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NASA Microgravity: Internal Structure and Recovery Method Optimization

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NASA Microgravity: Internal Structures and Recovery Method Optimization

May 3, 2018
Submitted to the Honors Program

Brenna Doherty
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University of Wyoming
Honors Thesis
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Executive Summary

Microgravity is defined as a state of having very little gravity, such as that experienced in space. NASA has performed research for over 25 years as a way to determine how a microgravity environment impacts space technologies. To simulate microgravity, an aerodynamic package, containing the space technology being researched, is dropped in a vacuum chamber or from high altitudes until a state of freefall is reached. Microgravity is simulated during freefall. NASA drop towers are the standard microgravity testing platforms used today. These towers can produce microgravity environments of $1 \times 10^{-3}\text{G}$ to $1 \times 10^{-5}\text{G}$ for 2.2-5.2 seconds; however, these platforms are expensive and require months of advanced planning. The University of Wyoming (UW) microgravity project aims to develop a low cost and timeline sensitive alternative, while also producing microgravity environments that are equal to or better than that of drop towers. For this project, microgravity is achieved by dropping an aerodynamic package from a weather balloon from an altitude of 75,000 feet. If successful, 15-20 seconds of microgravity can be achieved. The first UW microgravity drop occurred in August 2017. Shock force data from the drop revealed that the internal frame, baseplate, and parachute attachment were significantly overdesigned. These components were designed to withstand a 947 lbf shock force, while drop data revealed a shock force of only 18 lbf. Incorrect stress analysis of the recovery method contributed to this overdesign. The overdesigned components add unnecessary mass to the payload. The drop also revealed poor integration between the payload’s electronic systems and internal frame. The main objective of this senior design project was to optimize the recovery method to reduce shock force, decrease the mass of the internal structure, and provide enhanced integration between electronic systems and the internal frame. Using computer modeling and finite element analysis, the opening shock force was optimized to 77.9 lbf and the internal structure mass was reduced by 0.5 lbm. Modification of the internal frame design also provided enhanced integration between electronic and structural components. These improvements to the payload design will be verified using ground-based drop simulations and will be tested in a planned summer 2018 drop.

Background

Microgravity is defined as a state of having very little gravity, such as that experienced in space. NASA has studied and conducted tests to create microgravity environments; however, these tests are expensive and can be time consuming. To simulate microgravity, an aerodynamic payload, containing the space technology being researched, is dropped in a vacuum chamber or from high altitudes. Microgravity is simulated during freefall. NASA drop towers and Vomit Comets are examples of microgravity testing platforms; however, the Vomit Comet is no longer in commission today. A drop tower creates a microgravity environment by dropping the testing package (in our case a CubeSat) in a vacuum tube that simulates microgravity. The NASA Glenn Research Center Drop Tower is one of the most successful drop towers on the market today because it can produce microgravity for up to 5.2 seconds and reaches $10^{-5}\text{G}$. However, the cost for one experiment can be over $100,000 and it takes up to 6 months of advanced scheduling to use the drop tower.

The University of Wyoming microgravity project aims to create a quality, inexpensive, and timeline sensitive alternative microgravity platform that will simulate microgravity for times
equivalent too or better than the current marketed drop facility capabilities. Previous work conducted by University of Wyoming senior design teams yielded a working microgravity package. The working package utilizes a large helium balloon to lift the microgravity package to an altitude of 75,000 feet. Once the package reaches the desired altitude, the monocoque disconnects from the weather balloon and enters into a state of free fall. During free fall, the monocoque experiences a microgravity environment and data is collected. However, data from a previous drop revealed that the current package was designed to withstand forces much greater than those experienced during testing. The overdesigned components add unnecessary weight and volume to the package, which increases testing costs. Specifically, the internal frame, baseplate, and recovery method are overdesigned and add excess weight to the microgravity package.

**Design Objectives**

The design objective for this senior design project is to modify the current internal frame, baseplate, and recovery method designs to optimize weight, improve electronic integration, and correct the method of calculating the opening shock force on the microgravity package. Proposed design alternatives include the following:

1. Select a new recovery method that reduces weight and packing volume.
2. Correct shock force analysis method.
3. Modify the internal frame geometry to minimize mass and improve accessibility to the electronic stack.
4. Design components for symmetry about the major axes.
5. Modify the baseplate design to trim mass.
6. Use mass optimization of the internal frame, baseplate, and recovery method to move the package's center of mass to the front of the package.

**Customer Requirements**

The main stakeholder for this senior design project is the National Aeronautics and Space Administration (NASA). They are funding the UW microgravity project through a $199,577 Wyoming NASA Space Grant and this senior design project was allotted $1,500 of this budget. Referencing the Wyoming NASA Space Grant criterion, the following are customer requirements that must be met through this senior design project:

1. Develop a microgravity package with an internal structure that holds 2 customer CubeSats.
2. Develop a recovery method that will return the microgravity package safely to earth with minimal damage.

**Functional Design Descriptions**

**Overall Package Design**

For the remainder of this document, the “front” of the package will be referred to as the end which faces the ground and the “back” of the package will be referred to as the end of which faces the sky. The following figures (*Figures 1* and 2) illustrate the microgravity package.
During the ascent, the back of the monocoque is attached to a helium-filled weather balloon and houses the internal frame, recovery method, baseplate, and the electronics. The removable nose cone also attaches to the front of the monocoque, taking the impact from the ground. The overall package design is demonstrated in Figure 3 below.

As the figures above show, the nose cone screws in to the front of the baseplate, which is adhered to the inside of the monocoque. The internal frame houses the electronic stack and the front of it screws in to the back of the baseplate. The parachute then attaches to the back of the internal frame. To deploy the parachute, the monocoque splits in half as shown.

**Recovery Method**

The recovery method is used to slow the microgravity package down prior to impact. The chosen method must successfully deploy, after 15-20 seconds of free fall, while enduring environmental conditions at an altitude of 75,000 feet. When selecting the new recovery method, the following considerations were taken into account:
1. Choose a new recovery method that has an impact velocity between 15-20 ft/s.
2. Select a recovery method that reduces the packing volume and weight from the previous recovery method.
3. Complete a shock force analysis to confirm reduction of opening parachute shock force experienced by the microgravity package.

**Internal Frame**

The internal frame contains both the customer CubeSat as well as the electronic stack used to control the microgravity package. The frame attaches to the parachute and, therefore, the design must be able to withstand the opening shock force from the parachute to ensure the protection of the customer’s product. This project intends to:

1. Remove excess mass from the internal frame while retaining the structural integrity
2. Redesign the internal frame to improve accessibility to the electronic stack
3. Design component for symmetry about the major axes.
4. Resign parachute attachment method to decrease mass and improve GPS signals

**Baseplate**

The baseplate holds the internal components in place and attaches to the wall of the monocoque to ensure package stabilization. The design must be able to withstand shock forces while maintaining the package’s center of mass during flight. This project looks to:

1. Trim unnecessary mass from the baseplate while retaining the structural integrity
2. Use mass optimization and modified baseplate design to move the package’s center of mass to the front of the package.

**Engineering Specifications**

The parachute chosen for the previous design was the IFC-72 and had a diameter of 72 in, causing it to have a velocity just before impact of 9.15 ft/s. This slow descent caused the package to drift far from the launch sight and making it difficult to track down after landing. The nose cone is capable of withstanding impact velocities up to 20 ft/s, so the desired impact velocity for the package is between 15-20 ft/s. A new parachute was chosen using a trade study with the following weight factors presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Trade Study Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factor</strong></td>
</tr>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>Shock Factor</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Packing Volume</td>
</tr>
<tr>
<td>Impact Velocity</td>
</tr>
<tr>
<td>Aesthetics</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>
The trade study analyzed six different parachutes and the SP-72 had the highest trade study score, according to Figure 4 below.

![Figure 4. Trade Study Results](image)

The parachute selected for the current design is the SP-72 and has a diameter of 45.8 in resulting in an impact velocity of approximately 17.25 ft/s. The SP-72 has a minimum packing volume of 49.5 in$^3$, which is a 33.5% reduction from the IFC-72. This decreases the chance of snagging upon deployment. The SP-72 also has a weight of 6.7oz, which decreases the weight by 50% from the IFC-72. A side-by-side comparison of the old IFC-72 and new SP-72 is shown in Table 2 below.

<table>
<thead>
<tr>
<th>Parachute Comparison Factors</th>
<th>IFC-72</th>
<th>SP-72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock Force</td>
<td>331 lbf</td>
<td>77.9 lbf</td>
</tr>
<tr>
<td>Impact Velocity</td>
<td>9.15 ft/s</td>
<td>17.25 ft/s</td>
</tr>
<tr>
<td>Weight</td>
<td>13.4 oz</td>
<td>6.7 oz</td>
</tr>
<tr>
<td>Packing Volume</td>
<td>74.4 in$^3$</td>
<td>49.5 in$^3$</td>
</tr>
<tr>
<td>Cost</td>
<td>$210.00</td>
<td>$82.50</td>
</tr>
</tbody>
</table>

The previous design utilized an incorrect model to determine the shock force upon parachute deployment. This model estimated the shock to be 947 lbf on the IFC-72, when test data from the previous drop produced a shock force of only 18 lbf, indicating serious flaws in the original model. The flaw was that the model neglected to utilize a parachute opening shock factor. The opening shock factor reduces the shock force by removing flaws in theoretical models by considering experimental data from the summer 2017 drop. Equations 1 and 2 show the corrected model for calculating opening shock force.
\[
F = \left( \frac{F_{exp \ 10,000 \ ft}}{F_{theor \ 10,000 \ ft}} \right) \times F_{theor \ 75,000 \ ft} \tag{1}
\]

\[
Opening Shock Factor = \left( \frac{F_{exp \ 10,000 \ ft}}{F_{theor \ 10,000 \ ft}} \right) \tag{2}
\]

A corrected model implements an opening shock factor of 0.35, which more accurately estimates the shock force for the IFC-72 to be 331 lbf and for the SP-72 to be 77.9 lbf.

The maximum stress that the package is subjected too is due to the shock force during parachute deployment. Therefore, the shock force is the leading design factor when considering the structural integrity of the package. The internal frame body and lid were reworked to minimize mass while maintaining structural integrity. A Finite Element Analysis (FEA) on the internal frame is discussed in the next section. The mass of the previous internal frame body and lid were 1.13 lbm and the current body and lid have a mass of 0.69 lbm. The material of the body and the lid are both 1/16” thick Aluminum 5052-H36.

Several changes were made to the redesigned internal frame. All of the following changes discussed can be seen in a side-by-side comparison of the previous design to the current design of the internal frame found in Figures 5 and 6. The frame is composed of two pieces of Aluminum 5052-H36 sheet metal, that are cut using water-jet machining and then are bent into shape. In the previous design, the two pieces were attached using aerospace fasteners. In the current design, the two pieces are connected using spot welds along the sides and at the bottom. First, the cross bars on each side of the frame were removed because they were not necessary to the structural integrity of the frame. This improved the accessibility to both the electronic stack and to the customer CubeSat, as well as reduced the mass of the package. Next, the parachute attachment was replaced by a hole centered on each of the four sides of the lid. The holes are offset ¼ in from the side of the lid. The parachute will attach to these four holes with eyebolts. This reduced the mass of the package as well as distributed the shock force between the four eyebolt attachments. In the new design, the GPS receiver will now sit on top of the internal frame lid. A 3D-printed piece was placed on top of the lid to mount the GPS receiver to ensure no interference occurred between the metal frame and the GPS. Also, a hole was placed in the corner of the lid to allow for a 9-pin d-shell connector to run through the lid and connect to the electronic stack. The final change to the internal frame is that the lid is now attached using self-clinching fasteners. This eliminates the tab that extends from the top of the lid, minimizing any chance of the parachute snagging when deployed.
The baseplate was also modified from the previous design to accommodate the corrected shock force. No major changes to the baseplate were made, although, the geometry of it was modified to minimize mass while maintaining structural integrity. Figures 7 and 8 show the front and back views of the previous design, while Figures 9 and 10 show the front and back views of the current design. The baseplate was decreased from a mass of 0.543 lbm to 0.366 lbm. Both were 3D-printed from ABS plastic. Multiple baseplates will be manufactured once in use, so the material was chosen in part due to ease of manufacturing. In addition, there are multiple symmetrically placed indents on the backside of the baseplate. If needed, small masses are placed inside of them to move the center of mass in front of the center of pressure or to balance the package along the major axes.
Finite Element Analysis

After using engineering specifications to modify the original internal structure components, FEA was utilized to ensure that when the opening shock force was applied, the structural integrity of the components would not be compromised. As stated before, the opening shock force for the SP-72 parachute was calculated to be 77.9 lbf. But, to take into consideration any inaccuracies in the FEA, a factor of safety (FOS) of 2 was applied to all models, yielding an increased opening shock force of 179 lbf.

**Internal Frame Lid Model**

The internal frame lid takes a majority of the opening shock force because it is directly attached to the parachute using four holes spaced evenly around the top of the lid. Therefore, FEA of the lid was essential. The FEA loading condition and boundary condition for the internal frame lid are shown in *Figure 11* below. The opening shock force loading condition is applied as a surface traction with a magnitude of 179 lbf at each of the four holes where the parachute is connected. The fixed boundary conditions are applied at the holes on each tab of the lid. These holes are connected to the internal frame body using self-clinching fasteners, and, therefore, act as the fixed boundary conditions for this model.
Figure 11. Loading condition and boundary conditions on the internal frame lid

The mesh for this model is shown in Figure 12 below. Since this component was imported from Solidworks into Abaqus FEA software, the only type of mesh elements available were tetrahedron free elements. These elements are constant strain elements and, therefore, can cause flaws in the FEA model. However, by choosing 10-node quadratic elements and refining the mesh with a 0.05 in seed size, the constant strain issue was minimized.

Figure 12. Mesh for the internal frame lid

The loading conditions, boundary conditions, and mesh were applied to the model using a static, general loading step and the model was run. The stress contour result is shown in Figure 13 below.
The stress contour was presented using a quilted contour. This type of contour ensures that there is no integration between elements such that the element location of maximum stress can easily be identified. Doing this, the maximum stress was found to be 27.4 ksi. Comparing this to the yield strength of 31 ksi for Aluminum 5052-H36, these results yield that the lid is in the elastic deformation zone after the opening shock force is applied. Backing up this result, is the displacement contour shown in Figure 14 below.
The displacement contour was analyzed using a banded contour. This contour results in the most conservative result for deformation modeling. Using this contour, the maximum deformation was found to be 0.009 in. This result confirms that the lid is in the elastic deformation zone after the opening shock force is applied and that no significant deformation is going to occur. Upon performing this FEA, a conclusion has been drawn that the structural integrity of the internal frame lid will not be compromised.

**Internal Frame Welds Model**

Another possible cause of failure, is shear failure of the spot welds that hold the internal frame sides and bottom together. To assess the likelihood of this occurring, the same FEA model as was used for the internal frame lid was applied to the entire internal frame body. Using this model, the following quilted stress contour was produced (*Figure 15*).

![Figure 15. Quilted stress contour for the assessment of potential weld shear failure](image)

Looking to this stress contour, at the location of the welds (the sides and bottom of the frame) there is a maximum stress of only 3 psi. It should also be noted that these stresses are purely tensile. Given this result, it is concluded that shearing of the welds will not occur.
**Baseplate Model**

The major difference between the internal frame FEA and baseplate FEA is how the components could be modeled. The internal frame could be modeled as a single component in space because its boundary conditions were only internal. The baseplate, on the other hand, has both internal and external boundary conditions and, therefore, had to be modeled with its surrounding components. The original baseplate FEA model is shown in *Figure 16* below.

![Figure 16. Original baseplate FEA model](image1)

Limitations of the student version of Abaqus FEA (node limit) required that the baseplate model be simplified in order to refine the baseplate mesh as much as was necessary. Therefore, the following simplified model was used (*Figure 17*).

![Figure 17. Simplified baseplate FEA model](image2)
The same loading condition was applied to the simplified baseplate model as was applied to the internal frame lid and internal frame welds models: a surface traction with magnitude 179 lbf. The fixed boundary conditions were applied to the model around the circumference of the baseplate (where the baseplate is attached to the monocoque with 2-part epoxy) and at the end of the shaft at the location of what would be the nose cone. The loading condition and boundary conditions are illustrated in Figure 18 below.

![Figure 18. Loading condition and boundary conditions](image)

When creating the mesh for the model, it was most important to refine the mesh on the baseplate because this was the area of interest. Therefore, the mesh was composed of 10-node quadratic tetrahedron free elements, with a refined seed size of 0.08 in on the baseplate and a larger seed size of 0.25 in on the shaft. The mesh for this model is shown in Figure 19 below.

![Figure 19. Refined baseplate and shaft mesh](image)
The loading condition, boundary conditions, and mesh were applied to the model using a static, general loading step and the model was run. The stress contour result is shown in Figure 20 below.

**Figure 20.** Quilted stress contour for the FEA baseplate model

Once again using a quilted contour, the maximum stress on the baseplate was found to be 15.5 ksi, shown as the red elements in the figure above. Considering this result, the model appears to fall within the failure region because the ultimate tensile strength for ABS plastic is only 16.5 ksi. However, there are two safety factors built into the model that significantly minimize the chance of baseplate failure: 1) there is a FOS of 2 built into the model and, 2) the baseplate is located near the front of the package, such that the shock force experienced by the baseplate will be significantly less than the 79 lbf shock force experience by the internal frame lid that is directly connected to the parachute. Given the two safety measures, a conclusion has been drawn that the structural integrity of the baseplate will not be compromised.

**Benchmarking**

The biggest competition for the University of Wyoming microgravity project is the NASA drop tower located in the NASA Zero Gravity Research Facility. Advantages of conducting microgravity tests in the Zero Gravity Research Facility are use of video cameras, analog and digital recording capabilities, microgravity duration, and increased payload capabilities compared to the UW microgravity project. However, the Zero-G facility is expensive, costing $100,000 or more per test. Scheduling tests in the Zero-G facility can be an issue as well, taking more than six months to plan and conduct a test. NASA is seeking an inexpensive way to test microgravity environments, and the University of Wyoming microgravity project offers a solution. This project is benchmarked against the NASA drop towers, with results shown in Table 3.
Table 3. UW microgravity benchmarked against NASA Glen Drop Tower

<table>
<thead>
<tr>
<th>Specifications</th>
<th>NASA Glen Drop Tower</th>
<th>UW Microgravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost:</td>
<td>$100,000+</td>
<td>$1,500</td>
</tr>
<tr>
<td>Scheduling Time:</td>
<td>6 Months +</td>
<td>1 Month</td>
</tr>
<tr>
<td>Microgravity Time:</td>
<td>5.2 seconds</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Microgravity Quality:</td>
<td>10 E-6 G's</td>
<td>0.1 G's</td>
</tr>
</tbody>
</table>

New Knowledge Development

Research was conducted on different types of materials during the design the internal frame. Specifically, grade 4 Titanium was found to have qualities that were attractive for this project's specific needs. The internal frame was modeled using grade 4 Titanium, which revealed that the overall mass of the frame would be reduced from our Aluminum 5052-H36 model. The Titanium model was submitted to the machine shop for manufacturing. However, the Titanium snapped during the machining process and exhibited the materials inability to bend. Therefore, Aluminum 5052-H36 was used for design.

Additive manufacturing was utilized to produce the nose cone and baseplate. The complex honeycomb structure produced during 3-D printing caused non-uniformity in the components microstructure. As a result, FEA was not a full proof means of testing the components structural integrity. It was determined that scanning electron microscopy and experimental testing were the only effective ways to test the integrity of the 3D printed components.

Multiple recovery methods were researched for this project to ensure that the microgravity package could be successfully recovered after descent. Specifically, comparisons were made between different models of parachutes and streamers with the purpose of finding the optimum recovery method. Factors used in the comparison included drag, packing volume, shock force, and cost. Calculations revealed that many streamers were needed to produce the same drag as the parachute. This lead to a higher packing volume with streamers, which made the microgravity package heavier. These factors lead to the choosing of a SP-72 parachute as a recovery method.

Product Design Factors

Cost

The amount of money granted for this microgravity project was $1,500. The final parachute selected was the SP-72 Spherachute parachute, costing $89.50; however, two parachutes were purchased, one for use and one for backup, for a total cost of $165. The materials and manufacturing of the three internal frame prototypes cost $709. The material used to construct the internal frame was Aluminum 5052-H36 and the manufacturing process included water-jet
machining, welding, and joining (fasteners). The baseplate and GPS receiver holder within the monocoque were 3D printed from ABS plastic and had a manufacturing cost of $59. As a way of improving electronic integration, a feed through to the electronic stack and a GPS receiver were also purchased. This cost amounted to $5. After purchasing all components for the project, $562 of the original $1500 remained. A cost breakdown is shown in Table 4 below.

<table>
<thead>
<tr>
<th>Table 4. Cost Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
</tr>
<tr>
<td>Labor</td>
</tr>
<tr>
<td>Machining</td>
</tr>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>3D Printing</td>
</tr>
<tr>
<td>Parachute</td>
</tr>
<tr>
<td>Fasteners</td>
</tr>
<tr>
<td>Electronics</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
</tr>
<tr>
<td><strong>Budget Remaining</strong></td>
</tr>
</tbody>
</table>

**Safety**

The recovery method was designed to slow the microgravity package to a velocity of 15-20 ft/s upon impact. The SP-72 parachute will be the recovery method used for the University of Wyoming microgravity product. Designing for this parachute predicts an impact velocity of 17.25 ft/sec. Impact velocities above 20 ft/sec could result in animal or human injury. Testing will be conducted in open areas where risk of injuries and risk of critical damage to the package will be minimal. Finally, there is no flammable equipment involved with the internal frame or the recovery parachute and, therefore, fire safety is not an issue.

**Sustainability**

The IME product is designed to sustain multiple test drops without replacement. Many of the internal and external components are constructed so that they can endure repeated use. The only microgravity package component that requires replacement after every test drop is the nose cone. The 3D printed nose cone deforms upon impact with the ground and is designed to be easily manufactured after each drop.

**Prior Art**

According to the grant, a thorough patent search was conducted regarding technologies to be used in this project and no patents related to NASA endeavors within the last 20 years were uncovered.
Creativity and Innovation

The updated internal frame allows for improved electronic accessibility and significant weight reduction. This design innovates the way in which the customer CubeSat is tested in a microgravity environment.

Group Member Contribution

This project was a group effort. All components were modified, built, and analyzed as a team. Each group member did an equal amount of the work.

Design Objectives Met

The design objectives for this senior design project were to modify the current internal frame, baseplate, and recovery method designs to optimize weight, improve electronic integration, and correct the method of calculating the opening shock force on the microgravity package. All of the design objectives were met over the academic year.

1. The previous parachute, the IFC-72, has a weight of 13.4 oz and a packing volume of 74.4 in³. The newly selected parachute, the SP-72, has a weight of 6.7 oz and a packing volume 49.5 in³. The overall weight reduction for the recovery method is 6.7 oz and the reduction in packing volume is 24.9 in³.
2. The shock force analysis was corrected by implementing an opening shock factor that took into account experimental data from the previous test drop as well as theoretical calculations. The initial shock force calculation omitted the opening shock factor, while the opening shock factor for the corrected analysis was 0.35.
3. The internal frame geometry was modified to improve accessibility to the electronic stack by removing the cross bars from the previous design. The geometry modifications of the internal frame and the baseplate resulted in a total mass reduction of 0.627 lb.
4. The components are symmetrical around the major axes allowing for ease of assembly and stable flight.
5. Due to mass reduction near the back of the package, the package’s center of mass has been moved forward. This allows for more stable flight.

Next Steps

Following the completion of this project, the modified components will be integrated with the other microgravity senior design projects. Upon successful integration of designs, a ground-based test will be conducted. If the ground-based test confirms the structural integrity, then a drop test from 75,000 ft will be conducted in Summer 2018.