Human Spaceflight Structures Engineering Internship

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NASA's Johnson Space Center – Spring 2017
University Science Research Association (USRA)

Content

- Background
- Lightweight External Inflatable Airlock (LEIA)
- Cislunar Habitat Module
- Artificial Gravity Study
- Additional Projects
- Conclusions

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Background

- Hometown – Suwanee, Georgia
- School – Georgia Institute of Technology
  - 4th Year BS Aerospace Engineering
  - Graduation: May 2018
- Engineering Work Experience
  - NASA's Armstrong Flight Research Center
  - Lockheed Martin, Missiles and Fire Control
  - Conway & Owen MEP Consulting Engineers
- Engineering Research Experience
  - Georgia Institute of Technology, High Power Electric Propulsion Laboratory
  - Georgia Institute of Technology, Unmanned Aerial Vehicle Laboratory

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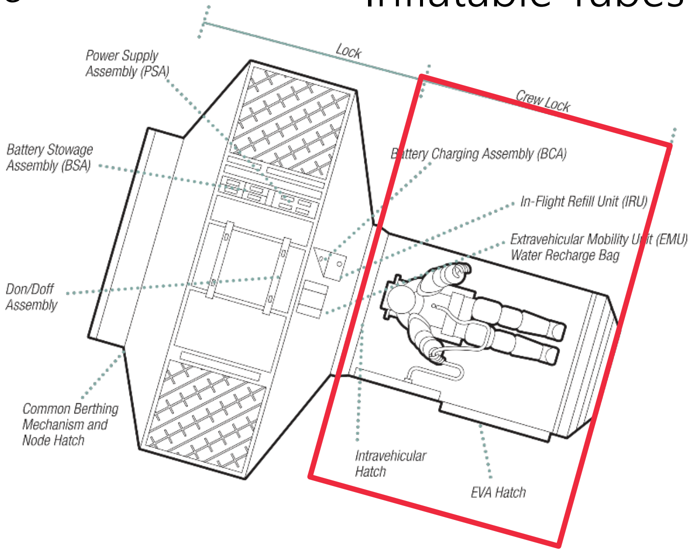
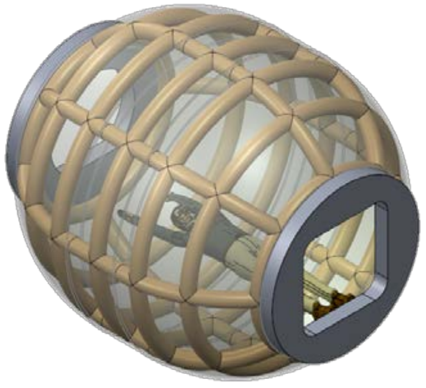
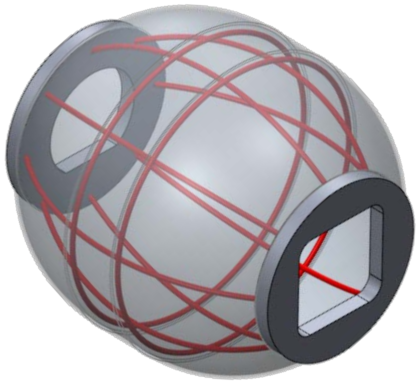
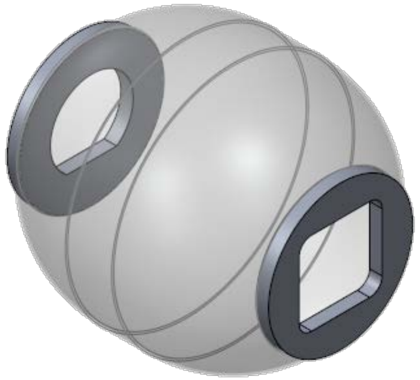
Lightweight External Inflatable Airlock (LEIA) – Overview

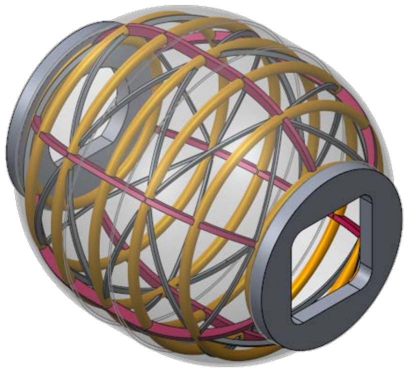
- An inflatable crewlock, coupled with an equipment lock, can provide significant weight savings from its metallic counterpart
- Inflatable structures only have shape, size, and rigidity when inflated
- In order to use an inflatable as an airlock, an additional structure is necessary to maintain shape, size, and rigidity
- Conceptual designs based on Bigelow Expandable Activity Module (BEAM) interior envelope
- Design Concepts
  - Inflatable Tubes
  - Shark Cage
  - Resin Rigidized Structure
  - Expandable Truss
  - Inflatable Walls

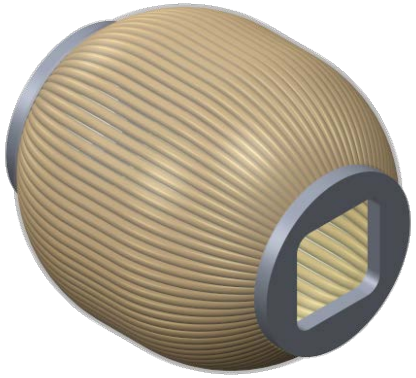



Inflatable Tubes


Shark Cage

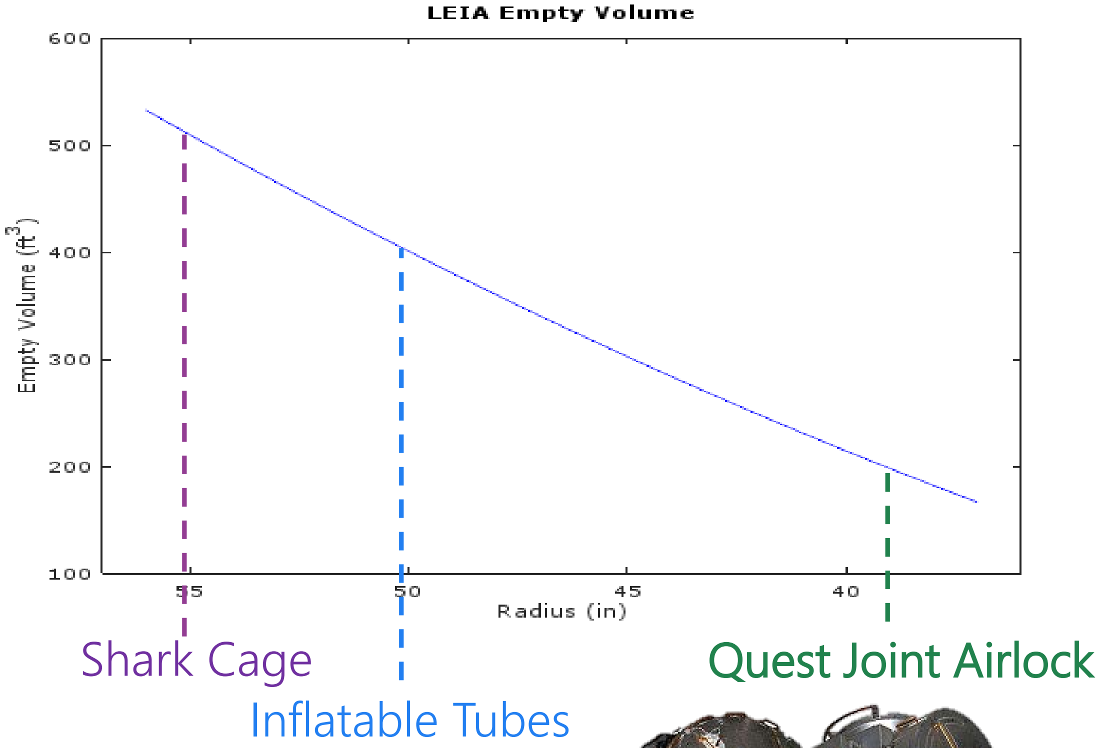

Resin Rigidized Structure

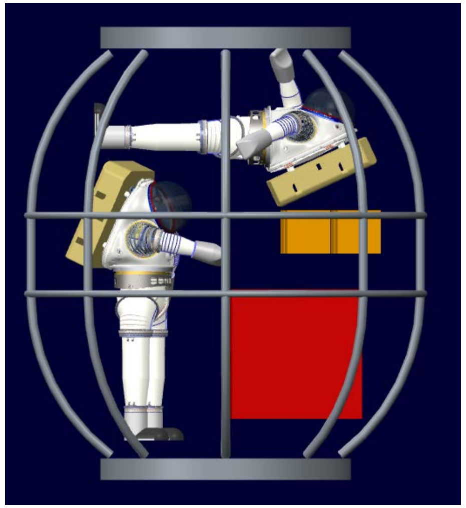

Expandable Truss

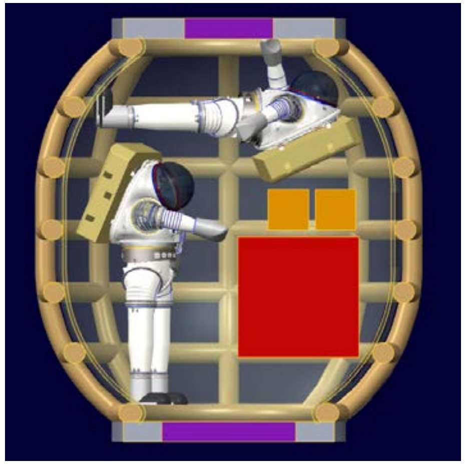

Inflatable Walls

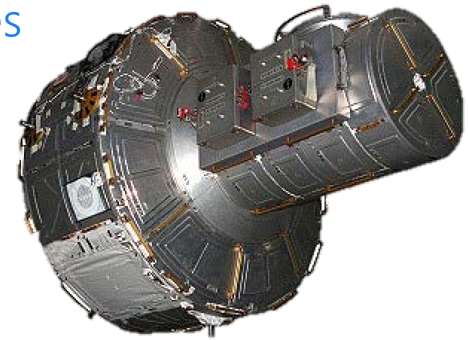
Lightweight External Inflatable Airlock (LEIA) – Volume Analysis

- Compared LEIA volume concepts to the Quest Joint Airlock
- Found that all LEIA concepts had plenty of volume to perform airlock procedures
- Additional Questions
  - Will astronauts have trouble rotating to operate EV hatch?
  - Will the extra volume in LEIA designs create problems with translation and rotation?



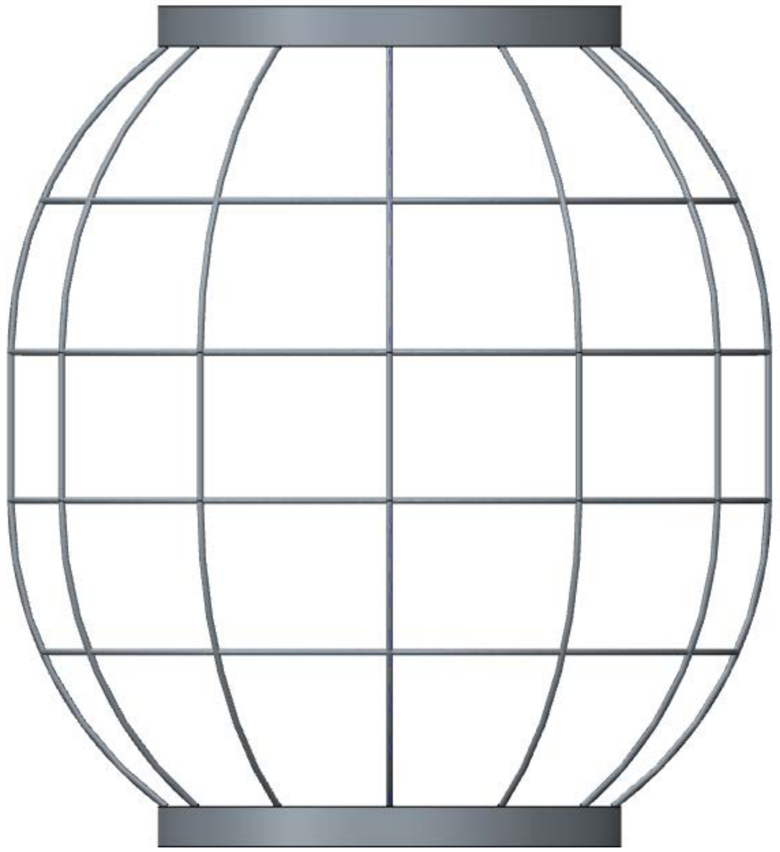






Lightweight External Inflatable Airlock (LEIA) – Shark Cage

- Composed of 2024-T3 aluminum tubes
- Design includes longitudinal tubes and hoop tubes that are fastened together
- Crew will receive Shark Cage in several pieces and assemble within inflatable structure
- Major Advantages
  - Low Mass
  - High Available Volume
  - Simple Manufacturing
  - Simple In-Space Assembly

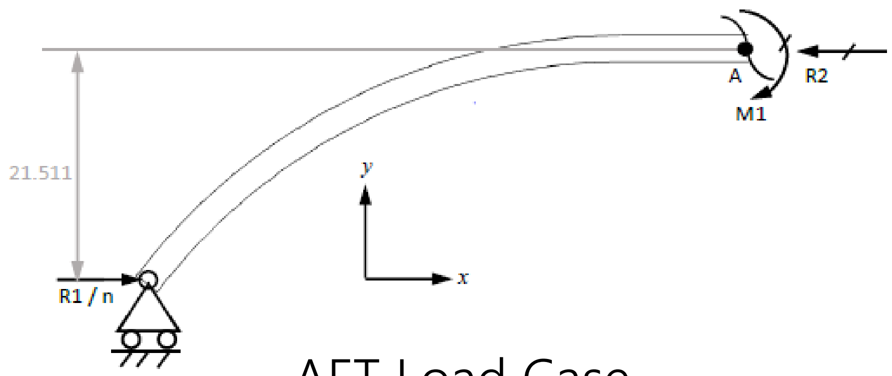


Lightweight External Inflatable Airlock (LEIA) – Initial Analysis

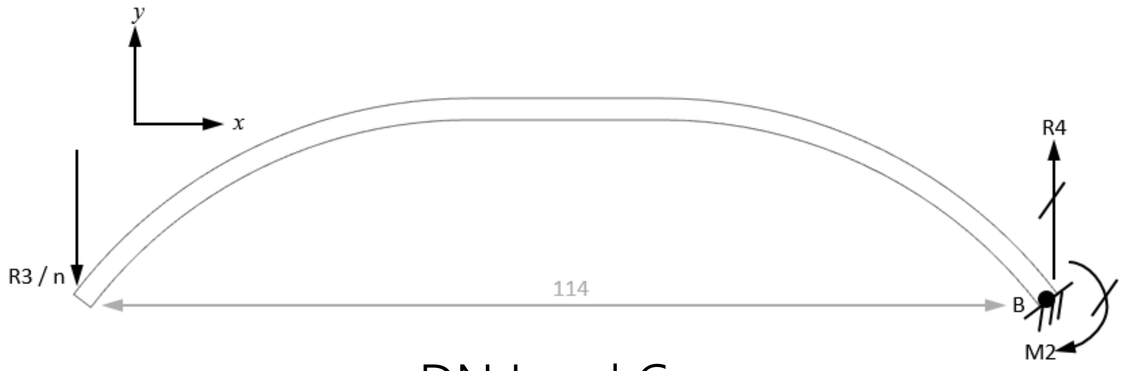
- Hand calculations performed on 125 lb. incidental loads located on outside of EV Hatch
- The factor of safety used was 2.25 for metallic structure
- Margins shown are for one longitudinal member with a 2.5″ outer diameter and a 1.8″ inner diameter

DESC.	MATL	SPEC	SOURCE	F_{tu}	F_{su}	F_{cy}	UNITS
Shark Cage Member	2024-T3	QQ-A-250/4	MMPDS-11, 3-118	64	39	42	ksi

DETAIL	LOAD CASE	FAILURE MODE	M.S.*
Shark Cage – EV Hatch Connection	125 lbs AFT	Shear Stress	+High
Shark Cage – Midpoint	125 lbs AFT	Compression	+High
Shark Cage – Midpoint	125 lbs AFT	Buckling	+0.06
Shark Cage – IV Hatch Connection	125 lbs DN	Compression	+0.52



AFT Load Case

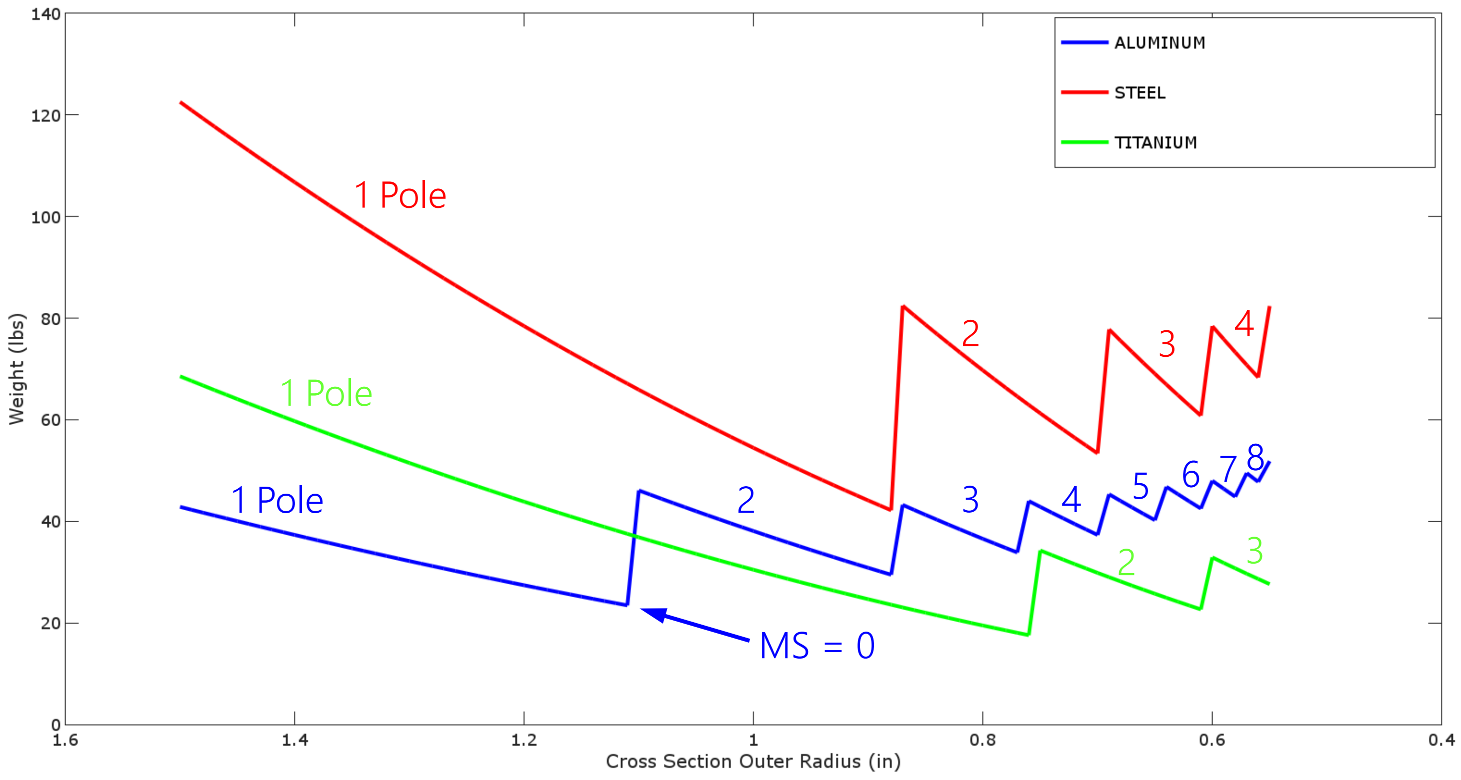


DN Load Case

Lightweight External Inflatable Airlock (LEIA) – Initial Analysis

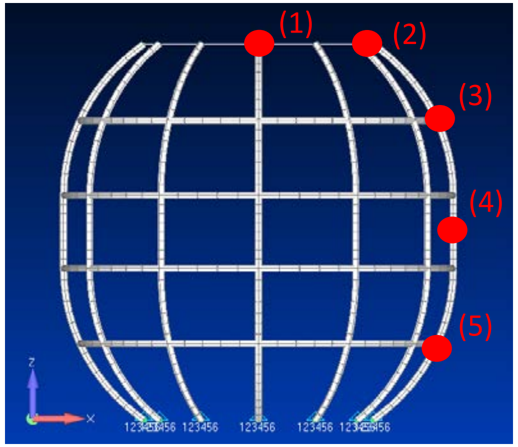
- Compared likely weights for aluminum, steel, and titanium tent poles
- While each material could withstand all loads with only one pole, the application of more longitudinal members will be convenient for handholds and will provide additional stability
- **Initial Conclusion:** Between 4 and 8 longitudinal members are feasible as a secondary support structure for an inflatable airlock

Material and Cross Section Weight Comparison

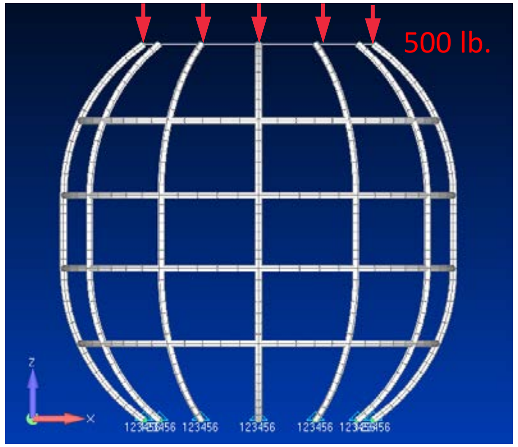


Lightweight External Inflatable Airlock (LEIA) – FEM Analysis

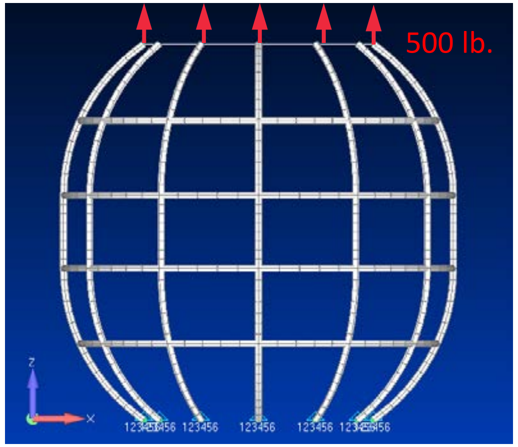
- Set out to optimize the weight of the Shark Cage concept
- Loads
  - Incidental Loads
  - Crew Egress
  - Crew Ingress
  - Crew Ingress and Rest
  - EV Hatch Opening
  - Crew Movement
- Constraints
  - Longitudinal members fixed to IV Hatch and rigidly connected along EV Hatch



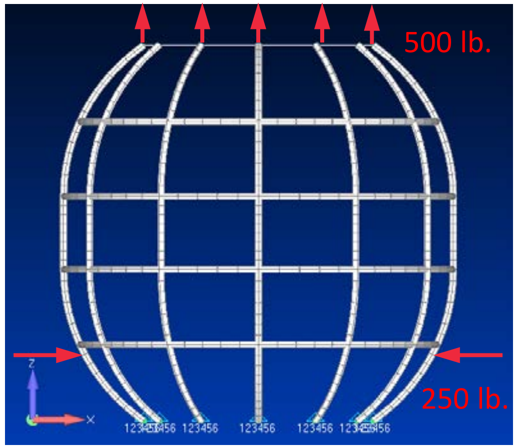
Incidental Loads



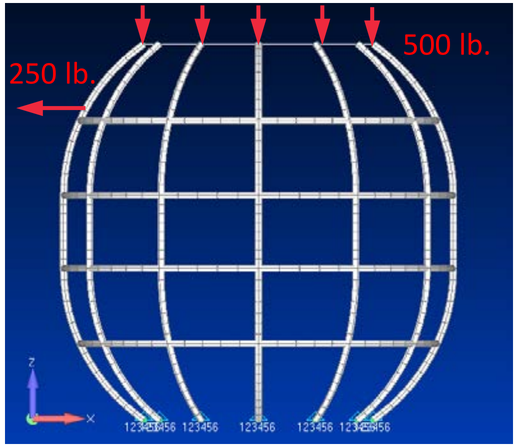
Crew Egress



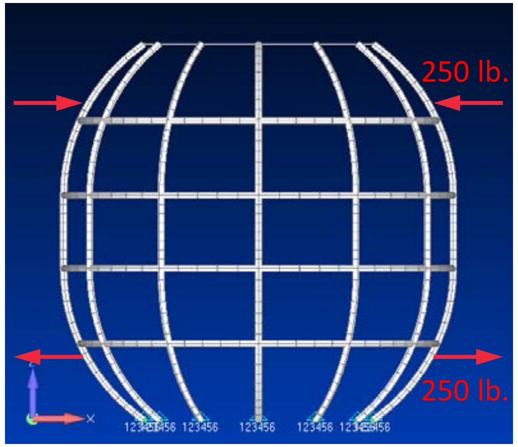
Crew Ingress



Crew Ingress and Rest



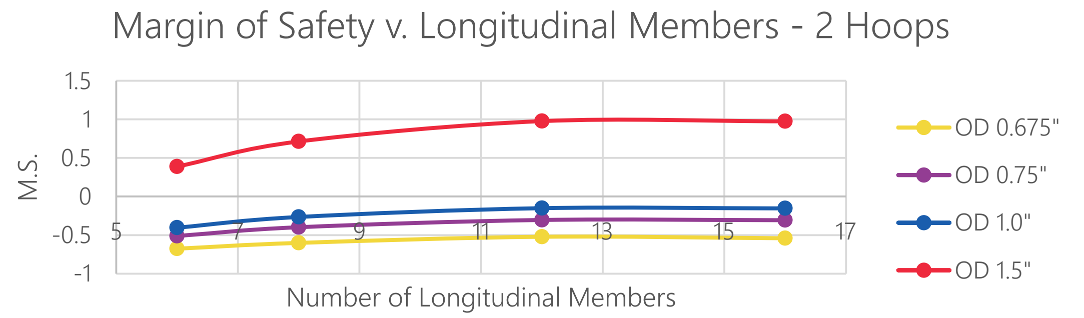
EV Hatch Opening

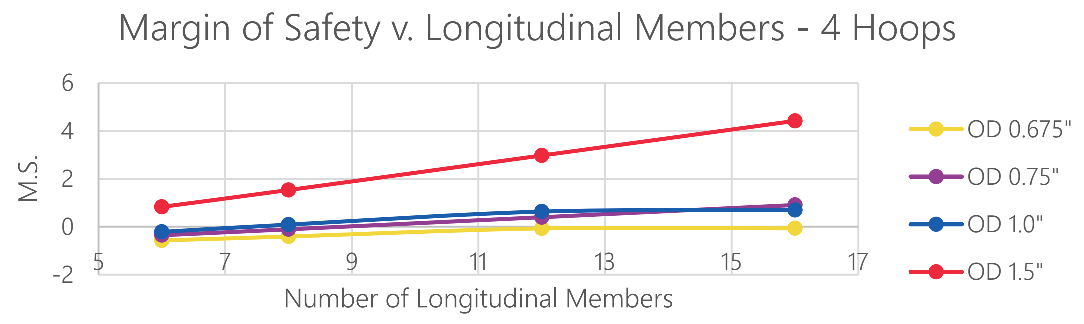


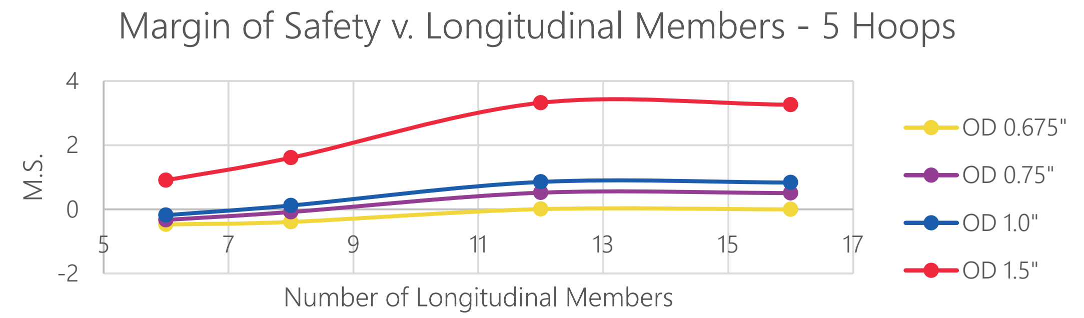
Crew Movement

Lightweight External Inflatable Airlock (LEIA) – Design Study

- How does the stress change with different geometries?
- Task: Optimize the Shark Cage design
- Design Variables:
  - Cross Section Outer Diameter
    - 5/8", 3/4", 1", 1.5", 2"
  - Number of Longitudinal Members
    - 6, 8, 12, 16
  - Number of Circular Members
    - 2, 4, 5







Lightweight External Inflatable Airlock (LEIA) – Design Study

- The first table displays lightest designs for each number of longitudinal members
  - The highlighted design is not the lightest overall design but it does provide an optimal amount of members for movement about the airlock
  - This design was chosen for a subscale structural test and a full-scale mockup evaluation
- The second table displays the results of the stress analysis performed on the optimized Shark Cage design
  - Analysis will be confirmed by full-scale structural test

OD (in)	ID (in)	Longitudinals	Hoops	Weight (lbs)	Max Stress (psi)	M.S.
1.5	1.43	6	2	24	46112	0.387925
1.5	1.43	8	2	28	37356	0.713246
1	0.93	12	4	31	39269	0.629784
1	0.93	16	4	36	37799	0.693166

Design Trade Summary

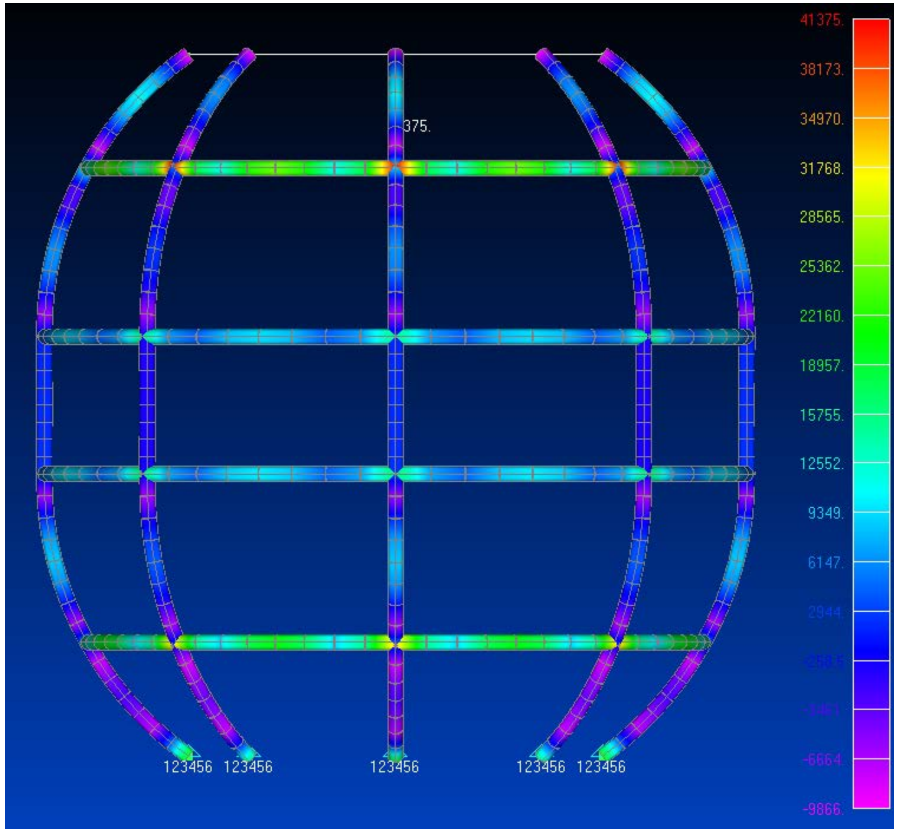
DETAIL	LOAD CASE	FAILURE MODE	M.S.*
Location 4	125 lbs +X	Ultimate Tensile Strength	+0.63
Load Case 34	EV Hatch Opening	Compression Yield	+0.12
Load Case 34	EV Hatch Opening	Buckling	+2.60

Margin of Safety Summary

Lightweight External Inflatable Airlock (LEIA) – Compression Test

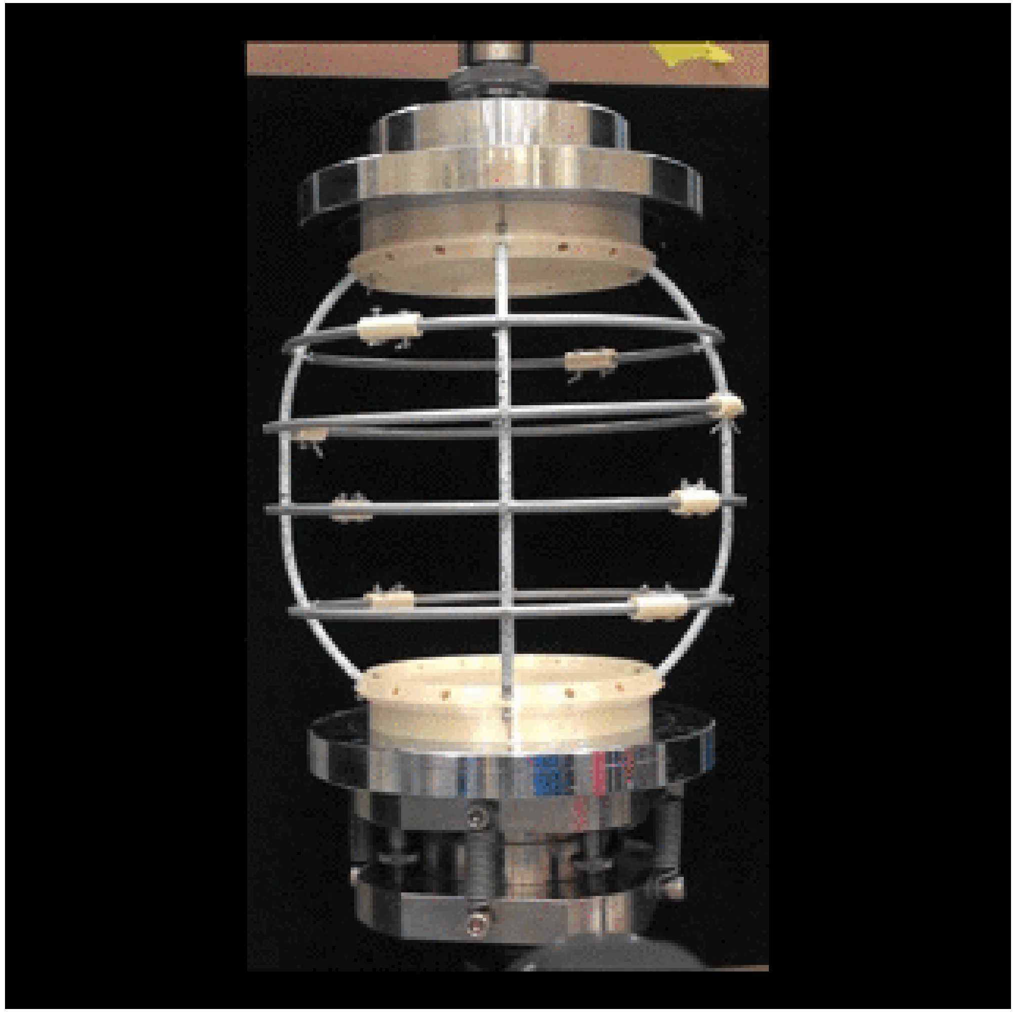
- Finite element analysis is a useful tool, but Shark Cage must be tested before it is considered flight ready
- Developed a 1:10 scale FEM of Shark Cage which uses the geometry and material of the small-scale test article developed by Mykale
  - Determined likely failure modes and ultimate stresses
  - Will correlate test data to FEA data

DESC.	MATL	SPEC	SOURCE	F_{tu}	F_{su}	F_{cy}	UNITS
Shark Cage Member	6061-T6	WW-T-700/6	MMPDS-11, 3-447	42	34	35	ksi



Lightweight External Inflatable Airlock (LEIA) – Compression Test

- Test consisted of 3 configurations each with 4 hoop tubes: 4, 8, and 16 longitudinal tubes were arranged in a small scale test article
- Small-scale test article was 1:10 scale to size of Bigelow Expandable Activity Module (BEAM)
- Each configuration was compressed until failure in a load frame



Lightweight External Inflatable Airlock (LEIA) – Compression Test

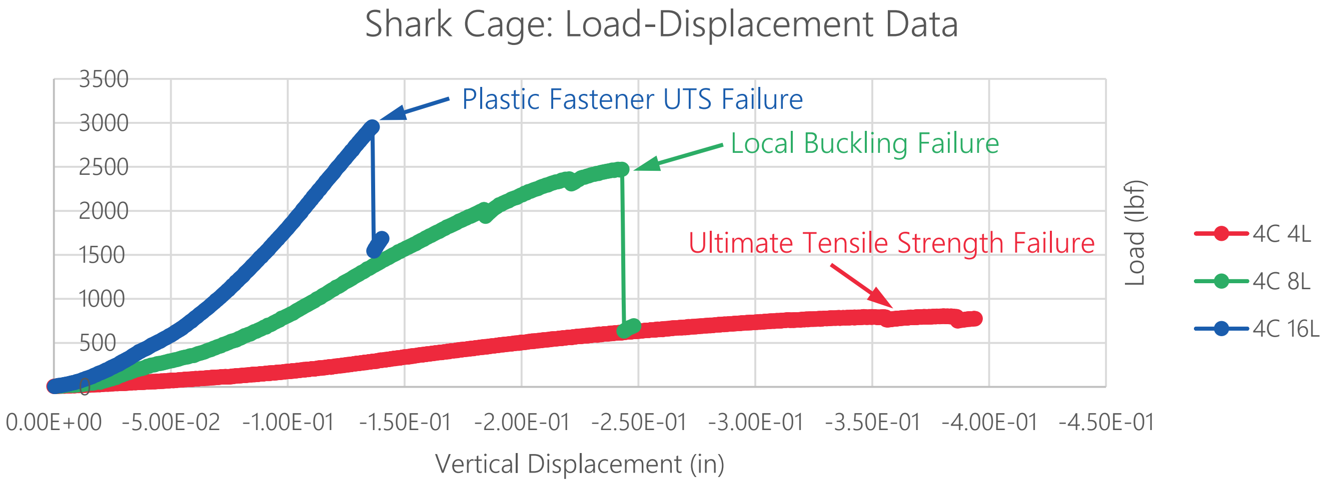
- The small-scale compression test showed my FEA was conservative and needs to be tuned to represent real-world results
- Error between FEA and Test Data:

$$\varepsilon = \frac{Observed - Expected}{Expected} \text{ X } 100$$

  - Configuration A: 60% (UTS)
  - Configuration B: 67% (Buckling)
  - Configuration C: -23% (UTS)
- Possible sources of discrepancy
  - All members except EV Hatch connections in FEA were clamped-clamped configuration (did not account for fasteners and distributed load interactions)
  - EV hatch longitudinal connections in FEA were allowed to rotate
  - Did not take into account the plastic connectors used in assembly of test article

Analytical Prediction

Test Article Configuration	Number of Longitudinals	Expected Yield Strength	Expected Ultimate Strength	Expected Buckling Strength	Expected Max Elastic Deflection	Observed Failure Load
A	4	375 lbf	500 lbf	625 lbf	0.0569 in	800 lbf
B	8	1125 lbf	1375 lbf	1500 lbf	0.0307 in	2500 lbf
C	16	3000 lbf	3875 lbf	3500 lbf	0.0350 in	3000 lbf



Lightweight External Inflatable Airlock (LEIA) – Future Work

- Refine FEM for better correlation with test data
- Develop and test full-scale mock-ups of Inflatable Tube and Shark Cage design
- Continue developing resin rigidizable technology
- Launch and test final concept on ISS

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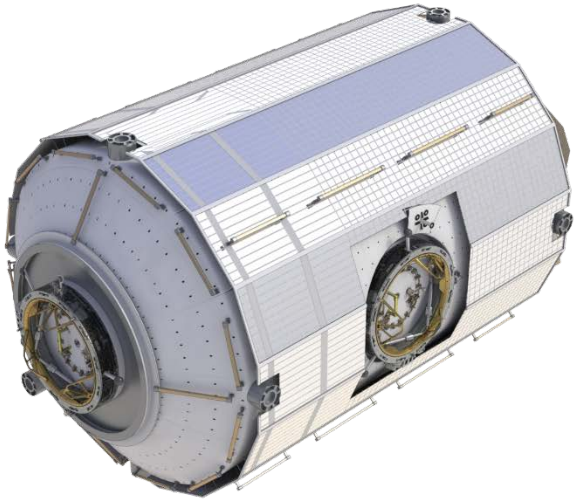
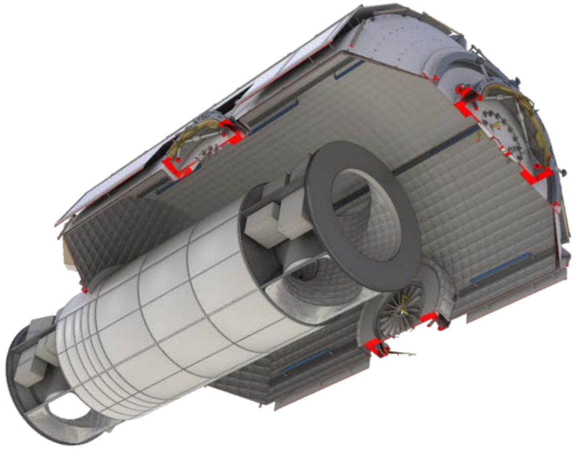
Cislunar Habitat Module – Overview

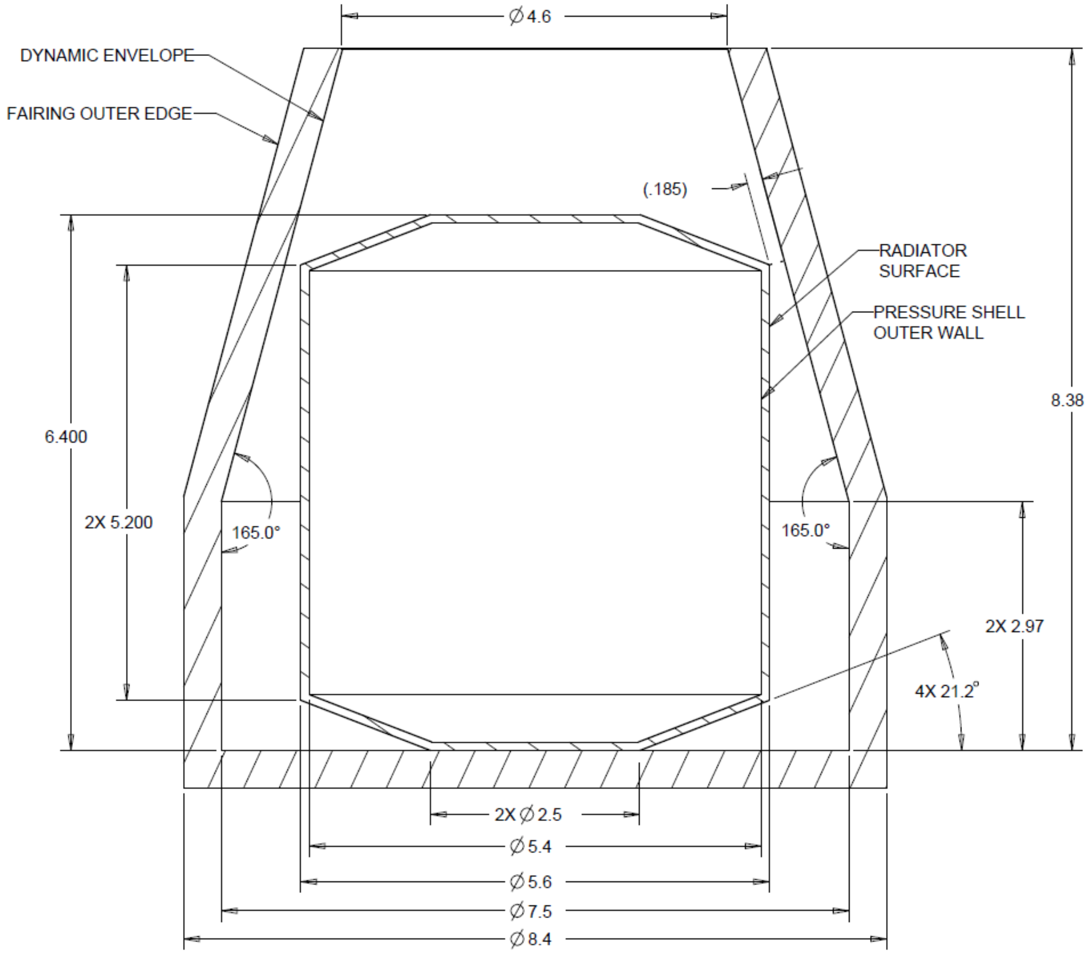
- Working to develop next generation space station habitat modules for cislunar space
- ISS era modules carried launch loads and instruments around the outer edge of the module
- Future cislunar modules will carry launch loads and instruments in the center of the module core structure much like a fighter jet





Cislunar Habitat Module – Task

- Previous cislunar habitat module model had a diameter of 4.0 m
- Redesigned the module with a maximum diameter for the SLS – Block 1 Fairing
  - Increased diameter to 5.6 m
  - 40% larger diameter than previous model



Cislunar Habitat Module – Analysis

- Rebuilt finite element model in Femap and used NASTRAN to analyze stress within the structure
- Expected Loads
  - SLS Launch
  - Operational / Docking
- A safety factor of 1.4 for UTS and buckling and 1.0 for yield during launch was used per NASA document SSP-30559-C, Section 3.3.1. A safety factor of 1.5 for UTS and buckling and 1.1 for yield on orbit was used per the same document
- Additionally, the minimum resonant frequency is 8 Hz
- Analyzed load cases for maximum von Mises stress in plate elements and maximum combined stress in beam elements
- All iterations were analyzed using linear buckling analysis

Load Case	Axial Load (G)	Lateral Load (G)
Transonic X	-2	0.75
Transonic Y	-2	0.75
Max Q X	-2.5	0.5
Max Q Y	-2.5	0.5
Boost Max X	-3.25	0.3
Boost Max Y	-3.25	0.3
Core Max X	-3.5	0.3
Core Max Y	-3.5	0.3
Conservative X	-4	2
Conservative Y	-4	2

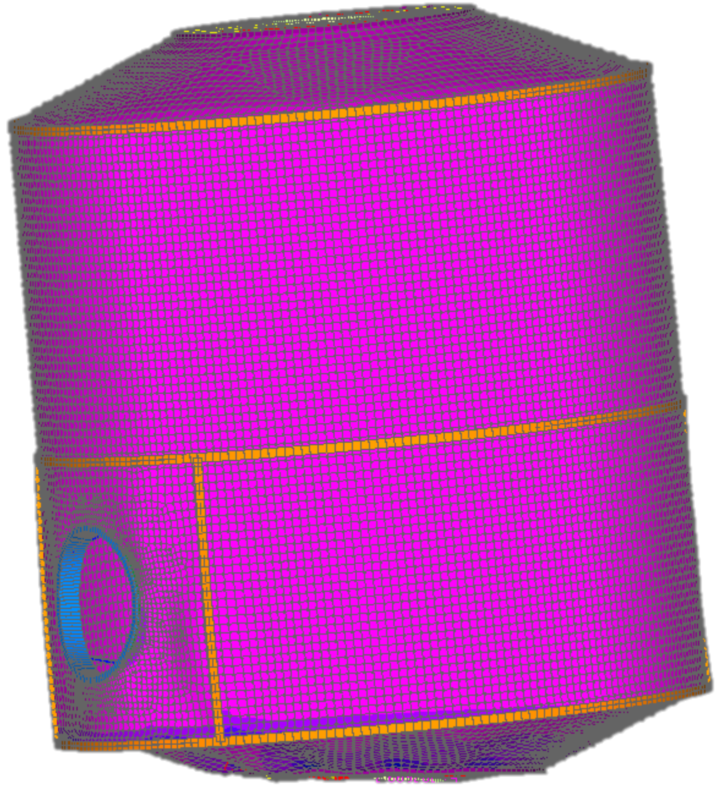
SLS Launch

Load compnent	Axial Hatch +z	Axial Hatch -z	Radial Hatch +y	Radial Hatch -y
Compressive Axial load (N)	0	0	5000	5000
Tensile Axial Load (N)	5000	5000	0	0
Shear Load (N)	5000y	5000x	5000x	3535.5x+3535.5z
Torsion Moment (N.m)	-15000z	-15000z	-15000y	15000y
Bending Moment (N.m)	65300y	65300x	65300z	65300z
Pressure (Pa)	110000 (over entire shell)			

Operational / Docking

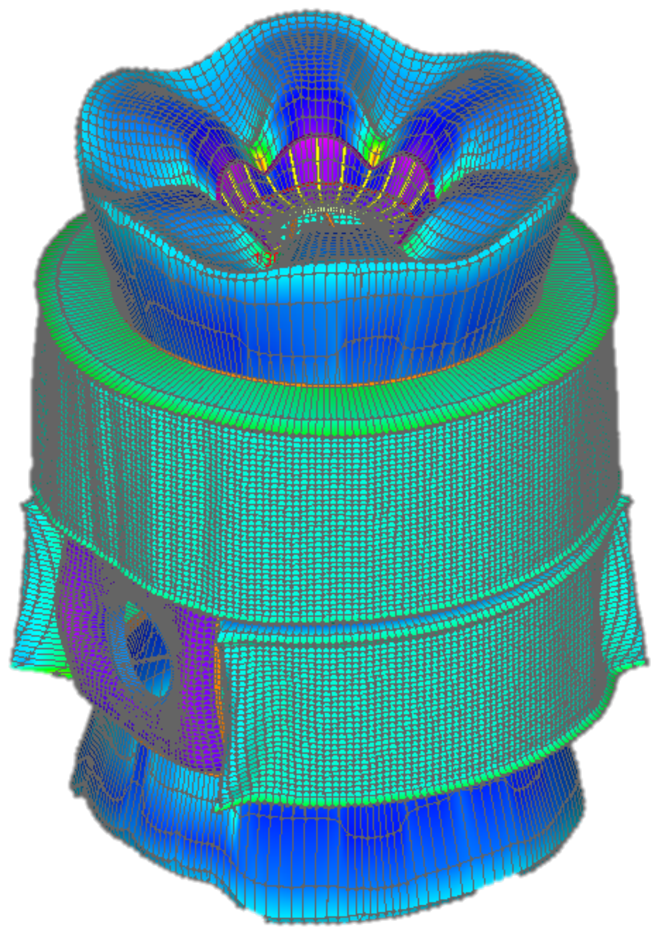
Cislunar Habitat Module – Launch

- Launch loads largely translate through core structure
- The increased width of the module mitigated much of the stress associated with launch
- Local buckling is still a concern

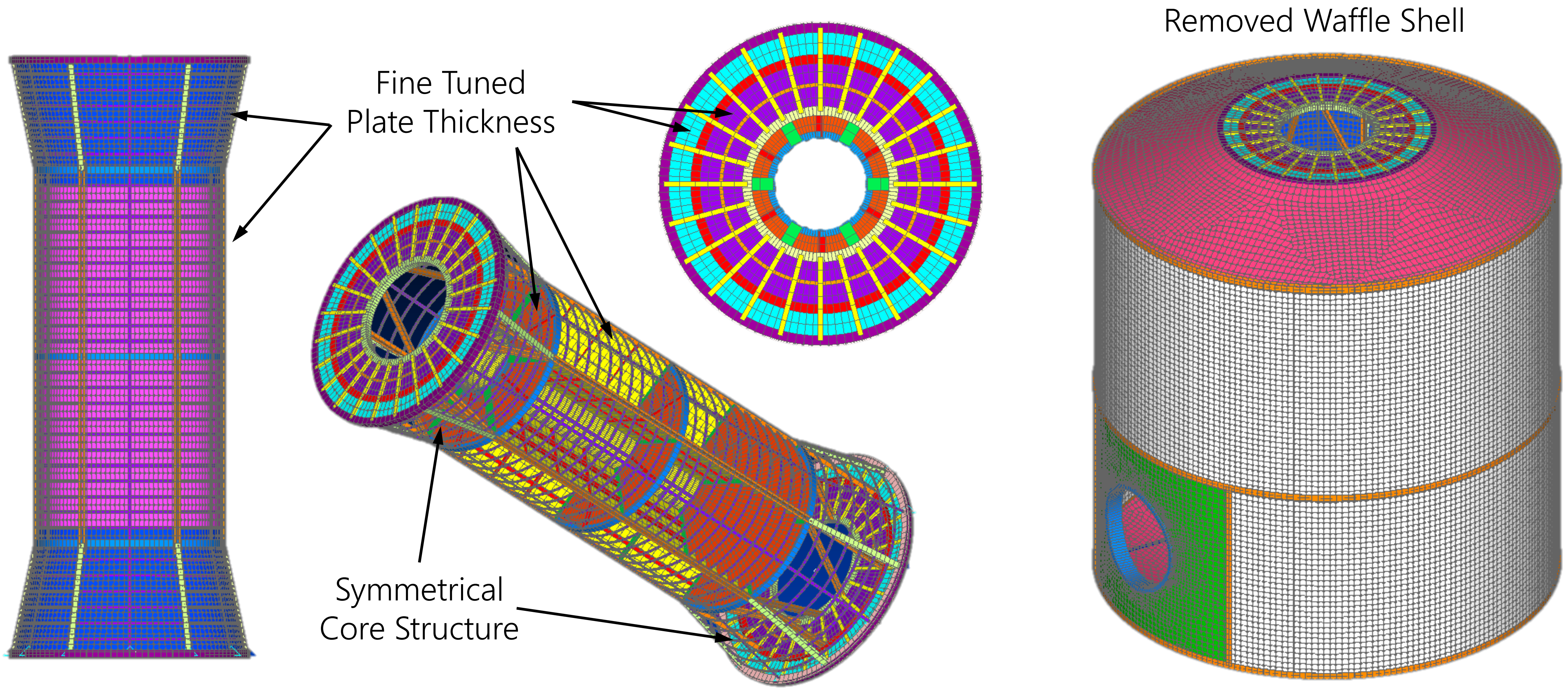


Cislunar Habitat Module – Operational / Docking

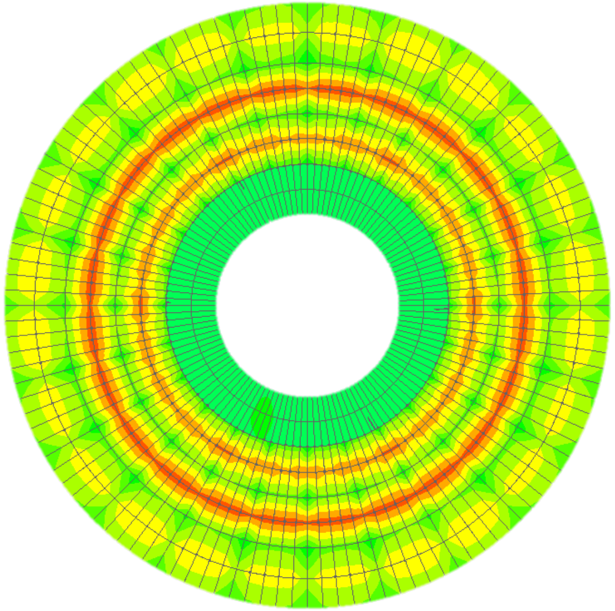
- Operational and docking loads are largely translate through the pressure shell
- The increased width of the module greatly increased the stress associated with maintaining atmospheric pressure within the module
- Docking loads and moments are less of a concern than operating pressure

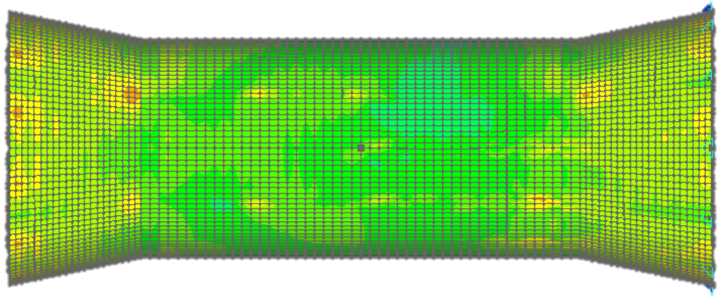


Cislunar Habitat Module – Major Design Changes



Cislunar Habitat Module – Optimization



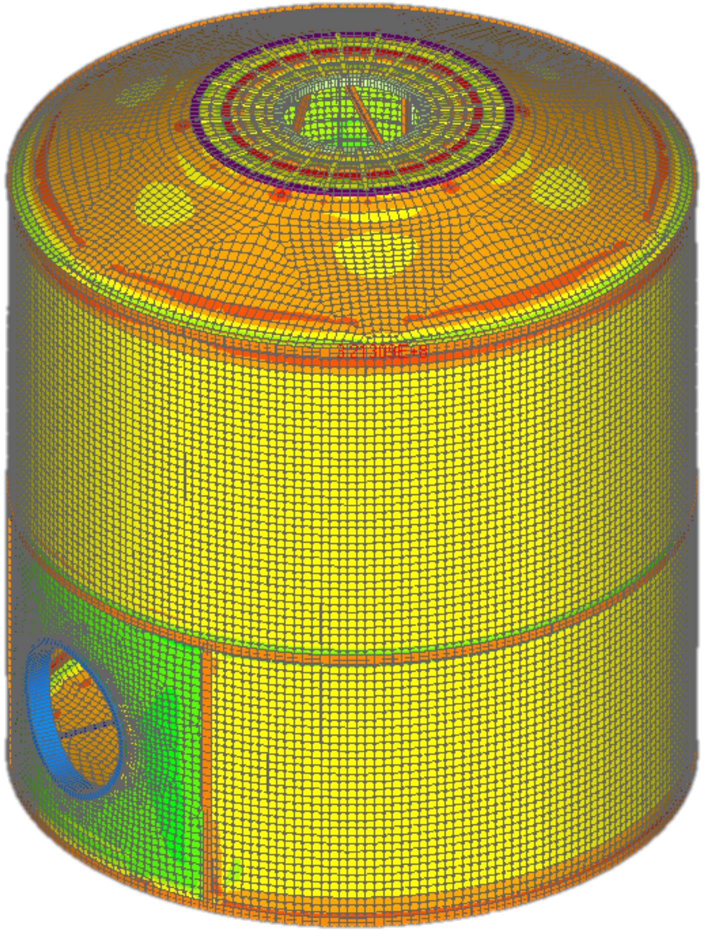


First Working Model

Item	Mass (kg)
Habitat Subsystems	3225
Shell Structure	983
Core Structure	1251
Mating Plates	518
Total	**5977**

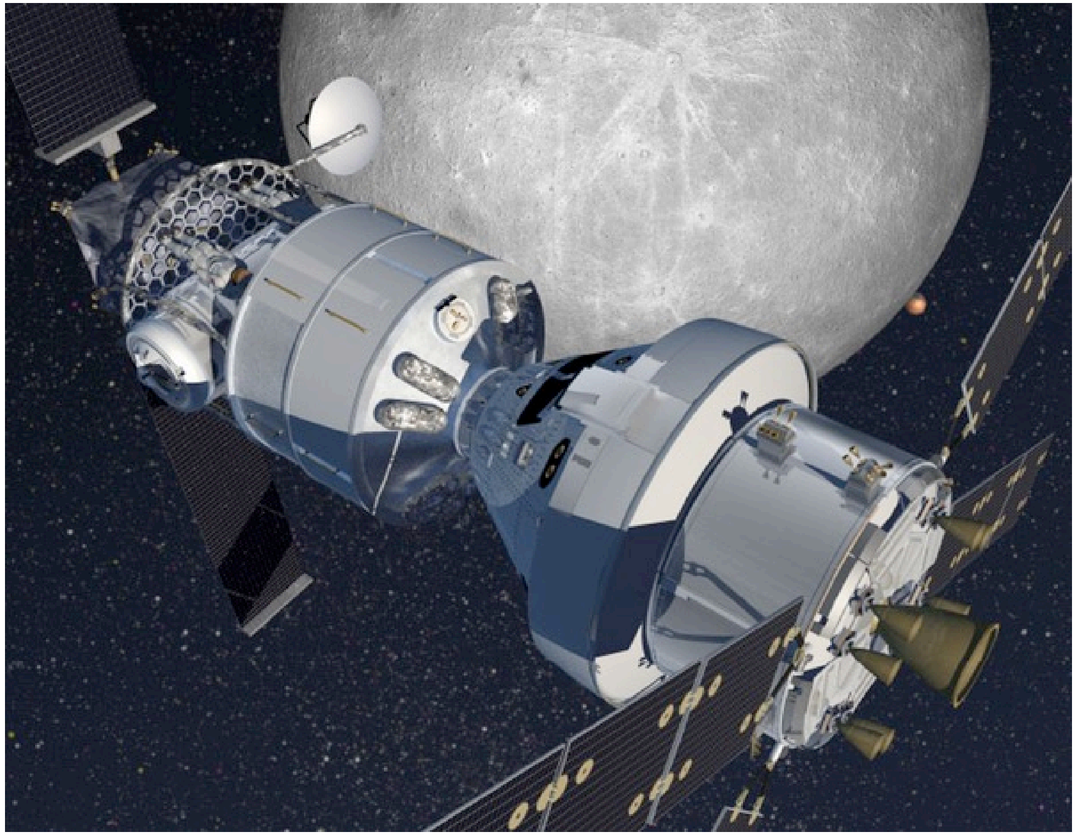
Item	Mass (kg)
Habitat Subsystems	3225
Shell Structure	976
Core Structure	1021
Mating Plates	456
Total	**5678**

Final Model



Cislunar Habitat Module – Future Work

- Continue optimizing core structure and pressure shell design
- Begin developing higher fidelity models and finalize mechanical design



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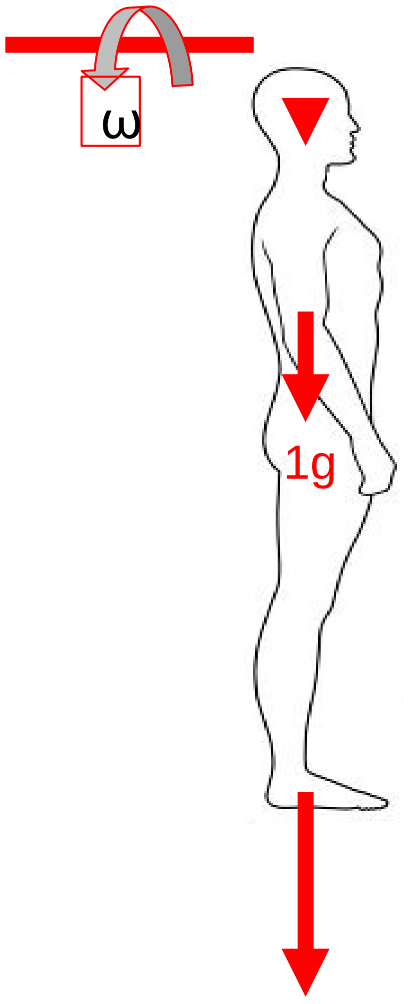
Artificial Gravity Study – Overview

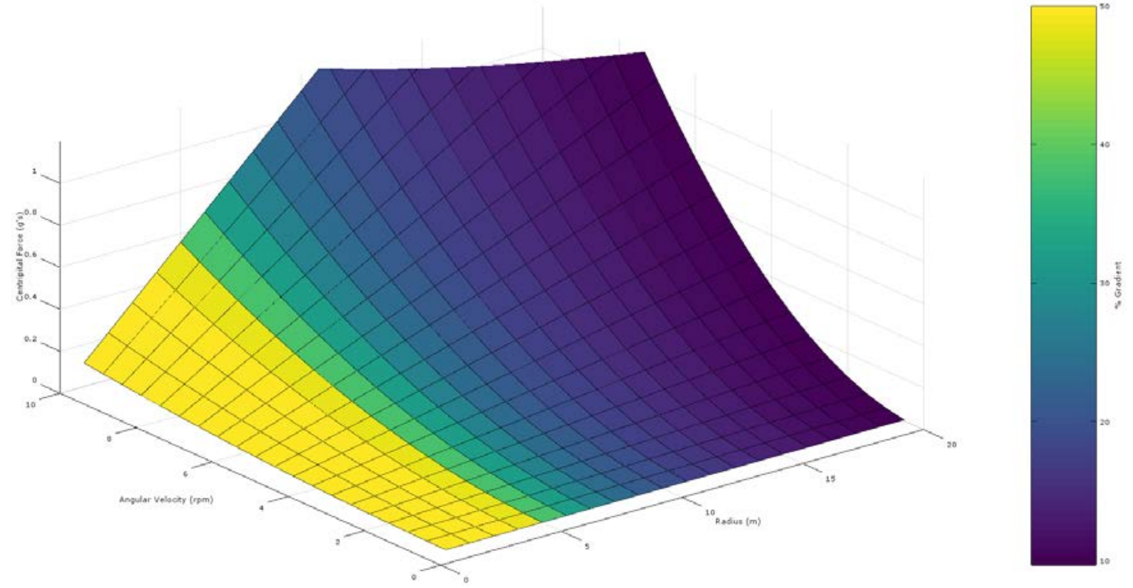
- Overall Objectives
  - Artificial gravity (AG) forces should be directed through the feet
  - The AG gradient should be minimized
  - The duration of AG exposure should be around 1.5 hours/day
  - The cross coupled angular accelerations caused by rotations of the head should be minimized
  - AG at the feet shall be less than 2 g's

- Design Drivers
  - Pressure shell diameter
  - Volume limitations of the intended launch vehicle
  - Mass limitations of the intended launch vehicle
  - Isolation of the AG architecture from other parts of the vehicle
  - Angular velocity required to achieve required accelerations



Artificial Gravity Study – RPM Trade

- Two major physical constraints drive the size and shape of the artificial gravity spacecraft
  - Radius
    - Drives gravity gradient
    - Inverse relationship with angular velocity
  - Angular Velocity
    - Drives centripetal force which produces the feeling of artificial gravity
    - Increased angular velocity increases cross-coupled accelerations in head which induces nausea
- Much of our work had to do with optimizing the tradeoff between radius and angular velocity



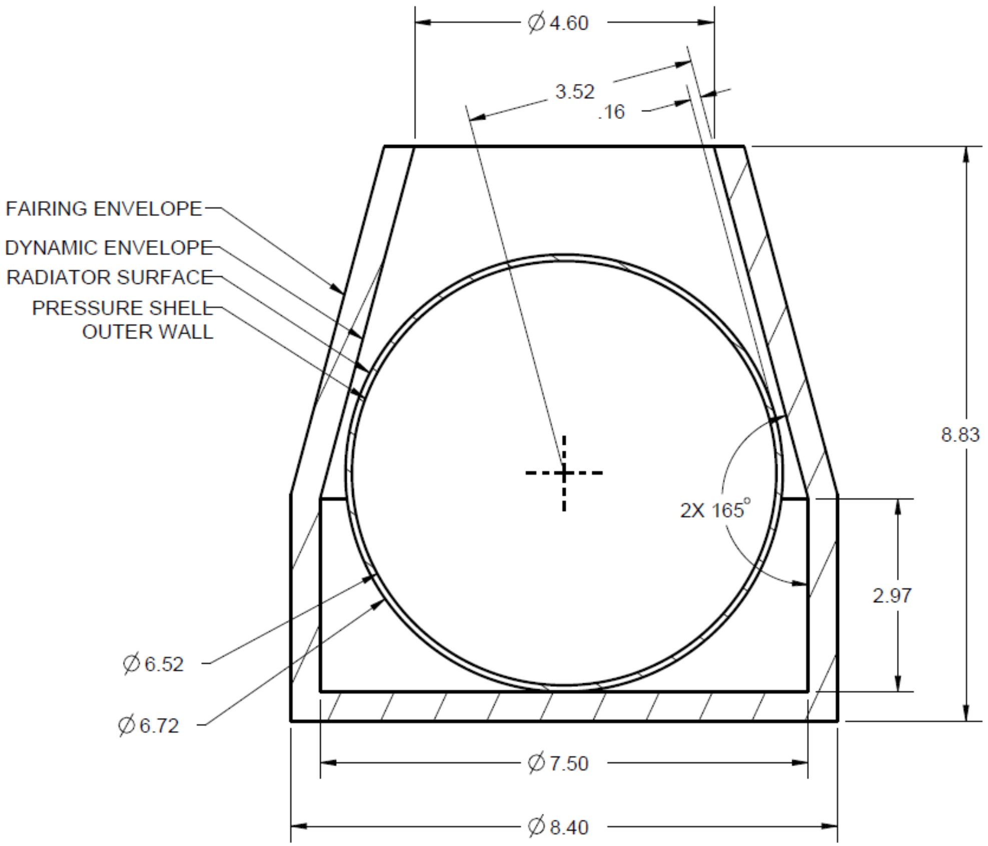
$$G = \frac{F-H}{F} = \frac{\frac{\omega^2 r}{g} - \frac{\omega^2 (r-h)}{g}}{\frac{\omega^2 r}{g}} = \frac{r-(r-h)}{r} = \frac{h}{r}$$

$$\frac{dG}{dr} = -\frac{h}{r^2} \quad \rightarrow \quad r = \sqrt{\frac{h}{\left|\frac{dG}{dr}\right|}}$$

Artificial Gravity Study – Launch Vehicle Integration

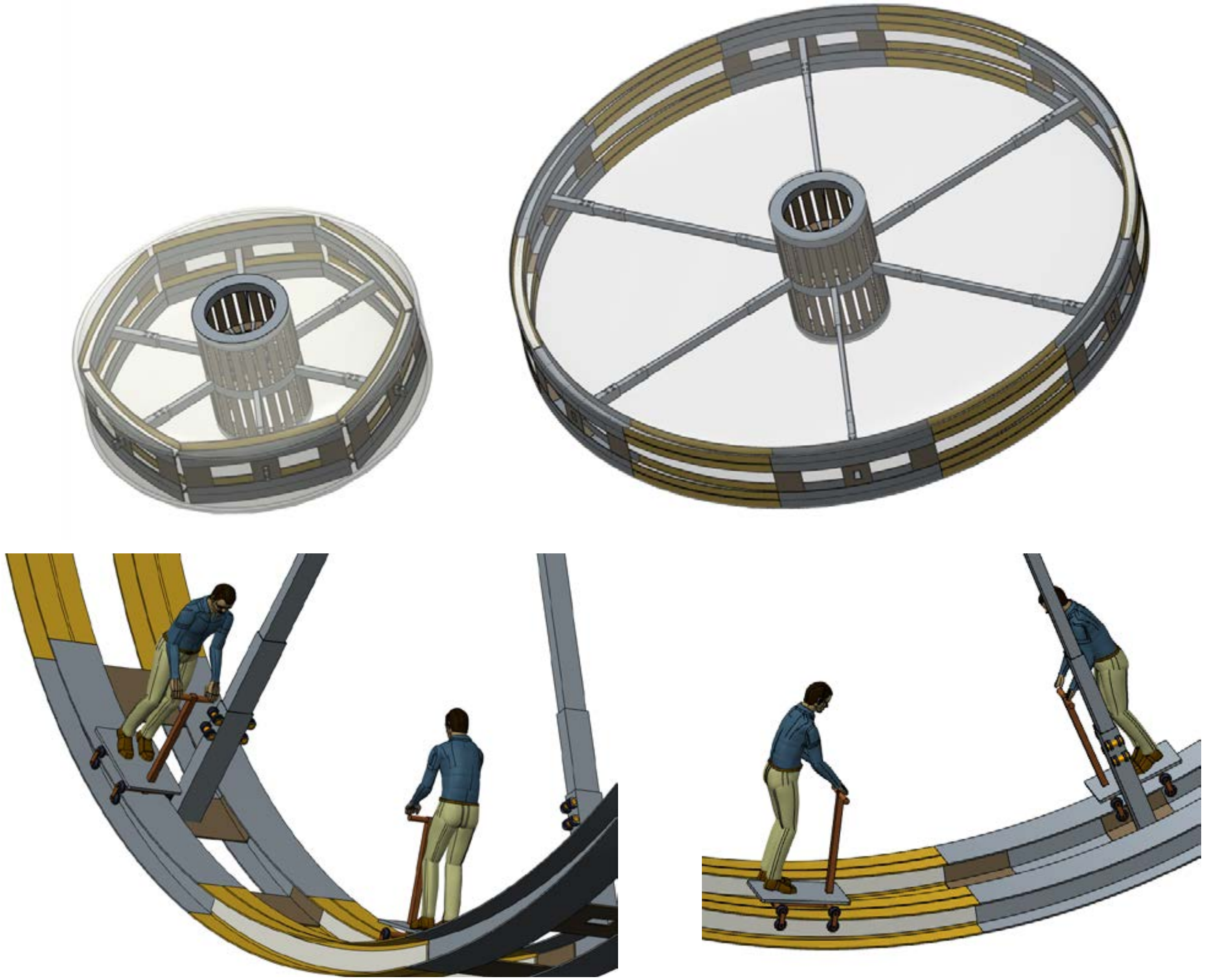
- Spacecraft radius and mass is limited by current and planned launch vehicle capabilities

- SLS Block 1 Cargo
  - 6.5 m maximum diameter
  - 100,000 kg to LEO
  - $1-5 billion cost per launch
- SLS Block 2 Cargo
  - 8.1 m maximum diameter
  - 130,000 kg to LEO
  - $1-5 billion cost per launch
- Delta IV Heavy
  - 4.6 m maximum diameter
  - 29,000 kg to LEO
  - $350 million cost per launch
- Falcon Heavy
  - 4.6 m maximum diameter
  - 63,800 kg to LEO
  - $90 million cost per launch



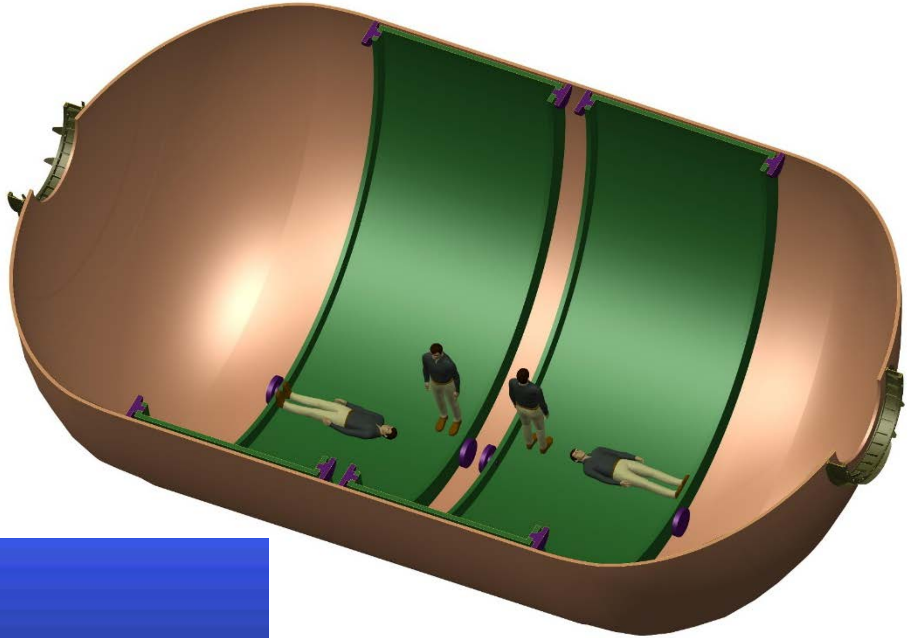
Artificial Gravity Study – Handcart Design Concept

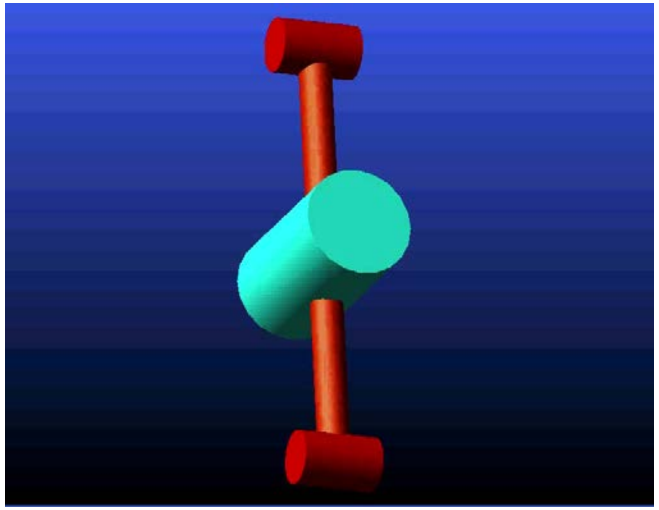
- Expandable habitat with rigid outer wall for use as a track
- 7m stowed design
- 13m deployed design
- Determined the geometry and mechanisms that would make this design feasible



Artificial Gravity Study – Future Work

- Human Health Performance Directorate will have to conduct further research into the feasibility of artificial gravity at higher angular velocity
- Structures team has presented findings to SA & ES management
- We would like to see one of our concepts come to fruition and be used on either the ISS or the Deep Space Gateway





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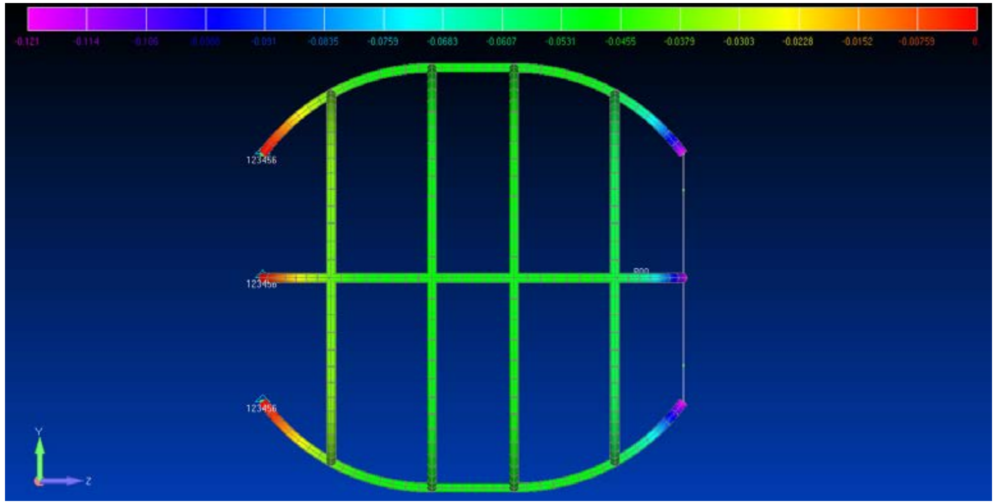
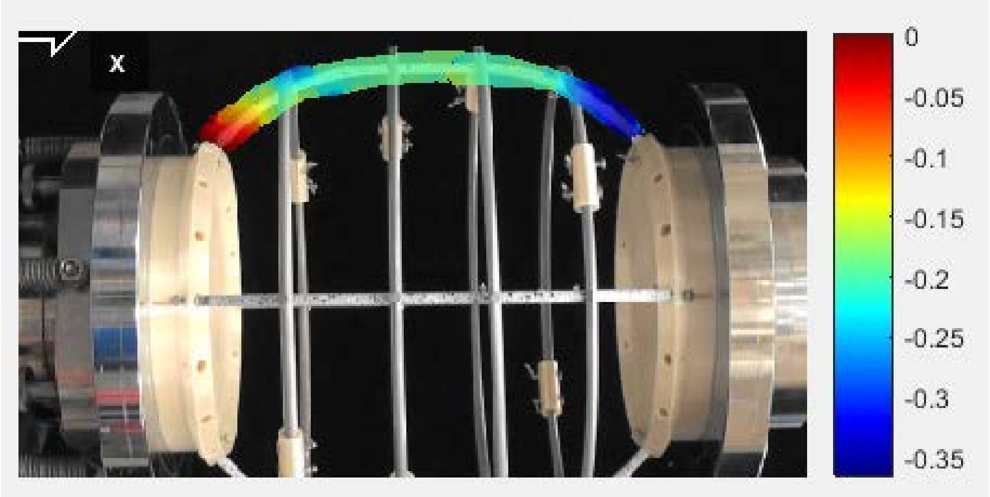
Additional Projects – Digital Image Correlation

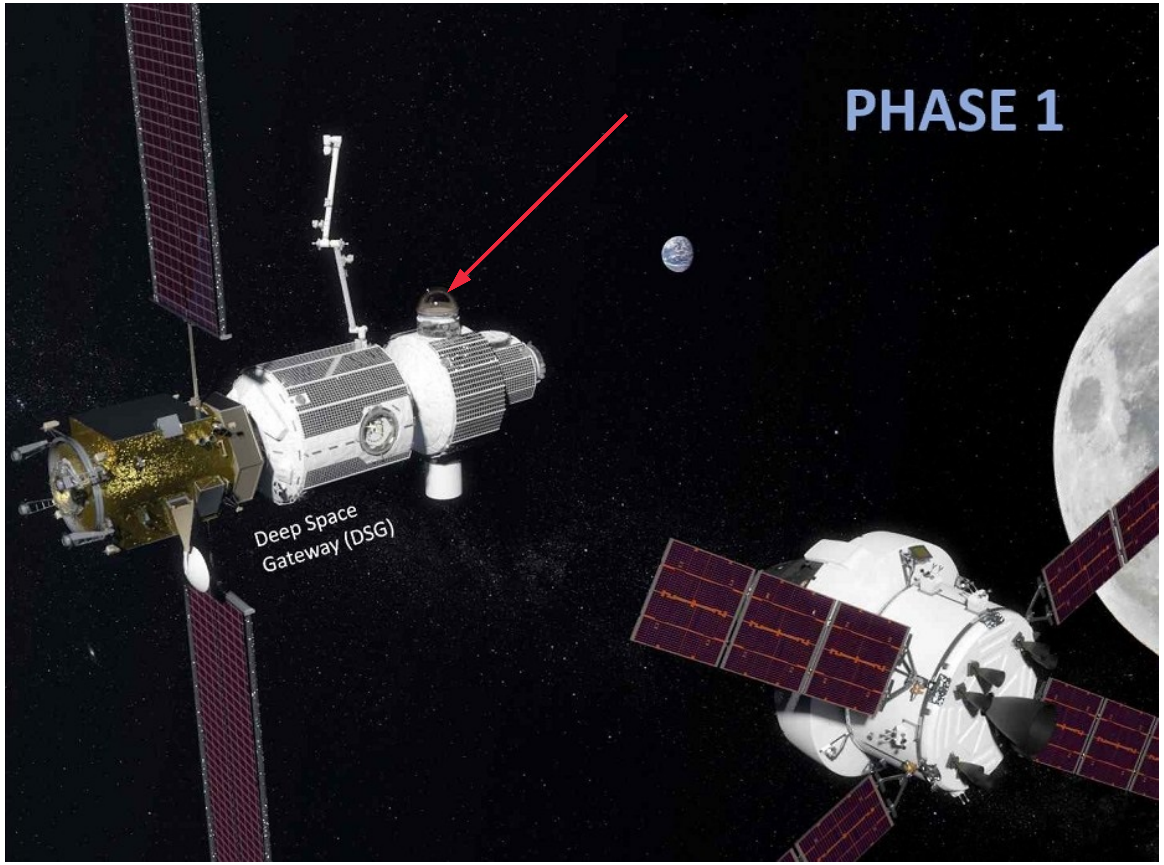
- Set up and wrote instructions for use of Digital Image Correlation software, Ncorr, for future use in the branch
  - Allows engineers to view strain heat maps on real-world test articles
  - Increases our understanding of the correlation between model and test data
- Ran the first test with the software
- This will make Digital Image Correlation more accessible at JSC





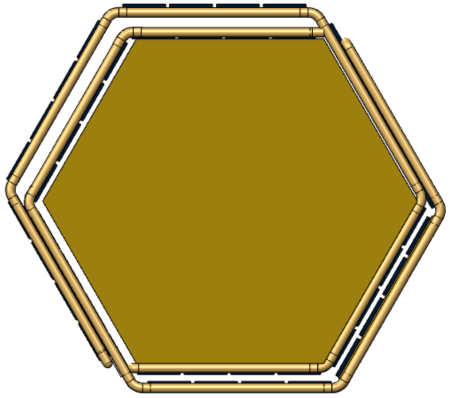
Additional Projects – Habitat Observation Port

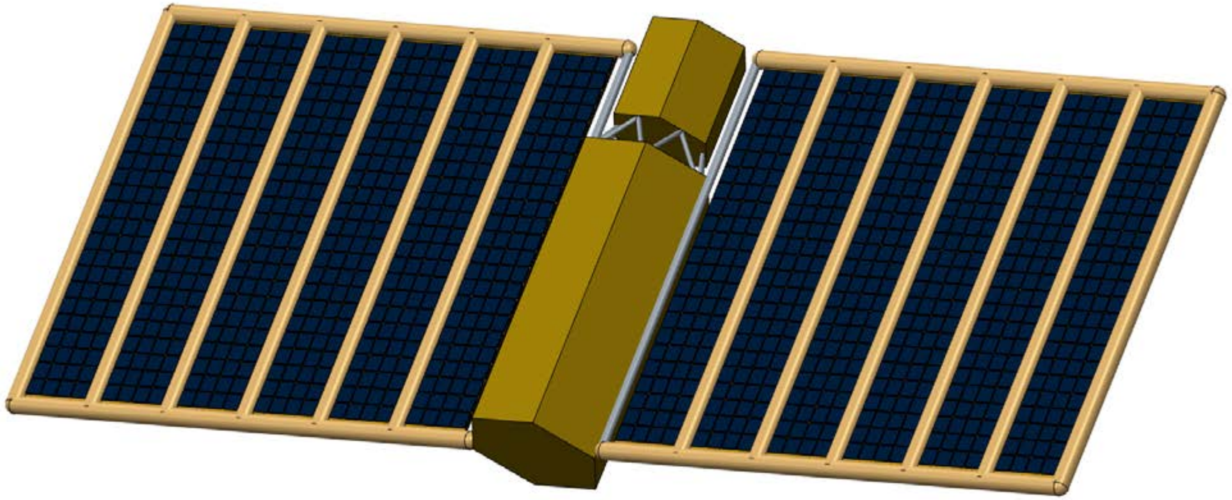
- Lighter and simpler version of the ISS cupola which allows for larger viewing angle
- Provided CAD models and drawings for Future Capabilities Team
- Featured in a presentation by the Associate Administrator of Human Exploration and Operations, Will Gerstenmaier
- Included as a contributor for a NASA New Technology Report



Additional Projects – Inflatable Solar Array

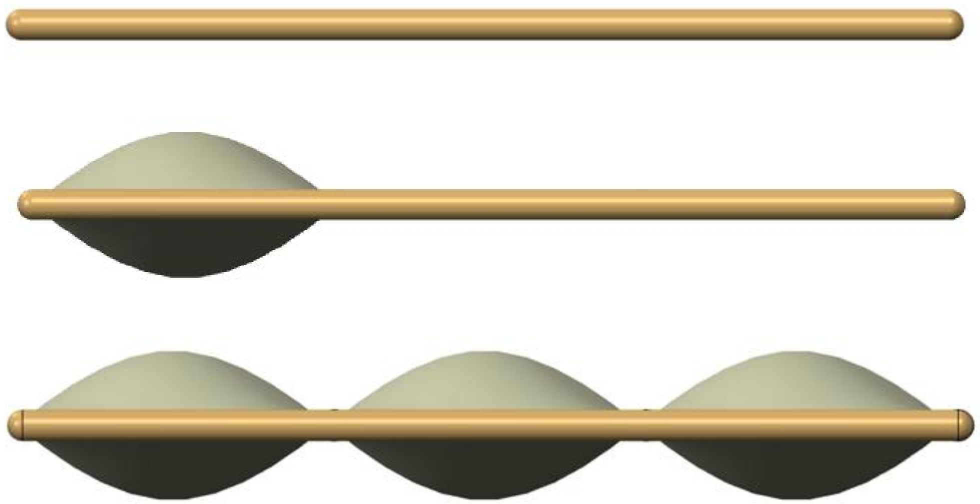
- Lighter version of the ISS solar panels
- Provided CAD models for feasibility assessments of deep space missions
- Included as a contributor for a NASA new technology report

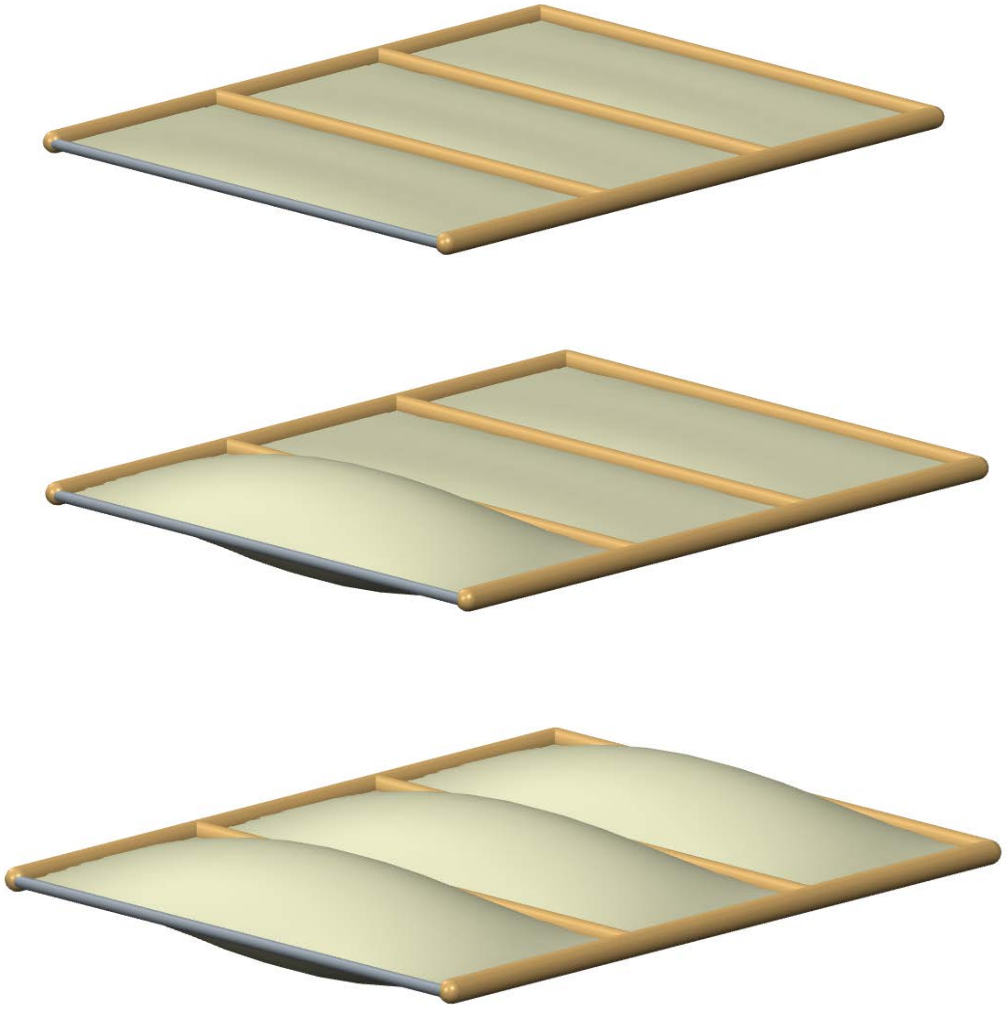




Additional Projects – Inflatable Radiator

- Lighter version of the ISS radiators
- Provided CAD models for feasibility assessments of deep space missions
- Included as a contributor for a NASA New Technology Report





Additional Projects – John Figert School of Metallurgy

- Weekly lectures taught by John Figert
- Course Content
  - Raw Metal Forms and Material Test Reports
  - Mechanical Testing
  - Metallic Alloy Selection
  - Corrosion
  - Heat Treatment of Steel Alloys
  - Heat Treatment of Aluminum Alloys
  - Work-Hardening, Compressive Residual Stress, Thermal Stress Relief, and Distortion Issues
  - JSC Central Manufacturing
  - Coatings
  - Welding
  - Lubrication

Additional Projects – Around JSC

- Super Bowl
- Astronaut food testing
- JSC intern ultimate Frisbee team
- Tour of Ellington Field by Victor Glover
- Tour of moon rock facility
- Lectures from several high-ranking astronauts, flight directors, and JSC administrators
- Lecture on the causes and return to flight operations of the Challenger and Columbia disasters

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Conclusions – Lessons Learned

- Engineering Skills
  - Finite Element Modeling (first encounter)
  - Stress analysis
  - Structural optimization (first encounter)
  - Spacecraft design (first encounter)
- Non-Technical Skills
  - Communication
  - Prioritization and time management of multiple projects
- Software Skills
  - Creo Pro E
  - Femap (first encounter)
  - MATLAB
  - NASTRAN (first encounter)
  - NX (first encounter)

Conclusions – Acknowledgements

Thank you all for making this a rewarding semester!

- Courtney Barringer
- Melissa Corning
- John Figert
- Greg Galbreath
- Mykale-Jamal Holland
- Doug Litteken
- Kornel Nagy
- Khadijah Shariff
- James Smith
- Kayla Smith
- Pamela Vasseur
- John Zipay
- Room 219
- Everyone in ES

Conclusions – Future Plans

- Summer 2017
  - Propulsion Engineering intern at SpaceX
- Fall 2017 – Spring 2018
  - Finish undergraduate aerospace engineering degree at Georgia Tech
  - Determine the best course of action for my early career
- Summer 2018 – Unknown
  - Begin career
  - Begin grad school

Questions?