Development of an Experimental Hybrid Rocket: CSU IREC Team

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The Intercollegiate Rocket Engineering Competition (IREC) is a contest supported by the Experimental Sounding Rocket Association. The Colorado State University IREC Team is producing a rocket for this competition for the first time in CSU’s history. The rocket is designed to launch ten pounds of payload to 10,000 feet above ground level. The rocket is propelled by a team built hybrid rocket motor that implements a hydroxyl-terminated polybutadiene (HTPB) based fuel grain and nitrous oxide oxidizer. The ten pounds of payload consists of three systems: atmospheric carbon dioxide sensing, orientation logging through video analysis, and a pod simulating a human occupancy zone.

The majority of the IREC Team’s rocket consists of student designed and manufactured parts. The entire motor and many of the structural components are fabricated by the student team. The hybrid rocket motor implements a novel filling and injection system never documented before. The injection system allows the rocket to be filled and ignited remotely while injecting oxidizer through multiple diverging orifices in flight. The rocket features a dual parachute deployment recovery system: a smaller drogue parachute and a main parachute. The drogue parachute controls the rocket’s descent and prevents lateral drifting. The main parachute deploys approximately 1,000 feet above the ground and slows the rocket to a safe landing velocity.

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I. Introduction

The Intercollegiate Rocket Engineering Competition (IREC) is hosted by the Experimental Sounding Rocket Association (ESRA). The general rules of the IREC are to produce a sounding rocket capable of lifting ten pounds of payload to 10,000 feet of altitude above ground level. A sounding rocket is a rocket capable of recording measurements for scientific reasons during its flight, and the ten pounds of payload will accomplish this task.

Many of the scoring points of the competition are for student designed and built components. Early in the design process, we decided to incorporate a hybrid rocket motor for the propulsion of our rocket. A hybrid rocket motor is a combination of solid and liquid rocket motors. A hybrid rocket motor uses a liquid oxidizer and solid fuel grain. Figure 1 is a schematic of a typical hybrid rocket motor.

![Hybrid Rocket Engine](http://www.spg-corp.com/space-propulsion-group-resources.html)

At a minimum, a hybrid rocket motor consists of an oxidizer tank, valve mechanism, fuel grain, oxidizer injector, and nozzle. There can be many alterations to this design that improve or change the performance of the hybrid rocket motor for its specific application.

The payload of the rocket consists of three sections: a human occupancy simulation zone, a horizon tracking video analysis system, and a carbon dioxide sensor. The human occupancy simulation zone was originally intended to be a K-12 project, but due to lack of time and issues contacting local high schools early on, we decided to create it ourselves. The horizon tracking system collects a live video stream and analyzes it for the angle of the horizon and if the sun is in frame records the relative position of the sun. This package is intended to be the starting point of an orientation logging and potential flight control system. The carbon dioxide sensor was generously donated to the project by the CSU Colorado Space Grant and refitted for flight in the rocket. The carbon dioxide sensor will record data on the descent of the rocket because the ascent is such a high velocity.

The rocket returns safely to the ground through the use of drogue and main parachutes. The drogue parachute deploys at the apogee (highest altitude) of the rocket’s trajectory, and will keep the rocket under controlled descent and reduce the amount of drifting. The main parachute is released 1,000 feet above the ground level to slow the descent to approximately twenty feet per second for a soft landing.
II. The Design Process

Preliminary Design
The preliminary design of the sounding rocket required an analysis of the objectives and requirements the rocket would need to meet.

*Design Objectives:*  
Success of our term goals relies on several measureable objectives. Prioritization of these objectives was derived from the corresponding points in the ESRA Judging Sheet. Our main objective is to reach as close to 10,000 feet as possible at apogee. With similar priority, we will need the rocket to be statically stable to ensure a successful flight. In addition to the requirements of the competition, an objective proposed by our team was to have a successful test launch prior to the competition.

*Design Requirements:*  
In the process of completing these objectives, our team is required to adhere to a strict set of design requirements due to safety concerns. A condensed list of the requirements is provided in Appendix A within Table 1. Any deviation to the design requirements would require immediate approval from the ESRA board.

*Flight Calculations:*  
Before the propulsion system could be designed, a series of flight calculations needed to be performed in order to properly size the motor to reach the desired 10,000 ft. Several different analysis tools were used in the development of a program to simulate a rocket flight with different propulsion performance. An evaluation of Hybrid Rocket Engine performance was completed with a NASA Chemical Equilibrium with Applications (CEA) program. Data from the results of the CEA were used in the mathematical model to increase the accuracy of the preliminary design from a propulsion standpoint.

A set of equations was used to develop a program to simulate the aerodynamics of rocket flight. Using this program, a predicted thrust curve from the motor, and design parameters of the rocket, we could accurately predict the achieved height of the rocket. Through several iterations of this program, our team was able to select a set of design parameters that was best suited for our needs given a predicted engine performance.

Primary Design
Once the general parameters of the rocket were decided upon, the individual subsystems needed to be designed, while staying within the set parameters. The primary subsystems of the project design include the hybrid rocket engine, airframe, payload, and recovery system.

*Engine Assembly*  
The hybrid rocket engine is comprised of a liquid oxidizer supply that is filled remotely and then released to flow over a solid propellant encased in PVC as insulation.
The figure shown above is a breakdown of the basic elements of the design for the motor. The nylon fill tube will allow our team to fill the oxidizer tank above the motor (not shown) through this line while the rocket is in the launch configuration. Once the tank has been filled, the ammonium perchlorate preheater grain will be ignited and sever the nylon fill line, preheat the fuel grain for combustion, and melt the nylon washer in the injector system to actuate the oxidizer flow.

Once the oxidizer begins flowing into the combustion chamber, it will react with the fuel and begin the combustion process. The combustion products then evacuate the rocket at a high velocity through a graphite nozzle at the bottom thrusting the rocket upward.

As seen in the previously described figures, during the filling operation, the
injector is held in a closed position. The Yor-lok fitting is threaded into the piston which contains a custom made check-valve. This allows oxidizer to flow up through the nylon fill tube and into the oxidizer tank (situated above the entire assembly). Once the oxidizer tank is full, the preheater grain will melt the nylon washer to the point where the piston will be forced down by the pressure from the tank. Once in this configuration, shown in Figure 4, the injector orifices at the lower end of the injector are exposed and the oxidizer is free to flow through them to the combustion chamber.

**Airframe**
The airframe consists of a shock resistant body tube topped by a rounded nose cone (due to a subsonic maximum velocity) and stabilized at the bottom with four fins. The body tube was built in sections to provide ease of assembly and parachute deployment.

**Payload**
The payload section has four partitions: a carbon dioxide sensor, a network of accelerometers, a horizon tracker using video analysis, and a human occupancy simulation chamber. The CO2 sensor will document the changing CO2 levels at varying altitudes. The accelerometers and human occupancy chamber will measure the rocket’s vibration levels throughout flight.

**Recovery**
The recovery system consists of a drogue and main parachute made of rip stop nylon fabric. The drogue parachute is a 3 ft. diameter hemi-spherical parachute that deploys when the rocket reaches peak altitude. A 15 ft. diameter toroidal parachute is used as the main parachute and deploys at 1000 ft. to slow the rocket to its final decent velocity.

Both parachutes will be ejected with black powder ejections charges and a series of shear pins. When the black powder charges are initiated, the resultant pressure inside the parachute section will cause a controlled failure of the shear pins to separate that section of the rocket.

**III. Manufacturing**

As previously mentioned, a large portion of the points for the competition come from student designed and manufactured components. With the decision to develop a custom hybrid engine, the manufacturing process of the project became a very extensive aspect.

**Oxidizer Injection System**
The oxidizer injection and actuation system proved to be the most difficult portion of the project since traditional valves were not used.

Figure 6: Injector Plates

Figure 7: Evolution of Piston Design

Figure 8: Graphite Nozzle

The nozzle consists of a converging and diverging portion, O-ring grooves to seal against combustion gasses, and a specific throat diameter.

Fin Can

The fin can for the rocket was manufactured to specific dimensions to ensure stability. Each fin consists of a 6mm plywood base in between two 1/16” thick G10 fiberglass sheets for added rigidity. That fin assembly was then epoxied to the airframe for alignment.

Figure 9: Fin Can Construction

As seen in Figure 9, once the fins were aligned, they were fiberglass wrapped from tip to tip to increase the strength.

Payload/Avionics Bay

The payload /avionics bay is currently under construction and is estimated to be complete by the end of May 2015. All
aspects of the electronics have been completed, and the rigging/layout of the human occupancy zone are left to be complete.

**Full Assembly**

A full stack-up of the rocket was completed recently and the system can be seen in Figure 10.

![Figure 10: Rocket Assembly](image)

**IV. Testing**

Many of our original design decisions required testing to determine if any issues existed before we attempted to fly our rocket. The majority of the tests we conducted occurred during the second semester of the project, and included injector, motor, ejection, payload, and flight.

**Injector Testing**

The injector testing consisted of installing the injector assembly in a shortened motor casing section. The injector was then pressurized using carbon dioxide. Carbon dioxide was chosen because it is much more inert and cost effective compared to nitrous oxide and it also has similar physical properties. A solid rocket fuel preheater grain was then placed in a similar spot to its actual location in the motor, and we were able to test the controlled failure of the nylon washers supporting the piston. After performing over forty tests on failing the washers, we found a solution that has been extraordinarily consistent. We tried a different concept of heating the washers by using two thinner washers stacked together with a section of nichrome wire heater sandwiched between them. After conducting five more tests, it was obvious that nichrome wire was not necessary, but just the act of using two thinner washers made the failure of both of them very predictable. This is believed to occur because the washer nearest the preheater melts and the washer away from the preheater is insufficient to hold the piston. This concluded the fifty total tests of the injector system.

During the injector testing, it was also determined that the threads on the piston would deform and release the compression fitting after fifteen tests. This was caused by fatigue of the threads from the repeated loading, unloading, and impact loading of the piston actuation.
Hot Fire Testing

The next step was to conduct hot fire motor testing. This experience was greatly improved from Sierra Nevada Corporation’s contribution to our project: they provided us with a portable hybrid rocket motor test stand (HRMTS). We were able to quickly modify the HRMTS to satisfy our requirements. The HRMTS can be seen below in Figure 11.

The HRMTS was also provided with an extensive Data Acquisition and Control (DAQ) system. This included pneumatic and solenoid valves, pressure transducers, load cells, and a National Instruments cRIO module. To interface with the HRMTS we were required to modify or create our own LabVIEW program. After two weeks we were able to develop a LabVIEW program capable of controlling the valves and heaters we installed and collecting data at rates high enough for our purposes. A screen shot of the front panel of the interface is shown in Figure 12.

First Hot Fire Test

The first hot fire motor test that was performed was unsuccessful in that we had a burnout of our motor casing. This can be attributed to two main faults: a manufacturing error in our injector orifice pattern that caused more oxidizer to be sprayed in a particular area and a relatively low amount of insulation inside our motor casing. The following figures are of the motor burnout and the uneven fuel grain consumption. Figure 14 shows the first firing at the point in the burn where the fuel grain burned through. A spout of fire can be seen upstream of the nozzle through the motor casing.

Figure 11: HRMTS Setup

Figure 12: LabVIEW Testing Control Panel

Figure 13: First Test, Motor Failure

Figure 14: First Motor Firing
V. Conclusion

Through continued testing of our hybrid rocket engine, we will be able to solidify and prove our design to be reliable. Once an accurate thrust curve is produced from a test, we will be able to predict the flight trajectory using our custom developed MATLAB code. If the thrust is insufficient, alterations will be made to the fuel grain composition to increase the thrust.

When the motor configuration has been proved satisfactory, we will assemble the motor into the airframe and begin preparations for a test launch in May 2015. Based on observations during the launch, we will have adequate time to make alterations before the competition at the end of June 2015.

This has been an extremely beneficial learning experience for our team and CSU in the field of rocket engineering. Our team hopes that the progress we have made thus far will be furthered in future years. Our team sees this project as a stepping stone for even greater projects in the field of rocket development.

With the continued support of Colorado Space Grant Consortium, future teams will be able to make strides in this technology and attract new companies to CSU

VI. Recognition

Our team would like to acknowledge the contributions made by several individuals and companies.

- To the Colorado Space Grant Consortium for supplying critical funding to our project.

- To the CSU Senior Design Practicum program for supplying the majority of our funding as well as knowledgeable advisers to our project.

- To Sierra Nevada Corporation for their endless contributions in the form of financial, material, testing, and professional resources.

- To the members of the Northern Colorado Rocketry (NCR) community for sharing their experience regarding rocket construction.

  o Specifically, to Edward Wranosky for all resources provided and services rendered in order to make this project what it is.
# VIII. Appendix A

## Table 1: Project Requirements

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Method of Measurement</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety critical wiring</td>
<td>Wiring conforms to specified standards</td>
<td>No violations</td>
</tr>
<tr>
<td>Keep project cost under budget</td>
<td>Cost of design, production, testing, travel, etc.</td>
<td>&lt; ($4500 + additional funding)</td>
</tr>
<tr>
<td>Radio beacon for recovery</td>
<td>Wavelength of transmitted radio wave ($\lambda$)</td>
<td>70cm</td>
</tr>
<tr>
<td>Safety Analysis</td>
<td>Identify potential hazards, risk, and mitigating procedures</td>
<td>Completed by June 8, 2015</td>
</tr>
<tr>
<td>Non-toxic propellant</td>
<td>Requirement of breathing apparatus/protective equipment, special storage and transport</td>
<td>No violations</td>
</tr>
<tr>
<td>Descent velocity in acceptable range</td>
<td>Velocity of rocket during its descent from apogee to 1000 ft AGL (ft/s)</td>
<td>80 - 100</td>
</tr>
<tr>
<td>Carry one commercial altimeter</td>
<td>Altimeter present on-board to record apogee altitude</td>
<td>At least one altimeter</td>
</tr>
<tr>
<td>Carry 10 lb payload</td>
<td>Weight of payload (lb)</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Rocket leaves launch station at high enough speed</td>
<td>Velocity of rocket leaving launch station (ft/s)</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Launch rail compatibility</td>
<td>Deviation to ESRA two-guide launch rail specifications</td>
<td>None</td>
</tr>
<tr>
<td>Rail guide strength (both guides)</td>
<td>Support full rocket weight in pre-launch configuration (horizontal)</td>
<td>&gt; Launch weight</td>
</tr>
<tr>
<td>Rail guide strength (bottom guide)</td>
<td>Support full rocket weight in launch configuration</td>
<td>&gt; Launch weight</td>
</tr>
<tr>
<td>Chamber pressure or thrust trace</td>
<td>Full duration static test fire w/ no leaks or anomalies</td>
<td>Completed by June 24, 2015</td>
</tr>
<tr>
<td>Motor/engine armed at safe distance</td>
<td>A single action, away from the launch pad, is required for the engine to ignite</td>
<td>&gt;50 ft away from launch pad</td>
</tr>
<tr>
<td>Performance independent of payload</td>
<td>Effect on rocket performance if payload replaced with payload of different function but identical size and weight</td>
<td>None</td>
</tr>
<tr>
<td>Safe prelaunch preparations</td>
<td>Preparations that can be made in the horizontal or vertical position on launch rod</td>
<td>All</td>
</tr>
<tr>
<td>Secondary recovery initiation sensor</td>
<td>Additional apogee sensor on-board with separate power supply</td>
<td>Present at launch</td>
</tr>
<tr>
<td>Recovery system demonstration</td>
<td>Ground or flight demonstration prior to competition</td>
<td>Completed by June 24, 2015</td>
</tr>
<tr>
<td>Vertical filling and remote launch initiation</td>
<td>No personnel may approach rocket during or after fill operation</td>
<td>None</td>
</tr>
</tbody>
</table>