Concordia’s First Supersonic Sounding Rocket

Team 79 Project Technical Report to the 2018 Spaceport America Cup

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The following document consists of the summary of the functionality and operations of *Supersonice*, a sounding rocket competing in the 2018 Spaceport America Cup. Team 79 will be competing in the Advanced Category, for a 30,000 ft apogee target with a COTS motor system. For the first time at the SAC, the rocket fuselage will be entirely manufactured by automated fibre placement using thermoplastic composites in two components. This allows for rapid assembly of the vehicle and omits the use of doors which can be a source of weakness in the body of rocket. The rocket’s payload will observe the sloshing effects of launch while validating two different types of SRAD baffles, simulating a liquid rocket propellant draining simulated system. Each subsystem will validate the requirements set forth by the team, in addition to those outlined by the competition rules and requirements documentation.

I. Nomenclature

\[ A = \text{amplitude of oscillation} \]
\[ A_D = \text{drag area} \]
\[ A_{DA} = \text{drag area of aft} \]
\[ A_{DF} = \text{drag area of forward} \]
\[ a = \text{cylinder diameter} \]
\[ a_g = \text{gravitational acceleration} \]
\[ C_D = \text{coefficient of drag} \]
\[ C_p = \text{pressure coefficient} \]
II. Introduction

Space Concordia is a student society which aims to promote aerospace and astronautical engineering within Concordia University and Montreal by taking on projects and participating in competitions in these fields. Space Concordia's Rocketry Division is one of the four divisions which are supported by the society, alongside Spacecraft, Robotics and Special Projects. The rocketry team benefits from a society level management on several aspects, and is part of a “bigger picture”. It is the rocketry team’s mission to develop concordia’s rocket technology to the point where we can house our Spacecraft team’s CubeSat and eventually launch suborbital flights. This year, the team focused on achieving supersonic flight for the first time at Concordia. To further push the capabilities of the team, all structural components were student researched and developed (SRAD), from the carbon fibre boat tail to the sears-haack tip of the rocket. Additionally, research was conducted on a thermoplastic composite material used in sounding rocket airframes: glass fibre reinforced polyethylene terephthalate (PET). The research project conducted by one of our members served to validate the new composite fuselage through analysis and destructive testing.

This rocket is meant to be a milestone for Space Concordia as our first entry in IREC’s advanced category, first supersonic vehicle first rocket to house CubeSat format (our previous rockets used PocketCube). We also believe that we built the first rocket fuselage, built completely using Automated Fiber Placement (AFP) technology.

AFP technology is a new way of laying up composite materials, by using a powerful robotic arm to wrap individual tapes of fiber (toes) around a mandrel while applying high pressure and heat. This allows us to produce composite wraps that have extremely low void content (a very common defect in composites) and denser composite parts, dramatically increasing its strength to weight ratio. Previous iterations of our rockets have used this technology, but only to make simple cylindrical shapes. This year, we have done enough research to attempt to have the cylinder taper, and have the arm layup over a changing geometry, allowing us to make the nose cone on the machine. Due to the machine’s ability to make “perfect” layups, this prompted us to integrate the nose cone with the forward section, thus greatly improving the load pathways on the rocket, and reducing its complexity, allowing the whole structure stronger and easier to analyze.

\( C_x = \) force coefficient in the \( x \) direction
\( C_y = \) force coefficient in the \( y \) direction
\( c = \) chord
\( c_p = \) constant pressure specific heat
\( c_v = \) constant volume specific heat
\( dt = \) time step
\( F_D = \) Drag
\( F_x = \) \( X \) component of the resultant pressure force acting on the vehicle
\( F_y = \) \( Y \) component of the resultant pressure force acting on the vehicle
\( f, g = \) generic functions
\( K = \) trailing-edge (TE) nondimensional angular deflection rate
\( m = \) mass
\( n = \) number of moles
\( P = \) pressure
\( R = \) ideal gas constant
\( R_c = \) combustion gas constant
\( r_w = \) weight ratio
\( \rho = \) fluid density
\( T = \) temperature
\( V = \) volume
\( v_f = \) fluid velocity
The purpose of this rocket is to validate this new method of manufacturing, validating our supersonic analysis and performing a fluid slosh experiment during acceleration of the rocket to test the effects of our SRAD baffles on draining fuel simulant tanks. Our dual deployment rocket will allow us to validate out deployment bag design, while using for the first time GPS along with telemetry to ensure recovery of the rocket post flight.

The project is funded partially by the Engineering and Computer Science Association and by various sponsors. The team structure is divided into 5 subdivisions: structure, recovery, avionics, payload and flight performance, each responsible for their own subsystem and member productivity.

III. System Architecture Overview

The purpose of this rocket is to validate this new method of manufacturing, validating our supersonic analysis and to perform a fluid slosh experiment during acceleration of the rocket. A new structure was developed that has undergone heavy analysis and validation. The forward section of the rocket houses the avionics system which records the barometric pressure, temperature, 3-axis acceleration, pitch roll and yaw, battery voltage and GPS coordinates. Data is collected with both a commercial system and a SRAD system. Avionics is used to deploy the drogue chute at apogee, using an SRAD recovery system that separates the rocket by releasing pressurized gas. After the rocket has descended to a satisfactory height, the main cute is released by the recovery system to slow the rocket before landing. Throughout the flight, our payload will be testing the effects of our SRAD baffles on actively draining tanks. The payload will be using an analogue to RP1 (kerosene) and will compare the effectiveness of ball baffle design vs. ring baffle design, as well as study the inertial forces acting on a spray nozzle.
This will also be our first single deployment rocket, therefore would be validating our deployment bag design, and also our first rocket using GPS along with telemetry to ensure recovery of the rocket post flight.

Fig. 3 Rocket Assembly Rendering

A. Flight Performance

Requirements (Design, Test & Evaluation Guideline)

8.1. Launch Azimuth and Elevation
8.2. Launch Stability
8.3. Ascent Stability
8.4. Over-Stability

The flight simulation and analysis software selected was RASaero, which is known to be more precise for supersonic ballistic flights. Table 1 lists the input flight conditions used to simulate the rocket's flight.

Table 1 Simulation Inputs

<table>
<thead>
<tr>
<th>Simulation Conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Alt., AGL (ft.)</td>
<td>4595</td>
</tr>
<tr>
<td>Launch Elevation (deg.)</td>
<td>84±1°</td>
</tr>
<tr>
<td>Rail Length (ft.)</td>
<td>17</td>
</tr>
<tr>
<td>Avg. Wind (mph)</td>
<td>10</td>
</tr>
<tr>
<td>Worst Wind (mph)</td>
<td>20</td>
</tr>
<tr>
<td>High Temperature (F)</td>
<td>100</td>
</tr>
<tr>
<td>Avg. Temperature (F)</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 2 represents the output data at notable flight phases which was used for the flight phase analysis. From the above simulation inputs, an altitude of 3149 ft was attained in the least favorable conditions. Note that although this is higher than the desired altitude target, certain masses cannot be accurately accounted for until the full assembly of the launch vehicle, therefore giving a safety factor.

Table 2 Flight Phase Acquired Data

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time</th>
<th>Flight Conditions</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Handling</td>
<td>0</td>
<td>Static Loading: 362 N</td>
<td>N/A</td>
</tr>
<tr>
<td>Ignition</td>
<td>0</td>
<td>Thrust: 8034 N (17.5 G)</td>
<td>N/A</td>
</tr>
<tr>
<td>Rail Clearance</td>
<td>0.25</td>
<td>Stability Caliber: 2.7</td>
<td>43.2</td>
</tr>
<tr>
<td>Motor Burnout</td>
<td>3.4</td>
<td>Drag: 930 N</td>
<td>567.5 (Mach 1.64)</td>
</tr>
<tr>
<td>Drogue Deployment</td>
<td>40.6</td>
<td>Altitude: 30,149 ft.</td>
<td>73.2</td>
</tr>
<tr>
<td>Main Deployment</td>
<td>Deployment Load: 838 N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>287.6</td>
<td>Altitude: 755 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deployment Loads: 1604 N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground Impact</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>305</td>
<td>25.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B. Structures

Requirements

The following requirements further define the scope of the launch vehicle:

6.1 Adequate venting: 1/8” to 3/16” through any isolated compartment or bay

6.2 Overall Structural Integrity (See Table 3 for more details on the structural analysis)
   6.2.1 Material Selection: No PVC, low temp polymers or plastics were used in the fuselage structure
   6.2.3 Implementing Coupler Tubes: minimum coupler length used is 1.5 times the caliber
   6.2.4 Launch lug mechanical attachment: Implemented hardpoints able to lift vehicle by lugs
   6.2.5 Aft most launch lug: Support vehicles fully loaded weight while vertical prior to launch

6.3 RF Transparency: Implement radio frequency transparent windows at the top of motor mount and near greatest concentration of payload mass

Design Overview

The structure is composed of two components coupled together using coupler, as seen in Fig. 4. This design was chosen for several reasons. Consolidating the forward and the nose cone reduces weight while adding structural rigid and simplifying assembly procedures. The two sections are assembled together using a ring of equally spaced shear pins.

Fig. 4 Rocket Assembly

Fig. 5 Forward Section Assembly

The forward section consists of a rail system composed of 4 L-extrusions, used to support the bulkheads, housing the ballast, Payload, Avionics, and Recovery sections respectively from tip to aft. The rail system is first assembled
out of the rocket for ease of access, then slid into the fuselage secured by an array of machine screws to the fuselage, and at the nose using a threaded aluminum tip.

The aft section of the rocket houses the motor casing, aerodynamic boat tail fairing, recovery hoist ring coupler and fins. All components in the section were student developed. The boat tail mold was designed to minimize wave drag and weight, then manufactured by CNC lathe in Concordia’s Engineering, Design and Manufacturing Laboratory (EDML), then layed up using a prepreg carbon fibre. The aluminum thrust ring was optimized by iterating over several finite element analysis (FEA) using ANSYS explicit dynamics, to simulate the shock wave generated by the impulse of launch. To manufacture the entire fuselage on the AFP machine, an aluminum mandrel was designed with the following specifications:

- The end of the mandrel must extend 10 in passed the end of the effective layup section to avoid robotic head collision with the mandrel support.
- The straight sections could not be longer than 30 in, to accommodate the maximum working length of EDML’s largest lathe.
- The curved sections could not be longer than 17 in, to accommodate the maximum working length of EDML’s CNC lathe.
- The mandrel must be within a cylindricity tolerance of 0.002 in.
- A perpendicular through hole of 1 in diameter at 5 in length from the edge must be machined for the bolt used for the extraction of the composite final product.
- Surface finish must be less than 1.6 \( \mu \)m.

Further details on the mandrel can be found in Appendix E. The mandrel is then mounted to a rotating chuck and to apply the PET glass fibre composite using a hot gas torch to heat the thermoplastic to its melting temperature, bonding it to subsequent layers. Fig. 8 demonstrates the process during the forward fuselage layup. Given the change in material, the layer orientation was optimized to satisfy the structural loading requirements. This resulted in a quasi-isotropic layup sequence. Further details research report can be found in Appendix F.
Validation

To validate the structural integrity of the launch vehicle, each critical structural component was analyzed to determine the Factor of Safety. Other critical flight phases will be further detailed in the CONOPS section.

<table>
<thead>
<tr>
<th>P/N</th>
<th>Component</th>
<th>Event</th>
<th>Load (N)</th>
<th>FoS</th>
<th>Method of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR18-AF-00-001</td>
<td>Aft Fuselage</td>
<td>Ignition</td>
<td>8034</td>
<td>9</td>
<td>FEA Explicit Dynamic</td>
</tr>
<tr>
<td>SR18-AF-02-003</td>
<td>Thrust Ring</td>
<td>Ignition</td>
<td>8034</td>
<td>4.4</td>
<td>Rated Strength</td>
</tr>
<tr>
<td>SR18-AF-00-006A</td>
<td>Center Rings</td>
<td>Ignition</td>
<td>8034</td>
<td>17.2</td>
<td>Lap Shear Strength</td>
</tr>
<tr>
<td>SR18-PA-01-012</td>
<td>Payload Bulkhead</td>
<td>Ignition</td>
<td>8034</td>
<td>8.2</td>
<td>FEA Explicit Dynamic</td>
</tr>
<tr>
<td>SR18-FR-00-05</td>
<td>Fuselage Screw</td>
<td>Ignition</td>
<td>8034</td>
<td>4.5</td>
<td>Screw Shear</td>
</tr>
<tr>
<td>SR18-FR-00-001</td>
<td>Rail</td>
<td>Ignition</td>
<td>8034</td>
<td>14</td>
<td>Rated Strength</td>
</tr>
</tbody>
</table>

C. Avionics

Requirements

The avionics systems onboard Supersonice shall meet both the SA Cup - IREC requirements as well as the internal requirements and specifications. (Design, Test, & Evaluation Guide)

3.1 Dual-Event Parachute and Parafoil Recovery
3.1.1 Initial Deployment Event
3.1.2 Main Deployment Event
3.3 Redundant Electronics
3.3.1 Redundant COTS Recovery Electronics
3.3.2 Dissimilar Redundant Recovery Electronics
3.4  Safety Critical Wiring
3.4.1 Cable Management
3.4.2 Secure Connections
3.5  Recovery System Energetic Devices
4.1  Energetic Device Safing and Arming
4.1.1 Arming Device Access
4.1.2 Arming Device Location

(Rules and Regulations)
2.4  Range Tracking
2.5  Official Altitude Logging

Design Overview

The Altus Metrum Telemetrum is used in the rocket as the primary deployment device, and a PerfectFlite StratoLogger SL100 Altimeter is used as the redundant system. (3.3, 3.3.1) Each device is set to fire the drogue system at apogee event and the main deployment system at 755 feet AGL. (3.1, 3.1.1, 3.1.2) Both the Telemetrum and the Stratologger devices are COTS flight computers and will record flight data including Apogee. (2.5) Both the Telemetrum and the Stratologger devices are NOT modified and will be used as per manufacturer's recommendations and guidelines. (3.3.2)

The Telemetrum has its own 3.7V Li-Po battery to power its sensors and a standard 9V battery to fire the recovery systems. The stratologger will have its own standard 9V battery to power itself and the recovery firing systems. Each device has its own switch that can be physically activated/deactivated from outside the rocket easily and efficiently. (3.5, 4.1, 4.1.1, 4.1.2)

The wiring of each device going to each of the two recovery systems has its own shunt system. This will allow the recovery systems to not be armed until the physical pin is removed from the rocket. (3.5, 4.1, 4.1.1, 4.1.2) All the wiring is done with accordance to the guidelines of the competition. (3.4.1, 3.4.2)

The Telemetrum features a transmitting telemetry RF signal at 434 MHz that will be used to locate and track the movement of the rocket. (2.4) A Remove Before Flight (RBF) module with snap action switches and 3D printed guides serve as a safing mechanism for the recovery system and power switches for each avionic system. Below is a system overview of the onboard avionics systems.

Fig. 9 Overview of the Avionics Systems

**Note that this is not a representation of the structure and look of the rocket, simply a rough figure showing the deployment firing systems boards are not connected.

As depicted in the Fig. 9, there will also be a Raspberry Pi 3 Model B onboard with RF capabilities. We have chosen to do so to have a custom-made system transmitting telemetry using a few sensors. This system will also use the data to do some processing onboard that will predict the apogee in real time. The sensors and devices connected to the Raspberry Pi 3:

1. Adafruit Ultimate GPS breakout V3.
2. MPL3115A2 I2C Barometric Pressure/Altitude/Temperature Sensor
3. Pololu AltIMU-10 V5 Gyroscope and Accelerometer LSM6DS33, Magnetometer LIS3MDL
4. RFD 900+ RF Transceiver with 2 Dipole Antennas

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The callsign used with these frequencies is: KM6TKP registered with FRN number: 0027529932 to Anania Yeghikian. This is an American callsign associated with a Technician class amateur radio licence. Each of these devices have been picked to withstand the forces of flight as well as the temperature changes that the vehicle will encounter. The main goal of this system is to create a modular device that can hold various sensors that are not dependent on one another. This method is meant to be a foundation which allows future students to swap sensors and implement them to use in the way that they choose.

All the sensors will be connected to the Pi by means of a PCB shield with headers. The connection will be solid without a need for any wiring. The RFD transceiver is an exception as it will be connected to the Pi via USB. A portable power bank will power the Pi via micro-USB connection and the Pi in turn will supply all the power to the sensors. Data will be recorded onto a micro-SD card and some (speed, location, etc) of it will be transmitted to a ground station computer. All USB and SD card connections will be securely fastened to prevent them from disconnecting. Below is a 3D image of the avionics bay.

![3D Image of the avionics bay and its components](image)

The avionics systems will undergo various testing including deployment, telemetry and range. The Telemetrum and Stratollogger will be tested in high power rockets, going to altitudes from 1000 feet to 3000 feet and more while experiencing between 4g and 20g with possibly speeds over Mach 1. Vacuum tests will also be done prior to flights to ensure proper functionality of the firing systems of the boards. The devices will be carried onboard a drone and flown away from the ground station to test the maximum range of the connection to better prepare and set expectation for the competition. The Pi will undergo heavy programming loads to ensure it can handle a lower load during flight as well as staying within the power consumption rate expected.

**Fig. 10 3D Image of the avionics bay and its components**

D. Recovery

*Requirements*

(SAC Rules & Requirements)

3.1 Dual-Event Parachute and Parafoil Recovery
3.1.1 Initial Deployment Event
3.1.2 Main Deployment Event
3.1.3 Ejection Gas Protection
3.1.4 Parachute Swivel Links
3.1.5 Parachute Coloration and Marking
3.6.1 Ground Test Demonstration
4.1 Energetic Device Safing and Arming
6.2.1 Material Selection
6.2.2 Load Bearing Eye Bolts and U-Bolts

(Internal Requirements)
1. Bulkheads, eye bolts, and shock cords must be able to withstand the impulse generated by the deployment of the parachutes with a minimum factor of safety of 1.5.
2. The rocket must not separate before drogue deployment.
3. Main parachute must be retained in the forward section until it reaches an altitude of 755 ft.
4. The deployment system must be redundant. Meaning that a completely independent backup system must be able to deploy the parachutes in the case the main system fails. Completely independent is defined as a system that runs on its own flight computer, own battery and works regardless of the state of the other system.

Design Overview
The recovery device is a two-parachute system, which will be deployed at apogee and at 755 ft. AGL. At apogee, the drogue parachute (4, Recovery IPC) will be released by decoupling the rocket via chamber pressurization using a CO$_2$ canister (1, Recovery IPC). The main parachute (6, Recovery IPC) is released using a tender descender system where the deployment is triggered via a pyro system containing black powder (NI).

All deployment events are actuated by the avionic systems when target altitudes are reached. An E-Match will ignite a black powder charge to puncture a CO$_2$ canister. The gases released will generate pressure on the bulkheads causing a breach allowing the drogue parachute to evacuate. The piston bulkhead (5, Recovery IPC) serves to lessen the pressurized volume to optimize the ejection force. At 755ft, an E-Match will ignite black powder in a separate enclosure which will trigger the tender descender, allowing the main parachute to evacuate.

This design features 2 parachute deployments, but with only one decoupling. This allows all avionics to be installed in one location and improved safety. All components are designed with a minimum factor of safety of 1.5. Furthermore, double canisters and tender descenders are employed for redundancy. Spacers are also used to prevent the shock cords from damaging the fuselage due to deployment forces.
Parachute Selection

The requirements state that under the drogue parachute, the rocket’s speed should be between 21.3-46 m/s, and under the main parachute, the speed should be below 9 m/s. The speed was found by rearranging Newton’s laws and the drag equation:

\[ \frac{1}{2} \rho v_f^2 c_D A_D - m g = 0 \]  

\[ v_f = \sqrt{\frac{2m g}{\rho c_D A_D}} \]

The selected drogue chute is the 30” elliptical from Fruity Chutes. The speed under the drogue parachute at 30,000 ft, with a 27 kg load is 41.1 m/s. The selected main parachute is the 72” Iris Ultra, also from Fruity Chutes. The speed under this main parachute AGL with a 27.2 kg load is 8.6 m/s. Both parachutes were chosen due their availability in the Space Concordia inventory, and their designed properties.

Drag Forces (Number of Shear Pins)

The drag difference between the forward and the aft puts stress on the shear pins in the coupler. Thus, their number must be sufficient to resist these forces, but be broken at apogee. The difference in force was found using the drag force equation.

\[ \Delta F_D = \frac{1}{2} \rho v_f^2 (c_{DF} A_{DF} - c_{DA} A_{DA}) \]  

Fig. 11 Recovery System IPC
Fig. 12 Drag Data

The data above was used to find the area drag coefficient of the forward section (0.066 m²) and of the aft (0.068 m²). The air density was taken at the estimated motor burnout altitude, 3962 ft. Applying the above equation to both sections of the rocket, the net force was found to be 376N. The forward and aft sections will be held together by six shear pins, needing a total force of 570N to break. Therefore, the shear pins chosen are adequate (FoS 1.52), as the rocket will not separate due to the drag forces on the rocket. In practice, we believe that this FoS will be higher due to the fluid compression at the nose and subsonic flow at the aft.

**Deployment Forces**

The parachute deployment loads were found via the drag equation using the flight conditions during deployments. The force is distributed amongst the forward and the aft as a function of their weight ratio.

\[
F_D = \frac{1}{2} \rho v_f C_D A_D r_w
\]  

(4)

The drogue parachute deployment was found to generate a force of 838N (310N on the AFT & 528N on the FWD), and the main parachute deployment, 1604N (594N on the AFT & 1010N on the FWD). These values were used to determine the factor of safety (FoS) for all affected parts using the heaviest load felt:

**Table 4 Structural Analysis**

<table>
<thead>
<tr>
<th>P/N</th>
<th>Component</th>
<th>Event</th>
<th>Load (N)</th>
<th>FoS</th>
<th>Method of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR18-FW-RE-01-001</td>
<td>Recovery Bulkhead</td>
<td>Main Deploy.</td>
<td>1010</td>
<td>2.5</td>
<td>FEA</td>
</tr>
<tr>
<td>SR18-FW-RE-01-002</td>
<td>Hoist Swivel</td>
<td>Main Deploy.</td>
<td>1010</td>
<td>4.4</td>
<td>Rated Strength</td>
</tr>
<tr>
<td>SR18-FW-RE-01-004</td>
<td>Hoist Nut</td>
<td>Main Deploy.</td>
<td>1010</td>
<td>74.3</td>
<td>Rated Strength</td>
</tr>
<tr>
<td>SR18-FW-RE-01-006</td>
<td>4 x Bulkhead Screw</td>
<td>Main Deploy.</td>
<td>252.5</td>
<td>15.3</td>
<td>Rated Strength</td>
</tr>
<tr>
<td>SR18-FW-RE-01-007</td>
<td>4 x Bulkhead Nut</td>
<td>Main Deploy.</td>
<td>252.5</td>
<td>91.4</td>
<td>Rated Strength</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>SR18-FW-RE-03-003</th>
<th>2 x Tender Descender</th>
<th>Drogue Deploy.</th>
<th>264</th>
<th>33.7</th>
<th>Rated Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR18-FW-RE-03-005/ SR18-FW-RE-03-006</td>
<td>Shock Cords</td>
<td>Main Deploy.</td>
<td>1010</td>
<td>15.9</td>
<td>Rated Strength</td>
</tr>
<tr>
<td>SR18-FW-RE-03-007</td>
<td>Quicklink</td>
<td>Main Deploy.</td>
<td>1010</td>
<td>7.8</td>
<td>Rated Strength</td>
</tr>
</tbody>
</table>

**Black Powder Mass**

A force of 196.2 N is needed to pierce the CO\(_2\) canister. The following formula was used to calculate the pressure created by the detonation of FFFG black powder (12.1579 m/K).

\[
P = \frac{mR_cT\alpha_g}{V}
\]  
(5)

The pressure generated by the detonation is 21.796 Mpa, or a force of 4395.2N yielding a factor of safety of 22. Less black powder could be used, however this calculation does not account for pressure losses or inefficiencies during detonation. Smaller amounts of powder are also harder to manipulate.

**Ejection Pressure**

As mentioned previously, the required force to break the Shear Pins is 570N. Using the ideal gas law and isentropic expansion formula, the pressure created can be calculated according to the following equation.

\[
P_2 = \frac{nRT}{V_1}\left(\frac{V_1}{V_2}\right)^{\frac{\gamma p}{\gamma - 1}}
\]  
(6)

The final pressure was found to be 5,810 KPa in the recovery chamber, yielding a total force of 973 N and a safety factor of 1.7.

**Shock Cord Length**

The shock cord length is recommended to be three times the rocket length. Consequently, the shock cords will be 50 ft long, as per SR18-FW-RE-03, Parachute Assembly.

**System Integration**

The recovery system is part of the forward compartment and is attached to the Rails P/N SR18-FW-FR-00-001 via L-Brackets. The drogue parachute will be attached to both forward and aft compartments via a hoist swivel. Furthermore, 2 holes are drilled in the bulkhead for avionics wire routing.

**E. Payload**

The rocket is designed to accommodate a functioning payload conforming to the CubeSat standard. The experiment aims at building and further developing a slosh experiment by studying and understanding the influence of 2 types of baffles on slosh dynamics systems under varying gravity and loads. Such experimentations will provide us understanding about the behavior of fluids in space and varying effects of prominent parameters such as pressure, temperature, velocity, etcetera on fluids. The experiment is accomplished by using 3 polycarbonate transparent tanks accompanied by 2 high speed cameras mounted to record the video footage. The recorded data can further be utilized for post-flight analysis and to further understand the sloshing effect of liquid propellent in sounding rocket flight.
**Requirements**

Considering the IREC requirements, along with our internal Space Concordia Rocketry Division Specifications and Requirements, the below mentioned guidelines were formulated for the design of payload:

1. The payload should perform a scientific experiment.
2. It should have a minimum weight of 8.8lbs and a maximum of 10 lb.
3. It must function independent of the rocket with no interference with the vehicle’s stability and performance.
4. Must not contain any form of Toxic Materials.
5. Should have a CubeSat format
6. The payload should have a maximum weight of 9.5 lb.
7. It must be Structurally sound and should withstand 17.5 G launch force
8. Should be Watertight to avoid any leakage to the other components of the rocket.
9. It should be able to take all the required electronic components such as cameras, computer board for the performance of both the experiments.

**Design Overview**

The Payload constitutes two separate experiments. The objective of the first experiment is the study, analyze and record the influence of two different types of baffles (Vertical baffles and Baffle balls) on sloshing phenomenon under different atmospheric conditions, varying loads and gravity forces. The two upper smaller tanks located in the top unit contain the two different types of baffles, filled with demineralized water that been mixed with two different fluorescent pigments. Both the smaller tanks are identical in shape, structure, dimensions and contain the same fluid (demineralized water) filled up to same level in the tanks. This experiment will be captured through a Pi Zero camera pointed at both tanks. The bottom bigger tank is the collector tank as the liquid drains from the upper tanks to the bottom tank during the flight. in this tank we can also see the flight effects of the two fluids mixing during flight through the color ratio between the two liquids, which will show the effects of the baffles in terms of flow rates.

The second experiment is meant to study and examine the atomized fluid motion during the supersonic flight. This allows us to study the gaseous dynamics under the effect of varying forces, pressure and velocity. This is accomplished using a spray nozzle to spray the fluid coming from the upper smaller tanks into the bottom tank with a much higher force. The spraying rate of the atomized fluid will be observed by a secondary Pi Zero camera in the bottom unit. Both experiments will be conducted before the rocket hits apogee.

The liquid (demineralized water) used for the experimentation will be mixed with fluorescent particles that glow under ultra-violet LED light to obtain better contrast footage and to facilitate the observation of liquid sloshing. Both experiments will be conducted starting from the initial launch and will record data 10 seconds after launch and before the rocket has reached apogee.
Validation

1. **Performing a scientific experiment**
   As specified, the motive of this payload is to test the performance of two different types of baffles in reducing the sloshing phenomenon by placing them in two identical polycarbonate smaller tanks having same dimensions. The level of the working fluid which is alcohol is maintained same in both the tanks during the starting of the experiment. The second experiments involve the study of atomized fluid motion through a spray nozzle. It will help us to study the gaseous dynamics and record the obtained data for further implications in the future.

2. **The weight requirement of 8.8 – 10 lb.**
   To meet the weight requirements and to avoid any violations due to the overweight of the payload, all the materials are carefully chosen according to the design requirements. The 3 tanks (2 top and 1 bottom) are made from polycarbonate material which is lightweight and delivers the same strength and purpose which is required as per the experiment. Further, the piping is made of plastic in addition to the 4 bulkheads made of steel to meet the weight requirements. Being within the weight requirements also provides better flexibility.

3. **No interference with vehicle’s stability and performance**
   It is of optimum priority that payload works independent of the rocket without any sort of interference. This payload is designed in such a way that it does not interfere with the functionality and efficiency of other systems of the rocket. Moreover, required safety measures are taken so that each sub-part of the payload does not affect the working of other sub-parts. The selection of the liquid is based on the condition that it is non-conductive and non-toxic to avoid any chances of sparks and damage which can cause any damage to the payload and further to the rocket. Moreover, the payload has its own avionics for its functioning and performance. This enables payload work independent of the rocket and if the avionics of payload encounter any sort of malfunctioning or undesirable problem (which won’t happen but considering the worst cases), it will not affect the stability, functioning and performance of the other parts of the rocket and the rocket itself.

4. **CubeSat format of payload and use of non-toxic materials**
   The payload should have the dimensions of 10 x 10 x 30cm. This is the standard dimensions for the CubeSat (3U) and this is according to the rules of the competition for payload. Keeping the dimensions of the payload strictly as per
the directions of the competition is our main priority and this is taken care by using metric extrusions, which helped us to make a frame of specified dimensions. In addition to that, selection of size of all the components to be used in the payload including the piping arrangement was with respect to the CubeSat format of the payload. Hence, pre-planning and calculative manufacturing of all the payload parts helped us to remain within the desired dimensions of final payload.

It is well taken care of that there is no use of toxic element of any form within the payload no matter what purpose it may serve. This is as per the rules of the competition. The liquid which is used to conduct the 2 experiments is also carefully chosen after detailed study of its properties both physical and chemical. It is important to avoid the use of toxic things in the payload as it possess great danger to the internal parts of the payload and then further to the rocket in worst cases.

5. **It should be structurally sound and watertight**

This is one of the most prominent factor that affects the performance and working of the payload. The more structurally sound a system is, the more is its output and lesser are the chances of any failure or malfunctioning. The payload is designed to withstand 17.5G’s to conserve the structural integrity of the payload. Hence, specified tests are conducted using the shaker table for vibration testing to ensure that payload do not add unwanted vibrations to the rocket. This is taken care of by using self-locking nylon nuts for securing bulkheads together. Also, strong materials with high impact strength and the ones which can withstand maximum loads such as steels, aluminum, polycarbonate and plastics are being used for numerous specified purpose to impart strength to the payload. This will help the payload withstand worst conditions and still function and perform its task as desired. Moreover, sensitive and important components such as Avionics and cameras are fitted and adjusted with care to avoid getting detached and thus damaging the payload.

Also, to ensure that there is no leakage from the payload or within the payload subsystems due to the flow of the fluid under varying pressure and temperature conditions, redundant sealing of the parts wherever necessary is done. For instance, compressed gaskets are being used to avoid leakage of fluid. In addition to that, O-rings are also used to take every preventive measure to avoid any problem that the payload may encounter during the flight.

IV. **Mission Concept of Operations Overview**

The launch vehicle flight phase analysis is organized into six separate phases, which outlines the worst conditions encountered at each stage. A governing safety factor is determined to validate the vehicle’s integrity at each stage.

![Fig. 15 Flight Phase Graph](image-url)
A. **Phase 0: Ground Handling**

As the rocket sits statically on the launch rod, the lugs support the vehicle’s full weight. The lugs must therefore be analyzed for worst case scenario, which considers a vertical launch rod. Thus, the reactions at the bottom lug and top lug were calculated, and a safety factor of 9.3 was found. Although this factor of safety is very high, its consideration comprises an important portion of the flight’s nominal operation.

B. **Phase 1: Motor Ignition**

The ignition of the motor creates a large initial shock on the system. This has a maximum force of 8034N. The force is handled by the motor block and thus, the motor block must be analyzed with respect to this initial force. Thus an FEA model was built in ANSYS consisting of the assembly of the aft section was conducted, where the maximum thrust was applied to the motor block and boat tail. The resulting safety factor for the correct operation of the vehicle was 7.8. This section is considered safe, as it last year’s rocket was made of the same composites, thus has flight heritage.

![Figure 17. ANSYS Explicit Dynamic Simulation](image)

C. **Phase 2: Launch Rod Clearance**

When the rocket leaves the rod, it encounters two issues: the tendency of the rocket to be unstable at low velocities and high wind speeds and the risk the lugs may detach from the rocket. Both these conditions are considered at the maximum wind condition (8.33 m/s).

A minimum dynamic stability caliber was calculated to give a safety factor of 2.7. A one kilogram ballast can be removed or added to accommodate varying wind conditions. The dynamic forces on the launch lugs caused by the high wind speeds were within operational limits of the vehicle, after calculations were conducted.

D. **Phase 3: Maximum Dynamic Pressure**

The third phase begin right before motor burnout, at maximum velocity. At this point in flight, the rocket has reached transonic speeds (Mach 1.7). Due to these high speeds, the rocket’s dynamic pressure is at a maximum of 930 N. At this point, fin flutter is most likely to occur. Using the NACA TN-4197 equation, a flutter velocity of 693 m/s was found, which, given the ANSYS analysis performed previously demonstrates the equation to be conservative, thus validating the fins at a safety factor of 4.8. Additionally, the honeycomb fins are part of the many components with flight heritage.

E. **Phase 4: Drogue Deployment**

On drogue deployment, a shock will travel through several components, including the parachute swivel, shock cord, quick link, eye bolt, shear pins, and bulkhead. These components’ rated strengths were compared with the ejection shock force of 167N. A governing safety factor was given by the array of 6 shear pins, meant to withstand only the shock of the drogue chute, to avoid deployment of the main chute at apogee. To simulate worst case conditions, the force of shock for the drogue was calculated for the rocket after 4 seconds of freefall. This allows ample time for the deployment system to notice a change in pressure due to altitude.

F. **Phase 5: Main Deployment**

As the rocket, falls below 755 ft, the deployment of the main parachute will be triggered, thus shearing the nylon screws, and ejecting the main chute. The shock of the main deployment, considered the second largest load to act on the launch vehicle, was calculated to 1604 N. Once again, structural components were analyzed, and the
forward recovery bulkhead assembly was analyzed in ANSYS resulting in a safety factor of 2.5.

IV. Conclusions and Lessons Learned

This has been one of the most ambitious projects conducted by Space Concordia’s rocketry team, with many “firsts”. We are very proud of our team and accomplishments this year. In order to achieve all these milestones, we were required to find workarounds to multiple problems. Due to our annual budget ($11,000), we were required to manufacture every single mechanical component in house. This meant we had to learn to use new manufacturing techniques that we have never used before such as CNC machining and complex AFP layup in parallel with improving our previous techniques of hand layups and manual machining. We also worked to acquire a total in-kind sponsorship value of over $45,000.

We quickly learned that to achieve our goals, we needed to adhere to a very tight and rigid development cycle. There must be a priority to projects, and sacrifices might need to be made to achieve more important goals. Examples of projects that were cut this year: fall away launch lugs, transition sections, ejecting payload and downwards facing cameras. These projects, nonetheless exciting, take time away from the team that needs to focus on our fundamentals. We learned that having a strong foundation is more important than a feature-filled rocket.

We have attempted to do more than any previous iteration before us. With regards to the design, manufacturing, analysis, and performance of this rocket, the scope of this project has dwarfed anything that has come before. The ambition, dedication and hard work shown by the entire team has made this a reality. We are very proud of our team and accomplishments this year. We look forward to launching our rocket at Spaceport America and cannot wait to apply what we learn to our future designs and further push the limit of what we are capable.
APPENDIX A: SYSTEM WEIGHTS, MEASURES, AND PERFORMANCE DATA
**Team Information**

<table>
<thead>
<tr>
<th>Rocket/Project Name:</th>
<th>Supersonice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Organization Name:</td>
<td>Space Concordia - Rocketry Division</td>
</tr>
<tr>
<td>College or University Name:</td>
<td>Concordia University</td>
</tr>
<tr>
<td>Organization Type:</td>
<td>Club/Group</td>
</tr>
<tr>
<td>Project Start Date:</td>
<td>2017-09-01</td>
</tr>
<tr>
<td>Category:</td>
<td>30k – COTS – All Propulsion Types</td>
</tr>
</tbody>
</table>

**Member Information**

<table>
<thead>
<tr>
<th>Member</th>
<th>Name</th>
<th>Email</th>
<th>Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student Lead</td>
<td>Olivier D'Angelo</td>
<td><a href="mailto:olivier.dangelo@spaceconcordia.ca">olivier.dangelo@spaceconcordia.ca</a></td>
<td>5142416115</td>
</tr>
</tbody>
</table>
Demographic Data
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.

<table>
<thead>
<tr>
<th>Number of team members</th>
</tr>
</thead>
<tbody>
<tr>
<td>High School</td>
</tr>
<tr>
<td>Under grad</td>
</tr>
<tr>
<td>Masters</td>
</tr>
<tr>
<td>PhD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gender</th>
<th>Male</th>
<th>Female</th>
<th>Veterans</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Just a reminder the you are not required to have a NAR, Tripoli member on your team. If your country has an equivalent organization to NAR or Tripoli, you can count them in the NAR or Tripoli box. CAR from Canada is an example.

STEM Outreach Events
If you perform any STEM related outreach events, please place a brief description here.

STEM stands for Science, Technology, Engineering, and Mathematics.
Presentation for FIRST Robotics Competition to promote STEM Education

Rocket Information
Overall rocket parameters:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Additional Comments (Optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe Length (inches): 120</td>
<td></td>
</tr>
<tr>
<td><strong>Experimental Sounding Rocket Association</strong></td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Airframe Diameter (inches):</strong> 6</td>
<td></td>
</tr>
<tr>
<td><strong>Fin-span (inches):</strong> 5</td>
<td></td>
</tr>
<tr>
<td><strong>Vehicle weight (pounds):</strong> 36.49</td>
<td></td>
</tr>
<tr>
<td><strong>Propellent weight (pounds):</strong> 32.69</td>
<td></td>
</tr>
<tr>
<td><strong>Payload weight (pounds):</strong> 8.8</td>
<td></td>
</tr>
<tr>
<td><strong>Liftoff weight (pounds):</strong> 77.98</td>
<td></td>
</tr>
<tr>
<td><strong>Number of stages:</strong> 1</td>
<td></td>
</tr>
<tr>
<td><strong>Strap-on Booster Cluster:</strong> No</td>
<td></td>
</tr>
<tr>
<td><strong>Propulsion Type:</strong> Solid</td>
<td></td>
</tr>
<tr>
<td><strong>Propulsion Manufacturer:</strong> Commercial</td>
<td></td>
</tr>
<tr>
<td><strong>Kinetic Energy Dart:</strong> No</td>
<td></td>
</tr>
</tbody>
</table>

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

1st Stage: Cesaroni Pro 98, 20146N5800-P, N Class, 20145.7 Ns

Total Impulse of all Motors: 20145.7 (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.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Additional Comments (Optional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Rail:</td>
<td>ESRA Provide Rail</td>
</tr>
<tr>
<td>Rail Length (feet):</td>
<td>17</td>
</tr>
<tr>
<td>Liftoff Thrust-Weight Ratio:</td>
<td>15.55877461</td>
</tr>
<tr>
<td>Launch Rail Departure Velocity</td>
<td>160.7</td>
</tr>
<tr>
<td>(feet/second):</td>
<td></td>
</tr>
<tr>
<td>Minimum Static Margin During</td>
<td>3</td>
</tr>
<tr>
<td>Boost:</td>
<td></td>
</tr>
<tr>
<td>Maximum Acceleration (G):</td>
<td>21.4</td>
</tr>
<tr>
<td>Maximum Velocity (feet/second):</td>
<td>1901</td>
</tr>
<tr>
<td>Target Apogee (feet AGL):</td>
<td>30K</td>
</tr>
<tr>
<td>Predicted Apogee (feet AGL):</td>
<td>30420</td>
</tr>
</tbody>
</table>

**Payload Information**

**Payload Description:**

This year’s payload submission is a functional fluid slosh experiment. It is designed to simulate a liquid fuel rocket engine, where the mixing of oxidizer and fuel will be observed qualitatively with the eventually objective of constructing a student built, liquid fuel engine. There will be two upper tanks both filled with isopropyl alcohol. One of the tanks will contain baffles designed to limit fluid slosh, while the second upper tank will not have baffles to act as a control. To help observe mixing, both tanks will be dyed different fluorescent colours. At the moment of motor ignition, the upper tanks will be drained into a single lower tank with a small pump. The tanks and the tubing will be clear, so that the fluid may be observed during the whole process. The payload will remain in the rocket forward section during rocket launch and recovery.
Recovery Information

The recovery device is dual parachute system which will be deployed at apogee using a barometric sensor and at 700 ft. AGL. At apogee, the drogue parachute will be released by decoupling the rocket via chamber pressurization with a CO2 canister. The main parachute deployment is triggered via barometric sensor from the avionics system. It is deployed by ejecting the bulkhead cap via chamber pressurization with another CO2 canister.

An E-Match will ignite a 0.2 grams of black powder to puncture a CO2 canister. The gases released will generate pressure on the bulkheads causing a breach for the parachutes to evacuate.

This design features 2 parachute deployments, but with only one decoupling. This allows all avionics to be installed in one location, and improved safety. All components are designed with a minimum factor of safety of 2.

Planned Tests

<table>
<thead>
<tr>
<th>Date</th>
<th>Type</th>
<th>Description</th>
<th>Status</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-26-17</td>
<td>Ground</td>
<td>Recovery System Activation Test</td>
<td>Successful</td>
<td>Activate E-match to test piercing of canister</td>
</tr>
<tr>
<td>12-28-17</td>
<td>Ground</td>
<td>Avionics Deployment Activation Testing</td>
<td>TBD</td>
<td>Trigger avionics system deployment using vacuum sealed chamber</td>
</tr>
<tr>
<td>12-1-17</td>
<td>Ground</td>
<td>Payload Leak Testing</td>
<td>Minor Issues</td>
<td>Flowrate was constricted due to lack of air intake</td>
</tr>
<tr>
<td>1-10-18</td>
<td>Ground</td>
<td>Glass/PET fuselage bending/Compression test</td>
<td>Successful</td>
<td>Test fuselage thermoplastic sample in bending and compression</td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
<td>Test Description</td>
<td>Status</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>------------------------------------------</td>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>4-1-18</td>
<td>Ground</td>
<td>Ground Deployment Test</td>
<td>Minor Issues</td>
<td>Test deployments of parachute from within the fuselage, on the ground</td>
</tr>
<tr>
<td>2-15-18</td>
<td>Ground</td>
<td>Payload Waterpump testing</td>
<td>Successful</td>
<td>Minor leaks were found and are being worked on</td>
</tr>
<tr>
<td>2-16-18</td>
<td>Ground</td>
<td>Avionics GPS Tracking Test</td>
<td>Successful</td>
<td>test gps accuracy and data feed</td>
</tr>
<tr>
<td>4-4-18</td>
<td>Ground</td>
<td>Ultrasonic Inspection on AFP Nosecone Fuselage</td>
<td>TBD</td>
<td>Test advanced composite component for damage</td>
</tr>
<tr>
<td>4-10-18</td>
<td>Ground</td>
<td>Payload Modal Testing</td>
<td>TBD</td>
<td>Test assembly on a shaker table to define natural frequencies</td>
</tr>
</tbody>
</table>
Abstract

As part of the Supersonice Rocket technical package, this report outlines a vertical stationary ground test of the drogue deployment’s fuselage separation, as well as the deployment of the main parachute. Both deployments were a success. The tests confirm the functionality of the system and gives confidence in the design.
1 Introduction

This report summarizes observations and analysis of the recovery system ground testing which occurred on the 7 & 23 May 2018. This test is part of the technical package for the ESRA 2018 competition.

2 Test Configuration

This test was done in parts A & B: a pull test for the main parachute deployment, and an ejection test for the drogue parachute deployment.

Part A – Main Parachute Pull Test

The parachute assembly was packed as per SR18-FW-RE-03, Parachute Assy [1], minus the pyrotechnics, and ejection components of the assembly. The FWD shock cord was fixed in place and the AFT shock cord was manually pulled in order to simulate the deployment sequence of the parachute.

![Part A Test Set Up](image)

Figure 1 - Part A Test Set Up

Part B – Ejection Test

For the ejection test, the FWD and AFT held together by 6 shear pins, and inside the fuselage, was the SR18-FW-RE-01, Recovery Bulkhead Assy [2] and the SR18-FW-RE-03, Parachute Assy [1]. The ejector was activated via command wire detonation.

The recovery preflight checklist (see Annex) was followed for this test.
3 Results

The tests were captured by videos (see Ref [3] & [4]). The tests are summarized below:

Table 5 – Test Results

<table>
<thead>
<tr>
<th>TEST</th>
<th>RESULT</th>
<th>PICTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PART A – MAIN PARACHUTE PULL TEST</td>
<td>SUCCESS</td>
<td><img src="image1.png" alt="Picture" /></td>
</tr>
<tr>
<td>PART B – EJECTION TEST</td>
<td>SUCCESS</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
</tbody>
</table>

4 Conclusions and Recommendations

These tests have allowed us to confirm that the recovery system is functional, and suitable for flight on Supersonice.

5 References
### RECOVERY PREFLIGHT CHECKLIST

**PARACHUTE ASSY**

<table>
<thead>
<tr>
<th>Assy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fold Parachutes</td>
<td></td>
</tr>
<tr>
<td>Pack Parachute Bags</td>
<td></td>
</tr>
<tr>
<td>Pack Shock Chords to Bag</td>
<td></td>
</tr>
<tr>
<td>Ensure Quick Links are Locked</td>
<td></td>
</tr>
<tr>
<td>Close Parachute Bags</td>
<td></td>
</tr>
<tr>
<td>Secure Shock Chords to Hoist Rings</td>
<td></td>
</tr>
</tbody>
</table>

**TENDER DESCENDER**

<table>
<thead>
<tr>
<th>Prm</th>
<th>Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check E-Match Resistance 1.4Ω and Continuity</td>
<td></td>
</tr>
<tr>
<td>Remove E-Match Guard</td>
<td></td>
</tr>
<tr>
<td>Cut to 9 Inches and Expose Leads</td>
<td></td>
</tr>
<tr>
<td>Feed Through Tender Descender</td>
<td></td>
</tr>
<tr>
<td>Solder Terminal Lugs</td>
<td></td>
</tr>
<tr>
<td>Short E-Match Leads</td>
<td></td>
</tr>
<tr>
<td>Fill Tender Descender with Black Powder</td>
<td></td>
</tr>
<tr>
<td>Assemble with Quick Links and Cap</td>
<td></td>
</tr>
<tr>
<td>Attach Tender Descender to Assembly</td>
<td></td>
</tr>
</tbody>
</table>

**EJECTOR ASSEMBLY**

<table>
<thead>
<tr>
<th>Prm</th>
<th>Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check All E-Match Resistance 1.4Ω and Continuity</td>
<td></td>
</tr>
<tr>
<td>Cut to 7 Inches and Expose Leads</td>
<td></td>
</tr>
<tr>
<td>Trim E-Match Guard Cap ¾ of the Way</td>
<td></td>
</tr>
<tr>
<td>Feed Through Bushing and Housing</td>
<td></td>
</tr>
<tr>
<td>Solder Terminal Lugs</td>
<td></td>
</tr>
<tr>
<td>Short E-Match Leads</td>
<td></td>
</tr>
<tr>
<td>Fill Bushing with Black Powder</td>
<td></td>
</tr>
<tr>
<td>Insert Needle with Busing in Housing</td>
<td></td>
</tr>
<tr>
<td>Screw On to Base, Seal With Teflon Tape</td>
<td></td>
</tr>
<tr>
<td>Insert Canisters, Seal With Teflon Tape</td>
<td></td>
</tr>
</tbody>
</table>

**GENERAL**

<table>
<thead>
<tr>
<th>Assy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix Terminal Lugs to Terminal</td>
<td></td>
</tr>
<tr>
<td>Check All E-Match Resistance 1.4Ω and Continuity</td>
<td></td>
</tr>
<tr>
<td>Check Hoist Swivel Clearance</td>
<td></td>
</tr>
<tr>
<td>Secure Wiring</td>
<td></td>
</tr>
<tr>
<td>Teflon Tape Around Recovery Bulkhead</td>
<td></td>
</tr>
<tr>
<td>Hazard</td>
<td>Possible Causes</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------------------------------------------------</td>
</tr>
<tr>
<td>Explosion of Solid Rocket Propellant motor</td>
<td>Cracks in propellant grain</td>
</tr>
<tr>
<td></td>
<td>Propellant chunks breaking off and blocking the nozzle</td>
</tr>
<tr>
<td></td>
<td>Motor case fails under normal operation</td>
</tr>
<tr>
<td></td>
<td>Failure of motor closures</td>
</tr>
<tr>
<td>Main parachute deploys at the maximum altitude</td>
<td>Failure of the shear pins by motor forces</td>
</tr>
<tr>
<td></td>
<td>Payload section is pressurized by CO2 recovery system</td>
</tr>
<tr>
<td></td>
<td>Shear pins damaged before launch</td>
</tr>
<tr>
<td></td>
<td>Some shear pins are omitted during assembly</td>
</tr>
<tr>
<td></td>
<td>Software Error</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Event Description</td>
<td>Potential Failure Points</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Partial deployment of recovery system</td>
<td>Failure of computer after drogue deployment shock</td>
</tr>
<tr>
<td></td>
<td>Failure of computer power after drogue deployment shock</td>
</tr>
<tr>
<td></td>
<td>Wires to deployment system (Peregrine) disconnected after drogue</td>
</tr>
<tr>
<td></td>
<td>Deployment shock</td>
</tr>
<tr>
<td>Recovery system completely fails to deploy</td>
<td>Failure of computer through software error</td>
</tr>
<tr>
<td></td>
<td>Failure computer due to mechanical failure of PCB or avionics bay</td>
</tr>
<tr>
<td></td>
<td>Batteries run out of power before launch</td>
</tr>
<tr>
<td>Recovery system deploys while the rocket is still being handled by team members</td>
<td>Static electricity builds up and fires Peregrine system</td>
</tr>
<tr>
<td></td>
<td>CO2 canisters heat above 50 degrees Celsius and could possibly explode</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocket Detaches from rail during</td>
<td>Failure of either for or aft rail guide during</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure of rocket structure at ignition, potentially creating fast moving debris (Phase 1 failure)</td>
<td>Failure of internal motor mount</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Failure of rocket fins at maximum dynamic pressure, potentially causing the destruction of the vehicle and creating dangerous debris (Phase 3 failure)</td>
<td>Fins fail in fin-flutter</td>
</tr>
<tr>
<td>Deviation of flight path when the rocket clears the launch rod, potentially creating a hazard to personnel and property (Phase 2 failure)</td>
<td>High winds cause instability at launch</td>
</tr>
<tr>
<td></td>
<td>Lug failure due to high moments induced by high winds</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure of Structure at Drogue Deployment, potentially causing the destruction of the vehicle and creating dangerous debris (Phase 4 failure)</td>
<td>Hoop stress causes failure of fuselage</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Deployment shock causes failure of structural components</td>
<td>Deployment shock causes failure of structural components</td>
</tr>
<tr>
<td>Failure of the SRAD recovery system (Phase 4 Failure)</td>
<td>The piston fails to pierce the CO2 canister, caused by the needle inaccurately hitting the center of the canister</td>
</tr>
<tr>
<td>Failure of structure at main parachute deployment, potentially causing the destruction of the vehicle and creating dangerous debris (Phase 5 Failure)</td>
<td>Hoop stress causes failure of fuselage</td>
</tr>
<tr>
<td>Deployment shock causes failure of structural components</td>
<td>Deployment shock causes failure of structural components</td>
</tr>
</tbody>
</table>

**Recovery System**

<table>
<thead>
<tr>
<th>Possible Mode of Failure</th>
<th>Severity</th>
<th>Tests</th>
<th>Contingency Plan</th>
<th>Results &amp; Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted collar isn’t triggered by recovery</td>
<td>-Pitot functions - Retraction failure</td>
<td>Test in rocket</td>
<td>-Increase collar weight and lubricity</td>
<td>Test Successful</td>
</tr>
<tr>
<td>Issue Description</td>
<td>Possible Cause</td>
<td>Proposed Solution</td>
<td>Test Result</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Weighted Collar wedges on nosecone</td>
<td>Possible retraction failure</td>
<td>Test in retraction in nosecone</td>
<td>-elongate sliding distance -reduce outer diameter of collar</td>
<td>Test Successful No changes necessary</td>
</tr>
<tr>
<td>3D printed Capsule is torn by tension</td>
<td>Data lost - Retraction failure</td>
<td>Run tensile strength tests printed samples with same print settings</td>
<td>-improve material selection -modify geometry to be stronger</td>
<td>Capsule geometry was changed to account for print shrinkage (current capsule fully functional)</td>
</tr>
<tr>
<td>Rigidity of latches prevent quick release</td>
<td>-Pitot functions - Retraction failure</td>
<td>Assemble mechanism and test</td>
<td>-Decrease thickness of latches -Use different material</td>
<td>Test Successful (materials &amp; geometry still optimised)</td>
</tr>
<tr>
<td>Latches wedge collar in place</td>
<td>-Pitot functions - Retraction failure</td>
<td>Assemble and test mechanism and test</td>
<td>-Increase lubricity -Increase clearance between latches and collar</td>
<td>Test Successful (clearance still increased)</td>
</tr>
<tr>
<td>Wires from PCB Capsule wedge capsule in place</td>
<td>Possible retraction failure</td>
<td>Test in retraction in nosecone</td>
<td>-Arrange ribbon cable in coil around sensor shaft/extrusion</td>
<td>Wire management successful and implemented</td>
</tr>
<tr>
<td>Weighted collar triggered prematurely by rocket deceleration</td>
<td>Data cut short -Pitot recovered</td>
<td>-Test in rocket and check data - Test rocket deceleration impulse on mechanism with jig</td>
<td>-Include shear pin that fails at recovery impulse</td>
<td>Tests Successful in jig, further tests in rocket planned</td>
</tr>
<tr>
<td>Vibrations amplified by sliding member could spoil data</td>
<td>Data may be erroneous</td>
<td>-Test in rocket -Test in wind tunnel</td>
<td>-Reduce clearance between shaft and pitot tube -Use vibration dampening materials</td>
<td>Test Successful Data smooth</td>
</tr>
<tr>
<td>Stuctural failure (compressive or tensile)</td>
<td>Possible retraction failure</td>
<td>Compressive and Tensile strength tests</td>
<td>Inspect point of failure and improve design</td>
<td>Tests successful at 1.5 times expected stress</td>
</tr>
<tr>
<td>Risk</td>
<td>Possible cause</td>
<td>Consequence</td>
<td>Mitigation plan</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------------------------</td>
<td>---------------------------------------</td>
<td>-----------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Fluid Leak</td>
<td>Improper Sealing</td>
<td>Damaged Avionics</td>
<td>Compressed Sealing Gaskets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tank Cracks</td>
<td>Camera Bay Shoutout</td>
<td>Fluid: Isopropyl Alcohol</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nonconductive</td>
<td></td>
</tr>
<tr>
<td>Structural Failure</td>
<td>Weak Nanobeam Structure</td>
<td>Damaged Avionics</td>
<td>Additional structural support: plate mounts</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage to Rocket Interior</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment Incomplete</td>
<td>Solenoid Valve Fails</td>
<td>Data Loss</td>
<td>Data gathered by slosh experiment in upper tanks constitutes experiment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pump Fails</td>
<td>Incomplete Experiment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Differential</td>
<td>Change in temperature and pressure at 30000 feet</td>
<td>Leaking of liquid causing a short circuit of electrical components</td>
<td>Sealing of tanks and securing piping to structure</td>
<td></td>
</tr>
<tr>
<td>Electrical malfunction</td>
<td>Loose connection</td>
<td>No data collection</td>
<td>Attach connections to structure to avoid disconnection or vibration shear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Component malfunction</td>
<td>Experiment fails to run</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(pump/solenoid)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D: ASSEMBLY, PREFLIGHT, AND LAUNCH CHECKLISTS
1. RECOVERY
   1.1. PARACHUTE ASSY
   - Fold parachutes
   - Pack parachute bags
   - Pack shock chords to bag
   - Ensure quick links are locked
   - Close parachute bags

   1.2. TENDER DESCENDER
   - Wear protective eye wear when dealing with explosives
   - Check E-match resistance 1.4Ω and continuity
   - Remove E-match guard
   - Cut to 9 inches and expose leads
   - Feed through tender descender
   - Solder terminal lugs
   - Short E-match leads
   - Fill tender descender with black powder
   - Assemble with quick links and blasting cap

   1.3. EJECTOR ASSY
   - Wear protective eye wear when dealing with explosives
   - Check all E-match resistance 1.4Ω and continuity
   - Cut to 7 inches and expose leads
   - Trim E-match guard cap ¾ of the way
   - Feed through bushing and housing
   - Solder terminal lugs
   - Short E-match leads
   - Fill bushing with black powder
   - Insert needle with busing in housing
   - Screw on to base, seal with Teflon tape
   - Insert canisters, seal with Teflon tape

2. PAYLOAD
   - Fill compartments with liquid

3. CAMERA BAY
   - Ensure cameras are fully charged
   - Ensure cameras have empty SD cards

4. STRAIN GAUGES
   - Ensure strain gauge battery are fully charged
   - Ensure strain gauge has empty SD cards

5. AVIONICS
   - Ensure all batteries are fully charged
<table>
<thead>
<tr>
<th>ENSURE ALL SD CARDS ARE INSTALLED AND EMPTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERIFY ALL CONNECTIONS</td>
</tr>
</tbody>
</table>

6. **MOTOR**
- INSTALL MOTOR TO AFT AS PER OEM INSTRUCTION
- INSTALL SNAP RING

7. **FORWARD ASSY**
- INSTALL PAYLOAD ASSY TO FRAME
- INSTALL CAMERA ASSY TO FRAME
- INSTALL AVIONICS ASSY TO FRAME
- CONNECT SHOCK CORDS TO FORWARD AND AFT
- ENSURE MASTER AVIONICS SWITCH ON RECOVERY BULKHEAD IS OFF
- CONNECT POWER TO BOARDS
- WEAR PROTECTIVE EYEWEAR WHEN DEALING WITH EXPLOSIVES
- FIX TERMINAL LUGS TO TERMINAL
- CHECK ALL E-MATCH RESISTANCE 1.4Ω AND CONTINUITY
- CHECK HOIST SWIVEL CLEARANCE
- SECURE RECOVERY WIRING
- TEFNON TAPE AROUND RECOVERY BULKHEAD
- INSTALL FRAME IN FORWARD FUSELAGE
- SET UP RBF SYSTEM
- ACTIVATE MASTER AVIONICS SWITCH ON RECOVERY BULKHEAD

8. **FULL ASSEMBLY**
- COUPLE FORWARD AND AFT
- INSERT SHEAR PINS
- VERIFY THE TOTAL WEIGHT OF THE ROCKET (_______ G)
Analysis & Validation of PET Thermoplastic Composite Rocket Fuselage Manufactured by Automated Fibre Placement

Final Report
Honours Research Project – ENGR 412

By:
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Submitted to:
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&
Jeffrey Fortin-Simpson

Concordia University
Engineering and Computer Science

Revision: 2

Date of report submission: April 16th, 2018

45
Experimental Sounding Rocket Association
Abstract

This report presents the honours research project on the analysis and validation of a glass fibre reinforced polyethylene terephthalate (PET) thermoplastic composite fuselage manufactured by automated fibre placement (AFP) machine in tandem with Concordia’s Center for Composites (CONCOM) research laboratory. A buckling analysis due to pure bending and axial compression was conducted by finite element analysis (FEA) using ANSYS. The results were verified using a MATLAB script implementing a strength of materials approach and further validated by testing cylindrical shell samples in axial compression. Results indicate that the theoretical and experimental modulus agree, although the tested samples would likely fail compression due to maximum stress is more likely than non-linear buckling.
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### List of Symbols

- $E_m$: Matrix Elastic Modulus, Pa
- $G_m$: Matrix Shear Modulus, Pa
- $E_f$: Fibre Elastic Modulus, Pa
- $G_f$: Fibre Shear Modulus, Pa
- $\zeta$: Tsai-Hill Shape Parameter
- $\eta$: Correction Factor for the theoretical transverse modulus
- $V_f$: Fibre volume fraction
- $E_1$: Lamina elastic modulus in longitudinal direction, Pa
- $E_2$: Lamina elastic modulus in transverse direction, Pa
- $G_{12}$: Lamina shear modulus in longitudinal-transverse direction, Pa
- $\nu_{12}$: Lamina Poisson’s Ratio in longitudinal-transverse direction
- $[\bar{Q}]$: Reduced stiffness matrix
- $[T]$: Transformation matrix
- $[\bar{Q}]$: Transformed reduced stiffness matrix
- $[A]$: In-plane stiffness matrix
- $n$: total number of laminate layers
- $E_x$: Laminate elastic modulus in x-direction, Pa
- $E_y$: Laminate elastic modulus in y-direction, Pa
- $G_{xy}$: Laminate shear modulus in xy-direction, Pa
- $\nu_{xy}$: Laminate Poisson’s ratio in xy-direction
- $M_{cr}$: Critical Bending Load, Nm
- $R$: Inner Radius of Cylinder, m
- $L$: length of cylinder, m
- $t$: Thickness of laminate, m
- $\sigma_{cr}^x$: Critical buckling stress, with transverse shear effects along axial direction, Pa
- $\sigma_{Euler}^x$: Critical Euler buckling stress for orthotropic materials, Pa
- $\sigma^*$: Effective stress, after knockdown factor, Pa
- $\gamma$: Empirical knockdown factor derived in NASA SP-8007
- $P_{cr}$: Critical buckling load for cylindrical shell, N
- $D$: Drag force, N
- $\rho$: density of flow, kg/m$^3$
- $V_\infty$: Flow velocity before impacting object, m/s
- $A$: Reference area, (frontal cross-sectional area), m$^2$
1. Introduction

1.1. Background

Automated fibre placement (AFP) machines have increased the ease and reliability of manufacturing for composite components of complex, closed-shaped geometry while achieving accurate fibre angles and improved quality than traditional hand layup processes, common in sounding rockets [1]. For this reason, Space Concordia’s sounding rocket is manufactured with the help of this advanced manufacturing technology. Previously, the fuselage was composed of APC-2 polyether ether ketone (PEEK) and AS4 carbon fibre laminated, 12 layers thick in the following sequence [90° / 45 / -45 / 0°]_S. This resulted in a lightweight yet strong fuselage with a safety factor of 22 in buckling due to axial compression, which is conservative [2].

An alternative thermoplastic, glass fibre reinforced polyethylene terephthalate (PET), was proposed for the forward fuselage section of the sounding rocket. This material requires lower processing temperatures, allows for radio wave permeability, and results in a more affordable product when compared to PEEK thermoplastic composites. Note that for the suggested research, thermal loads due to heat transfer on the composite will be neglected, as the rocket does not spend sufficient time flying at speeds greater than Mach one to consider aerodynamic heating [3]. Given that PET/glass fibre composite have not been used before for such a structurally demanding application according to the authors knowledge, the analysis of the airframe and validation using a manufactured sample is evaluated. The scope of the analysis will consider buckling due to bending and axial compression, respectively.

1.2. Scope of Work

- Literature studies on classical lamination theory, thin-walled composite cylindrical shells subjected to axial compressive loading and pure bending, non-linear buckling analysis.
- Estimate acting loads on forward fuselage section.
- Define theoretical critical buckling and bending loads using the strength of materials approach.
- Simulate non-linear buckling in bending and axial compression.
- Test sample cylindrical specimen in axial compression.
- Compare test results to theoretical and numerical results.
- Determine the factor of safety of the component.

1.3. Limitations

To conduct the research within reasonable time and cost, several limitations were imposed. The following consists of a list of points that have not been considered.

- Vibration effects of the rocket motor are unknown, nor are the effects of the vibrations known.
- Possible manufacturing induced defects.
- Thermal loads and moisture effects.

1.4. Theory

A general overview of the concepts and theory used in the research follows. The following equations and analysis were implemented in a MATLAB script to aid in the calculation. The code itself can be found in the Appendix B. Results can be found in section 3.

1.4.1. Prediction of Lamina Engineering Properties

The data sheet provided by the PET/GF manufacturer is limited in the reported material properties. To predict the proper response of the composite, the modified rule of mixtures and Halpin-Tsai semi-empirical formulations were used to calculate the unknown mechanical properties of the lamina based on properties of the fibre and matrix.

The transverse modulus is given by

\[ E_2 = \frac{E_m(1 + \xi \eta V_f)}{1 - \eta V_f} \]  

where

Experimental Sounding Rocket Association
\[ \eta = \frac{E_f - 1}{E_f + \xi} \]

(2)

Here, \( \xi \) is a parameter that accounts for packing, fibre geometry and loading condition. For fibres with circular cross-sectional area, \( \xi = 2 \) is used [4].

The in-plane shear modulus is given by

\[ G_{12} = G_m \left( 1 + \xi \eta V_f \right) \]

\[ \frac{1}{1 - \eta V_f} \]

(3)

Where \( \eta \) is previously defined in equation 2. For G-modulus, \( \xi = 1 \) is used [4].

The Poisson’s ratio in the longitudinal-transverse direction and vice-versa are defined using the rule of mixtures as

\[ \nu_{12} = \nu_f V_f + \nu_m V_m \]

(4)

\[ \nu_{21} = \frac{E_2}{E_1} \nu_{12} \]

(5)

1.4.2. Effective Laminate Properties

To calculate a laminate’s effective properties, it is important to first understand the basic equations governing classical lamination theory. The assumptions used in the theory are briefly stated below:

- The laminate consists of perfectly bonded layers. There is no slip between the adjacent layers. In other words, it is equivalent to saying that the displacement components are continuous across layer interfaces.
- Each lamina is considered as a homogeneous layer such that its effective properties are known.
- Each lamina is in a state of plane stress.
- The individual lamina can be isotropic, orthotropic or transversely isotropic.
- The laminate deforms according to the Kirchhoff - Love assumptions for bending and stretching of thin plates (as assumed in classical plate theory). The assumptions are:
  - The normals to the mid-plane remain straight and normal to the midplane even after deformation.
  - The normals to the mid-plane do not change their lengths.

![Figure 3 - Global and Principal Lamina Element Directions](image)

Generally, the laminate global direction is defined in x and y coordinates, while the 1 and 2 directions describe the longitudinal and transverse directions of the lamina, as shown in Figure 3. The direction of the fibre within a laminate will dictate its properties. As such, each layer must be transformed to the global coordinate system following the calculation of the transformed reduced stiffness matrix.
\[ [Q] = [Q] \times [T] \]

where

\[
\begin{bmatrix}
Q_{11} & Q_{12} & 0 \\
Q_{12} & Q_{22} & 0 \\
0 & 0 & Q_{66}
\end{bmatrix}
\begin{bmatrix}
m^2 & n^2 & 2mn \\
n^2 & m^2 & -2mn \\
-2mn & 2mn & m^2 - n^2
\end{bmatrix}
\]

\( Q_{11} = \frac{E_1}{1 - \nu_{12} \nu_{21}} \)  

(7)

\( Q_{12} = \frac{\nu_{12} E_2}{1 - \nu_{12} \nu_{21}} \)  

(8)

\( Q_{22} = \frac{E_2}{1 - \nu_{12} \nu_{21}} \)  

(9)

\( Q_{66} = G_{12} \)  

(10)

\( m = \cos^2 \theta \)  

(11)

\( n = \sin^2 \theta \)  

(12)

The ABD matrix, a 6x6 matrix which represents the elastic properties of the laminate, can then be built using the transformed reduced stiffness matrix. This is done by summing the \( \bar{Q} \) for \( n \) layers while accounting for the thickness of each layers. The effective engineering properties of a laminate can then be computed using the in-plane stiffness matrix [5]:

In-plane Stiffness matrix:

\[
[A] = \sum_{k=1}^{n} [Q]^k (h_k - h_{k-1})
\]

Effective engineering properties:

\[
E_x = \frac{A_{11}A_{22} - A_{12}^2}{A_{22}H}
\]

(14)

\[
\bar{E}_x = \left( \frac{A_{11}A_{22} - A_{12}^2}{A_{22}H} \right)
\]

(15)

\[
\bar{G}_{xy} = \frac{A_{66}}{A_{12}}
\]

(16)

\[
\bar{\nu}_{xy} = \frac{A_{12}}{A_{22}}
\]

(17)

\[
\bar{\nu}_{xy} = \frac{A_{12}}{A_{11}}
\]

(18)

1.4.3. Buckling of Composite Cylindrical Shells

1.4.3.1. Pure Bending

Buckling is a critical failure condition by which the fuselage is likely to fail. To estimate composite failure of fuselage section, the load case of pure bending is studied.
The common modes of failure of long cylinders in bending is determined by the cross-section instability leading to the flattening of the cross section as shown in Figure 2-f and 2-g. This phenomenon was first derived by Brazier leading to the following equation for the critical bending moment [7]:

\[ M_{cr} = \frac{2\sqrt{2}}{9} \pi R t^2 \left[ \frac{E_xE_y}{1-v_{xy}v_{yx}} \right]^{1/2} \]  

(19)

### 1.4.3.2. Axial Compression

Cylindrical shells loaded axially in compression will buckle under the following critical stress [8].

\[ \sigma_x^{cr} = \sigma_x^{Euler} \left[ 1 + \frac{2}{3} \left( \frac{\pi R}{L} \right)^2 \left( \frac{E_x}{G_{xy}} \right) \right]^{-1} \]  

(20)

Note that the equation includes the effects of transverse shear flexibility of a thin-walled cylinder. The Euler buckling stress, modified for orthotropic materials, is given as

\[ \sigma_x^{Euler} = \frac{\pi^2}{2} \left( \frac{R}{L} \right)^2 \bar{E}_x \]  

(21)

Considering the NASA SP-8007 empirical knockdown factor, which considers the shape factor. The corrected maximum stress is given by [9]

\[ \sigma'_x = \sigma_x^{cr} \gamma \]  

(22)

where

\[ \gamma = 1 - 0.901 \left( 1 - e^{-\frac{1}{16\sqrt{t}}} \right) \]  

(23)

For the above stress, the maximum loading for a cylindrical shell can be defined as

\[ P_{cr} = \sigma'_x \pi \left( \frac{d_0}{2} \right)^2 - \left( \frac{d_i}{2} \right)^2 \]  

(24)
It should be noted that the knockdown factor $\gamma$ is considered a lower bound within the 99% range to an empirical data set, and therefore yields conservative results. A nonlinear buckling analysis by FEA will more accurately define a critical buckling load.
2. Methodology

2.1. Model Geometry

The forward section consists of a 63 in. long glass fibre reinforced PET thin-walled tube consisting of a combined 40 in. straight section and 23 in. nosecone. The design of the forward fuselage section with respect to the rockets overall assembly is shown in Figure 3.

![Rocket Exploded Assembly View](image)

**Figure 5 - Rocket Exploded Assembly View**

The array of rails represents a structural mounting interface between the internal bulkhead assemblies and the fuselage shell. A set of screws secure the rail structure to the outer shell. The coupler acts as a joint between the forward and aft components, stiffening the rocket at its weakest point. Figure 6 details the placement of the above-mentioned components.

![Forward Section Structural Components](image)

**Figure 6 - Forward Section Structural Components**

2.2. Loads

During the powered flight of the rocket, the fuselage section will be subjected to an axial compression impulse from initial take-off. Next, an increase in dynamic pressure at relatively constant thrust along with an oscillatory damping motion about its center of gravity causes the rockets corrective aerodynamic forces, acting at the center of pressure (cp in Figure 7), to realign the rocket with respect to its trajectory. To simulate the flight’s
loading conditions within a greater accuracy, an aerodynamic flight simulation software, RASAero was utilized. Details on the simulation model can be found in APPENDIX E-C.

2.2.1. Axial Loading

Transient axial loads associated with an elastic wave moving up the rocket from the thrust chamber at launch were investigated. The loads at launch are applied onto the forward fuselage edge axially. The shock force can be clearly identified in the Figure 8 as the blue curve. The maximum thrust peaks at 8034 N. Given this load is applied as an impulse, a design safety factor greater than 10 is recommended for composite laminates [7]. This loading condition will be analyzed as the second loading condition on the rocket and considered as a steady state axial load, considering the higher safety factor to account for the transient shock wave.

2.2.2. Bending

Bending in a rocket is the result of aerodynamic corrective forces acting on the center of pressure to realign itself with its flight path. The resulting moment then becomes a function of the normal force coefficient, $C_{N\alpha}$, which defines the strength of the normal corrective force. This force is influenced by conditions such as the thrust misalignment, wind gusts, rocket center of gravity offset. This will be used to more accurately define the rockets maximum bending loads [10]. To define the point along the flight with maximum loading conditions, the thrust and drag given by the equation below were plotted as a function of time (see Figure 8). The point with the maximum drag and thrust was found at 1.8 seconds to be 7295 N.

$$D = \frac{C_d \rho V_o^2 A}{2}$$ (25)
Using the simulation data output at 1.8 seconds describing the flight conditions, found in APPENDIX E-C, the bending loads on the rocket were calculated. The system of equations from reference [10] used to derive the bending moment are further described in APPENDIX E-C. These equations are applied to each body element, as shown in Figure 9, and solved numerically.

Figure 9 represents the bending load along the fuselage. The maximum bending load is 210.6 Nm. The load found here will be compared to the critical bending loads found theoretical to determine the safety factor of the component.
2.3. Finite Element Analysis

The finite element analysis was used to compare the analytical closed formed solution of the Euler buckling equation to a numerical nonlinear buckling analysis. The analysis performed utilizes the maximum length of the fuselage within the rocket which is unsupported. This consists of an 18 in. long section found between the coupler and start of the rail system. An additional analysis was conducted with a length equal to the test specimen length.

2.3.1. Mechanical Properties

The material properties of each layer of fibreglass reinforced PET were obtained from the Tencate (TC940) datasheet. The unknown material properties were derived using the micromechanics equations described in section 1.4.2 Effective Laminate Properties. The properties for fibre glass and PET individually were obtained from reference [5, 11], respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_f$</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>$\nu_m$</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>$E_m$</td>
<td>0.7</td>
<td>GPa</td>
</tr>
<tr>
<td>$G_m$</td>
<td>0.05</td>
<td>GPa</td>
</tr>
<tr>
<td>$\nu_f$</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>$E_f$</td>
<td>72.3</td>
<td>GPa</td>
</tr>
<tr>
<td>$G_f$</td>
<td>30</td>
<td>GPa</td>
</tr>
</tbody>
</table>

Table 6 - Mechanical Properties of PET and Glass Fibre Individually

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1890</td>
<td>Kg/m$^3$</td>
</tr>
<tr>
<td>Orthotropic Elasticity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_1$</td>
<td>32</td>
<td>GPa</td>
</tr>
<tr>
<td>$E_2$</td>
<td>3.11</td>
<td>GPa</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>0.1713</td>
<td>GPa</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.282</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>0.125</td>
<td>mm</td>
</tr>
</tbody>
</table>

Table 7 - Material Properties of Glass Fibre/PET

The stacking sequences selected are shown below:

1. $[90 / 45 / -45 / 25 / -25 / 0]$,
2. \([0 / 25 / -25 / 45 / -45 / 90]_s\)
3. \([90_2 / 45 / -45 / 0_2]_s\)

The change in layer orientation from 45 to 25 degrees resulted, as seen in Table 8, in an increase in shear modulus, and decrease in elastic modulus in both \(\text{x}\) and \(\text{y}\) directions, along the tube and hoop wound, respectively. Additionally, the selected layup sequences were made quasi-isotropic, balanced and symmetric because the loading in bending experienced by the fuselage will never be along the same bending axis. The last layup was selected for testing given that the optimal results for buckling and critical loading were greater for this layup sequence.

Table 8 - Effective Laminate Properties of Selected Layup Sequences

<table>
<thead>
<tr>
<th>Parameter</th>
<th>([90_2/45/-45/0_2]_s)</th>
<th>([0/25/-25/45/-45/90]_s)</th>
<th>([90/45/-45/25/-25/0_2]_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_x) (GPa)</td>
<td>17.58</td>
<td>16.96</td>
<td>16.96</td>
</tr>
<tr>
<td>(E_y) (GPa)</td>
<td>17.58</td>
<td>10.28</td>
<td>10.28</td>
</tr>
<tr>
<td>(G_{xy}) (GPa)</td>
<td>7.063</td>
<td>11.10</td>
<td>11.10</td>
</tr>
<tr>
<td>(\nu_{xy})</td>
<td>0.2367</td>
<td>0.52</td>
<td>0.52</td>
</tr>
</tbody>
</table>

2.3.2. Meshing

The mesh used for the FEM uses QUAD4 elements, generally for analysis of shell structures. A mesh convergence study verified the quality of the mesh and assuring convergence of the stresses. The maximum stress is compared to the increase in mesh quality until the stress converges. Figure 11 represents the mesh chosen for which stress values were found to converge.

![Figure 11 - Shell Mesh Density](image)

2.3.3. Boundary Conditions

The conditions used for the numerical analysis of the tubes defines the imperfection which will cause nonlinear buckling. An induced transverse force under compressive loads were input as shown as a 0.5 N force in the \(\text{y}\)-direction to trigger nonlinear buckling. This is achieved by applying a load acting as an imperfection (non-symmetric) in the load distribution, causing the shape to deform in a non-linear fashion. Next, displacement boundaries are set at a single end. One edge is completely constrained, while the other is used to apply the coupled bending and compression loads.
2.4. Experimental Setup

The test specimens were manufactured by AFP using the same inner diameter as the rocket using the following layup sequence $[90_{\circ} / 45 / -45 / 0_{\circ}]$, as this yielded improved resistance to bending when observing the theoretical critical bending loads. The specimen ends were wrapped with additional 90° layers to prevent failure close to the loading fixture.

2.4.1. AFP Manufacturing Parameters

The process parameters for the material were noted for repeatability. These parameters have been determined by producing a set of rings with varying process parameters that were subsequently sectioned and subjected to a short beam shear test to determine the interlaminar shear stress. The optimum process parameters for manufacturing of GF/PET which resulted in the highest interlaminar shear stress are given as:

- Nozzle Temperature $= 590 \, ^{\circ}C$;
- Process Rate $= 50 \, \text{mm/s}$;
- Compaction Force $= 70 \, \text{lbf}$
- Gas Flow Rate $= 80 \, \text{SLPM}$
Two end plates were machined from aluminum to within 0.002” to keep the load aligned with the tube axial direction. To achieve results comparable to the analysis, premature failure due to edge defects must be avoided. This was accomplished using a low melting point alloy (LMPA). The LMPA is placed within the slot before the sample is slid in place to act as additional shear surface and to keep ends grounded. Figure 13 demonstrates the grounded end of a sample in the alloy.

![Figure 13 - Sample Edge Secured in LMPA](image)

Four strain gauges were mounted onto the outer wall of the tube at 180° in pairs with one sensor directed axially, and the other in the hoop direction. Figure 12 shows the experimental setup of a specimen before testing.

![Figure 14 - Sample Setup in Uniaxial Testing Machine](image)
3. Results

3.1. Analysis

The finite element analysis yielded conservative results when comparing the short cylindrical test sample. Table 8 compares the theoretical, finite element method and experimental results. The longer 18 in. simulation results fall within 10% error margin of the analytical solution to buckling as shown in Tables 9. Although the results are not far off from one another, additional samples of longer length should be tested in compression, and in bending, to validate the analytical model.

<table>
<thead>
<tr>
<th>Critical Load Type</th>
<th>Analytical</th>
<th>FEM</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{cr}$ ($\gamma = 0.6816$) (kN)</td>
<td>120</td>
<td>80.16</td>
<td>&gt;96</td>
</tr>
<tr>
<td>$M_{cr}$ (Nm)</td>
<td>2882</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>13.65 (Bending)</td>
<td>10.01</td>
<td>&gt;12</td>
</tr>
</tbody>
</table>

Table 9 - Critical Buckling Load Results for 5.19 in specimen, Layup 1

<table>
<thead>
<tr>
<th>Layup</th>
<th>Critical Load Type</th>
<th>Analytical</th>
<th>FEM</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P_{cr}$ (kN)</td>
<td>82.02</td>
<td>83.1</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>$M_{cr}$ (Nm)</td>
<td>2341</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$P_{cr}$ (kN)</td>
<td>82.02</td>
<td>88.1</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>$M_{cr}$ (Nm)</td>
<td>2341</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$P_{cr}$ (kN)</td>
<td>74.21</td>
<td>80.16</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>$M_{cr}$ (Nm)</td>
<td>2882</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

Table 10 - Results for 18 in. Specimen

3.2. Experiment

The test was performed on 2 samples of 5.19 in. length, giving an aspect ratio smaller than 1. At the time of the manufacturing of the components, the effect of specimen aspect ratio on the buckling of the cylinder was not known. Further research has shown that short cylinders are more likely to fail due to the compressive stress rather than buckling [12]. As the compression test results show in Figure 13, no failure, either in buckling or compression was perceived as the sample reached the maximum achievable compressive load of the machine. Following the stress-strain relationship from the linear portion below, the elastic modulus along the axial direction can be determined. The average modulus $E_x$, was 17.89 GPa, which agrees with theoretical calculations, giving an error margin of 1.71%.
4. Conclusion

The critical bending moment and compression loads were calculated for 3 separate composite laminated cylindrical PET/GF shells for a sounding rocket fuselage manufactured by automated fibre placement. The loads experienced by the rocket during flight were calculated to determine the safety factor. A non-linear buckling analysis by FEA using ANSYS was conducted on the longest unsupported cylindrical specimen with the launch vehicle to validate the determined loading conditions. Cylindrical samples were manufactured and tested following the selection of the layup sequence resulting in the highest critical loads.

The results demonstrated similar values for the elastic modulus. The samples did not fail when tested in axial compression due to a low length to diameter ratio. The analytical and numerical solutions for axial compressive loads result in safety factors within operation limits of the material. Further testing in bending should be conducted to generate conclusive evidence for the analytical bending calculations.

Figure 15 - Load versus Displacement Graph
5. **Recommendations for future work**

To further validate the simulation results, a pure bending test should be conducted on samples, following the same approach used in axial compression. Additionally, material failure properties, such as $\sigma_{2u}^{uc}$, $\sigma_{2u}^{ut}$ should be determined through standard test methods ASTM D5450, D5449. This will lead to a more thorough analysis by determining the failure criteria and more accurately simulating FEA models. Finally, an ultrasonic inspection should be conducted on the nosecone section, as it consists of the section which will contain the most defects due to its complex geometry. The ultrasonic inspection will serve to identify the weakest points on the shell structure. Further considerations should also be taken regarding the manufacturing induced defects, such as voids and high resin concentration areas.
References


Experimental Sounding Rocket Association
APPENDIX E-A

Polar properties of PET/Glass Fibre:

<table>
<thead>
<tr>
<th>PET/GF 12L Balanced Symmetric Laminate AP</th>
<th>Polar Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/PET, α=90.0, t=0.00012</td>
<td>E1: 1.57e+10</td>
</tr>
<tr>
<td>Glass/PET, α=90.0, t=0.00012</td>
<td>E2: 1.18e+10</td>
</tr>
<tr>
<td>Glass/PET, α=45.0, t=0.00012</td>
<td>7.86e+09</td>
</tr>
<tr>
<td>Glass/PET, α=45.0, t=0.00012</td>
<td>3.93e+09</td>
</tr>
<tr>
<td>Glass/PET, α=0.0, t=0.00012</td>
<td>90</td>
</tr>
<tr>
<td>Glass/PET, α=0.0, t=0.00012</td>
<td>180</td>
</tr>
<tr>
<td>Glass/PET, α=-45.0, t=0.00012</td>
<td>270</td>
</tr>
<tr>
<td>Glass/PET, α=-45.0, t=0.00012</td>
<td></td>
</tr>
</tbody>
</table>

Experimental Sounding Rocket Association
APPENDIX E-B

%Sounding Rocket Fuselage Analysis
clc;
clear;

%%%%%%% MICROMECHANICS %%%%%%%%

%Material Properties of PET/Glass Fibre (Tencate TC940):
Vf = 0.4343; % (Tencate TC940 TDS)

%PET Resin Material Properties Source: http://www.goodfellow.com/E/Polyethylene-terephthalate.html
NUm = 0.37;
Em = 700e+06; %Pa (Tencate TC940 TDS)
Gm = 50e+06; %Pa

%Fibre Material Properties (E-Glass) Source: MATWeb, E-Glass Fibre, Generic
NUf = 0.21;
Ef = 72.3e+09; %Pa
Gf = 30e+09; %Pa

%Elasticity
E1 = E1(Vf,Ef,Em); %MPa (E1_Theoretical < E1_Datasheet **)
zeta = 2;
eta = (Ef/Em-1)/(Ef/Em+zeta);
E2 = Em*((1+zeta*eta*Vf)/(1-eta*Vf)); %MPa Source: Halpin-Tsai Formula Eq4.31

Barbero
E3 = E2; %MPa

%Poisson's Ratio
NU12 = NU12(Vf,NUf,NUm);

% Shear Modulus
G12 = G12(Vf, Gf, Gm, 0, 3); %MPa PMM: Eq4.41, E. Barbero 2nd Ed.
G13 = G12;
G23 = 2.714e+03; %MPa NOT NEEDED

% Laminate Engineering Constants (Example: [90_2/-45/45/0_2]s)
Q = ReducedStiffness(E1,E2,NU12,G12);
Qbar_0 = Q;
Qbar_neg45 = Qbar(Q,-45);
Qbar_45 = Qbar(Q,45);
Qbar_90 = Qbar(Q,90);
A = zeros(3,3);
z1 = 0;
z2 = 0.125e-03; %m

% Laminate Thickness
H = (z2-z1)*12;

% 0 layers
A = Amatrix(A,Qbar_0,z1,z2);
A = Amatrix(A,Qbar_0,z1,z2);
A = Amatrix(A,Qbar_0,z1,z2);
A = Amatrix(A,Qbar_0,z1,z2);

% 90 layers
A = Amatrix(A,Qbar_90,z1,z2);
A = Amatrix(A,Qbar_90,z1,z2);
A = Amatrix(A,Qbar_90,z1,z2);
A = Amatrix(A,Qbar_90,z1,z2);

% +45 layers
\( A = \text{Amatrix}(A,Qbar_{45},z1,z2); \)
\( A = \text{Amatrix}(A,Qbar_{45},z1,z2); \)
\( \% -45 \text{ layers} \)
\( A = \text{Amatrix}(A,Qbar_{neg45},z1,z2); \)
\( A = \text{Amatrix}(A,Qbar_{neg45},z1,z2); \)

\( \% \text{Engineering Constants} \)
\( Ebarx = Ebarx(A,H); \)
\( Ebary = Ebary(A,H); \)
\( NUbaryx = NUbaryx(A,H); \)
\( NUbarxy = NUbarxy(A,H); \)
\( Gbarxy = Gbarxy(A,H); \)

\( \% \text{Geometry Parameters} \)
\( r_0 = 73.025e-03; \) \( \% \text{m Inner Radius} \)
\( t = H; \) \( \% \text{m thickness} \)
\( L = 131.83e-03; \) \( \% \text{m Length} \)

\( \% \text{Critical Buckling Moment due to Bending of Composite Tubes:} \)
\( M_{\text{crit}} = \frac{2\sqrt{2}}{9\pi r_0 t^2} \sqrt{Ebarx*Ebary/(1-NUbaryx*NUbarxy)}; \)

\( \% \text{Critical Buckling Stress due to Axial Compression} \)
\( \sigma_{\text{cr}} = \pi^2/2*(r_0/L)^2*Ebarx*(1+(2/3*(\pi*r_0/L)^2*(Ebarx/Gbarxy)))^{(-1)}; \)

\( \% \text{Empirical Knockdown Factor} \)
\( KDF = 1-(0.901*(1-\exp(-1/16*\sqrt{r_0/t}))); \)

\( \% \text{Effective maximum critical axial compressive load} \)
\( P_{\text{cr}} = \sigma_{\text{cr}}*KDF*\pi*/((r_0+t)^2-(r_0)^2); \)

\textbf{function} \( y = E1(Vf,E1f,Em) \)
\textbf{function} \( y = E2(Vf,E2f,Em,\eta,NU12f,NU21f,NUm,E1f,p) \)
%% p = 1 - use equation (3.4)
%% p = 2 - use equation (3.9)
%% p = 3 - use equation (3.10)
%% Use the value zero for any argument not needed
%% in the calculations.
Vm = 1 - Vf;
if p == 1
  y = 1/(Vf/E2f + Vm/Em);
elseif p == 2
  y = 1/((Vf/E2f + Eta*Vm/Em)/(Vf + Eta*Vm));
elseif p == 3
deno = E1f*Vf + Em*Vm;
etaf = (E1f*Vf + ((1-NU12f*NU21f)*Em + NUm*NU21f*E1f)*Vm)/deno;
etam = (((1-NUm*NUm)*E1f - (1-NUm*NU12f)*Em)*Vf + Em*Vm)/deno;
y = 1/(etaf*Vf/E2f + etam*Vm/Em);
end

function y = G12(Vf,G12f,Gm,EtaPrime,p)
%G12 This function returns the shear modulus G12
% Its input are five values:
% Vf - fibre volume fraction
% G12f - shear modulus G12 of the fibre
% Gm - shear modulus of the matrix
% EtaPrime - shear stress-partitioning factor
% p - parameter used to determine which equation to use:
% p = 1 - use equation (3.5)
% p = 2 - use equation (3.13)
% p = 3 - use equation (3.14)
%% Use the value zero for any argument not needed
%% in the calculations.
Vm = 1 - Vf;
if p == 1
  y = 1/(Vf/G12f + Vm/Gm);
elseif p == 2
  y = 1/((Vf/G12f + EtaPrime*Vm/Gm)/(Vf + EtaPrime*Vm));
elseif p == 3
  y = Gm*((Gm + G12f) - Vf*(Gm - G12f))/((Gm + G12f) + Vf*(Gm - G12f));
end

function y = NU12(Vf,NU12f,NUm)
%NU12 This function returns Poisson's ratio NU12
% Its input are three values:
% Vf - fibre volume fraction
% NU12f - Poisson's ratio NU12 of the fibre
% NUm - Poisson's ratio of the matrix
% This function uses the simple rule-of-mixtures
% formula of equation (3.3)
Vm = 1 - Vf;
y = Vf*NU12f + Vm*NUm;

function y = NUxy(E1,E2,NU12,G12,theta)
%NUxy This function returns Poisson's ratio
% NUxy in the global
% coordinate system. It has five arguments:
function y = NUyx(E1,E2,NU12,G12,theta)
%NUyx This function returns Poisson's ratio
% NUyx in the global
% coordinate system. It has five arguments:
% E1 - longitudinal elastic modulus
% E2 - transverse elastic modulus
% NU12 - Poisson's ratio
% G12 - shear modulus
% theta - fibre orientation angle
% The angle "theta" must be given in degrees.
% NUyx is returned as a scalar
m = cos(theta*pi/180);
 n = sin(theta*pi/180);
denom = m^4 + (E1/G12 - 2*NU12)*n*n*m*m + (E1/E2)*n*n;
numer = NU12*(n^4 + m^4) - (1 + E1/E2 - E1/G12)*n*n*m*m;
y = numer/denom;

function y = ReducedStiffness(E1,E2,NU12,G12)
%ReducedStiffness This function returns the reduced stiffness
% matrix for fibre-reinforced materials.
% There are four arguments representing four
% material constants. The size of the reduced
% stiffness matrix is 3 x 3.

NU21 = NU12*E2/E1;
y = [E1/(1-NU12*NU21) NU12*E2/(1-NU12*NU21) 0 ; NU12*E2/(1-NU12*NU21) E2/(1-NU12*NU21) 0 ; 0 0 G12];

function y = Qbar(Q,theta)
%Qbar This function returns the transformed reduced
% stiffness matrix "Qbar" given the reduced
% stiffness matrix Q and the orientation
% angle "theta".
% There are two arguments representing Q and "theta"
% The size of the matrix is 3 x 3.
% The angle "theta" must be given in degrees.

m = cos(theta*pi/180);
n = sin(theta*pi/180);
T = [m*m n*n n*m m*m m*m m*m n*n n*n -2*m*n ; n*n n*n m*m m*m m*m m*m m*m -2*m*n ;
     -m*n m*n m*m m*m m*m m*m m*m m*m -2*m*n];
Tinv = [m*m n*n -2*m*n ; n*n m*m 2*m*n ; m*n -m*n m*m m*m m*m m*m -2*m*n ;
        -m*n m*n m*m m*m m*m m*m m*m -2*m*n];
y = Tinv*Q*T;

function y = Amatrix(A,Qbar,z1,z2)
This function returns the $[A]$ matrix after the layer $k$ with stiffness $[Qbar]$ is assembled.

$[Qbar]$ - $[Qbar]$ matrix for layer $k$

$z1$ - $z(k-1)$ for layer $k$

$z2$ - $z(k)$ for layer $k$

for $i = 1 : 3$
    for $j = 1 : 3$
        $A(i,j) = A(i,j) + Qbar(i,j)*(z2-z1)$;
    end
end

$y = A$;

function $y = Ebarx(A,H)$
% This function returns the average laminate modulus in the x-direction. Its input are two arguments:
% $A$ - 3 x 3 stiffness matrix for balanced symmetric laminates.
% $H$ - thickness of laminate
a = inv(A);
y = 1/(H*a(1,1));

function $y = Ebary(A,H)$
% This function returns the average laminate modulus in the y-direction. Its input are two arguments:
% $A$ - 3 x 3 stiffness matrix for balanced symmetric laminates.
% $H$ - thickness of laminate
a = inv(A);
y = 1/(H*a(2,2));

function $y = Gbarxy(A,H)$
% This function returns the average laminate shear modulus. Its input are two arguments:
% $A$ - 3 x 3 stiffness matrix for balanced symmetric laminates.
% $H$ - thickness of laminate
a = inv(A);
y = 1/(H*a(3,3));
APPENDIX E-C

Table 11 - Parameters for rocket at maximum loading condition

<table>
<thead>
<tr>
<th>Altitude, ft AGL</th>
<th>Launch Altitude, ft</th>
<th>Launcher Length, ft</th>
<th>Mach Number</th>
<th>Flight Speed, fps</th>
<th>Dynamic pressure, lb/ft²</th>
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<tr>
<td>1050</td>
<td>5500</td>
<td>17</td>
<td>1.04</td>
<td>1200</td>
<td>1397</td>
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</table>

Aerodynamic reference area, ft²

<table>
<thead>
<tr>
<th>Max Body Diameter, in</th>
<th>Axial Acceleration, ft/sec⁴</th>
<th>Thrust, lb</th>
<th>C.G. Lateral Offset, ft</th>
<th>Thrust misalignment angle, rad.</th>
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</thead>
<tbody>
<tr>
<td>0.1875</td>
<td>706</td>
<td>1548</td>
<td>0.003</td>
<td>0.015</td>
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</table>

Body Station: location along longitudinal direction of the rocket starting from the nose tip.

Table 12 - Rocket Elements Input Data

<table>
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<tr>
<th>Element Counter</th>
<th>Element Contents</th>
<th>xi, Element, inches from nose</th>
<th>Ri, Element body external radius at body station xi, in</th>
<th>wi, Element weight (finless), lb</th>
<th>Element CNαi (finless), per radian</th>
<th>Element Xcpi, from element front, in</th>
<th>Element CNαi, per radian</th>
<th>Element Xcpi, from nose tip, in</th>
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<tr>
<td>1</td>
<td>Nose Cone</td>
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<td>2.39</td>
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<td>2</td>
<td>13.957</td>
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<td>13.957</td>
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<td>2</td>
<td>NC + Forward</td>
<td>42</td>
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<td>18.764</td>
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<td>3</td>
<td>Body Tube</td>
<td>57</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>4</td>
<td>Aft Fuselage</td>
<td>90</td>
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<td>0</td>
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<tr>
<td>5</td>
<td>Fins</td>
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<td>19</td>
<td>0</td>
<td>0</td>
<td>9.07</td>
<td>112</td>
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<tr>
<td>6</td>
<td>Boattail</td>
<td>121</td>
<td>6</td>
<td>2</td>
<td>-1.1</td>
<td>0</td>
<td>-1.1</td>
<td>114</td>
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System of equations used to calculate the bending loads from Reference [10]:

Summing the forces acting on the element in the +z direction gives

$$S_{i+1} - S_i - qS_{ref} C_{Nai} \alpha = m_i \left( A_z - \left( X - x_{cg} \right) \frac{d^2 \alpha}{dt^2} \right), \text{ where}$$

$$X = \text{The total rigid body center of mass given by}$$

$$X = \frac{\sum m_i x_{cg} }{\sum m_i}, \text{ and}$$

$$A_z = \text{The normal acceleration given by}$$

$$A_z = -\frac{ qS_{ref} \alpha \sum C_{Nai} }{\sum m_i} \text{ (3)}$$

Similarly, summing the y axis torques (right hand rule) about the element center of mass gives

$$M_i - M_{i+1} + \left( x_{cg} - x_i \right) S_i + \left( l_i + x_i - x_{cg} \right) S_{i+1} + qS_{ref} C_{Nai} \alpha \left( x_{cg} - x_{cg} \right) = J_i \frac{d^2 \alpha}{dt^2} \text{ (4)}$$

The nose tip initial conditions are that

$$S_1 = M_1 = 0 \text{ (5)}$$
A marching solution of these difference equations is straightforward. Starting with the known value of $S_1$, eq. (1) can be used to find $S_2$. Then, given $M_1, S_1$ and $S_2$, eq. (4) can be used to find $M_2$. This marching process can be used for the second element, and so on.

Finally, it must be emphasized that the air load acting on a body element is composed of contributions from both the body itself and any attached fins. For a discussion of the latter, see Appendix F.

Rigid Body Motion

Equations (1) and (4) have terms in $A_z, \alpha$ and $\frac{d^2\alpha}{dt^2}$. The rigid body moment equation relates the latter two. First, the total moment of inertia can be found from the parallel axis theorem:

$$I_{yy} = \sum J_i + m_i (X - x_{cg})^2.$$  \hspace{0.5cm} (2b)

Then,

$$I_{yy} \frac{d^2\alpha}{dt^2} = qS_{ref} \alpha \sum C_{Na}(X - x_{cp}),$$  \hspace{0.5cm} (6)

As noted in the Introduction, $\alpha$ can be one of the major BENDIT inputs, or one can estimate it in BENDIT from first principles as described in Appendix D. Using eq’s (3) and (6) to find $A_z$ and $\frac{d^2\alpha}{dt^2}$ enables the marching solution of eq’$’s. (1) & (4).

Static Aeroelastic Effects

Up until now, the rocket body has been assumed to be perfectly rigid. But, sometimes rockets have slender upper stages or darts much more susceptible to bending than the main vehicle. At angle of attack their nose curls up increasing the normal force loading. And, the increased normal force causes additional deflection, and so on. In theory this cycle of air load and deflection can continue until divergence occurs. In practice this cannot happen because the increased loads cause structural failure first.

Our point of departure is equations (1), (3), (4) and (6). The way to look at this problem is to consider that the $C_{Na}$ for the nose is increased by a factor $F$ to allow for flexibility effects. Equations (3) and (6) show that the rigid body motions, $A_z$ and $\frac{d^2\alpha}{dt^2}$, are slightly affected by the increase in nose normal force. Then, to estimate $F$ model the flexible nose as a uniform beam with a concentrated load at its tip. Reference (10) describes this process in detail.

The slope $\frac{dy}{dx}$ of the bent nose at its tip is

$$\frac{dy}{dx} = (qS_{ref} C_{Na\alpha} (\alpha + \frac{dy}{dx}) + m_N (A_z - (X - x_{CGN}) \frac{d^2\alpha}{dt^2})) I_N^2 / (2EI).$$  \hspace{0.5cm} (7a)

After substituting from eq’s. (3 and 6), this can be solved for $\frac{dy}{dx}$, and then for the total nose tip angle of attack,
\[
\alpha_{\text{TOT}} = \alpha + \frac{dy}{dx} = \alpha + \frac{2EI - qS_{\text{ref}} \left[ \frac{m_N}{m} C_{Na} + \frac{m_N}{I_y} (X - x_{CG}) \sum C_{Na} (X - x_{CP}) \right]}{2EI - qS_{\text{ref}} C_{NaN} l_N^2} \]

(7b)

Note that the dynamic pressure which will make the denominator vanish in eq. (7b) is the divergence dynamic pressure:

\[
q_D = \frac{2EI}{S_{\text{ref}} C_{NaN} l_N^2}
\]

Next, to incorporate this effect in BENDIT7, it is only necessary to increase the nose tip normal force slope to

\[
C_{NaN} \left[ \frac{2EI - qS_{\text{ref}} \left[ \frac{m_N}{m} C_{Na} + \frac{m_N}{I_y} (X - x_{CG}) \sum C_{Na} (X - x_{CP}) \right]}{2EI - qS_{\text{ref}} C_{NaN} l_N^2} \right] = FC_{NaN}.
\]

(7c)

That is, in eq. (7c) the term in brackets is the amplification factor, \( F \), applied to all elements forward of \( x_N \).

When eq. (7c) is substituted into eq's. (3) and (6) the result is we still have two linear equations with two unknowns giving solutions for \( A \) and \( \frac{d^2\alpha}{dt^2} \), both proportional to \( \alpha \).

Finally, note that the bending stiffness is the product of the material Young’s modulus, \( E \), and the cross section moment of inertia, \( I \). For a beam of circular cross section,

\[
I = \frac{\pi}{4} (R_o^4 - R_i^4),
\]

where \( R_o \) and \( R_i \) are the outer and inner radii respectively.
APPENDIX F: ENGINEERING DRAWINGS
NOTES
INTERPRET DWG AS PER ANSI Y14.51.
COUPLE SUCH THAT PAINT PATTERN IS ALIGNED.

ITEM NO. PART NUMBER DESCRIPTION NOTES QTY.
1 SR18-FW FORWARD 1
2 SR18-AM AFT 1
3 SR18-FW-RE-03-010 SHEAR PIN MCMASTER P/N 97263A709 6

D
C
B
A

E
F

SUPERSONICE

TITLE
DESIGNER
MATERIAL
DATE
REV NO.
SHEET
SCALE
TOLERANCES
FINISH
USED ON
SURFACE
ROUGHNESS
UNLESS OTHERWISE SPECIFIED
ALL DIMENSIONS IN INCHES
UNLESS OTHERWISE SPECIFIED
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NOTE

1. INTERPRET DWG AS PER ANSI Y14.5.
2. MOUNT FRAME TO FUSELAGE SUCH THAT CAMERA & RBF HOLES ALIGN.

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INTERNAL VIEW
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DRAFT NO. 1 / 1

O.KHALIMONOV
SR18-FW-FR-00 00 M.HOANG-CAO O.D'ANGELO

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SECTION A-A
SCALE 1:1

2x.05" 45°

1/4 - 28 UNC 1.5"

REFER TO CAD FOR CURVE

MATERIAL: Aluminum 60601 T6 Ø 2.5"x6"
FINISH: Clean

SURFACE ROUGHNESS: 32

DIMENSIONS UNLESS OTHERWISE SPECIFIED

TOLERANCES:
- X ± .1
- XX ± .05
- XXX ± .005
- ANGLE ± .5°

ANGLE ± .5°

EXTRACTION

Refer to CAD for curve

O.Khalimonov

PROPRIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY

DATE: 25-May-2018
USED ON: SC - Rocketry

DWG NO.: 00025
REV NO.: 00

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Baffles 1 and 2 are in separate tanks.

<table>
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NOTES:
1 DO NOT MEASURE DRAWING
2 UOS DIMENSIONS ARE IN INCHES
3 INTERPRET AS PER ASME Y14.5M-1994
4 UOS BREAK EDGES .003-.015
5 UOS CORNERS MUST HAVE FILLETS R.005-.020

SCALE 1:1

DETAIL B
SCALE 1:1

SECTION A-A

OMIT FOR PROTOTYPE BUILD

SOLIDWORKS Educational Product. For Instructional Use Only.
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### Dimensions

- ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED
- TOLERANCES:
  - DSIZE:
    - ± .1
    - ± .05
    - ± .005
    - ± .002
  - ANGLE ± .5

### Design Information

- TITLE: SR18-FW-AV-11-Avionics_Assembly
- DESIGNER: [NAME]
- MATERIAL: ANSI 4130
- DATE: 5/28/2018
- REV NO.: 1
- SHEET: 1 / 1
- DRAFTER: [NAME]
- APPROVED SCALE: 1:1
- TOLERANCES:
  - ± .1
  - ± .05
  - ± .005
  - ± .002
  - ANGLE ± .5

### Notes

- SEE NOTE 3
- PROPIETARY INFORMATION NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY
- UNLESS OTHERWISE SPECIFIED
SR18-FW-RE-01
RECOVERY BULKHEAD
ISOMETRIC VIEW
LOOKING INBD FWD

NOTES
GENERAL
1. DWG TO BE INTERPRETED AS PER ANSI Y14.5
2. WIRING NOT FULLY SHOWN FOR SIMPLICITY

ASSEMBLY
3. SEAL W/ TEFLO TAPE OR ADHESIVES A/R
4. SECURE WIRING A/R
5. EJECTOR ASSY MAY BE INSTALLED IN VARIOUS CONFIGURATIONS
6. ENSURE ROTATION AREA CLEAR FROM OBSTRUCTIONS

IDENTIFICATION
7. CLEARLY MARKUP TERMINAL ZONES ON BULKHEAD AND WIRES:
   - EJECTOR, MAIN - "EJ1"
   - EJECTOR, SECONDARY - "EJ2"
   - TENDER DESCENDER, MAIN - "TD1"
   - TENDER DESCENDER, SECONDARY - "TD2"

ITEM NO. | PART NUMBER | DESCRIPTION | NOTES | QTY.
---------|-------------|-------------|-------|-----
1 | SR18-FW-RE-01-001 | BULKHEAD | | 1 |
2 | SR18-FW-RE-01-002 | HOIST SWIVEL | MCMASTER P/N 2994T64 | 1 |
3 | SR18-FW-RE-01-003 | WASHER | MCMASTER P/N 93744A160 | 1 |
4 | SR18-FW-RE-01-004 | HOIST NUT | MCMASTER P/N 95462A031 | 1 |
5 | SR18-FW-RE-01-006 | BULKHEAD SCREW | MCMASTER P/N 92949A199 | 8 |
6 | SR18-FW-RE-01-007 | BULKHEAD NUT | MCMASTER P/N 90480A009 | 8 |
7 | SR18-FW-RE-01-010 | TERMINAL | MCMASTER P/N 7527K44 | 2 |
8 | SR18-FW-RE-01-011 | SCREW | MCMASTER P/N 91292A029 | 14 |
9 | SR18-FW-RE-01-012 | LOCKNUT | DIN 985-3-C | 14 |
10 | SR18-FW-RE-02 | EJECTOR ASSY | | 2 |
11 | SR18-FW-FR-01-01 | L-BRACKET | | 4 |
**NOTES**

**GENERAL**
1. DWG TO BE INTERPRETED AS PER ANSI Y14.5

**ASSEMBLY**
- Seal w/ Teflon tape A/R
- Check for continuity, and ensure resistance ~1.4Ω prior to installation
- Trim wires to 7in. and solder on terminal lugs
- Use caution and wear protective eyewear when handling explosives

<table>
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<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
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<th>NOTES</th>
<th>QTY.</th>
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<tr>
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<td>Spring</td>
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<td>Terminal Lug</td>
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**SECTION F-F**
## GENERAL
1. Interpret DWG as per ANSI Y14.5

## MODIFICATION
2. Zig-zag stitches, spacing 5
3. Simple single stitches, spacing 5

## ASSEMBLY
4. Check for continuity, and ensure resistance ~1.4Ω prior to installation
5. Trim wires to 9in, and solder on terminal lugs
6. Use caution and wear protective eyewear when handling explosives
7. Z-fold along lines
8. Untangle suspension lines
9. Seal with Teflon tape and adhesives
10. Lock in place w/ Prusik knot

### NOTES

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**Material:** REFER TO B.O.M.

**Finish:**

**Design:** M.HOANG-CAO

**Draft:** M.HOANG-CAO

**Approved:** O.KHALIMONOV

**Scale:** NTS

**Title:** PARACHUTE ASSY

**Dimensions:**

**Tolerances:**

**Surface finish:**

**Remarks:**

**Drawn by:**

**Not to scale:**

**Used on:** SR18

**Design date:** 05/18/2018

**Sheet:** 1 of 6

**Drawing number:** SR18-FW-RE-03-REV NO. 00
SR18-FW-RE-03
PARACHUTE ASSY
PACKED VIEW

TO FWD HOIST RING

TO AFT HOIST RING

18

4.5

SR18-FW-RE-03
### Assembly Notes

- Bond with Loctite H600 A/R.
- 3 layers 3K-70P plain weave Carbon fiber & AeroPly PR2032 + PH3665.

#### Surface Finish (All Exterior US)

- Sand surface until smooth.
- Primer: 4 layers Rust-Oleum 2X Ultra Cover White Primer.
- Paint: 4 layers Rust-Oleum.
- Do not paint surface.

### Parts List

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<th>Item No.</th>
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**Title**

- Designer: O. Khalimonov
- Draft: O. D'Angelo

**Materials**

- Fuselage: APC-2 PEEK Carbon fiber tube, thickness: 0.060
- Motor: Carbon fiber & AeroPly PR2032 + PH3665

**Surface Finish**

- Sand surface until smooth.
- Primer: 4 layers Rust-Oleum 2X Ultra Cover White Primer.
- Paint: 4 layers Rust-Oleum.
- Do not paint surface.
DETAIL A
SCALE 1 : 1

NOTES:
1- UOS. ALL DIA. + \( \phi 0.010 \) A
2- MATERIAL AL 6061-T6

MATERIAL 6061 T6 - \( \phi \) 2-1/8" x 14-1/4"

TO FIT WITH NOSECONE PART 1 -0.002

SURFACE ROUGHNESS 63
TOLERANCES X ± 0.01, XX ± 0.005, XXX ± 0.0003, ANGLE ± 5°

CONCORDIA UNIVERSITY

NOTE 5 4 3 2 1

REV NO. 00

DATE 04-Oct-2017

USED ON ROCKET17

SOLIDWORKS Educational Product. For Instructional Use Only.
NOTES:
1- UOS. ALL DIA. \( \Phi .010 \) A

DETAIL B
SCALE 1 : 1

FIT WITH FORWARD PART 2
-.003"

SECTION A-A
SCALE 1 : 4

FIT WITH NOSECONNE PART 2
+0.003"

DETAIL E
SCALE 1 : 1.5

FIT WITH FORWARD PART 2
-.003"

FIT WITH NOSECONNE PART 2
+0.003"

SOLIDWORKS Educational Product. For Instructional Use Only.
Coupler Mandrel

MATERIAL: Aluminum 60601 T6 6"ODx5"IDx48"

FINISH: Clean

SURFACE ROUGHNESS: \( \sqrt{3} \)

TOLERANCES: 
- X ± .1
- X ± .05
- X ± .005
- X ± .002
- ANGLE ± .5°

ANGLE: ± 0°

SCALE: 1:10

DATE: 21-Mar-2018

USED ON: SC - Rocketry

CONCORDIA UNIVERSITY

PROPRIETARY INFORMATION

NOT TO BE RELEASED WITHOUT WRITTEN AUTHORIZATION FROM CONCORDIA UNIVERSITY

APPROVED: O.Khalimonov

DRAFTER: O.Khalimonov

DESIGNER: O.Khalimonov

DWG NO.: 00018

REV NO.: 00

SOLIDWORKS Educational Product. For Instructional Use Only.
Motor Tube Mandrel

Material: 6061 T6 - Ø4" x .5" x 60"

Finish: Clean

Surface Roughness: 63

Tolerances:
- X ± .1
- XX ± .05
- XXX ± .005
- ANGLE ± .5

All dimensions in inches unless otherwise specified.

Design: O. Khalimonov

Draft: O. Khalimonov

Approved: O. Khalimonov

Scale: 1:5

Date: 26-Nov-2017

Used on SC-Rocketry

DWG NO. 0008

REV NO. 00
MATERIAL: Mild Steel
FINISH: Clean

TITLE: Supersonic Profile

DESIGNER: O. Khalimonov
DRAFTER: O. Khalimonov
APPROVED: O. Khalimonov

SCALE: 1:2

DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

SURFACE ROUGHNESS: R.035

TOLERANCES:
- ±.1
- ±.05
- ±.005
- ±.002
- ±.001

ANGLE: ±.5

DATE: 25-May-2018

DWG NO.: 00018

REV NO.: 00

SOLIDWORKS Educational Product. For Instructional Use Only.
SECTION A-A
SCALE 3 : 1

MATERIAL Steel - \( \phi 0.5" \times 1.25" \)
FINISH Clean

SURFACE ROUGHNESS

TOLERANCES
X ± .1
XX ± .05
XXX ± .005
ANGLE ± 3°

DESIGNER O.Khalimonov
DRAFTER O.Khalimonov
APPROVED O.Khalimonov

DATE 14/11/2017
USED ON SC-Rocketry

SIZE 1 / 1
DWG NO. 0001
REV NO. 00

SOLIDWORKS Educational Product. For Instructional Use Only.
SECTION A-A
SCALE 3 : 1

MATERIAL Steel - \( \phi \) .5" x 1.25"
FINISH Clean

SURFACE ROUGHNESS
TOLERANCES
X ± .1
X ± .05
XX ± .005
XXX ± .002
ANGLE ± .3

DESIGNER O.Khalimonov
DRAFTER O.Khalimonov
APPROVED O.Khalimonov

SCALE 3:1

DATE 14/11/2017
USED ON SC-Rocketry

DWG NO. 0001
REV NO. 00

SOLIDWORKS Educational Product. For Instructional Use Only.