Case Rocket Team: Dwayne "The Rocket"

Team 100 Project Technical Report for the 2019 IREC

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Case Rocket Team hails from Case Western Reserve University in Cleveland, Ohio. This is the team's first entry into the Spaceport America Cup, and the rocket will be competing in the 10,000ft COTS division. Therefore, Case Rocket Team's goal is to reach an altitude of exactly 10,000ft AGL and return to the ground for safe recovery. Onboard is a technical payload, designed to take readings of the atmosphere in the rockets descent and relay them

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to a nearby ground station. The electronics bay also houses a video streaming camera system for real-time video and GPS tracking capabilities.

Nomenclature

AGL	=	*Above Ground Level*
CAD	=	*Computer Aided Design*
cal	=	*Caliber*
CG	=	*Center of Gravity*
COTS	=	*Commercial Off-The-Shelf*
CP	=	*Center of Pressure*
CRT	=	*Case Rocket Team*
CWRU	=	*Case Western Reserve University*
DLC	=	*Diamond-like Carbon*
E-bay	=	*Electronics Bay*
ESRA	=	*Experimental Sounding Rocket Association*
FOS	=	*Factor of Safety*
ft	=	*Foot*
g	=	*Gram*
IREC	=	*Intercollegiate Rocket Engineering Competition*
lb	=	*Pound*
m	=	*Meter*
N	=	*Newton*
s	=	*Second*
SA	=	*Spaceport America*
TIG	=	*Tungsten Inert GasA =* amplitude of oscillation

I. Introduction

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ASE Rocket Team was established in 2013, and is comprised of undergraduate and graduate students from Case Western Reserve University in Cleveland, Ohio. Aerospace and mechanical engineers make up the largest contingent of the team; however, all majors are welcome, and the team also has a number of members from other technical disciplines including computer science, physics, materials science, and chemical engineering. Case Rocket Team is proud to bring Dwayne to the Spaceport America Cup 2019, as this is the team's first year participating in ESRA IREC, and we are excited to showcase our team's hard work throughout the 2018-2019 academic year.

Case Rocket Team has an executive council of seven, consisting of the president, vice president, treasurer, secretary, lab manager, certification lead, and PR manager. The president and vice president act as general managers for the team's projects, while the remainder of the executive council fulfills more specific organizational roles. Under the executive council, the team's general body members are split into three subteam: structures, systems, and testing. The structures team is responsible for the design and modeling of the competition launch vehicle's airframe and payload integration as well as simulating overall flight trajectories and stability. Systems focuses on the design of the E-bay and produces the payload design. The testing subteam is responsible for creating small-scale models for launch tests and performing materials and manufacturing tests as required to determine the viability of new design options. CRT's team structure is presented in **Figure 1**.

Figure 2. Full view, section view, and diagram of Dwayne with all subsystems integrated.

The work of all three subteams have come together to produce Case Rocket Team's Dwayne, our entry into the 2019 SA Cup.

II. Procedure for Paper Submission

Figure 1. Tree diagram of CRT's structure.

The design of Dwayne may be split into four major subsystems: propulsion, aerostructures, recovery, and payload. Additionally, the rocket may be divided in terms of four separable modules: the payload-carrying nose cone, the recovery bay, the electronics bay, and the fin can. A visual representation of these divisions within the launch vehicle is presented below as **Figure 2**.

A. Propulsion Subsytem

The rocket is propelled by a Cesaroni M795 "Moonburner," motor that contains 4892 grams (171.22 ounces) of composite propellant and has a peak thrust of 387 pounds and a burn time of 12.76 seconds. The thrust curve for the M795 is provided as **Figure 3.**

This motor has been selected for its extended burn time and low peak thrust, keeping the maximum velocity below mach 0.72 in order to reduce aerodynamic stresses on the rocket by avoiding the transonic region. The motor is housed within a Pro98 series 98mm motor casing which is placed within the motor mount tube. The motor mount is secured to the rocket by way of three 0.5in thick polycarbonate centering rings. The motor and associated casing are held in place by an Aeropack 98mm motor retainer. The retainer is secured to an aluminum thrust plate at the rear of the rocket, distributing the thrust of the motor evenly through the back of the fiberglass airframe to prevent structural failure.

Figure 4. Rocket position, velocity, and acceleration over time from ignition to landing.

All flight simulations are produced using OpenRocket 15.03. The predicted flight characteristics of the rocket obtained from an OpenRocket simulation are shown in **Figure 4**. The simulation predicts that the vehicle will reach an apogee of 11,500 ft AGL. According to OpenRocket, the stability is 1.97 cal. OpenRocket assumes ideal conditions to simplify its simulation calculations, and will always overestimate the peak flight altitude as a consequence. Previous launches of other rockets that the team has conducted and collected altitude data from have revealed roughy a 20% reduction in altitude from the simulation prediction, thus, the team is confident that the launch vehicle will approach the 10,000 ft goal.

Figure 3. Thrust curve for the M795 "Moonburner".

The thrust-to-weight of the rocket over time is shown in **Figure 5**. The thrust-to-weight off the pad is 5.62:1.

Figure 5. Thrust-to-weight ratio over motor burn duration.

B. Aerostructures System

The airframe of Dwayne primarily consists of 6.17” OD G12 fiberglass tubing, divided into a 30” upper section and 48” lower section. Between them is a coupler, which contains the E-bay. The lower section secures the motor tube, fins, and the lower rail button. The upper section is 30” long and contains the parachutes and the upper rail button, and is secured to the top of the coupler. The lower part of the coupler is secured to the lower section of the airframe with adhesives. Four steel 1/4-20 threaded rods secure the top of the coupler to the lower section. A 2” switch band between the sections of the airframe provides access to the electronics. The ogive nose cone is made of G12 fiberglass as well and is 31.25” long from tip to shoulder. The payload is secured into the nose cone by two shaped bulkheads fastened with two 1/4-20 threaded rods. The payload itself primarily consists of steel members TIG welded together to create an 8.8lb 3U form factor. The nose cone is secured to the upper section of the airframe by four nylon shear pins to prevent premature separation. The main and drogue chutes are secured to a shock cord mounted to steel ¼” U-bolts at the top of the coupler and the bottom of the nose cone. The fins are constructed out of G12 fiberglass and ½” end grain balsa wood, and fiberglassed to the lower section of the airframe.

1. Material Selection

The outer structure of our high-powered rocket is made almost entirely of G12 fiberglass tubing. This material has been selected because fiberglass is a material that is light, durable, and cost efficient. The closest competitors for our airframe were phenolic tubing that is lighter, but weaker, and carbon fiber tubing that is stronger, but more expensive. Fiberglass presents the best compromise between high performance and affordability for this team. For the centering rings we chose polycarbonate as it is a durable, lightweight material that will be able to support the load from the motor during flight and for its high machinability and low cost. The motor retainer mount was chosen to be machined out of 6061-T6 aluminum due to its strength, resistance to thermal deformation, low density, and high machinability. For the payload we chose to make the frame out of 1045 medium carbon steel due to its weldability and high density in order to meet the 8.8 lb. payload weight requirement. The sheet of birch plywood that our avionics are secured to was chosen for its ease of manufacturing as well as its low density. Our internal fasteners and vertical structural members are made out of medium steel due to its high tensile strength and low cost. Our bulkheads were selected from varying thicknesses of 6061-T6 aluminum and polycarbonate for the same reasons as the motor retainer and centering rings, favoring aluminum for bulkheads loaded in tension and polycarbonate for compression.

2. Manufacturing Methods – Fiberglassing

The central component to the manufacturing of the aerostructure was fiberglassing the fins. The team’s initial design called for a “fin can” that would allow team members to slide the fins in and out. This was to make them modular, as to maximize the ability to tweak or change the fin design. The main manufacturing test article utilized this design. However, the fit and assembly made removal difficult. Team members were also concerned about the strength and stability of the fins. This was due to a worry that if a fin were to break, it could take the whole assembly out of the back of the body tube. The fins themselves seemed relatively flexible, which could be a liability at higher speeds than our test launch.

When the team learned about fiberglassing the fins tip to tip, mounted to the wall of the body tube, the team realized that this removed most of the issues we were concerned about. The fiberglassed fins were stronger, more rigid, and had a far larger surface area adhering the fins to the rocket. Since each fin is fiberglassed directly to its neighbors, they resist shear movement. To test this, the team initially had small tests using pressure or a vacuum chamber to remove bubbling. This yielded strong results, which gave the team confidence that the change could work. The team then assembled a jig to be able to fiberglass the fins accurately at a 90 degree angle. This fin jig was used to test foam cut fins onto a piece of cardboard. This test yielded strong results as well, demonstrating that the fins were able to handle the expected flight stress, while also ensuring that any failure would not result in more dramatic failure.

For manufacturing, a balsa wood core was used. This increased the ability of the fins to take stress perpendicular to the direction of the fibers. The body tube was placed in the fin jig, positioned to the correct placement. Adjustments were made to the plates to position the fins at 90 degrees from each other. Using epoxy, sheets of fiberglass were layered across both fins. The final rocket used 15 layers of fiberglass for each quarter of the rocket. Then using sandbags and weights, the fins were applied constant pressure This helped to reduce bubbling. Each fin, after allowing for the epoxy to dry, was then trimmed down to reduce the excess volume.

Figure 6. End-grain balsa wood fin cores.

Figure 7. (From left to right) fiberglass, peel ply, and bleeder cloth.

Figure 8. The airframe in the fin jig.

Figure 9: Using JB Weld to create fillets.

3. *Manufacturing Methods – Waterjet Cutting*

To manufacture components with two dimensional contours, the team primarily relied on an OMAX 5555 Waterjet. The team made this choice to reduce manufacturing time of the parts. Some of the parts also contained complex geometry that would have made both milling and turning difficult as the method of manufacturing. For most of our bulkhead components, the waterjet allowed the team to ensure that all holes were cut in the exact positions and angles needed. The team created the CAD model in Solidworks. This then allowed the team to extract a .DXF drawing file of the face of the components and move that into the OMAX Design and Layout programs. These programs controlled the operation of the waterjet, allowing for control of the tool path for cuts and placement of cuts. While a mill and lathe could have been used to achieve the same goal, the waterjet dramatically reduced the time to manufacture the parts by cutting them in bulk.

Figure 10. The aluminum (left) and polycarbonate (right) bulkheads.

Initially, the team had considered using fiberglass components to increase the bond strength to the main body tubes. To reduce the dust and hazards of working with fiberglass, the team attempted to use the waterjet in order to make cuts underwater and reduce dust creation and tool wear. However during manufacturing of a test article for this design, the team noticed that the initial piercing of the fiberglass sheet by the waterjet caused it to delaminate. This caused bubbling and cracking, which made the parts unusable. To correct this, the team changed the tool path to start off of the sheet and move in to limit bubbling and cracking. This change created markedly better results, although fiberglass sheet was foregone in the assembly in favor of polycarbonate and aluminum sheets already available to the team. This helped the team reduce cost by using previously available material while reusing components.

4. Manufacturing Methods – Machining

We used traditional machining methods for most material removal processes that did not involve the waterjet. The bulkheads and centering ring blanks that were cut on the waterjet were then turned down on a JET Elite E134OVS lathe. This allowed us to quickly make blanks with precise hole patterns and then turn them down exact diameters. A Powermatic PM2800B mill with a dividing head was used to make holes in the side of the centering rings for the rail buttons and mounting screws. This allowed us to position the holes at precise angles and ensure that they would align with each other. The fiberglass tubes for the airframe and coupler were cut to length and squared off with a Hyd-Mech S20 hydraulic horizontal bandsaw. The holes for mounting screws and pockets for mounting the fins were also cut on the Powermatic mill using a dividing head and a tailstock to support the end of the tubes. To achieve a clean cut with the G12 Fiberglass we used a spiral 3-flute ¼” carbide end mill with a DLC coating.

Figure 11. Cutting the airframe on the horizontal bandsaw.

Figure 12. Using the mill to locate and drill features.

C. Recovery Subsytem

1. *Altimeters*

Concerning avionics, the team will use two Raven3 altimeters from Featherweight Altimeters, running on independent circuits. These altimeters serve as the units controlling the rocket's ejection charges located above the electronics bay. The conditions for an ejection can be programmed into the Raven3 and are customizable to recognize the conditions for an ejection through altitude, velocity, and pressure once programmed from any computer running a windows operating system. The two ejection charges will be set at apogee for the drogue parachute and at 1,000 ft for the main parachute. The team will be utilizing 2 Raven3 altimeters for redundancy purposes in the event that one altimeter is unable to function appropriately.

2. *Televmetry*

Our rocket will be transmitting numerical telemetry data through a digital radio signal to a ground station. The transmitted data includes air pressure and temperature.

Additionally, we will record and transmit live video through an analog radio signal. The transmitter includes two omni-directional antennas broadcasting at 5.8 gigahertz, while the receiver consists of an omni-directional antenna and a directional antenna connected to a diversity receiver which is in turn connected to a computer via an analog to digital video converter.

The live video system is the main power drain in the electronics bay, so to save power we will turn it on via radio only immediately before launch.

Figure 12. Live video and transmitter system diagram.

Figure 13. Live video and transmitter system.

3. *Ejection Charge*

A traditional black powder charge is used for separation and drogue chute deployment. At apogee, this charge shears four nylon 4-40 screws to separate the rocket. There are two criteria that must be met when sizing the shear pins and black powder charges. The first criterion is that the force on the nose cone at the maximum altitude, caused by static pressure differences, not exceed the minimum shear strength of the screws. If this criterion is not met, the rocket may prematurely separate which may result in severe zippering or even total launch failure. The second criterion is that the force from the ejection charge must exceed the maximum shear strength of the screws in order to ensure that the rocket separates when the black powder fires. A necessary black powder weight of 3.26 g was established by solving the system of linear equations created by the two criteria and implementing a safety factor of

Table 1. Black powder sizing.

1.5. The input and calculated values used to determine this result can be found in **Table 1**.

4. Recovery System Diagram

The recovery system, **Figure 14**, can be categorized into two parts, the fixed part and the "moving" part. The fixed part consists of two shock cord, A and C. Cord A holds on to the deployment bag which stores the main chute so that the main chute does not get tangled inside the body tube, prior to deployment due to the pressure generated to pop the nose cone out. This shock cord is covered in a flame-resistant coat so it does not get burned by the heat generated from the combustion of the black powder. The length of cord A is not very significant, but it should allow the deployment bag to be held close to the top of the body tube for the ease of later main-chute-deployment.

Cord C is also covered in a flame-resistant coat for the same reason. Cord C holds on to the tender descender and handles the tension from the drogue chute in the first state of descent. The length of Cord C should be similar to the length of the body tube (20 inches) so that drogue should can be reliably deployed.

The "moving" part of the recovery system can be described in two phases. The first phase is when the drogue chute is deployed at or near the apex where the rocket starts falling. At this state, the main chute is still stored in the deployment bag, while the drogue chute carries the whole weight of the rocket. The cord length F, which consists of the length of the shock cord that connects to the chute and the length of the chute's cords (300 mm), must be shorter than the length E, connecting to the nose cone. This will ensure the drogue chute is fully deployed and avoid getting stuck in the body tube. The intermediate length between the joint of E and F and the tender descender allows slack so that the chute does not get tangled with the body tube when the nose cone is initially shot out.

When the second phase of the falling stage happens, the tender descender will release the joint between B, D, and the intermediate piece of shock cord. It is noted that shock cord length B should be longer than the length of the body tube (24 inches) and the length D combine so that the main chute can be pulled all the way out without getting stuck inside the body tube. Length D consists of the length of the shock cord that connects to the main parachute and the length of the main chute's cords (300 mm). At this stage, shock cord B would handle the tension from both chutes to carry the rocket down safely. Shock cord B is also covered in a flame-resistant coat as a portion of it is inside the body tube and is in contact with the heat generated from the combustion of the black powder used to pop the nose cone out.

All shock cords used in the rocket are 11/16th inch tubular Kevlar, and are rated for 2000 lbs. They should be more than durable enough to handle the yanking force created when a parachute is deployed and the constant tension when the rocket falls.

Figure 14. Recovery system diagram.

5. Tender Descender

The tender descender is designed with two main parts, the housing and the link retainer. The housing has slots for the link retainer to slide in, a reservoir or combustion chamber for black powder, and a hole for an electric match to go into the reservoir.

In its initial state, the link retainer slides in the slots on the housing, creating a joint for two quick-links. At the desired time, the electric match can be triggered, triggering the black powder inside the reservoir (usually about 1 gram) to "explode" the link retainer out from the slot, detaching the joint and releasing the quick-links.

The electric match is connected to the altimeter so it can be triggered at a specific height.

Figure 15. The Level 3 Tender Descender Used on the Rocket (Picture by *Wingnut* on *Australian Rocketry Forum*)

The goal of the tender descender is a partial deployment of the recovery system. This rocket is designed with two parachutes, one 48-inch drogue chute and one 84-inch main parachute. The drogue chute is deployed at or near the apex, i.e. when the rocket starts falling, and is the first parachute to be deployed to lower the rocket's descent velocity (to be discussed in the section below) before the deployment of the main chute, whilst maintaining a relatively high falling velocity in order to avoid drifting caused by the wind. When this happens, the tension created by the drogue chute will be transmitted through the tender descender and string C directly to the rocket's fixture, while the main chute's string suffers no tension, hence, the main chute remains stored inside the deployment bag. The main chute is then deployed at the height of 1,000 ft in order to decrease the descent velocity even more (to be discussed in the section below) so that the rocket can be landed without damaging the airframe and/or any structural and/or interior component. This happens by triggering the electric match inside the tender descender, thus combusts the black powder inside the reservoir of the tender descender, separating it into two halves and disconnecting the joint between the main chute-drogue chute's strings and string C. When this happens, the drogue chute will pull the main chute out from the deployment bag and the tension, from both chutes, will be transmitted through string B to the rocket's fixture.

6. Descent Velocities

After apogee the drogue parachute will be deployed and the rocket will have a descent velocity of around 43 ft/s. The velocity will decrease to around 38 ft/s over time then the main parachute will deploy at 1,000 ft to bring the landing descent velocity to around 18 ft/s upon landing according to our OpenRocket simulation. This is below our self-imposed 20 ft/s requirement for our descent velocity to avoid any significant structural damage.

7. Redundancy

The ejection charges will have redundancy as there will be two Raven3 altimeters on independent circuits to programmed emit the same signal with the same conditions with regards to velocity, pressure, and altitude. These two altimeters will have e-matches that feed directly into the black powder ejection charge and tender descender, ensuring that the drogue and main chutes will be deployed during flight.

D. Payload Subsystem

1. Payload Frame

Given a mass floor of four kilograms, the team decided to make the payload frame as structurally secure as possible. 1" square steel tubing with a ⅛" wall thickness was used for the top and bottom of the frame and 1" L brackets with 1⁄8" thickness was used for the vertical members. The members were TIG welded together using a Lincoln Electric Square Wave TIG 200 in order to maximize the strength of the structure, simplify the design, and minimize the clearance needed for fasteners. TIG welding was chosen due to its precision and the cleanliness of its weld seams.

Figure 16. Welded payload frame.

2. Payload Wiring

Elecctronics Diagram

Figure 17. Payload wiring diagram.

3. Payload Function

The payload primarily functions as a data recorder for the rocket and is equipped with air quality sensors for high altitude air measurements. The payload is controlled by a microcontroller which collects data from the onboard Inertial Measurement Unit (IMU), Barometer, Thermometer, and Gas Quality sensors to provide a basis of evaluating the flight of the rocket, as well as to provide data on the environment the payload is exposed to. The microcontroller stores the collected data on a non-volatile flash storage for later data recall and analysis after the flight. The payload is also equipped is a radio telemetry unit to stream data back to a ground station both as a means for protecting data in case of recovery failure, and to provide real time data on the flight of the rocket. The payload is powered from a 3.3 volt, 660 milliamp-hour battery that will provide enough power for several hours of data recording and transmitting in case of launch delays. Once recovered following a flight, data will be accessed on the ground using the flash storage to be analyzed and displayed at the ground station.

III. Mission Concept of Operations Overview

A. Concept of Operations Major Events

Figure 18. Altitude over time.

B. Concept of Operations Phase Breakdown

Phase	Task	Time	Description
1	Pre-Launch Checks and Installation		Dwayne is fully assembled, all e-bay subsystems powered down. Payload is powered on prior to assembly. Dwayne is placed on launch rails, with arming keys inserted. This phase ends when all pre-launch checks have been completed.
2	Arming and Safety Checks		Arming keys are turned on and removed, driving power to both Raven Altimeters and the camera transmitter. The Ravens will emit a series of beeps to signal they are powered. The motor is inserted and locked into place, with an e-match inserted. All pre-flight safety checks are completed before the e-match circuit is connected to battery power. This phase ends when all safety checks are completed and the ground team receives a downlink from the camera.
3	Ignition	T+0:00.00	Launch authorization is given. Launch operator gives a vocal countdown and ignition. Motor is ignited by a spark created by a short circuit in the e-match. This phase ends when smoke becomes visible from the ignited solid propellant.
4	Liftoff	T+0:00.17	Dwayne is beginning ascent using thrust from the motor. The Ravens are triggered by the acceleration of the rocket. This phase ends when Dwayne has cleared the launch tower and is being stabilized by the aerostructure.
5	Powered Ascent	T+0:00.64	Motor provides thrust to continuously accelerate the rocket. The aerostructure of the rocket provides flight stabilization. This phase runs from clearance of the launch tower to motor burnout.
6	Unpowered Ascent	T+0:12.76	Dwayne is coasting after motor burnout until it reaches its estimated flight apogee of 11,500 ft AGL. This phase ends when the rocket begins to descend.
7	Drogue Parachute Deployment	T+0:27.96	The Ravens' sensors detect descent and ignite the blackpowder charge to deploy the drogue parachute. The nose cone separates and pulls the deployment bag out of the body tube. The parachute then unfolds, slowing the rocket to a descent velocity of 43 ft/s. The main parachute is also pushed to the end of the body tube, but is held from being deployed by the tender-descender. This phase ends when the rocket reaches 1,000 ft AGL.
8	Main Parachute Deployment	T+3:04.28	The Ravens are triggered again when Dwayne passes 1,000 ft AGL. The tender-descender is triggered and separates, pulling the main parachute out of the body tube. It then unfolds and inflates, bringing the rocket to a velocity of 18 ft/s. This phase ends when the rocket reaches the ground.
9	Landing and Ground Operations	T+3:38.97	Dwayne lands on the ground. An onboard GPS provides the recovery team its position. The recovery team retrieves the rocket and brings it to the judges for inspection.

IV. Conclusions and Lessons Learned

The Case Western Reserve Rocket Team was founded six years ago, and the team has participated in other competitions nationally for four years. However, as previously mentioned, this is our first time participating for ESRA IREC and competing for the Spaceport America Cup 2019, and Dwayne is the largest and fastest rocket the team has built. The decision to compete in IREC has brought upon new challenges and learning experiences for all our team members.

In creating our largest rocket, the team had decided for the first time in our history to design and build a rocket with an airframe made from fiberglass tubing and fins that are reinforced by fiberglass. The team has been confident in our decision to use fiberglass over phenolic tubing and carbon fiber tubing, but the team needed to do extensive research on how to manufacture fiberglass. Although machining fiberglass was similar to machining other materials such as steel, there were extra safety precautions to consider, so extra coordination had to be taken for the team to go over the learning curve in a timely manner. The team has also taken care to document the learning process including failed and successful tests so that future team members will not start from square one again. Aside from gaining the technical skills of working with G12 fiberglass that can be used in future endeavors, the team honed its collaboration and communication to learn cohesively as a group.

Experimenting with new materials was an interesting experience for the team, but the team also had to consider the stress and strain limitations of each material and how the overall design of the rocket was affected. The team's initial plans for the "fin can" were an experimental attempt at modular design, but further analysis of the design revealed stress weaknesses that were a significant liability to the rocket's structural integrity.

The amount of teamwork that was involved in all steps of the design process and construction resulted in many opportunities to develop a cohesive and productive dynamic within the group. Every team member has their strengths and weaknesses, and when a group of people diverse in skills worked towards the common goal of completing the rocket, each member learned how to build on each other's qualities. Furthermore, accountability was integral to finishing tasks in a timely manner because assigning tasks to members helped the team keep track of what needed to be done. Long-term planning sessions with clear deadlines gave the team a clear idea of everything that needed to be completed.

Six months worth of team meetings and outside work resulted in the final designs reviewed in this report. Every team member applied what they had learned in their engineering courses to design and construct a working rocket. The team is looking forward to giving a strong introduction to Case Western Reserve University at the competition.

Appendix A: System Weights, Measures, and Performance Data

Appendix B: Project Test Reports

Construction Testing: Because the team has little experience working with fiberglass tubing, a 3” diameter test rocket was constructed to experiment with construction techniques as well as test the tender descender in our new recovery system. This design incorporated a removable fin can with through the wall mounting and a removable E-bay. The CAD model and finished product can be seen in **Figure 19** The team was able to machine the fiberglass using a specially purchased end mill with a DLC coating, and used a dividing head on a mill to create accurate slots and hole patterns on the sides of the tubes. The machined features were accurate and produced excellent surface finishes, while familiarizing the team with the process of using the dividing head and working with cylindrical workpieces. The feasibility of securing the body tubes to the interior bulkheads using bolts instead of using adhesives was also tested it was determined that the system was as strong as adhesives and far easier to work with. The team also experimented with using a waterjet to cut fiberglass sheet and create thin fins and centering rings. It was determined that usable parts could be made by not using the waterjet to pierce the laminated material. However, due to concerns with the fin mounting system, it was determined that we would surface mount our fins and fiberglass them tip to tip instead of using through the wall.

Figure 19. CAD model and final version of the testing rocket.

Recovery System Design: A primary design target for the recovery system was for the rocket to separate in only one place. Because of the need for dual deployment and because all sections of the rocket will descend in one piece, a single dual event recovery system is incorporated. In order to store the main and drogue chutes in the same bay, a Tender Descender, a device capable of releasing two tethered links by using a black powder charge ignited by an e-match, is used to release the main chute at a specified altitude. For the prototype, a drogue parachute is deployed at apogee (approximately 3500ft AGL), the main parachute is deployed from a deployment bag by use of a tender descender. We had never used a Tender Descender before, and wanted to ensure that we could set up the recovery system properly.

Recovery System Testing: A set of ground tests were conducted on our ½ scale prototype to verify the functionality of the aforementioned system. The first test involved a drogue deployment and revealed that the length of the chord between nose cone and the drogue parachute swivel must be appropriately sized such that the drogue fully deploys. This refers to length **E** in **Figure 14**. It also revealed that using a deployment bag for the drogue chute may hinder the chute deployment if the nose cone is ejected with insufficient velocity to separate the drogue chute from the bag.

Figure 20. Drogue parachute deployment test.

This test was completed several times until an appropriate black powder charge was confirmed. The same procedure will be conducted for the full scale rocket. Throughout this testing process, the deployment bag for the main chute was also properly located. After several test deployments, the deployment bag was set to be protruding out of the body tube by about half its length. This entailed fine tuning the length **A** in **Figure 14**. Throughout this process, best practices for handling the Tender Descender were established. These include the following:

- Use a safety factor on top of the minimum recommended black powder weight in the reservoir
- Make sure that the sheath is properly tied into the lines as not to lose it
- Seal the e-match side of the device with electrical tape to prevent loss of black powder during handling

The system is unlikely to experience tangling/fouling of the shroud line and shock cords. The main parachute shroud lines are routed through elastic straps on the deployment bag, minimizing the chance of them snaring and preventing the main chute from opening. The drag force from the drogue parachute directly pulls the main parachute out of the deployment bag once triggered. In turn, the drag force from the main parachute pulls all of its chord out of the rocket. The drogue parachute is installed in the nose cone. In order to prevent tangling, the cord connecting the drogue parachute and the nose cone is installed into the nose cone first, so the shroud lines of the parachutes should never intersect with each other or the shock cord.

Test Flight: One flight test was conducted with our ½ scale prototype using a J270W motor. This flight was set up with a single Raven 3 altimeter with a redundant drogue ejection charge. Two e-matches were installed on mian charge, and one in the tender descender. This test flight went perfectly, reaching an altitude of 3400 ft AGL, exhibiting expected drogue and main recovery events, and landing in good order. The only mistake identified was failure to properly tether the sheath for the Tender Descender, which nearly separated from the Tender Descender during descent.

Figure 21. Raven3 altimeter data from test flight.

Figure 22. Recovery deployment on test flight.

Live Video Ground Test: To test the live video telemetry system, we walked the transmitter away from the receiver as far as we could reasonably go while maintaining line of sight visibility (approximately 700ft). We found that as long as line of sight visibility was maintained, even the weakest power setting worked reasonably well.

Figure 23. Test launch of video payload.

Figure 24. Still from transmitted video (approx. 2 seconds after takeoff).

Live Video Flight Test: To test how the live video telemetry system would work in flight, we isolated the system inside of the nose cone of an existing 4” rocket and launched it on a J270W motor to an altitude of approximately 3300ft AGL. The result of this test was a very low quality video stream with lots of background noise, which worsened while the rocket was above approximately 1000ft AGL. Upon analysis, the poor signal was linked to the orientation of the transmitting antenna. To mitigate this problem, we purchased another antenna and now have two transmitters in order to transmit in every direction. This new scheme was subject to the same ground test as the old one and had similar results.

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Appendix C: Hazard Analysis

The highest precautions that should be taken in regards to the rocket are handling flammable and explosive materials. The motor that the rocket uses is the Cesaroni M795 “Moonburner,” which is powered by 4892 grams (171.22 ounces) of composite propellant and has a burn time of 12.76 seconds. As outlined in the Spaceport America Cup 2019 Rules and Requirements Section 2.0, the composite propellant is non-toxic and does not require a breathing apparatus to handle. However, the motor will always be stored in a room temperature environment away from objects such as spark plugs, matches, lighters, liquid propellant, and other devices and chemicals that could ignite the propellant.

The airframe of the rocket, couplers, and the nosecone will be manufactured from filament wound G12 fiberglass. Although traditional machining methods can be used to machine fiberglass, extra safety precautions must be taken. When fiberglass is machined, fibrous, highly abrasive dust is released into the air. Due to this, respirators as well as safety glasses must be worn when working with fiberglass. To prevent this dust from entering the ways of the machine and abrading the ground surfaces, the machine must be protected by tarps or similar coverings. Machine tools should have a hardened finish such as DLC coating, which will abrade less over time and give a better surface finish. Dust control methods such as vacuum systems and immersing the cutting bit in a coolant stream can also be used. Regular cleaning and maintenance of the machines is still needed, but air and oil filters must be changed more frequently.

The rocket will be launched with an electrical launch system and electrical launch igniters. To prevent premature launches and reduce the risk of electrocution and burns, the launch system will have a keyed safety interlock in series with the launch switch. If the rocket does not launch when the button is pressed for the electrical launch system, the launcher’s safety interlock will be removed, or the battery will be disconnected. There will then be a wait time of ninety seconds after the last launch attempt before any person is allowed to approach the rocket.

During the launch procedure, all persons must be at least 200 feet away from the rocket, and all persons must be behind a physical barrier such as a vehicle. If the safety and stability of the untested rocket is uncertain, the stability will be checked before launch, and spectators and all other persons will be warned and cleared away past the 200-foot radius.

The launch rail will be pointed within 30 degrees of the vertical to ensure that the rocket launches straight up, and a blast deflector will be used to prevent the motor’s exhaust from hitting the ground.

The rocket will have a two-stage parachute system so that it can be recovered safely, and it will also prevent the rocket from being damaged upon return and can be used again. Rocket recovery will not be attempted from power lines, tall trees, and other dangerous locations.