SPACEMOD

Secondary Payload Adapter Concerned with Eliminating Mass and Optimizing Design

Critical Design Review

Industry Customer:

United Launch Alliance (ULA)

Faculty Advisor:

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12/6/2021

ASEN 4018-011

SPACEMOD Team

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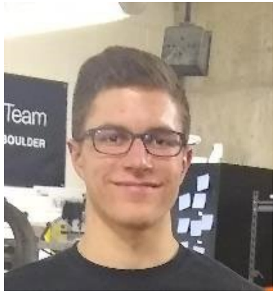

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2

Presentation Outline

1. Project Overview
2. Design Solution
3. Critical Project Elements
4. Design Requirements Satisfaction
5. Project Risks
6. Verification and Validation
7. Project Planning

Project Overview

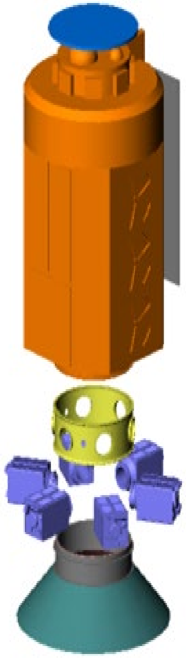
Project Overview

Background:

- The United Launch Alliance (ULA) desires an **optimized** Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Ring.
- How can the design be optimized if it is **not required** to support the primary payload?

Motivation:

- **Mass Reduction:** Without top payload (P/L) requirement, the redesigned ESPA should have a reduced mass compared to the standard ESPA.
- **Shifting Market:** Favoring many smaller payloads rather than a single large payload.



Source: 2018 Moog [1]

Primary Project Objectives

- **Design** a payload carrier that:
    - Maintains ESPA Port Compatibility
    - Maintains ESPA Field of View Compatibility
    - Support six 400 [lb] payloads
- **Reduce mass** compared to legacy ESPA ring
- **Support payloads** through two 8.5 [g] loads radially and axially
    - 12 [g] Root Square Sum (RSS) load
- **Withstand** separation shock environment from a scaled separation system
- **Characterize** shock propagation

Current ESPA Design

SPACEMOD Design

Concept of Operations

Manufacturing
6/25 scale at Aero Machine Shop

→

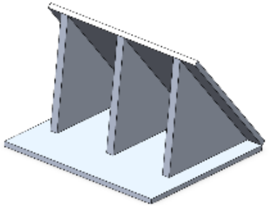
Centrifuge Testing
15.026g RSS load

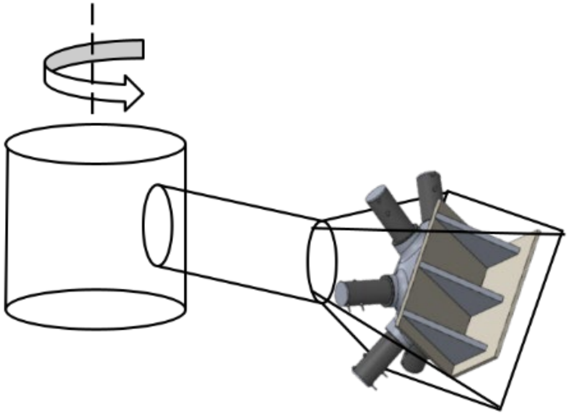
→

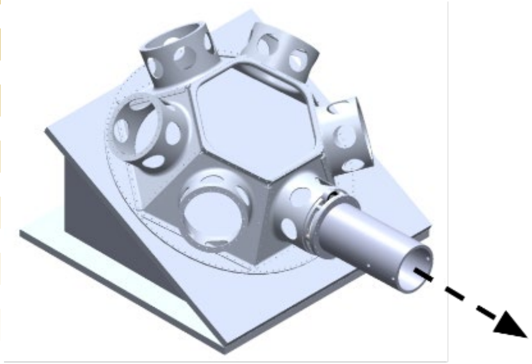
Shock Testing
Scaled PSC 2000785G MkII MLB

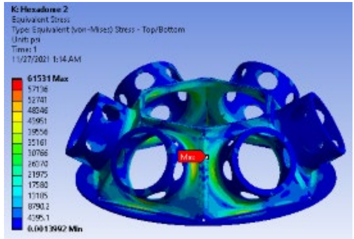
→

Model Validation
Test Data vs ANSYS Model









Concept of Operations: A Day in the Life

Sources: 2021 Spaceflight Inc. [4] & 2020 NASA [2]

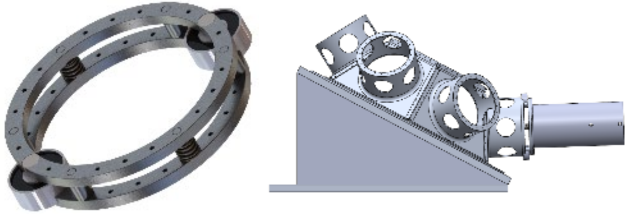
Design Solution

Changes Since PDR

- Structural design has been modified to be manufacturable in the Aero Machine Shop
- SPACEMOD has been analyzed to address thermal concerns
- Now using AL 7075-T6 for additional mass savings and stock availability
- Development of our own separation testing apparatus to more accurately model shock
- Acceleration testing (previously static load testing) will be conducted using a Civil Engineering centrifuge

Design at PDR

Current Design



Separation System

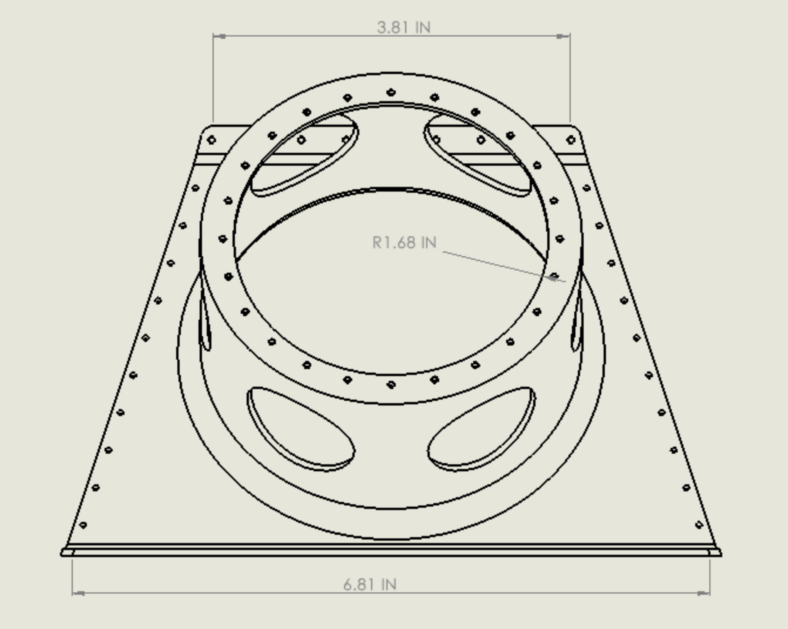
SPACEMOD Design

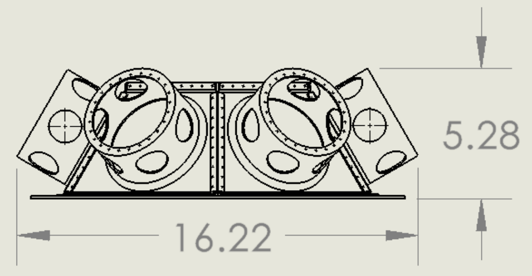
Unscaled Model Dimensions:

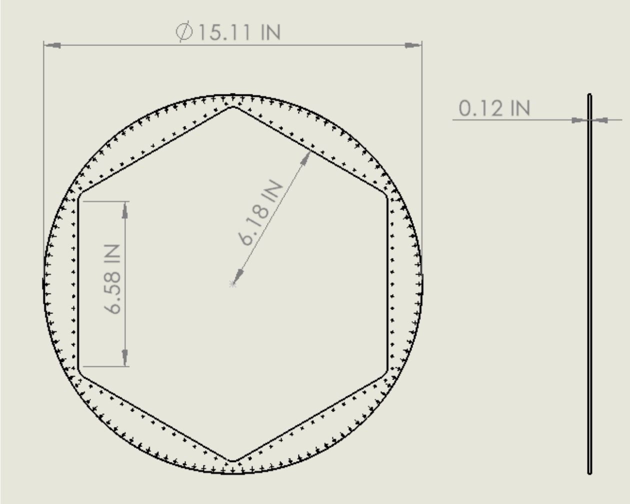
- Mass - 214.6lb
    - **27% mass reduction** from traditional ESPA
- Base diameter - 63”
- Height - 19.6”

Scaled Design for Manufacturing

- Scale Factor: 6/25
- Bolts are No. 0







Material Selection

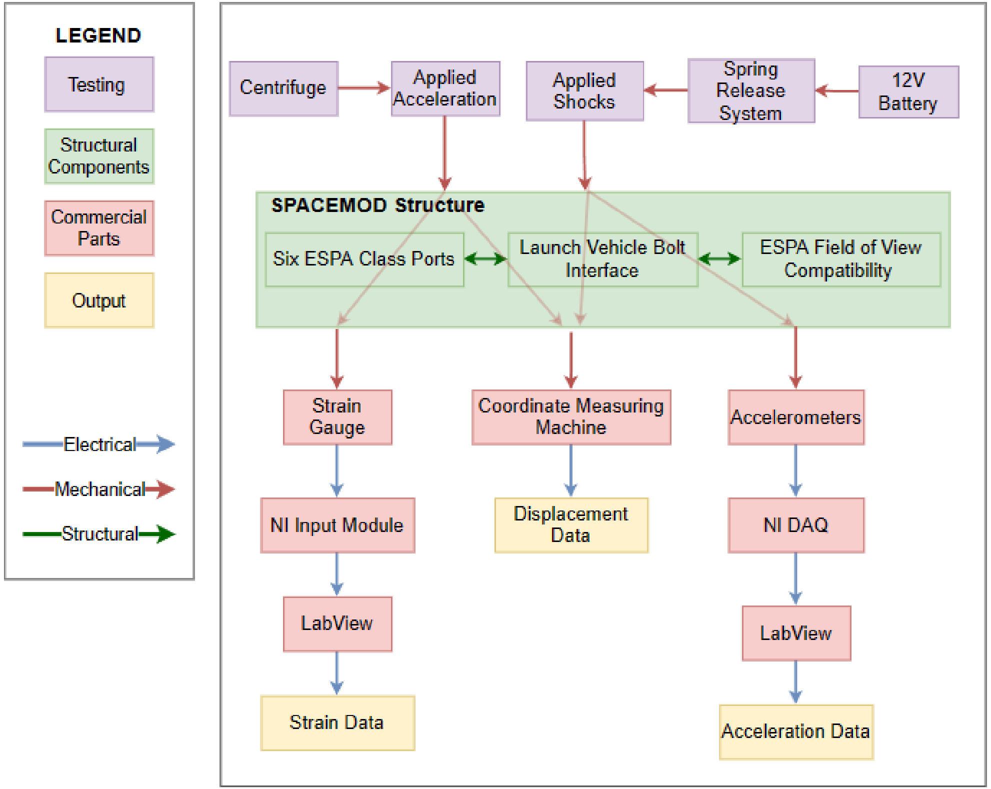
- **Aluminum 7075-T6 was selected**
  - Sufficient stock options for our application
  - High strength to weight ratio
  - Allows for further mass reduction
- Thermal considerations
  - -50° and 100° **C**
  - **Based on Atlas V fairing temperature range***
  - **76.6 ksi to 65 ksi**

Criteria	Property
Density	0.102 [lb/in^3]
Yield Strength	73 [ksi]
Modulus of Elasticity	10,400 [ksi]
Shear Modulus	3900 [ksi]
Cost[1]	$260

1: Estimated cost for raw materials for 1 scaled SPACEMOD

*Source: 2010 United Launch Alliance [4]

Functional Block Diagram



Critical Project Elements

Most Important Critical Project Elements (CPE's)

Category	CPE	Reasoning
1. Technical	**1.1** Manufacturing	**1.1** Manufacturability of model is necessary for testing
	1.2 Simulation and Validation	**1.2** Shock propagation must be characterized (DR 3.3)
	1.3 Testing and Analysis	**1.3** Necessary to verify FR 1, 2, 3
	1.4 Mechanical Design	**1.4** Design must withstand required loads and shocks
2. Logistical	**2.2** Data Recording and Presentation	**2.2** Physical product is not delivered; therefore, data and process are vital

Design Requirements Satisfaction

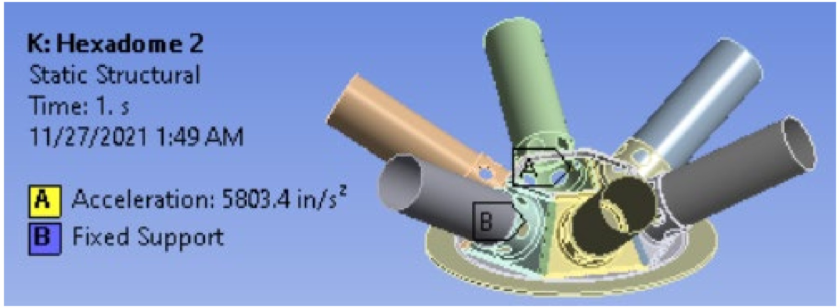
Critical Design Requirements (DR)

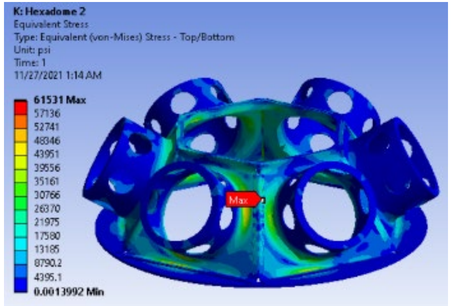
	Description	Satisfaction
DR 1.1	Under 12 [g] RSS static loads or equivalent acceleration with a Factor of Safety (FOS) of 1.25, the SPACEMOD shall not see any plastic deformation.	TBD
DR 3.1	When exposed to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system, the SPACEMOD shall not see any plastic strain.	TBD
DR 3.3	The shock propagation through the SPACEMOD due to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system shall be characterized through simulation and testing.	TBD

DR 1.1 Satisfaction

DR 1.1 Under 12 [g] RSS static loads or equivalent acceleration with a Factor of Safety (FOS) of 1.25, the SPACEMOD shall not see any plastic deformation.

- Extra base component modeled for more accurate contact treatment
- Bolts modeled only in worst case region due to student license mesh limits
- Shell elements used for every component except the upper stiffener
- Iterative process in ANSYS achieved by varying thickness of shell elements
- Verified in testing via strain gauges placed in areas of high stress





DR 1.1 Satisfaction (cont.)

FEM based worst case component yield margins (%)*:

- All margins shown are positive
- Margins are computed from FEM driven worst case values. If there are more than one of a component, the margin shown is the component with the highest stress in the analysis
- Yield strength reduction of Al 7075-T6 at 120F: **70.4ksi**

	Base	Panel	Panel Connector	Upper Stiffening Ring	Bolted Joint
MS_y**	59.0	30.3	19.7	69.3	85.1

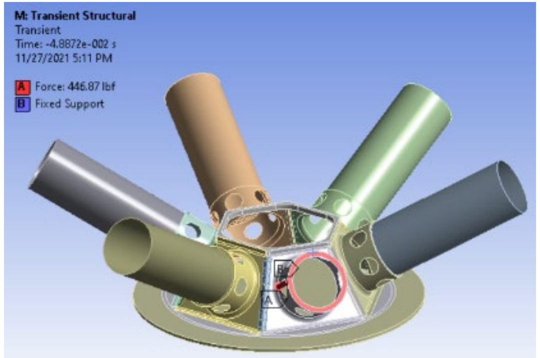
$$MS = \frac{\sigma_{allow}}{FOS * \sigma_{actual}} - 1$$

*Margin calculation method is shown on slide 56

DR 3.1 Satisfaction

DR 3.1 When exposed to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system, the SPACEMOD shall not see any plastic strain.

- Custom force curve data generated by the simple spring force equations
  - Utilizes spring specific information from the Planetary Systems Corp. release mechanism user guide*
- Results here will be used to compare with results from the scaled and simplified release mechanism

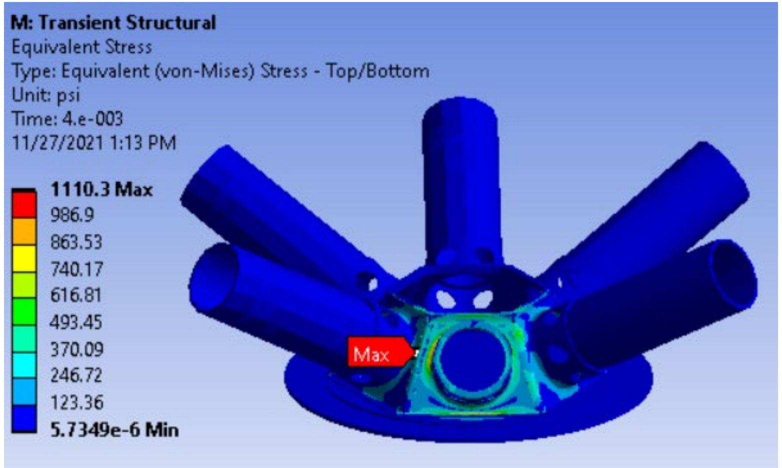


*Source: 2018 Planetary Systems Corp. [3]

DR 3.1 Satisfaction

DR 3.1 When exposed to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system, the SPACEMOD shall not see any plastic strain.

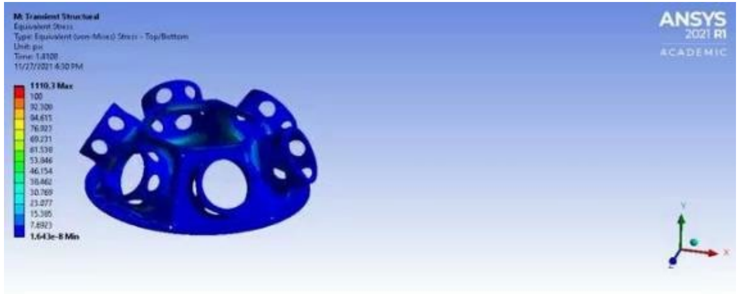
- Peak stress seen - **1100.3 psi**
  - Implies no plastic strain
    - Validated through CMM
  - Occurs at t = 0.004 seconds
- Low shock separation systems do not result in significant local accelerations nor deflection
  - SPACEMOD sees very low resulting stress

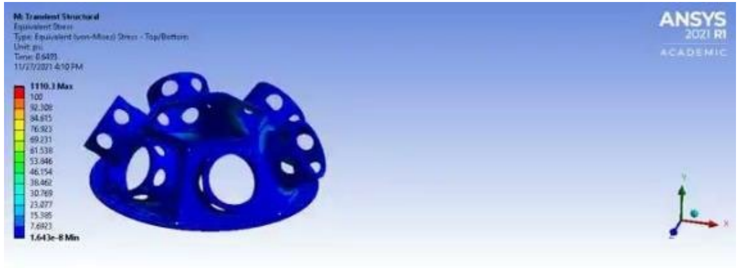


DR 3.3 Satisfaction

DR 3.3 The shock propagation through the SPACEMOD due to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system shall be characterized through simulation and testing.

- Accelerometers can be placed at specified locations
  - Results will be compared with FEM values
- Shock Response Spectrum (SRS) plots will be generated from FEM and experimental data obtained from spring shock mechanism
  - Error can be calculated between expected and experimental SRS plots

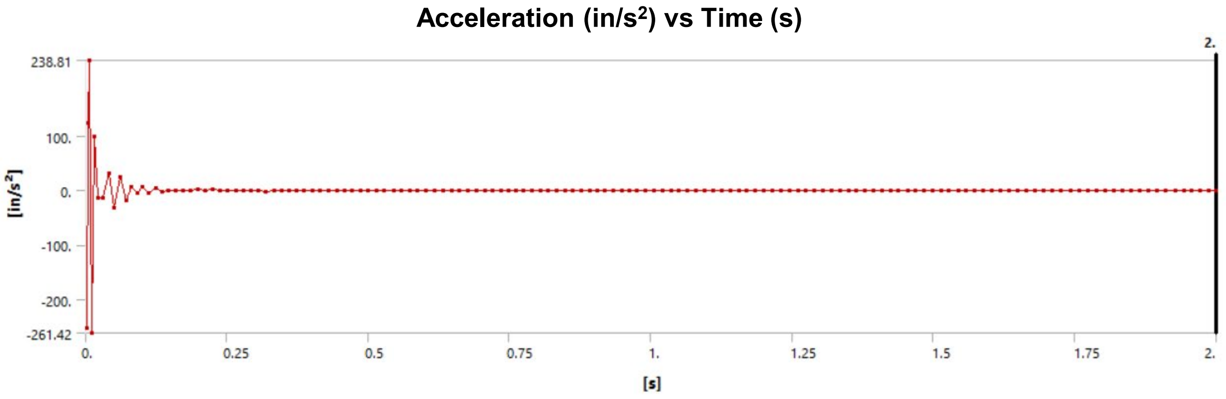


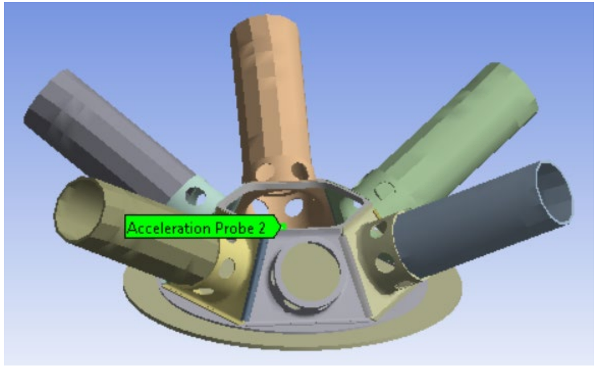


DR 3.3 Satisfaction

DR 3.3 The shock propagation through the SPACEMOD due to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system shall be characterized through simulation and testing.

Example acceleration plot:





Critical Design Requirements (DR)

	Description	Satisfaction
DR 1.1	Under 12 [g] RSS static loads or equivalent acceleration with a Factor of Safety (FOS) of 1.25, the SPACEMOD shall not see any plastic deformation.	✓
DR 3.1	When exposed to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system, the SPACEMOD shall not see any plastic strain.	✓
DR 3.3	The shock propagation through the SPACEMOD due to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system shall be characterized through simulation and testing.	✓

Project Risks

Risk Scoring Definitions

Consequence	Definition
(1) Minor	All load cases are withstood and models validated except one.
(2) Major	Either two load cases are withstood, two models are validated, or a load case is withstood and model is validated. All else fails.
(3) Serious	Either a single load case is withstood or a single model is validated. All else fails.
(4) Catastrophic	Specimen cannot withstand either load case, and neither model cannot be validated.

Likelihood
(1) Extremely Remote
(2) Remote
(3) Probable
(4) Frequent

Risk Table

Risk	Description	Consequence
M	Mistakes during manufacturing	Neither test
N	Specimen plastically strains at port neck	No second test
S	Specimen plastically strains at side stiffeners	No second test
H	Bolt holes do not line up due to imperfections	Neither test

Pre-Mitigation Risk Matrix

M - Manufacturing
N - Neck fails
S - Stiffeners fail
H - Bolt holes

Consequence					
Minor					
Major					
Serious		**N, S**			
Catastrophic		**M**	**H**		
	Extremely Remote	Remote	Probable	Frequent	**Likelihood**

Risk Mitigation

Risk	Description	Mitigation
M	Manufacturing	Build in material margin and time margin to manufacture additional segments
N	Neck fails	Manufacture additional segments
S	Stiffeners fail	Build in material margin and time margin to manufacture additional stiffeners
H	Bolt holes	Manufacture additional segments

Post-Mitigation Risk Matrix

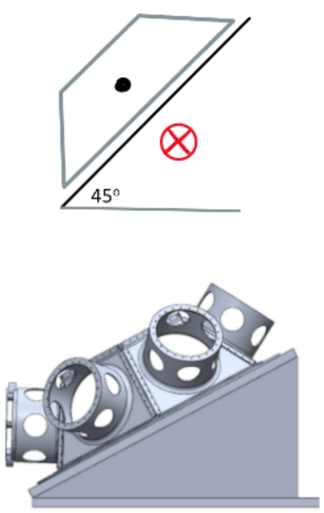
M - Manufacturing
N - Neck fails
S - Stiffeners fail
H - Bolt holes

Consequence					
Minor		**N, S**	**H**		
Major					
Serious		N, S			
Catastrophic	**M**	M	H		
	Extremely Remote	Remote	Probable	Frequent	**Likelihood**

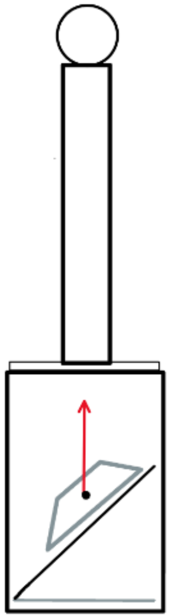
Verification and Validation

Acceleration Testing Diagram

Placed into Centrifuge: Side View



Top-Down View as Centrifuge is Spun Up



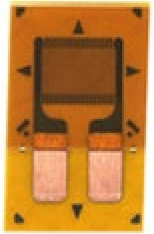
Acceleration Load Testing

- **CIEST Lab** located on Main Campus
- Medium Centrifuge can support up to 15 g/tons
- Centrifuge bucket has a max volume of 18x17.5x23 in
- Will install a plate onto the centrifuge basket to angle our design at 45 degrees
- Can achieve 8.5 g with a 1.25 FOS in the horizontal and vertical directions
- Uses a SCXI-1520 machine that supports 32 strain gauge channels using customizable LabView Software

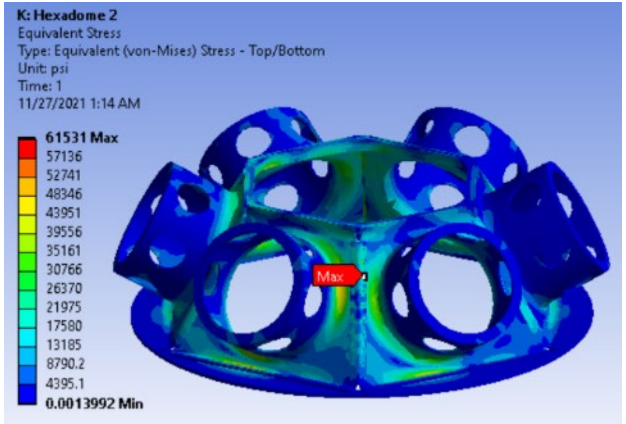
Medium Centrifuge in CIEST

Acceleration Load Testing: Strain Gauges

- Strain Gauge selected: CEA-13-062UWA-350
- 12 Strain Gauges placed at stress concentrations around the SPACEMOD
  - Two on each panel of the design at strain concentrations
- Placed at stress concentrations to compare simulated counterparts
- Will ensure that the physical design matches simulated expectations



CEA-13-062UWA-350
Strain Gauge



Acceleration Load Testing: Data Acquisition & Software

- CIEST Lab Data Acquisition System:
  - NI SCXI-1520 Input Module
    - 12 Strain gauge channels utilized over 2 modules, 8 channels per module
- MAX software is used to configure strain gauge channels
- Customizable Labview software is used to output strain measurements vs time in .csv file

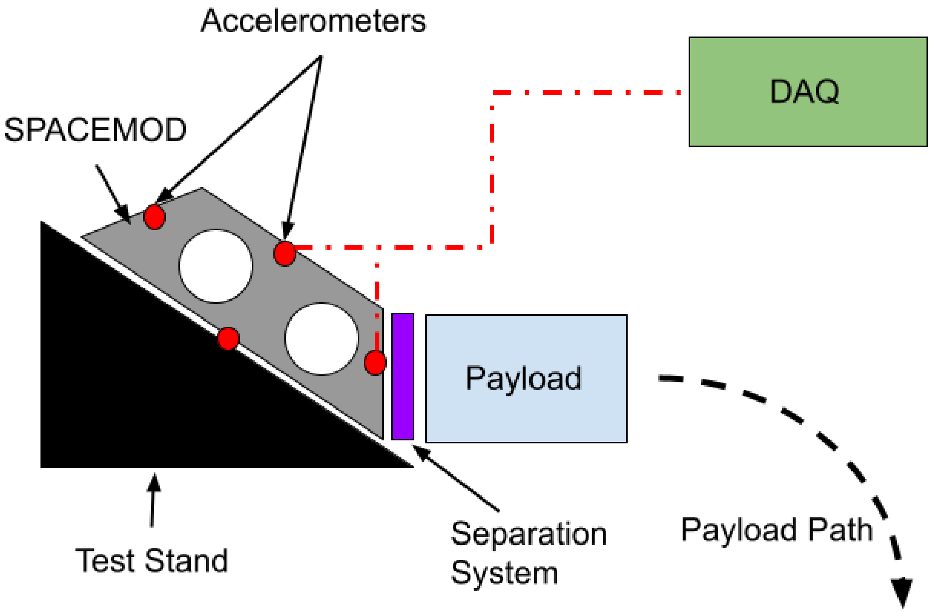
Acceleration Testing Verification and Validation

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

CPE 1.4 Design must withstand required loads and shocks

- Strain Gauges are used to verify the stresses and strains seen in the analysis within the structure
- Comparison of the real structure strain gauge data and the analysis simulation allows for unforeseen plastic deformation/high stress concentrations within the structure to be identified by the SPACEMOD team
- Any unforeseen plastic deformation and high stress concentrations can then be measured using a CMM

Shock Testing Diagram



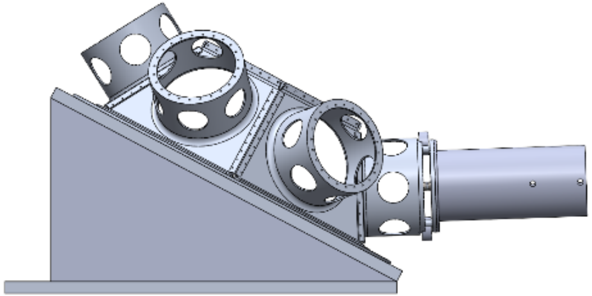
1. Place accelerometers and mount structure
2. Mount payload and prime separation system
3. Separate payload
4. Collect data on shock response

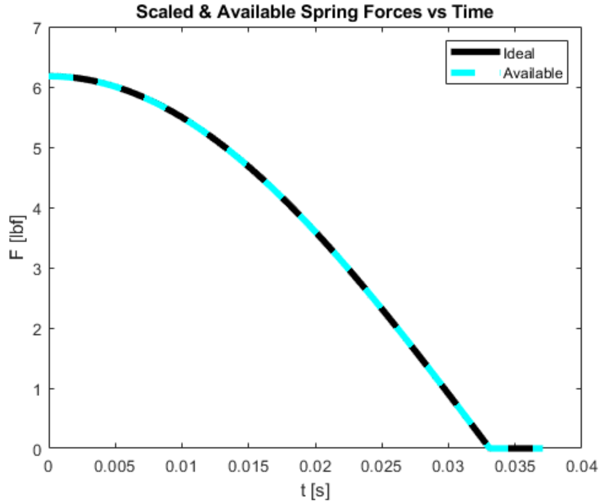
Shock Testing: Facilities and Equipment

- Facilities
  - IdeaForge Shock Tower Data Acquisition System
  - Test will be performed using our own method and separation system
- Equipment
  - Accelerometers
  - DAQ
  - Scaled separation system
  - Scaled payloads
  - Coordinate Measuring Machine (CMM)

Shock Testing: Separation System

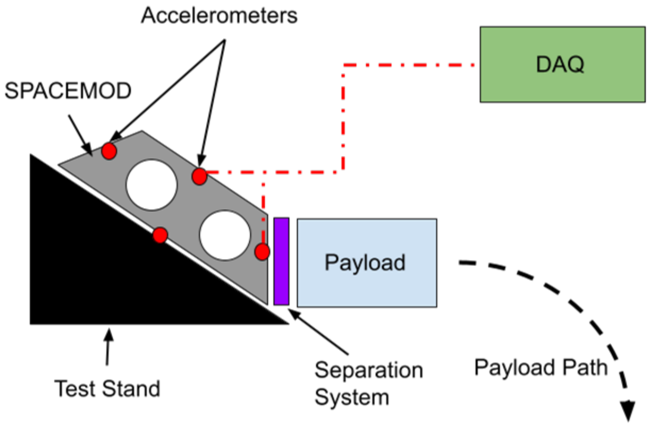
- Planetary Systems Corp. (PSC) separation system (2000785G MkII MLB)
  - Peak acceleration of ~1.12 [g]
- Dual Spring Electromagnetic release mechanism
  - Peak acceleration of ~1.12 [g]





Shock Testing: Accelerometers

- Accelerometers selected:
  - PCB Piezotronics Model 353B17
    - Frequency Range: (±5%) 2-10000 Hz
    - Resolution: 0.005 g rms (0.05 m/s^2 rms)
  - PCB Piezotronics Model U35C22
    - Frequency Range: (±5%) 2-10000 Hz
    - Resolution: 0.004 g rms (0.04 m/s^2 rms)
- Placement:
  - Port of separation
  - Top ring
  - Bottom ring
  - Backside
- Accelerometers return acceleration vs time for specific locations



Shock Testing:
Data Acquisition & Software

- Idea Forge Data Acquisition System:
  - NI 9234 DAQ
    - 4 accelerometer inputs
    - Sampling frequency up to 51.2 kHz
    - Built-in anti-aliasing filter that adjusts to sampling rate
- Test partner software at Idea Forge will be used to collect data
  - Can edit trigger level, time to record, and sensitivity

Shock Testing Verification and Validation

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

CPE 1.4 Design must withstand required loads and shocks

- Test provides a scaled simulated separation shock with our own developed separation system.
- Accelerometers will be placed on the surface of SPACEMOD, and acceleration vs time data generated for various points along structure.
- Coordinate Measuring Machine at Advanced Precision Machining will be used to ensure plastic deformation hasn't occurred.

Project Planning

SPACEMOD Org Chart for Next Semester

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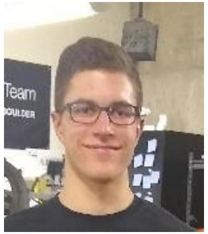
Project Manager

Ryan Collins
Finance Lead

Scott Mansfield
Safety Lead



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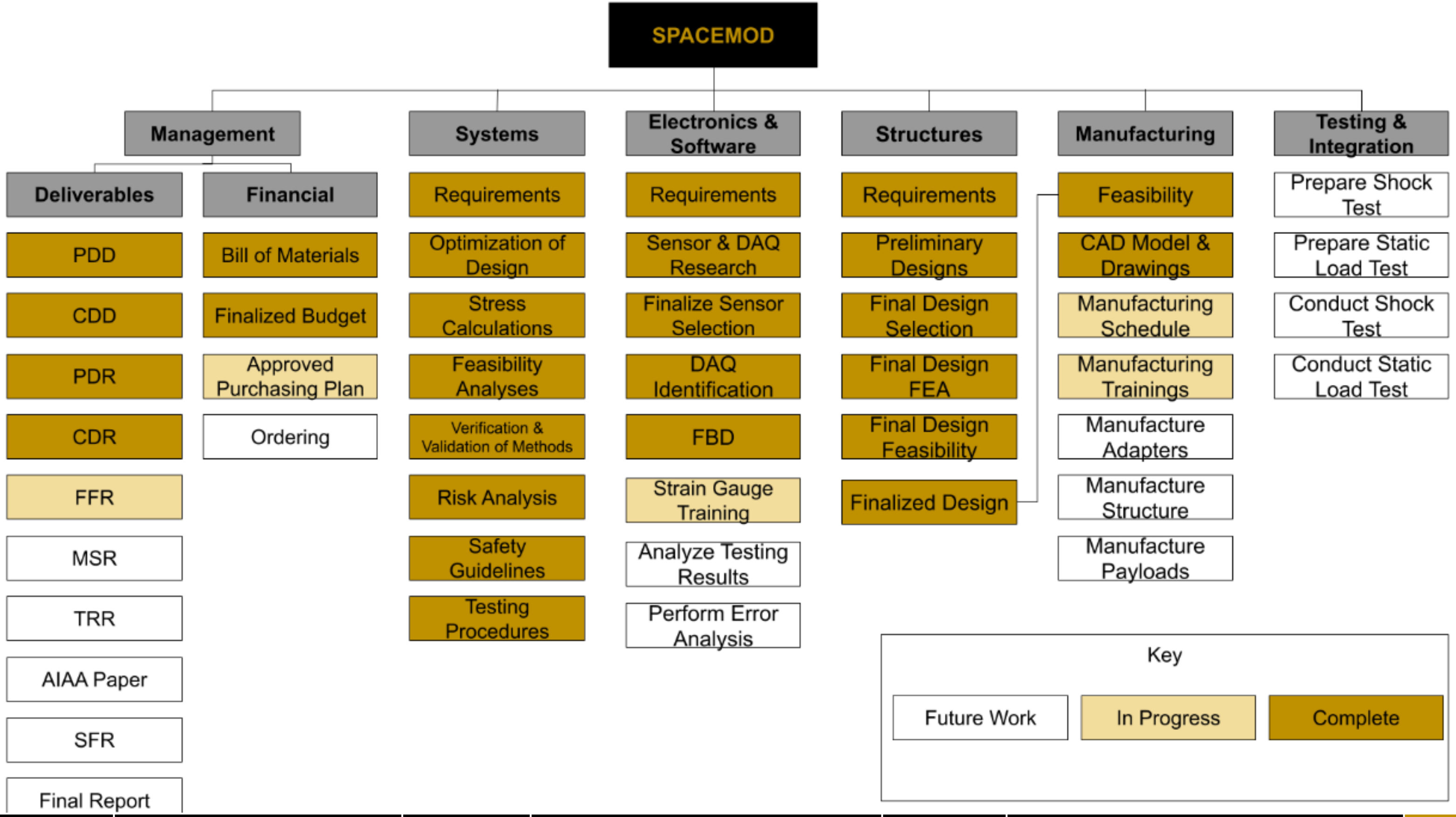
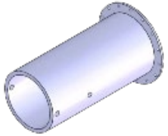
Work Breakdown Structure



Manufacturing Plan

Structure	Week 1 1/10 - 1/16	Week 2 1/17 - 1/23	Week 3 1/24 - 1/30	Week 4 1/31 - 2/6	Week 5 2/7 - 2/13	Week 6 2/14 - 2/20	Week 7 2/21 - 2/27	Week 8 2/28 - 3/6
	Prepare Fixtures	Manufacture Sides and ESPA Ports (x 6)		Manufacture Top and Bottom Rings		Assemble SPACEMOD		
						Manufacture Separation System		
						Manufacture Centrifuge Assembly		
								Manufacture Payloads

** All Manufacturing to be Performed in the Aero Machine Shop

Tests to be Conducted

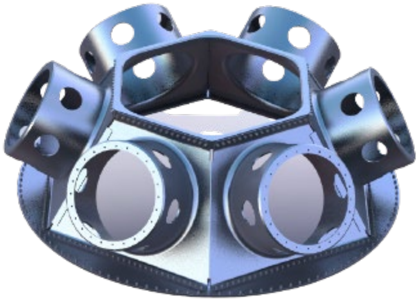
Acceleration Testing

- Tests will be conducted using medium-sized centrifuge (50g-ton) in CIEST Laboratory in Engineering Center.
- We have maintained communication for scheduling and cost purposes with lab coordinators.
- Rotating centrifuge creates safety risk
  - CIEST safety procedures

Shock Testing

- Will be conducted using our own pseudo-separation system using IdeaForge safety equipment and DAQ software.
- We have maintained communication for scheduling purposes with the lab coordinator.
- Airborne payload creates safety risk
  - IdeaForge safety procedures
  - Additional safety procedures (clamps, distance, no flagging, etc)

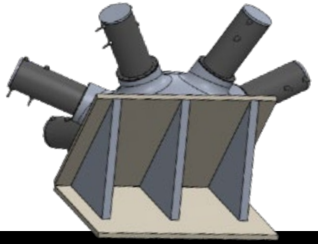
Cost Plan - Hexadome



SPACEMOD - Bill Of Materials - 2021-2022						
Section	**Subsection**	**Item**	**Sub-Item (Tooling)**	**Amount**	**Cost**	**Total Cost**
Software						
Hexahedron						
	Hexahedron					
		7075 T6 Aluminum Blocks		6	$41.67	250.02
			1/4" Ballmill	1	$40.20	40.20
		18-80 Washer		5	$9.37	46.85
		18-8 Socket Head Screw		20	$10.29	205.80

$542.87

Cost Plan - Centrifuge Testing



SPACEMOD - Bill Of Materials - 2021-2022						
Section	Subsection	Item	Sub-Item (Tooling)	Amount	Cost	Total Cost
Software						
Hexahedron						
Centrifuge Testing (CT)						
	CT Adapter					
		Top Angled Plate (Cast Aluminum)		2	$67.31	134.62
		45 degree Wedge Plates (Cast Aluminum)		2	$53.39	106.78
	PL Adapter					0.00
		Lead Buckshot		1	$60.00	60.00
		Aluminum Cylinder (6061)		6	$16.72	100.32
		Steel Sheet (7 Ga)		1	$68.86	68.86
		External Hex Drive, 1/4"-20 Thread Size, 4" Long		2	$3.70	7.40
		1/4 - 20 Nuts		1	$7.15	7.15
	Testing					0.00
		Medium Centrifuge (400 g-ton)		3	$50.00	150.00
		Staff Engineer time		6	$61.00	366.00
		Strain Guages (6)		4	$40.00	160.00
		Strain Guage Neutralizer		1	$18.59	18.59
		Strain Guage Conditioner		1	$20.02	20.02
		Strain Gauge Adhesive		1	$104.81	104.81
		Strain Guage Wiring (326-DFV)		20	$7.50	150.00
		Isopropyl 99		1	$5.50	5.50
		DAQ		2	$1.10	2.20

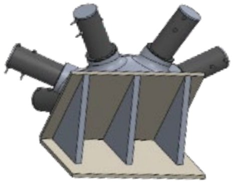
$1,462.25

Cost Plan - Shock Testing

SPACEMOD - Bill Of Materials - 2021-2022						
Section	Subsection	Item	Sub-Item (Tooling)	Amount	Cost	Total Cost
Software						
Hexahedron						
Centrifuge Testing (CT)						
Shock Testing (ST)						
	Seperation System					
		Electromagnets - 1 set of 10		1	$30.99	30.99
		Neodynium Magnets		2	$1.88	3.76
		Compression Springs		2	$11.87	23.74
		Base Ring (6061 Aluminum)		1	$30.86	30.86
		Top Ring (6061 Aluminum)		1	$19.62	19.62
	Testing	Battery (12 V)		1	$20.00	20.00
		Accelerometers		10	$20.00	200.00

$328.97

Cost Plan - Overview

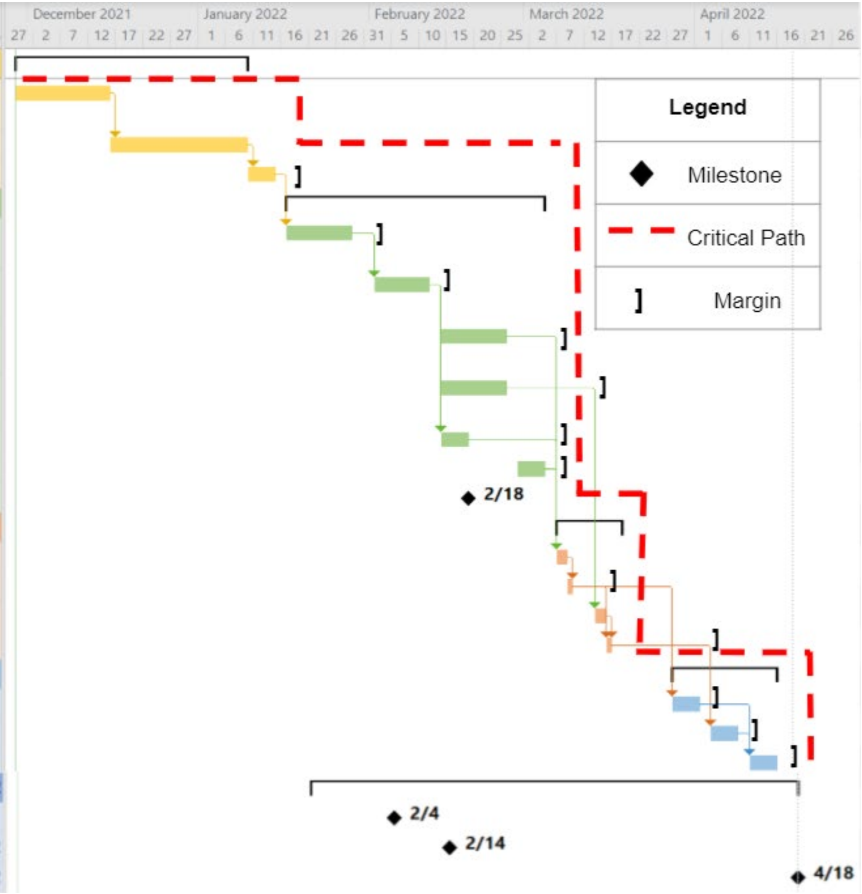


SPACEMOD - Bill Of Materials - 2021-2022						
Section	**Subsection**	**Item**	**Sub-Item (Tooling)**	**Amount**	**Cost**	**Total Cost**
Software						$0.00
Hexahedron						
	Hexahedron					
		7075 T6 Aluminum Blocks		6	$41.67	$250.02
			1/4" Ballmill	1	$40.20	$40.20
		18-80 Washer		5	$9.37	$46.85
		18-8 Socket Head Screw		20	$10.29	$205.80
Centrifuge Testing (CT)						
	CT Adapter					
		Top Angled Plate (Cast Aluminum)		2	$67.31	$134.62
		45 degree Wedge Plates (Cast Aluminum)		2	$53.39	$106.78
	PL Adapter					
		Lead Buckshot		1	$60.00	$60.00
		Aluminum Cylinder (6061)		6	$16.72	$100.32
		Steel Sheet (7 Ga)		1	$68.86	$68.86
		External Hex Drive, 1/4"-20 Thread Size, 4" Long		2	$3.70	$7.40
		1/4 - 20 Nuts		1	$7.15	$7.15
	Testing					
		Medium Centrifuge (400 g-ton)		3	$50.00	$150.00
		Staff Engineer time		6	$61.00	$366.00
		Strain Guages (6)		4	$40.00	$160.00
		Strain Guage Neutralizer		1	$18.59	$18.59
		Strain Guage Conditioner		1	$20.02	$20.02
		Strain Gauge Adhesive		1	$104.81	$104.81
		Strain Guage Wiring (326-DFV)		20	$7.50	$150.00
		Isopropyl 99		1	$5.50	$5.50
		DAQ		2	$1.10	$2.20
Shock Testing (ST)						
	Seperation System					
		Electromagnets - 1 set of 10		1	$30.99	$30.99
		Neodynium Magnets		2	$1.88	$3.76
		Compression Springs		2	$11.87	$23.74
		Base Ring (6061 Aluminum)		1	$30.86	$30.86
		Top Ring (6061 Aluminum)		1	$19.62	$19.62
	Testing	Battery (12 V)		1	$20.00	$20.00
		Accelerometers		10	$20.00	$200.00
						$2,334.09

- Total expected expenditures of ~$2,300±$200
- Maximum lead time 7 days
- All materials in stock within continental U.S.
- Includes tooling, welding, adhesives, etc.

Timeline Moving Forward

Task Name	Duration	Start	Finish
Preparation	**31 days**	**Mon 11/29/21**	**Sun 1/9/22**
Order Parts and Materials	13 days	Mon 11/29/21	Wed 12/15/21
Part Arrivals	18 days	Thu 12/16/21	Sun 1/9/22
Prepare Fixtures	5 days	Mon 1/10/22	Fri 1/14/22
Manufacturing	**35 days**	**Mon 1/17/22**	**Fri 3/4/22**
Manufacture Panels and ESPA Ports	10 days	Mon 1/17/22	Fri 1/28/22
Manufacture Top and Bottom Rings	8 days	Wed 2/2/22	Fri 2/11/22
Manufacture Separation System	10 days	Mon 2/14/22	Fri 2/25/22
Manufacture Centrifuge Assembly	10 days	Mon 2/14/22	Fri 2/25/22
Assemble SPACEMOD	5 days	Mon 2/14/22	Fri 2/18/22
Manufacture Payloads	5 days	Mon 2/28/22	Fri 3/4/22
Model Assembled	1 day	Fri 2/18/22	Fri 2/18/22
Testing	**10 days**	**Mon 3/7/22**	**Fri 3/18/22**
Prepare Shock Test	2 days	Mon 3/7/22	Tue 3/8/22
Conduct Shock Test	1 day	Wed 3/9/22	Wed 3/9/22
Prepare Static Load Test	2 days	Mon 3/14/22	Tue 3/15/22
Conduct Static Load Test	1 day	Wed 3/16/22	Wed 3/16/22
Analysis	**15 days**	**Mon 3/28/22**	**Fri 4/15/22**
Shock Test Analysis	5 days	Mon 3/28/22	Fri 4/1/22
Static Load Analysis	5 days	Mon 4/4/22	Fri 4/8/22
Error Analysis	5 days	Mon 4/11/22	Fri 4/15/22
Deliverables	**62 days**	**Fri 1/21/22**	**Mon 4/18/22**
AIAA Abstract	11 days	Fri 1/21/22	Fri 2/4/22
TRR	21 days	Mon 1/17/22	Mon 2/14/22
SFR	26 days	Mon 3/14/22	Mon 4/18/22



Acknowledgements

The ULA team would like to thank Dr. Donna Gerren, Professor Matt Rhode, Mr. Nate Coyle, Professor Wingate, and Teaching Fellow Emma Markovich for their contributions in guiding and shaping the content and organization of this presentation.

Thank you to everyone who supported the SPACEMOD team!

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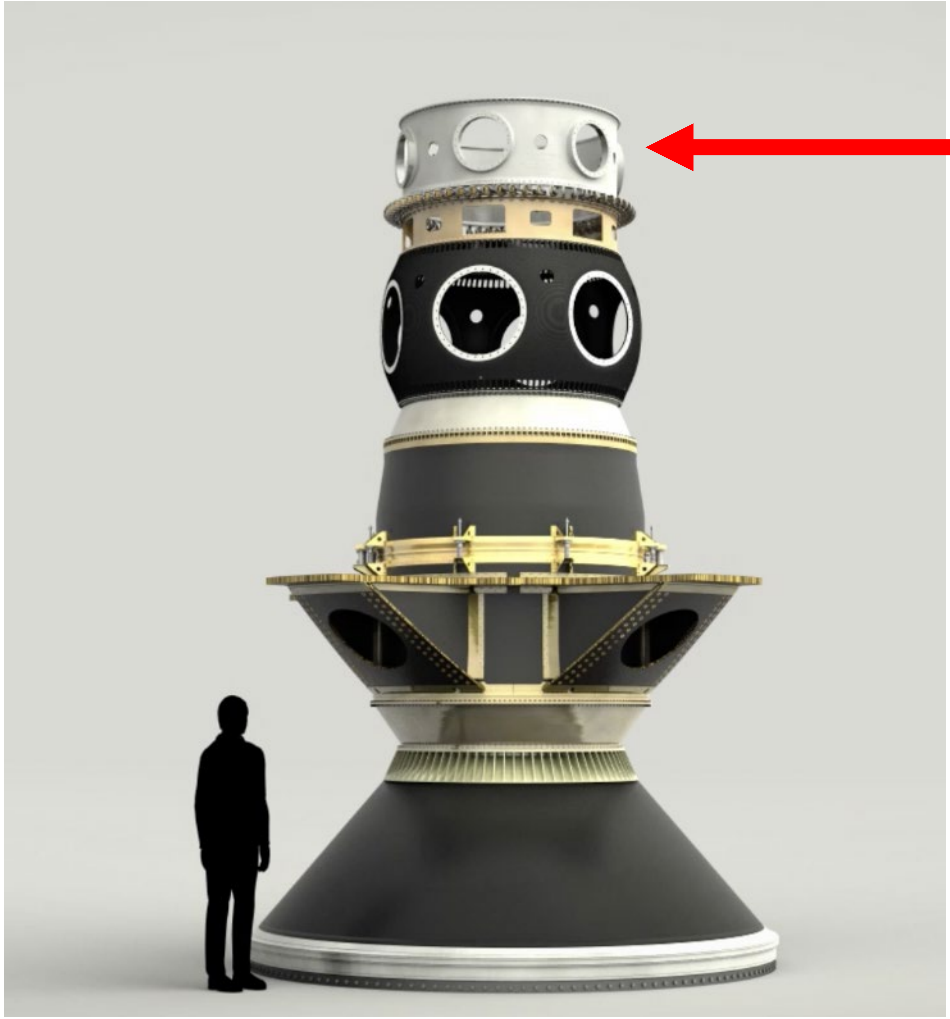
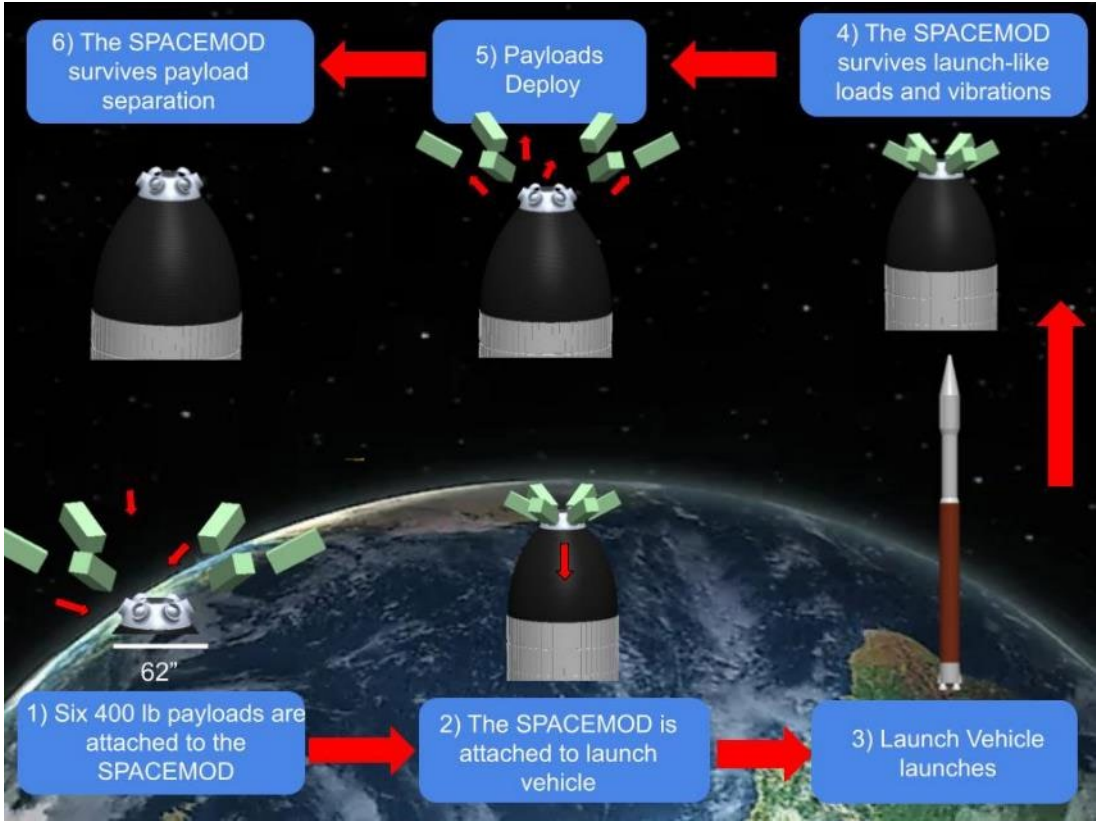
Questions?

Additional Resources



SSO-A Spaceflight
Launched December 2019

Concept of Operations



Functional Requirements (FR)

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

FR 2 - The SPACEMOD shall maintain standard ESPA Interface compatibility as defined in Section 4 of the MOOG “ESPA’s User Guide” [2] and the self-defined Field of View (FOV) compatibility.

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

Design Requirements (DR)

DR 1.1	Under 12 [g] RSS static loads or equivalent acceleration with a Factor of Safety (FOS) of 1.25, the SPACEMOD shall not see any plastic deformation.
DR 1.2	The SPACEMOD shall maintain the attachments to all six attached payloads during exposure to static loads or equivalent accelerations, provided the payloads are scaled models of ESPA-class payloads, as defined in requirement DR 2.1.
DR 2.1	The SPACEMOD shall have the ability to successfully attach up to 6 scaled ESPA-class payloads in evenly spaced locations about the carrier. ESPA-class payloads are defined as 400 [lb] payloads with a center of gravity located 20 [in] or less 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.

Design Requirements (DR) Continued

DR 2.2	To maintain Field of View (FOV) compatibility, the SPACEMOD shall have six circular ESPA interfaces or equivalent mechanisms, each with a diameter of 15 [in] scaled by a scale factor, whose centers are in a circular pattern 60 degrees apart from one another on a plane parallel to the standard interface plane with the below launch vehicle. The normal vectors of the ESPA ports shall have a non-zero component in any non-axial, transverse direction.
DR 3.1	When exposed to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system, the SPACEMOD shall not see any plastic strain.
DR 3.2	The SPACEMOD shall maintain the attachments to the five payloads that are intended to remain attached during exposure to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system, provided the payloads are scaled models of ESPA-class payloads, as defined in requirement DR 2.1.
DR 3.3	The shock propagation through the SPACEMOD due to a shock provided by a scaled model of the Planetary Systems Corporation 2000785G MkII MLB separation system shall be characterized through simulation and testing.

All Critical Project Elements (CPE's)

Category	CPE	Reasoning
1. Technical	**1.1** Manufacturing	**1.1** Manufacturability of model necessary for test
	1.2 Simulation and Validation	**1.2** Shock propagation must be characterized (DR 3.3);
	1.3 Testing and Analysis	**1.3** Necessary to verify FR 1, 2, 3
	1.4 Mechanical Design	**1.4** Design must withstand required loads and shocks
	1.5 Electronics	**1.5** Necessary to run tests
2. Logistical	**2.1** Testing Limitations	**2.1** Some tests can't be performed at CU and require larger testing facilities
	2.2 Data Recording and Presentation	**2.2** Physical product is not delivered; therefore, data and process are vital
3. Budgetary	**3.1** Financial Limitations	**3.1** Budget of $5,000

FOS Justification

Table 3.3-1: Spacecraft Structural Tests, Margins, and Durations

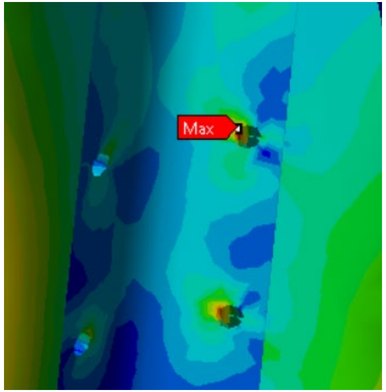
Test	Qual	Protoflight	Flight
Static • Level • Analyses	1.25 x Limit (DLF or CLA)	1.25 x Limit (CLA)	1.1 x Limit (Proof Tests)
Acoustic • Level • Duration	Limit + 3 dB 2 Min	Limit + 3 dB 1 Min	Limit Level 1 Min
Sine Vib • Level • Sweep Rate	1.25 x Limit 2 Oct/Min	1.25 x Limit 4 Oct/Min	Limit Level 4 Oct/Min
Shock	1 Firing	1 Firing	1 Firing
*Note: The Protoflight test levels are also used for validation of ICD dynamic environments when supplemental FM measurements (Mission Satisfaction Option) are made for a specific mission.			

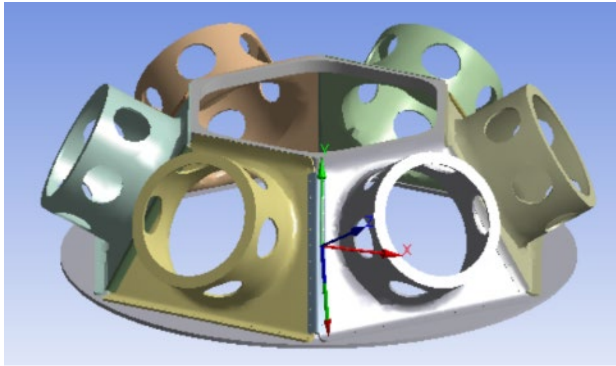
Why did we rule out Vibration Testing?

1. Customer did not specify vibration testing
2. There is no great way to scale vibration modes for our unique structure.
   a. We would have to find an analytical model for a similar structure
   b. Create a vibrational model in FEM
   c. Validate the model using **many** iterations of testing different models
3. Vibrational testing would have to be performed while the static load is applied.

FEM Analysis

- Initially modeled as beam elements with preload
  - Had many issues with contacts during set-up, decided to abandon and go with a simpler method
  - Results show that bolts are not significantly loaded, thus the simplified results are likely satisfactory
- Worst case bolted joint loads occur in the center of the panel connections
- Bolts modeled as revolute joints
  - Loads pulled from joint probes and used in worst case bolt shear margin calculations
  - $MS_{shear} = 0.851$

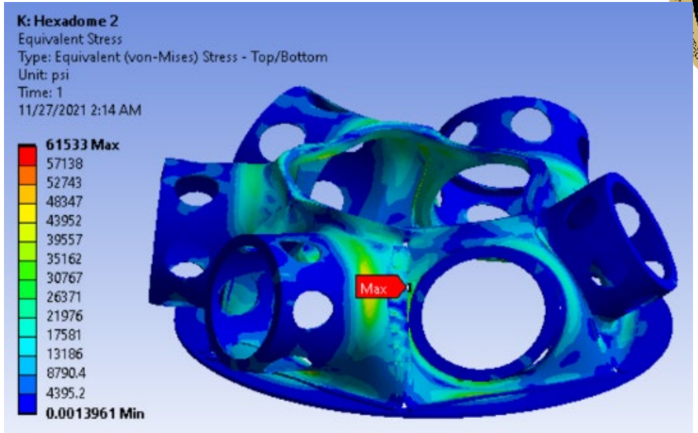


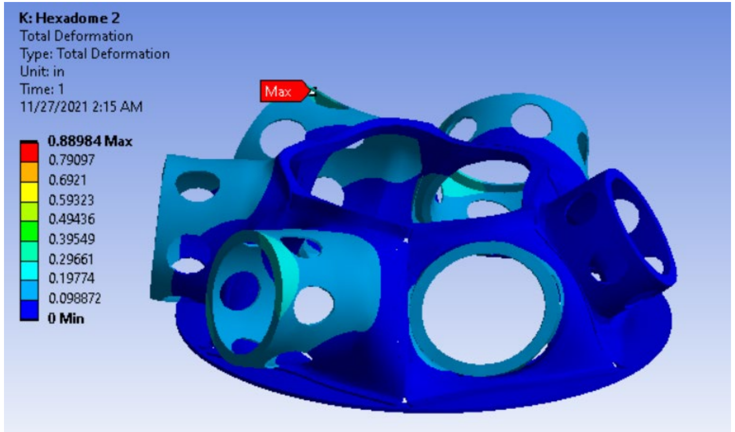


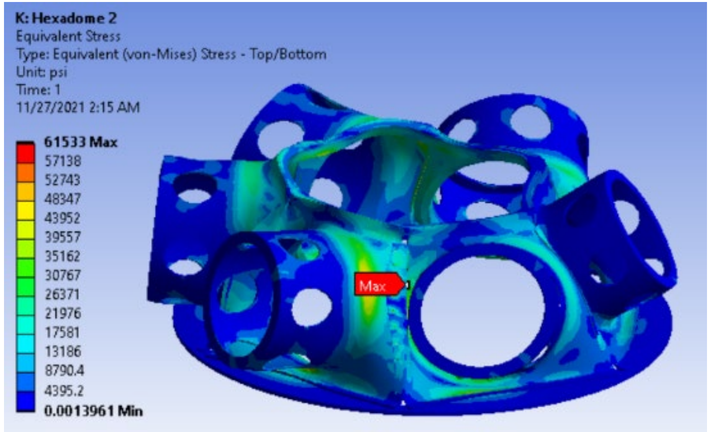
FEM Analysis Cont.

Material properties:

- Same as described on material slide
- Linear model used since the design should not exceed YS
- 41X deflection shown here







Margin Calculation Process

1. Determine allowable values in the structure (stress, strain, or deflection)
2. Choose a Factor of Safety, in this case 1.25
3. Determine actual critical value in the structure (stress, strain, or deflection)
4. Use the below equation to calculate margin
    a. The stress based formula is used as an example, but this can be replaced with whatever you care about
    b. Margins can be computed directly from FEM stresses if the loads applied are scaled by the Factor of Safety

$$MS = \frac{\sigma_{allow}}{FOS * \sigma_{actual}} - 1$$

Shock Testing: Accelerometer Specifications

PCB Piezotronics: Model 353B17 (Qty. 3)

- Sensitivity: (±10%)10 mV/g (1.02 mV/(m/s²))
- Measurement Range: ±500 g pk (±4905 m/s² pk)
- Broadband Resolution: 0.005 g rms (0.05 m/s² rms)
- Frequency Range: (±5%)1 to 10000 Hz
- Sensing Element: Quartz
- Overload Limit (Shock): ±98100 m/s² pk

Model 353B17

PCB Piezotronics: Model U35C22 (Qty. 3)

- Sensitivity: (±15%)10 mV/g (1.0 mV/(m/s²))
- Measurement Range: ±500 g pk (±4900 m/s² pk)
- Broadband Resolution: 0.004 g rms (0.04 m/s² rms)
- Frequency Range: (±5%)1.0 to 10000 Hz
- Sensing Element: Ceramic
- Overload Limit (Shock): ±98000 m/s² pk

Model U35C22

Shock Testing: NI 9234 DAQ

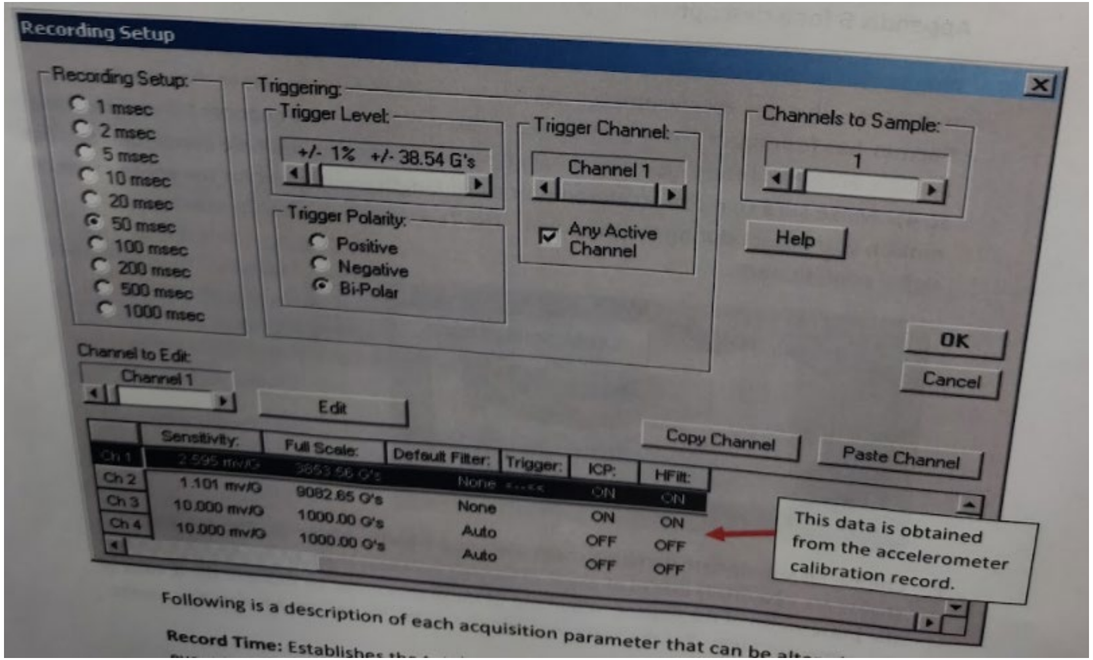
DATASHEET

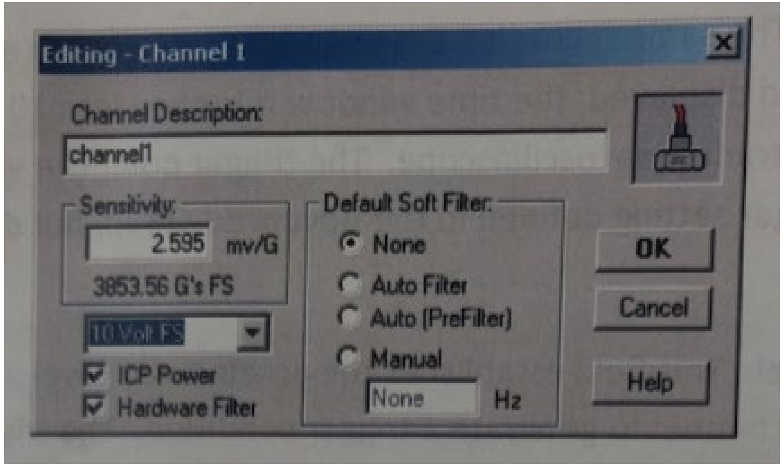
NI 9234

4 AI, ±5 V, 24 Bit, 51.2 kS/s/ch Simultaneous, AC/DC Coupling, IEPE AC Coupling

- Software-selectable AC/DC coupling (AC coupled at 0.5 Hz)
- Software-selectable IEPE signal conditioning with AC coupling (2 mA)
- -40 °C to 70 °C operating, 5 g vibration, 50 g shock
- 24-bit resolution
- Anti-aliasing filters
- 102 dB dynamic range
- Smart TEDS sensor compatibility

Shock Testing: Idea Forge Test Partner Software





Strain Gauges for Quasi Static Load Testing

- Strain gauges are a measuring device that turns displacement into strain by measuring the change in its resistance when it is compressed or extended (In this experiment when under load the gauge will be compressed)
- These measurements are then turned into electrical signals using a wheatstone bridge circuit
- These measurements are then put into a measurement device to turn the signals into strain data over a time span

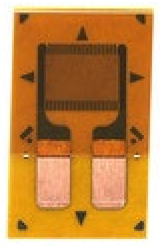


Figure: CEA-13-062UWA-350 Strain Gauge

Strain Gauge Selection

Strain Gauge Selection:

CEA-13-062UWA-350

- 350 Ω: Ohm Resistance (Higher resistance to get more precise results)
- 13: Type of metal in gauge (Picked to match with the Aluminum we will be using in manufacturing)
- 062: Length of strain gauge (Smaller size picked to get more accurate results on curved surfaces)
- UWA: Grid and tab geometry (Standard geometry used in testing)
- CEA: General use strain gauge (Standard strain gauge used in testing)

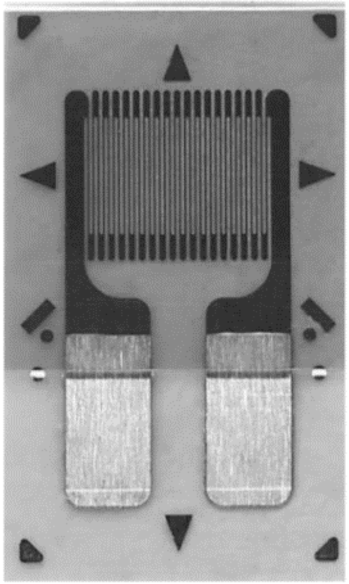
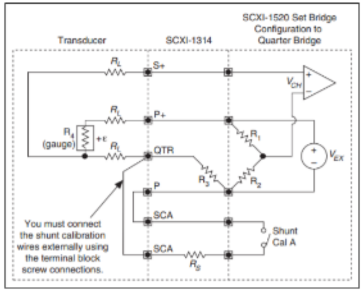


Figure: CEA-13-062UWA-350 Strain Gauge

Strain Gauge Setup

- M-Bond 200: Adhesive to attach strain gauge to design
- M-Prep Neutralizer 5A: Neutralizes any chemical reactions introduced by Conditioner A and preps surface for strain gauges placement
- M-Prep Conditioner A: Phosphoric compound that accelerates surface clearing process
- ¼ Wheatstone Bridge: This is used to turn the resistance from the strain gauges into a meaningful electrical signal (Using a ¼ bridge because it is widely used for our type of testing and our test is not influenced temperature changes so only one gauge will be needed)
- 3 Conductor Cable: Used to connect the strain gauge to the ¼ wheatstone bridge circuit (soldered to the strain gauge and attached to the SCXI-1520 module, S+ and QTR attached to one tab and P+ to other)



Testing Facility

CEIST Lab:

- Located on main campus
- Uses an SCXI-1520 machine that has the ¼ wheatstone SCXI-1520 bridge circuit we will use already built into it for data gathering
- can support up to 32 strain gauge channels going through it at once using custom Lab View software
- Can use medium centrifuge which can go up to 50 g/tons
- Can install a plate onto the centrifuge basket in order to angle our design at 45 degrees to achieve the 8.5 g with a 1.25 FOS in the horizontal and vertical directions
- For each channel strain gauge and wire specifications (lead resistance, gauge resistance, gauge) can be imputed into Measurement and Automation Explorer program in order to set up calculation for strain

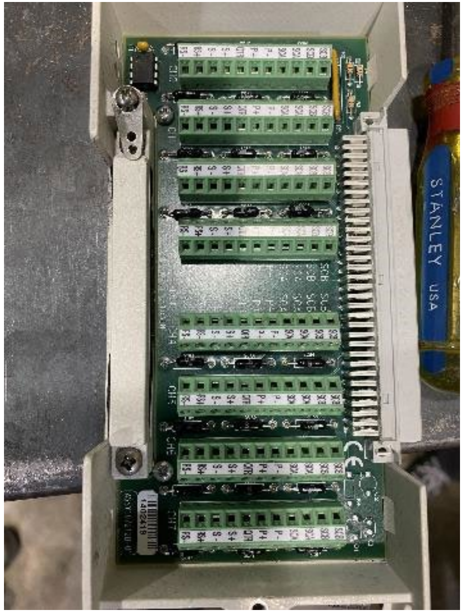


Figure: Medium Centrifuge at CEIST

Acceleration Testing: SCXI-1520

Table 3-1. Excitation Voltage for Configuration and Gauge Resistances

Configuration/ Sensor	Resistance	NI-DAQmx Excitation Voltage Range	Traditional NI-DAQ (Legacy) Excitation Voltage Range
Quarter- or Half-Bridge	120 Ω	≤6.96 V	0 to 6.875 V
	350 Ω	0 to 10 V	0 to 10 V
	1000 Ω	0 to 10 V	0 to 10 V
Full-Bridge or Full-Bridge Sensor	120 Ω	≤3.48 V	0 to 3.125 V
	350 Ω	0 to 10 V	0 to 10 V
	1000 Ω	0 to 10 V	0 to 10 V

Acceleration Testing: SCXI-1520

Input Voltage Range:

$$\textit{quarter bridge} = (\textit{max strain}) \times (\textit{excitation voltage}) \times (0.5\ \mu\text{V/V}/\mu\varepsilon)$$

$$\textit{half bridge} = (\textit{max strain}) \times (\textit{excitation voltage}) \times (1.0\ \mu\text{V/V}/\mu\varepsilon)$$

$$\textit{full bridge} = (\textit{max strain}) \times (\textit{excitation voltage}) \times (2.0\ \mu\text{V/V}/\mu\varepsilon)$$

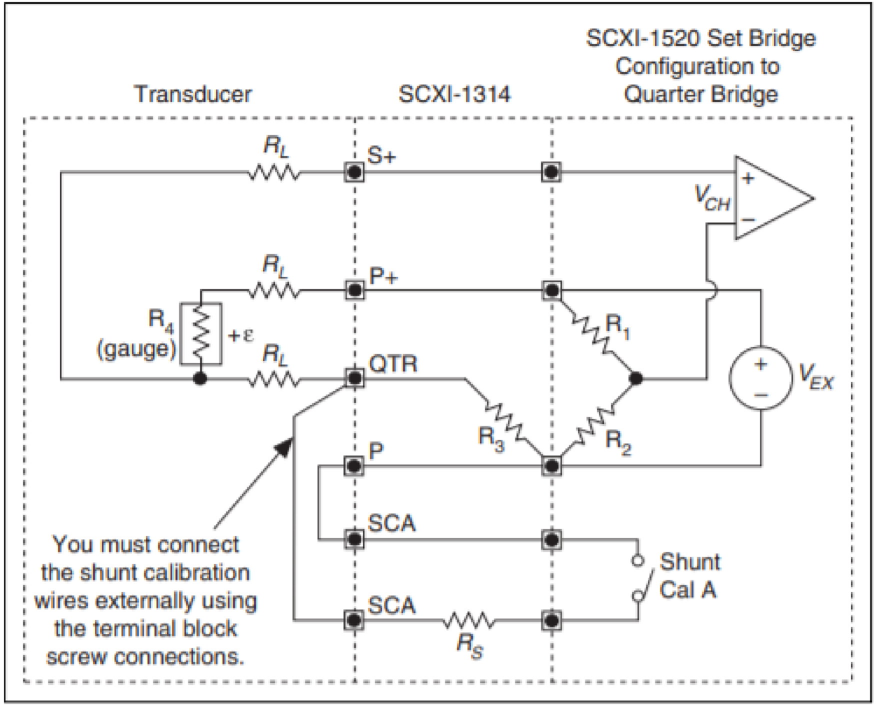
Maximum Input Voltage:

$$(\textit{max input signal voltage}) = \frac{(\textit{sensor sensitivity}) \times (\textit{excitation voltage}) \times (\textit{maximum input})}{(\textit{sensor full-scale input})}$$

$$\textit{gain} \le \frac{(\textit{SCXI-1520 output voltage range}) \times (10\ \text{V})}{(\textit{input signal voltage})}$$

¼ Wheatstone Bridge Circuit Diagram

- Will not be using lower shunt section (do not need that accurate of results, increase difficulty of use)
- R1, R2, R3 are the load resistors used and R4 is the strain gauge resistance



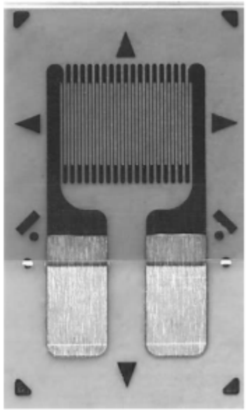
Strain Gauge Data Sheet

MICRO MEASUREMENTS
A VPG Brand

062UW / 062UWA

General Purpose Strain Gages—Linear Pattern

GAGE PATTERN DATA



actual size

GAGE DESIGNATION (See Notes 1, 2 and 3)	RESISTANCE (OHMS)	OPTIONS AVAILABLE
CEA-XX-062UW-120	120 ±0.3%	P2, SP35
CEA-XX-062UW-350	350 ±0.3%	P2, SP35
CEA-XX-062UWA-350	350 ±0.3%	P2, SP35
W2A-XX-062UW-120	120 ±0.6%	
W2A-XX-062UW-350	350 ±0.6%	

DESCRIPTION

General-purpose gage. Exposed solder tab area is 0.07 x 0.04 in (1.8 x 1.0 mm).

Pb-free Available
RoHS* COMPLIANT

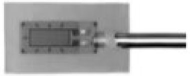
GAGE DIMENSIONS

Legend
ES = Each Section
S = Section (S1 = Section 1)
CP = Complete Pattern
M = Matrix
inch / millimeter

Gage Length	Overall Length	Grid Width	Overall Width	Matrix Length	Matrix Width
0.062	0.220	0.120	0.120	0.31	0.19
1.57	5.59	3.05	3.05	7.9	4.8

GAGE SERIES DATA — See Gage Series datasheet for complete specifications

Series	Description	Strain Range	Temperature Range
CEA	Universal general-purpose strain gages.	±3%	–100° to +350°F (–75° to +175°C)
W2A IPX8S Rated	For water-exposure applications. Based on the CEA Series with Option P2 pre-attached cables, W2A strain gages are fully enclosed with a silicone rubber coating and tested to 10 GΩ insulation resistance, 1 meter water depth, 30 minutes duration. Other requirements can be addressed on demand.	±3%	–60° to +180°F (–50° to +80°C)



Example of the W2A construction:
IPX8S Rated

Note 1: Insert desired S-T-C number in spaces marked XX.
Note 2: W2A leadwires are attached with lead-free solder and are RoHS compliant.
Note 3: Pattern names ending with "A" are built with Advanced Sensors Technology.

* CEA gages with Option P2 are not RoHS compliant.

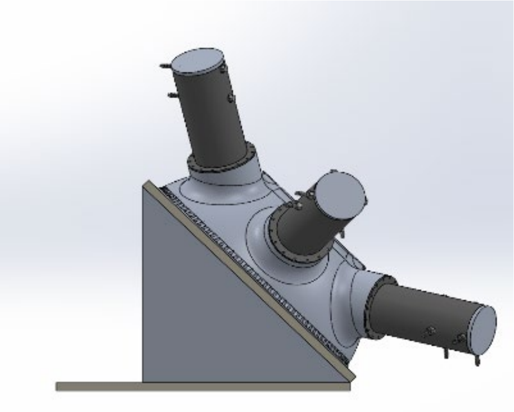
Technical Data References: SEARCH our website using the document number.
11506 – Gage Series; **11507** – Optional Features

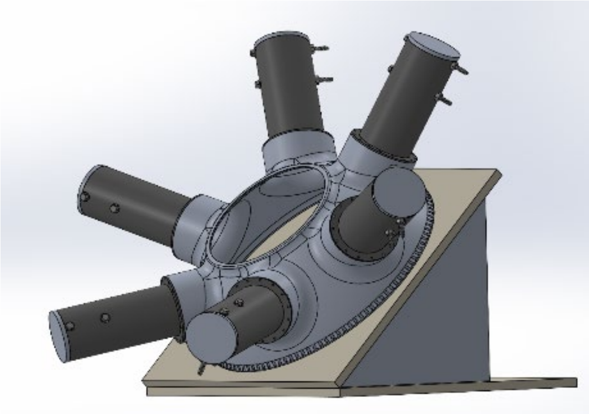
Document No.: 11189
Revision: 02-Feb-2019

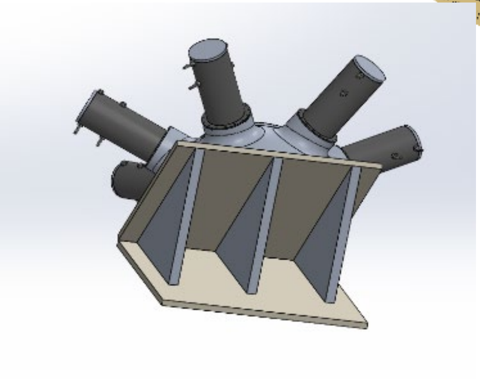
For technical questions, contact mm@vpgsensors.com

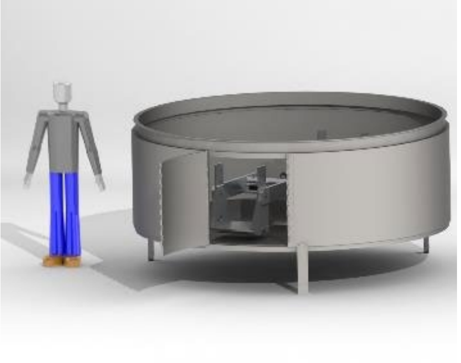
www.micro-measurements.com
1

Centrifuge Testing Assembly (CAD)

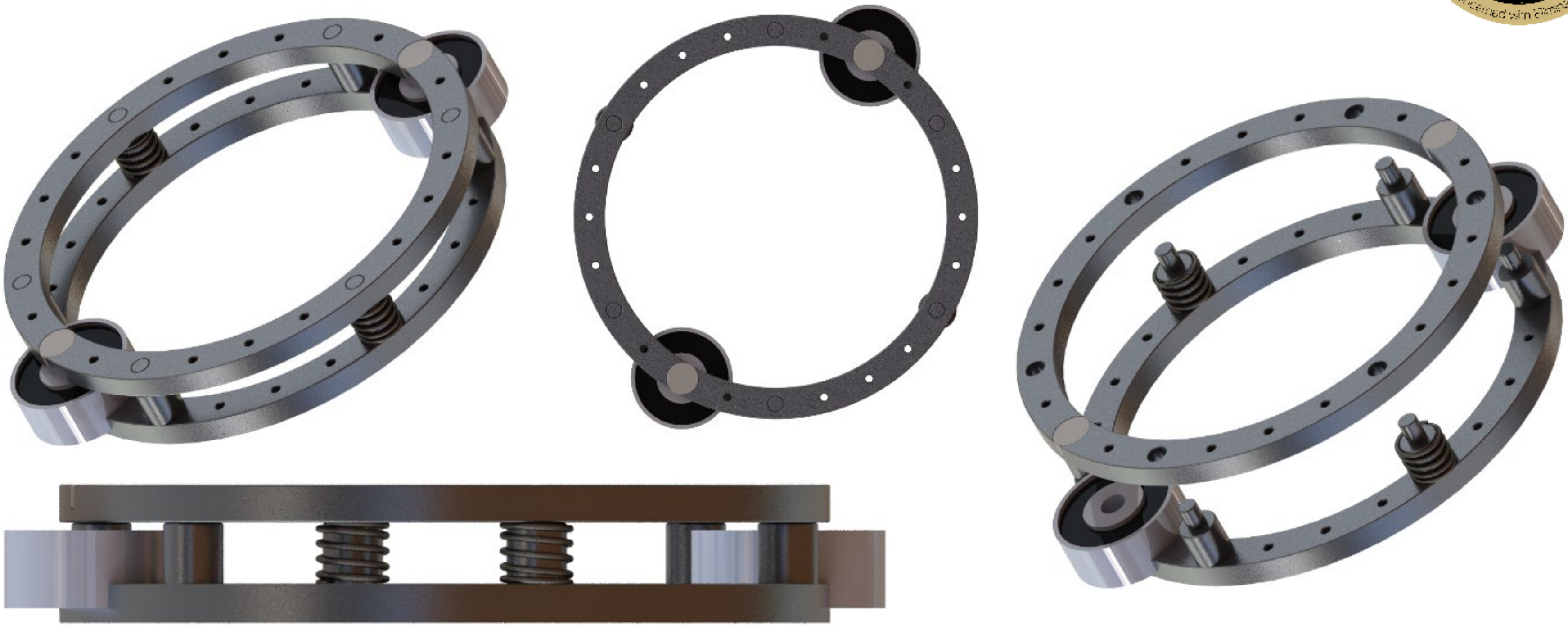




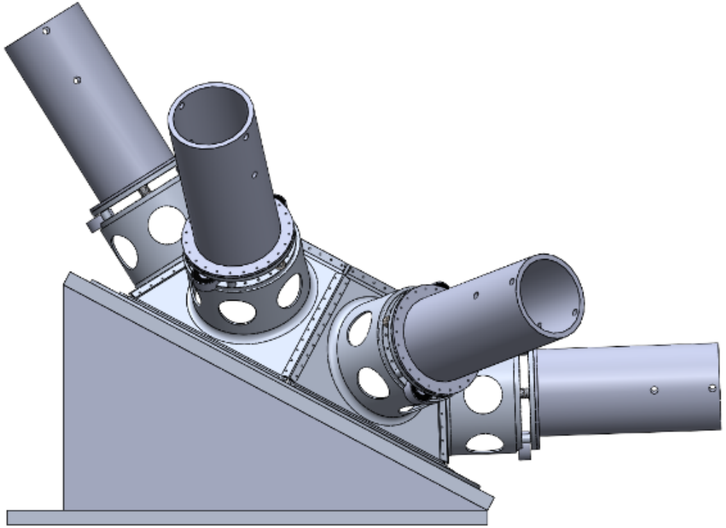


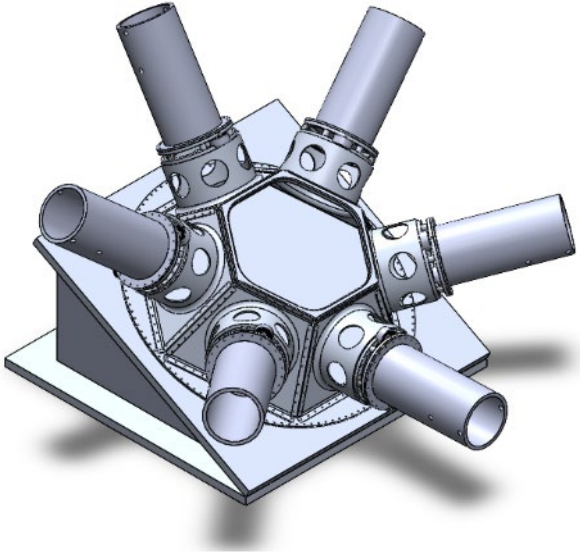


Separation System Design

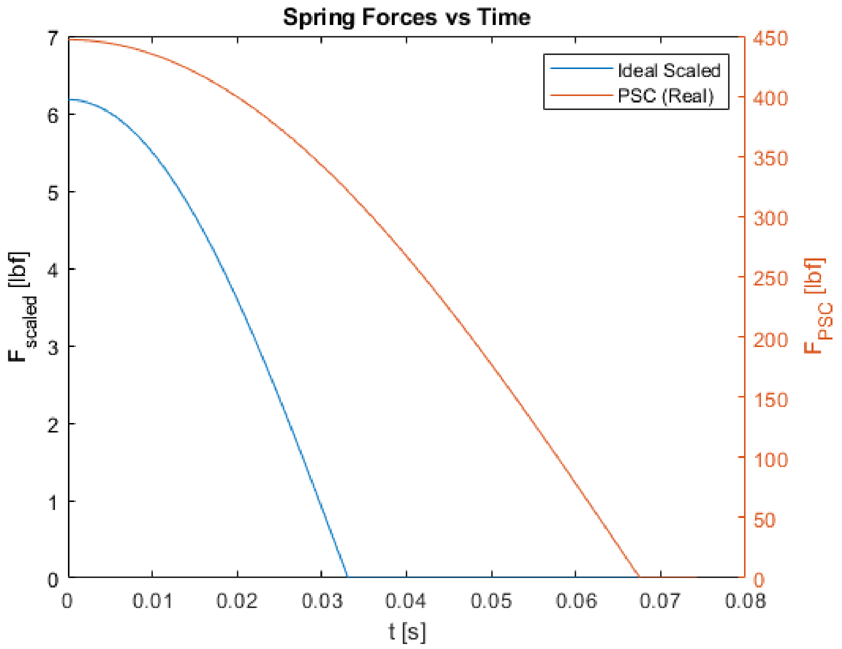


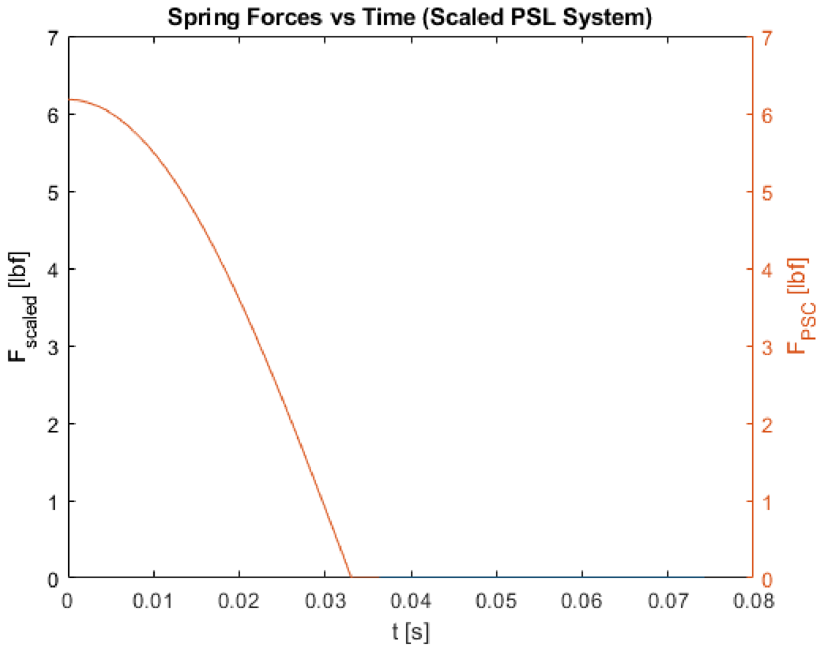
Shock Test Setup





Shock Testing

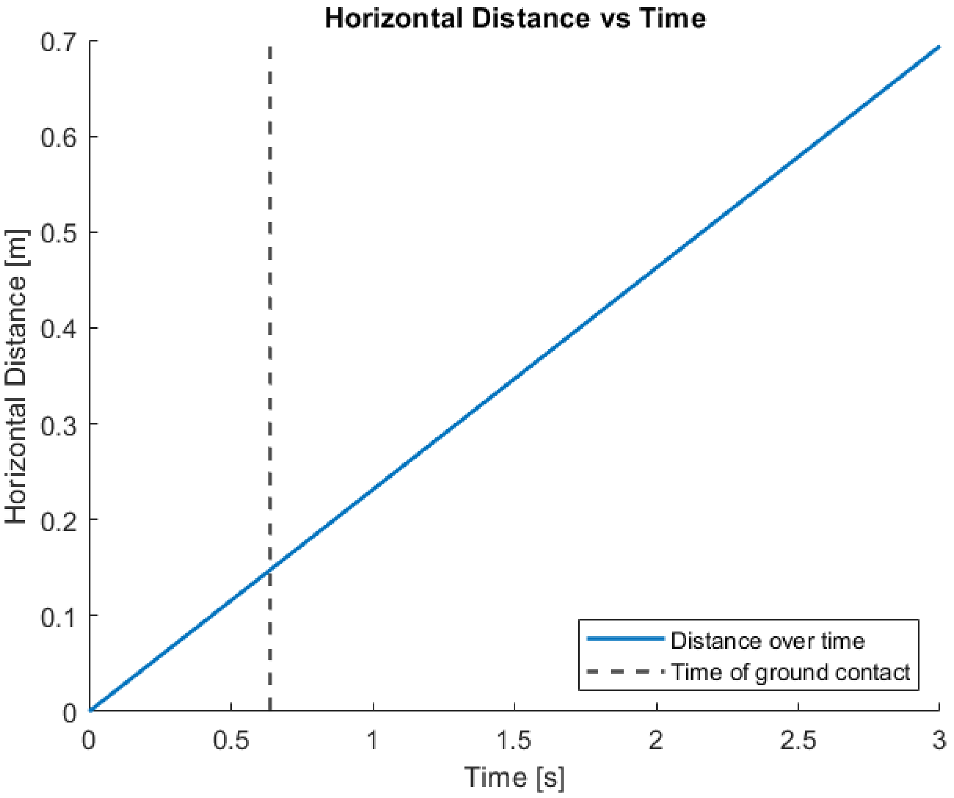




Safety Considerations

- Manufacturing
  - Aero Machine Shop safety regulations
- Acceleration Testing
  - CIEST Lab Safety Procedures
- Shock Testing
  - Only two team members may prime separation system; all others must be behind a screen and not in the direct line of fire at at distance of at least 4 ft (projected launch distance of 6in yields FOS of 7.9)
  - All team members must wear safety glasses throughout procedure
  - Do not point payload separation system at anything you do not want to be destroyed
  - Push separation system into place, engage electromagnets, and apply clamps
    - One to two team members remove clamps while keeping body parts outside of payload launch direction
    - These team members move behind screen with rest of team
    - Test is immediately conducted thereafter (i.e. electromagnets are disengaged)

Shock Test Launch Distance




```
Final x distance traveled: 0.154202 m
Final x distance traveled: 6.070956 in
```

- Assuming y_0 = 2 meters
  - Extreme over approximation
- All team members must be 4 ft away (FOS = 7.9) and not in direct line of fire

Linear Expansion of Bolts Calculations

```
The bolt will contract by 0.00029983 [in] when in a -50°F environment.
 The bolt diameter decreased to 0.2497 [in]

The bolt hole diameter will need to be 0.2501 [in] to meet
 contraction requirements when in a -50°F environment

The bolt will expand by 0.00030079 [in] when in a 200°F environment.
 The bolt diameter decreased to 0.2503 [in]

The bolt hole will expand by 0.00041021 [in] when in a 200°F environment.
 The bolt hole diameter decreased to 0.2505 [in]
```

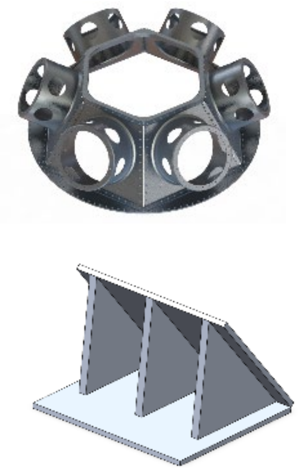
Fully Expanded Bill of Materials

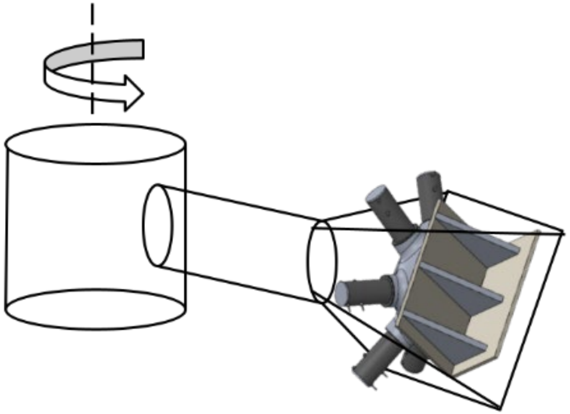
SPACEMOD - Bill Of Materials - 2021-2022															
Section	Subsection	Item	Sub-Item (Tooling)	Size	Package Size	Amount	Cost	Total Cost	Expected Lead Time	Ordered on	Received on	RFQ/Purchase Web Link	PM Sig	Section Lead Sig	Fiance Sig
Software								$0.00							
	Structural Analysis							$0.00							
		FEMAP, Solidworks, etc...						$0.00							
	CT Analysis							$0.00							
		Unknown						$0.00							
	ST Analysis							$0.00							
		Unknown						$0.00							
	Vibration Analysis							$0.00							
		Unknown						$0.00							
	Thermal Analysis							$0.00							
		Unknown						$0.00							
	Presentation Enhancements							$0.00							
								$0.00							
Hexahedron															
	Hexahedron														
		7075 T6 Aluminum Blocks		6x8x1.75		6	$41.67	$250.02	7 Days (MAX)			https://www.midweststeelsupply.com/store/7075aluminumplate			
			1/4" Ballmill			1	$40.20	$40.20				https://www.mscdirect.com/product/details/07767635			
		18-80 Washer		1/4	100	5	$9.37	$46.85				https://www.mcmaster.com/98017A660/			
		18-8 Socket Head Screw		1/4 7/8 length	25	20	$10.29	$205.80							
Centrifuge Testing (CT)															
	CT Adapter														
		Top Angled Plate (Cast Aluminum)		16.5x16.5x.5	1	2	$67.31	$134.62				https://www.midweststeelsupply.com/store/castaluminumplateatp5			
		45 degree Wedge Plates (Cast Aluminum)		16.5x13X.5	2 (Cut at angle)	2	$53.39	$106.78				https://www.midweststeelsupply.com/store/castaluminumplateatp5			
	PL Adapter														
		Lead Buckshot		25 lbs	6 PL's worth	1	$60.00	$60.00				https://www.rotometals.com/lead-shot/			
		Aluminum Cylinder (6061)		3x3/16/6in	1	6	$16.72	$100.32				https://www.midweststeelsupply.com/store/steeldomroundtubing			
		Steel Sheet (7 Ga)		24x8	1	1	$68.86	$68.86				https://www.midweststeelsupply.com/store/hotrollsteelsheet			
		External Hex Drive, 1/4"-20 Thread Size, 4" Long			1	2	$3.70	$7.40				https://www.mcmaster.com/90096A343/			
		1/4 - 20 Nuts		1/4-20	25	1	$7.15	$7.15				https://www.mcmaster.com/94575A110/			
	Testing														
		Medium Centrifuge (400 g-ton)				3	$50.00	$150.00				https://www.colorado.edu/center/ciest/content/getting-started			
		Staff Engineer time				6	$61.00	$366.00				https://www.colorado.edu/center/ciest/content/getting-started			
		Strain Guages (6)			5 Per	4	$40.00	$160.00	pons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzSUVGRFM4UzdLMzFBJmVuY3J5cHRlZElkPUEwMjA5NzgxMzZNRTRUNEE3MTI						
			Strain Guage Neutralizer			1	$18.59	$18.59				https://www.silmid.com/us/cleaners/water-soluble-cleaners/m-prep-neutraliser-5a-mn5a-1-60ml-bottle/			
			Strain Guage Conditioner			1	$20.02	$20.02				https://www.silmid.com/us/cleaners/water-soluble-cleaners/m-prep-conditioner-a-mca-1-60ml-bottle/			
			Strain Gauge Adhesive			1	$104.81	$104.81				https://www.silmid.com/us/adhesives/cyanoacrylate-adhesives/m-bond-200-2-part-28gm-kit/			
			Strain Guage Wiring (326-DFV)	ft	1 ft	20	$7.50	$150.00				https://www.digikey.com/en/products/detail/micro-measurements-division-of-vishay-precision-group/MMF006503/5903539			
			Isopropyl 99			1	$5.50	$5.50	pyl-alcohol.aspx?gclid=CjwKCAiAv_KMBhAzEiwAs-rX1HNuzYOz7dtnEgh6xalwbdEzJLWwhyiQhq-Zu4nq1u1bIKgKqw_6kBoCjbwQAvD_E						
		DAQ				2	$1.10	$2.20				https://www.colorado.edu/center/ciest/content/getting-started			
Shock Testing (ST)															
	Seperation System														
		Electromagnets - 1 set of 10			10	1	$30.99	$30.99				Amazon.com: Almencla Electromagnet DC 12V 50N Electric Lifting Magnet Solenoid Li			
		Neodymium Magnets		1/8 thick, 5/16 diam		2	$1.88	$3.76				https://www.mcmaster.com/magnets/neodymium-magnets-7/			
		Compression Springs		16.1 lbf	12	2	$11.87	$23.74				https://www.mcmaster.com/compression-springs/rate~16-1-lbs-in-/			
		Base Ring (6061 Aluminum)		4.5 OD 1 thick	1	1	$30.86	$30.86				https://www.midweststeelsupply.com/store/6061aluminumroundbar			
		Top Ring (6061 Aluminum)		4.5 .5 thick		1	$19.62	$19.62				https://www.midweststeelsupply.com/store/6061aluminumroundbar			
	Testing														
		Battery (12 V)				1	$20.00	$20.00	g&wl2=m&wl3=233427030436&wl4=aud-1308652556816:pla-384620874469&wl5=9028879&wl6=&wl7=&wl8=&wl9=pla&wl10=112561763&w						
		Accelerometers				10	$20.00	$200.00							
								$2,334.09							

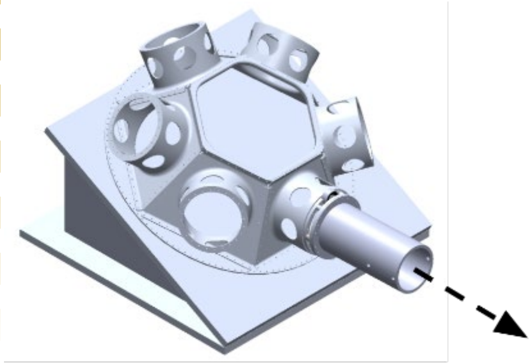
https://docs.google.com/spreadsheets/d/1DaWYpkNNcBWVXDFgzdPwMfb-2onLobXWImm-w2yunMY/edit#gid=0

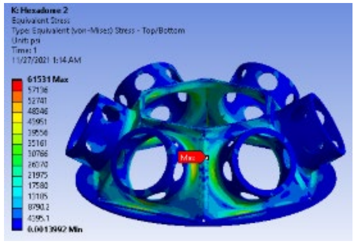
Concept of Operations: Developmental

Manufacturing	Centrifuge Testing	Shock Testing	Model Validation
6/25 scale at Aero Machine Shop	15.026g RSS load	Scaled PSC 2000785G MkII MLB	Test Data vs ANSYS Model









Concept of Operations

Manufacturing
6/25 scale at Aero Machine Shop

→

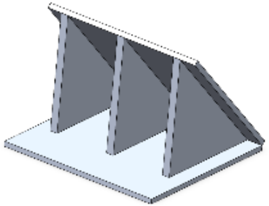
Centrifuge Testing
15.026g RSS load

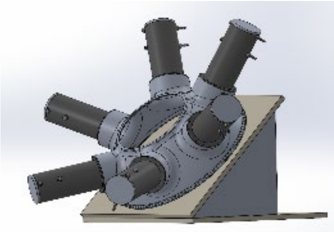
→

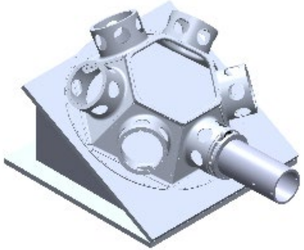
Shock Testing
Scaled PSC 2000785G MkII MLB

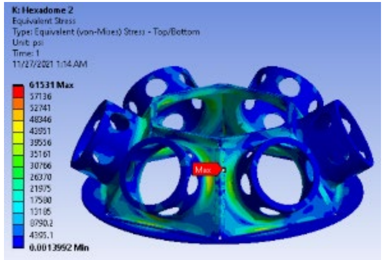
→

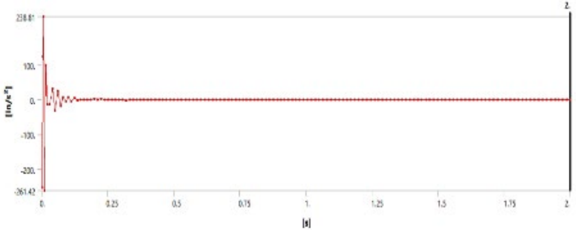
Model Validation
Test Data vs ANSYS Model











Longer CONOPS