University of Colorado - Boulder
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)

# Secondary Payload Adapter Concerned with Eliminating Mass and Optimizing Design (SPACEMOD)

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## Project Customers



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# Contents

# Nomenclature

| | |
|---|---|
| $CAD$ | Computer Aided Design |
| $CMM$ | Coordinate Measuring Machine |
| $CNC$ | Computerized Numerical Control |
| $CU$ | University of Colorado at Boulder |
| $DR$ | Design Requirement |
| $EELV$ | Evolved Expendable Launch Vehicle |
| $ESPA$ | EELV Secondary Payload Adapter |
| $FBD$ | Functional Block Diagram |
| $FEM$ | Finite Element Method |
| $FEA$ | Finite Element Analysis |
| $FOS$ | Factor of Safety |
| $FOV$ | Field of View |
| $FR$ | Functional Requirement |
| $K$ | Scaling Factor |
| $PDD$ | Project Definition Document |
| $P/L$ | Payload |
| $RSS$ | Root Sum Square |
| $SPACEMOD$ | Secondary Payload Adapter Concerned with Eliminating Mass and Optimizing Design |
| $ULA$ | United Launch Alliance |

# 1 Project Description and Objectives

## 1.1 Purpose and Objectives

In recent years there has been a rise in interest in small satellites and ride-sharing launch vehicles to space. As a result, the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring was designed to increase launch capacity by attaching secondary payloads below the primary payload. By utilizing excess launch capacity, the ESPA ring reduces launch costs for the primary mission and enables secondary and tertiary satellites to launch with minimal impact on the primary mission.

The current ESPA ring investigated in this senior project is seen in Figure 1 and allows for six secondary payloads to be launched below a primary payload. The current launch configuration with the ESPA ring below the primary payload can be seen in Figure 2. United Launch Alliance (ULA) presented the senior projects team with one overarching question: How can the design of the ESPA ring be optimized if it was not required to support a primary payload? In response, the Secondary Payload Adapter Concerned with Eliminating Mass and Optimizing Design (SPACEMOD) project will consist of designing, manufacturing, and testing a clean slate scaled design of a mass-optimized secondary payload adapter.

The main objective of this project is to design a six-payload carrier that maintains ESPA port and field of view compatibility. The adapter will be designed to support six 181 kilograms payloads and will be designed to minimize mass. The payload adapter will be designed to support payloads through an 12g Root Sum Square (RSS) and will be capable of withstanding a separation shock environment of at least 1000g. SPACEMOD will demonstrate all design objectives through simulation and tests on a manufactured scale model of the design. The scale model will then undergo static load, shock, and vibrational testing to simulate launch and separation conditions. The secondary objective of this project is to characterize separation shock propagation. This objective will be achieved through simulation and testing.

***Figure 1: ESPA Ring [2]***

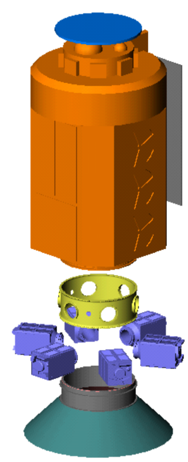

***Figure 2: ESPA Ring (Yellow) with Six Secondary Payloads (Purple) and the Primary Payload (Orange) [2]***

## 1.2 Specific Objectives

To determine the specific objectives for SPACEMOD, requirements given by the United Launch Alliance as well as information collected from publicly available reference documents were utilized. Table 1 defines the success criteria for the 6 critical project elements of SPACEMOD. The expected capability for each objective ranges from Level 1 to Level 3. Level 1 successes are defined as the baseline expectations for the outlined requirements and capabilities of SPACEMOD as given by the United Launch Alliance. Level 2 successes are defined as further development of Level 1 successes. Level 3 successes are defined as the goal or target expectations and capabilities of a specific objective. Level 3 is the maximum expectation that shall not be exceeded. The project will be considered an overall success if Level 1 objectives are achieved for all project elements.

Meeting the success criteria shall be validated and verified via testing such as demonstration, analysis, and/or inspection. Demonstration testing includes verification of the intended performance of the specific objective either partially or completely, depending upon the status of the project overall. Analysis testing includes computation or simulation followed by the analysis of numerical results. Finally, inspection testing will involve the qualitative analysis and validation of specific requirements upon the specific objective. All of the above tests will be demonstrated upon SPACEMOD as a cohesive component following the completion of all specific objectives.

Specific deliverables for SPACEMOD include the scaled, improved, and optimized payload adapter itself as defined in Section 2. It shall consist of a structural frame that will be constructed with 6 separate ring-like connectors on the surface of the structure. The adapter will be compatible with current low-shock satellite separation deployment mechanisms [1] and include the appropriate telemetry sensors necessary for the adapter to function independently.

[1] The three primarily considered ESPA port compatible deployment mechanisms are outlined in the Moog "ESPA User Guide" [2]. These mechanisms are the primarily used deployment methods for secondary payloads on the Atlas V, and are produced by Planetary Systems Corporation (PSC), Sierra Nevada Corporation (SNC), and RUAG Space.

*Table 1: Specific Objectives for SPACEMOD*

| Project Elements | Level 1 (Threshold) | Level 2 (Objective) | Level 3 (Target) |
|---|---|---|---|
| **Structural** | -Supports six P/L, each with a mass of 50% of 400 lbs scaled linearly to match model dimensions | -Supports six P/L, each with a mass of 75% of 400 lbs scaled linearly to match model dimensions | -Supports six P/L, each with a mass of 100% of 400 lbs scaled linearly to match model dimensions |
| **Compatibility** | -Maintain standard ESPA port compatibility | -Maintain standard ESPA port compatibility<br><br>-Maintain standard ESPA Field of View compatibility | |
| **Quasi-Static Loads** | -Perform scaled simulation of 12g RSS quasi-static load test with no simulated plastic strain | -Perform scaled 12g RSS quasi-static load, to test and gather data | -Perform 12g RSS quasi-static load and gather data<br>-Withstand test with no plastic strain |
| **Vibe/Acoustics** | -Perform simulation of launch-like vibrations based on Atlas V User Guide** with no simulated plastic strain | -Perform test and gather data on vibration table that enacts launch-like vibrations as described in Atlas V User Guide** | -Perform test and gather data on vibration table that enacts launch-like vibrations as described in Atlas V User Guide**<br><br>-Withstand test with no plastic strain |

*Table 1: Specific Objectives for SPACEMOD*

| Project Elements | Level 1 (Threshold) | Level 2 (Objective) | Level 3 (Target) |
|---|---|---|---|
| **Separation** | -Characterize shock propagation of separation-like shocks from a singular 1000g low-shock separation mechanism through simulation | -Characterize shock propagation of separation-like shocks from a singular scaled 1000g low-shock separation mechanism through test and data gathering | -Characterize shock propagation of separation-like shocks from a singular 1000g low-shock separation mechanism through test and data gathering<br><br>- Exhibit no plastic strain due to separation-like shocks from a singular scaled 1000g low-shock separation mechanism<br><br>-Maintain attachment to all other attached P/L's due to separation-like shocks from a singular scaled 1000g low-shock separation mechanism<br><br>-Withstand a scaled synchronized separation of 2 or more simultaneous 1000g shocks without any permanent plastic strain, or impart any undesirable destabilization of the secondary payload adapter. |
| **Weight** | -Weight of ESPA is reduced by 15% compared to Standard ESPA | -Weight of ESPA is reduced by 25% compared to Standard ESPA | -Weight of ESPA is reduced by 40% or more compared to Standard ESPA |

** Atlas V User Guide Table 3.2.1-1 provides launch environment load limits. Table 3.2.2-1 provides maximum acoustic levels [4].

## 1.3 Concept of Operations

The Concept of Operations (CONOPS) for the SPACEMOD is to adapt the current secondary payload system to fit the changing market demand for satellites. While a clean slate design to address this change in market demand is necessary, it is important to keep aspects of the old ESPA ring. The SPACEMOD will need to maintain existing compatibility with current separation systems while decreasing the mass of the adapter when compared to the old ESPA ring. During integration and launch, the new design will need to support six 181 kg payloads and be able to withstand a 12 g root sum square (RSS) load and launch-like vibrations. Lastly, during separation, the design needs to maintain the current field of view and be able to withstand separation shock. This process is outlined in stages in the CONOPS image shown in Figure 3.

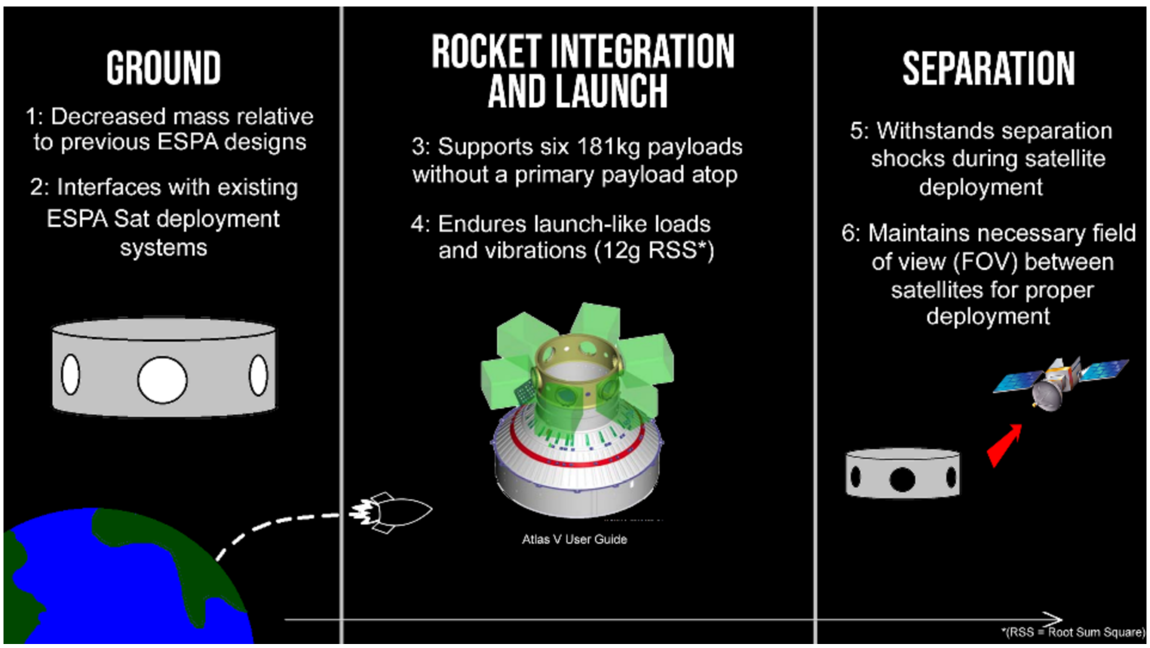


***Figure 3: SPACEMOD Concept of Operations***

## 1.4 Functional Block Diagram

The Functional Block Diagram for the SPACEMOD project is seen below in Figure 4. SPACEMOD will begin in the design phase to identify weight reduction methods. The design will be iterated until ready to be manufactured. Once SPACEMOD has been manufactured, testing will be performed and results will be analyzed. The final results will be delivered to the customer for more in-depth analysis.

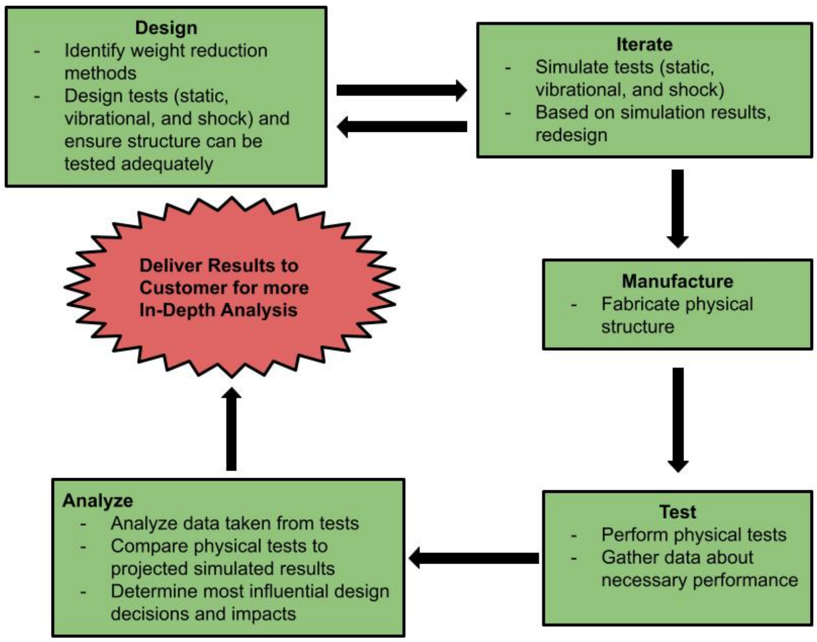


***Figure 4: SPACEMOD Functional Block Diagram***

## 1.5 Functional Requirements

The SPACEMOD project has three Functional Requirements (FR) based on the CONOPS and the customer presentation. The Functional Requirements listed below define the project and will be used to measure the project success.

1. FR 1 - The SPACEMOD scaled launch ring shall maintain structural integrity and payload attachments when exposed to launch-like loads.

2. FR 2 - The SPACEMOD shall maintain standard ESPA Interface compatibility, scaled by a $\frac{47}{250}$ scale factor, as defined in Section 4 of the MOOG "ESPA's User Guide" [2].

3. FR 3 - The SPACEMOD shall maintain structural integrity and additional payload attachment when exposed to scaled, simulated payload separation shocks, which will be characterized.

# 2 Design Requirements

From the functional requirements, the following design requirements were created through a flow-down process. The functional requirements describe broadly what the SPACEMOD needs to do to accomplish its mission, while the design requirements break down these broad requirements into specific, testable requirements. Functional requirement 1 flows down in three design requirements that fully describe the desired behavior of the SPACEMOD when exposed to the defined launch-like loads. Functional requirement 2 flows down into two specific design requirements that better define the interfacing necessary to attach ESPA-class payloads to the SPACEMOD. Functional requirement 3 flows down into two design requirements that specify behaviors for the SPACEMOD to conform to during separation-like testing, as well as one design requirement that specifies the behavior that must be characterized through simulation and testing.

1. FR 1 - The SPACEMOD scaled launch ring shall maintain structural integrity and payload attachments when exposed to launch-like loads.
   (a) DR 1.1 - The SPACEMOD shall not see any plastic deformation up to 12g RSS loads with a FOS of 1.4.
      i. Verification and Validation: Characterization – High fidelity geometric inspection prior to and after testing in a coordinate measuring machine (CMM), strain gauges in areas of concern during testing.
   (b) DR 1.2 - The SPACEMOD shall maintain the attachments to all six attached payloads during exposure to launch-like loads, provided the payloads are scaled models, scaled by a scale factor of $\frac{47}{250}$, of ESPA-class payloads, as defined in requirement DR 2.1.
      i. Verification and Validation: Demonstration – The payloads shall be visually inspected after the launch-like loads have been applied in order to confirm that they maintain their attachment to the SPACEMOD.
   (c) DR 1.3 The SPACEMOD shall not undergo plastic strain when exposed to vibration conditions as defined in Section 3.2 in the "ATLAS V Launch Services User's Guide" [6].
      i. Verification and Validation: Characterization – High fidelity geometric inspection prior to and after testing in a CMM, strain gauges in areas of concern during testing.
2. FR 2 - The SPACEMOD shall maintain standard ESPA Interface compatibility, scaled by a $\frac{47}{250}$ scale factor, as defined in Section 4 of the MOOG "ESPA's User Guide" [2].
   (a) DR 2.1 - Design: The SPACEMOD shall have the ability to successfully attach up to 6 scaled ESPA-class payloads, scaled by a $\frac{47}{250}$ scale factor, in evenly spaced locations about the ring. ESPA-class payloads are defined as 400 [lb] payloads with a center of gravity located 20 [in] from the interface plane that can fit entirely within a volume that is 24 [in] in height, 28 [in] in width, and 38 [in] in depth.
      i. Verification and Validation: Inspection – Through inspections of the physical device, it shall be concluded that the SPACEMOD maintains the ability to attach ESPA payloads.
   (b) DR 2.2 - The SPACEMOD shall have 6 circular ESPA interfaces at evenly spaced locations around the ring, with a diameter of 15 [in], scaled by a scale factor of $\frac{47}{250}$.

        i. Verification and Validation: Inspection – Through inspections of the physical device, it shall be concluded that the SPACEMOD has these required circular ports.

3. FR 3 - The SPACEMOD shall maintain structural integrity and additional payload attachment when exposed to scaled, simulated payload separation shocks, which will be characterized.

    (a) DR 3.1 - When exposed to two synchronized symmetric simulated payload separation shocks of no more than 1000 g acceleration each for ESPA-class separation and scaled by a scale factor of $\frac{47}{250}$, the SPACEMOD shall not see any plastic strain.

        i. Verification and Validation: Characterization – High fidelity geometric inspection prior to and after testing in a CMM, strain gauges in areas of concern during testing.

    (b) DR 3.2 - All payloads attached to the SPACEMOD that are not intended to be released during the test shall maintain their attachment to the SPACEMOD.

        i. Verification and Validation: Demonstration – The payloads shall be visually inspected after the separation-like loads have been applied in order to confirm that they maintain their attachment to the SPACEMOD.

    (c) DR 3.3 - The shock propagation through the SPACEMOD due to simulated versions of the common ESPA-class separation methods shall be characterized through simulation and testing.

        i. Verification and Validation: Inspection – Data from the separation shock test described above will be analyzed and presented to characterize the separation shock propagation.

# 3 Key Design Options Considered

## 3.1 Testing

When analyzing all options for testing facilities, SPACEMOD settled upon three possible options. The first being on campus at CU, the second being off campus at the NTS Longmont Testing Laboratory, and the third being at the Lockheed Martin Waterton Campus. Facilities outside of CU were researched due to the limitations that would be imposed upon SPACEMOD by the capabilities of CU testing facilities. Per the design requirements, the testing SPACEMOD has determined necessary for the article are vibration, shock, and static load. Static load testing can be completed at CU. Vibration testing can also be completed at CU, however, size restrictions will apply. Shock testing, cannot be completed at CU. NTS Longmont provides a great range of testing options and supports the university via LASP. Lockheed Martin is also a large supporter of senior projects at the university and may agree to supporting SPACEMOD. Pros and Cons for each facility can be seen in Table 2. In the coming weeks, the testing facility to be used will be chosen and agreements between outside companies will be drawn up.

***Table 2: Testing Facility: Pros and Cons***

| Facility | Pros | Cons |
|---|---|---|
| CU | - Free<br>- On campus<br>- Faculty and Staff Support | - Vibration testing Only<br>- Significant size limitations |
| NTS | - Vibration Testing<br>- Shock Testing<br>- Environmental/Tvac Testing<br>- Industry support<br>- No applicable size limitations | - May cost up to $1,800<br>- Off campus (20 minute drive)<br>- Schedule coordination |
| Lockheed Martin (Waterton Campus) | - Vibration Testing<br>- Shock Testing<br>- Environmental/Tvac Testing<br>- Industry Support<br>- No applicable size limitations<br>- Free | - Off campus (1 hour drive)<br>- Schedule coordination<br>- May not want to support ULA project |

## 3.2 Materials

The current standard ESPA Ring uses forged 7000-series Aluminum. Without the force on top of the ESPA from a primary payload, alternative material options can be considered. Material properties are tabulated in Table 3.

***Table 3: Material: Properties***

| Criteria | AL 6061 | AL 7075 | Stainless Steel | Titanium (6AL-4V) |
|---|---|---|---|---|
| Density | $2.7\ \frac{g}{cm^3}$ | $2.81\ \frac{g}{cm^3}$ | $8\ \frac{g}{cm^3}$ | $4.54\ \frac{g}{cm^3}$ |
| Yield Strength | 131 MPa | 500 MPa | 215 MPa | 1050 MPa |
| Modulus of Elasticity | 68.9 GPa | 71.7 GPa | 193 GPa | 118 GPa |
| Shear Modulus | 26 GPa | 26.9 GPa | 77 GPa | 44.5 GPa |
| Cost* | $37.24 | $77.54 | $205.12 | $2101 |

* Please refer to the trade studies for cost determination technique.

*Table 4: Materials: Pros and Cons*

| Material | Pros | Cons |
|---|---|---|
| Aluminum 7075 | - Affordable<br>- Accessible<br>- Proven feasibility | - Heavier than Aluminum 6061 |
| Aluminum 6061 | - Lowest density<br>- Affordable | - Low Yield Strength |
| Titanium | - High yield strength<br>- Strength to weight ratio | - Heavy<br>- Costly |
| Stainless Steel | - High yield strength | - Heavy |

## 3.3 Geometry

In the trade study process, three candidate design spaces with differing geometries were considered. While not fully designed in CAD, rough sketches have been produced, and back of the envelope calculations were performed in order to establish a baseline confidence that these designs were even possible. While the back of the envelope calculations were used in order to establish some degree of engineering confidence, it is acknowledged that the assumptions made in this process may not accurately model the true capability of the future designs. For that reason, while a design candidate is chosen at the end of this trade study, the design space is still considered open until PDR and multiple CAD prototypes will be modeled in order to explore the design space further with more in depth analysis. The three candidates considered were an improved ring design, a flat plate approach, and a struts based approach. These design candidates are described in the next three sections.

### 3.3.1 Design Candidate 1: Ring

The ring design space is the most similar to the current ESPA. This design would look most similar to the following:

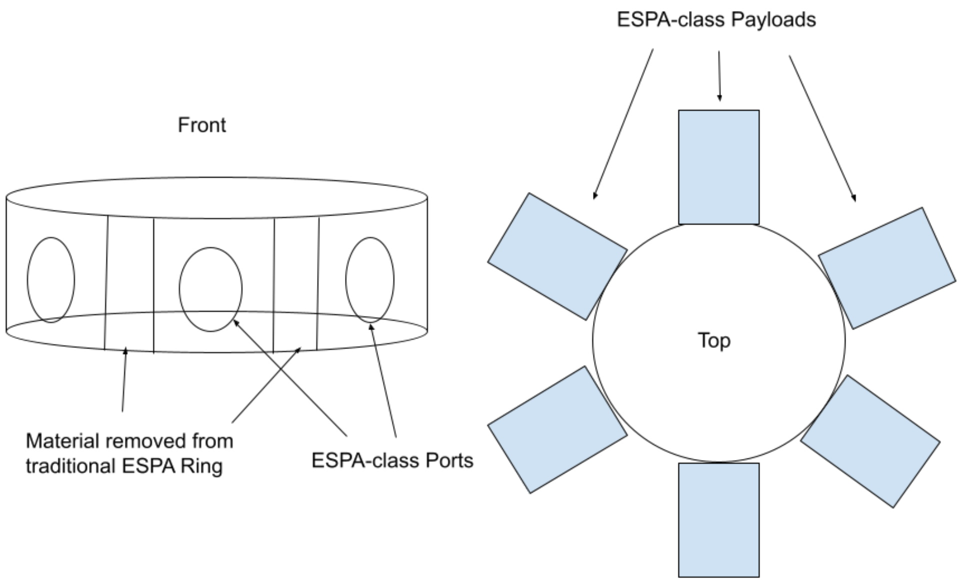


***Figure 5: Ring Design Candidate Schematic***

***Table 5: Ring Design Pros and Cons***

| Pros | Cons |
| --- | --- |
| Strong resemblance to current ESPA | Costly and difficult to manufacture |
| Possibly machined in one solid part | May require welding, multiple parts |
| Allows for interfacing above and below | Over-designed for ESPA with no primary payload |
| Flight heritage surviving launch like loads and vibrations (FR 1, FR 2 FR 3 all satisfied) | Dramatically limits scale of physical test model |
| Easily modeled as a thin walled cylinder | |
| Easily maintains FOV requirements (DR 2.2 satisfied) | |

### 3.3.2 Design Candidate 2: Flat Plate

Leveraging the fact that the new ESPA now has no primary payload weight, this design asks the question: Does the SPACEMOD need to be a ring? This design is a flat plate, with angled ramp-like interfaces for the payloads to attach to. The payload attachments are angled and not completely flat in order to satisfy the customers desire to maintain legacy field of view requirements, 30 degrees on either side of the payloads, 60 total degrees to deploy into. By making this design a semi-flat plate, it is believed that significantly less material is needed to sustain the same high loads. This design was also quoted by Matt Rhode of the University of Colorado at Boulder Ann and HJ Smead Aerospace machine shop as requiring half the material of the ring and being significantly easier to CNC machine, requiring no welds.

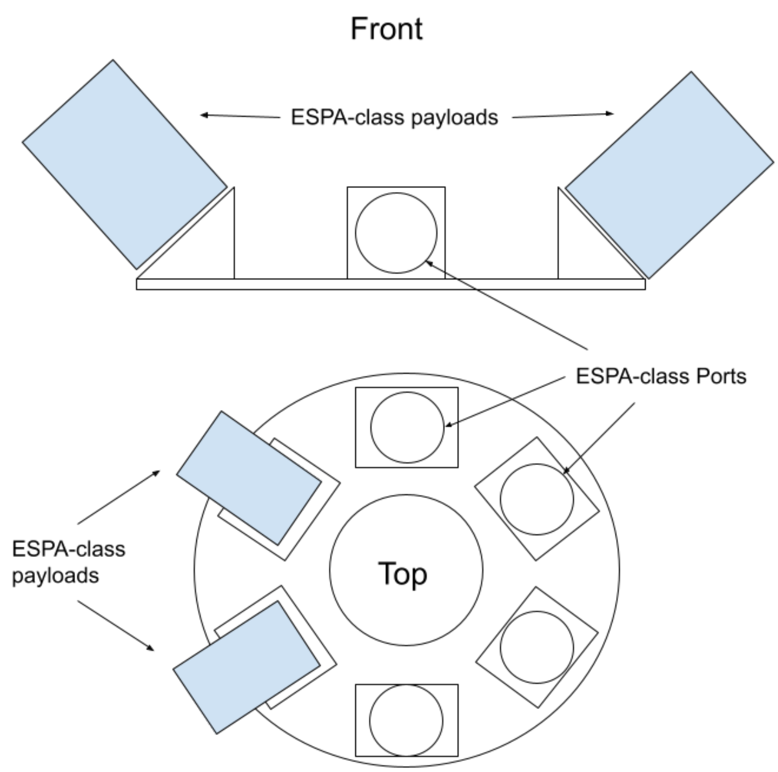


***Figure 6: Flat Plate Design Candidate Schematic***

*Table 6: Flat Plate Pros and Cons*

| Pros | Cons |
|---|---|
| Can be machined in one part | Will be laterally "wider" than current ESPA, with a larger axial surface area |
| Low mass | Angle may increase material needed |
| Low volume | |
| Solid structure suggests it will easily withstand launch like loads and vibrations (FR 1, FR 2, FR 3, all satisfied) | |
| Easily modeled as ramp/beam system | |
| Angled ramp-like interfaces maintain FOV requirements (DR 2.2 satisfied) | |

### 3.3.3 Design Candidate 3: Struts

The third candidate design space is a strut based design, which projects to have the least mass of the three design candidates. Figure 7 shows an example of what this design could look like.

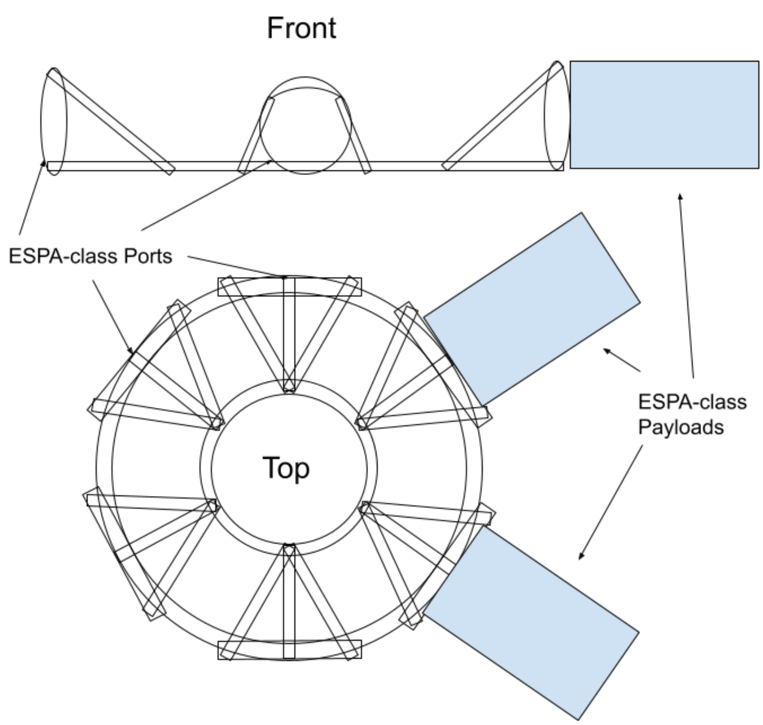


*Figure 7: Struts Design Candidate Schematic*

*Table 7: Struts Pros and Cons*

| Pros | Cons |
|---|---|
| Lowest mass | Many parts |
| Easily modeled truss system | Requires additional fasteners, cannot be machined in one piece |
| Easily maintains FOV requirements (DR 2.2 satisfied) | Requires additional struts in the middle of the ring, possibly inconvenient for future mission ops |
| Truss structure performs better damping for shocks and vibrations (FR 1, FR 2, FR 3, all satisfied) | Highest level of stress concentrations in thin struts, constrains materials for manufacture |

## 3.4 Scaling Factor

Per the scope of this project the SPACEMOD payload adapter will have to be a scaled down compared to the actual size of an ESPA ring. SPACEMOD considers three different scale factors: small ($\frac{47}{250}$), medium ($\frac{99}{250}$), and large ($\frac{69}{125}$).

*Table 8: Scaling Factor: Pros and Cons*

| Scale Factor | Pros | Cons |
|---|---|---|
| $\frac{47}{250}$ Scale | - Able to manufacture on CU campus<br>- Can be constructed out of a single piece of material<br>- Able to be vibration tested on CU campus<br>- Lower monetary and time costs for construction<br>- Very easy to transport | - Difficult to test on<br>- Harder to construct |
| $\frac{99}{250}$ Scale | - Can be manufactured on CU campus<br>- Easy to test on<br>- Easy to construct<br>- Easy to transport<br>- Mid-range manufacturing, monetary, and time costs | - Cannot be constructed out of a single piece of material<br>- Cannot be vibration tested on the CU campus |
| $\frac{69}{125}$ Scale | - Very easy to construct<br>- Very easy to test on | - Hard to transport<br>- Cannot be manufactured on CU campus<br>- Very high manufacturing, monetary, and time costs<br>- Cannot be constructed out of a single piece of material<br>- Cannot be vibration tested on the CU campus |

## 3.5 Analysis Methods

The analysis methods used during the design process of the SPACEMOD will determine the degree to which the structure is validated prior to manufacturing and testing. There are a multitude of ways to validate a structure for different criterion, and one method is not always best for every load case or structural characteristic. In the case of the SPACEMOD structure, a main evaluation criteria is whether or not the structure yields up to 1.4 times the applied RSS load of 12g, spanned out in all directions. Since it is not practical to run a FEM simulation in every direction, the analysis must broken down into a set of chosen directions with an applied load multiplication factor.

### 3.5.1 Workflow Considerations

There are multiple considerations that will be taken into account throughout the design process. No one analysis method will be used to validate the structure.

1. Assumptions: Every step of the design and analysis process will come with its own set of necessary assumptions. As the number of assumptions increases, the accuracy of the results and preliminary analysis decrease. If a preliminary analysis of the system is done on paper with "hand calculations", the assumptions made must also be applicable to the constraints applied to the FEM to maintain efficient workflow. The aim of the analysis process will be to make as few simplifying assumptions as possible in order to speed up the design process and capture accurate stress distributions for proper evaluation of system performance.

2. Analysis tool accuracy: Considering the limitations of analysis tools used on this project is crucial prior to diving deep into shock, vibration, and static load analyses. Capabilities vary by program or method.

3. Time to implement: Different scenarios warrant different analysis tools and methods. Not all tools are similarly easy to implement effectively. The time that each analysis takes to set up and run will be driven by the type of analysis, team member expertise, ease of use of a chosen program, number of constraints present, mesh density, and solver run time.

4. Clarity of results: If a certain software makes it challenging to make meaning of the results from an analysis, then the results mean nothing.

### 3.5.2 Expected Analysis Necessary for In-Depth FEA

**ANSYS Mechanical**: This software is great for quick iteration on preliminary models and simple geometry. This software provides a very user friendly UI with a significant amount of program controlled inputs. The ease of use provided with ANSYS Mechanical will allow for quick set up and runs of models, but with an ease of use comes a loss of accuracy in the results on more complex models. Only the student version of ANSYS is available for this project, so models will be limited to 128k elements. This will be fine for initial runs of the model, but this project will need higher mesh density with such a large structure to prove that there is no localized plastic strain present at 1.1 times the limit load. ANSYS Mechanical will be more than sufficient for validation of ground test hardware, and any other tooling necessary for the validation of the SPACEMOD.
**Simcenter FEMAP:** This software utilizes the Nastran solver, which is the standard code base used for validation of aerospace hardware like the SPACEMOD. Accurate use of FEMAP requires a more in depth understanding of FEM software than ANSYS Mechanical, but if used correctly

it will provide higher fidelity results. The team's analysis lead has extensive experience with the FEM and software like ANSYS and FEMAP, and will be able to implement this model into the software for structural validation of the SPACEMOD. The analysis lead also has access to a full license of Simcenter FEMAP, meaning that there will be no accuracy limiting maximums placed on the software. FEMAP will be utilized for final validation of the structure under static limit load, modal, vibe, and shock analysis.

## 3.6 Safety Factor

For this project, an Ultimate Safety Factor of 1.4 and a Yield Safety Factor of 1.1 were chosen. The justification for these Safety Factors comes from a NASA document, the Structural Design And Test Factors Of Safety For Spaceflight Hardware [4]

## 3.7 Separation Systems

As stated previously, SPACEMOD is not responsible for the development of a separation system. That said, it is worth noting that the maximum anticipated shock operating range affects the weight of the payload itself, and thus becomes an important parameter for the overall capabilities of SPACEMOD.

The available options for separation systems span greatly depending on the needs of the individual payload's mission. Industry standard has transitioned from relatively simple, yet aggressive method of explosive bolts to more complex but low-shock systems that include clamping belts, springs, pneumatic devices, and the like. Evaluation of various systems was performed based off of shock force created, most commonly used systems, weight added to the system as a whole, and complexity of implementation in that order of importance. See Table 9 for an evaluation of different methods of separation while deciding upon which specific shock forces must be considered prior to design.

***Table 9: Separation System Types***

| **Separation Type** | **Shock Force g-force** | **Commonly Used (1-5)** | **Avg Weight of System (lbs)** | **Complexity (1-5)** |
|---|---|---|---|---|
| Explosive Bolt/flange | <20,000 g | 2 | <1 lb | 5 |
| Servo Band | <750g | 3 | <15 lb | 2 |
| Spring | <1,000g | 4 | <10 lb | 4 |
| Clamp Band | <1,000g | 5 | <10 lb | 3 |

With the information presented in Table 9, it becomes clear that the majority of separation methods operate at a shock factor of less than 1000g. As all of the legacy Atlas V payload separation systems utilize either Springs or clamp bands at a shock force of less than 1000g, it was decided that this would be the maximum used value. The only obvious candidate that is not included from this list is explosive bolts and explosive flanges which operate at a lower weight, are substantially more simple, and have a lower likelihood of failure. There is a wide range of capabilities for these explosive bolts - but the trade off in over designing SPACEMOD to account for cases which are few and far between was not worth the convenience for the customer of a more diverse set of options for separation methods.

# 4 Trade Study Process and Result

## 4.1 Testing

### 4.1.1 Rationale

One of the most important elements of the project is testing of the article to validate and analyze the design. Due to the nature of the SPACEMOD project, testing presents unavoidable obstacles due to the size of the product and types of testing required for the product. While many testing capabilities are available at CU on campus, SPACEMOD may not be able to sufficiently complete necessary tests without utilizing third party facilities. Therefore, SPACEMOD has performed a trade study for the three possible testing facilities that may be used to help select a facility that will provide the necessary capabilities for adequate project completion.

### 4.1.2 Criteria and Weighting

Five criteria were determined for the testing trade study. The justification of each and their corresponding weight are detailed below. Further, Table 10 outlines the weight, driving requirement, and a brief description of each criteria. Table 11 presents the scoring criteria to be used for the trade study.

1. Cost - 20% Weight - SPACEMOD has been given a total budget of $5,000 to allocate appropriately towards specific project elements. SPACEMOD understands that the testing necessary to complete required elements of the project will likely be associated with a cost. However, it is important to stay within the given budget to maintain adequate funds for other project elements.

2. Accessibility - 15% Weight - Due to the selection of facilities, SPACEMOD team members may be required to obtain special access to particular facilities. Ideally, members would not have to, however, SPACEMOD understands, anticipates, and accepts this risk. Members are willing to complete necessary requirements to obtain access.

3. Testing Available - 35% Weight - The primary concern for testing facilities is the type of testing available. As stated in FR 3, SPACEMOD shall maintain structural integrity via testing of simulated shocks. Additionally, as stated in FR 1, SPACEMOD must maintain structural integrity when exposed to launch like loads. Therefore, it has been determined that shock, vibration, and static load testing are all required for the article leading the kinds of testing available to be the most important criteria to be satisfied with regard to testing facility.

4. Size Restrictions - 25% Weight - While SPACEMOD anticipates constructing a scaled model of the actual product, SPACEMOD would ideally prefer to avoid size limitations due to testing capabilities. The design of the article should not be designed to the testing facilities and instead testing facilities should be able to support the article's size within reason.

5. Convenience - 5% Weight - The final criteria to be evaluated is convenience of the testing facility. While SPACEMOD has the ability to travel (within reason) to testing facilities, it would be ideal to utilize facilities at the university or in the Boulder vicinity. Therefore, while it is not a pressing concern, the weighting for convenience was determined to be 5%.

*Table 10: Testing: Criteria and Weighting*

| Criteria | Weight | Driving Reqs | Description |
|---|---|---|---|
| Cost | 20% | Total budget of project is $5,000 | - The cost of testing in professional facilities can be expensive<br>- SPACEMOD must consider costs elsewhere and must allocate funds appropriately |
| Accessibility | 15% | N/A | - Some facilities may require team members to be granted special access which may be difficult |
| Testing Available | 35% | DR 1.1, 1.3, 3.1, 3.4 | - SPACEMOD needs testing facilities that can support all kinds of testing deemed necessary for the project<br>- Without proper testing the project cannot be completed adequately |
| Size Restrictions | 25% | DR 2.1, 2.2, 3.1, 3.2 | - Some testing facilities do not have the capability to support larger scale articles<br>- SPACEMOD does not want to be limited due to testing capabilities |
| Convenience | 5% | N/A | - Testing facilities that are further away require more scheduling consideration |

*Table 11: Testing: Scoring*

| Criteria | 1 | 2 | 3 |
|---|---|---|---|
| Cost | 1000+ USD | 0-1000 USD | Free |
| Accessibility | Requires Badge Access | All Members can Access with Permission | All Members can Access Easily |
| Testing Available | No Shock Testing | | Shock Testing Available |
| Size Restrictions | Strict Size Limits | | No Size Limits |
| Convenience | 30+ minute drive | 0-30 minute drive | No drive necessary |

### 4.1.3 Trade Study

*Table 12: Testing Facility: Trade Study*

| Criteria | Weight | Candidate 1: CU | Candidate 2: NTS | Candidate 3: Lockheed Martin |
|---|---|---|---|---|
| Cost | 20% | 3 | 1 | 3 |
| Accessibility | 15% | 3 | 2 | 1 |
| Testing Available | 35% | 1 | 3 | 3 |
| Size Restrictions | 25% | 1 | 3 | 3 |
| Convenience | 5% | 3 | 2 | 1 |
| Total | 100% | 1.8 | 2.4 | 2.6 |

## 4.2 Materials

### 4.2.1 Rationale

A handful of materials have been used on similar ESPA class rings in the past, although primarily, Aluminum 7050 is the material of choice. Other materials such as carbon fiber and titanium have found their way into designs of more critical elements.

One of SPACEMOD's primary requirements is to reduce the overall mass of the payload adapter. Aside from the overarching design, material selection will also naturally drive the design process, as it determines if the structure can endure certain stresses and loads without undergoing a structural failure.

### 4.2.2 Criteria and Weighting

1. Density - 30% Weight - Reduction of mass is the primary objective of this project. A material with a lower density will have a lower mass, which will contribute to achieving that objective.

2. Yield Strength - 25% Weight - The material selected has to be strong enough to withstand the stresses experienced by SPACEMOD. Stronger materials will have a higher yield stress values, which corresponds to the mechanical stresses at which the material enters the plastic deformation region.

3. Cost - 15% Weight - With only a $5,000 budget, The cost of the material must be considered. Cheaper materials allow more money in the budget in the budget to be directed elsewhere

4. Manufacturability - 15 % Weight - The machine shop at CU has limitations with what it can build both due to size constraints and tooling constraints. Determining the manufacturability of a certain material in the machine shop is a key step step to determining its feasibility.

5. Accessibility - 10 % Weight - Not all materials are easily accessible. Determining how many vendors provide each material, as well as vendor locations, are important considerations in determining the type of material used.

*Table 13: Materials: Scoring*

| **Criteria** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|
| Density | $\leq 10\frac{g}{cm^3}$ | $\leq 8\frac{g}{cm^3}$ | $\leq 5\frac{g}{cm^3}$ | $\leq 4\frac{g}{cm^3}$ | $\leq 3\frac{g}{cm^3}$ |
| Yield Strength | $\geq 100MPa$ | $\geq 200MPa$ | $\geq 400MPa$ | $\geq 600MPa$ | $\geq 800MPa$ |
| Cost* | $\leq$ \$500 | $\leq$ \$300 | $\leq$ \$150 | $\leq$ \$75 | $\leq$ \$25 |
| Manufacturability | Can't be Manufactured | Requires Specialty Tooling and Facilities | Difficult to CNC | Easy to CNC | Able to do with CU Facilities |
| Accessibility | Only Foreign Vendors | | | | Many Domestic Vendors |

Table 13 shows the scoring system used for each criteria in the trade study, where a 1 is least desirable and 5 is most desirable. The scoring was performed as follows:

1. Density - The scoring system for density was created relative to the densities of the chosen materials, where a 5 was given for the lowest density material, and a 1 was given for the highest density material. The range was then created between those densities.

2. Yield Strength - The scoring system for the yield strength was once again created relative to the strengths of each material, where materials with higher yield strengths score higher. This approach was taken based on the general trend that stronger materials with higher yield stresses also have the higher densities. There is then a trade off amongst using *less*, strong material, as opposed to *more* weaker material.

3. Material Cost* - The cost scoring system was developed by finding prices for half-inch thick, one-by-one foot sheets of each material. This allowed us to normalize the price of each material by a baseline volume. Lower prices yield a higher score in this trade study.

4. Manufacturability - As mentioned previously, there are limitations as to what materials can be machined and manufactured at CU facilities, both due to size constraints and tooling limitations. The scoring system was first developed by determining what facilities are available to students and faculty at the University. In addition, research was done on typical material behavior during certain tasks, like cutting, and CNC machining. Generally, harder/stronger materials will put more stress on machinery and generate large amounts of heat, whereas softer materials do the opposite. This trade study ranks the manufacturability by how feasible it is to cut and form a substance, with *easier* materials scoring higher.

5. Accessibility - The current COVID-19 pandemic has complicated the process for obtaining raw materials. Many vendors have low to no stock because of pandemic restrictions and safety precautions. This scale was determined by how easy it was to find American vendors, and whether they had material in-stock. Foreign vendors are to be avoided, as shipping delays and quality may be sacrificed. In addition, long wait times for shipping would likely negate any cost-savings by shopping overseas. Materials that had many US-based retailers with product in-stock score higher, while materials with only foreign vendors score lower.

#### 4.2.3 Trade Study

***Table 14: Materials: Trade Study***

| Criteria | Weight | AL 6061 | AL 7075 | Stainless Steel | Titanium (6AL-4V) |
|---|---|---|---|---|---|
| Density | 30% | 5 | 5 | 2 | 3 |
| Yield Strength | 25% | 1 | 3 | 2 | 5 |
| Cost | 15% | 4 | 3 | 2 | 1 |
| Accessibility | 15% | 5 | 3 | 3 | 3 |
| Manufacturability | 10% | 5 | 4 | 3 | 2 |
| **Total** | 100% | 3.6 | 3.55 | 2.15 | 2.95 |

### 4.3 Geometry

#### 4.3.1 Rationale

There are many options for the geometry of this project, as the only constraints are that the payload interface rings and the bottom of the structure can interface with the launch vehicles the same way as the legacy system. This allows for a nearly clean sheet design, which can be overwhelming. In order to narrow the design space and bring focus to the project, a trade study on geometry concepts was performed. The legacy ESPA ring is a good baseline for one way to weigh designs against each other, and therefore many of the criteria considered in the trade study are compared to the characteristics of the old ESPA design.
Below are justifications for the inclusion of all criteria and the weighting factors applied to each criteria evaluated within the trade study. The main considerations while determining all weighting factors was the importance of the specified criteria in achieving the objectives and satisfying the requirements of the project.

1. Mass - 35% Weight - The primary objective for the project was the reduction in weight of the secondary payload adapter system. While this is not defined explicitly in a requirement, since there is no defined numerical weight reduction required, the pursuit of minimum possible weight was heavily stressed by the customer. Therefore, the mass of the design was assigned the highest weighting factor of all criteria.

2. Manufacturability - 20% Weight - In order to satisfy every single requirement, a scaled model of the SPACEMOD must be physically manufactured and tested. Therefore, the SPACEMOD design must be feasibly manufacturable with the resources available to the team. In order to maximize the realistic results of the data obtained from all tests, it is desirable for the design to be manufacturable in such a way that it does not require additional welds, fasteners, etc, that were not included in the paper design. Since this collected data is one of the primary requests from the customer, manufacturability receives the second highest weight of all criteria.

3. Payload Support Strength - 10% Weight - In order to meet DR 1.2, the SPACEMOD must be capable of supporting the specified ESPA-class payloads during the launch-like static loads. The ability for the SPACEMOD to complete its mission carrying secondary payloads into space requires that it supports them through these loads. Since this support is of equal

importance to the other two types of loads the SPACEMOD must withstand to complete its mission, this criteria receives the same weighting factor as the Predicted Shock Response and Predicted Vibration Response.

4. Predicted Shock Response - 10% Weight - In order to meet DR 3.1, 3.2, and 3.3, the SPACEMOD must be capable of withstanding satellite separation-like shocks. This capability is required for the SPACEMOD to complete its mission of successfully separating from its payloads. Since this capability is of equal importance to the other two types of loads the SPACEMOD must withstand to complete its mission, this criteria receives the same weighting factor as the Payload Support Strength and Predicted Vibration Response.

5. Predicted Vibration Response - 10% Weight - In order to meet DR 1.3, the SPACEMOD must be capable of withstanding launch-like vibrations. This capability is required for the SPACEMOD to complete its mission of successfully moving the secondary payloads from the ground into space on a launch vehicle. Since this capability is of equal importance to the other two types of loads the SPACEMOD must withstand to complete its mission, this criteria receives the same weighting factor as the Payload Support Strength and Predicted Shock Response.

6. Material Cost - 11% Weight - In order to meet all of the requirements, a scaled model of the SPACEMOD must actually be physically constructed. For this to be feasible given the project budget of $5000, the cost of the amount of material required to construct the prototype is important to consider. Without the budgetary capability to construct the SPACEMOD, the physical tests cannot even be conducted. This nullifies the above three criteria about the capability of the SPACEMOD to withstand different loads, so Material Cost receives a slightly greater weight than those criteria. In order to perform this trade study, the material was assumed to be Al 7050, which may increase the projected cost to higher than reality, but allows for comparison between designs,

7. Number of Parts - 4% Weight - In order to meet DR 1.1, 1.2, 1.3, 3.1, 3.2, and 3.3, the SPACEMOD must withstand the loads associated with its mission. Common logic associated with all mechanisms intending to enter space indicates that fewer parts involved in a design results in less possible point of failure. While this is an important design aspect to consider, it receives the lowest weight of all criteria in this trade study due to the inherent nature and function of the design not requiring a large number of parts in the first place.

#### 4.3.2 Criteria and Weighting

***Table 15: Geometry: Scoring***

| Criteria | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Mass | Does not reduce mass compared to current ESPA | Reduces mass by 0-15% | Reduces mass by 15-30% | Reduces mass by 30-45% | Reduces mass by 45% or more |
| Payload Support Strength | Cannot support 6 payloads | | | | Can support 6 payloads |
| Number of Parts | 100+ parts | 30-100 parts | 11-30 parts | 2-10 parts | 1 part |
| Material Cost | 5000+ USD | 3000-5000 USD | 2000-3000 USD | 1000-2000 USD | <1000 USD |
| Manufact-urability | Not manufact-urable | Requires welds and multiple fasteners | Requires pins and fasteners | Can be CNC machined, but difficult | Easily CNC machined |
| Predicted Shock Response | Design does not survive shock | Geometric characteristics provide below average shock response | Geometric characteristics provide average shock response | Geometric characteristics provide above average shock response | Geometric characteristics provide superior shock response |
| Predicted Vibration Response | Design does not survive vibration | Geometric characteristics provide below average vibration response | Geometric characteristics provide average vibration response | Geometric characteristics provide above average vibration response | Geometric characteristics provide superior vibration response |

Table 15 explains the heuristics used to rate the expected performance of the three different potential geometric designs in the trade study criteria. These heuristics are similar to those used in previous trade studies in this document. A score of 1 is the least desirable, while a score of 5 is the most desirable. The scoring for the specific heuristics in this table was performed as follows:

1. Mass - In our scoring system, a score of 5 was a mass reduction of greater than 45% and a score of 1 was no reduction of mass at all. The legacy ESPA ring has a mass of 133 kg, and while none of the design candidates are fully designed out, back of the envelope calculations were performed in order to estimate how much mass will be reduced for each of the designs.

2. Payload Support Strength - This metric accounts for whether the designs can support the Payloads and associated g loads, which directly corresponds to FR 1 and FR 2. This is a crucial component of this project, and was necessary to trade, but does not exist on a continuum; for example, a design that could only hold 3 payloads is just as bad as a design

that holds no payloads, and a design that can hold greater than 6 payloads is no more valuable than one that can hold the required amount. For this reason, this metric is a scored on a pass fail basis- it either can hold the payloads and receives a 5 or it fails gets a value of 1. In order to validate the candidate designs, back of the envelope, first principles based engineering analysis was performed. The "Struts" design was modeled first as an Euler column and then the method of joints was applied to solve for the internal forces on each of the individual bars, which was in tern taken to a materials science level to determine the necessary size of the bars for various materials. The "Ring" and "Flat Plate" designs were both modeled as walls/columns, solving for reaction forces and moments and then estimating internal stresses and strains. While the calculations were not overly advances, they do give the SPACEMOD design process a baseline idea of confidence in the feasibility of the designs. All loads were statically applied in both the lateral and axial directions, with an 8.5 g increase, and a yield safety factor of 1.251 was used to match the design process methodology of the original ESPA.

3. Number of Parts - The less parts this design has, the easier it is to analyze, manufacture, and test. The inconvenience caused by multiple parts does not scale linearly, and the part estimates used to trade the designs against each other do not include fasteners for the SPACEMOD to the payloads and the SPACEMOD to the launch vehicle interface.

4. Material Cost - In order to perform this trade study, the material was assumed to be Al 7050, which may increase the projected cost to higher than reality, but allows for comparison between designs. Material cost was based extensively off of conversations with experts in the University of Colorado Boulder Aerospace machine shop and research into cost of buying material stock online. Both the "Ring" and "Flat Plate" design require a large block of metal stock to be CNC machined. The "Flat Plate" requires roughly half of the mass of raw stock compared to the "Ring" design, but both are costly. The "Struts" design requires far less material and will cost less, but comes with a host of challenges as well.

5. Manufacturability - Much like material cost, manufacturability was based extensively off of conversations with experts in the University of Colorado Boulder Aerospace machine shop. In order to preserve the accuracy of the analysis for the customer, avoiding welding and build techniques that are not accurate to space-based structures was prioritized over ease of manufacture. Conversely, however, the designs must be able to be built with the resources available to the team, and the "Ring" design was deemed unmanufacturable on the 4-axis CNCs at certain scales, severely limiting the design space. This category rewards designs that can be CNC machined out of one solid piece and requires no welds, pins, or fasteners, and detracts the more complicated manufacturing becomes.

6. Predicted Vibration Response - Since the design concepts are still in the conceptual phase and have not been developed enough to allow for even basic simulation within structural analysis software, the rating for this metric was performed qualitatively using evidence found in research papers about the general performance of different structures in response to vibration. Specifically, Joseph E. Bondaryk, in his paper "Vibration of truss structures," published in the The Journal of the Acoustical Society of America, states that "trusses can be an effective isolation system, particularly at higher frequencies, where wavelengths are much smaller than the strut members" and that a "further study with random strut lengths showed that the observed low-pass filtering effect can be compared to an equivalent applied damping" [1]. Based on these conclusions, it can be assumed that the "Struts" design candidate qualitatively has

greater potential to damp vibrations than the other two design candidates, resulting in its score of 5 and their scores of 3.

7. Predicted Shock Response - Since the desired response of the SPACEMOD to shock is the same as its desired response to vibration – namely, effective damping – it can be generalized that the scores for the Predicted Vibration Response metric can be transferred to the scoring for this category. Therefore, this category was scored in the same fashion as the Predicted Vibration Response category, and used the same paper by Bondaryk to predict the qualitative superiority of the "Struts" design in terms of shock response compared to the other two designs.

#### 4.3.3 Trade Study

***Table 16: Geometry: Trade Study***

| Criteria | Weight | Candidate 1: Ring | Candidate 2: Flat Plate | Candidate 3: Struts |
|---|---|---|---|---|
| Mass | 35% | 3 | 3 | 5 |
| Manufacturability | 20% | 2 | 5 | 3 |
| Payload Support Strength | 10% | 5 | 5 | 5 |
| Predicted Shock Response | 10% | 3 | 3 | 5 |
| Predicted Vibration Response | 10% | 3 | 3 | 5 |
| Material Cost | 11% | 2 | 3 | 4 |
| Number of Parts | 4% | 4 | 5 | 2 |
| Total | 100% | 2.93 | 3.68 | 4.37 |

### 4.4 Scaling Factor

#### 4.4.1 Rationale

The testing of the SPACEMOD design is crucial to proving validity of the final design. A one to one model of the final design would be out of the projects budget and be difficult to transport and test. Thus, it is important to consider scaling down the final design to ensure it remains within the budget as well as, meets all the sizing limitations for manufacturing and testing. Determining the scale factor will allow for correct scaling of testing loads as outlined in the "About the Size of it" document [5]. Trade studies were carried out for three different sizes of ESPA ring, a small size, medium size, and large size, corresponding to scale factors of $\frac{47}{250}$, $\frac{99}{250}$, and $\frac{69}{125}$ respectively. The scale factors described roughly correspond to one foot, two feet, and three feet diameters. These sizes were chosen based upon access to testing, manufacturing, and interfacing constraints. Scales larger than $\frac{69}{125}$ were excluded from this study due to manufacturing costs and time being impractical for this project. Designs with a scale factor less than $\frac{47}{250}$ were additionally excluded due to testing, manufacturing and interfacing being significantly harder when working at such a small scale.

#### 4.4.2 Criteria and Weighting

Five criteria were determined for the scaling trade study. The justification of each and their associated weight is outlined below. Further, table 17 outlines the weight, driving requirement, and a brief description of each criteria.

1. Testing - 30% Weight - One of the most important components of the project is to test the design to prove it's ability to withstand the loads outlined in design requirements 3.1 and 3.2. In order to test the design, it must fit within the testing facilities being utilized. As this is a critical aspect of the project, the testing criteria was given a, relatively, higher weighting.

2. Manufacturing - 30% Weight - An additional important component of the project is manufacturing. While proving that the design can be manufactured, manufacturing the design will allow for testing of the design. It is important to ensure that the design can fit within the manufacturing facilities being utilized. As this is a crucial aspect of the project, the manufacturing criteria was given the same weight as testing.

3. Cost - 15% Weight - Cost of material will be the main expense throughout this project and the scale factor will greatly influence spending. A design that is low cost will be rated higher than a design that is high cost. While this criteria is not weighted as high as manufacturing and testing, it is very important for keeping within set budgetary constraints.

4. Interfacing - 25% Weight - Interfacing is another concern to be considered as the scaling decreases. If the scaling factor is too small bolt holes may require special bolt orders to attach the standard ESPA ports. These ports play a crucial role in testing separation shocks as required in section 3.1 of the design requirements.

***Table 17: Scaling Factor: Weight***

| Criteria | Weight | Driving Reqs. | Description |
|---|---|---|---|
| Testing | 30% | DR 3.1-3.2 | Testing is an important aspect to the project as it will be used to validate our design and findings. As the scale of the model increases, the testing facilities become limited. |
| Manufacturing | 30% | DR 1.2 & 2.1-2.2 | Manufacturing is important to test our design and it is important that the design can be manufactured with the available machines |
| Cost | 15% | N/A | It is required to stay within the budget provided and as the scale factor is increased, the cost of material increases |
| Interfacing | 25% | DR 2.1-2.2 | Testing requires interfacing with dummy satellites. To connect these dummy satellites bolt diameters need to be consider such that the scaled model can support standard bolt diameters |

#### 4.4.3 Trade Study

The trade study for the scaling factor is presented in Table 19 and it is accompanied by the scoring table, Table 18, which detail how the scores for each criteria are defined.

***Table 18: Scaling Factor: Scoring***

| Criteria | 1 | 2 | 3 |
|---|---|---|---|
| Testing | Can be tested at 1 facility | Can be tested at 2 facilities | Can be tested at 3 or more facilities |
| Manufacturing | Can't be manufactured using CU's CNC machine | Difficult to manufacture using CU's CNC machine | Easy to manufacture using CU's CNC machine |
| Cost | >$2000 | $2000-$1000 | <$1000 |
| Interfacing | Compatible with bolt diameters (i.e. less than 0.06") | Compatible with bolt diameters from 0.06" to 0.099" | Compatible with bolt diameters greater than 0.099" |

Each of the three levels of scoring for the 4 different categories in the Scale Factor trade study were chosen specifically to ensure that the scale factor of the final model would not end up causing more complications then needed. The justifications for the scoring levels are given below.

1. Testing - Scoring for testing was based upon which facilities the scale model could be tested at. These are the same facilities described in Testing Facility trade study, Table 12, which

were CU Boulder, NTS, and Lockheed Martin. The lowest score, 1, was used for scale models that could be tested at only one facility, 2 was used for models that could be tested at 2 facilities and 3 was for models that could be tested at all 3 facilities.

2. Manufacturing - Scoring for the manufacturing category was based off of how easy or hard the scale model could be designed using CU's CNC machines. This was chosen to be the scoring method as utilizing larger facilities outside of CU was impractical due to time and cost restrictions. A 1 to 3 score was given to each model size with 1 being impossible to manufacture using CU Boulder's CNC machines and 3 being easy to manufacture using CU Boulder's CNC machines.

3. Cost - Scoring for the cost was based off of the $5,000 budget that we were given as well as the estimated maximum cost of testing facilities which was 1,800 when using NTS's equipment. A score of 1 was given to any scale model that would cost more than $2,000 to manufacture, a score of 2 was given to any scale model that was between $1,000 to $2,000 to manufacture and a score of 3 was given to any model that cost less than $1,000 to manufacture.

4. Interfacing - The scores for interfacing were determined off of the diameter of bolts that would be used to attach the pieces of the scale model together. Smaller bolts of less than 0.06" in diameter were given the lowest score of 1 because they would be very difficult to work with and install on the model. A score of 2 was given to bolts with a diameter between 0.06" and 0.099" due to them being harder than a normal sized bolt to work with but also being big enough that they wouldn't cause complication in the testing phase of the project. A score of 3 was given to any scale model that used bolts that had a diameter larger than 0.099". These bolts would be easy to work with and would make the testing phase simpler and faster.

***Table 19: Scaling Factor: Trade Study***

| **Criteria** | **Weight** | **Small ($\frac{47}{250}$ Scale)** | **Medium ($\frac{99}{250}$ Scale)** | **Large ($\frac{69}{125}$ Scale)** |
|---|---|---|---|---|
| Testing | 30% | 3 | 2 | 1 |
| Manufacturing | 30% | 3 | 2 | 1 |
| Cost | 15% | 3 | 2 | 1 |
| Interfacing | 25% | 1 | 2 | 3 |
| Total | 100% | 2.5 | 2 | 1.5 |

# 5 Selection of Baseline Design

## 5.1 Evaluation of Trade Studies

### 5.1.1 Testing

Per the testing trade study, the best testing facility candidate is Lockheed Martin, however, depending on the cost of testing at NTS (which is currently only an estimate), NTS may be the more favorable candidate. Therefore, SPACEMOD will move forward with both candidates and continue the selection process based of the cost and ability to access both facilities. Overall, CU is the least favorable option and SPACEMOD will work to ensure testing can be completed at either NTS or Lockheed Martin since those facilities can better support the project and allow adequate completion as compared CU.

### 5.1.2 Materials

As seen in Table 14, the materials trade study, the scores are close between Aluminum 6061 and Aluminum 7075. Aluminum 6061 received a slightly higher score than the latter, thus this material will be used in the baseline design. Due to the close results the team will perform further analysis to characterize the expected internal stresses and will make a final decision between AL 6061 and AL 7075 after analysis.

### 5.1.3 Geometry

In the course of the geometry trade study, Design Candidate 3: Struts won. This was a victory buoyed by 5s in Mass, Payload Support Strength, Shock Response, Vibration Response. Mass and Payload support strength were calculated with back of the envelope hand calculations, utilizing principles of beam bending and method of joints. Vibration and Shock response were discussed above, and were generalizations levied from the paper "Vibration of truss structures," published in the The Journal of the Acoustical Society of America, specifically that "trusses can be an effective isolation system, particularly at higher frequencies, where wavelengths are much smaller than the strut members" and that a "further study with random strut lengths showed that the observed low-pass filtering effect can be compared to an equivalent applied damping" [1]. The weaknesses in the trade study, manufacturing ability and number of parts, are concerns, but the potential gains likely outweigh the negatives. However, the analysis used to to prove feasibility of the individual designs was primitive and first order, and for that reason, the team has elected to carry Design Candidate 2: Flat Plate and Design Candidate 3: Struts onto the PDR phase. This will be discussed further in the possible variations section. By carrying forward two designs there is an opportunity to perform more advanced Finite Element Analysis on CAD models of both designs.

### 5.1.4 Scaling Factor

The highest scoring scaling factor from the trade study is the smallest scale factor which is $\frac{47}{250}$. This scale factor preformed the best in the testing, manufacturing, and cost criteria. It is vital to this project that the design can be manufactured and tested and this scale factor is ideal for ensuring an easy process though those two processes. Where the smallest scale factor design struggles is with bolt interfacing diameters. By scaling down the model it was important to keep the bolt diameters in mind. Although, this was considered during the scale factor determination and the $\frac{47}{250}$ scale factor will use no.0 bolts which are available. In the end, the $\frac{47}{250}$ scale factor will reduce costs while maintaining manufacturing and testing capabilities.

## 5.2 Synthesis of Baseline Design

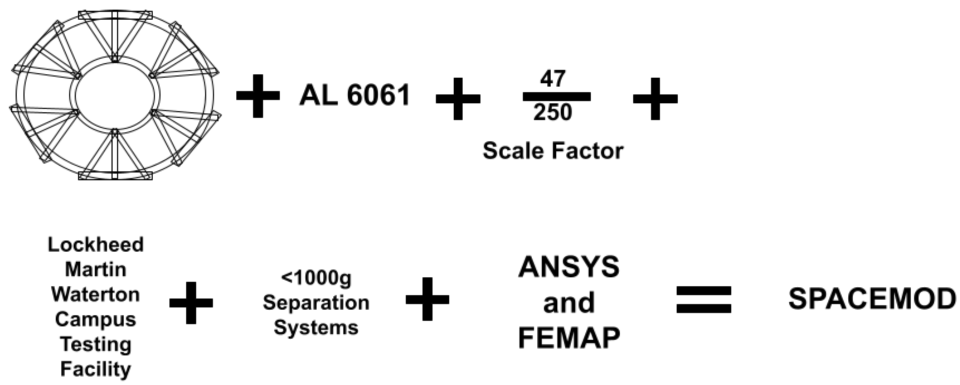


***Figure 8: Baseline Design Equation***

As Fig. 8 demonstrates, the conceptual baseline design of SPACEMOD was synthesized from the results of all the trade studies, as well as critical portions of the project not specifically analyzed through trade studies (separation systems and strucutral analysis software). The preliminary baseline design of the SPACEMOD is a secondary payload adapter consisting of the "Struts" geometry concept constructed out of Aluminum 6061 in a scale factor of $\frac{47}{250}$. It will be analyzed using the structural analysis computer programs ANSYS and FEMAP, and will undergo Quasi-static 12g RSS load vector tests, launch vibration tests similar to the those corresponding to those experienced during an Atlas V launch (as defined in Section 3.2 in the "Atlas V Launch Services User's Guide"), and shock propagation tests similar to those experienced by common low-shock satellite separation methodologies that enact less than 1000g of acceleration on the structure. This shock propagation through the structure will be characterized. Additionally, this initial baseline design is not final. As discussed below in the Possible Variations Section, some of these trade study results are subject to change. As additional analysis is performed, the geometry, material, testing facility, and other aspects of the project may be altered. However, the above definition of the baseline design of SPACEMOD is the current path along which the group is moving forward.

## 5.3 Possible Variations

### 5.3.1 Testing

Per the trade study in Table 12, Lockheed Martin and NTS received scores extremely close in value. As Lockheed Martin did win the trade study, SPACEMOD did ultimately select them for testing. However, as stated previously, depending upon the cost of NTS, NTS is the more favorable option.

Therefore, if there are limited budgetary restrictions, NTS may be utilized for testing instead of Lockheed Martin.

### 5.3.2 Materials

As discussed previously, the materials trade study yielded two very close scores with Aluminum 6061 and Aluminum 7075. Further stress analysis will be conducted to characterize internal stresses. Based on the calculations and material properties listed in Table 3, the team will decide between Aluminum 6061 and Aluminum 7075.

### 5.3.3 Geometry

As discussed previously, the Struts geometry is not the definitive solution to this problem. For greater analysis purposes, the Flat Plate and the Struts design will be carried forward to the PDR phase in order to establish feasibility with greater engineering confidence. We will be creating CAD models of both designs, helping to visualize them in the space of the launch vehicle, and then performing FEM analysis and ANSYS-based stress and strain visualization in order to down-select designs.

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