Abstract

Sounding rockets support an important role in conducting scientific experiments in the atmosphere as well as in sub-orbital space. The performance of the rockets can be further advanced with innovation in propulsion, structure, recovery and controls to reduce overall costs. Apogee and size of experiments can be increased by utilizing liquid fuels with higher energy densities, reducing weight in the airframe, and implementing a control system to optimize ascent. The proposed rocket design involves being propelled by a tribrid engine, constructed from advanced composite materials, and governed by a roll control and aero braking system. To verify the reliability and effectiveness of the rocket design, multiple test launches will be conducted iterating toward a complete and final launch of the vehicle. Pending on the success, the standards of sounding rockets will be furthered allowing the deployment of larger or more experiments to higher apogees.

1 Introduction

1.1 Project Overview

Sounding rockets provide multiple advantages and opportunities for scientific experiments in Earth’s atmosphere and with different technologies on suborbital trajectories. The payloads typically include apparatuses that conduct upper atmospheric measurements, X-ray sampling and microgravity experiments. They are also used to validate instruments and develop new technologies.

Figure 1: Sounding Rocket Flight Profile

The greatest advantage of these rockets are their low
cost and rapid turnaround times. Innovative systems in propulsion, airframe, and aero-controls can increase efficiency and reliability in turn reducing the costs of launching payloads. Colorado State University will be participating in the Intercollegiate Rocket Engineering Competition (IREC) at Spaceport America where these systems will be demonstrated.

The rocket, named Aries III, will be launched to 10,000 feet above ground level (AGL) and carry an 8.8-pound payload of scientific merit. Acceleration and visual data will be recorded upon ascent of a small scale liquid fuel tank slosh apparatus. The Coaxial Self-Pressurizing Liquid Rocket Engine (tribrid) will produce between 450 and 500 pounds of thrust using three different fuels. Ignition begins by lighting a preheater grain in the combustion chamber where ABS plastic is burned and oxidized by Nitrous Oxide. An intentional failure of a nylon plug then releases denatured alcohol (ethanol) into the combustion chamber switching the engine from a hybrid to the tribrid mode. The plastic burns away and the rest of the burn is continued with the liquid fuel and oxidizer. The overall weight of fuel required is decreased by approximately 50% when compared to a solid engine burning ammonia perchlorate. Costs of launch is decreased significantly as well due to ease of maintainability and refueling. This tribrid propulsion system will fire for approximately 10 seconds after which the rocket will then coast to the set apogee. Just before apogee, four grid fins will rotate and counter each other’s aerodynamic effects thereby slowing down the rocket. Aiding in the overall flight efficiency, the control system will inhibit roll to minimize redundant work. The airframe will be constructed from a sandwich panel type construction where fiberglass is bonded to either side of a honeycomb core. A fuselage built with this technique will provide exceptional stiffness while remaining extremely lightweight. The airframe, including the nose cone, will weigh approximately 8 pounds for a 14.5-foot rocket. This is a considerable weight savings as compared to an aluminum airframe that would weigh at least 34 pounds. With more efficient and less costly fuels, lighter airframe and a control system, the standard of performance for sounding rockets can be advanced.

1.2 - Project Goals

The goal of this project is to design and build a sounding rocket that carries an 8.8-pound scientific payload to an apogee of 10,000 feet and return to the ground in a re-flyable condition. The CSU IREC team is using this opportunity to incorporate experimental technology on as many subsystems of the rocket as possible; these include the honeycomb core sandwich panel material, the coaxial self-pressurizing liquid propellant rocket engine, as well as the grid fin’s and active control system. In this way, the experimental payload that the rocket carries will not be the only experiment being conducted on Aries III.

2 Analysis

2.1 - Design Overview

The Aries III rocket has been designed as a subsonic, dual deployment, sounding rocket. The specifications of the rocket are based on the rules specified by IREC. The main constraints for the project that are designated by IREC are as follows:

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage inner diameter</td>
<td>&lt;5.6”</td>
</tr>
<tr>
<td>Thrust to weight ratio</td>
<td>&gt;= 4</td>
</tr>
<tr>
<td>Payload weight</td>
<td>&gt; 8.8 lbs</td>
</tr>
<tr>
<td>Stability</td>
<td>&gt;1 &amp; &lt;2 body calibers</td>
</tr>
</tbody>
</table>

The fuselage inner diameter constraint is derived from the payload size, which is constrained to one CubeSat, which is equal to 5.6” along the diagonal. The other three constraints are based on rules that IREC has set for safety purposes.

2.2 Airframe/Systems Integration

The overall design of the body tubes and nosecone have been optimized for performance and assembly. Figure X below shows the performance of various nose cone profiles at different Mach numbers. The Von Karman nose cone profile has strong performance at speeds lower than Mach 1, which is the regime that the Aries III is designed to fly in. For
this reason, the Von Karman nose cone profile is the basis for the Aries III nose cone design.

![Figure 2: Nosecone Profile](image)

1 - Superior performance, 2 - Good performance, 3 - Fair performance, 4 - Inferior performance

The ratio of the length of a nose cone to the base diameter is critical in the aerodynamic performance of a nose cone. This characteristic is called the Fineness Ratio. Figure 3 below illustrates the effect of fineness ratio and Apogee as well as drag loss. The figure demonstrates that as this ratio approaches five, drag reduction and apogee gains diminish. This indicates that a fineness ratio of five is the optimum value between drag reduction and weight.

![Figure 3: Nose cone profile performance](image)

The fuselage of Aries III is constructed using sandwich panel geometry to create a lightweight, yet strong body tube. Fiber is bonded on both sides of a honeycomb core which uses the same concept as an I-beam and optimizes use of the material. When using these composite materials in high stress applications, hard points must be constructed around stress concentrations such as fasteners. Aries III has been designed to include two varieties of hard points:

- Aluminum inserts
- Epoxy and filler injection

![Figure 4: Honeycomb core sandwich panel with hard points](image)

The airframe is constructed to have a safety factor of two and is validated through computational simulations and mechanical testing. Tensile testing of multiple fiberglass coupons was conducted to obtain the properties of the selected material. A graph of the data collected can be seen in Figure 5 in the appendix.

Fiberglass Average Max Stress

- 10,439 psi (at 45°)

It is difficult to perform compression testing on composites so as a rule of thumb, the fiberglass is only half as strong in compression than it is in tension. Helius is a great software package that can be used to simulate multiple conditions for composite materials. Figure 6, located in the appendix, illustrates the case for panel stability with fixed sides to simulate a tubular geometry. The overall failure of the sheet is lower than the face wrinkling failure mode so failure is predicted to be in delamination of the fiber from the core and result in buckling. Helius predicts this to occur at 11221.3 PSI though it is known to overestimate strength due to the assumption of perfect parts.
ANSYS Workbench was used to identify the stress that the fuselage will experience at high acceleration. Results of the analysis are shown below in Figure 7 and Figure 8 in the appendix.

The accepted failure theory used is Tsai-Wu which is generally associated with composite materials. The maximum principal stresses of 91.43 and -72.42 psi seen in the FEA analysis did not exceed that of the predicted overall stability failure of from Helius, even at an excessive compression force of 500 pounds.

Mechanical testing was performed on a small scale sample section of the fuselage and loaded under compression to 1000 pound-force. This is where failure would have likely occurred but did not even at a calculated normal stress of 1500 psi.

The data collected from the compression of the honeycomb core sandwich panel material can be seen in Figure 10 in the appendix.

2.3 - Propulsion
The Coaxial Self-Pressurizing Liquid Propellant Rocket Engine (tribrid) is pictured below in Figure 11.

A small scale version of the Aries III engine has been constructed and test fired. The first series of test fires were conducted in order to test the feasibility of the tribrid engine, as well as to evaluate predictions of chamber pressure and thrust. The max chamber pressure was predicted to be about 400 psi and max thrust was predicted to be between 125 and 150 pounds. The data from one of the test fires from the first series of test fires is shown in Figure 12 in the appendix.

For the second round of test fires, the injector orifice and nozzle throat diameters were increased in order to simulate the estimated thrust of the full scale tribrid. The estimated max thrust for these test fires was 400 to 420 lbs. The chamber pressure for Test Fire 2 was unusually low due to the small diameter of the combustion chamber relative to the nozzle throat diameter. This chamber pressure will rise in the full scale tribrid engine, which will subsequently increase the thrust output. The data from one of these fires is shown in the appendix in Figure 13.

The full scale tribrid engine is projected to produce a maximum thrust of 475 to 500 lbs. The reach the target apogee of 10,000 feet, the tribrid will need to produce a total impulse of 15,000 - 16,000 N*s and to have a burn time of 9 - 10 seconds. These values were calculated using flight models produced in MS.
Excel as well as the open source software OpenRocket.

The tribrid engine is based on the original design by Rattworks. The benefits of this engine to a hybrid are higher energy densities, smaller length, simple design, and essentially having a liquid rocket engine that is far more simple in design than a standard liquid engine.

Figure 14: Tribrid Engine Hot Fire Test

2.4 - Controls

The overall goal of the Aries III Control system is to successfully maintain the rocket's roll and to slow the rocket flight in the event of overshoot past desired apogee. Grid fins experience similar aerodynamic forces as planar fins, but lower hinge moments making them easier to turn via actuator. This makes grid fins a strong candidate for an active control system control surface. However, grid fins perform very poorly in transonic flow, which constrains the max speed of Aries III to below Mach 0.75.

Static grid fins were tested on a small scale, solid engine rocket. This test was conducted in large part to test the feasibility of grid fins as a control surface. The static grid fin configuration is pictured in Figure 15 below:

Figure 15: Static Grid Fin configuration

The aerodynamic performance of grid fins was analyzed using CFD++, and substantial research has been conducted on existing literature about grid fin aerodynamics. There is little information on subsonic grid fin performance in the scientific community.

Figure 16 below shows the current prototype of the grid fin actuation system.

Figure 16: Grid fin mounting/actuation system prototype

The current design loop for the PID control will integrate a side swap option, as per IREC rules. A side swap option is a working duplicate of a sensor set – microcontroller – logic combination. In Figure 4C, a standard operating loop and a secondary take-over loop are pictured. The standard loop is the logic that is initially running and is what drives the motors. This Arduino microcontroller is nicknamed the
“operat”, and is what drives the motors and reads/interprets the data from sensor set 1 in normal circumstances. While constraints require that active control be aborted should certain scenarios occur, sensor set 1 will have stricter tolerances to give the second Arduino microcontroller a chance to take over and fix the problem before absolute constraints are reached. This action is called the side swap. The original operator Arduino is swapped out for the second loop consisting of a second sensor set-microcontroller-logic combination. This loop is nicknamed the “supervisor” loop, and only takes control in certain situations. Figure 17 below illustrates this system:

![Figure 17: Side Swap Configuration](image)

### 2.5 - Payload

The Aries III payload is an experiment that evaluates liquid fuel sloshing in rockets. The design consists of two small tanks containing liquid water, one containing a baffle and the other containing nothing other than the water. Each of these tanks will be suspended on springs, allowing them to oscillate in the z axis only. An accelerometer will be attached to each tank, recording acceleration data. Figure 18 below shows the 3D model of the payload.

![Figure 18: Model of payload](image)

### 2.6 - Recovery System

The recovery system will utilize two parachutes to fulfill the dual deployment constraint. This will consist of first a 5 feet diameter hemispherical drogue parachute that will deploy at apogee and then a 15’ diameter main toroidal parachute that will deploy once the rocket reaches an altitude of 1,500’. Both parachutes will be constructed from ripstop nylon and 275 paracord. Full felled seams will be used to improve the parachutes strength. The redundant electronics constraint will be fulfilled utilizing two different barometric dual-deploy altimeter systems, the Missile Works’ Rocket Recovery Controllers RRC3 and RRC2+. These will be connected to both ejection systems and will signal a high current to the electric matches when it is time to deploy the parachutes. A piston assembly will be used due to its increased reliability, reusability and need for significantly less black powder. Figure 19 is a diagram of the piston ejection system.
3 - Conclusion

All of these systems being implemented is expected to result in one synergistic, high performance rocket. The airframe has weight performance greater than that of aluminum reducing the required energy to reach a desired apogee. Discussed in a hobby rocketry page, the similar airframe was proven to be Mach capable which expands the range of experiments that can be flown. The tribrid engine can be custom tuned for each flight by simply modifying the mass flow rates of fuel entering the combustion chamber to reach different speeds and altitudes as well as flight duration. It can also be reused multiple times using less costly fuels reducing overall costs of launch. The control system will ensure that the flight is efficient as possible and can be used to target certain apogees with great accuracy. This system can be expanded upon by being able to control pitch and yaw furthering its versatility. The Aries III rocket design is hoped to further advance the standards of sounding rocket performance and provide an increased variety of experiments that can be performed.
Appendix

Figure 5: Fiberglass compression testing data

Figure 6: Helius Sandwich Panel Analysis

Figure 7: Maximum Principal Stresses with Tsai Wu Constraints

Figure 8: Maximum Shear Stress with Tsai Wu Constraints

Figure 10: Engineering Stress Strain Compression Data

Figure 12: Small Scale Test Fire 1

Figure 13: Small Scale Test Fire 2
References


