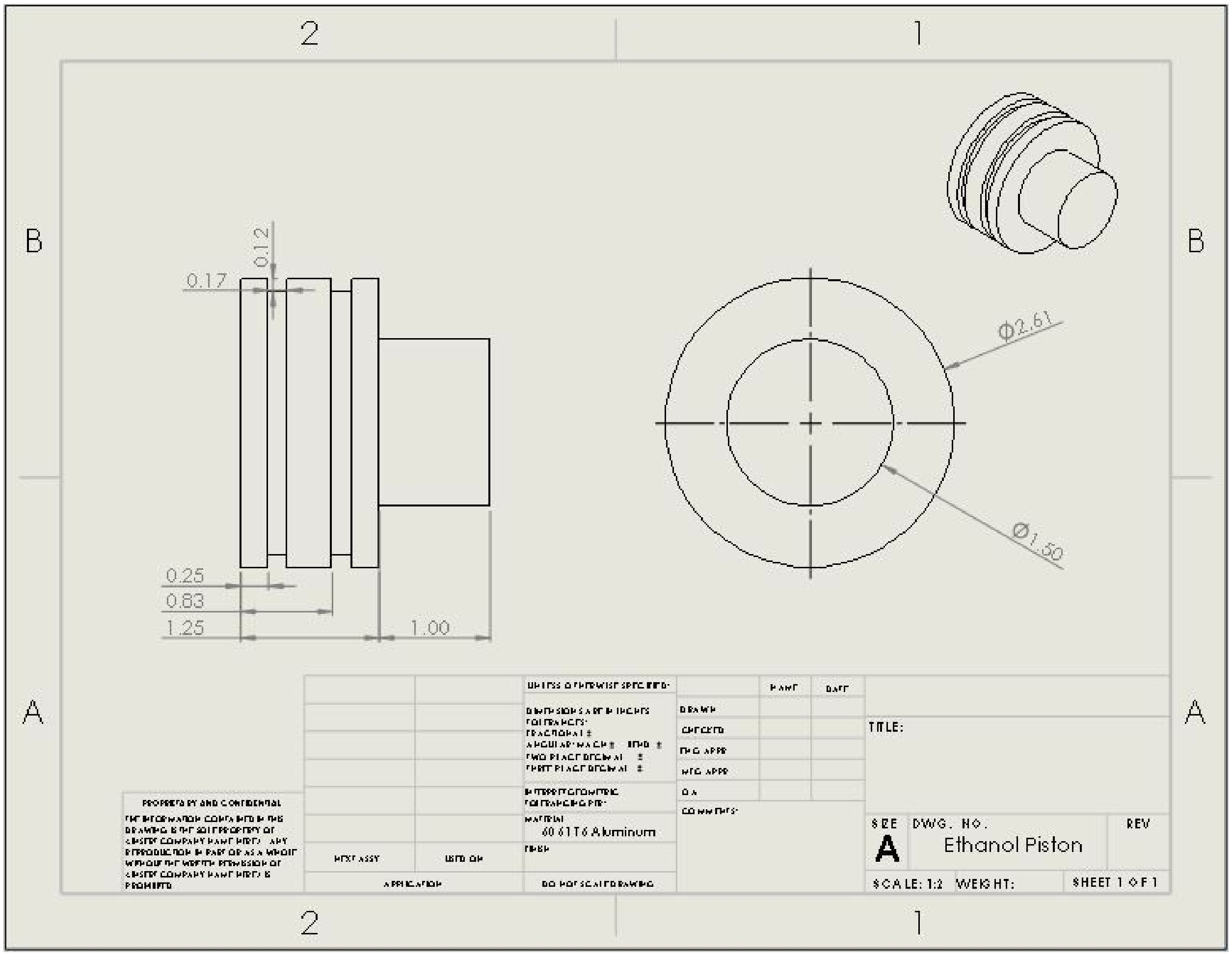


Figure 31. Engineering drawing of the ethanol piston.

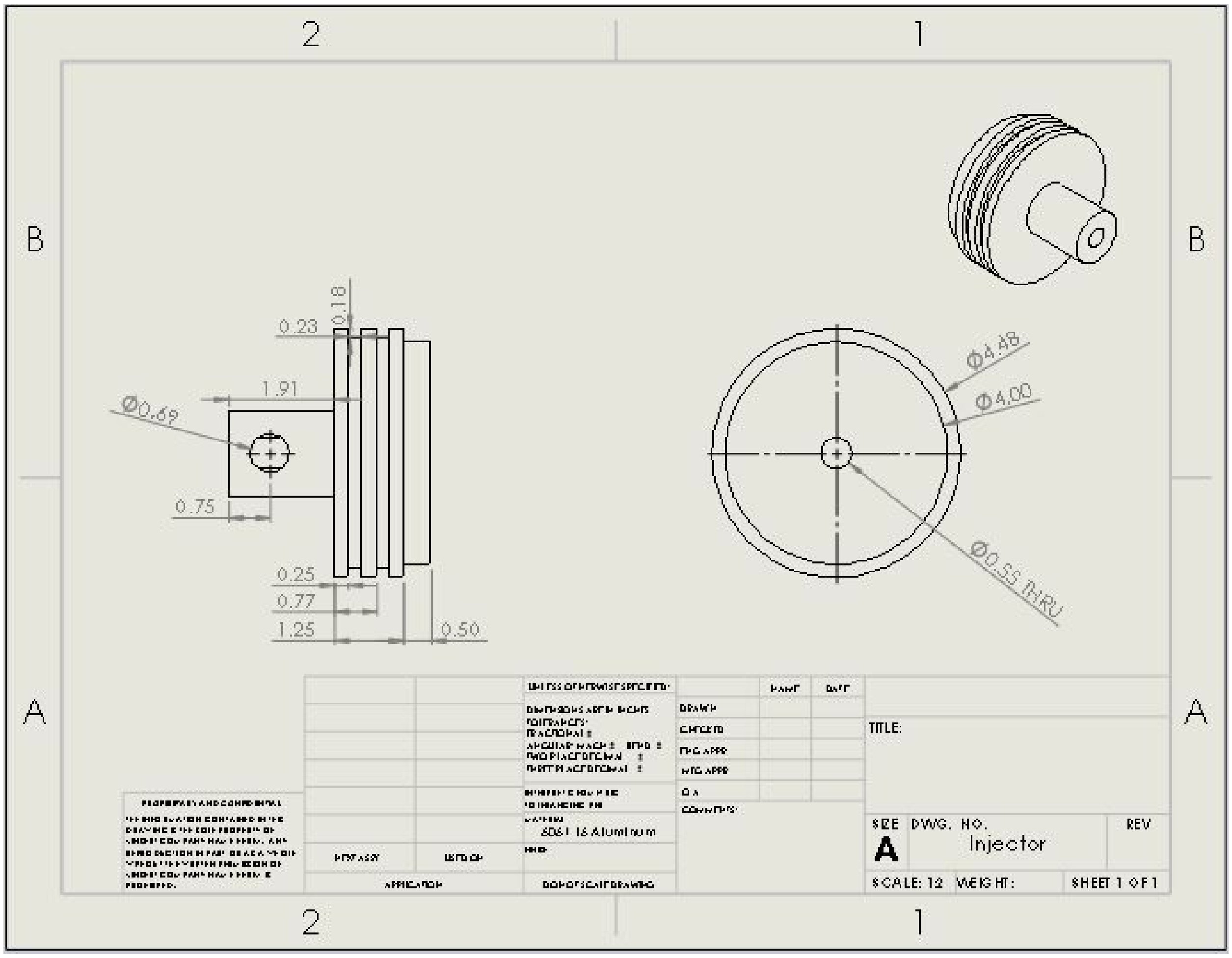


Figure 32. Engineering drawing of the motor injector.

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