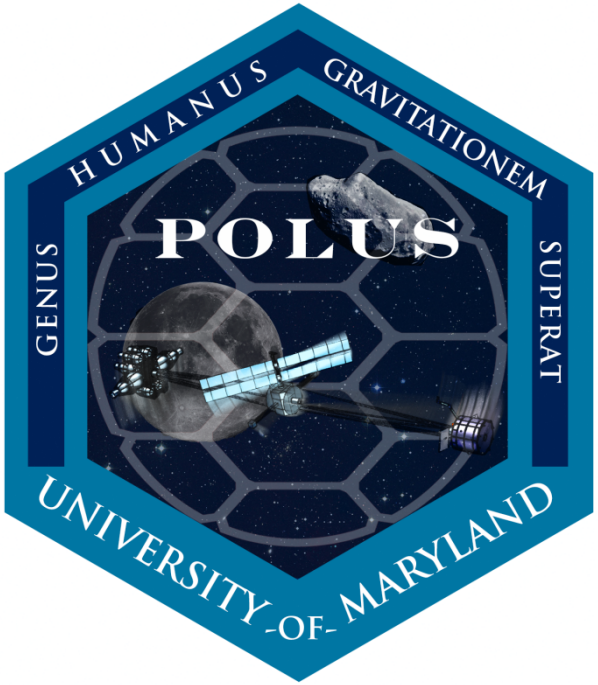
Polus

A Variable Gravity Habitat for Space Operations, Exploration, and Research



Critical Design Review

Tuesday April 29, 2014

Project Team

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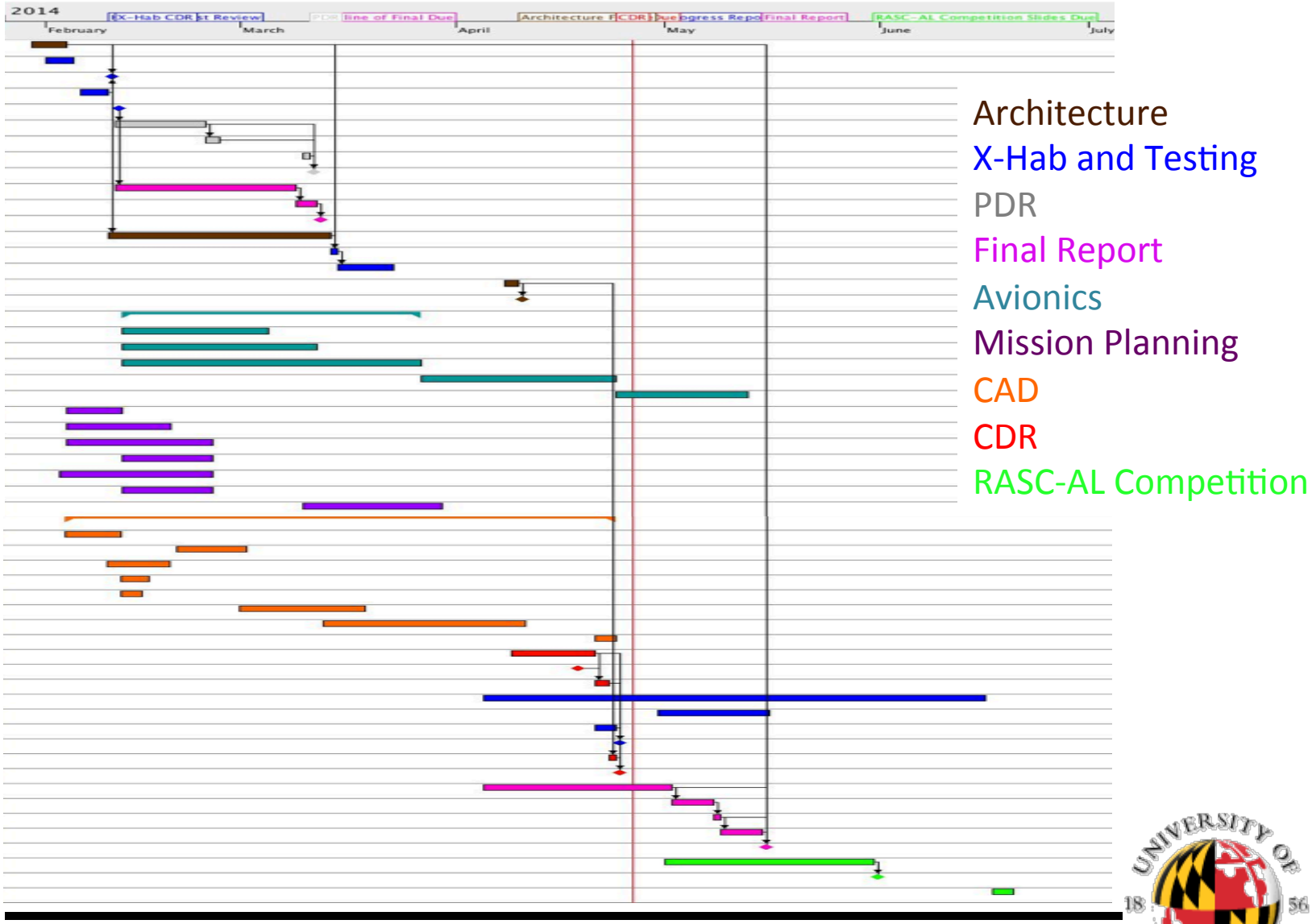
ENAE 484, RASC-AL, and X-Hab

- Design a space system to compete in the Revolutionary Aerospace Systems Concepts-Academic Linkage (RASC-AL) forum sponsored by NASA and the National Institute of Aerospace (NIA)
  - Theme for 2014: Enabling long duration missions through holistic habitat design
- X-Hab: Perform hardware testing of habitat layouts and workstations in 1 g and hypogravity

Presentation Outline

- Project Overview
- Team Organization
- Mission Requirements
- Concept of Operations
- Mission Phases
- Propulsion, Thermal, Power
- Communications and Avionics
- Human Factors
- Risk Analysis
- Project Budgets
- Cost Analysis

Gantt Chart


2014
February
March
April
May
June
July
Architecture
X-Hab and Testing
PDR
Final Report
Avionics
Mission Planning
CAD
CDR
RASC-AL Competition

Major Project Deadlines

- Current Project Tasks:
  - Oculus Rift Testing
  - Haven Testing
  - Final Report Preparation
  - RASC-AL Report and Presentation

- Upcoming Deadlines:
  - May 12: Final Report
  - June 17-19: RASC-AL Competition

Work Breakdown Structure

POLUS:
Variable Gravity Space Habitat

1. Project Management
2. System Integration
3. Mission Planning
4. Spacecraft Systems
5. Early Simulation and Training

Mission Planning Work Breakdown Structure

Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Cost	Risk (Lik.)	Risk (Sev.)	Risk (Overall)	TRL
3 Mission Planning	3.4 Crew System	3.4.1 Life Support System	3.4.1.1 Atm. Control	3.4.1.1.1 CO_2 Scrubbing	3.4.1.1.1.1 4BMS	TBD	2	1	2	
				3.4.1.1.2 O_2 Recovery	3.4.1.1.2.1 Sabatier Reaction	TBD	2	1	2	
					3.4.1.1.2.2 ACRS	TBD	2	1	2	
				3.4.1.1.3 Temp. Control	3.4.1.1.3.1 Therm. Ins.	TBD	2	2	4	
				3.4.1.1.4 Humidity Control	3.4.1.1.4.1 4BMS	TBD	2	1	2	
			3.4.1.2 Water Regen.	3.4.1.2.1 VCD	3.4.1.2.1.1 Tanks	15,000	2	4	8	9
					3.4.1.2.1.2 Pumps					
					3.4.1.2.1.3 Pipes					
				3.4.1.2.2 Multi-Filtration System		3,000	2	4	8	9
				3.4.1.2.3 Forward Osmosis Bag		TBD	3	1	3	6

Mission Overview

- Design a variable gravity space habitat to assess the need for artificial gravity on long term human exploration missions
- Phased approach to utilization:
  - Phase I: early microgravity
  - Phase II: artificial gravity
  - Phase III: full lunar/Mars mission simulations

Level 1 Requirements

Overall Mission Objective

To design a cislunar space habitat capable of providing data on long-term hypogravity and radiation effects prior to a manned Mars mission.

Phase I: Early Microgravity

Habitat shall support a crew of 4 in support of the proposed Asteroid Redirect Mission (ARM) in Selenocentric Distant Retrograde Orbit (SDRO)

Level 1 Requirements

Phase II: Artificial Gravity

Using 1 additional HLLV, the system shall be upgraded to support a crew of 6 for 6 months and shall generate up to 1g of artificial gravity

Phase III: Mars Mission Simulation

Using 1 additional HLLV, the system shall be upgraded to support a crew of 6 for a 1000 day simulated Mars mission, including simulated Martian EVAs

Asteroid Redirect Mission (ARM)

Capture and redirect a 7-10 m diameter, ~500 tons Near-Earth Asteroid (NEA) to a stable Distant Retrograde Orbit (DRO) around the Moon by 2021

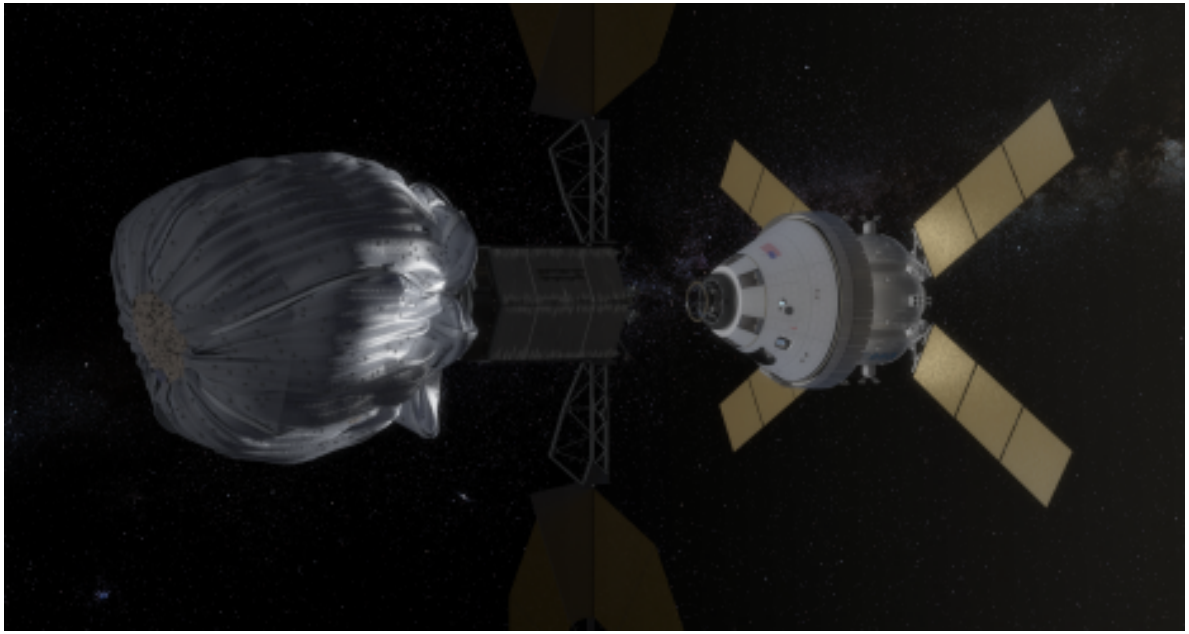
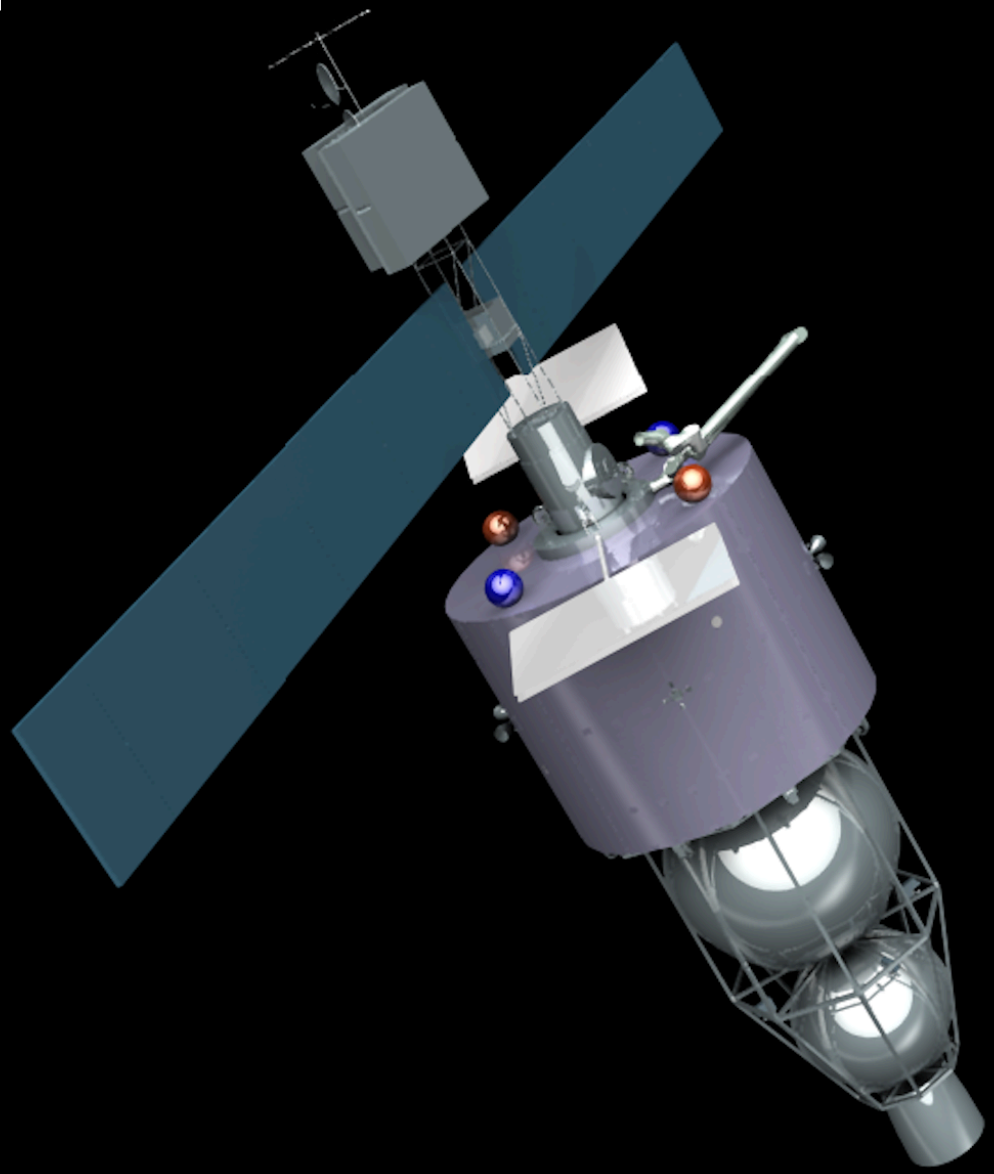
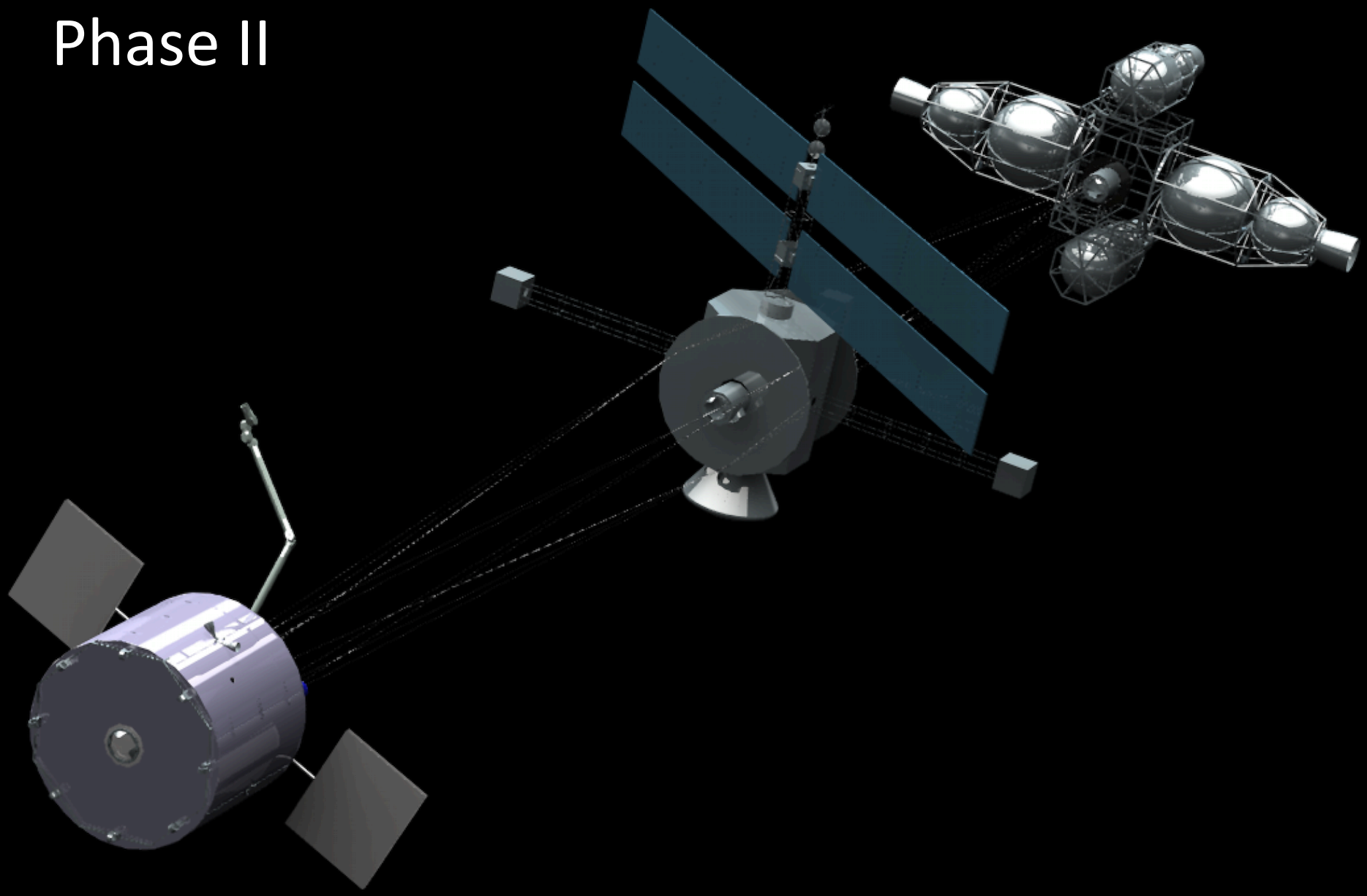


Image Credit: NASA

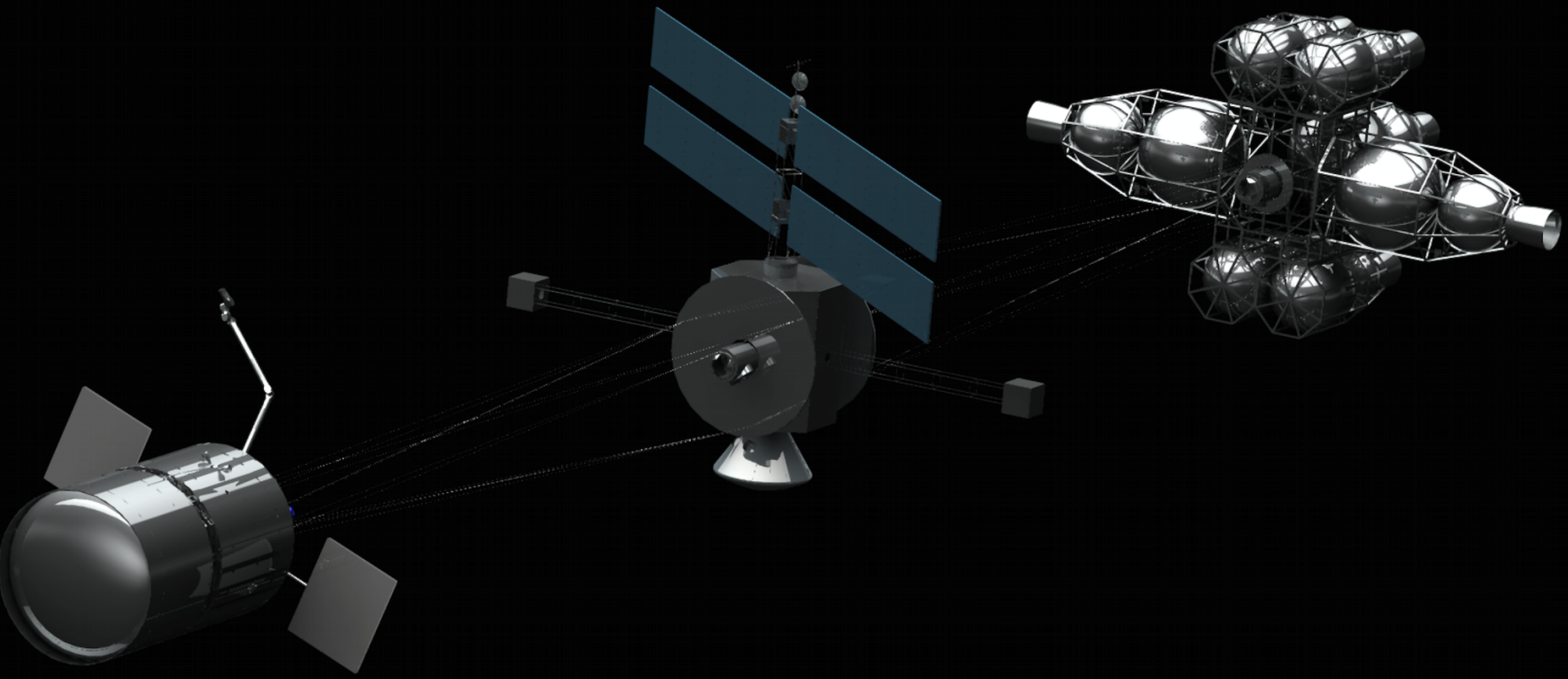
Phase I



Phase II



Phase III



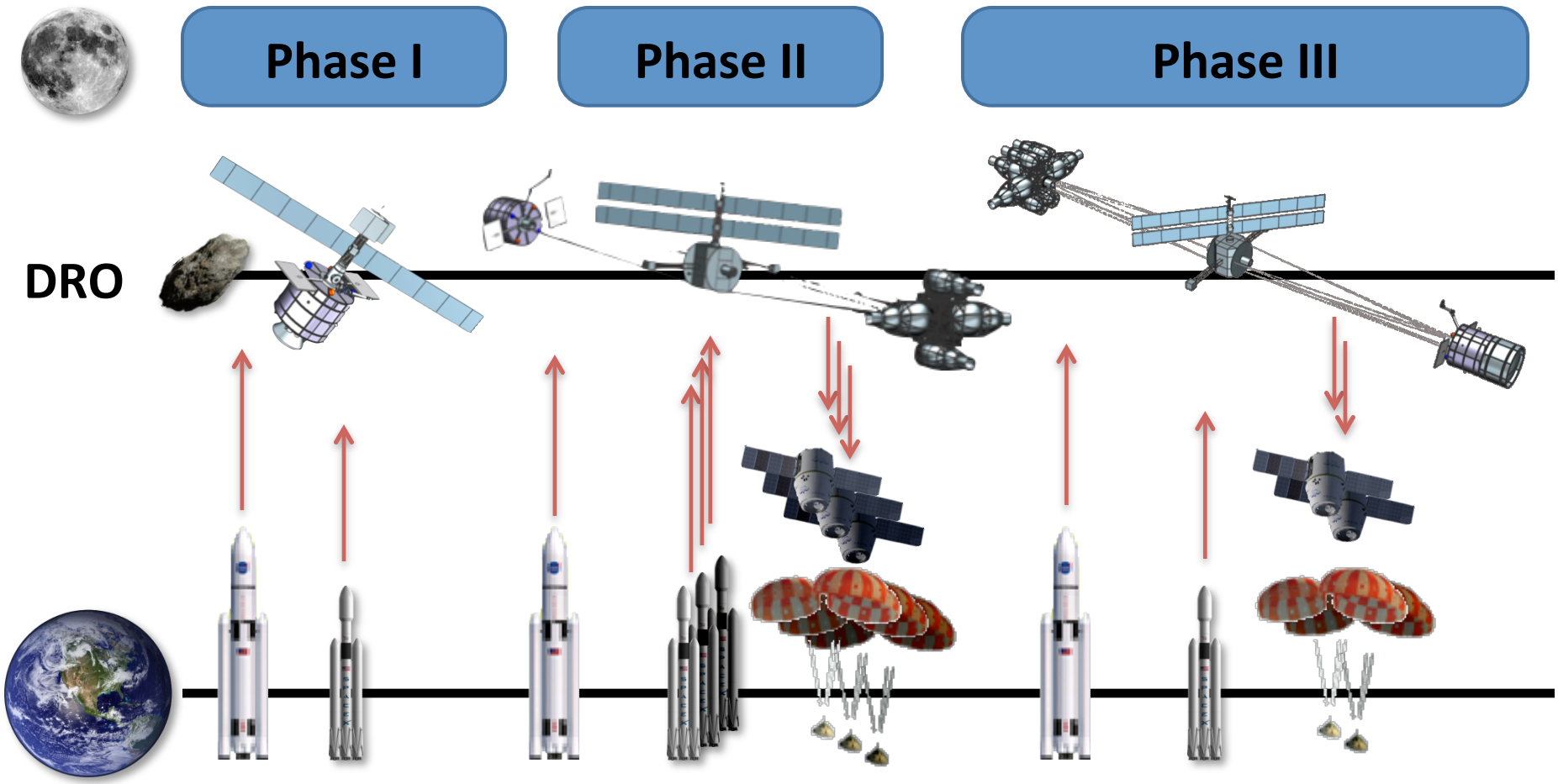
Mission Science Objectives

Primary Science Questions	
I	What is the asteroid's composition & chemical history?
	What are the physical & surface characteristics of the asteroid?
	What is the deep space environment near 1 AU?
	What volatiles exist & can be extracted from the asteroid?
II	What are the effects of long-term variable gravity on human physiology?
	What are the effects of long-term variable gravity on microbial life?
	What is the nature of radiation exposure outside the Van Allen Belts?
III	What are the effects of Martian gravity on long-term habitability?

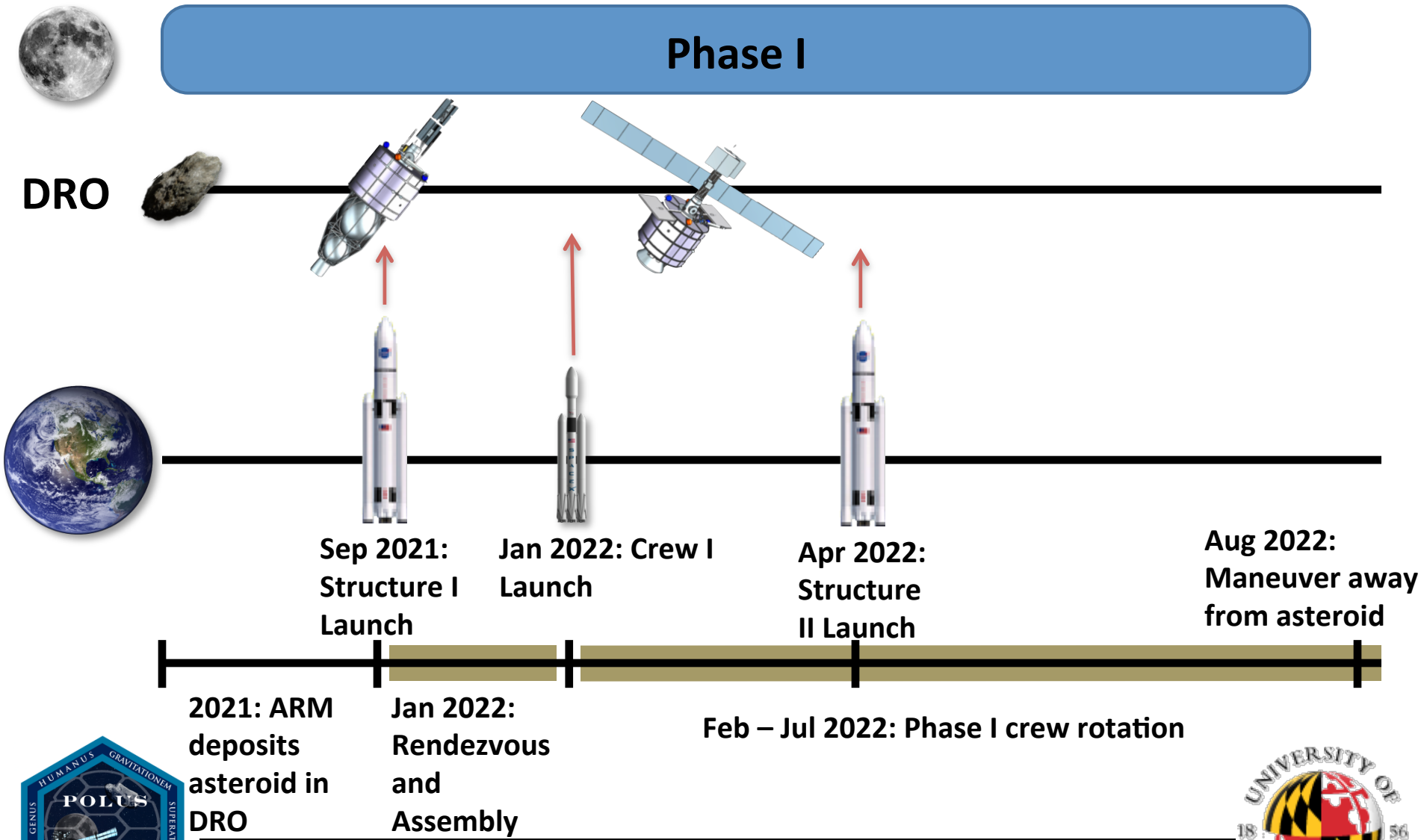
Mission Science Objectives

Operations Questions	
I	In what ways can an asteroid be repurposed to support space exploration?
	What are the most effective proximity operations procedures?
II	How does long-term artificial gravity affect habitability and station operations?
	How do the generated coriolis forces affect habitability and station operations?
III	How does Martian gravity affect EVA operations?
	What are effective construction methods in Martian gravity?
	What are effective stabilization methods for EVA operations in Martian gravity?
	How does Martian gravity affect astronaut interaction?
	What is the effectiveness of suit ports when tested in a controlled environment?

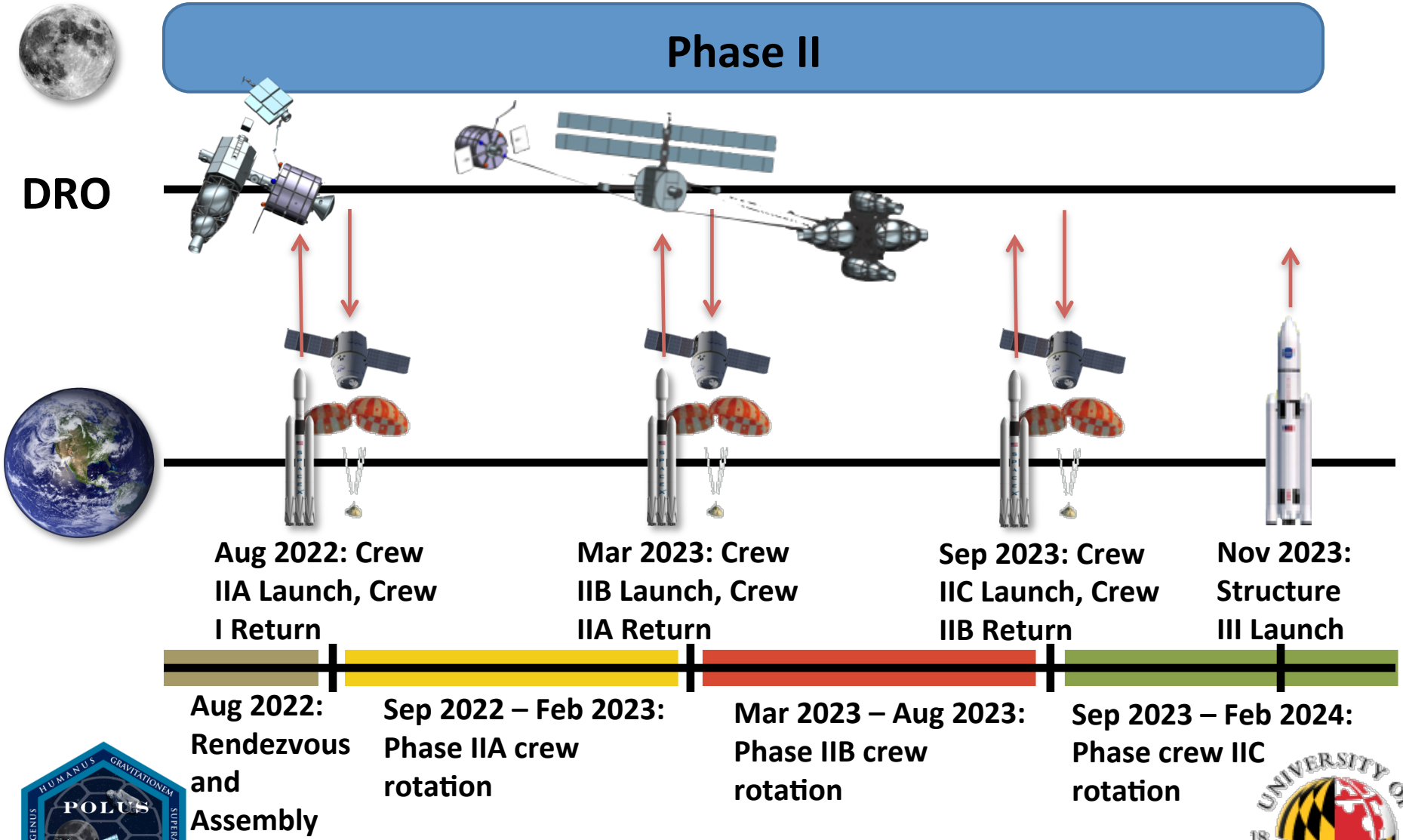
Mission Timeline



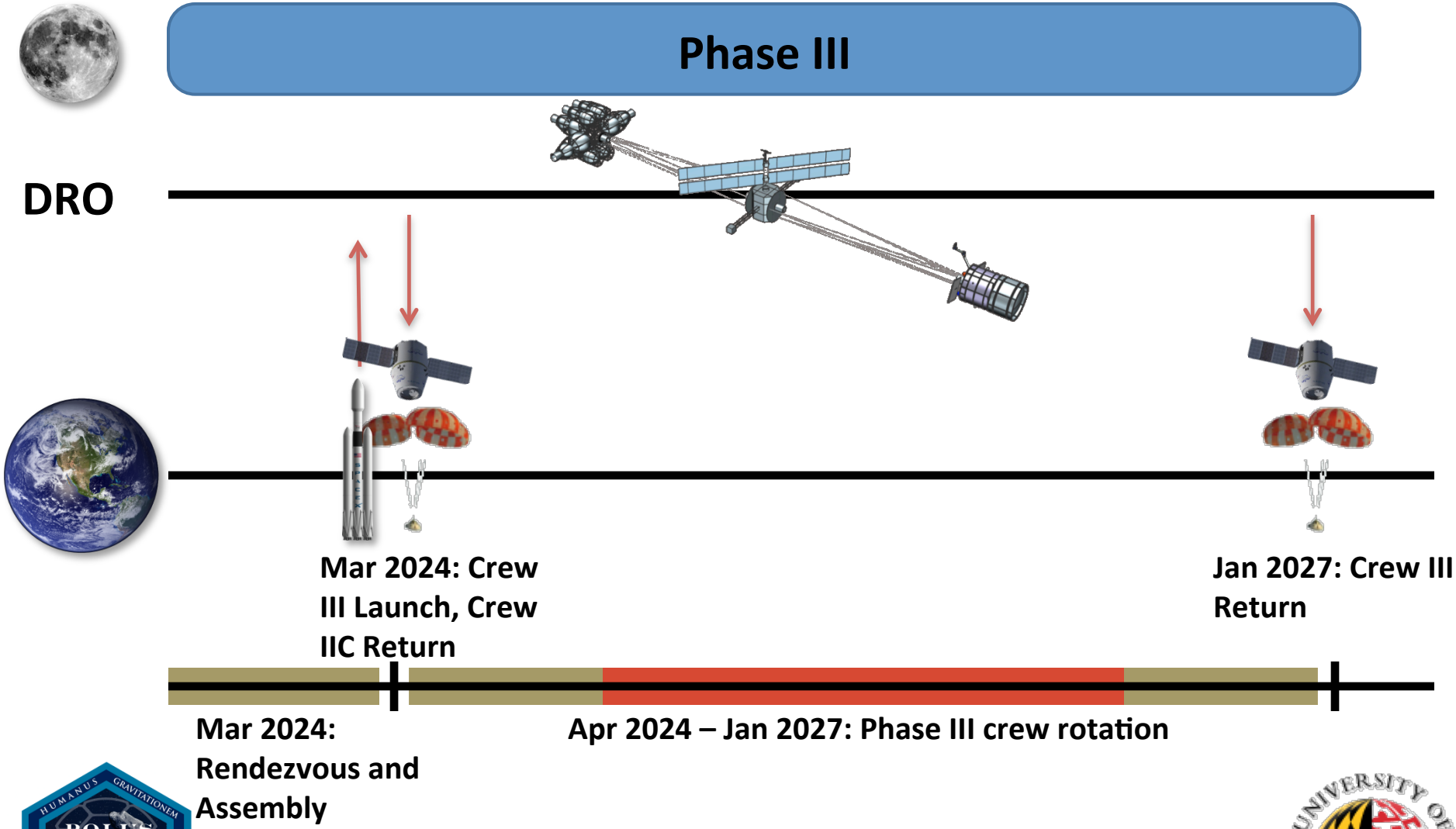
Mission Timeline: Phase I



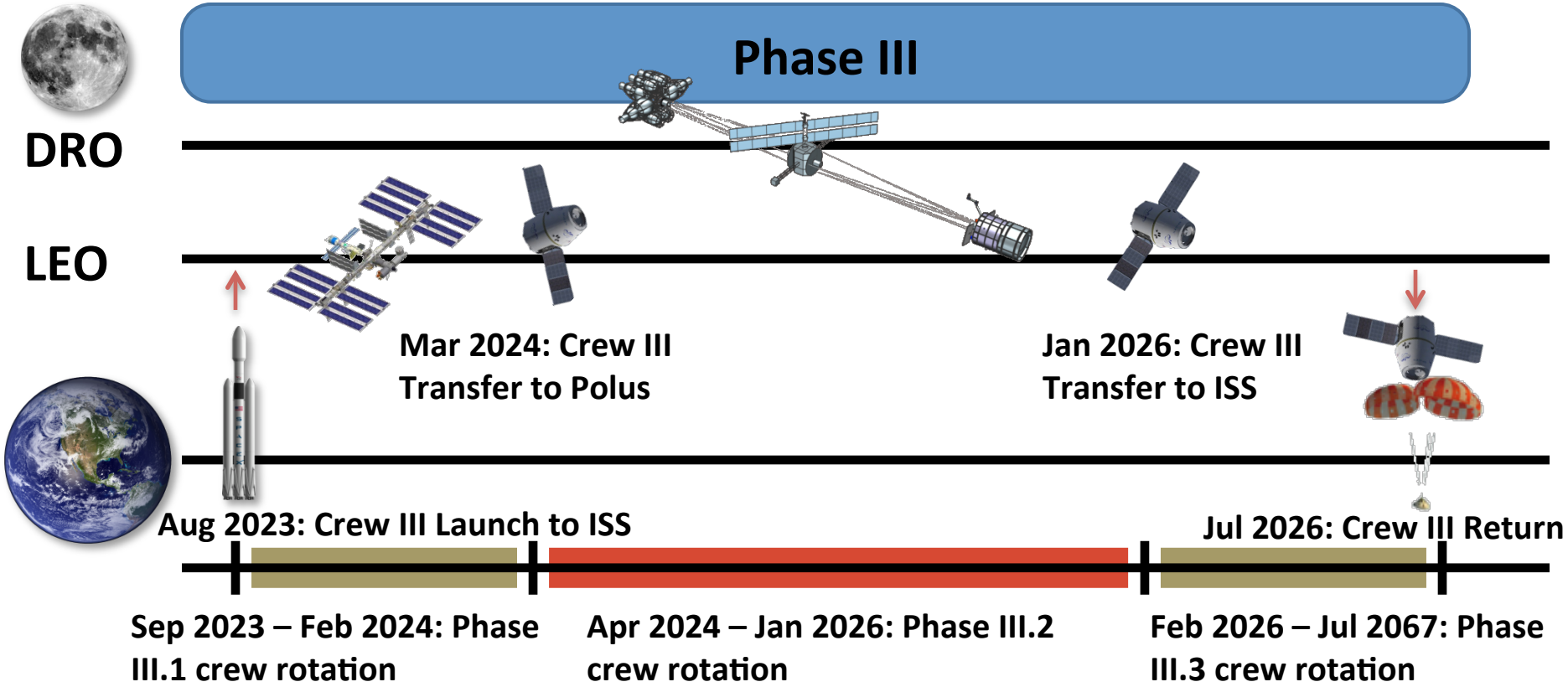
Mission Timeline: Phase II



Mission Timeline: Phase III



Mission Timeline: Alternate Phase III



Using ISS and Polus	Only using Polus
Maximizes Polus' capabilities	Higher fidelity mission simulation
Expedites mission timeline	Transfers between ISS and Polus require a very high ΔV
ISS mission extension	

Phase IV and Beyond

- Extended manned studies
  - Additional Mars simulations
  - Variable gravity, long-term space health, asteroid and lunar science, lunar telerobotic support
- Extended unmanned studies
  - Lunar observation, asteroid observation
- Logistics depot
- Contingency support for other missions
- Upgraded for manned Mars mission

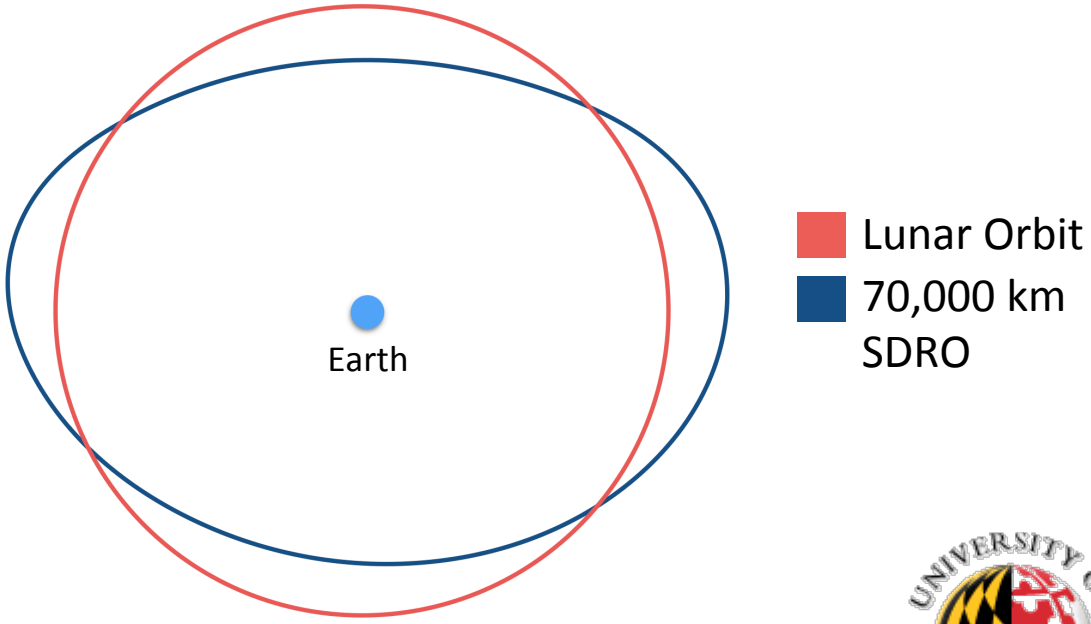
SDRO: A Quick Overview

- SDRO: Selenocentric Distant Retrograde Orbit
  - ~100 year stability with no stationkeeping
  - Similar ΔV for LEO → L1 and LEO → SDRO transfers
  - Exotic motion at 70,000 km lunar altitude:

Mean radius: 70,000 km

Note that with a 26 day orbital period, SDRO motion appears geocentric

Geocentric Inertial Frame



Transfers to SDRO

Classification	Primary Transfer ΔV [km/s]	Secondary Transfer ΔV [km/s]	SDRO Insertion ΔV [km/s]	Total ΔV [km/s]	Duration [days]
Low Energy Cargo [1]	3.2	---	0.090	3.29	100.5
High Energy Cargo [1]	3.14	0.67	0.075	3.88	32.5
High Energy Crew [2]	3.2	---	0.80	~4.00	~4

[1] X. Ming, X. Shijie "Exploration of distant retrograde orbits around Moon"

[2] General Mission Analysis Tool, Daniel R. Adamo, "Selenocentric Distant Retrograde Orbits (SDROs)"

Note: "Primary/Secondary" Transfer ΔV is analogous to TLI burn for Apollo missions, and SDRO Insertion ΔV with LOI

- DRO/L1 → Earth Return Trajectory
  - Maximum Earth Atmospheric Entry Interface Velocity: 12 km/s (Apollo)
  - Cislunar design space: Apollo limits will not be exceeded on reentry
  - No slow down needed; 0.5 km/s design target for Earth return maneuver

Launch Sites

- Launch Site Requirements:
  - Infrastructure to support heavy lift launches
  - Minimize LEO parking orbit inclination (to match lunar)

$$\cos i = \sin A \cos \phi$$

  - Maximize ΔV gain from Earth's rotation

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Launch Site	Latitude (ϕ)	Azimuth (A) Range	Minimum Inclination (i)	ΔV gain [m/s]
Cape Canaveral	**28.5˚**	**35˚ - 120˚**	**28.5˚**	**409**
Vandenberg	34.8˚	158˚ - 201˚	51˚	-382

Heavy Lift Launch Vehicles

Vehicle	Mass to LEO [kg]	Mass to TLI [kg]	Payload Fairing Diameter [m]	Payload Fairing Height [m]	Total Fairing Volume [m³]	Cost per kg, LEO	Cost per m³
SLS Block 1A	105,000	[1]	8.4	~25	~1400	$14,286	$1.071 M
Falcon Heavy	53,000	~16,000	4.6	11.4	~130	$7245	$2.954 M
Atlas V 551	18,500	~4000	5.4	26.5	~550	$5946	$0.2 M
Delta IV Heavy	20,500	~6000	5.0	19.8	~300	$6829	$0.467 M

Assumed launch prices:

- SLS Block 1A (Cargo): $1.5 Billion
- Falcon Heavy: $384 Million
- Atlas V 551: $110 Million
- Delta IV Heavy: $140 Million

Other assumptions:

- TLI ΔV is approximately equal to GEO total ΔV
- SLS and Falcon Heavy estimated launch prices will triple as they become operational due to unforeseen development costs

[1] SLS Block 1A mass to TLI dependent on upper stage

Cargo Launch Vehicle Selection

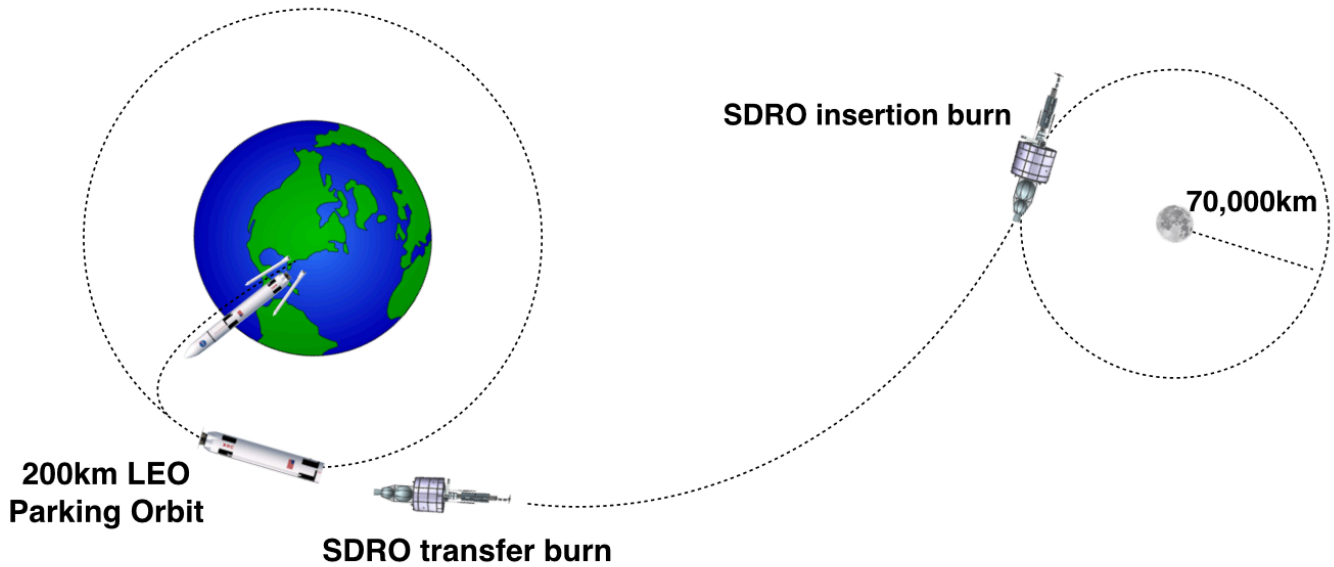
Top Level Requirement: 1 HLLV per mission phase (cargo)

- Though Atlas/Delta are cheaper by both cost metrics, the only viable candidate for a long endurance space habitat is **Space Launch System Block 1A.**

- **Launch Architecture**
  - Several options considered
    - SLS direct insertion to SDRO transfer, habitat insertion into SDRO
    - SLS to LEO, habitat insertion to SDRO transfer & into SDRO
    - SLS to LEO, cryogenic upper stage insertion to SDRO transfer, habitat insertion into SDRO

Deliverable habitat mass is maximized by using cryogenic propellant for large insertion burn, so the 3rd option is chosen. The upper stage mass is repurposed as ballast in Phases II and III to maximize usable mass.

Determination of Deliverable Mass



- 2 applications of the rocket equation (Transfer/SDRO insertion)
  - 10% estimation initially used for upper stage structural mass
    - Further refined by using a linear extrapolation from existing Delta Cryogenic Second Stage (DCSS)
  - Upper stage mass included in SDRO insertion
  - A linear system can be constructed to model the transfer procedure (4 variables and 4 constraints)

Determination of Deliverable Mass

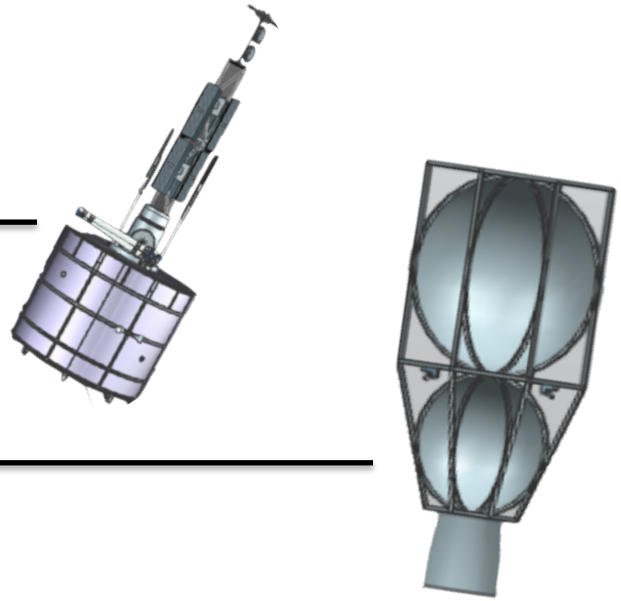
- **The scenario:** 105,000 kg of habitat dry mass + propellant, upper stage dry mass + propellant in LEO after SLS launch with a fixed SDRO transfer ΔV and a fixed SDRO insertion ΔV

- **4 variables to determine:** habitat dry mass, habitat propellant mass, upper stage dry mass, upper stage propellant mass

- **4 constraint equations:**
  - Upper stage dry mass = 10% of upper stage gross mass
  - Rocket equation #1: All upper stage propellant inserts gross habitat mass, upper stage dry mass into transfer trajectory
  - Rocket equation #2: All habitat propellant inserts dry habitat mass, dry upper stage mass into SDRO
  - All 4 unknowns sum to 105,000 kg

Determination of Deliverable Mass

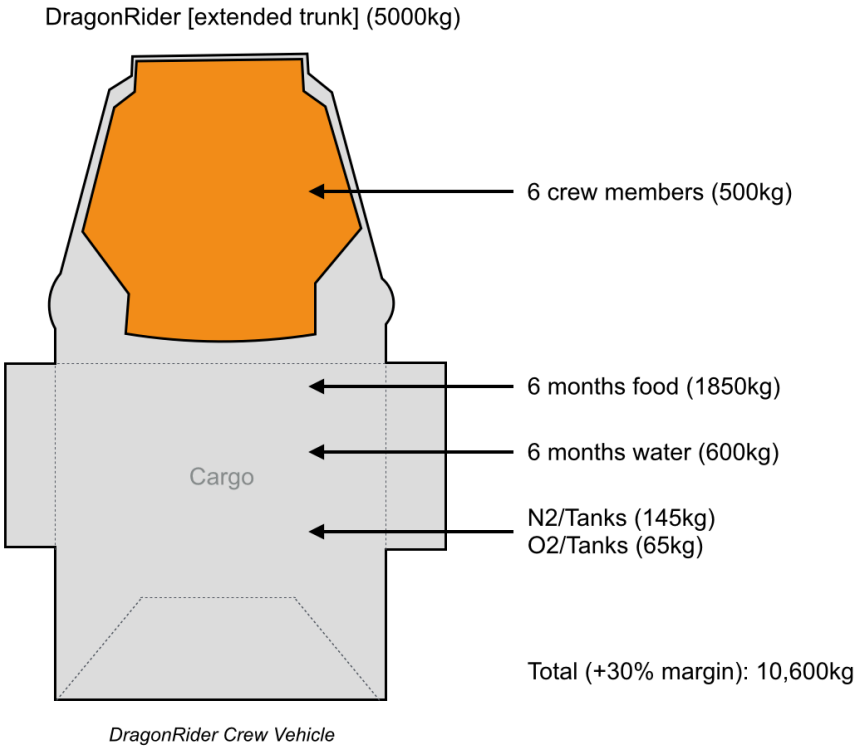
Variable	Value [kg]
Habitat Dry Mass	52,000
Habitat Propellant Mass	2000
Upper Stage Dry Mass	5250
Upper Stage Propellant Mass	45,750



- Habitat propellant mass models only impulsive maneuvers, not RCS. RCS & spin up/down propellant must be included in habitat dry mass
- The same analysis process is used for crew launches, but with a faster & higher energy transfer
- Upper stage dry mass is a *minimum* value, but can increase with a corresponding decrease in habitat dry mass.
  - Can be beneficial to increase ballast mass

Crew Launch Parameters

- **Requirements**
  - Capable of transporting DragonRider to SDRO, loaded with:
    - 6 crewmembers
    - Consumable & life support replenishment
    - Propellant replenishment
  - Higher energy transfers for tolerable transfer time (crewed transfers)



Total (+30% margin): **10,600 kg**

Crew Launch Vehicle Selection

Vehicle	Mass to LEO [kg]	Mass to SDRO (fast transfer) [kg]
SLS Block 1A	105,000	45,000
Falcon Heavy	53,000	16,500
Atlas V 551	18,500	5000
Delta IV Heavy	20,500	6250

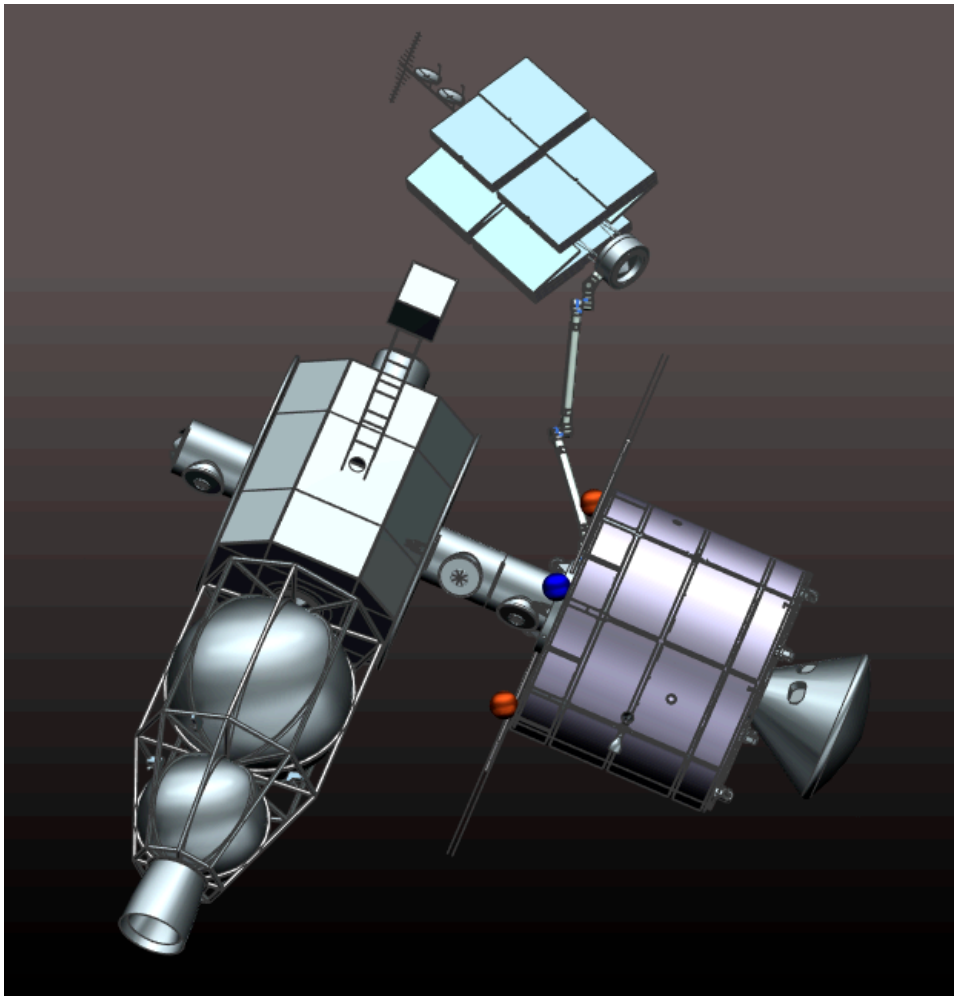
- Falcon Heavy selected for use with ~26,000 kg cryogenic upper stage for SDRO transfer insertion burn.
- On a cost basis, Atlas V 551 and Delta IV Heavy up to 20% less costly than Falcon Heavy. However, they cannot lift a 26,000 kg upper stage to LEO, adding extra complexity (multiple launches with on-orbit fuel top-off). The cost reduction is offset by this.

Station Assembly Mechanisms & Tools

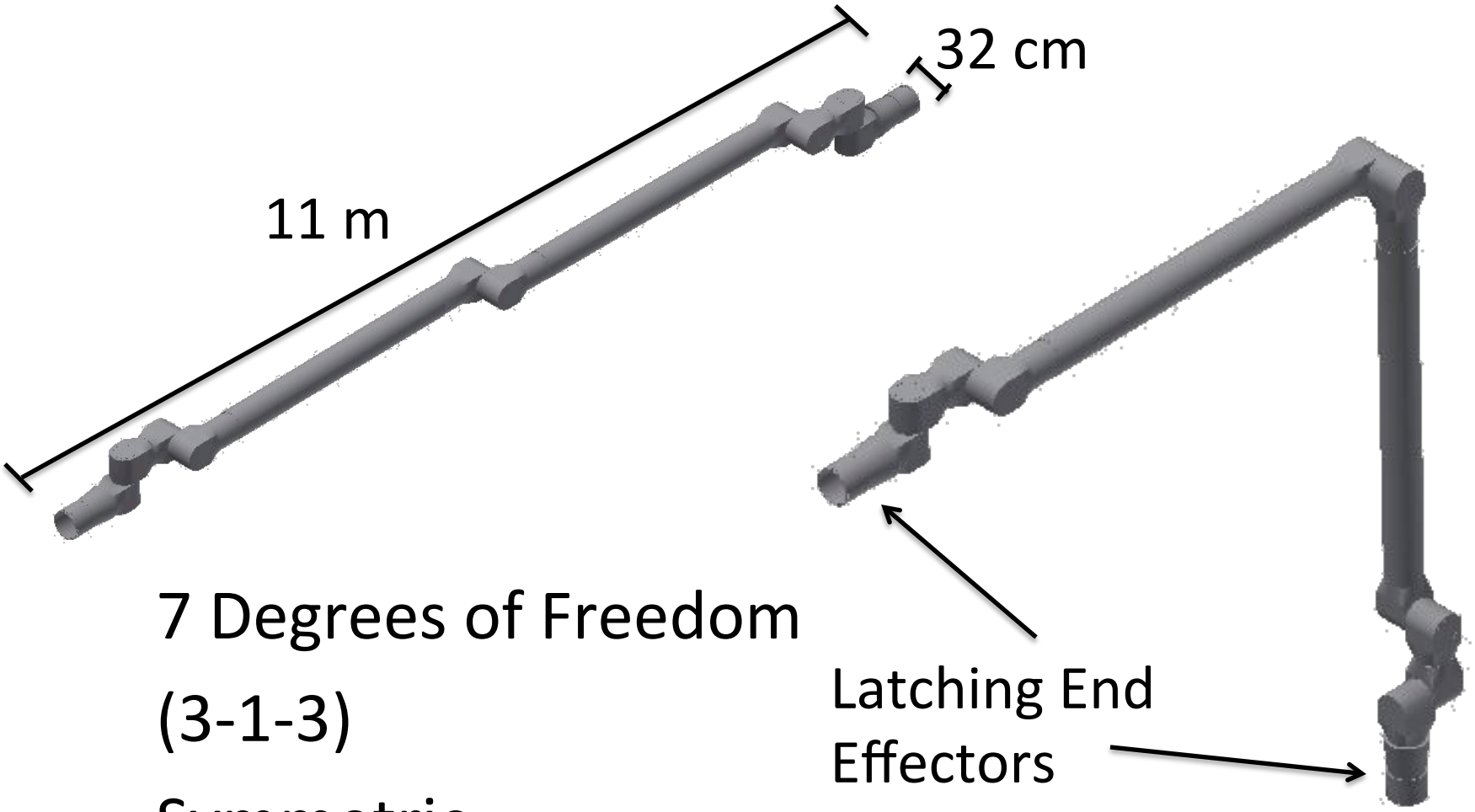
- Astronaut EVAs
  - Handrails and footholds
  - Harnesses and safety tethers
  - Toolboxes and supplies outside of the station
  - Robotic arm assistance
- Pistol-Grip hand drill
- Trace Gas Analyzer
- Video cameras and LIDAR
- Robotic Arm
  - Astronaut EVA assistance
  - Remote control from station or Earth
  - Station equipped with Power Data Grapple Fixtures and Flight Releasable Grapple Fixtures

Robotic Arm Requirements

- Assembly
- Maintenance
- Inspection
- EVA support
- Refueling



Robotic Arm Specifications

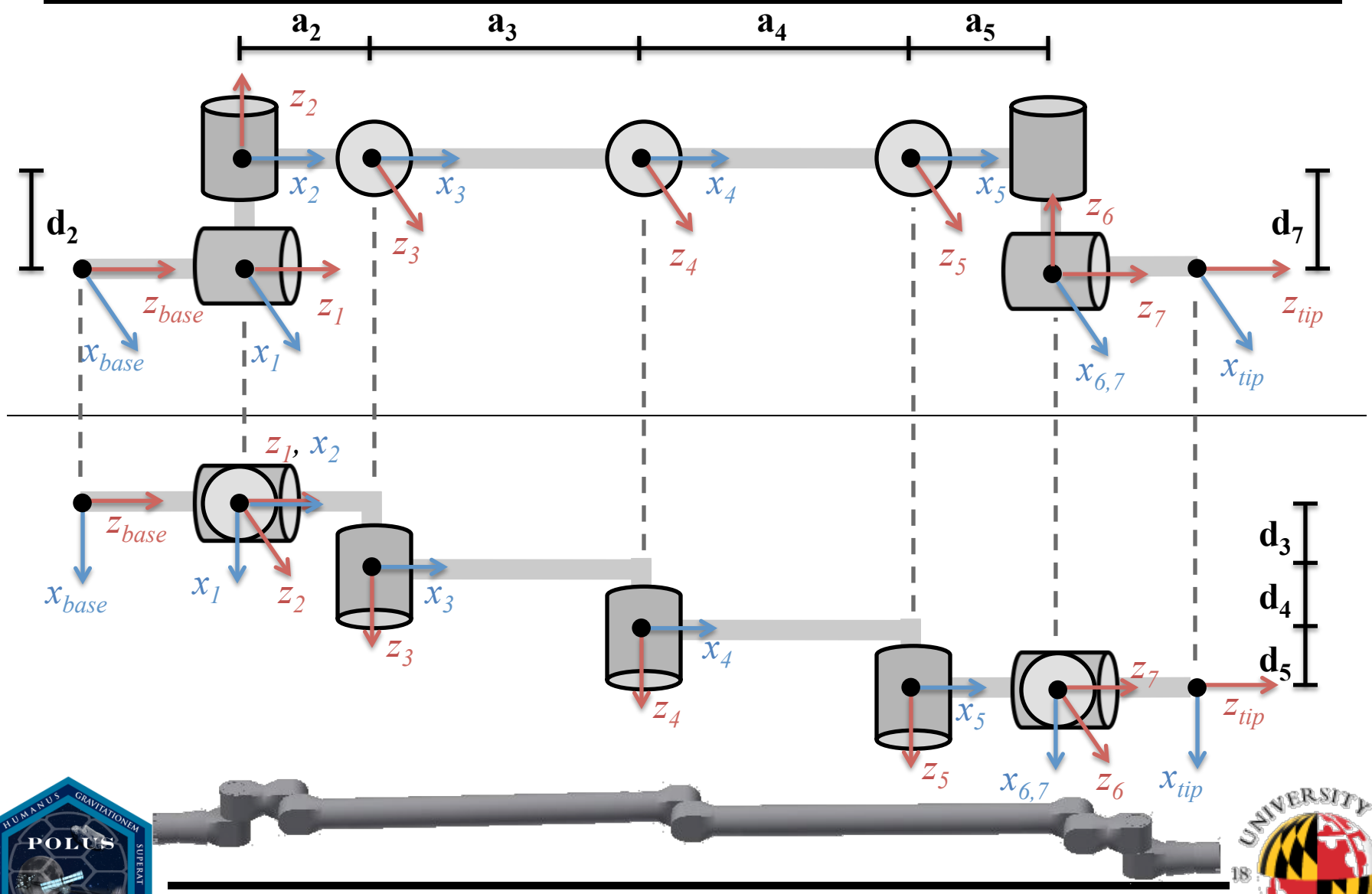


7 Degrees of Freedom

(3-1-3)

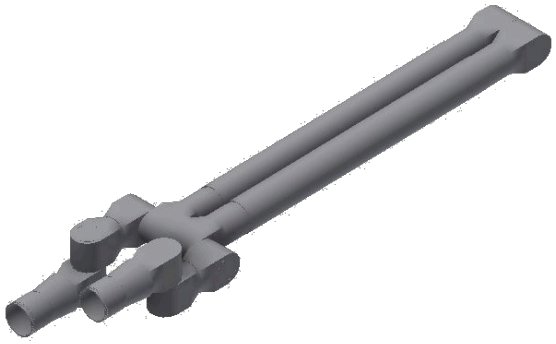
Symmetric

Robotic Arm Link Frames

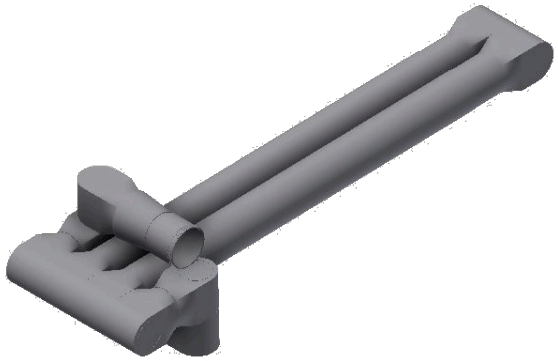


Robotic Arm D-H Parameters

i	α_i [°]	a_i [m]	d_i [m]	θ_i [°]
1	90	0	0	0
2	90	0.62	0.32	90
3	0	4.22	0.32	0
4	0	4.22	0.32	0
5	-90	0.62	0.32	0
6	-90	0	0.32	-90
7	0	0	0	0



Stowed configuration



Packed configuration

Robotic Arm Mobility

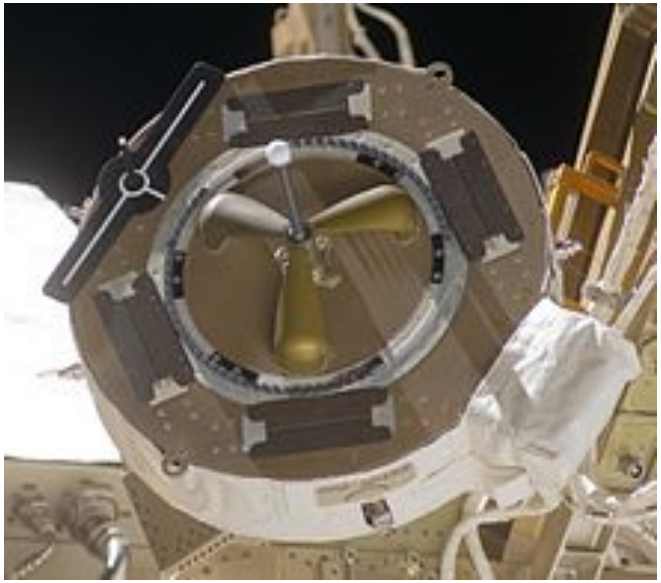


Image Source: NASA

Power Data Grapple Fixture (PDGF)

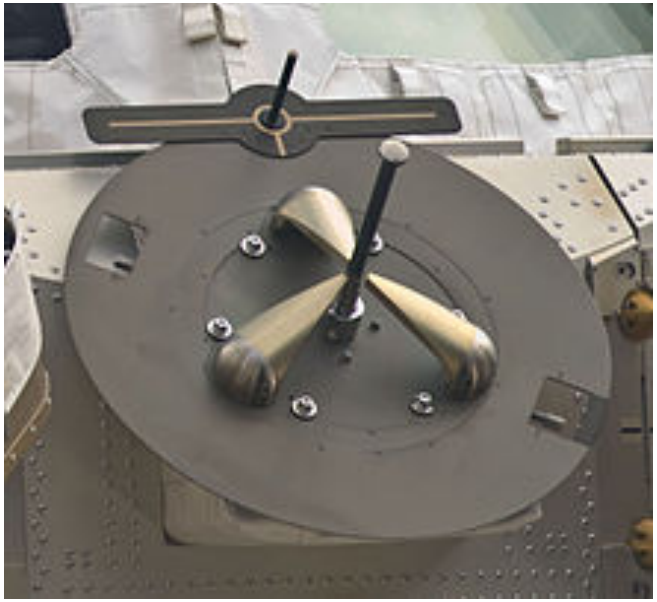


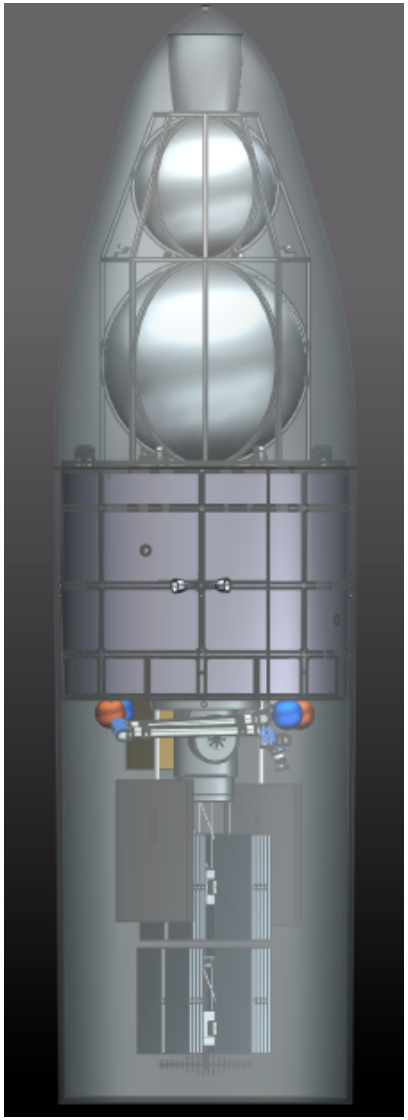
Image Source: NASA

Flight Releasable Grapple Fixture (FRGF)

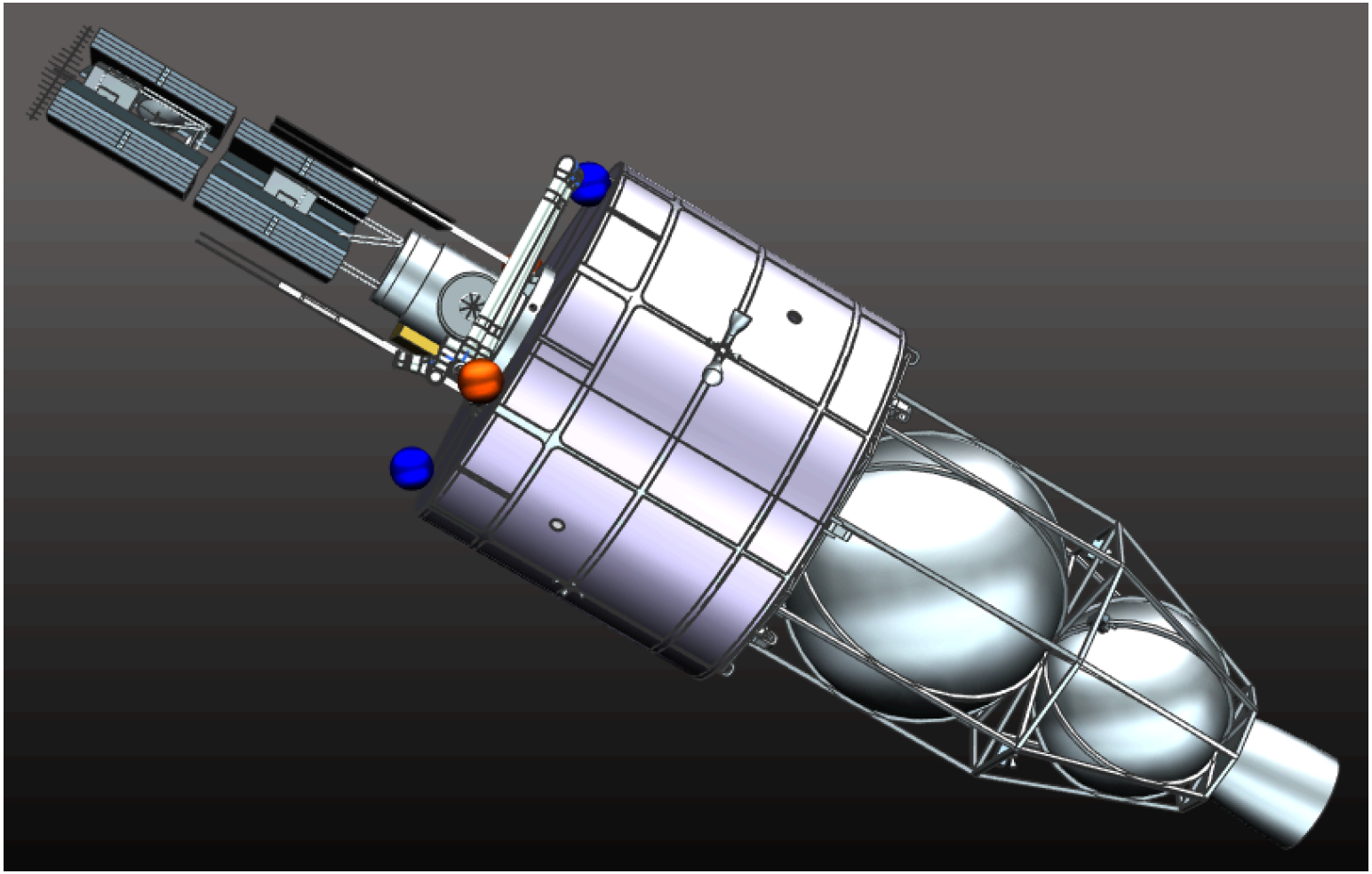
Robotic Arm Operation

- Primarily controlled by:
  - Sequences developed on Earth
  - Real-time Cartesian control from Polus
- Semi-autonomous
- Prior to operation:
  - Electronically isolate involved components
  - Activate support systems
  - Halt disruptive onboard activities
- Operational testbed for mid-latency telerobotic control interfaces

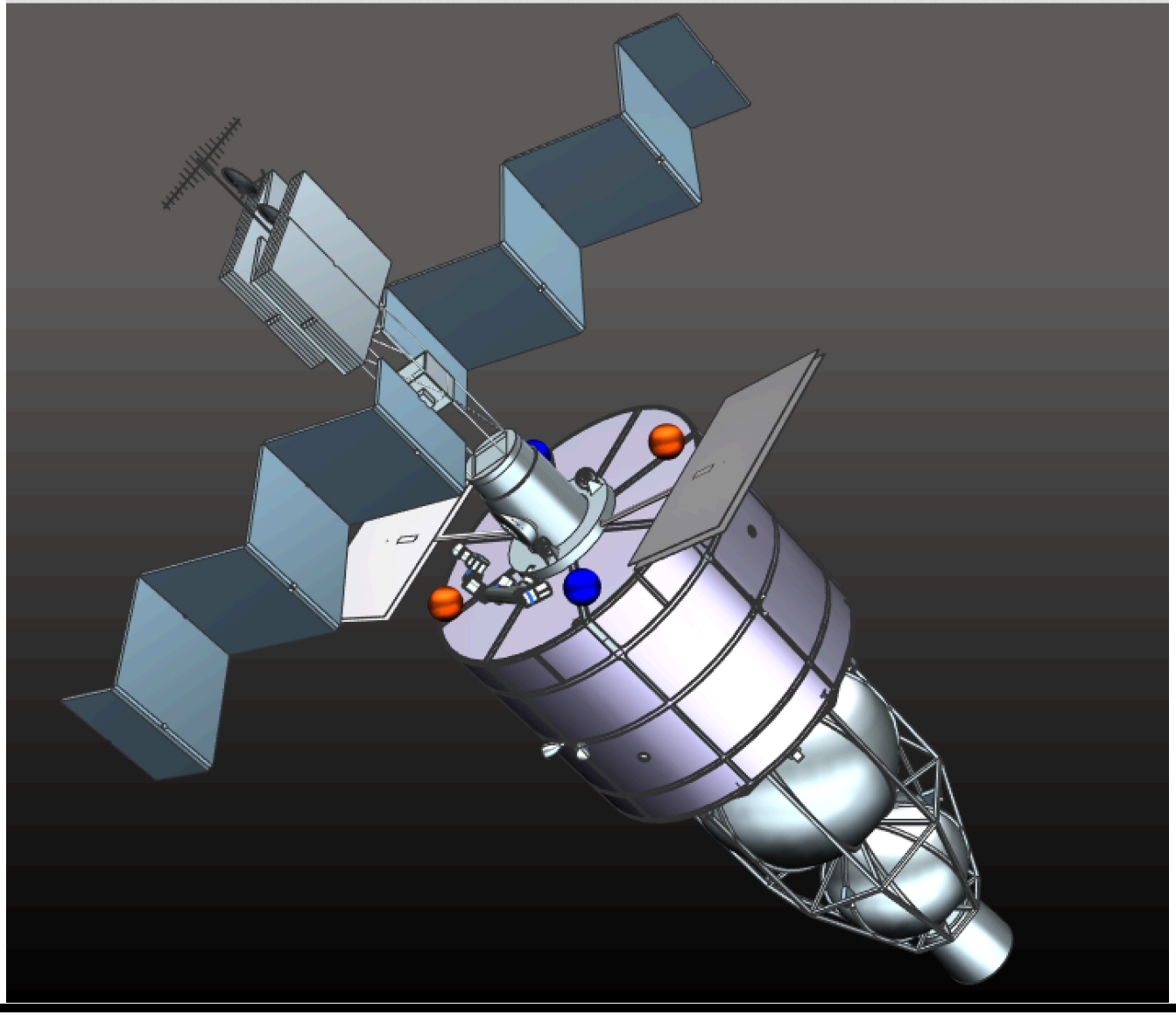
Phase I Fairing Configuration



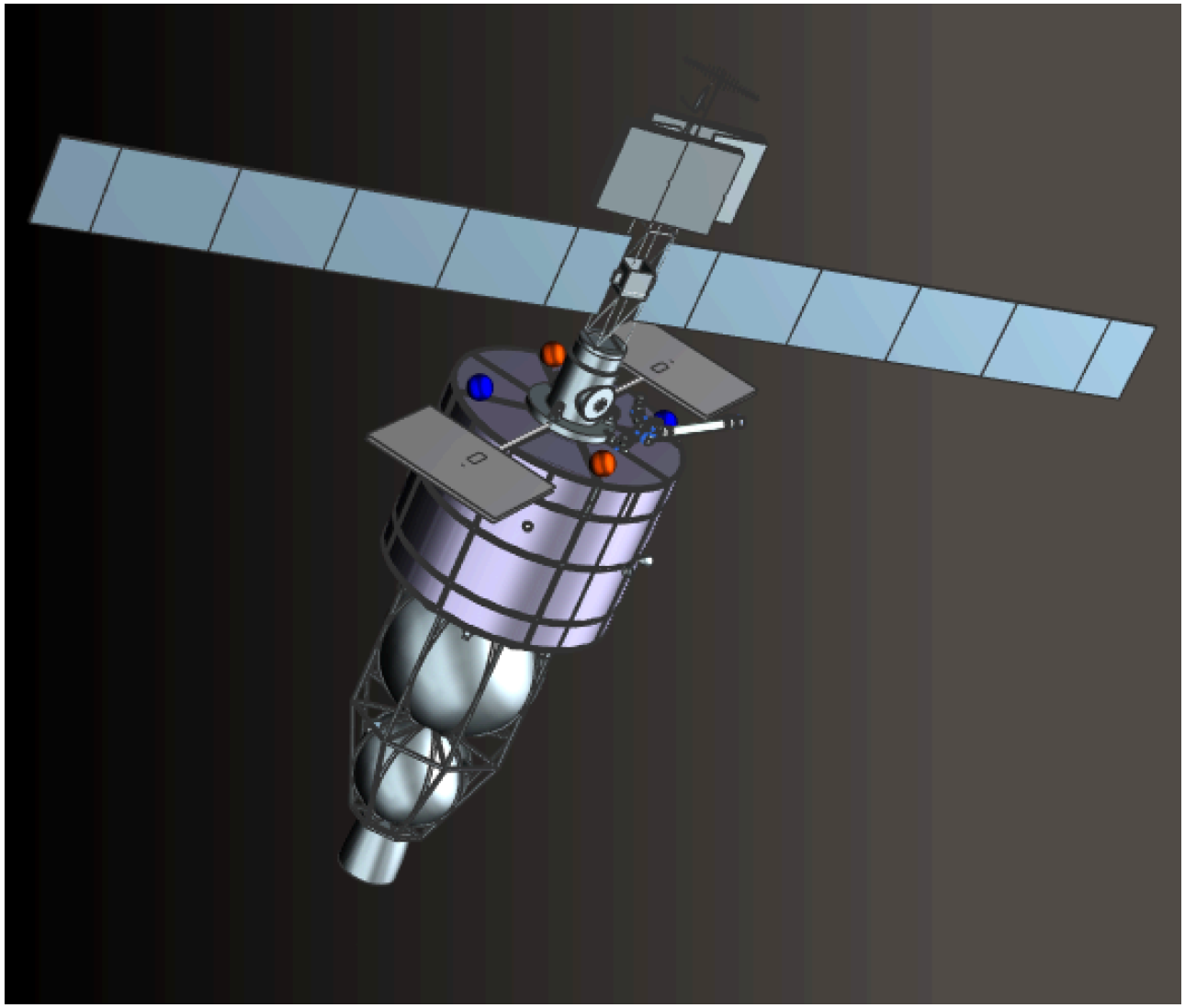
Phase I: Stowed Transfer Configuration



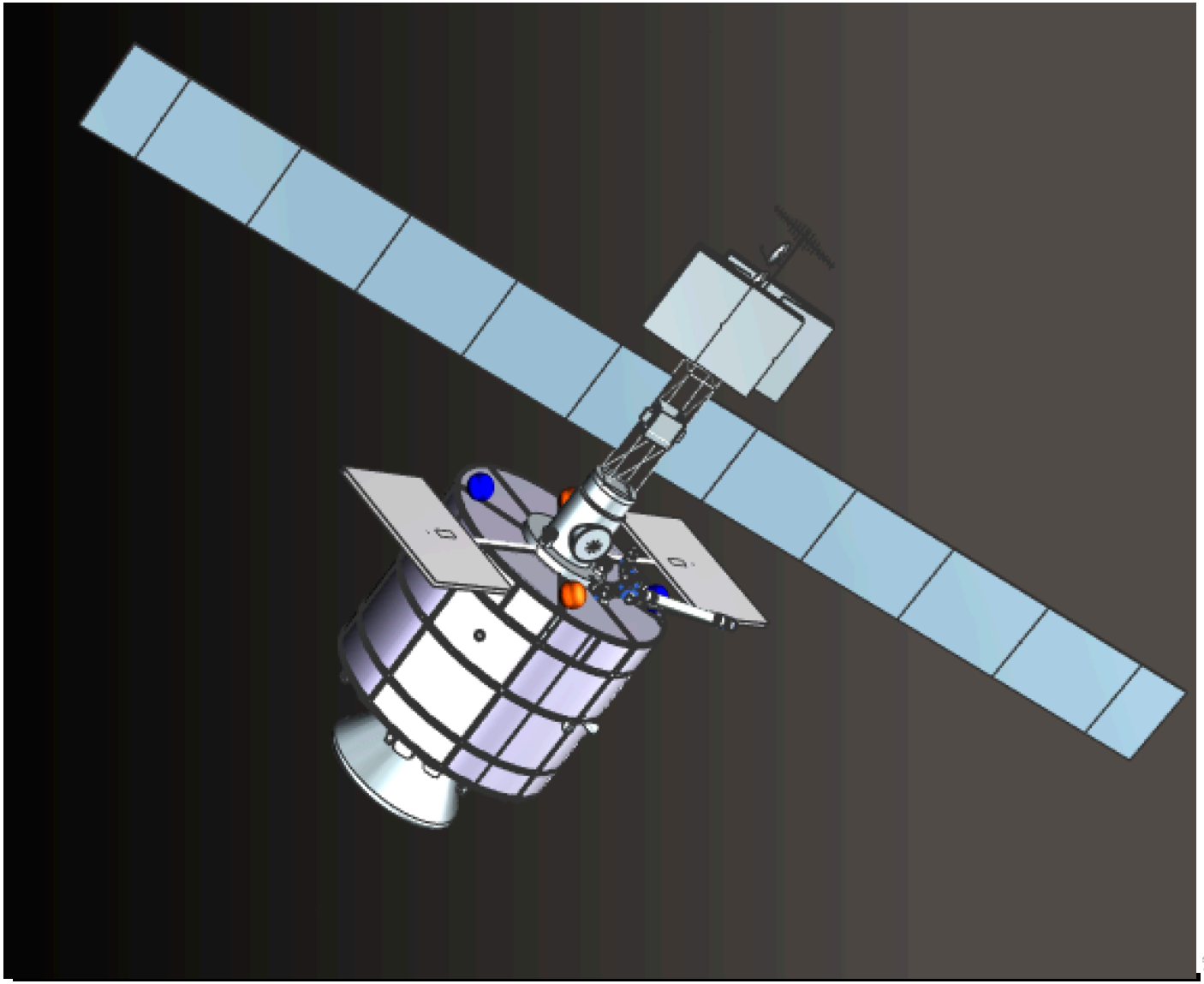
Phase I: Deploying in DRO



Phase I: Fully Deployed Configuration



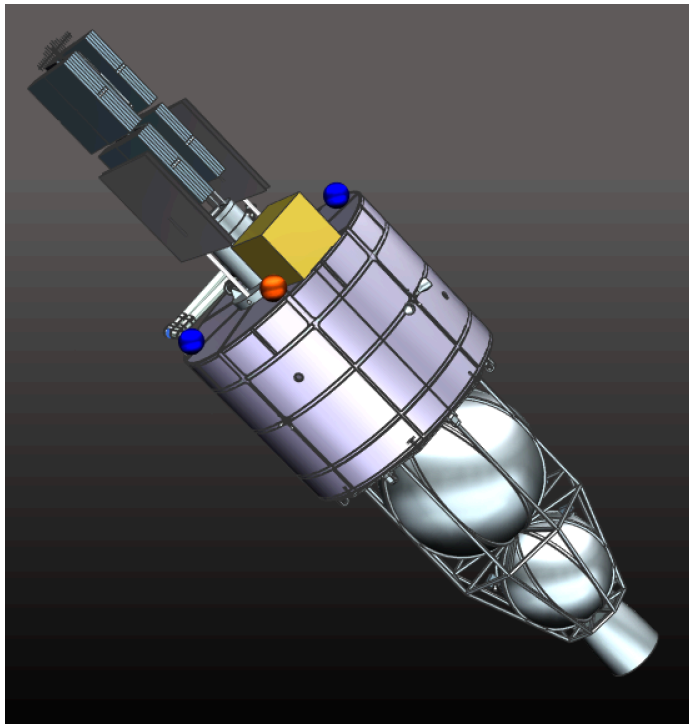
Phase I: DragonRider Rendezvous



Phase I Asteroid Science

- Phase I primary science payload package:
  - Camera Suite
  - Laser Rangefinder
  - Gamma Ray Neutron Spectrometer
  - Visible Infrared Spectrometer

Asteroid Redirect Mission Orbiter



- Canisterized Satellite Dispenser (CSD) from Planetary Systems Corporation
- Safety ellipse "orbit" around the asteroid
- Data relay directly to Polus and indirectly to Earth
- Total mass = 750 kg
- Total volume = 10 m^3

Phase I EVA Procedures

1. Two crew members will suit up with EVA suits
2. Pre-breathing will occur within the suit and take no more than 40 minutes
3. Habitat, in close proximity with asteroid during Phase I, will allow for astronauts to use propulsion module to intercept asteroid
4. Astronauts shall perform local anchoring techniques required for stabilization to collect samples
5. Astronauts shall not be anchored when making observations and collecting drifting samples
6. Astronauts shall return to habitat to refuel or end EVA

Tools and General Strategy

Tools	General Strategy
MMU/EVA Jetpack	Propulsive unit for navigation
Asteroid Harness Unit	Allows stabilization for astronaut when anchoring to asteroid
EVA Translation Lines	Used to set up a translation circuit on asteroid
Hand Rails	Used as a translation path on asteroid
Portable Foot Restraints	Used as an astronaut positioning system to increase stability
EVA Toolbox	Attached to asteroid to allow for easy access to EVA tools
EVA Saddle Bags	Used to collect regolith samples from asteroid. Can be stored on asteroid harness

Maneuvering Unit Operations

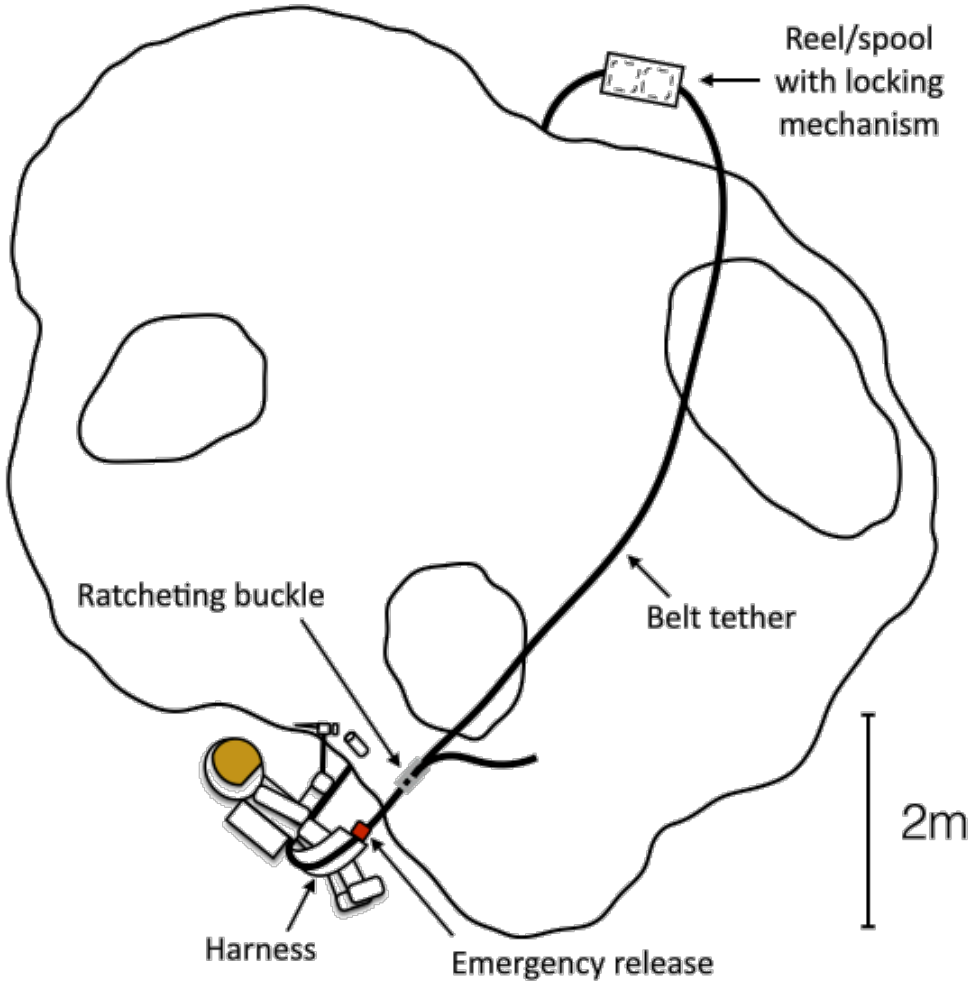
- Assumption: asteroid is not rotating relative to astronaut
- To minimize possibility of collision, habitat motion will track a safety ellipse around the body
  - Strategy used for ISS and visiting vehicles
  - Method of reaching asteroid: using EVA jetpacks/ propulsive unit
- Astronauts performing EVA using propulsive units will be required to perform local anchoring procedure for stabilization when collecting samples

NASA D-RATS 2011 Testing

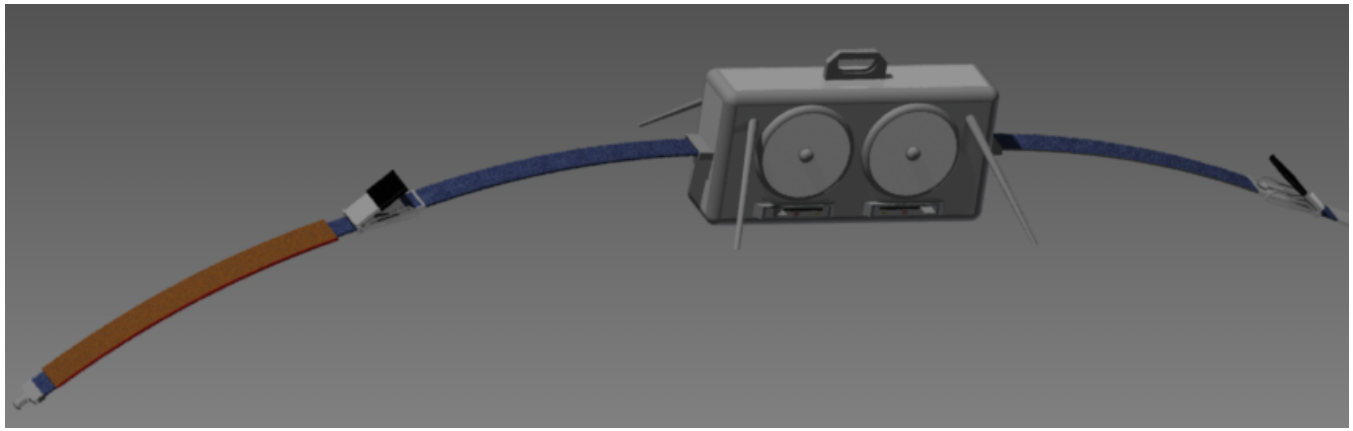
- NASA conducted a 3 week Desert Research and Technologies Studies (D-RATS 2011) to simulate and evaluate multiple aspects of mission operations approaches being considered for human exploration of NEA.
  - Crewmembers required to remain within 25 m line-of-sight with each other
  - Walking in straight lines, rate of translation was 0.3 m/s (1 ft/s)
  - Tasks required 2 minutes to establish local anchor
  - 1 minute to detach from anchor
  - ΔV required for anchoring: 1.2 m/s (4 ft/s))
- Previously, MMU allowed for a 6 hour EVA
  - Two tanks containing 5.9 kg of nitrogen each

Phase I EVA Operations

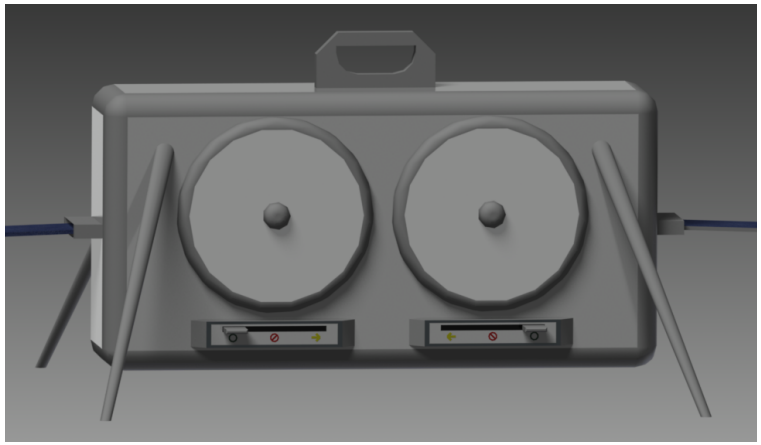
- Resistance method required for stabilization during EVA
- Multiple methods considered:
  - Handrails/ footholds
  - Recoilless anchor deployment
- Adjustable belt tethering – simple solution
- Allows effective proximity operations by providing counter force

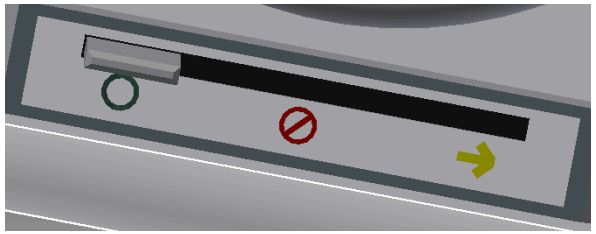


Phase I EVA Operations



- 35-40 m belt tether
- Deployable support legs
- Harness, ratcheting buckles
- Emergency release
- Lock, unlock, reel in switches





Safety Features and Requirements

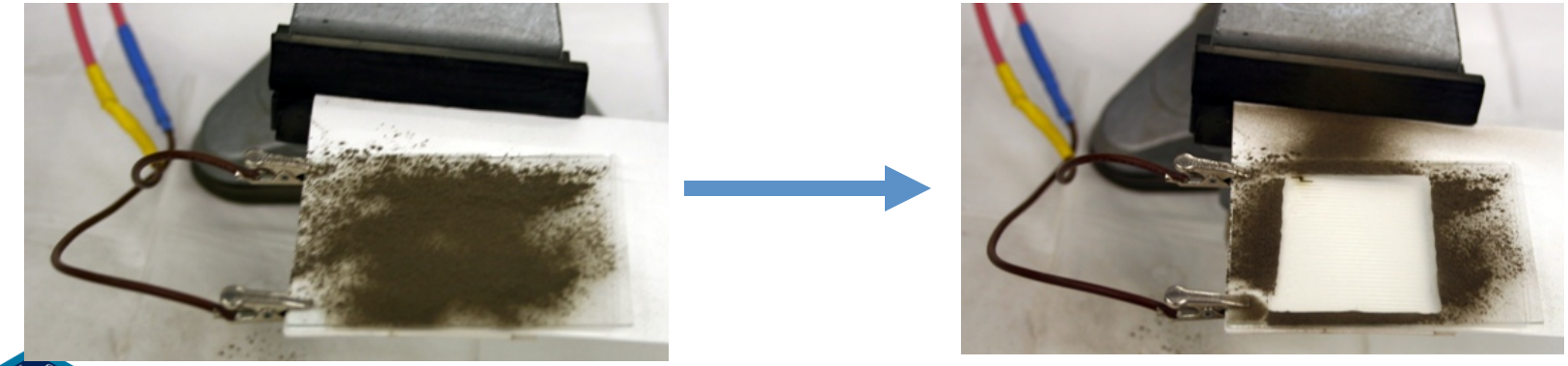
Safety Features	Requirements
Radiation	EVA system design and operational procedures shall protect the EVA crewmember from radiation for the duration of the EVA exposure during the mission
Micrometeoroids and Debris	EVA suit design shall protect the EVA crewmember from micrometeoroids and debris
Ingress/Egress	EVA crew members shall always have a positive method and means to return to the pressurized module
Tethering	EVA crew members will be safely tethered to the habitat at all times in microgravity, unless they are equipped with an EVA propulsive unit

Safety Features and Requirements

Safety Features	Requirements
Pressurization	EVA space suit shall be protected in the event that it ruptures by over pressurization due to failure of the pressure supply system
Sharp Edges and Protrusions	All structures which require EVA interface shall be designed to preclude sharp edges and protrusions, or be covered to protect crewmembers critical support system

Dust Mitigation

- Asteroid EVAs may encounter dust particles which can be harmful to habitat environment
- Before entering the airlock, astronaut will use the Electrodynamic Dust Shield (EDS) to remove 99% of dust from surfaces on the legs, arms, and chest



http://empl.ksc.nasa.gov/CurrentResearch/ElectrodynamicScreen/Electrodynamic.htm

Dust Mitigation

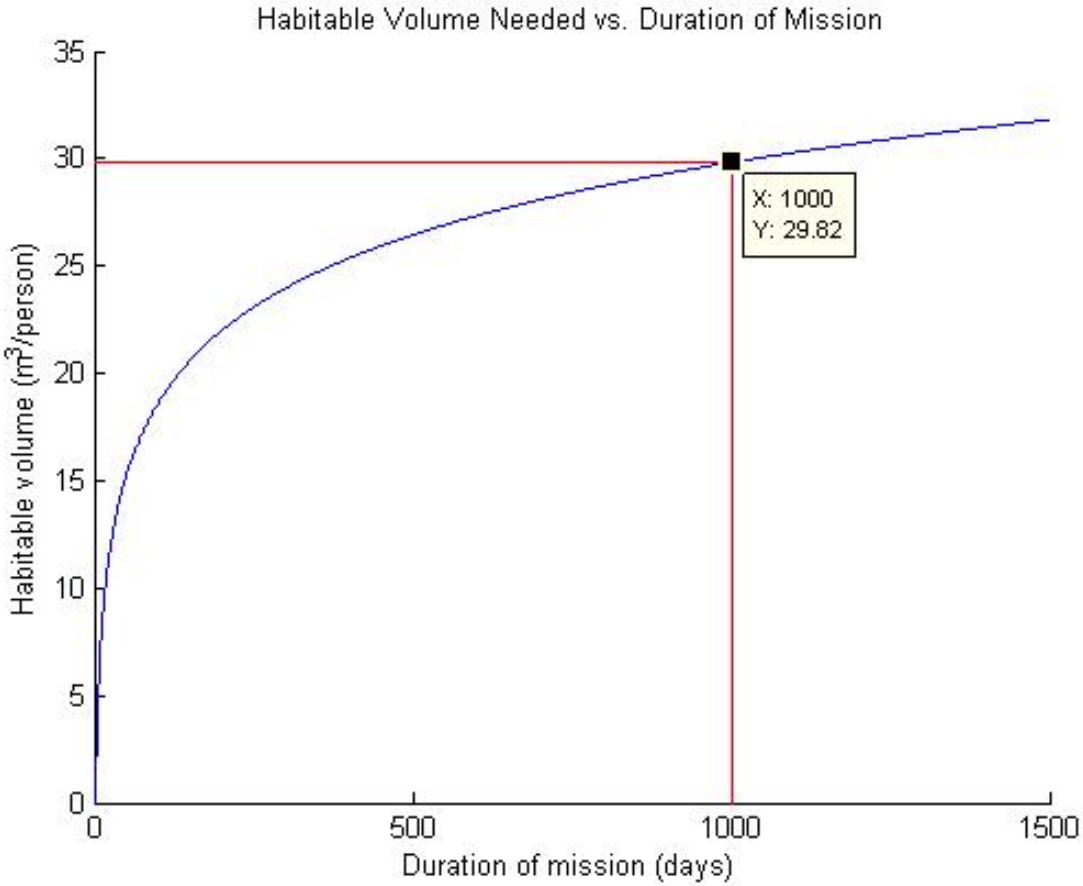
- Astronauts will use a dust brush tool brought on the EVA to remove large dust particles from other surfaces
- After entering the airlock and pressurizing, the Vacuum All-Surface Cleaner (VAC) will be used to clear all other surfaces of particles down to 0.3 μm prior to habitat reentry
- The VAC will have a HEPA (High-efficiency particulate air) filter to collect dust and exchange filtered air in the airlock

Phase I Science Lab

- Phase I & II Asteroid Science Rack
- Features:
  - High resolution & color digital cameras
  - Sealed glove box
  - Light Microscopy Module (LMM)
  - Gas chromatography
  - Mass spectrometry
- Overall mass: 300 kg
- Overall volume: 0.7 m^3

Spatial Requirements

Determining habitable volume needed



- For 1000 day mission:
  30 m³/person
- For 6 crew (1,000 day):
  179 m³

(Factors Impacting Habitable Volume Requirements: Results from the 2011 Habitable Volume Workshop. NASA/TM-2011-217352)

$$Habitable\ Volume[m\uparrow 3\ /person\ ] \approx 4.8827 \times \ln(duration\ in\ days)\ -3.9113$$

Spatial Requirements (0g, 95th % American Male)

Functions	Volume [m^3]	Dimensions (H x L x W) [m]
Eating, sleeping, hand washing, personal office, radiation shelter, conference	2.69	2.06 x 1.06 x 1.23
Shaving, grooming, oral hygiene	2.34	2.16 x 0.88 x 1.23
General workstations, food preparation, partial body cleaning, and housekeeping	4.34	2.06 x 1.06 x 1.99
Body waste management facilities, ascent and descent, and spacecraft duty station	1.70	1.52 x 0.91 x 1.23
Dressing and EVA suiting area	6.35	2.20 x 1.45 x 1.99
Accessing stowage and personal locker	6.00	2.76 x 0.88 x 2.47
Treadmill with Vibration Isolation System	6.12	2.10 x 2.37 x 1.23
Cycle Ergometer with Vibration Isolation System	1.70	0.97 x 1.43 x 1.23
Egress, translation, passageways	2.55	0.70 x 2.96 x 1.23
Egress, translation, passageways (EVA suits)	4.64	0.84 x 3.26 x 1.69

(Dimensions for 0g,Human Integration Design Handbook. NASA/SP-2010-3407)

Volume Breakdown

	Activity	Volume per person [m³]	Number of persons	Volume for all crew [m³]	Volume with multi-spaces [m³]	Total volume [m³]
Galley	Eating	2.69	6	16.14	16.14	22.14
	Food preparation	4.34	2	8.68		
	Accessing food stowage	6	1	6	6	
Working	General workstation	4.34	6	26.04	26.04	26.04
Personal space	Sleeping	2.69	6	16.14	16.14	90.24
	Accessing personal locker	6	6	36	36	
	Personal office	2.69	6	16.14	38.1	
	Dressing	6.35	6	38.1		
Hygiene	Hand wash	2.69	1	2.69	4.34	7.37
	Oral hygiene	2.34	1	2.34		
	Partial body cleaning	4.34	1	4.34		
	Shower	1.33	1	1.33	1.33	
	Body waste management facility	1.7	1	1.7	1.7	
Exercising	CEVIS	1.7	1	1.7	1.7	11.6
	TVIS	6.12	1	6.12	9.9	
	Resistance bands	9.9	1	9.9		
EVA	EVA suiting area	6.35	3	19.05	19.05	19.05
						176

Reminder: 179 m³ using curve

Source: Dimensions for 0g,Human Integration Design Handbook. NASA/SP-2010-3407

Surface Breakdown

	Activity	Area per person [m²]	Number of persons	Area for all crew [m²]	Area with multi-spaces [m²]	Total area [m²]
Galley	Eating	1.3	6	7.8		
	Food preparation	2.1	2	4.2	7.8	
	Accessing food stowage	2.17	1	2.17	2.17	9.97
Working	General workstation	2.1	6	12.6	12.6	12.6
Personal space	Sleeping	1.3	6	7.8	7.8	
	Accessing personal locker	2.17	6	13.02	13.02	
	Personal office	1.3	6	7.8		
	Dressing	2.89	6	17.34	17.34	38.16
Hygiene	Hand wash	1.3	1	1.3		
	Oral hygiene	1.08	1	1.08		
	Partial body cleaning	2.1	1	2.1	2.1	
	Shower	1.63	1	1.63	1.63	
	Body waste management facility	1.12	1	1.12	1.12	4.85
Exercising	CEVIS	1.76	1	1.76	1.76	
	TVIS	2.92	1	2.92		
	Resistance bands	6.54	1	6.54	6.54	8.3
EVA	EVA suiting area	2.89	3	8.67	8.67	8.67
						82

Source: Dimensions for 0g,Human Integration Design Handbook. NASA/SP-2010-3407

Spatial Requirements

	Volume [m^3]
Human Integration Design Handbook	176
Habitable Volume Workshop	179

Storage and equipment needed inside habitat for Phase III	Volume [m^3]
Water and food	8
Personal storage	10
Trash	5
Life support equipment	27
TOTAL	50

~230 m^3 needed inside the habitat

Habitat Design Requirements

- Fit into a SLS Block 1A fairing including launch displacement
- Interior volume of at least 230 m^3
- Four windows 45° off spin axis, 2 each floor
- Hold 10.4 psi with minimal leakage points
- Ballistic shielding to stop projectiles from puncturing pressurized areas
- Radiation shielding of 2 cm around cylindrical section and 1.5 cm around end caps

Habitat Design

- Total height = 6.37 m
- Diameter = 8 m
- Wall thickness = 66 mm
  - 16 mm Al
  - 20 mm Polyethylene
- 2 floors

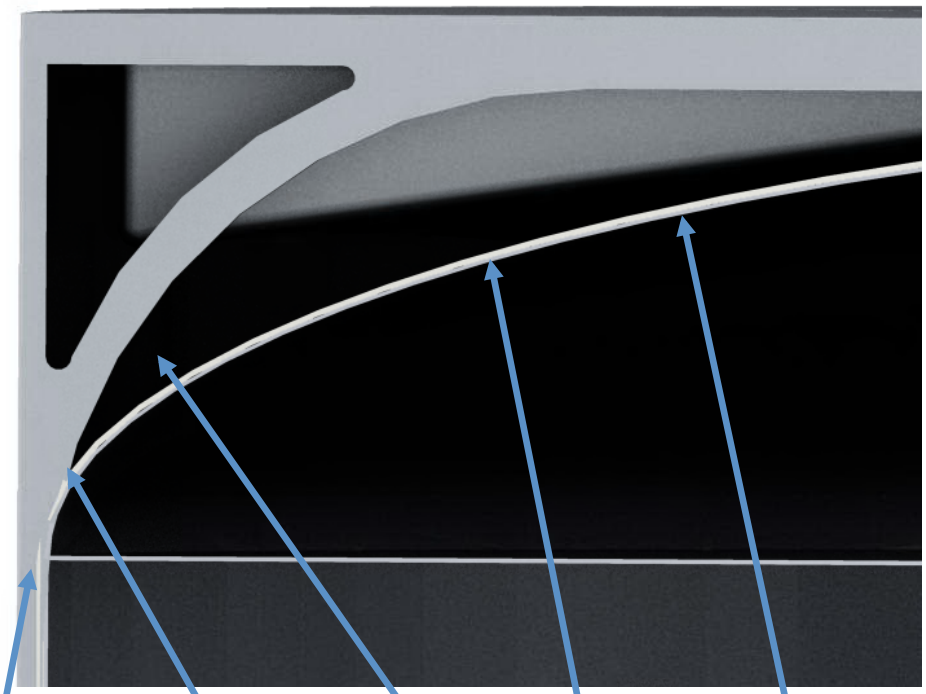
  Height = 2.13 m each
- Interior Volume = 281.5 m^3
- Surface area = 221.7 m^2
- Mass = 21,580 kg

Habitat Design Considerations

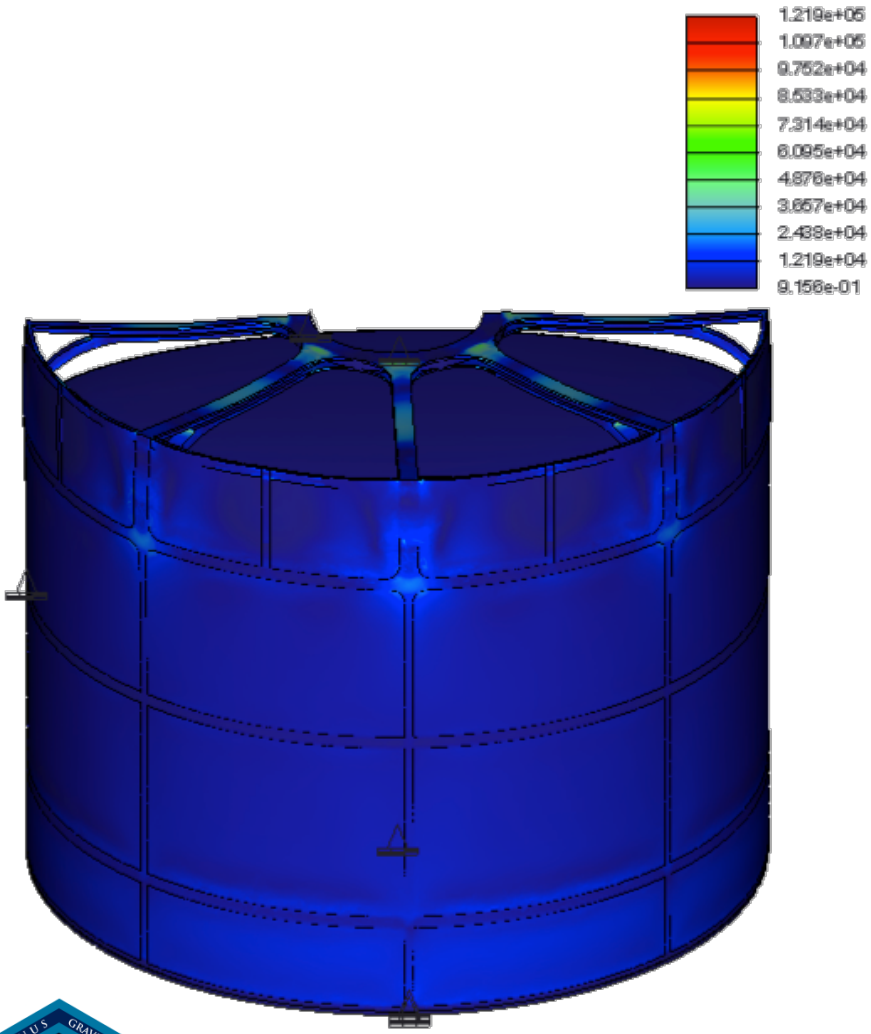
- Wall thickness
  - Whipple shielding
- Support Structure:
  - Launch loads
  - Attachment to cable system
  - Attachment to Mars SIM
- Floor Design
  - Honeycomb support structure attaching support wall

Habitat Layering

- Layers from outer to inner
  - Ballistics whipple shield
    - 6 mm
  - Empty whipple gap
    - 30 mm
  - Polyethylene radiation shielding
    - 20 mm
  - Support structure
    - 50 mm (cut out from radiation shielding
  - Interior pressure vessel
    - 10 mm



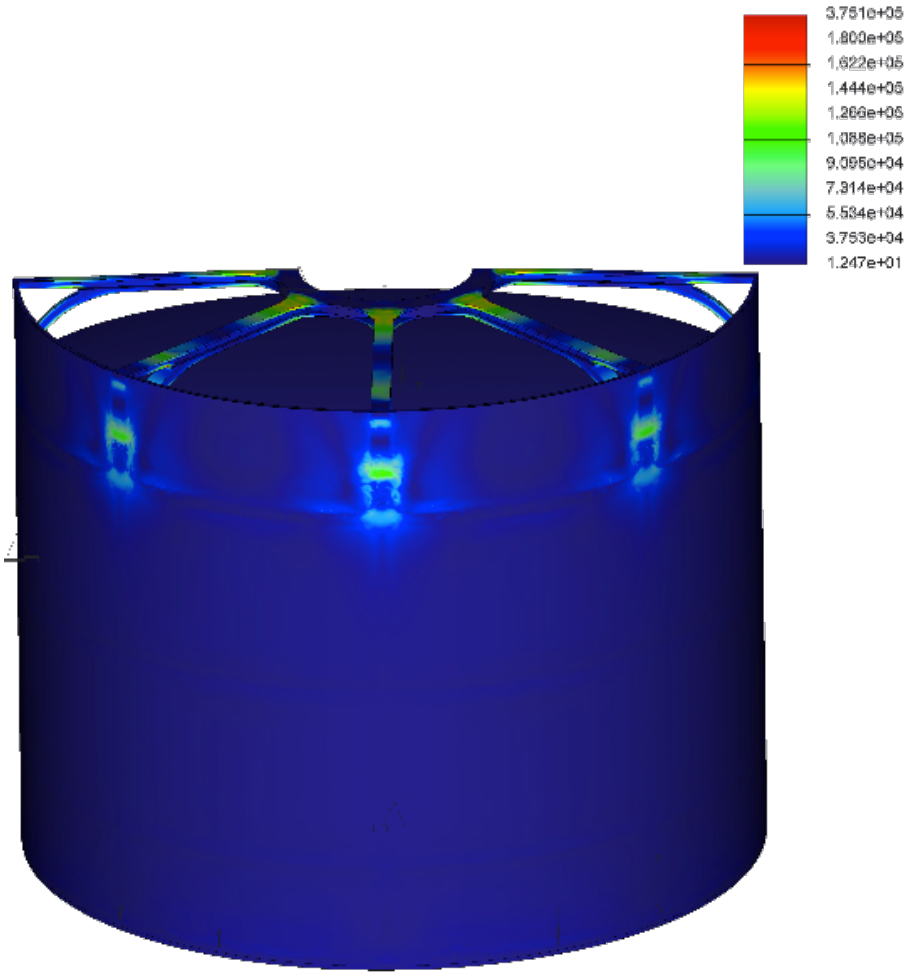
Finite Element Analysis: Habitat



- Part: habitat
- Load: launch accelerations
- Constraints: against displacement on bottom stringer (fairing attachment)
- Conclusion: high stress concentrations contain average stresses of $\sigma_{ave} \approx 60$ MPa

Feature will not yield

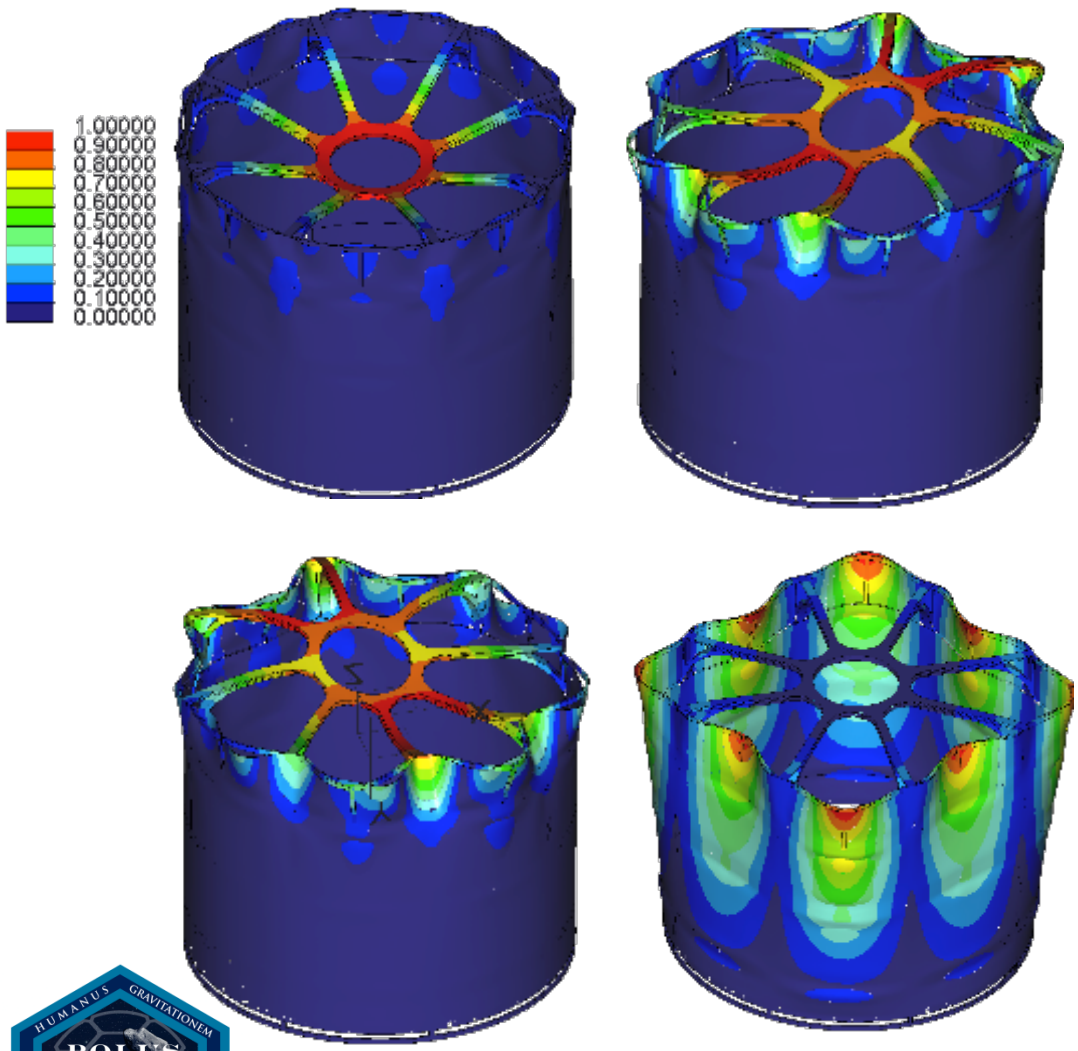
Finite Element Analysis: Habitat



- Part: habitat
- Load: 1g spinning with attached Mars SIM
- Constraints: against displacement on top I-beam connecting feature
- Conclusion: high stress concentrations contain average stresses of $\sigma_{ave} \approx 150$ MPa

Feature will not yield

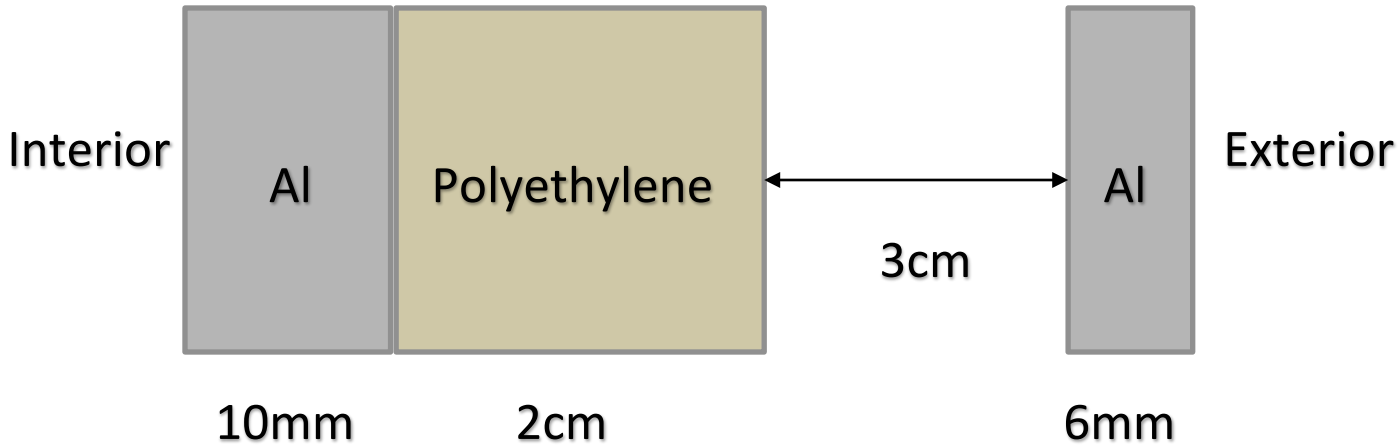
Modal Analysis



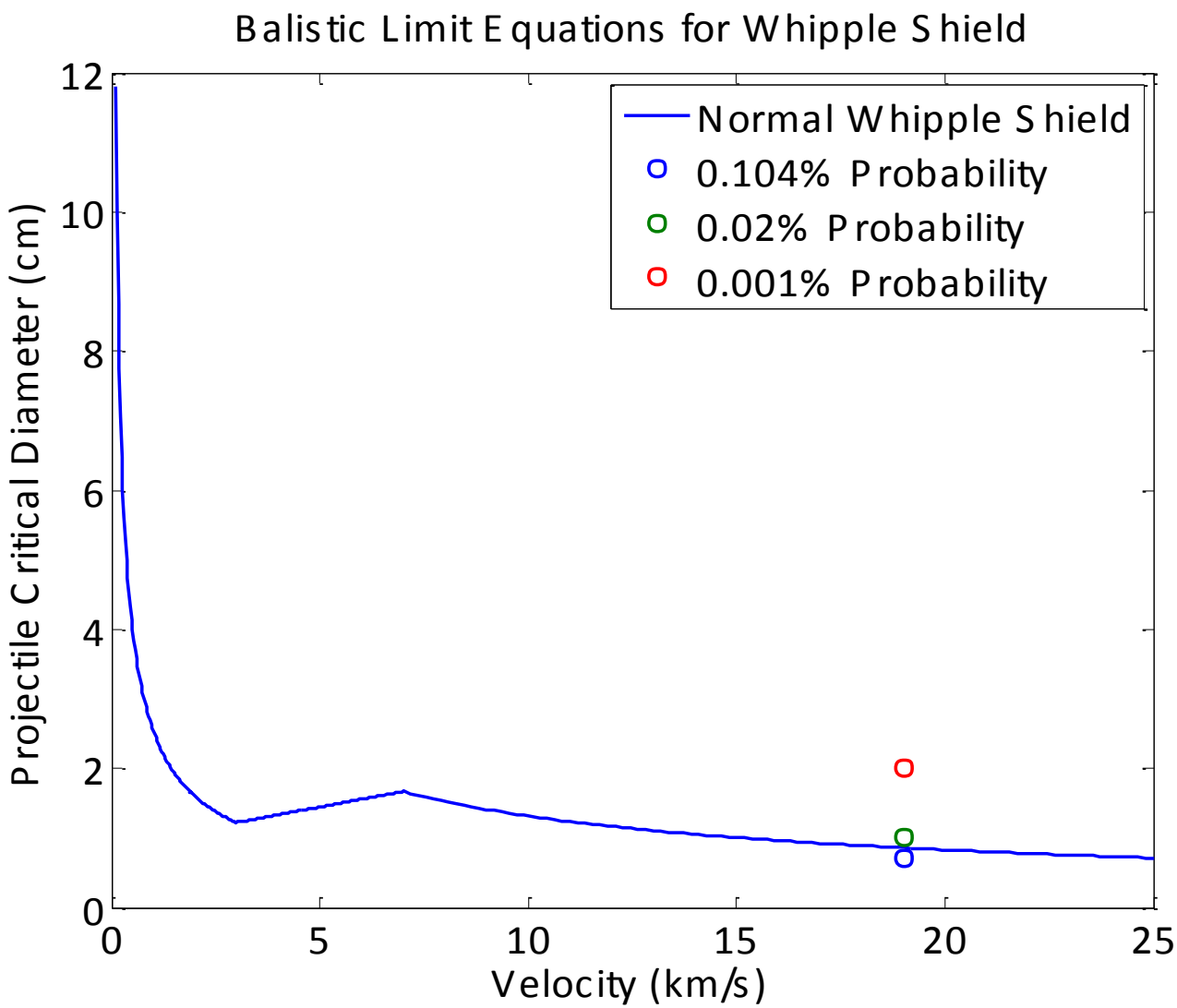
- Part: habitat
- Constraint: launch constraints
- Natural modes:
  - Mode 1: 14.3 Hz
  - Mode 2: 16.6 Hz
  - Mode 3: 16.6 Hz
  - Mode 4: 20.6 Hz

Ballistic Shielding

- Whipple Shield
  - Designed to withstand micrometeoroid impacts in LEO (worse than DRO)
  - Implemented on all pressure vessel surfaces
  - Ballistic limit equations



Ballistic Limit Equations



Space Radiation

Solar Particle Event (SPE)

- Occurs during solar maximum which happens approximately every 11 years
- Contains high flux of particles with low energy
- Lasts anywhere between a few hours to a few days
- Shelter is required to protect the crew from higher radiation dose in short period of time
- Crew must be alerted before SPE to seek shelter
- Shielding is highly effective

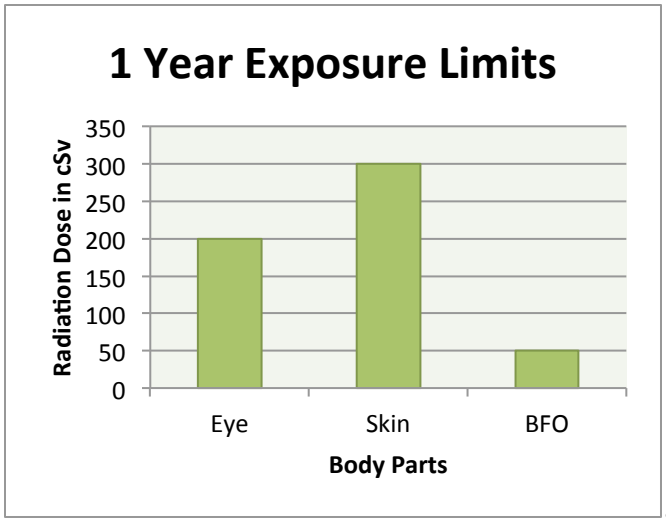
Galactic Cosmic Rays (GCR)

- Occur all the time
- Contain moderate flux of particles with high energy
- Radiation dose is lower during solar maximum
- Shielding is less effective

Historical High Radiation Exposures

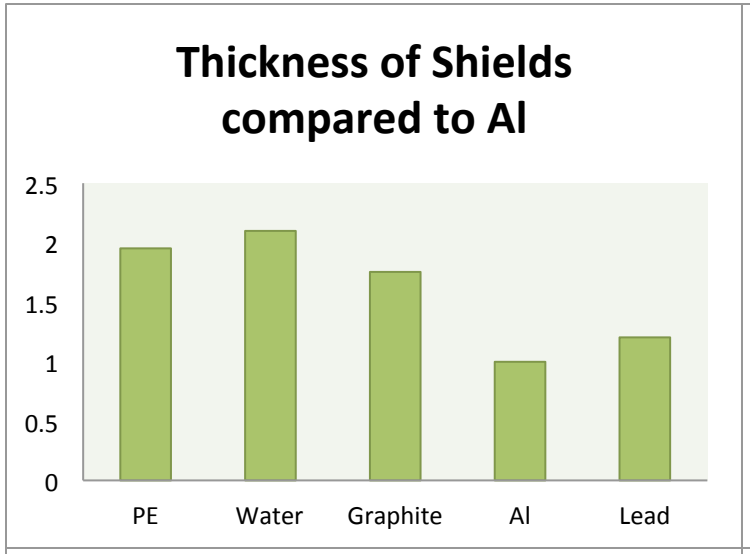
Missions	Dose to the BFO [cSv]
Mercury-Gemini	0.05
Apollo 14	0.114
SKYLAB 4 (84 days)	7.94
Space Shuttle	0.052

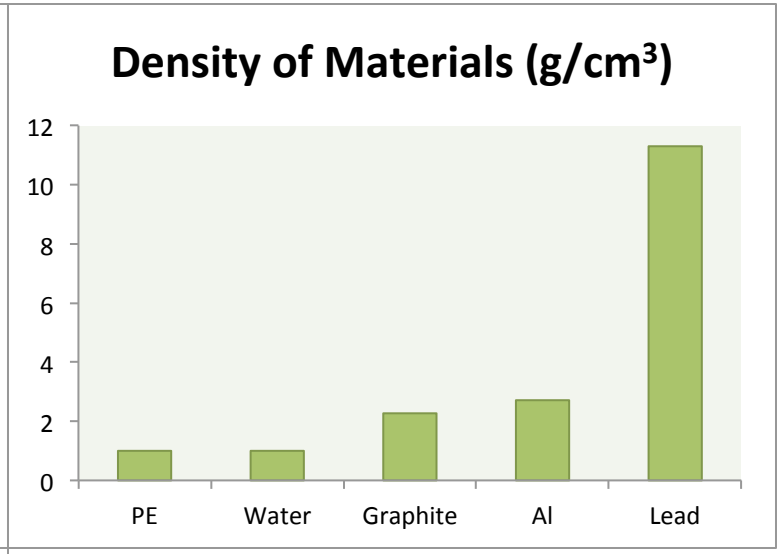
(Source: Adams, *2001)*

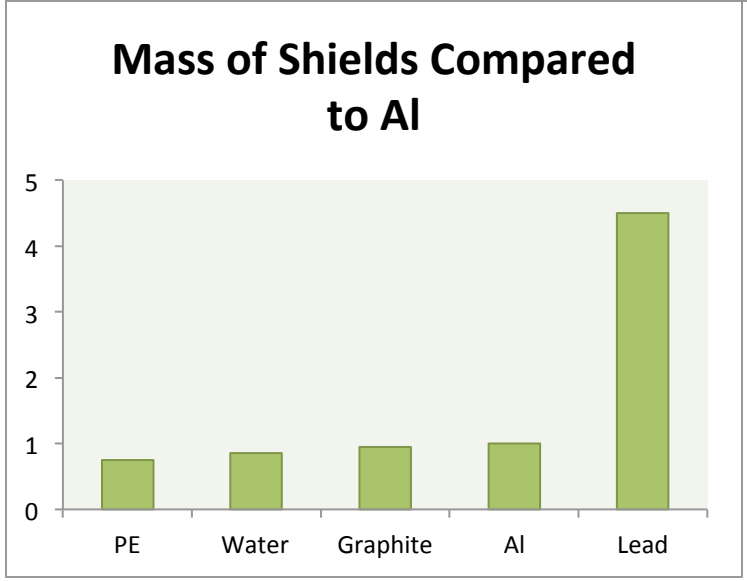


(Source: Cucinotta, *2001)*

Shielding Material Selection

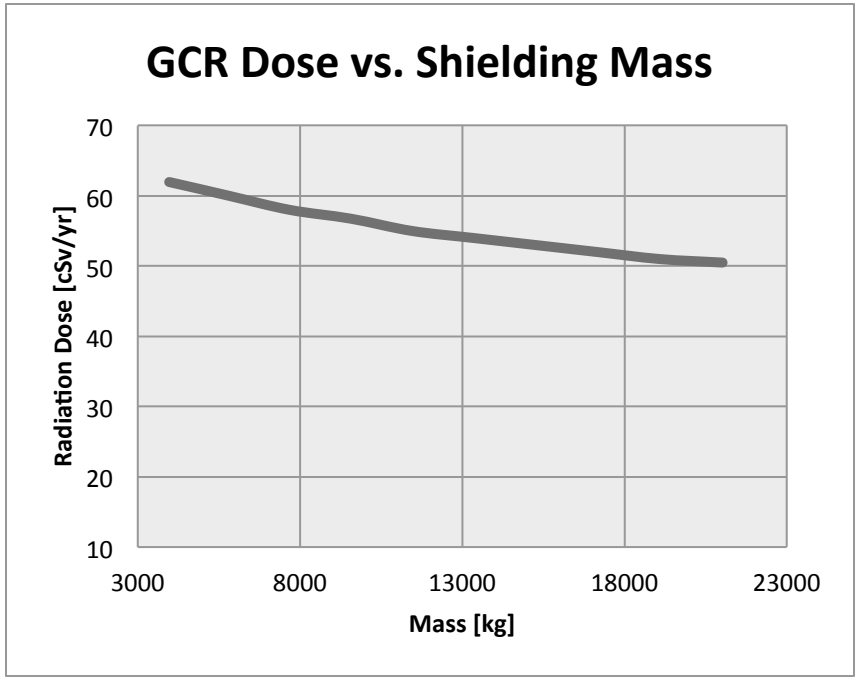






- Polyethylene (PE) is selected to minimize the mass
- PE contains higher number of H atoms which provides better shielding

Shielding Effect on GCR



- Shielding mass calculation is based on our habitat dimensions
- Shelter shield thickness was kept at 11 cm
- Habitat wall shield thickness was gradually increased to achieve the radiation dose of ~50 cSv/yr

- Mass goes up rapidly to lower small amount of radiation dose
- NASAs As Low As Reasonably Achievable (ALARA) principle was used to minimize the shielding mass

Radiation Shield Mass Calculation

Description	Habitat Wall	End Caps	SPE Shelter
Al Thickness [cm]	1.6	1.6 + 0.2*	0
Al Shielding Depth [g/cm^2]	4.32	4.86	0
PE Equivalent of Al [g/cm^2]	3	3.5	0
PE Shielding Thickness [cm]	**2**	**1.5**	**11**
PE Shielding Depth [g/cm^2]	2	1.5	11
Total Shielding Depth [g/cm^2]**	**5**	**5**	**16**
Volume of PE [m^3]	2.12	1.2	3.5
Mass of PE [kg]	2120	1200	3500
Total Mass of PE [kg]	**6820**		

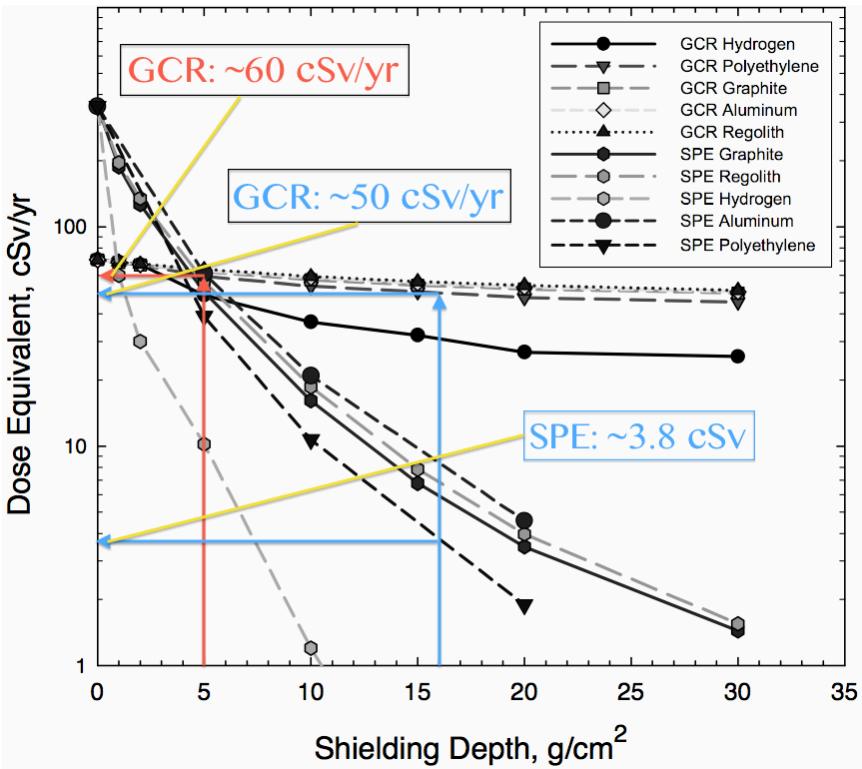
Windows Radiation Shielding Mechanism

- 30 cm dia. and 5 cm thick circular plate of PE
- Will be mounted on the wall by hinges
- Total mass estimation for 4 windows = 14 kg

- Density of Al = 2.7 g/cm^3
- Density of PE = 1.0 g/cm^3
- 1 g/cm^2 of PE = 1.4 g/cm^2 of Al
- Shielding depth = Thickness x Density

*~0.2 cm of floor thickness was added to end caps thickness
**Total shielding depth is equivalent to PE

Radiation Dose Calculation



Effective dose behind various shields exposed to the free space Solar Minimum GCR and August 1972 SPE environment

(Source: Cucinotta, *2005)*

- Berths are designed to shelter against the SPE radiation
- SPE dose of ~3.8 cSv can be neglected because SPE occurs during solar maximum which leads to lower GCR dose

Duration and radiation dose per year		
Location	Time [days]	Dose [cSv]
Shelter	122	16.7
Habitat	243	40

Total dose = 56.7 cSv/yr

- Total dose is 6.7 cSv higher than radiation exposure limit for a year
- It will take about 322 days to reach radiation exposure limit
- Radiation dose will be well below the limit for phase I and phase II
- High dose health risk can be minimized with the selection of crew age and gender for phase III

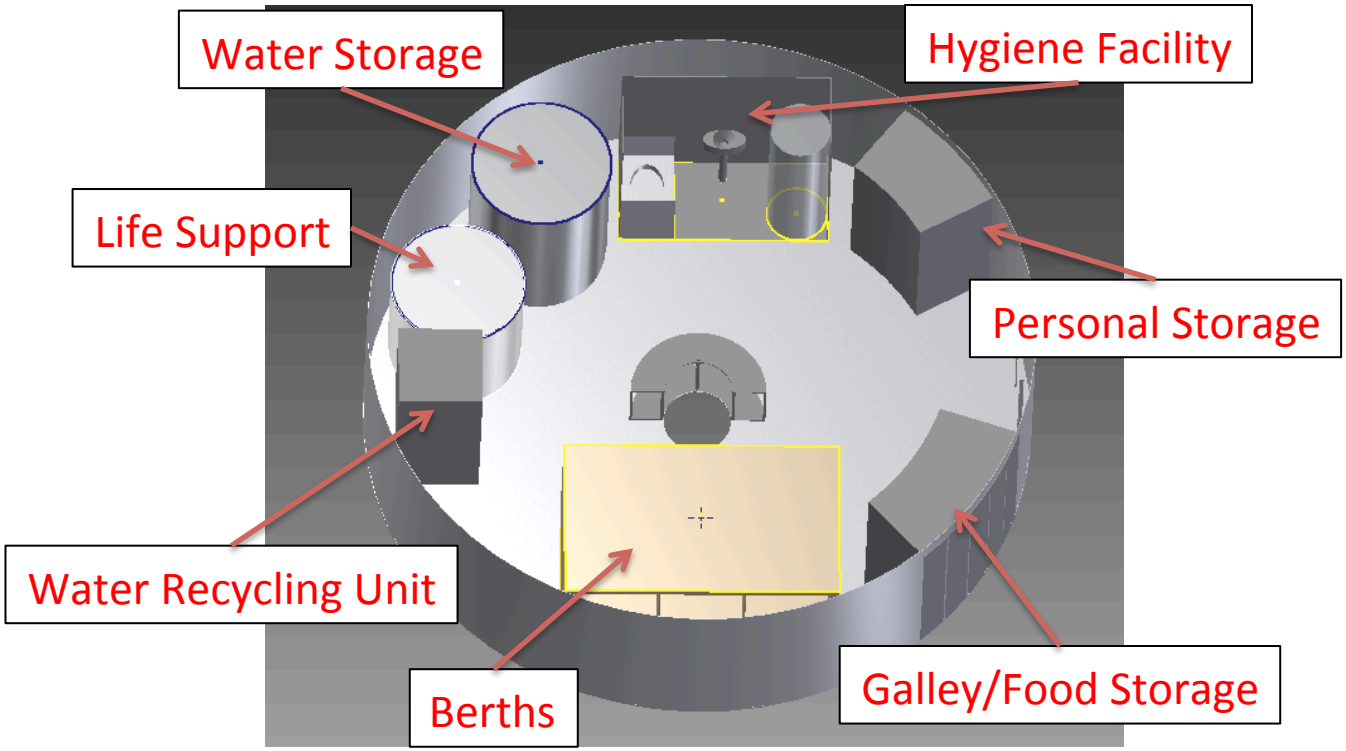
Virtual Reality Testing

- Purpose: to determine the characteristics of a layout that will satisfy a broad spectrum of personal movement preferences
- Test Protocol
  - Sampling size: 4 test subjects
  - Control test: subjects will stand inside a generic virtual reality setting for acclimation
  - Habitat test: subjects will start inside a crew berth and carry out a daily activity
  - Data Collection: subjects will complete task load index surveys based on the activities they performed while in virtual reality simulation. Their movement throughout the virtual habitat will also be recorded and timed
  - Post-testing: results from the virtual reality testing will determine which layouts will be used for final architecture

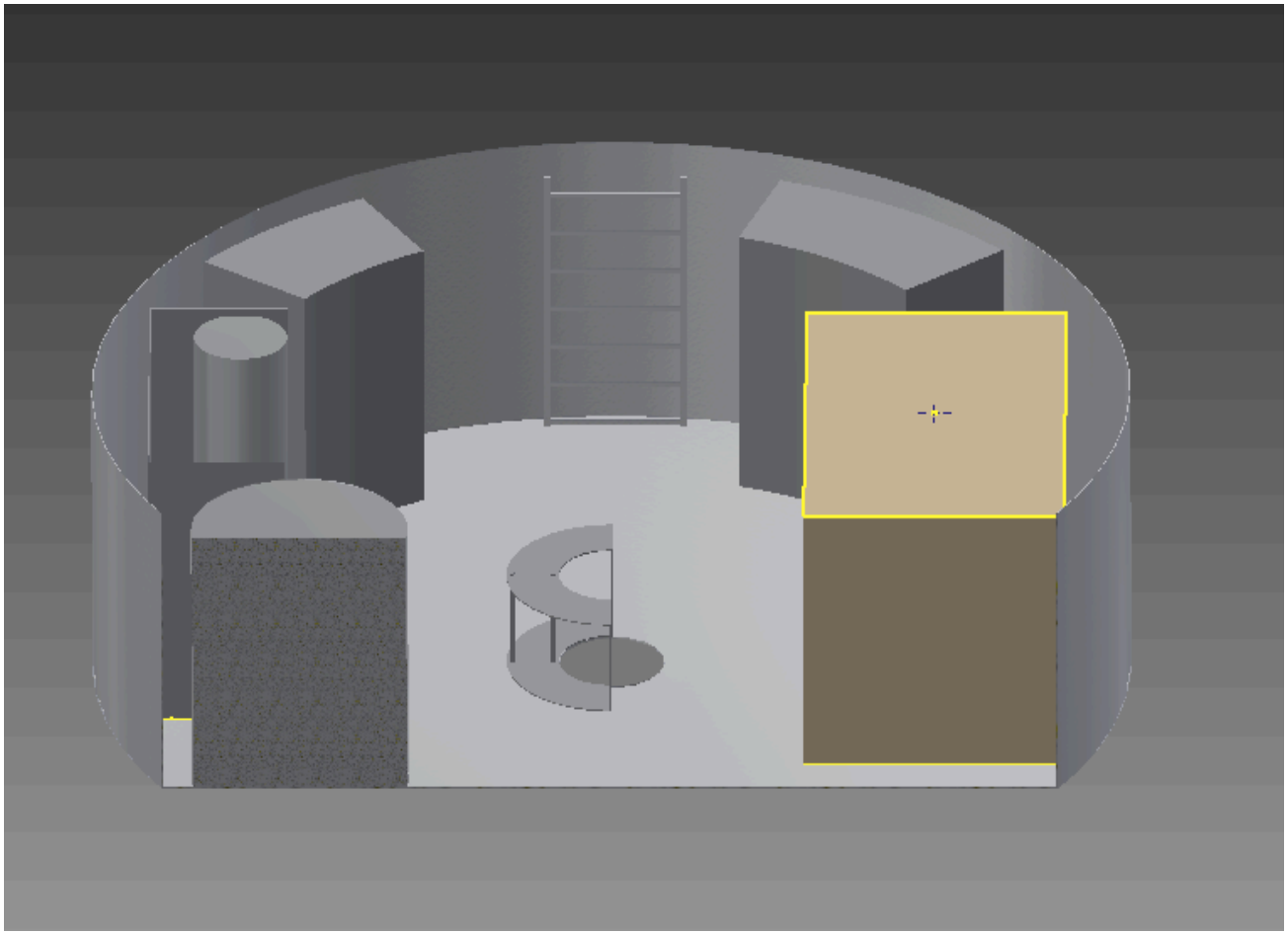
Layout Variations

- Crew berths
  - Centralized berths
    - "Pod Hotel"
    - Two "3-stack" berths, center of floor
  - De-centralized berths
    - Two "3 stack" berths, either side of berth
    - Two "L-configuration" berths, either side of berth
- Table placement
  - Common table fixed to berth
  - Two separate tables on either side of centralized berth

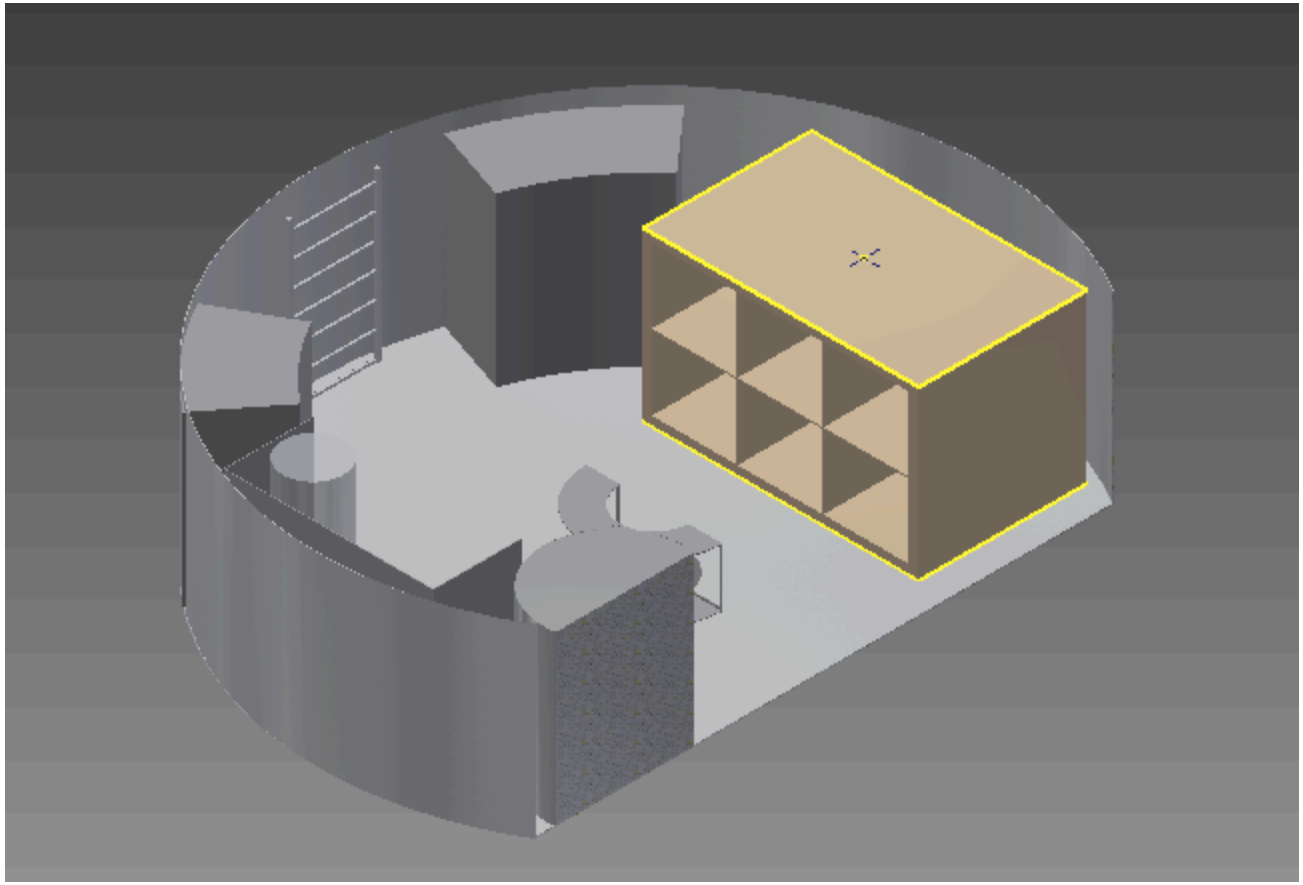
Centralized Berth: Pod Hotel



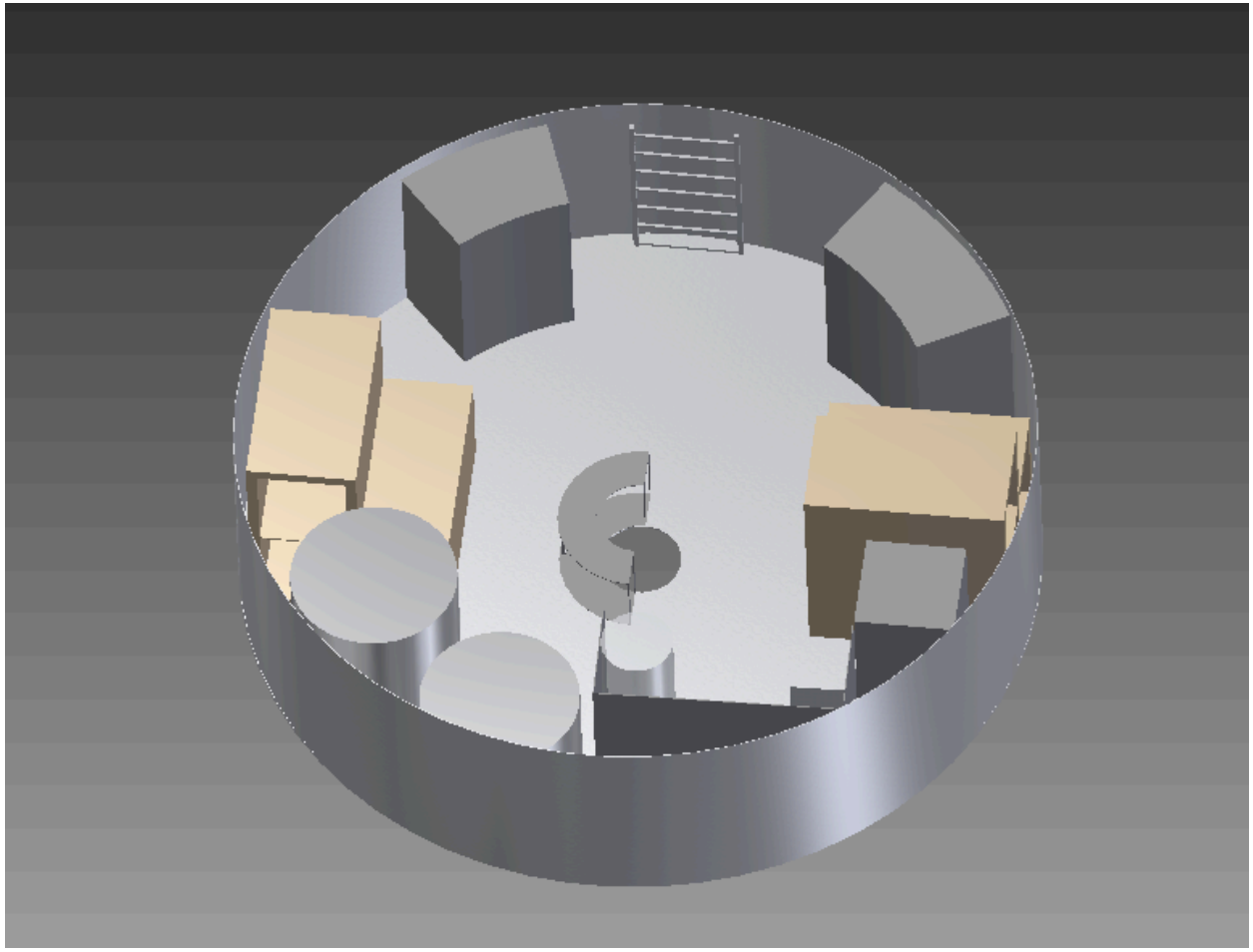
Centralized Berth: Pod Hotel



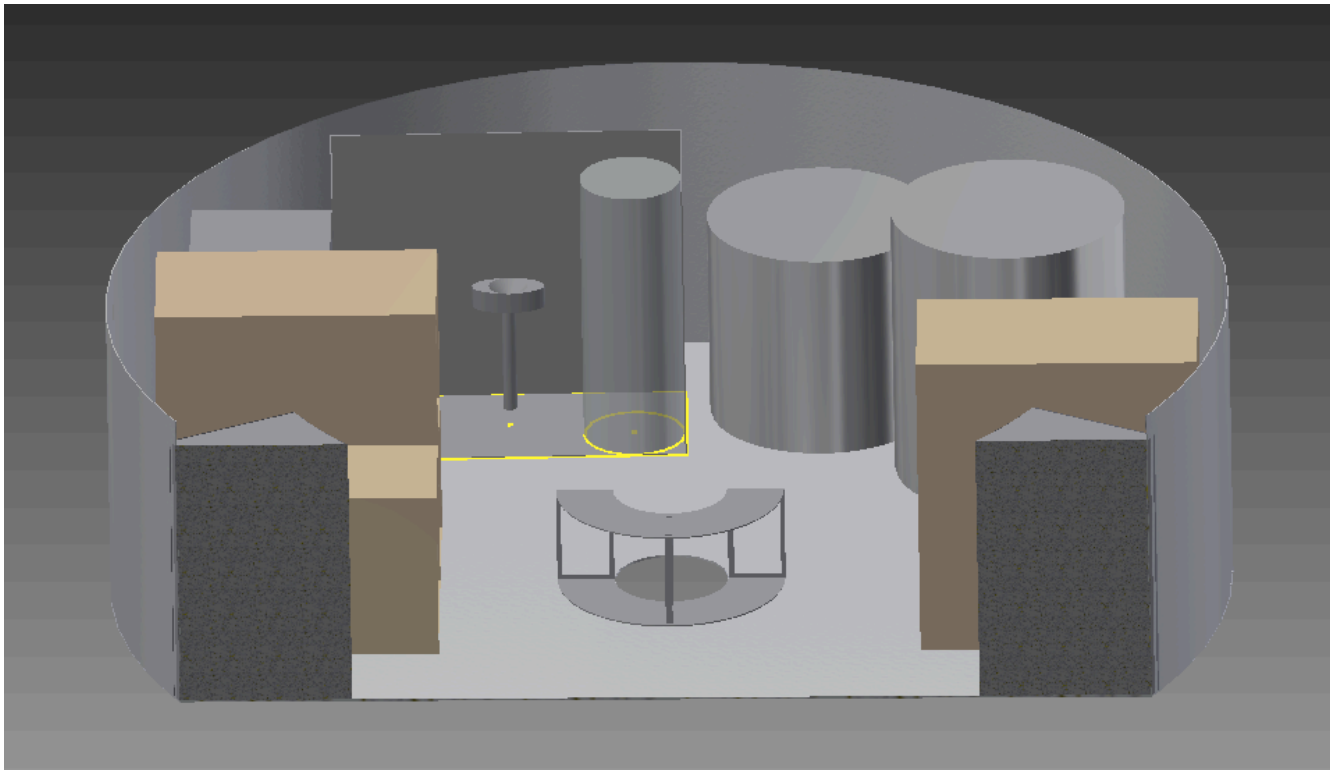
Centralized Berth: Pod Hotel



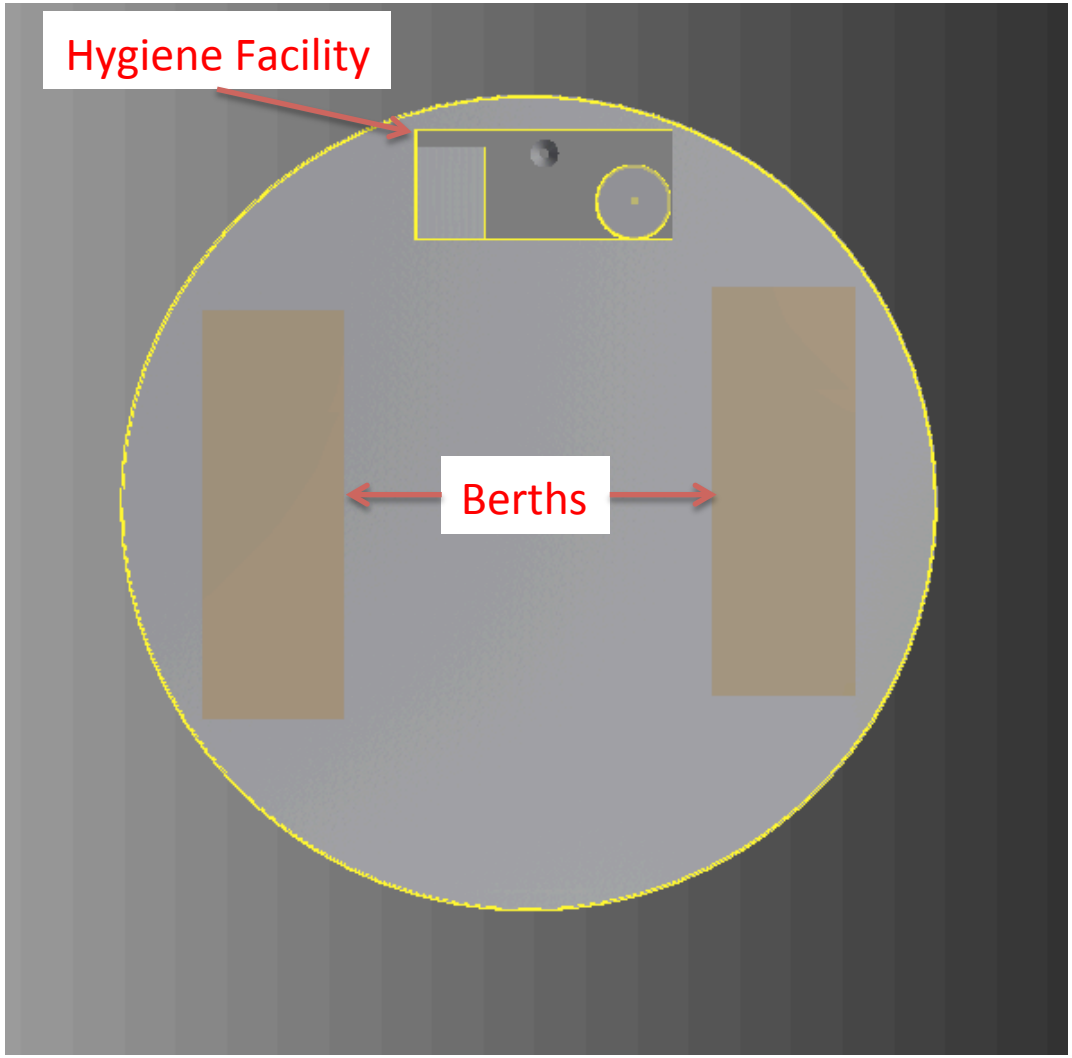
Decentralized Berth: L-Configuration



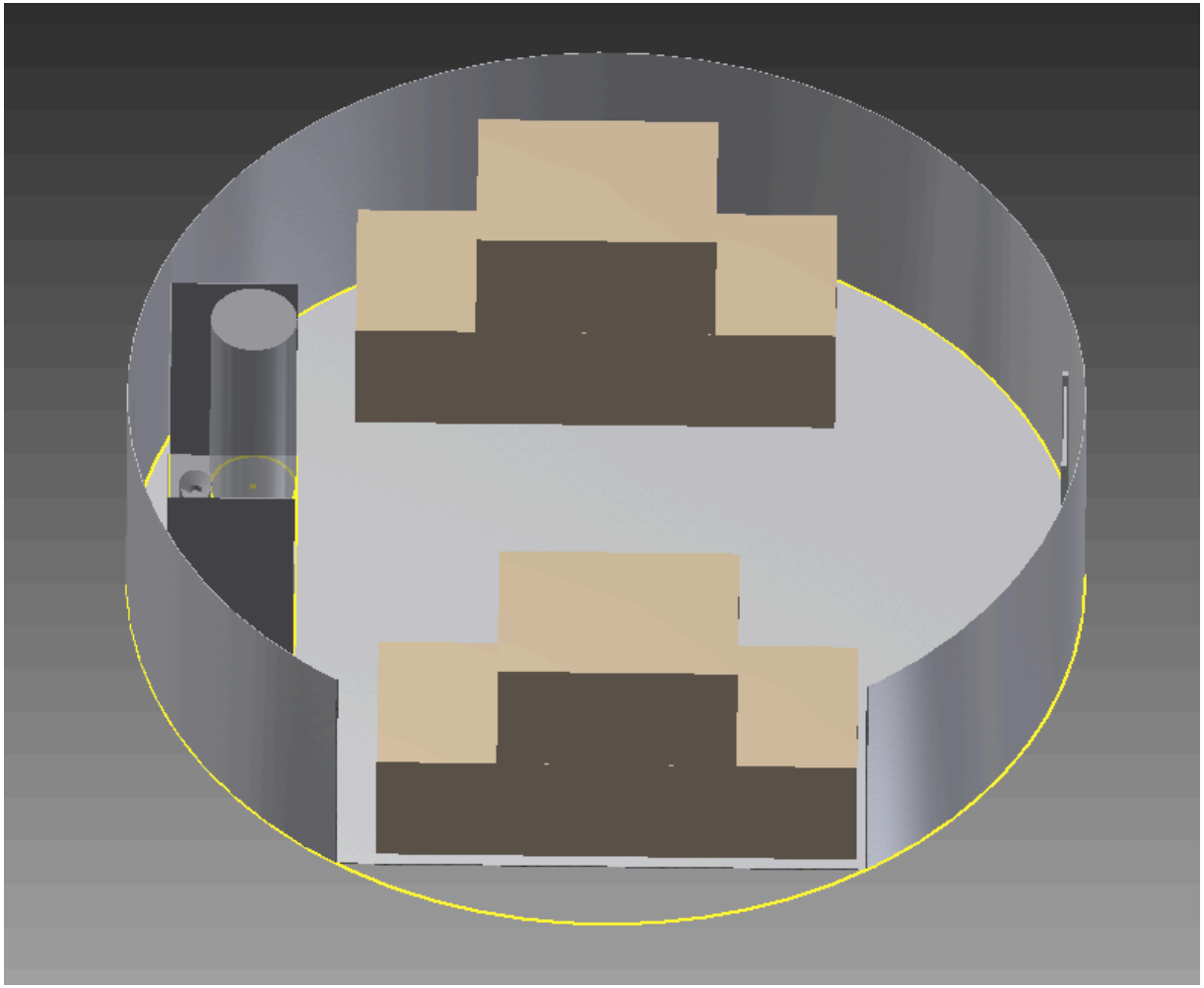
Decentralized Berth: L-Configuration



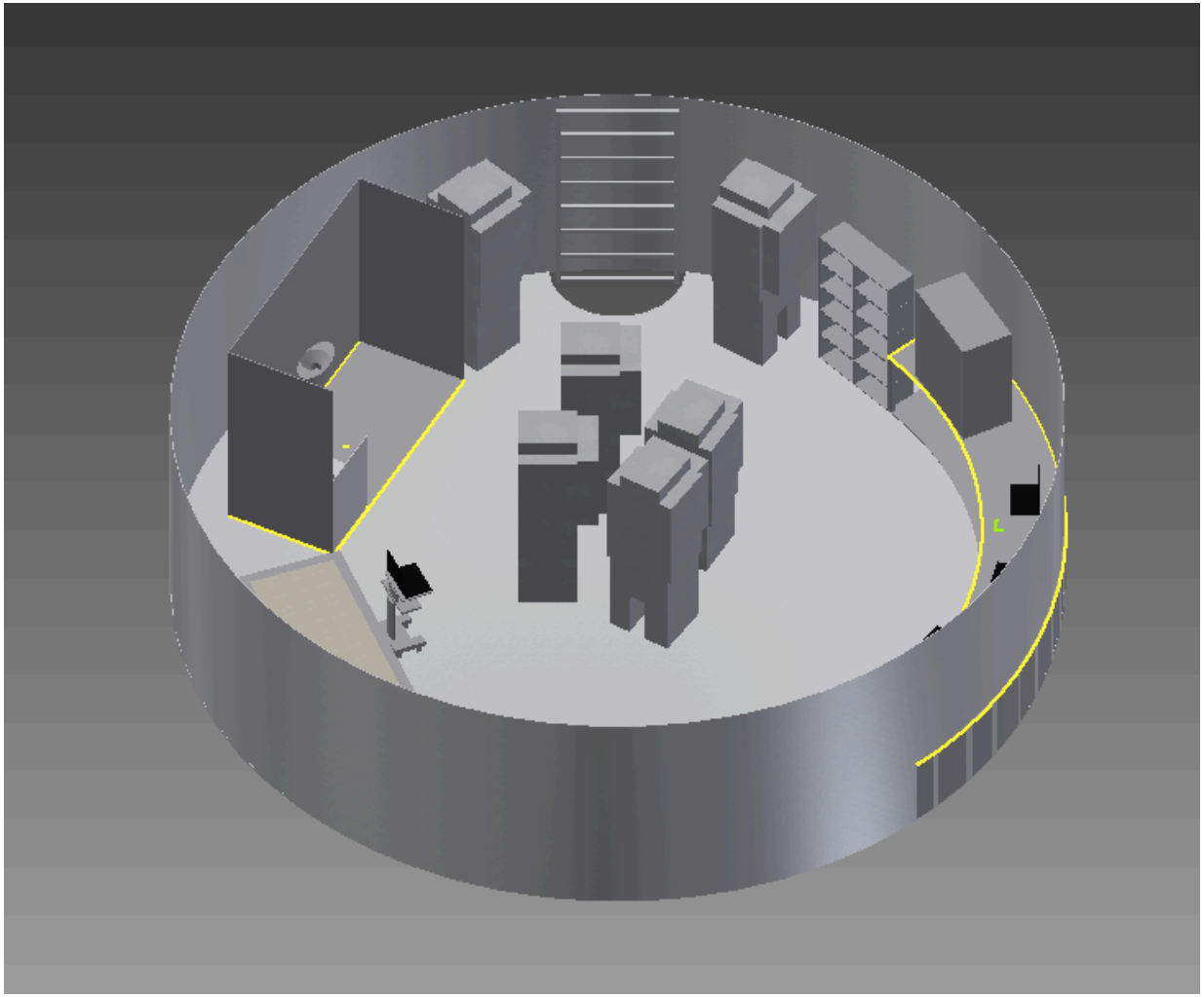
Decentralized Berth: 3-Stack



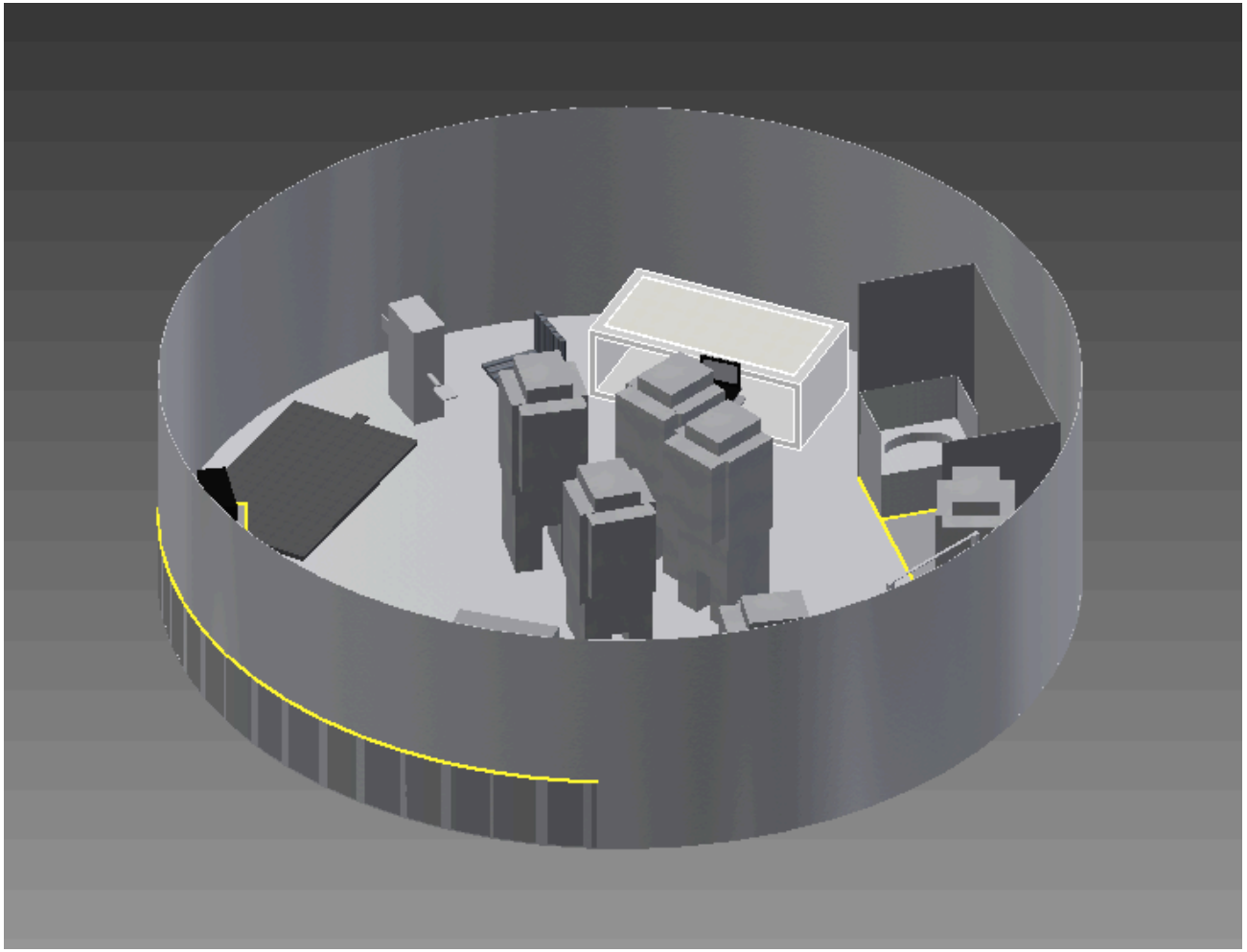
Decentralized Berth: 3-Stack



Science Floor Layouts

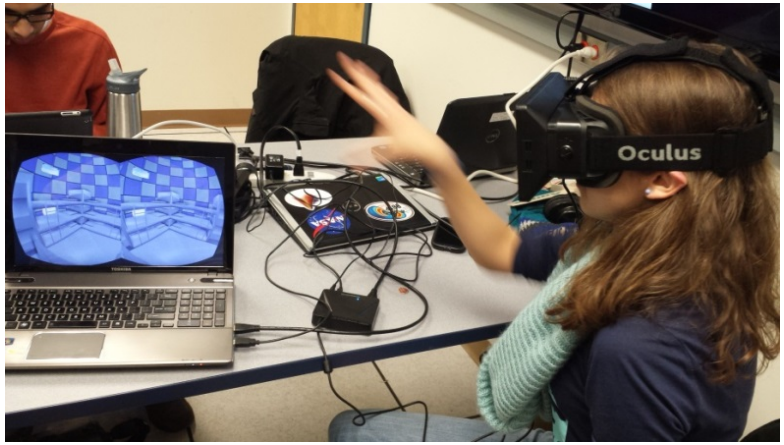


Science Floor Layouts



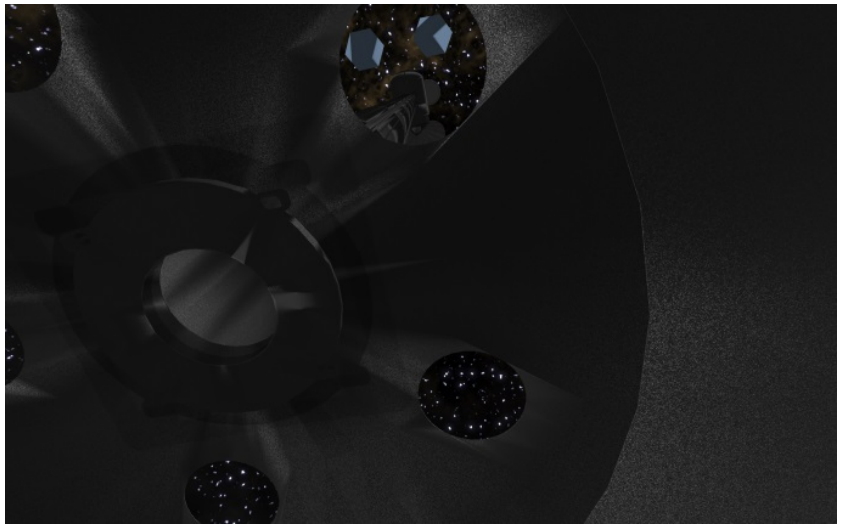
Virtual Reality Testing

- Preliminary habitability studies currently being designed and performed in virtual reality
- Results of VR studies will advise final decisions on interior layout
- Technology:
  - Oculus Rift HMD
  - Autodesk 3DS Max
  - Unreal Development Kit

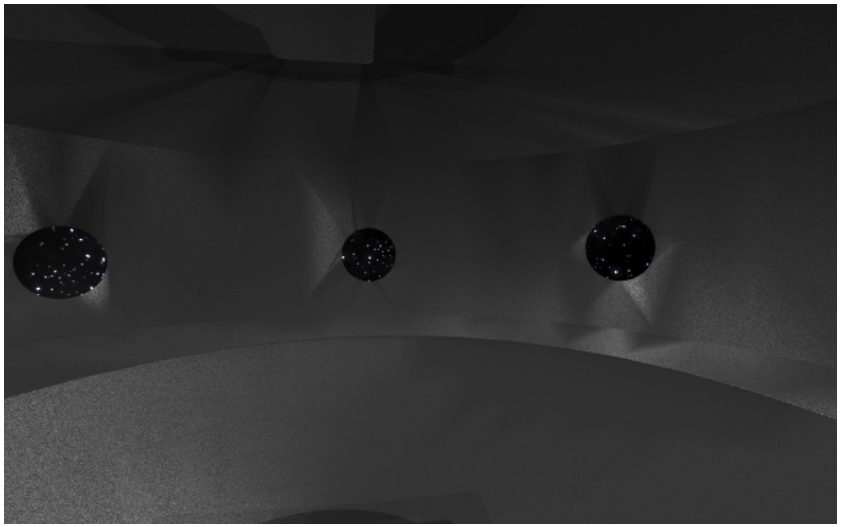


Baseline conceptual testing with early habitat prototype. Note stereoscopic rendering on laptop screen, which mirrors what is displayed on the Rift.

Virtual Reality Testing



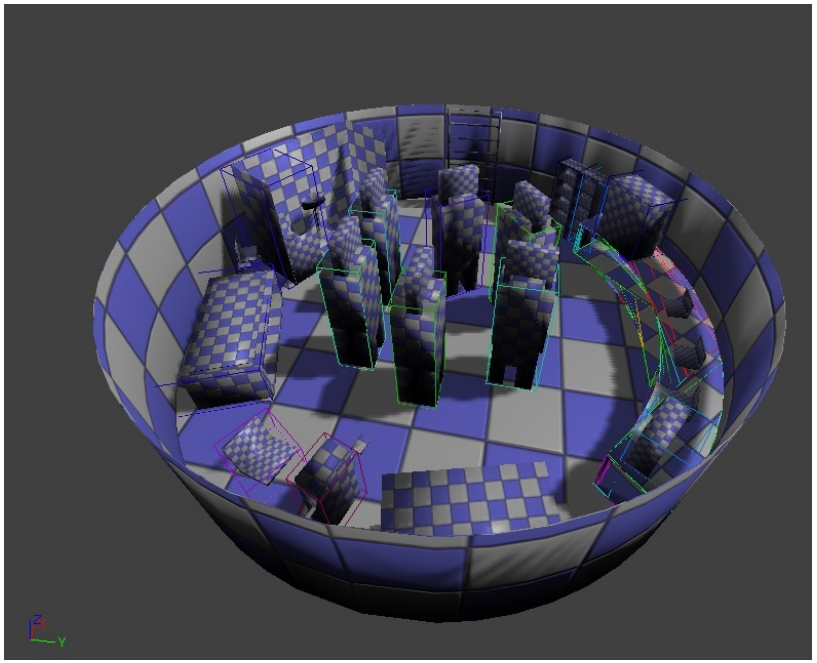
Windows positioned on roof; "up" relative to gravity. This configuration was not tested. Note visibility of station structure.



Windows positioned normal to gravity in various orientations relative to plane of rotation. Three orientations were tested.

- Previous work:
  - Motion sickness vs. window placement at design rotation rate, vs. control
  - High density star field found to represent unrealistic "worst case," results to be confirmed with more accurate scenery

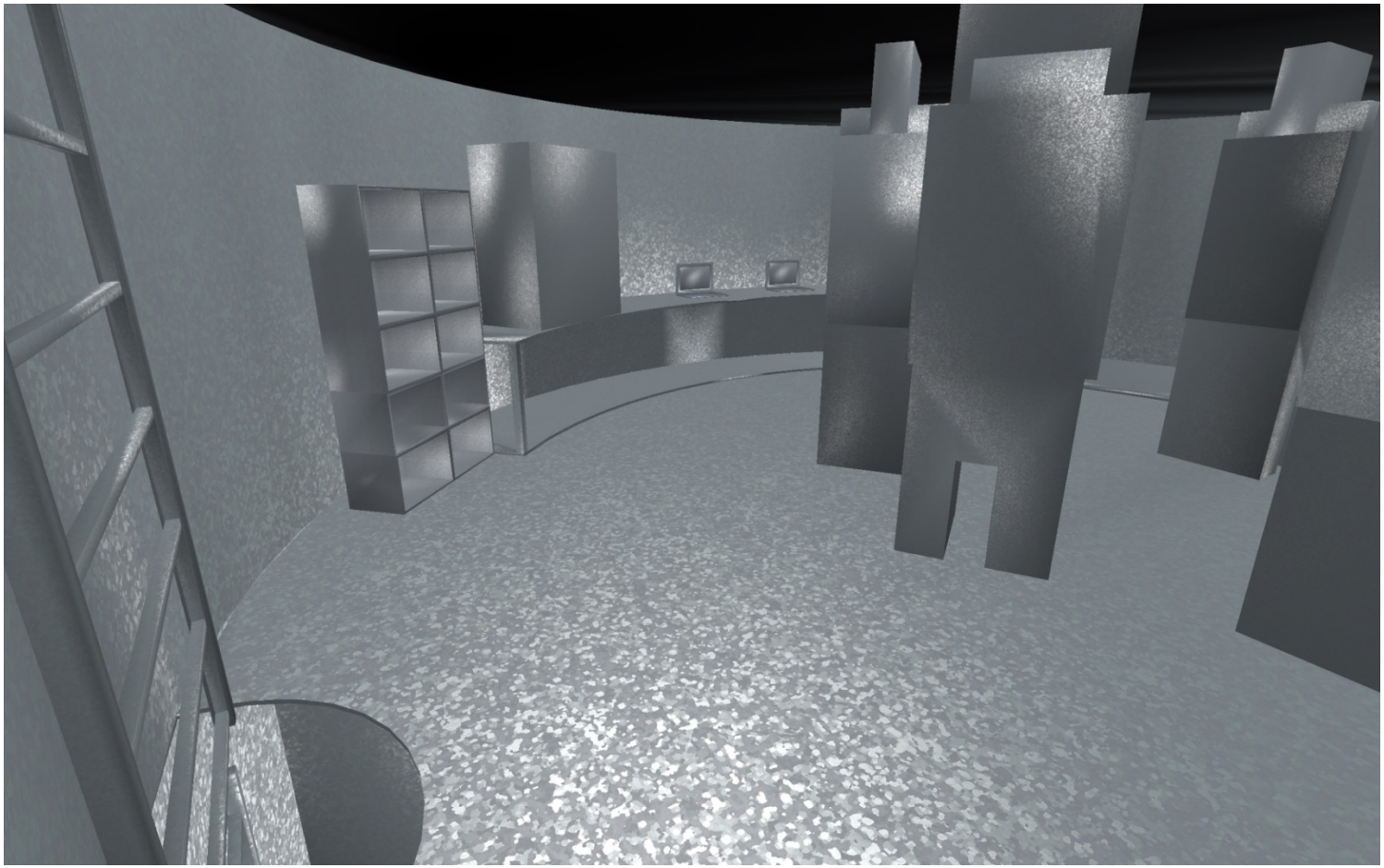
Virtual Reality Testing



Collision model being examined in UDK. The colored boxes define physical boundaries which the test subject cannot pass through and must work around.

- Current and future work:
  - Constructing high fidelity "station simulator" in UDK from existing CAD models
  - Updating virtual scenery to better reflect the actual view from the station
  - Identifying potential layout issues through testing in simulator
  - Using test results to downselect final interior layout design

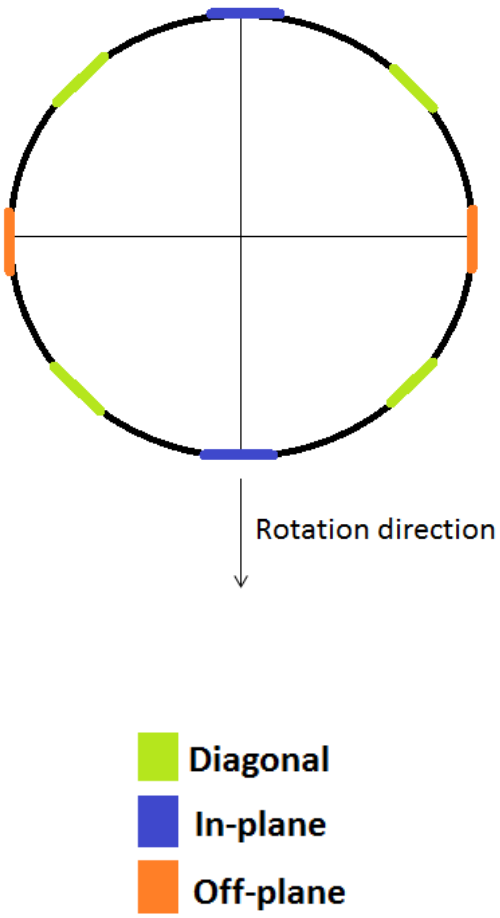
Virtual Reality Testing



Proposed upper floor layout rendered in UDK. The models in the center represent stowed space suits, which are one example of an obstacle crew members may have to negotiate when moving about the station.

Window Position Testing

- Background:
  - Windows indispensable for crew, but rotating habitat
    - Need to find out position of windows that cause less motion sickness (MS)
- Method
  - Simulate rotating habitat with windows using Oculus Rift
  - Number of subjects: 4
  - Testing:
    - 9 cases of 2 minutes each with 2 minutes of rest in between them
      - 3 control cases using Demo of Oculus Rift to get used to virtual reality (only grade last one)
      - 3 different window positions (in-plane of rotation, off-plane of rotation, diagonal) – 2 tests of each
    - Grading scale: Motion Sickness Assessment Questionnaire (MSAQ) developed by the Department of Psychology, Pennsylvania State University



MSAQ

The MSAQ is a valid instrument for the assessment of motion sickness as a multidimensional rather than unidimensional construct.

Gastrointestinal	Central	Peripheral	Sopite-related
Sick stomach	Feeling faint-like	Sweating	Feeling annoyed/ irritated
Feeling queasy	Feeling lightheaded	Feeling clammy/cold sweat	Feeling drowsy
Feeling nauseated	Disorientation	Feeling hot/ warm	Feeling tired/ fatigued
Feeling like vomiting	Dizziness		Feeling uneasy
	Feeling like spinning		

Source: "A Questionnaire for the Assessment of Multiple Dimensions of Motion Sickness". National Institute of Health.

MSAQ

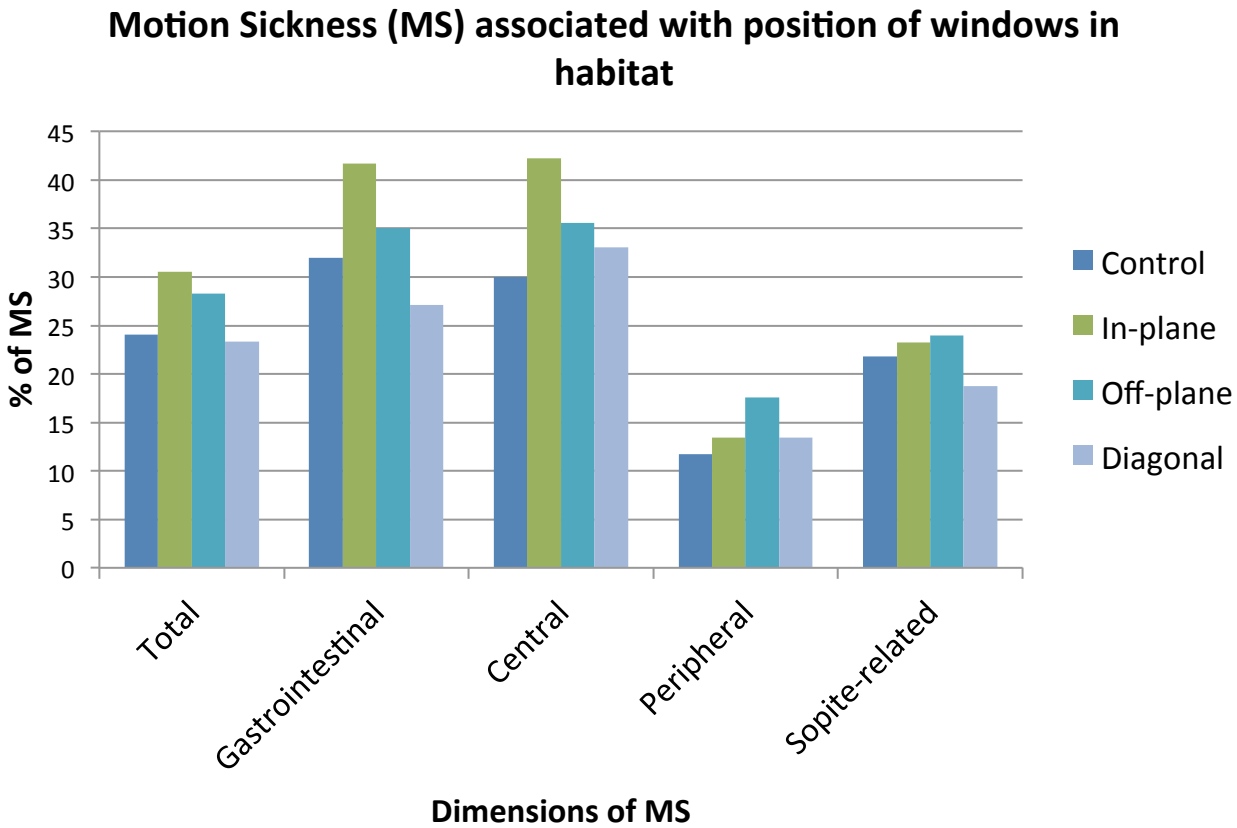
TEST SUBJECT NUMBER **Not at all** **Severely**

1 2 3 4 5 6 7 8 9

	Control	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
I felt sick to my stomach							
I felt faint-like							
I felt annoyed/irritated							
I felt sweaty							
I felt queasy							
I felt lightheaded							
I felt drowsy							
I felt clammy/cold sweat							
I felt disoriented							
I felt tired/fatigued							
I felt nauseated							
I felt hot/warm							
I felt dizzy							
I felt like I was spinning							
I felt as if I may vomit							
I felt uneasy							

Window Position Testing

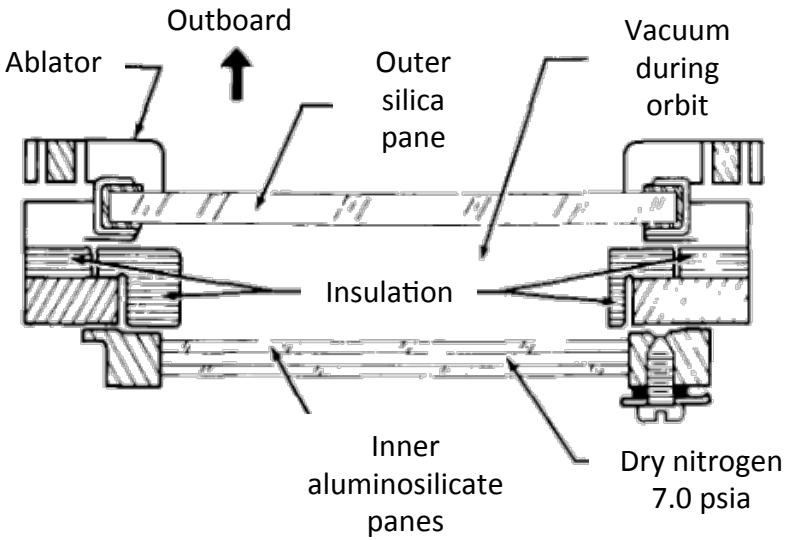
- Results



- Conclusions
  - Diagonal positioning is the one that causes less MS (for all dimensions)
  - In-plane positioning is ruled out due to its high MS in gastrointestinal (G) and central (C) items
  - Off-plane positioning has the highest peripheral (P) and sopite-related (S) items but these are more tolerable than G and C items

Windows

- Two viewing windows on each floor of the habitat
- Will be at a 45° angle relative to the plane of motion
- Design for windows based on Apollo Command Module Hatch Window
- Circular windows with 10 ⅝" diameter
- Structure integration
  - Attached to inner pressure vessel wall and outer Whipple shield
- Stress concentration due to window
  - K_c=2.6
  - Increase in stress $\sigma_{max}=\sigma_{press}$ +24MPa



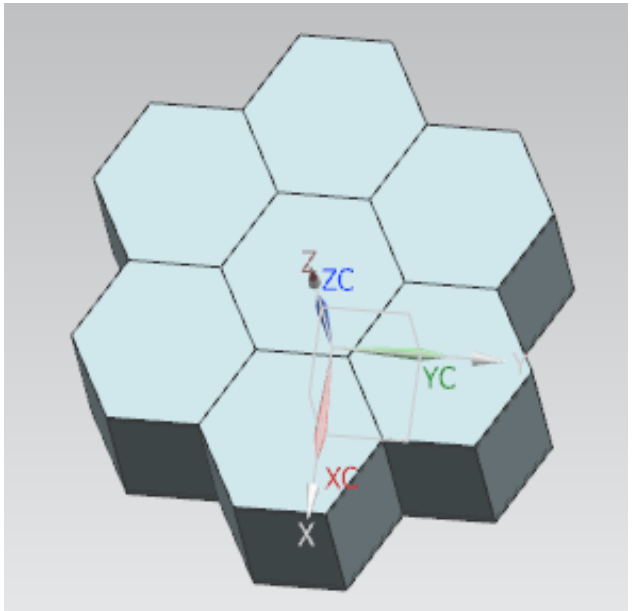
Source: NASA TN D-7439

Habitat Floor Design

- Honeycomb plate
- Design to masses on floor during launch
- Launch loads of 6g
- Material: 3003 Al

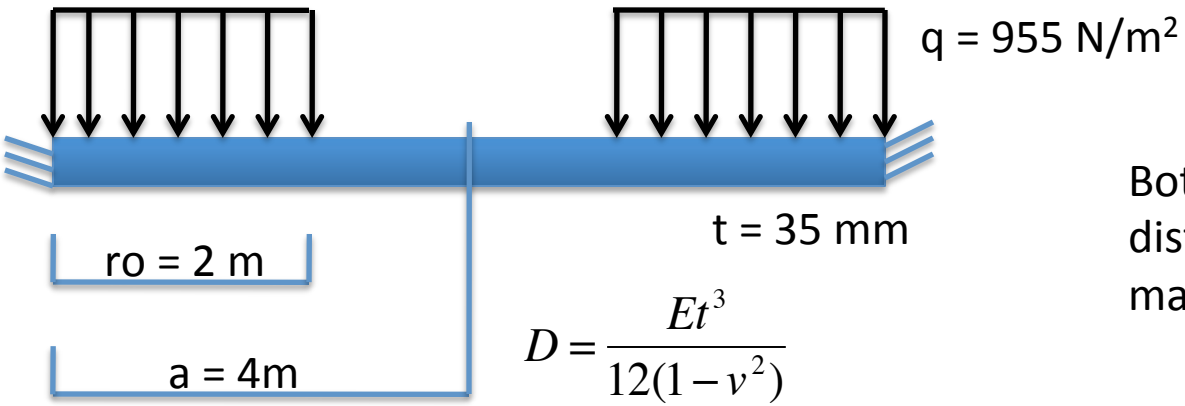
Dimensions	Upper Floor	Lower Floor
Thickness of floor	15 mm	35 mm
Cell diameter	25 mm	25 mm
Crush strength	0.03 kg/mm^2	0.03 kg/mm^2
Cell density	20 kg/m^3	20 kg/m^3
Cell weight	15.08 kg	25.13 kg
Face area density	6.9 kg/m^2	8.6 kg/m^2
Total mass	361.9 kg	457.4 kg

Highest mass concentration: 0.01 kg/mm^2 (H_2O storage tanks)



Source: http://www.universalmetaltek.com/pdf/Aluminum-Honeycomb-Panel.pdf

Lower Floor Analysis



$$D = \frac{Et^3}{12(1-v^2)}$$

$$L11 = \frac{1}{64}\left(1 + 4\left(\frac{ro}{a}\right)^2 - 5\left(\frac{ro}{a}\right)^4 - \left[4\left(\frac{ro}{a}\right)^2 (2 + \left(\frac{ro}{a}\right)^2 \ln\left(\frac{a}{ro}\right)\right]\right)$$

$$L14 = \frac{1}{16}\left(1 - 4\left(\frac{ro}{a}\right)^4 - \left[4\left(\frac{ro}{a}\right)^2\left(\frac{ro}{a}\right)^2 \ln\left(\frac{a}{ro}\right)\right]\right)$$

Bottom Floor mass: load is distributed on outer diameter mass 6000 kg under 6g

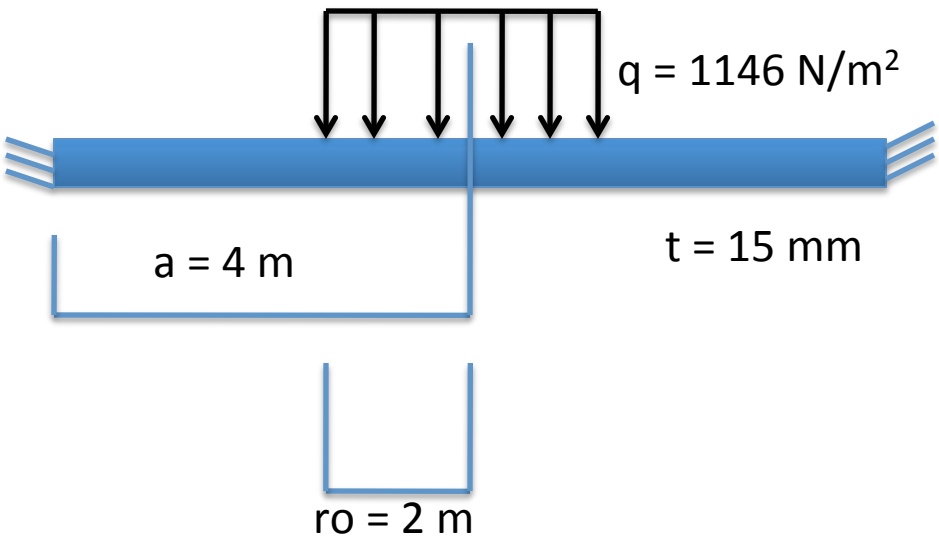
$$\sigma = \frac{SFk_2qa^4}{2D}$$

$$\delta = \frac{SFk_1qr^4(L14 - 2L11)}{Et^3}$$

Floor	Stress [Mpa]	Allow. Stress [Mpa]	M.O.S	Deformation [cm]	Deformation allow [cm]	M.O.S
Lower	22.93	220	8.6	-2.12	4	0.887

Source: http://www.roymech.co.uk/Useful_Tables/Mechanics/Plates.htm
Source:http://www.engineersedge.com/beam_bending/circular_plate-bending.htm

Upper Floor Analysis



Top Floor mass: load is distributed on in diameter mass 900 kg under 6g

$$e' = \sqrt{1.6ro^2 + t^2} - 0.675t$$

$$\sigma = \frac{SFq\ln\left(\frac{a}{e'}\right)}{t^2}$$

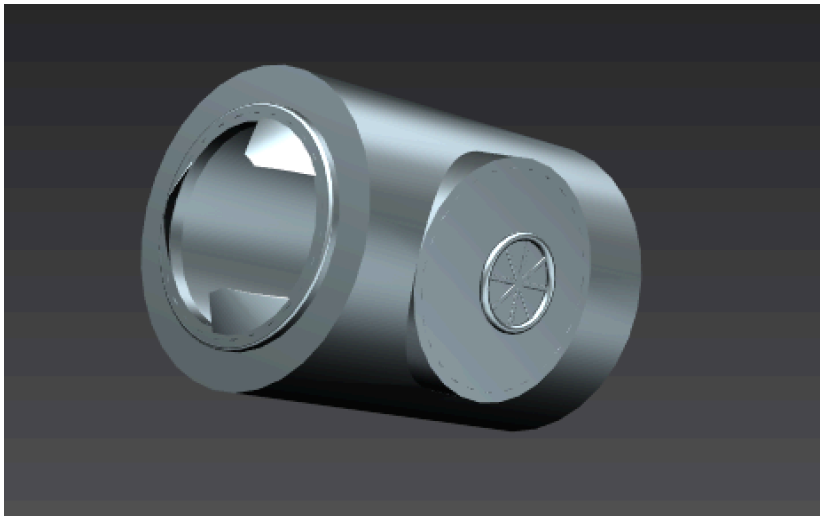
$$\delta = \frac{SF(0.217)qa^2}{Et^3}$$

Floor	Stress [Mpa]	Estimated stress at transfer hole [Mpa]	Allow. Stress [Mpa]	M.O.S	Deformation [cm]	Deformation allow [cm]	M.O.S
Upper	3.58	10.75	125	10.6	-2.36	4	0.695

Source: http://www.roymech.co.uk/Useful_Tables/Mechanics/Plates.htm

Airlock design

- Modeled the Polus airlock after the one found on the ISS
  - Inner diameter: 1.7 m
  - Length: 2.11 m
  - Wall Thickness: 10 mm
- International Docking System Standard (IDSS) interface integrated into tunnel axially for use with DragonRider Capsule
- Secondary emergency hatch centered on the side of the tunnel



Airlock Load Considerations

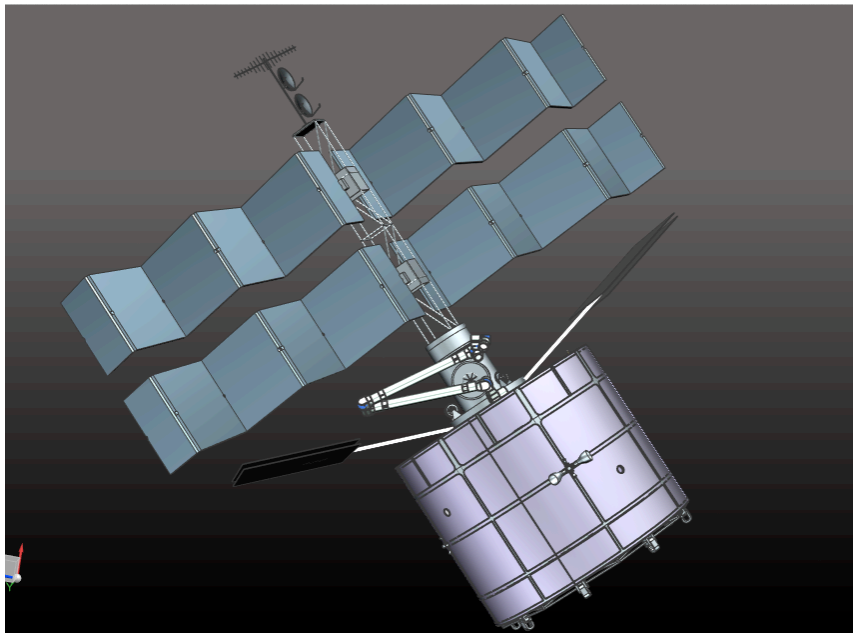
- Wall thickness set at 10 mm to stay consistent with habitat thickness and corresponding Whipple shield calculations
- Load cases – axial and buckling during launch, pressurization
- Geometry:
  - $A = 0.2140\ m^2$
  - $V = 0.4534\ m^3$
  - $I = 0.2142\ m^4$
  - Inner Diameter 1.7 m, outer diameter 1.72 m, length 2.11 m

Airlock Load Calculations

- Maximum launch load is 6g axially (determined by orientation of SLS)
  - σ = P/A = (6*9.8*0.453*2700)/0.2140 = **0.336 MPa**
  - Assumption made that launch supports will counter lateral launch loads
- Euler Buckling load during launch
  - F= π↑2 $EI/(KL)$↑2 = ((π↑2)*(68.9E9)*(0.214))/(1*2.11)^2
  - F = 32.7e+09 N
  - σ = P/A = 32.7e+09/0.2140 = **152.8 MPa**
- Pressurization load is 10.4psi
  - σ = P*r/t = (71710*(0.85)/0.01 = **6.095 MPa**

Photovoltaic/Communications Tower

- Truss structure designed to support 4 photovoltaic arrays and communications array
- Dimensions
  - Cross section of truss: 1 m^2
  - Length: 6.75 m
  - Diameter of truss members: 48.6 mm

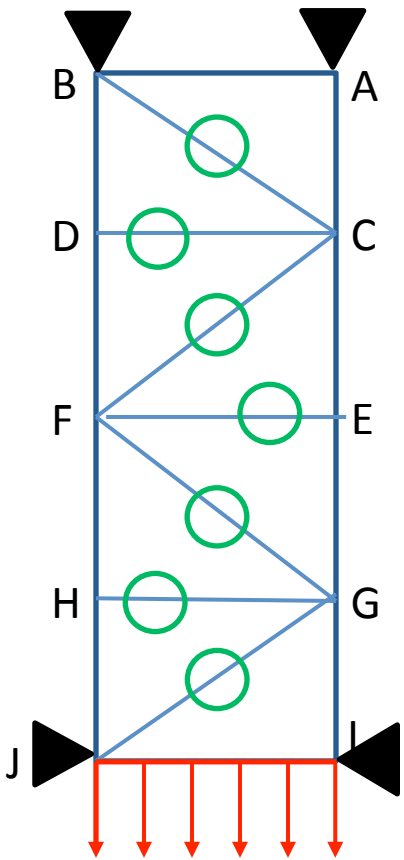


Truss Load Considerations

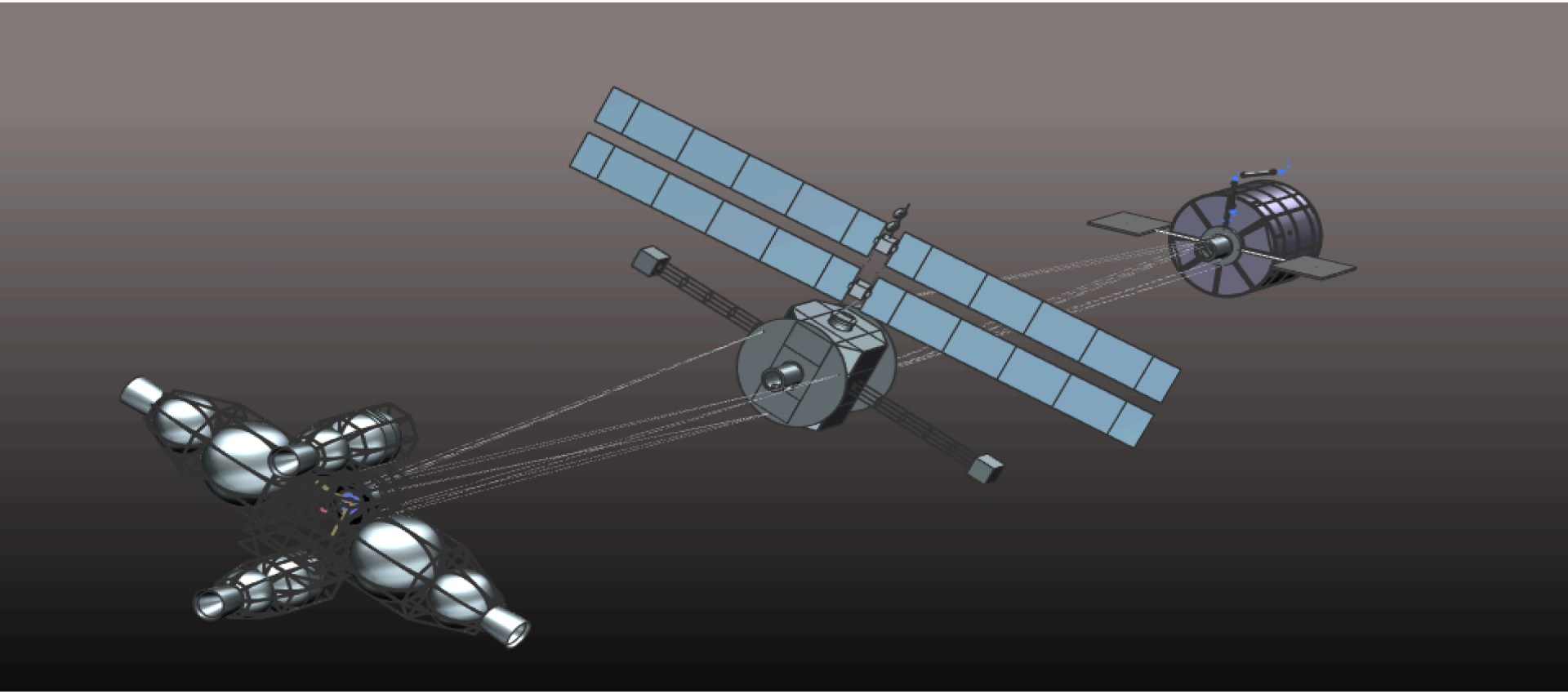
- Used largest maximum load to determine thickness of truss members
- Maximum load experienced at launch is 6g axially (determined by orientation of SLS)
- Under normal operating conditions, panels will be tracking the sun at 1°/day, which will keep the torques/bending moments minimal

Truss Load Calculations

- Launch Loads: 6g applied vertically
- In given launch configuration, the axial supports halve the g-force load and distribute it to all the vertical members (F_{member} = 28.5kN)
- All horizontal and cross-members are zero-force members
- Maximum axial force on a member = **1.5 MPa**
  - $\sigma = P/A = F_{member}/A = 28.5kN/0.0019m^2$
- Maximum Euler Buckling in member = **79.32 MPa**
  - $\sigma = \pi\uparrow 2\ E/(l/r)\uparrow 2$ = (($\pi\uparrow 2$)*(68.9e+09))/((2.25/0.0243)^2)



Phase II



Phase II: Approach and Rendezvous

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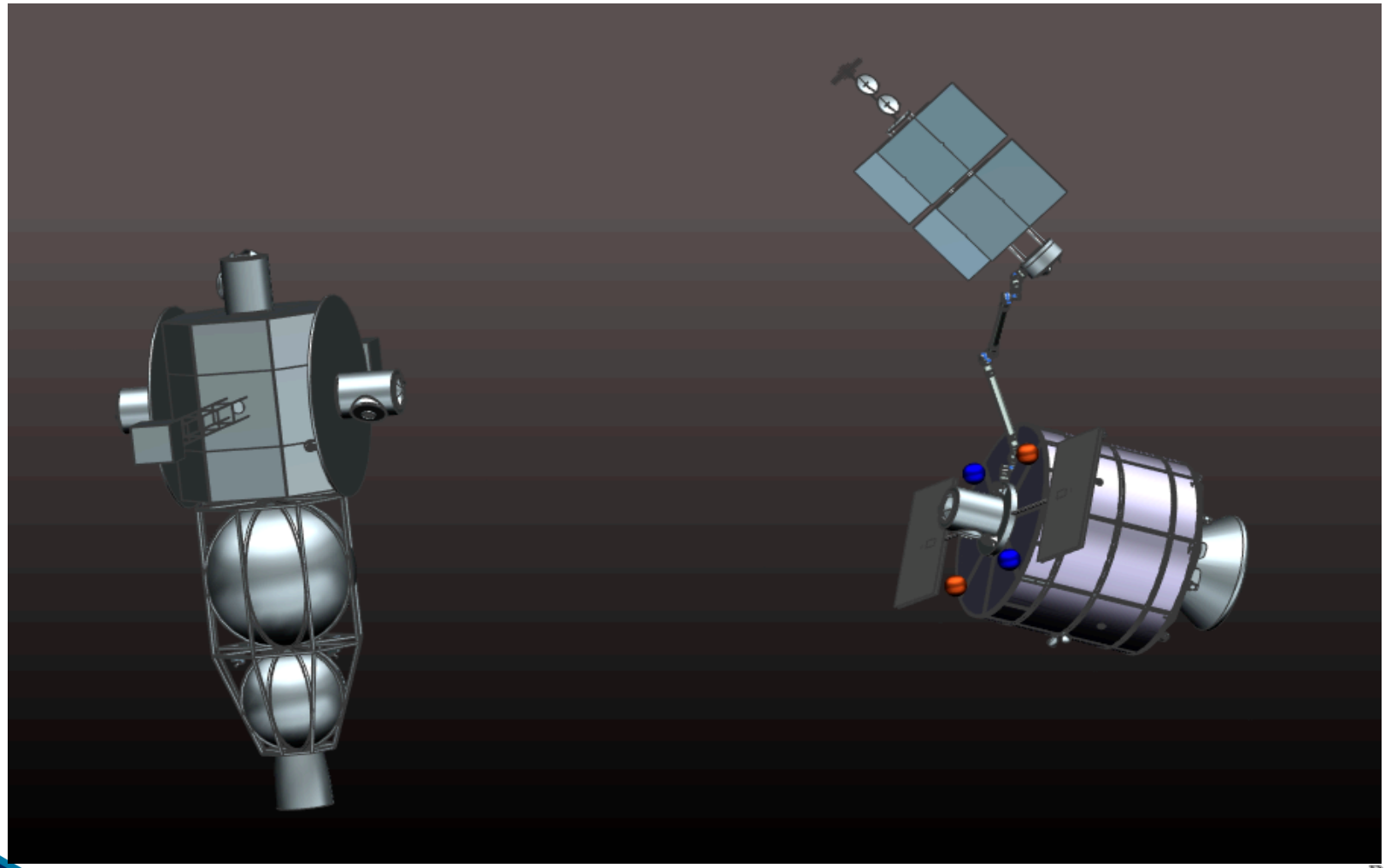

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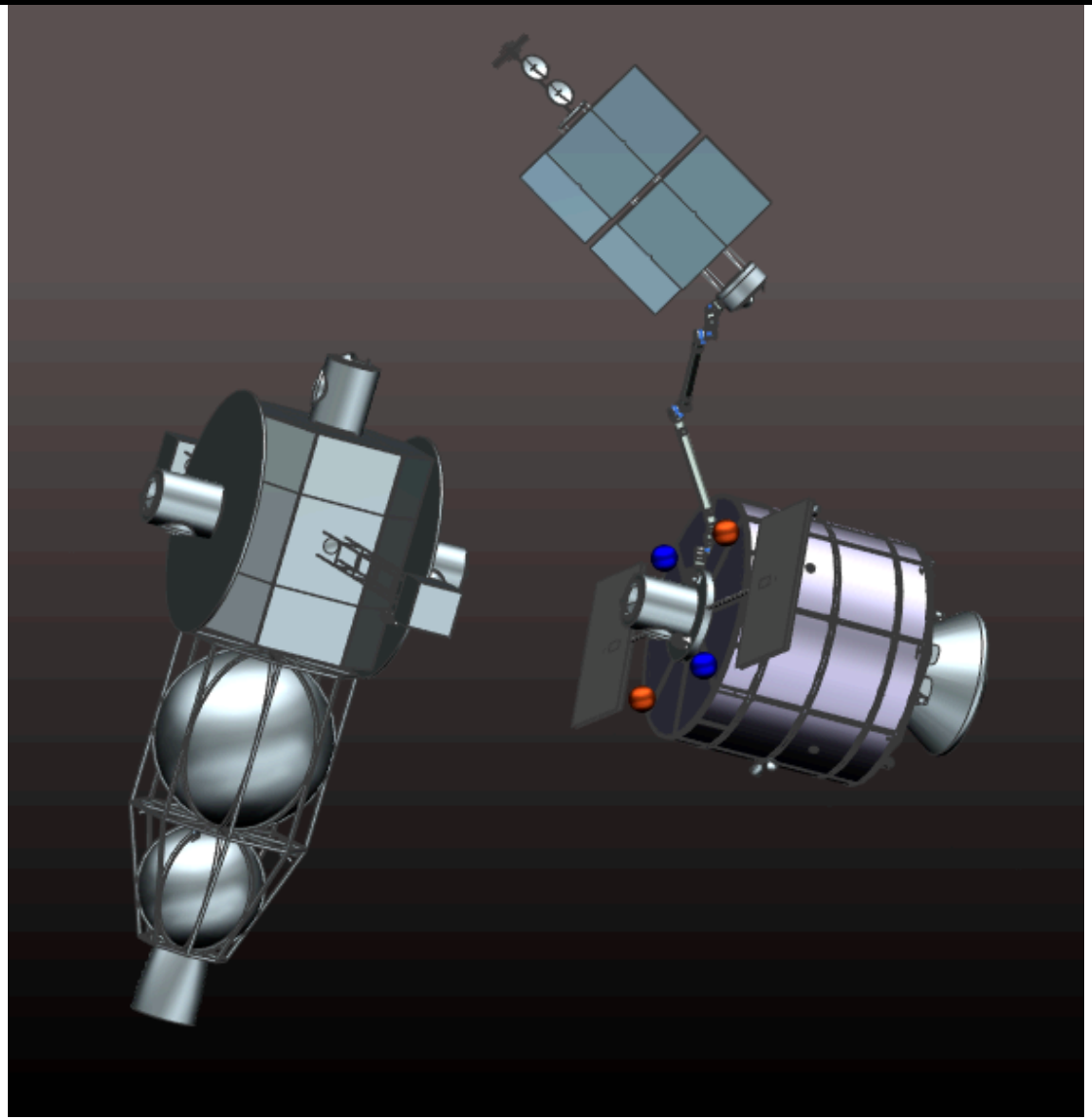

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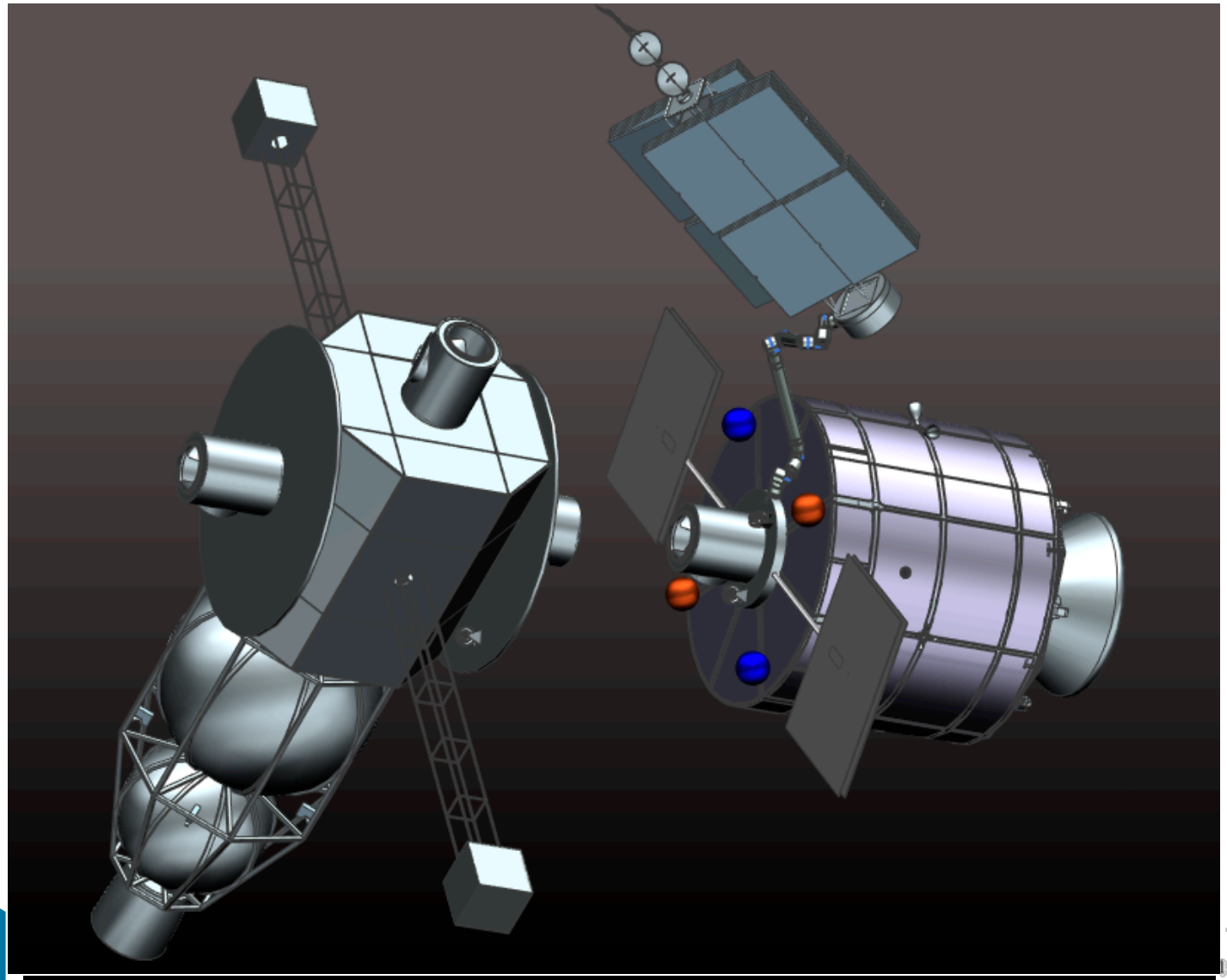
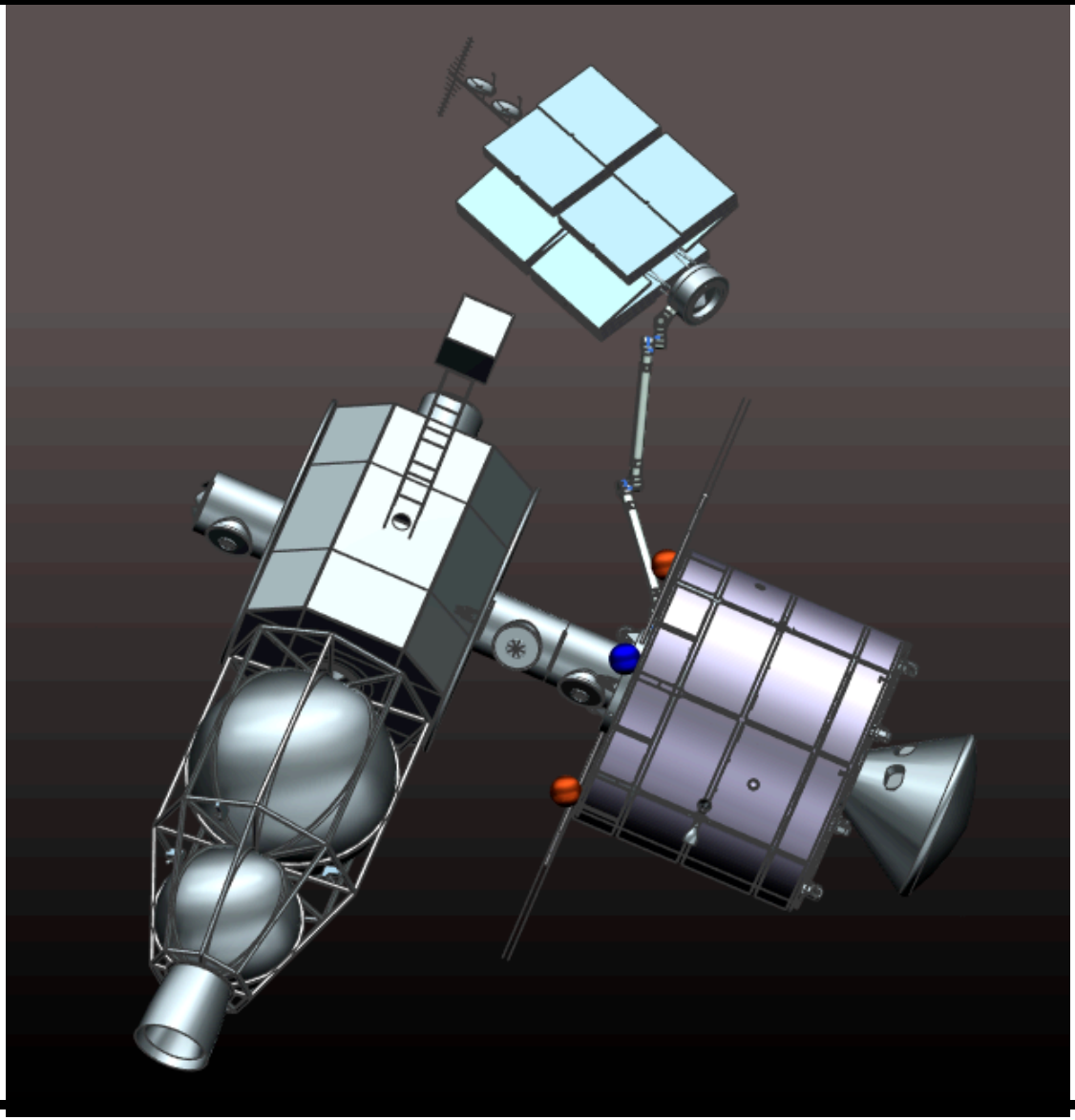
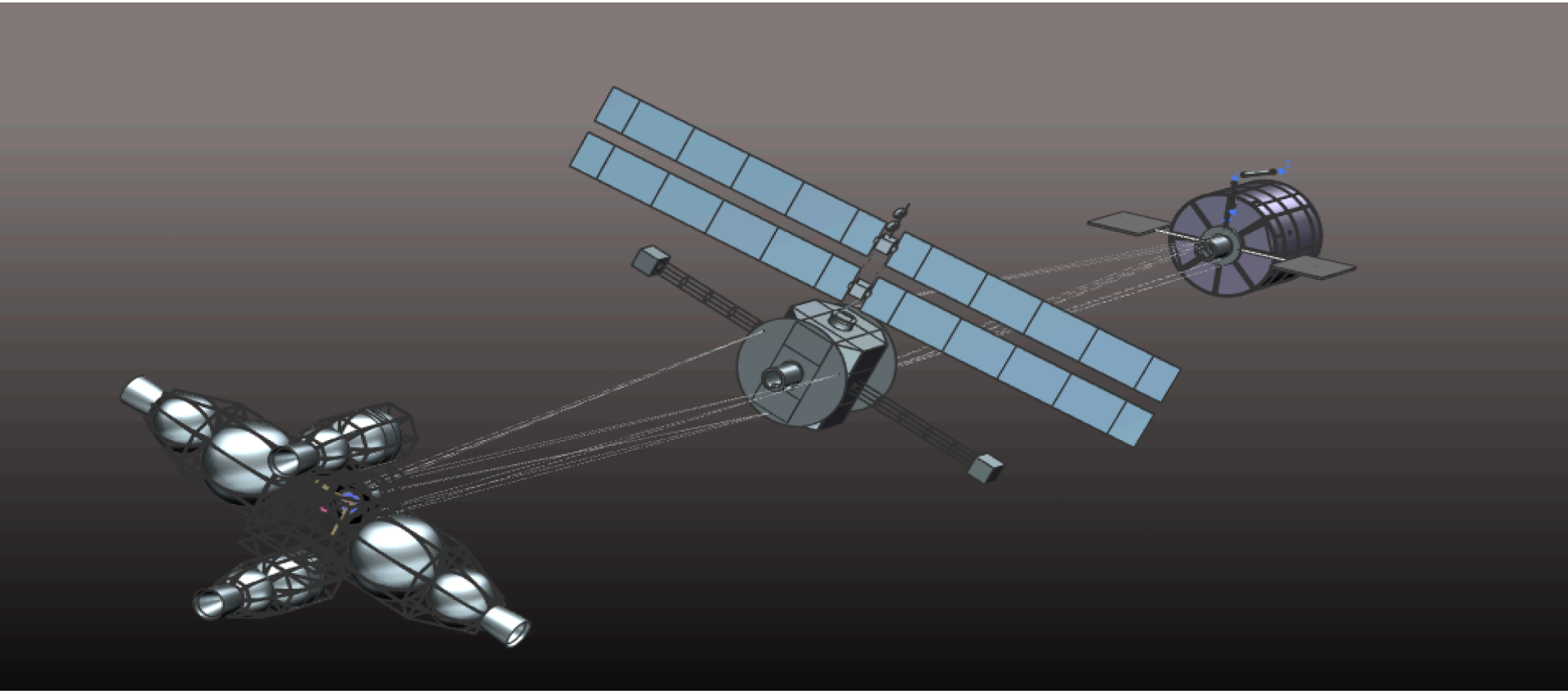


Phase II: Approach and Rendezvous



Phase II: Full Configuration



Phase II Physiology

- All equipment will be carried up in Phase I
- However, examining effects of artificial gravity on physiology is primary goal of Phase II
  - Bone loss
  - Muscle loss
  - Brain function
  - Vision
  - Spinal cord
  - Immune system

Phase II Science Lab

- Integrated workstation will incorporate multiple diagnostic tools
  - Ultrasound
  - Thermal imaging
  - Blood testing
  - Vision testing
  - Electrodes (ECG / EEG / EMG / ENG)
- Microscope from Phase I Lab will also be used

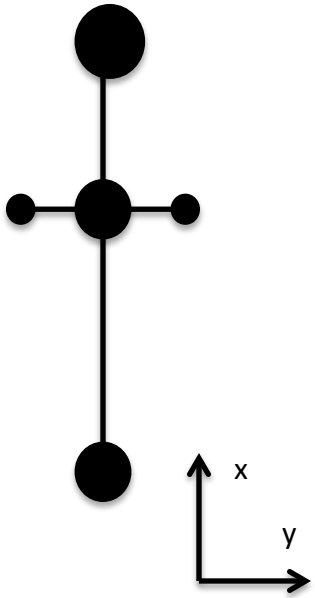
Load Table

Load type		Maximum Value
Pressurization		10.4 [psi]
Axial Launch		6 [g]
Lateral Launch		2 [g]
Inertial Tension Due to Spinning	Phase II	≈ 411.1 [kN]
	Phase III	≈ 822.3 [kN]
Docking*	Tension	3900 [N]
	Compression	3500 [N]
	Shear	3200 [N]
	Bending	2800 [N-m]
	Torsion	1500 [N-m]

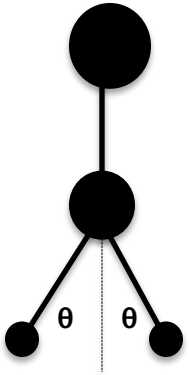
*Source: International Docking System Standard (IDSS) Interface Definition Document (IDD) Revision A; May 13,2011; www.internationaldockingstandard.com/download/IDSS_IDD_RevA_Final_0513

Ballast Configuration Trade

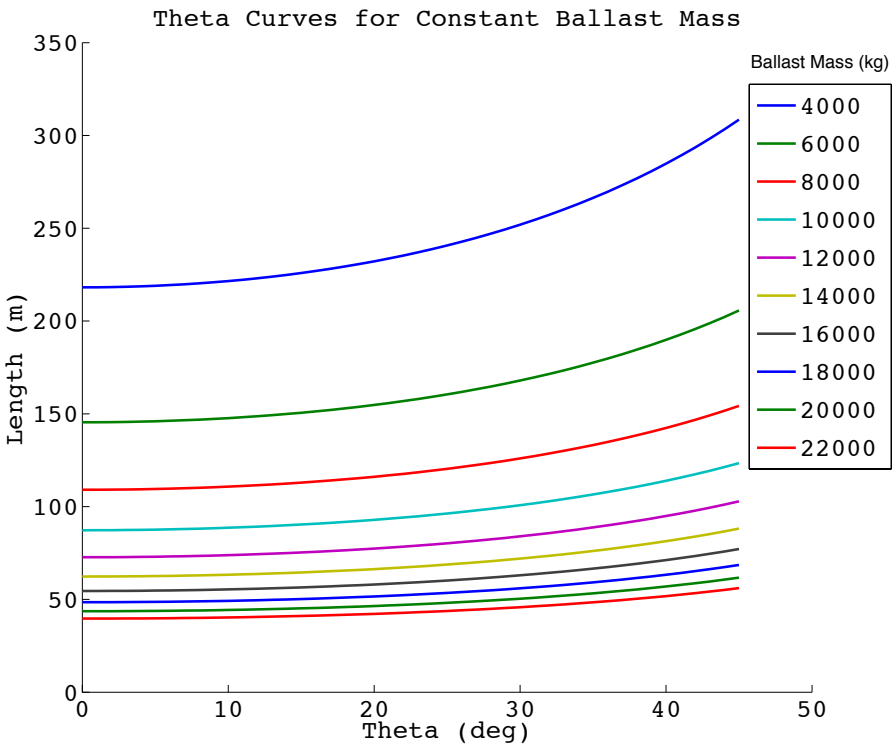
- 1 ballast + 2 stability arms
  - Ballast used to place rotational CoM in the center of the Hub
  - Stability arms ensure that the maximum MoI is around the spin axis (Iz)
  - Ballast and habitat arms are connected by cables
  - Stability arms are connected by a rigid rod
  - Trade: mass/length of stability arms

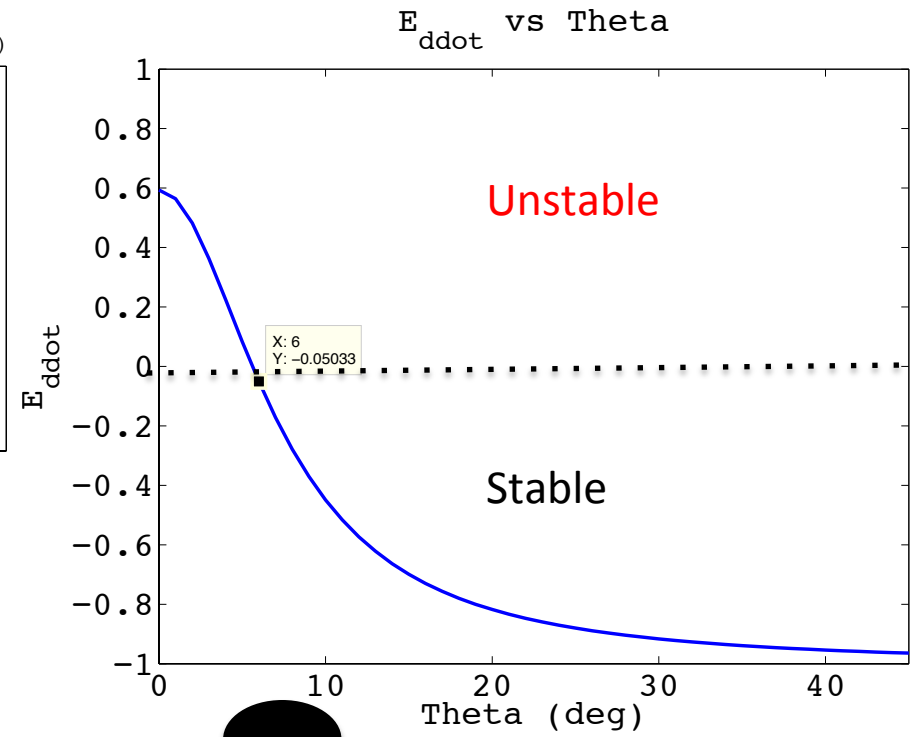


- 2 ballast/stability arms
  - Identical ballasts extend from the Hub at an angle
  - Counterweights serve as combined ballasts and stability arms
  - All arms are connected by cables
  - Trade: mass/length of ballasts

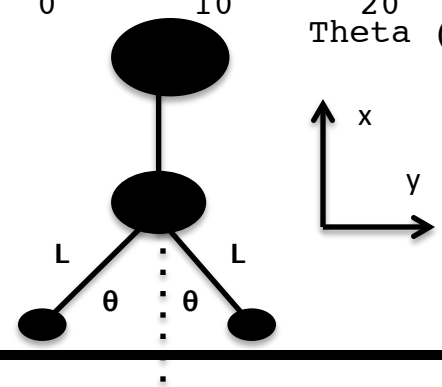


Three Arm

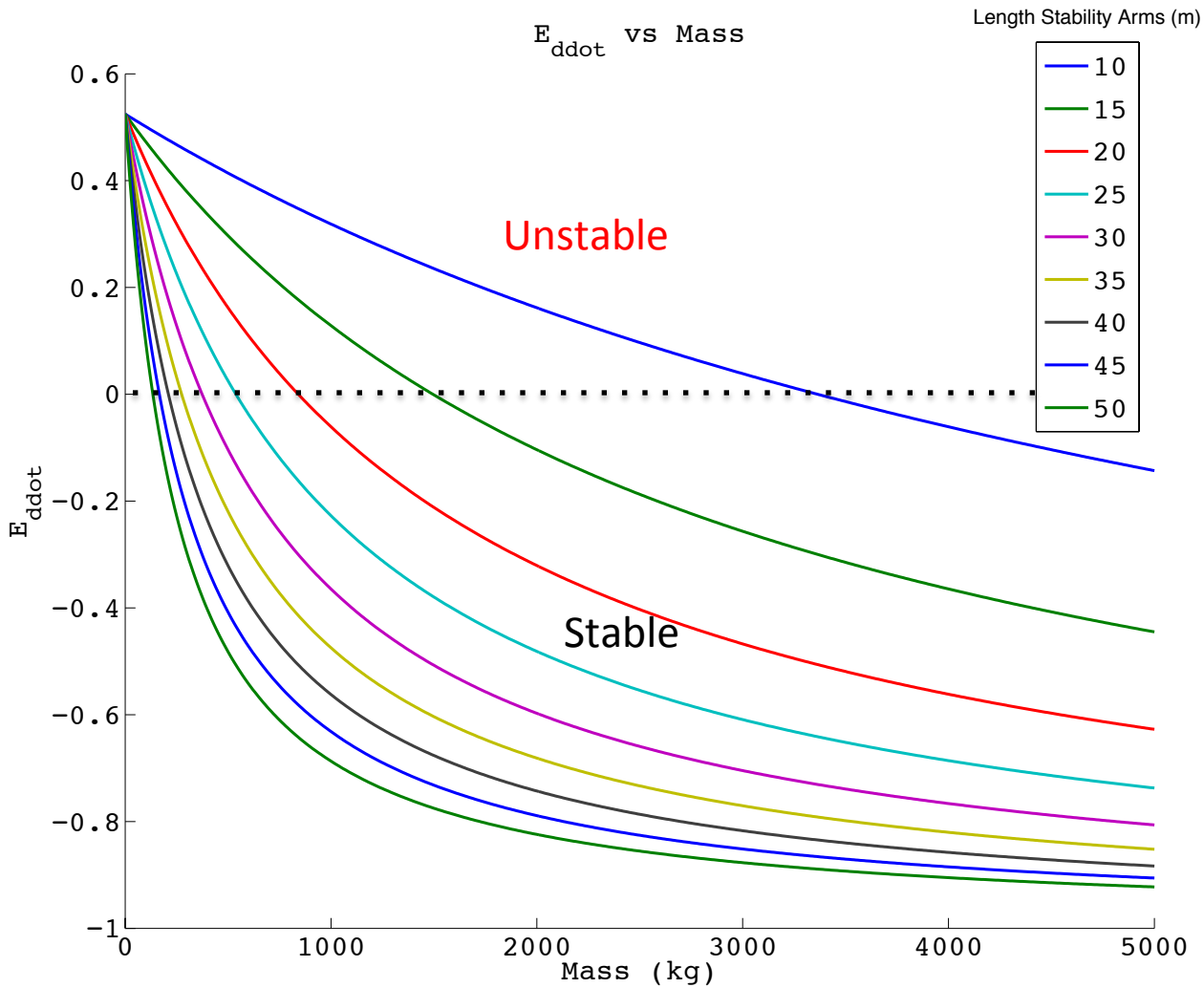




$$Leff = L\cos(\theta)$$



Stability Arm Design



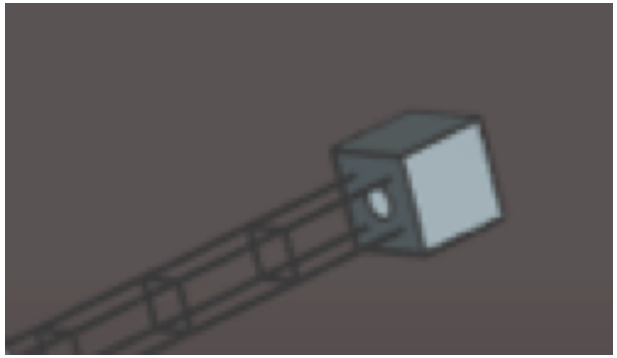
Three Arm vs Two Arm

	Two Arm	Two Arm	Three Arm	Three Arm	Three Arm
Mass Arms [kg]	7000	3400	-	-	-
Length Arms [m]	10	15	-	-	-
Theta [deg]	-	-	6	15	30
Ballast Cable Length P2 [m]	53	53	56	58	65
Cable Weight P2 [kg]	1325	1325	2800	2900	3250
Ballast Cable Length P3 [m]	85	85	91	94	105
Cable Weight P3 [kg]	2125	2125	4550	4700	5250
Additional Mass [kg]	14325	10725	14800	14900	15250
Iz P2 [kgm^2]	2.46E+08	2.46E+08	2.53E+08	2.60E+08	2.93E+08
Iz P3 [kgm^2]	5.10E+08	5.10E+08	5.34E+08	5.53E+08	6.39E+08

Based on the available masses that can be attached to the ballast and stability arm, a two arm configuration with stability arms ensures a rotationally stable system for less mass, cable length, power consumption, and complexity than the three arm configuration.

Stability Arm Design

- Stability arms are necessary to create a rotationally stable configuration for Polus
- Want arm masses to be 'necessary' to the design of Polus, not simply lead weights
- Casing that holds extra wire bundles
  - Each stability arm houses 6 spools of cables used to replace fatigued cables
  - Fatigued cables are switched back into the stability arms to keep constant mass and ensure a constant CoM



Rotational Stability

	Phase 2	Phase 3
Ballast Cable Mass (kg)	45100	70300
Ballast Cable Length (m)	59	54.5
Ix	1.8446e+06	2.0046e+06
Iy	3.2290e+08	4.5507e+08
Iz	**3.2299e+08**	**4.5516e+08**
Stability Ratio	**-0.0464**	**-0.0427**

The design is rotationally stable

Support Arm

- Size
  - Solid tunnel system
  - Pure cable system
  - Hybrid system
    - Comprised of a shortened solid tunnel and cables
- Compare mass properties of the systems over a range of rotation rates
- Consider advantages and disadvantages of all three systems

Support Arm: Equations

$$a_{design} = 9.81\ [m/s^2]$$

$$l_{design} = a_{design} / \omega^2$$

$$l_{design} = r_{design} - 2H_{HabFloor} - H_{HabEndcap} - r_{Hub}$$

$$C_{G\,HabandSIM} = (C_{G\,Hab} * M_{Hab} + C_{G\,SIM} * M\_SIM) / (M_{Hab} + M\_SIM)$$

$$W_{effective} = (M_{Hab} + M_{SIM})(\omega^2 * C_{G\,HabandSIM})$$

$$T_{Wire} = SF * W_{effective} * (1/6) \Rightarrow sizing \perp 1\ [in.]\ diameter\ and\ 2.5\ [kg/m]$$

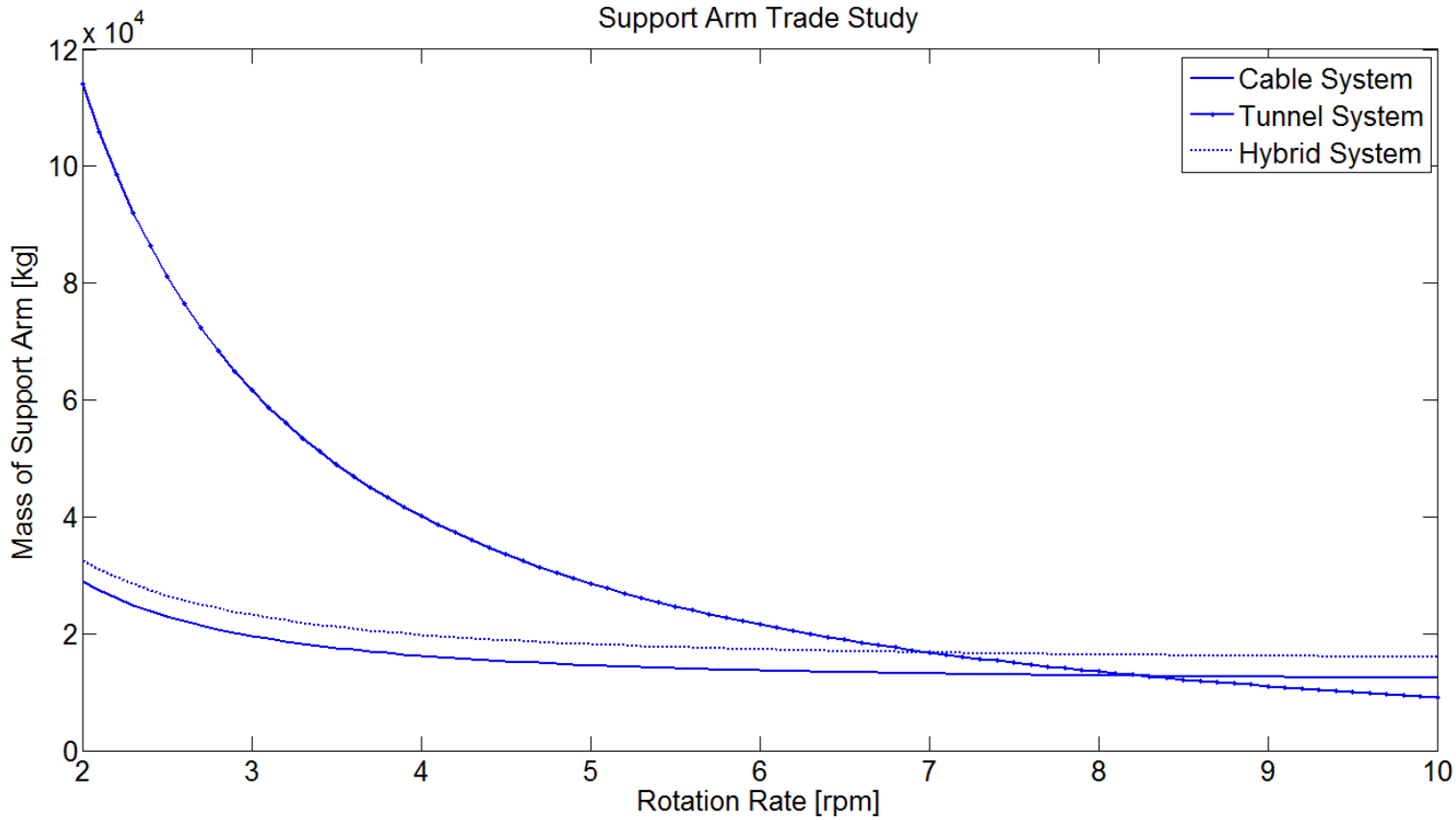
$$M_{tunnel} = l_{design} * m_{tunnel} \quad \text{and} \quad M_{Wire} = l_{design} * m_{Wire}$$

$$M_{WireSystem} = M_{Wire} + 6M_{motor} \qquad M_{Hybrid} = M_{WireSystem} + m_{tunnel} * 10$$

Support Arm: Considerations

- Sizing:
  - Take pressure, collision, and radiation demands into account
  - Mass estimate for rigid tunnel system is 900 kg per 5.5 m
  - Cable sized to 1 in. diameter with mass per unit length of 2.5 kg/m
- Other considerations:
  - Stability under different conditions
  - Ease of altering the system

Support Arm Trade: Results



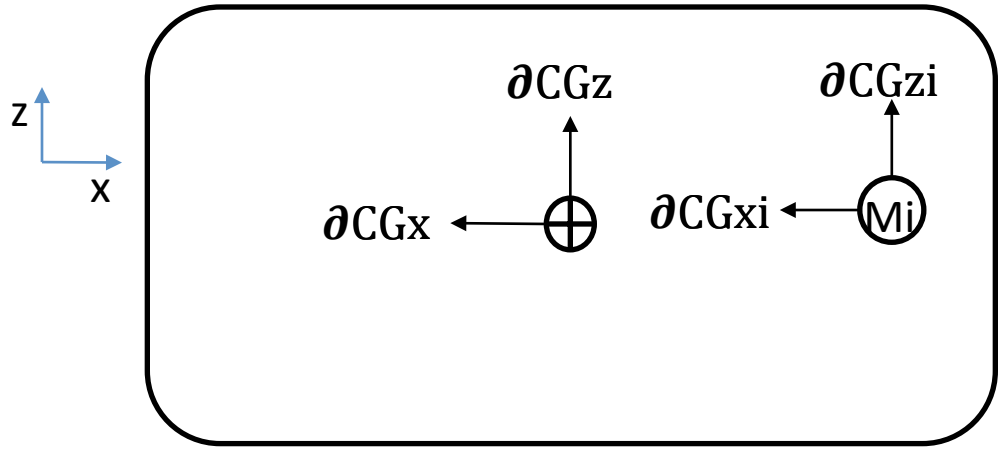
- **Conclusion**: Hybrid System
  - Mass superiority to solid tunnel
  - Ability to actively alter the system unlike tunnel system
  - More secure system on spin down than pure cables

Moving Mass and Center of Mass

- Estimate the total mass of the habitat, Mars SIM, and their moving components
- Find partial derivatives of center of gravity with respect to positions
- Focus on heaviest components (water, food, and people)
  - People are not "heavy" components but due to their constant movement, they have to be analyzed

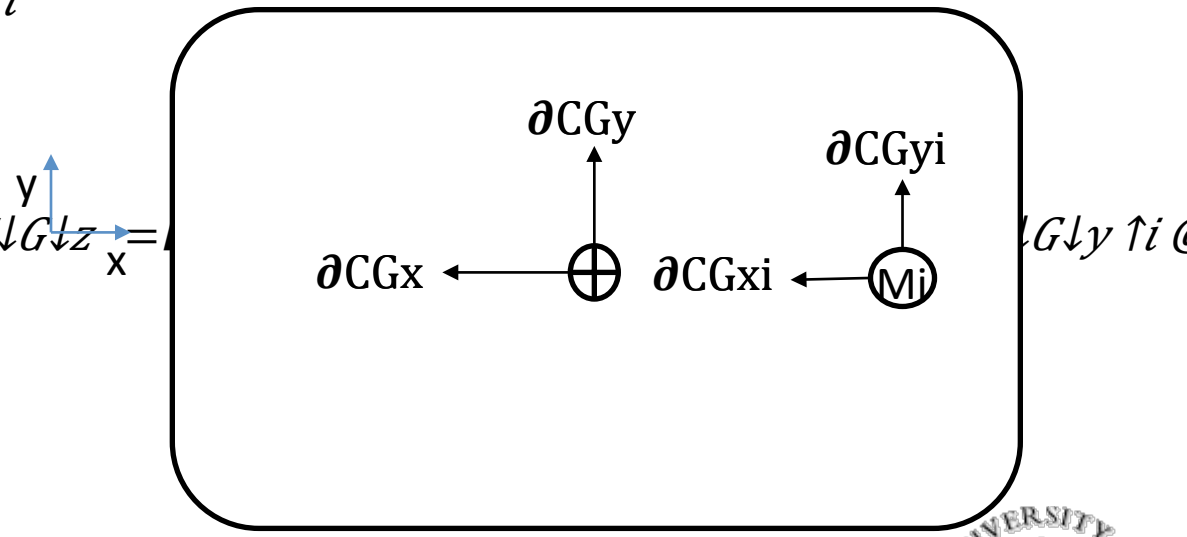
Moving Mass and Center of Mass: Calculations

$$\partial C_G / \partial C_{G_i} = M_i / \sum M_i = M_{ratio_i}$$



$$\partial C_G = M_{ratio_i} * \partial C_{G_i}$$

$$\partial C_{G_x} @ \partial C_{G_y} @ \partial C_{G_z} = \ldots \; {}_{G_y} {}_i @$$



Moving Mass and Center of Mass: Results

Mass Component	Food	Water	People*
Mass Ratio Phase II	$2.3*10^{-4}$	$7.522*10^{-5}$	$1.55*10^{-2}$
Mass Ratio Phase III	$4.127*10^{-5}$	$3.761*10^{-5}$	$7.7*10^{-3}$
Max dx Phase II [m]	$2.3*10^{-4}$	$4.34*10^{-4}$	$4.86*10^{-2}$
Max dx Phase III [m]	$2.78*10^{-4}$	$4.33*10^{-4}$	$6.86*10^{-2}$
Max dy / dz Phase II [m]	$9.2*10^{-4}$	$3.01*10^{-4}$	$6.19*10^{-2}$
Max dy / dz Phase III [m]	$1.65*10^{-4}$	$1.5*10^{-4}$	$3.09*10^{-2}$

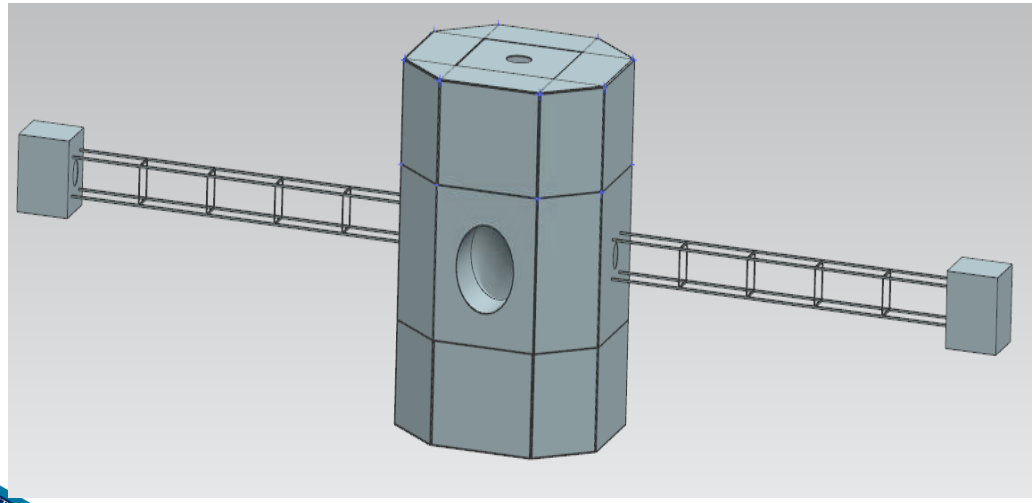
*This column assumes that all 6 people are moving together, and that each person is a 95th percentile man

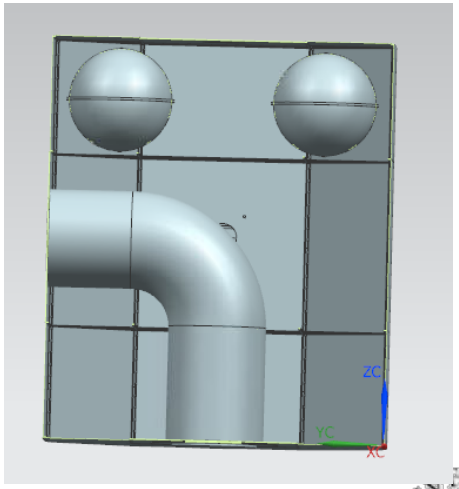
Moving Mass and Center of Mass: Conclusions

- Phase II and III inert habitat masses overpower the moving masses
- Center of mass is not expected to move more than 0.07 m
- Effectively the center of mass is constrained to the nominal center

Central Hub Design

- Requirements:
  - Dock DragonRider to Hub during Phase II and III
  - Support communications/power boom
  - Support the connecting arms for habitat, ballast, and stability arms
  - Contain fuel and oxidizer excess tanks
  - Contain personnel transfer tunnel and power transfer cables
  - Withstand launch loads





Central Hub Design: Calculations

Euler Buckling (During Launch)

$$SF*P_{buckling} = c*\pi^2 *E*I/l^2$$

Central Hub Support Beams:

$$(1/8)(2)(30000)(10)(6)=(4)(\pi)^2(7*10^{10})(I_{octagon})/(3)^2 \Rightarrow I_{octagon}=1.46*$$

Stability Arm Support Beams:

$$(1/4)(2)(2000)(10)(6)=(4)(\pi)^2(7*10^{10})(1/12*s^4)/(L)^2 \Rightarrow s^4/L^2 =2.61*10^{}$$

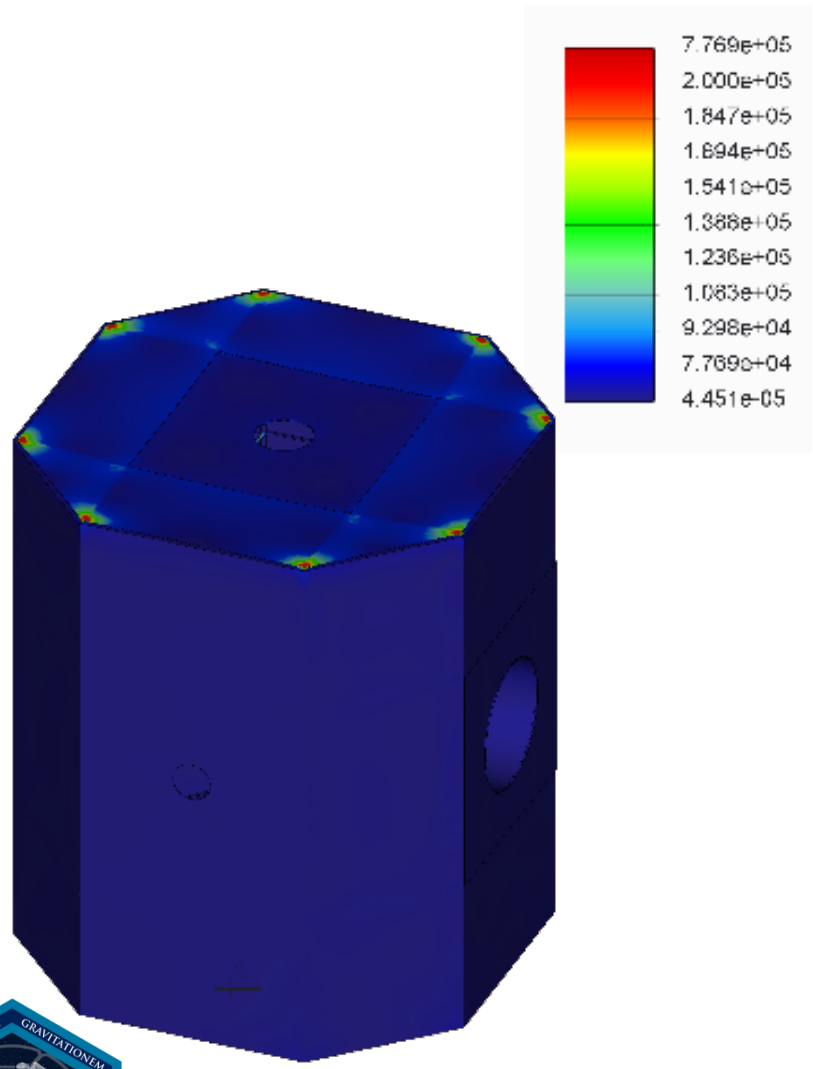
Hub Infrastructure Members:

$$F_{axial}=10*M_{HabandSIM} \quad F_1=F_{axial}/\cos(45) \quad F_2=F_{axial} \quad A_i=2*F_i/S_f$$

Central Hub Design: Sizing Results

- Cyclic tension loading:
  - Endurance limit: 97 MPa
  - Infrastructure:
    - Safety Factor: 2
    - Design to endurance limit
    - Results:
      - primary members 30 mm by 60 mm
      - secondary members 30 mm by 40 mm
- Buckling of vertical members:
  - Launch 6 g's:
    - Support 30,000 kg for Hub
    - Support 5000 kg for stability arms
    - Safety factor: 2
    - Axial load divided amongst 8 octagonal supporting rods for Hub
    - Axial load divided amongst 4 supporting beams for stability arms
    - Results:
      - Octagonal supporting rod has side length of 30 mm for Hub
      - Rectangular support beams 40 mm by 40 mm for stability arms

Finite Element Analysis Central Hub

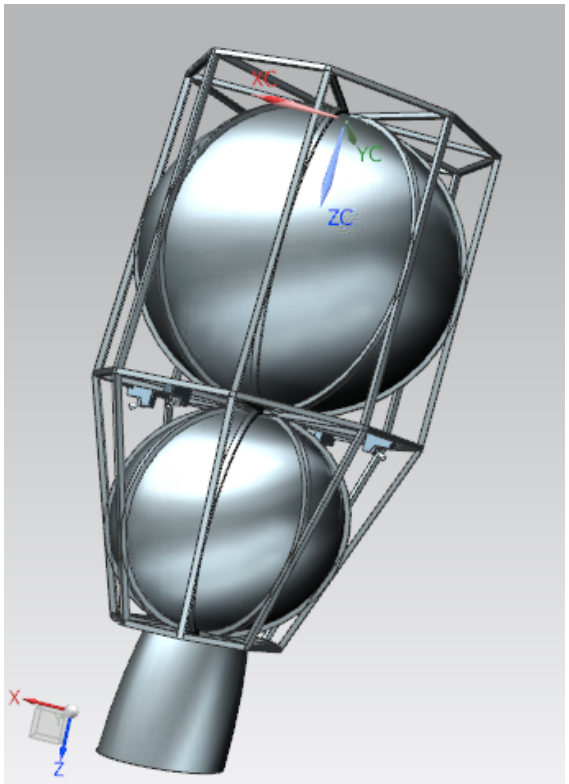


- Part: central Hub
- Load: launch accelerations
- Constraint: against displacement on the bottom
- Conclusion: high stress concentration contains average stresses of $\sigma_{ave} \approx 200$ MPa

Feature will not yield

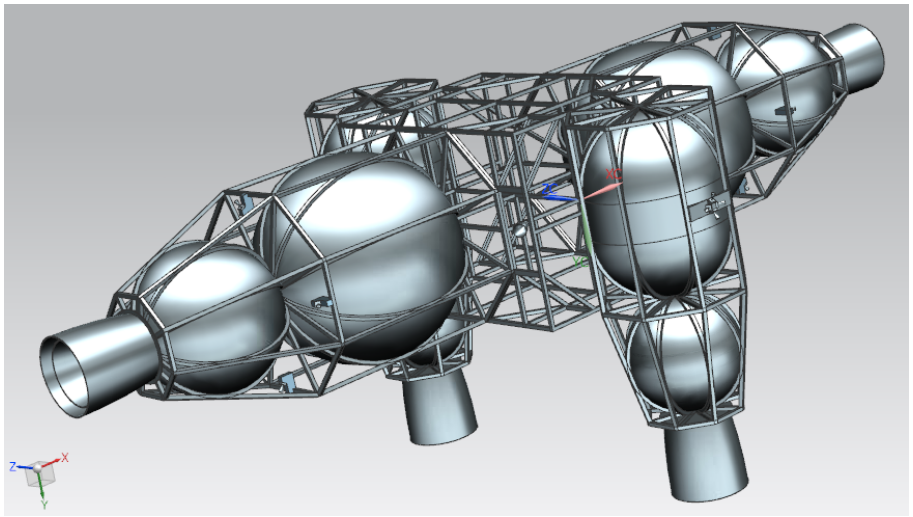
Upper Stage Ballast

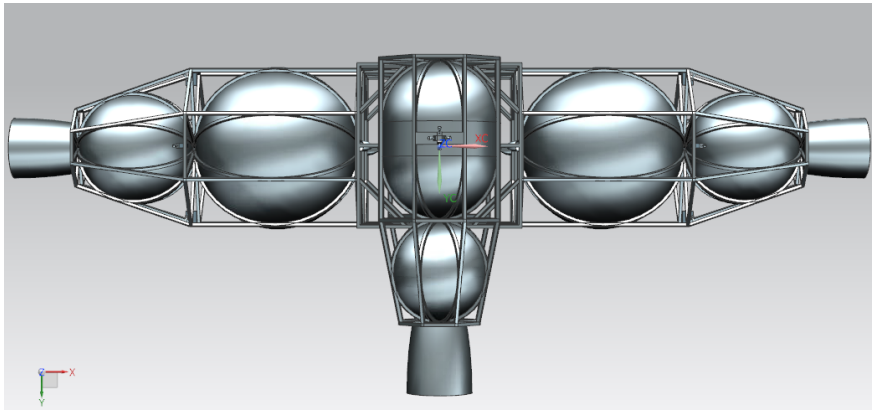
Ballast Structure	Mass [kg]
Heavy Lift Upper Stage	11,900
Crew Launch Upper Stage	6660
Support Structure	8500
Phase I Ballast	N/A
Phase II Ballast	45,100
Phase III Ballast	70,300



- The upper stages for each launch will be used to offset the center of mass for habitat in the rotating structure.

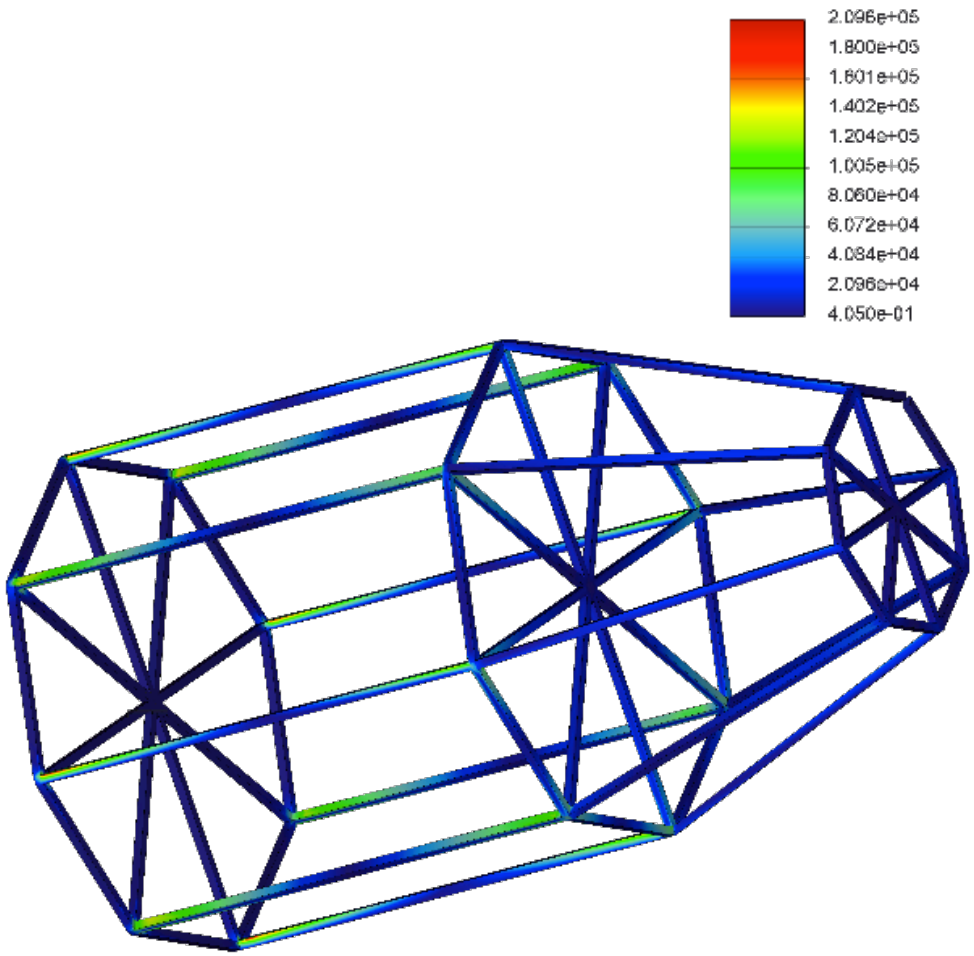
Phase II Ballast Configuration





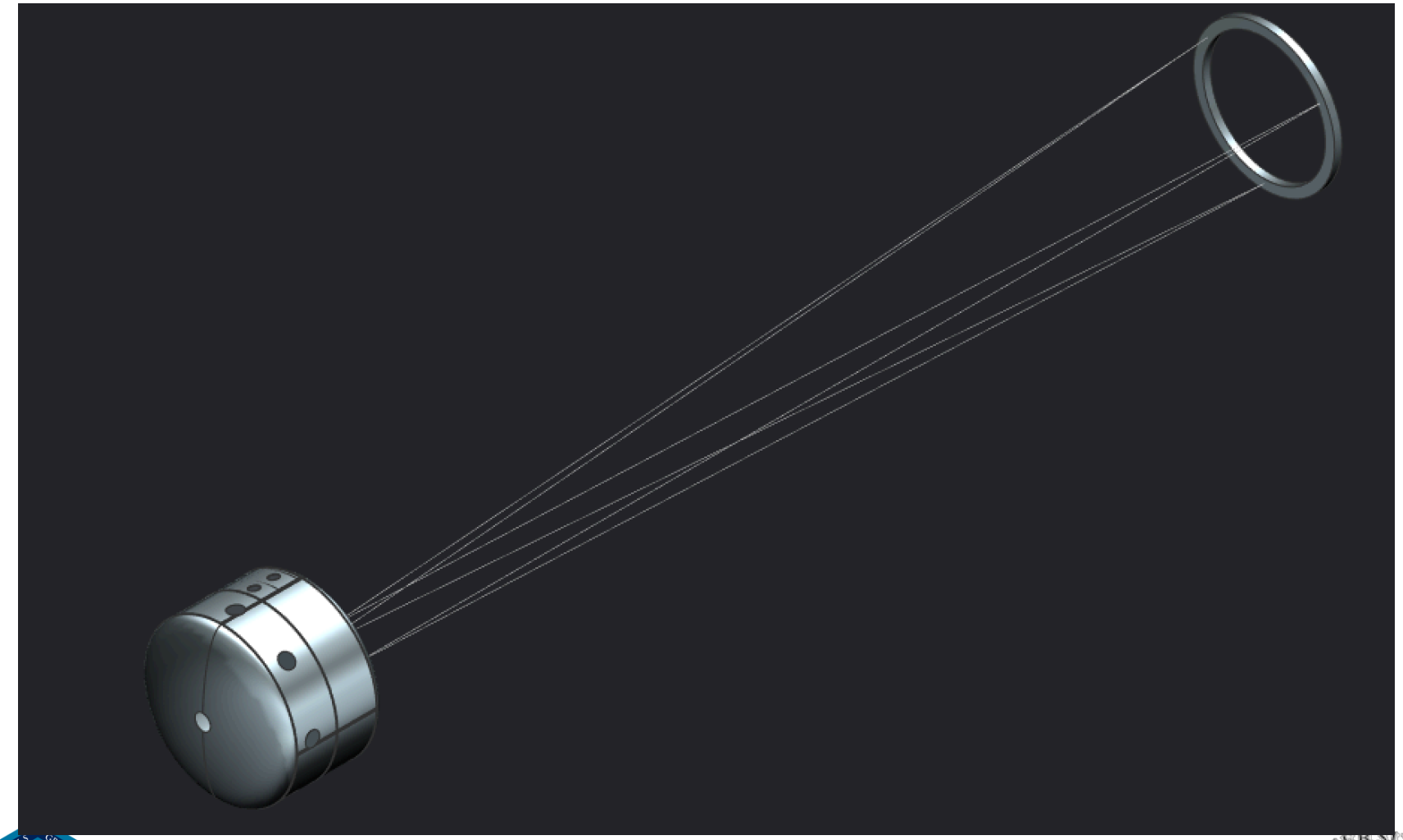
- 2 Heavy Lift Upper Stages
- 2 Crew Launch Upper Stages
- Mass: 45,100 kg

Finite Element Analysis: Ballast



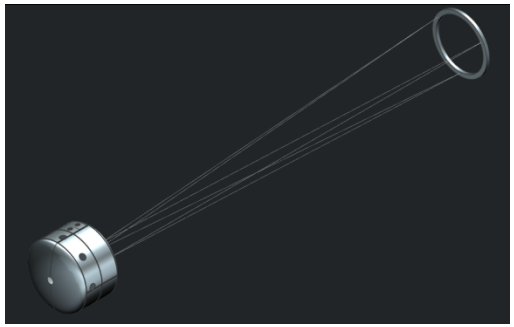
- Part: upper stage ballast
- Load: 2g spinning
- Constraint: against displace on attachment face
- Conclusion: high stress concentrations contain average stresses of $\sigma_{ave} \approx 140$ MPa

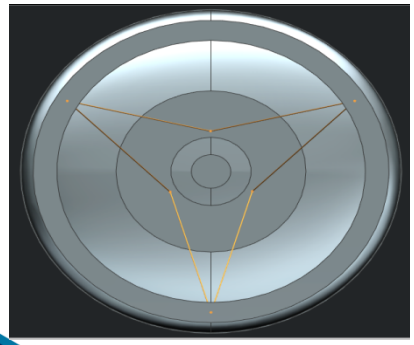
“Stewart” Wire Rope-Truss

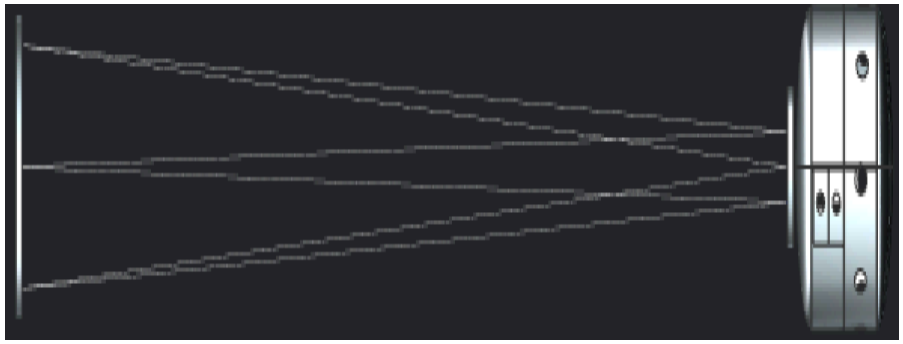


“Stewart” Wire Rope-Truss Overview

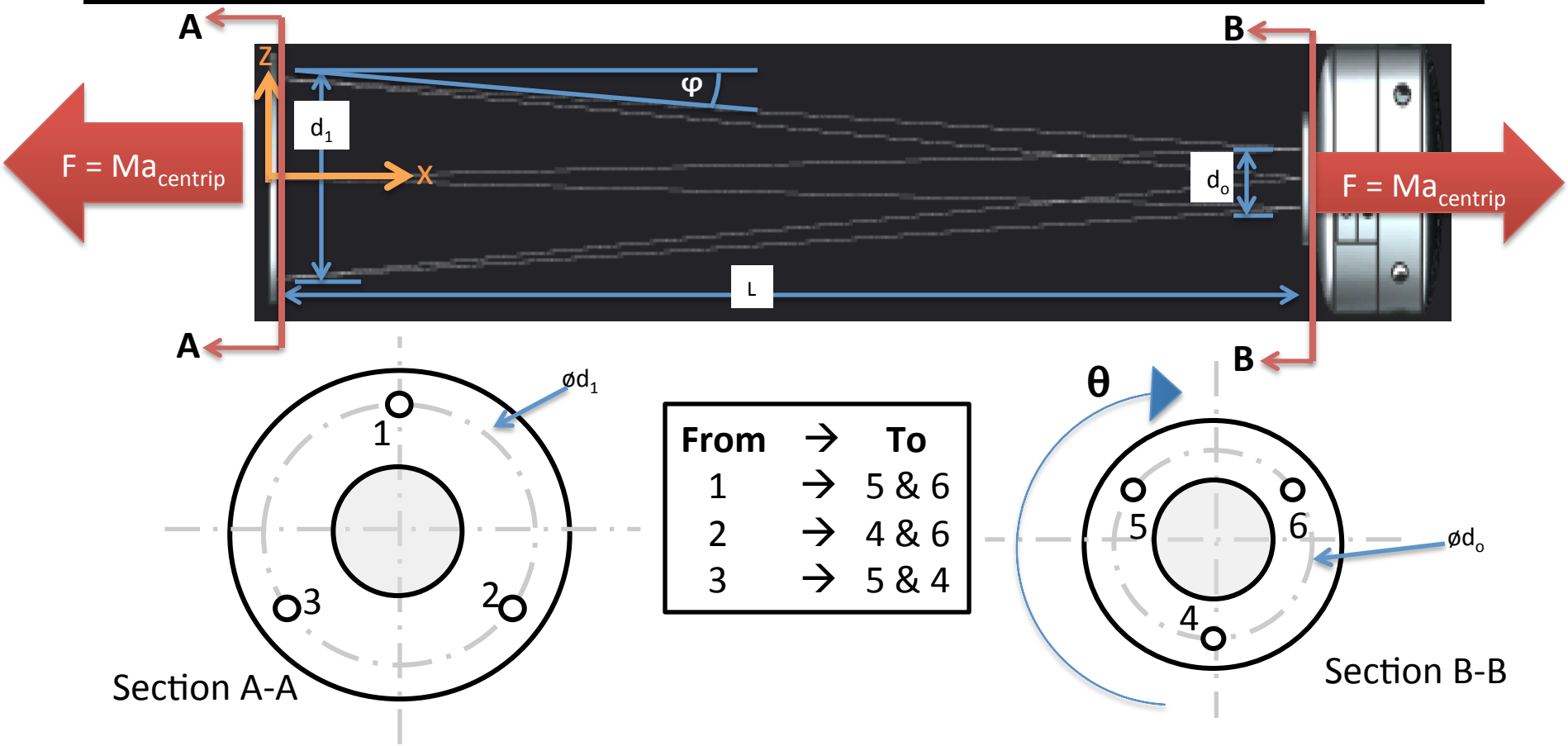
- Six (6) wire rope pairs in Stewart configuration
- Absorb shock loads, damp and isolate effects of vibration
- Geometry provides torsional vibrational stability
- Capability for active stability control
- Packaging benefits for launch and operations
- Simplifies the detailed design versus a rigid solution







“Stewart” Wire Rope-Truss Configuration



From	→	To
1	→	5 & 6
2	→	4 & 6
3	→	5 & 4

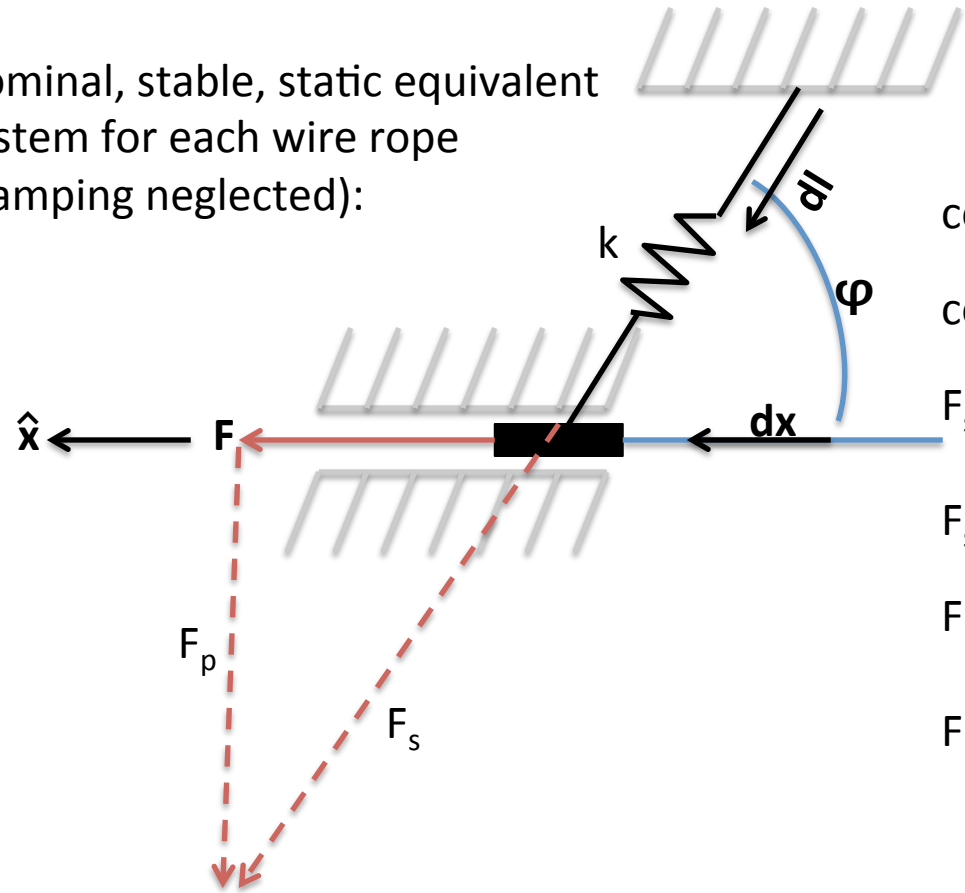
d_o = 2 m → Outer diameter of the tunnel section

d_1 = 7 m → Height of Hub in z-direction

L = 50 m → For < 4 RPM spin rate

"Stewart" Wire Rope-Truss Analysis

Nominal, stable, static equivalent System for each wire rope (damping neglected):



$\cos(\varphi) = F/F_s \rightarrow F_s = F/\cos(\varphi)$

$\cos(\varphi) = dx/dl \rightarrow dx = dl*\cos(\varphi)$

$F_{spring} = k_{eff}*dx = k*dl*\cos(\varphi)$

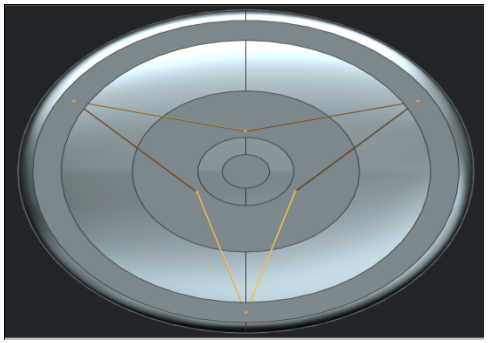
$F_s = F_{spring} \rightarrow F/\cos(\varphi) = k*dl*\cos(\varphi)$

$F = k*dl*\cos^2(\varphi)$

$F = k_{eff}*dx \rightarrow F/dl = \mathbf{k_{eff} = k*\cos^2(\varphi)}$

$k_{eff\text{-}spring}/k_{spring} = \cos^2(7.12^\circ) \rightarrow \boxed{\mathbf{k_{eff\text{-}spring}/k_{spring} = 0.985}}$

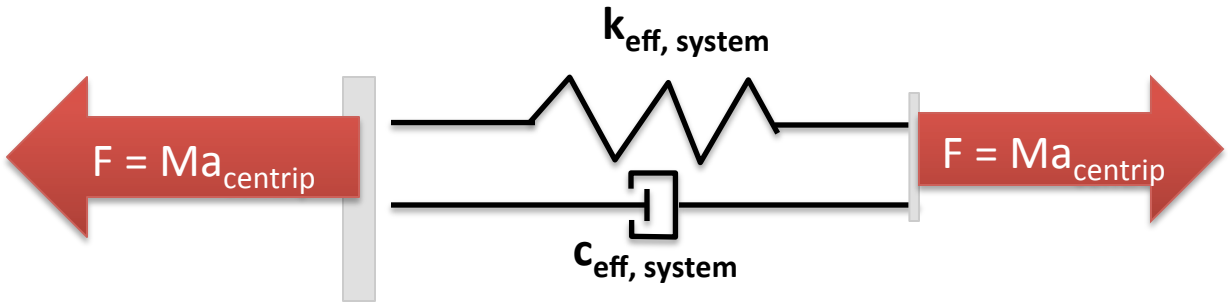
“Stewart” Wire Rope-Truss Analysis



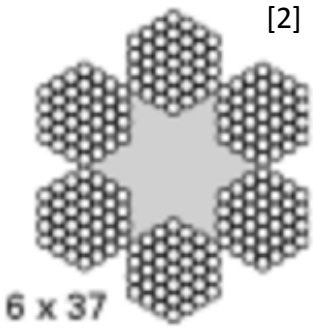
Six wire rope pairs in parallel, each with $\mathbf{k_{eff} \approx k*\cos^2(\varphi)}$

The effective spring constant is $\mathbf{k_{eff,\ system} = 12*k*\cos^2(\varphi)}$

Inevitably, there will also be some damping constant for the wire ropes due to internal friction between the wires/strands and material damping



“Stewart” Wire Rope-Truss Configuration

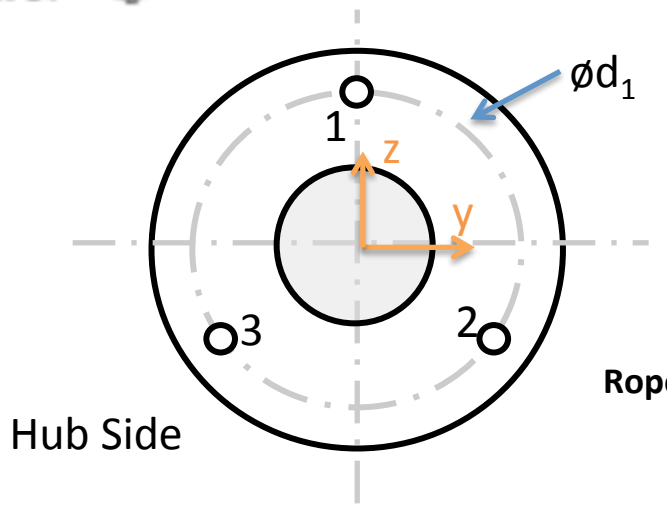


[2]

1 inch 6x37 Special Flexible, Regular Lay Monitor Steel Wire Rope[1]

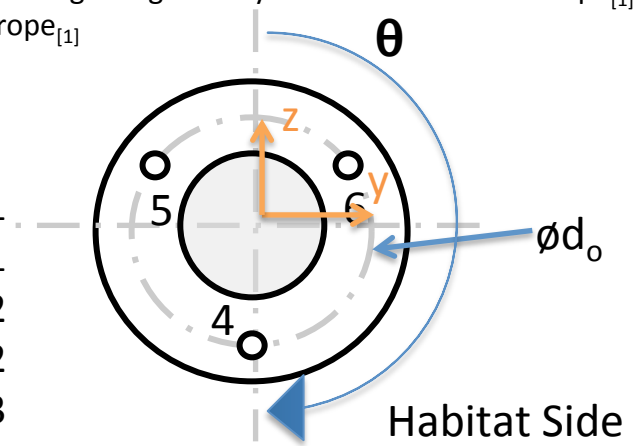
Weight [N/m]	Minimum Sheave Diameter [m]	Size of Outer Wires [m]	Modulus of Elasticity* [Gpa]	Strength** [Mpa]
6.89	0.457	0.0012	75.8	689.5

* Only approx., depends on loading and generally increases with life of rope[1]
**Based on nominal area of rope[1]



Rope Vectors

r_{15} = H5 – H1
r_{16} = H6 – H1
r_{24} = H4 – H2
r_{26} = H6 – H2
r_{35} = H5 – H3
r_{34} = H4 – H3

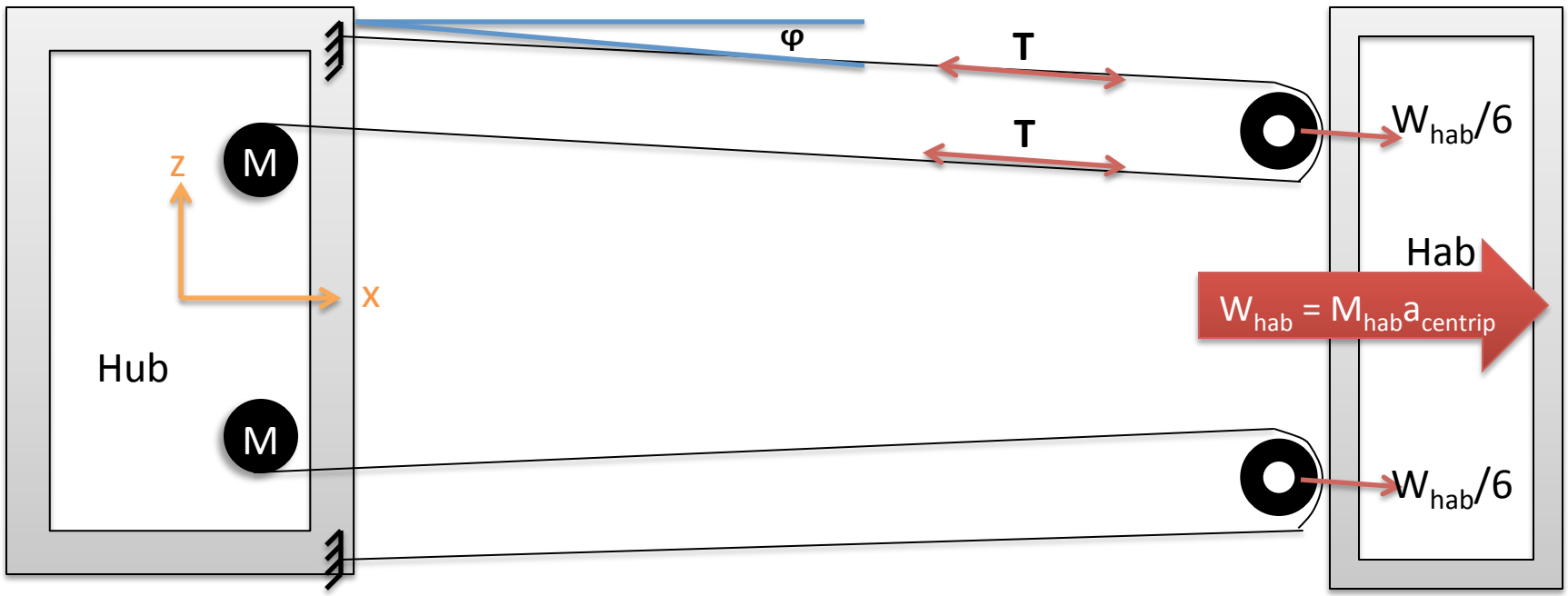


Hole Coordinates:

H1 = (0 , 0 , d_1)
H2 = (0 , $d_1\cos(30^\circ)$, $-d_1\sin(30^\circ)$)
H3 = (0, $-d_1\cos(30^\circ)$, $-d_1\sin(30^\circ)$)

H4 = (L, $d_o\cos(270^\circ-\theta)$, $d_o\sin(270^\circ-\theta)$)
H5 = (L, $d_o\cos(150^\circ-\theta)$, $d_o\sin(150^\circ-\theta)$)
H6 = (L, $d_o\cos(30^\circ-\theta)$, $d_o\sin(30^\circ-\theta)$)

"Stewart" Wire Rope-Truss Configuration



6 sheaves for each of the wire ropes, each sheave mount transmits 1/6th the total weight to a pair of cables:

$$2T\cos(\phi) = W_{hab}/6 \rightarrow \mathbf{T_{Nominal} = W_{hab}/(12\cos(\phi))}$$

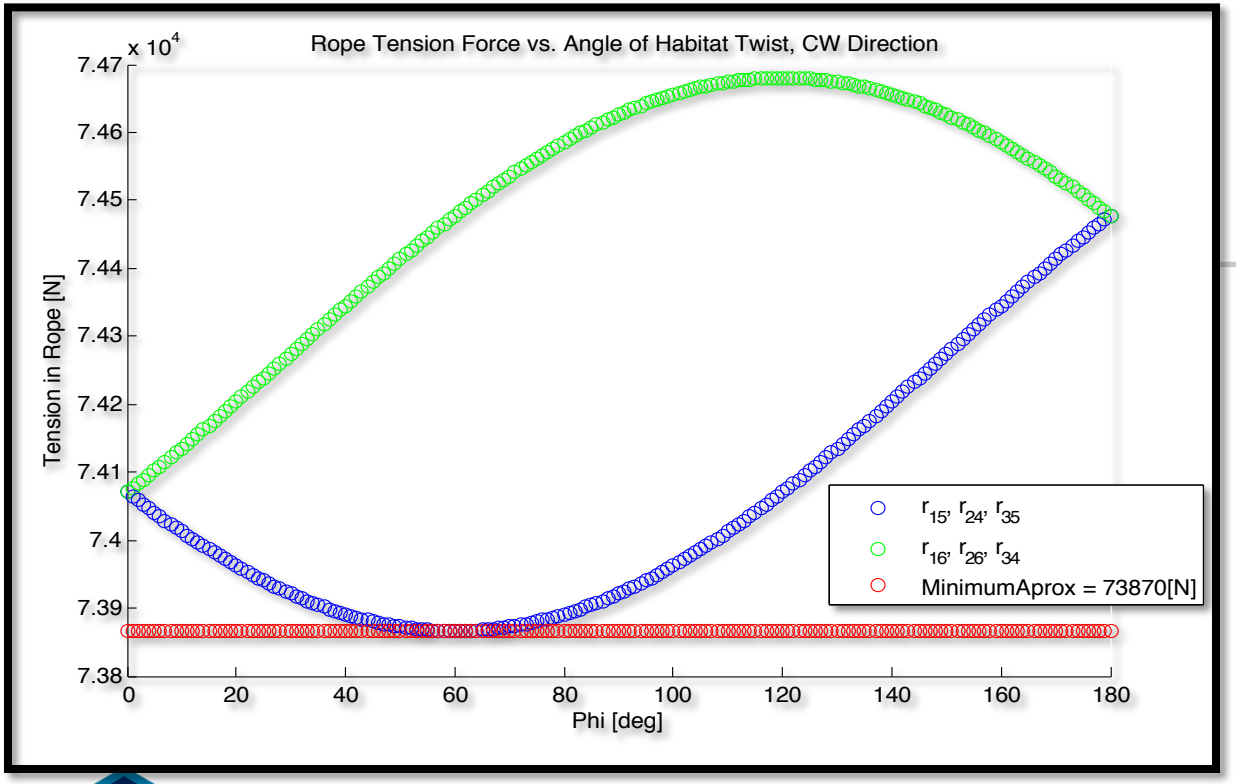
$$\phi = \mathrm{Cos}^{-1}\left[\, \mathrm{dot}(\mathbf{r}_{ij}, \mathbf{W}_{hab}) / (|\mathbf{r}_{ij}| * |\mathbf{W}_{hab}|) \,\right]$$

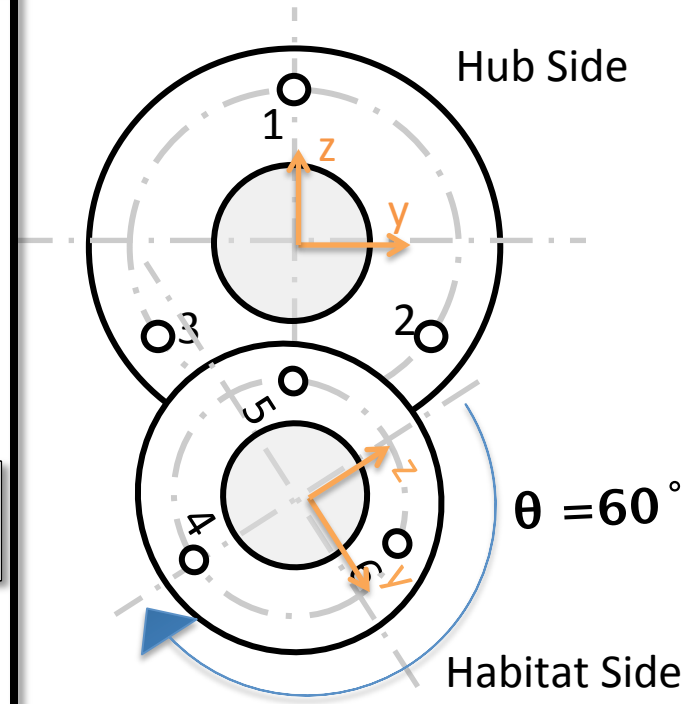
Tension is dependent on the angle, ϕ, between wire rope and force vector;
The angle ϕ changes with angle of rotation, θ, of habitat about the x-axis

“Stewart” Wire Rope-Truss Tension

Tension is a function of the angle, ϕ, between wire rope and force vector. Contributing factors to the angle ϕ are:

- Geometry of the cable holes and sheaves
- The angle of rotation, θ, of the habitat about the x-axis

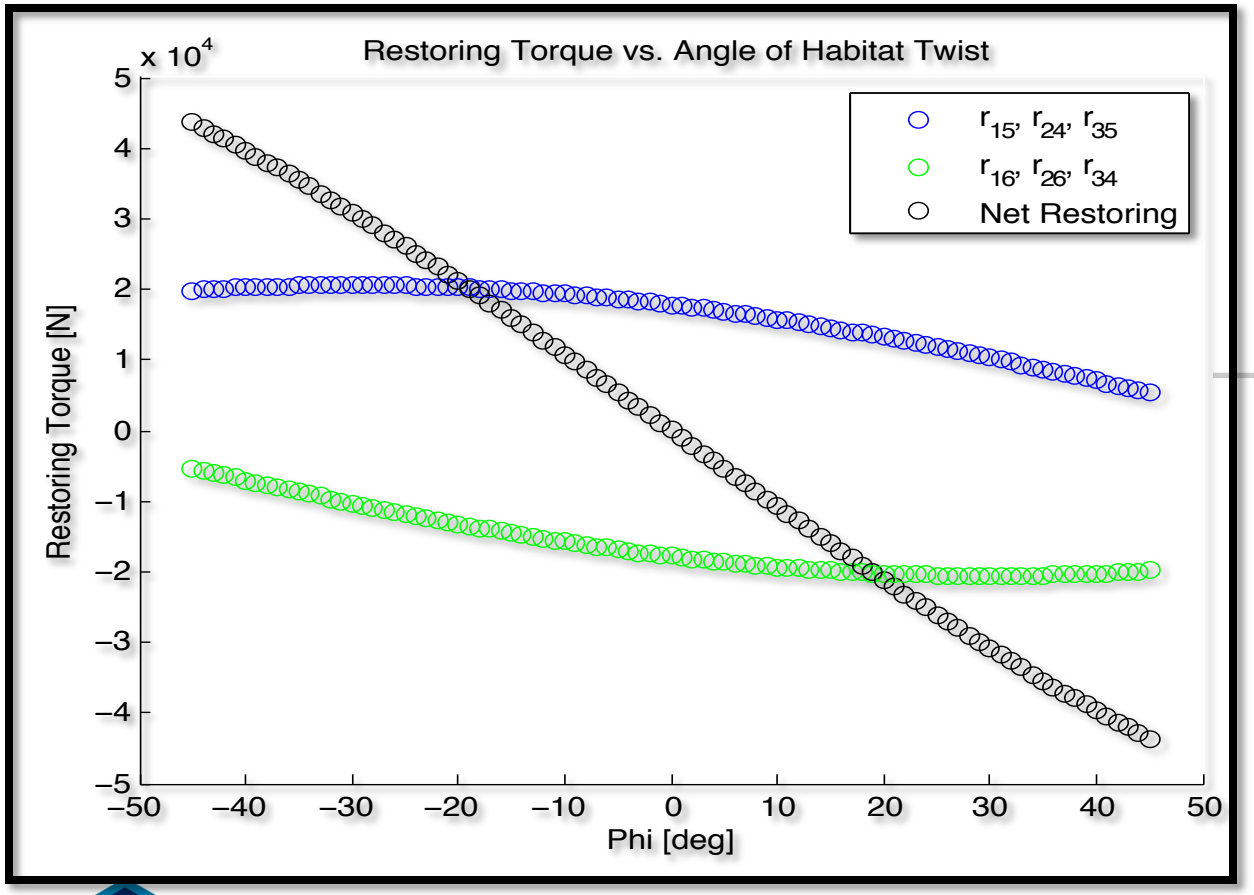


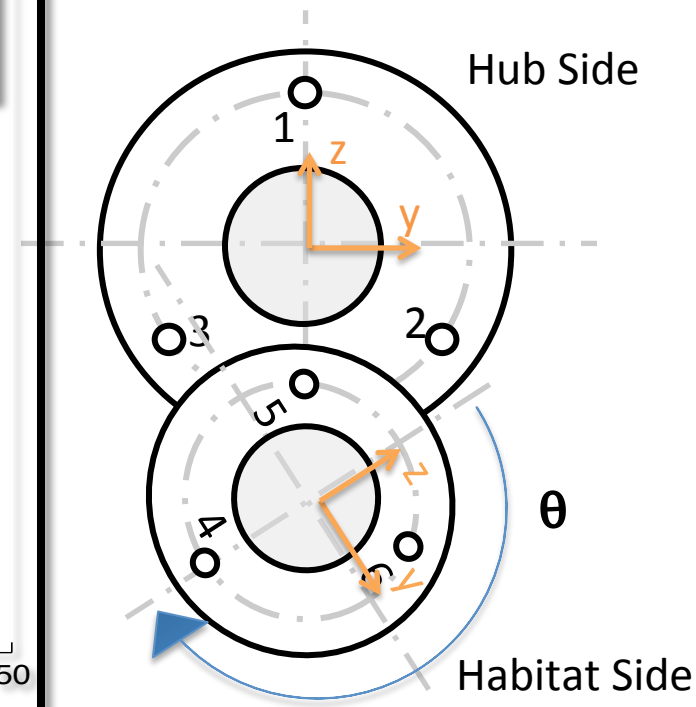


From geometry: $T_{min} = T(60^\circ) = \text{Total Weight}/(12*\cos(5.71^\circ)) = 73.8$ kN

“Stewart” Wire Rope-Truss Restoring Force

By virtue of the angled wire ropes in the Stewart Truss configuration, the system naturally restores itself to θ = 0˚





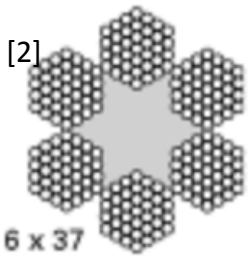
Perturbations from the nominal (θ = 0˚) condition produce a restoring force, tending the system back to θ = 0˚ → Stable Equilibrium

“Stewart” Wire Rope-Truss Analysis

- For large θ, wire ropes of a real system would wrap up or twist together, effectively forming 2 conical trusses connected by a center point
- Analysis neglects habitat migration effect in the x-direction due to the twisting of the cables pulling the habitat towards the Hub with increasing θ
- Analysis neglects the possibility of the habitat cable connection plate becoming non-parallel to the Hub cable plate
- Analysis more accurately depicts reality for small angles twist angles, θ
- Real system cables will be actively controlled by motor and break system keeping all cables loaded

“Stewart” Wire Rope-Truss Stress Analysis

[2]



$$T_{nominal} = W_{hab}/(12\cos(\phi))$$

$$\sigma_{nominal,\ tension} = T_{nominal}/A_{metal}$$

$$\sigma_{sheave\ bending} = E_r * d_w/D$$

$$\sigma_{total} = \sigma_{nominal,\ tension} + \sigma_{sheave\ bending}$$

E_r = Elastic modulus of rope = 75.8 GPa

Strength = 689.5 MPa

$d_{w[1]}$ = Outer wire diameter = d[in]/22 = 21 mm

$D_{[1]}$ = Min. sheave diameter = $18d_w$[in] = 457 mm

$A_{metal\ [2]} = 0.404*(d_w[in])^2$ = 10.3 mm

Safety Factor = 2

$T_{nominal}$ = (90000[kg] * 9.8[m/s^2]) / (12*cos(7.12˚)) = 74071 N

$\sigma_{nominal,\ tension} = T_{nominal}/A_{metal}$ = 74071 N /10.3mm ≈ 284 MPa

$\sigma_{sheave\ bending} = E_r*d_w/D$ = 75.8 GPa* 21 mm/457 mm ≈ 3.49 MPa

$\sigma_{total} = \sigma_{nominal,\ tension} + \sigma_{sheave\ bending}$ = 284 MPa + 3.49 MPa = 287.49 MPa

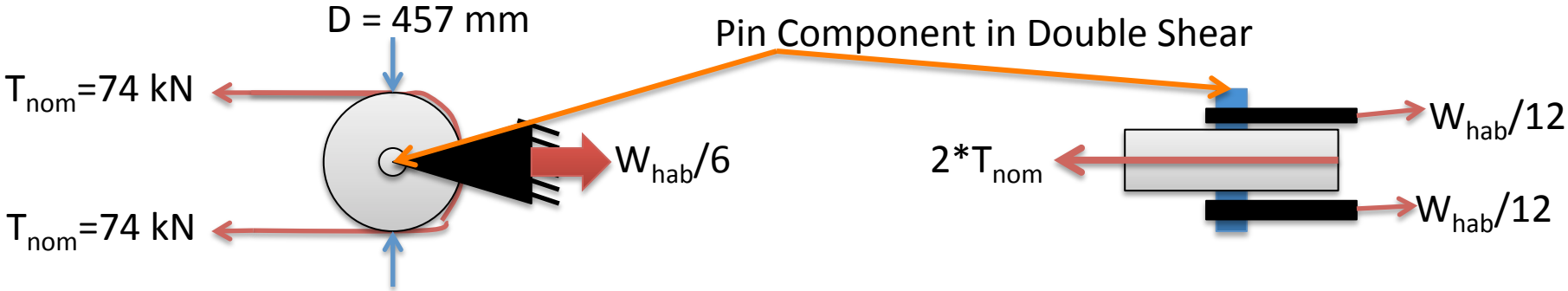
Ultimate Load = Limit Load *SF = 287.49 MPa * 2 = 574.98 MPa

Ultimate Margin of Safety = (689.5 – 574.98)/574.98 = 0.1992

Sheave Design

Outer diameter (D) of the sheave is determined by cable minimum sheave diameter

$D_{[1]} = 18*d = 18*25.4 \text{ mm} = 457 \text{ mm}$



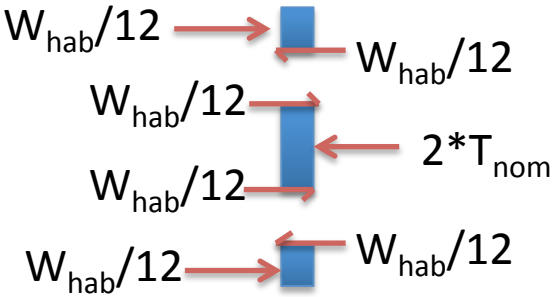
Shear Strength (6061-T6) ≈ 200 MPa = τ_{pin}

$UL = 2*T_{nom}*SF = 148[kN] * 2 = 296[kN]$

$\tau_{pin} = UL/(\pi*d^2_{pin}/4) \rightarrow d_{pin} = (UL/(\tau_{pin}*\pi/4))^{1/2}$

$d_{pin} = (296[kN] / (200[MPa]*\pi/4))^{-1/2} = 43.4 \text{ mm}$

Pin Component in Double Shear



Bearing pressure of the cable in the sheave groove: $\mathbf{p_{[1]} = 2*T/(d*D)}$

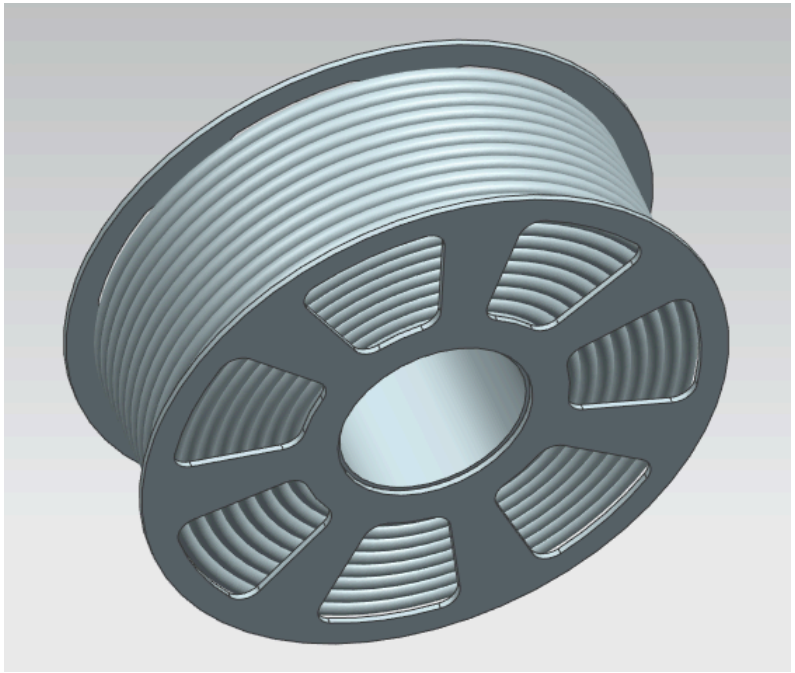
$p = 2*74071 [N] / (25.4 [mm] * 457 [mm]) = 12.8 \text{ MPa}$

$\sigma_{b\_sheave} = 2*T_{nom}/(W_{sheave}*d_{pin})$ $\sigma_{b\_holder} = P/(W_{sheave}*d_{pin})$

Wire Rope Spool Dimensions

For each 100 [m] Rope spool (+10 safety wraps):

- Inner spool wrap diameter: 0.31 [m]
- Overall diameter: 0.76 [m]
- Width of spool: 0.30 [m]
- Mass of wire rope: 231 [kg]



- 6 Spools per side, 2 sides → 12 wire spools
  - Total mass of cables: 2772 [kg]

Station Retraction Mechanism Requirements

- Up to 10kW draw during normal operation, 20kW available for contingencies
- Retractable in 1 hour for emergencies
- Can support habitat and Mars SIM or counterweight
- Less than 12 metric tons total system mass
- Reasonably failure tolerant

Other constraints:

- Minimum bend diameter, 1 in wire rope: 0.46m
- Diameter of full wire wrap: 0.71m
- Length to retract: 50m

Retractor Design Scenarios

- The "full spin" scenario:
  - Station does not spin down, but retracts
  - Retractors support full weight of 1g habitat/~2g counterweight for entire reel-in
- Wire failures
  - A Stewart truss wire rope snaps or otherwise fails
  - Remain capable of reel-in with 2 failed wire ropes
- Absolute worst case:
  - Fully loaded habitat, ~90 metric tons, on 4 cables and under 1g for entire duration

Retractor Motor Power Selection

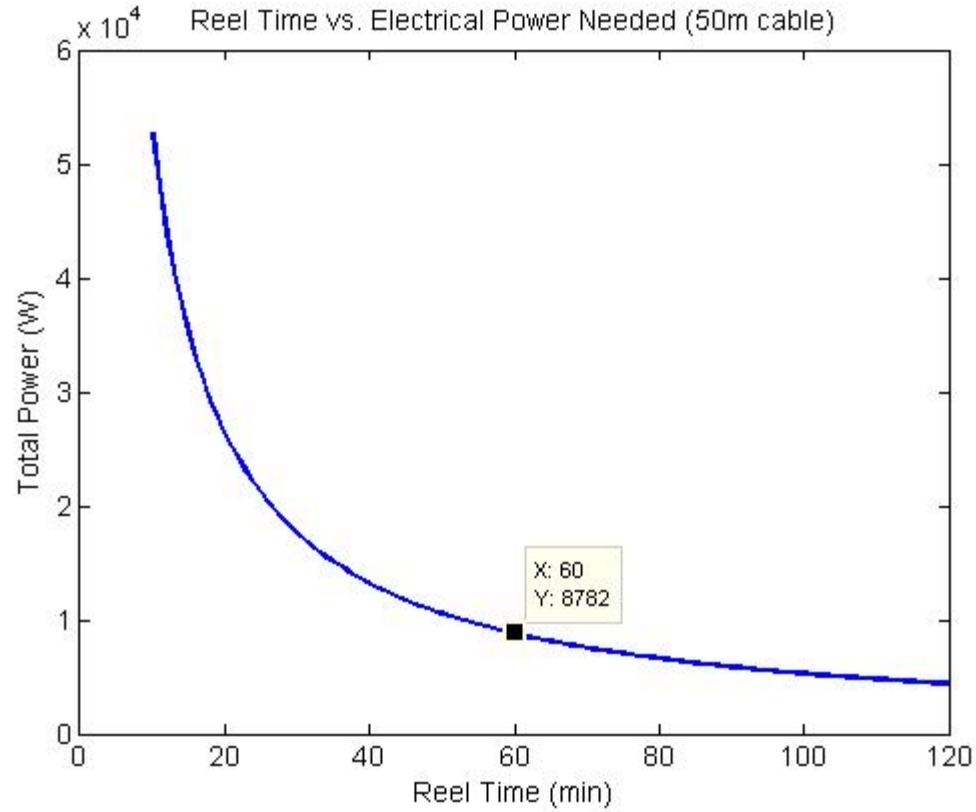
For a given retraction speed, required input power is constant:

gear ratio=required torque / motor torque

rpm=power×60×efficiency/ motor torque

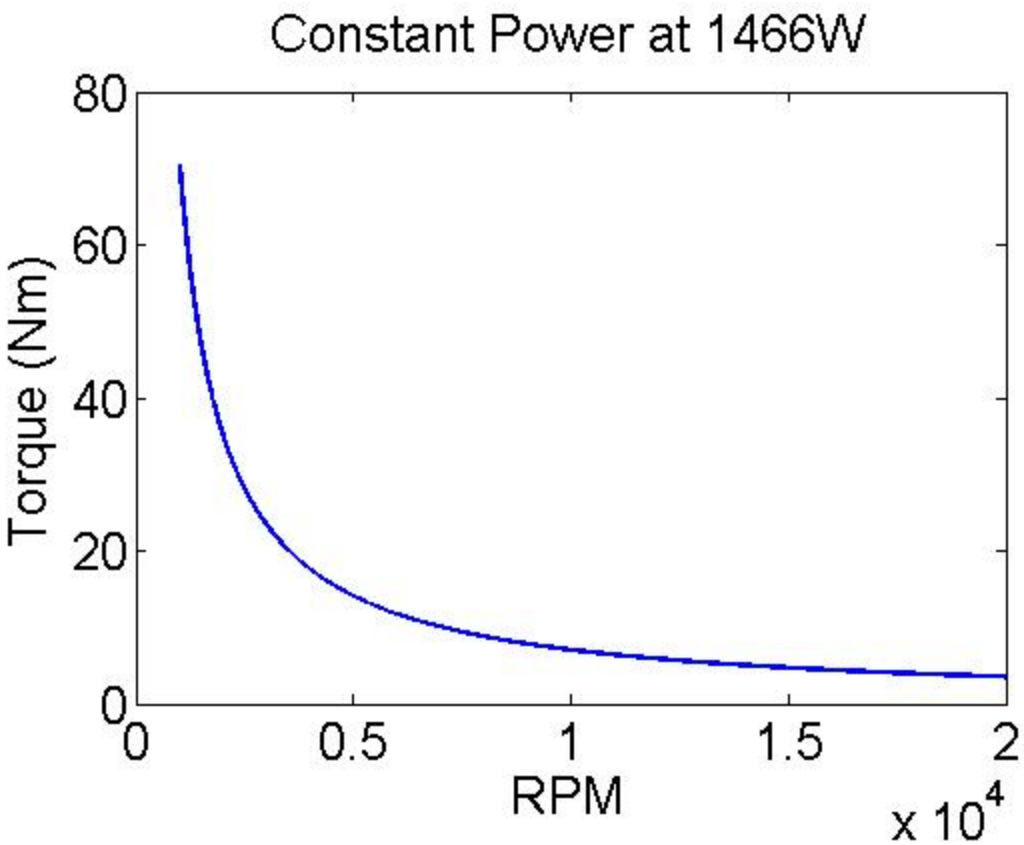
retract speed=π×bend diameter×rpm/60×gear ratio

time=length/retract speed



Power: 8800W per side of 6
1466W per motor
17600W Total

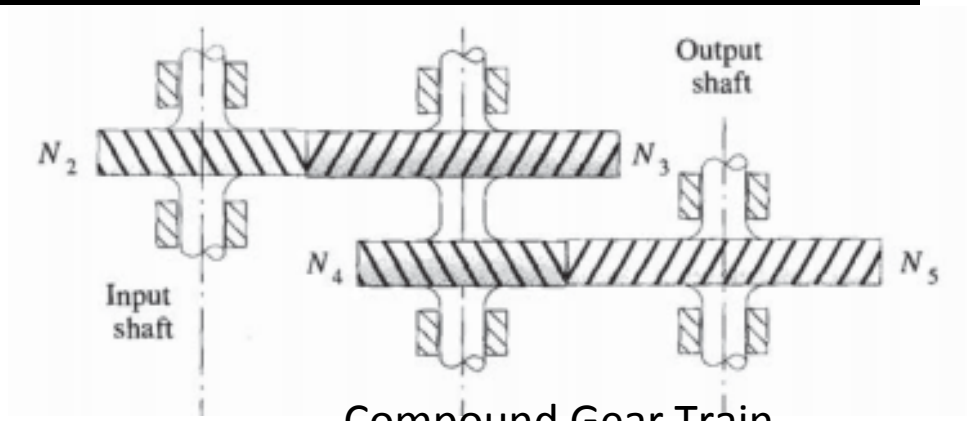
Retractor Motor Torque and Speed



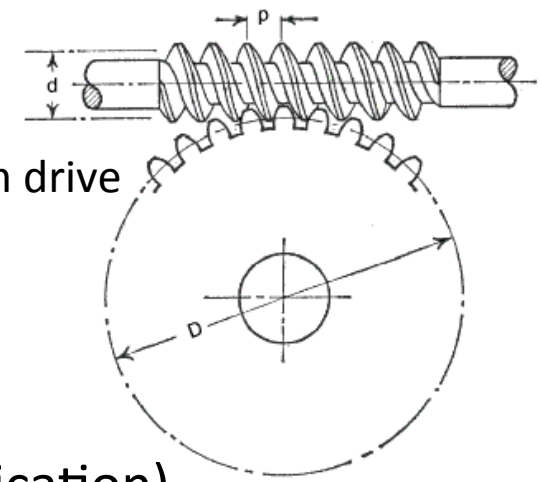
- Theoretical relation between RPM and torque
- Assumed 80% efficient
- Brushless DC motors

Retractor Gearbox Options

- Compound gear train
  - Simple
  - Flexible
- Worm drive
  - High gear ratios
  - Heavy
  - Efficiencies of large trains suffer
- Planetary (epicyclic) drives
  - Compact for their gear ratios
  - Possible high efficiency
  - High ratio drives cannot handle high torques
- Strain wave gearing ("Harmonic Drive")
  - High ratios for their size and weight
  - Low backlash (not very important for this application)
  - Low efficiency (~%70)



Compound Gear Train



Worm drive

Reference Gearbox – Compound Train

Variable	Calculation	Value
Motor Torque		21 Nm
Motor RPM		3300 rpm
Required Torque		78000 Nm
Torque Ratio	Required Torque/Motor Torque	3714:1
Stages		5
Gearset Ratio	$(\text{Torque Ratio})^{\text{Stages}}$	5.2
Pinion Teeth		17
Gear Teeth	Pinion Teeth(Gearset Ratio) (approximate)	88
Train Ratio	$(\text{Gear Teeth/Pinion Teeth})^{\text{Stages}}$	3717:1
Base Efficiency		98%
Train Efficiency	$(\text{Base Efficiency})^{\text{Stages}}$	90.4%
Power Input	Total Power/Train Efficiency	19500W

Reference Gearbox – Mass Estimation

- Gear volume fill factor – relates enveloped volume of gears to actual machined volume

$$\psi = 1 - V_{machined} / V_{solid}$$

Variable	Value
Gear Thickness	40 mm
Driven gear diameter	700 mm
Pinion gear diameter	135 mm
Total gearbox gear volume	79,800,000 mm^3
Fill factor	0.5
Volume after fill factor applied	39,900,000 mm^3
Estimated mass (steel gears) + 50% for support structures	210 kg

Prior to EVA Procedure

- Station will spin down to 0g
- Astronaut will put on space suit and attach necessary EVA tools and materials in the habitat
- Commence suit denitrogenation inside the habitat
- Enter the airlock by floating up in 0g and depressurize for EVA

Docking

- The DragonRider will use DragonEye for proximity operations with the habitat in Phase I and the Hub in Phase II & III
- It will utilize Light Detection and Ranging (LIDAR) and thermal imaging to accurately and automatically connect the crew vehicle
- Both docking ports will comply with the IDSS standards

Hardware Testing

- 1g testing
  - Make necessary renovations to HAVEN habitat
  - Test subjects will perform a typical activity that would reflect life in a space habitat
- Variable gravity testing
  - Ladder Spacing
  - Neutral Body Posture

1g Testing: HAVEN Renovations

- HAVEN habitat was prepared in order to conduct tests to determine acceptable ranges for crew volume dimensions
- Renovations include:
  - Full exterior painting
  - Weatherproofing
  - Attaching hatches
  - Installing electronics

HAVEN's Initial State

During Renovations

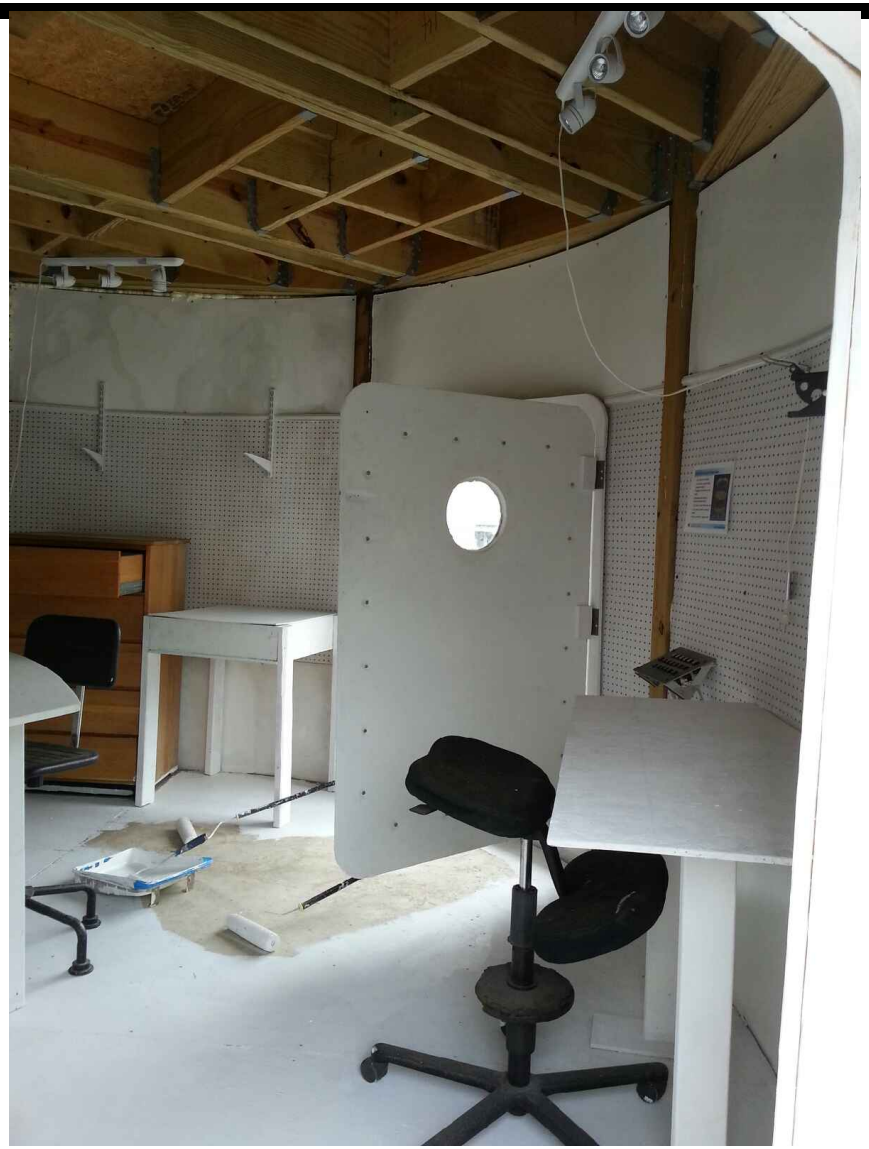
During Renovations

During Renovations

Current State

Current State

Current State



Current State

1g Testing

- Purpose: To determine acceptable ranges for crew volume dimensions
- Test Protocol
  - Sampling size: 6 test subjects
  - Volume Test: The test will begin with one subject performing a designated task. Subsequent tests will be performed with a gradually increasing number of subjects.
  - Data Collection: Subjects will complete surveys to gauge their ability to perform tasks. The results from these surveys and the time to perform tasks will be compared to the number of test subjects

Variable Gravity Testing: Ladder Rung Spacing

- Purpose: To determine whether ladder rungs should be spaced differently in various gravity environments
- Test Protocol
  - Sampling size: 4 test subjects
  - Control Test: Subjects will use the NBRF ladder in a 1g environment
  - Underwater Ladder Test: Subjects will use the same ladder in Mars gravity, Moon gravity and microgravity. Subjects will climb up and down the ladder four times per test.
  - Data Collection: Subjects will complete surveys to gauge their ability to climb the ladder. The tests will be recorded using a video camera.

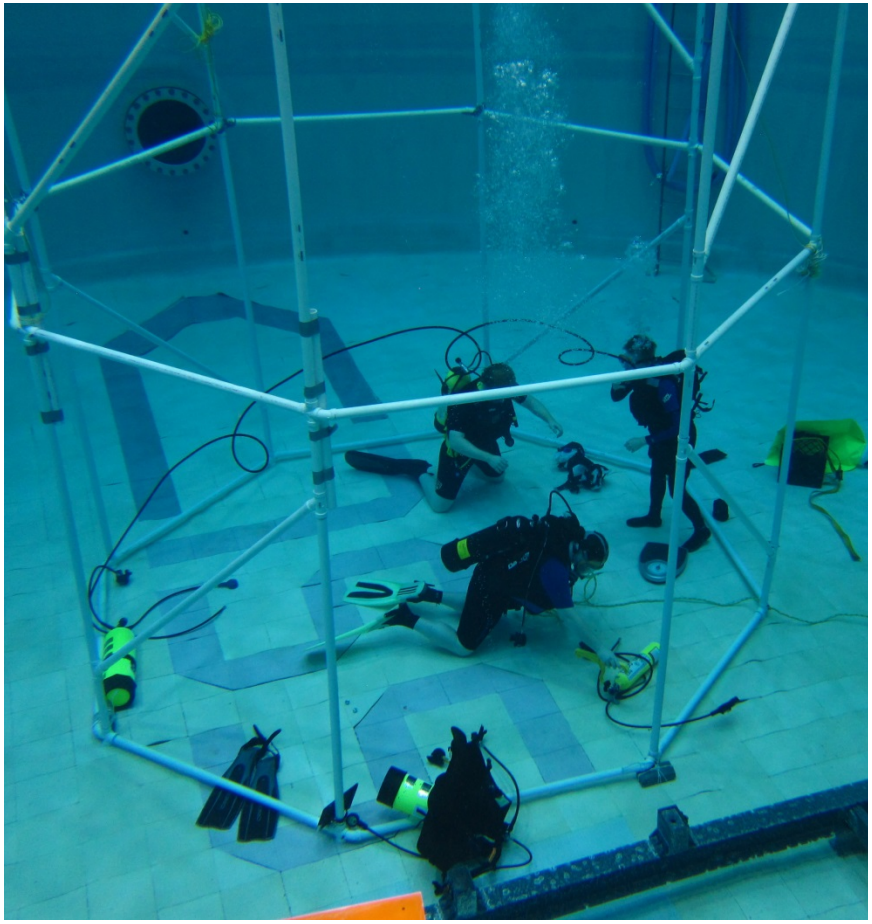
Variable Gravity Testing: Ladder Rung Spacing

Variable Gravity Testing: Neutral Body Posture

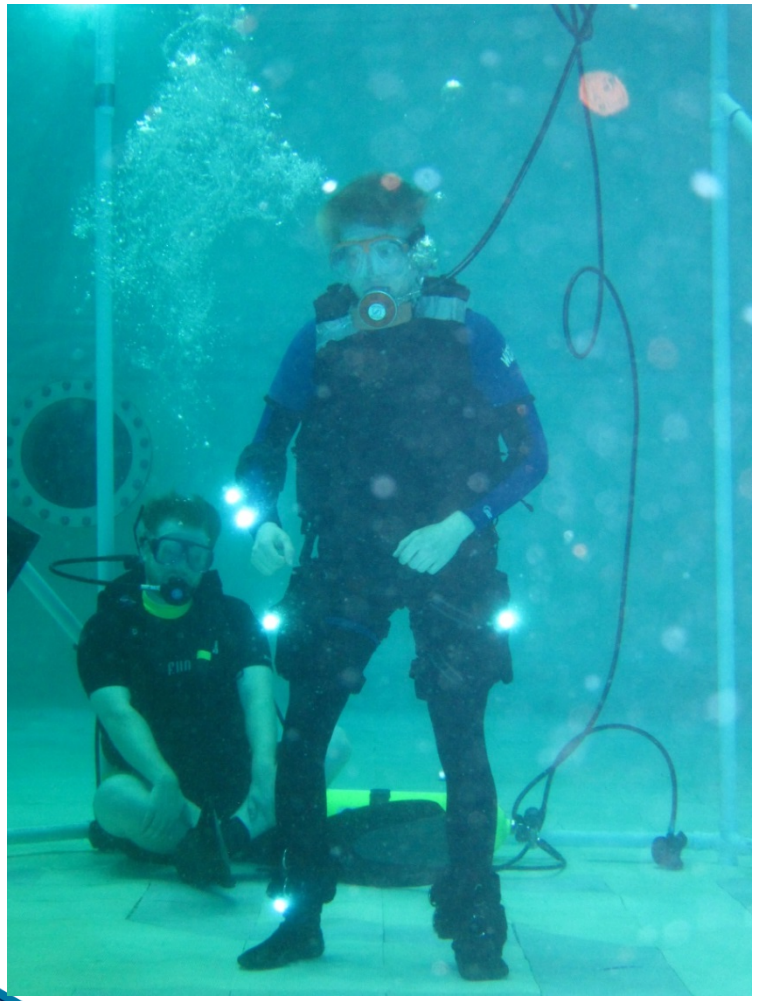
- Purpose: To determine the neutral body posture of the human body in various gravity environments. The results will be used to design a seating mechanism that satisfies different gravity fields.
- Test Protocol
  - Sampling size: 4 test subjects
  - Control Test: Subjects will perform a simple activity inside the NBRF in a 1g environment
  - Neutral Body Posture Test: Subjects will perform the same activity in Mars gravity, Moon gravity and microgravity.
  - Data Collection: The tests will be recorded using a video recorder.

Variable Gravity Test Procedures Checkout

- One subject was put through tests informally, weighted to simulate microgravity, Moon and Mars gravity
- Neutral body posture recorded with cameras and Qualsys motion tracker
- Ladder climb with recordings and qualitative findings from test subject



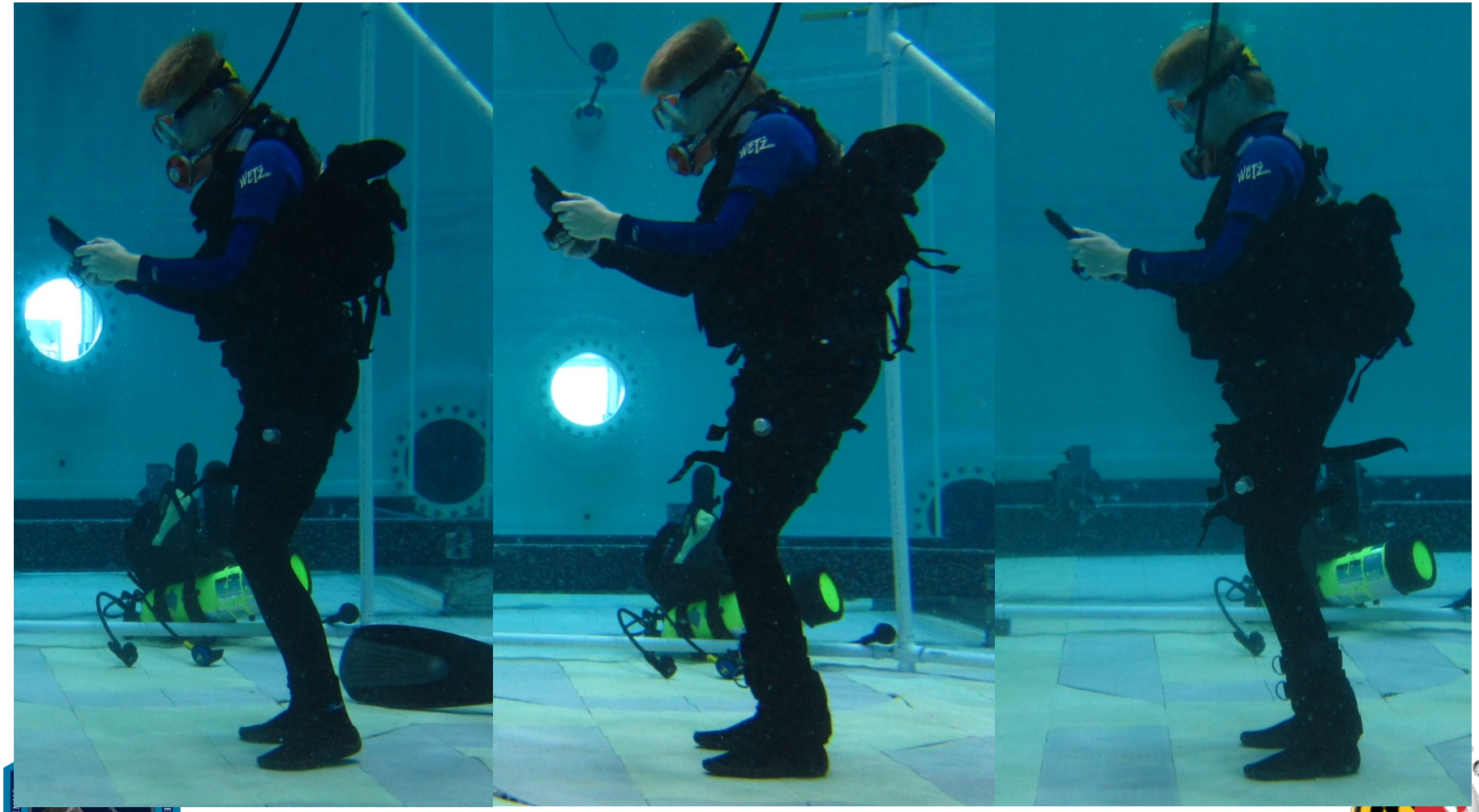
Neutral Body Posture



- Subject stood in neutral pose
- Data collected for weighting simulating microgravity, Moon and Mars gravity
- Tracked position with Qualysis system
- Identified issues with markers and weighting
  - Marker slip
  - Fatigue from weight vest

Neutral Posture Comparison

Microgravity | Lunar Gravity | Mars Gravity



Ladder Climb - Microgravity

- Subject mostly used their arms to pull themselves
- More like “gliding” than climbing
- Very little effort

Ladder Climb – Lunar Gravity

- Subject easily adapted their "climbing force" to the lower gravity so they did not overshoot rungs
- "My favorite method of traversal was climbing normally, just faster and with less effort. I could skip rungs if I wanted to, but not skipping was easier and more stable."

Ladder Climb – Mars Gravity

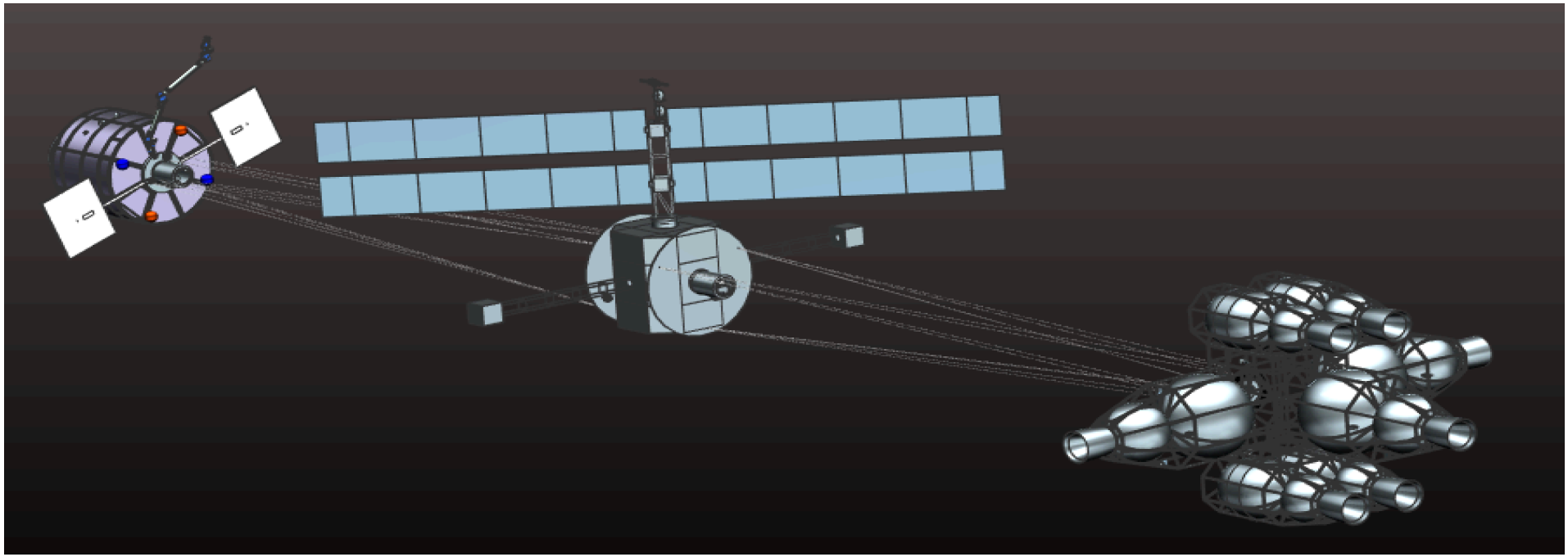
- Similar to climbing in 1g

Future Testing

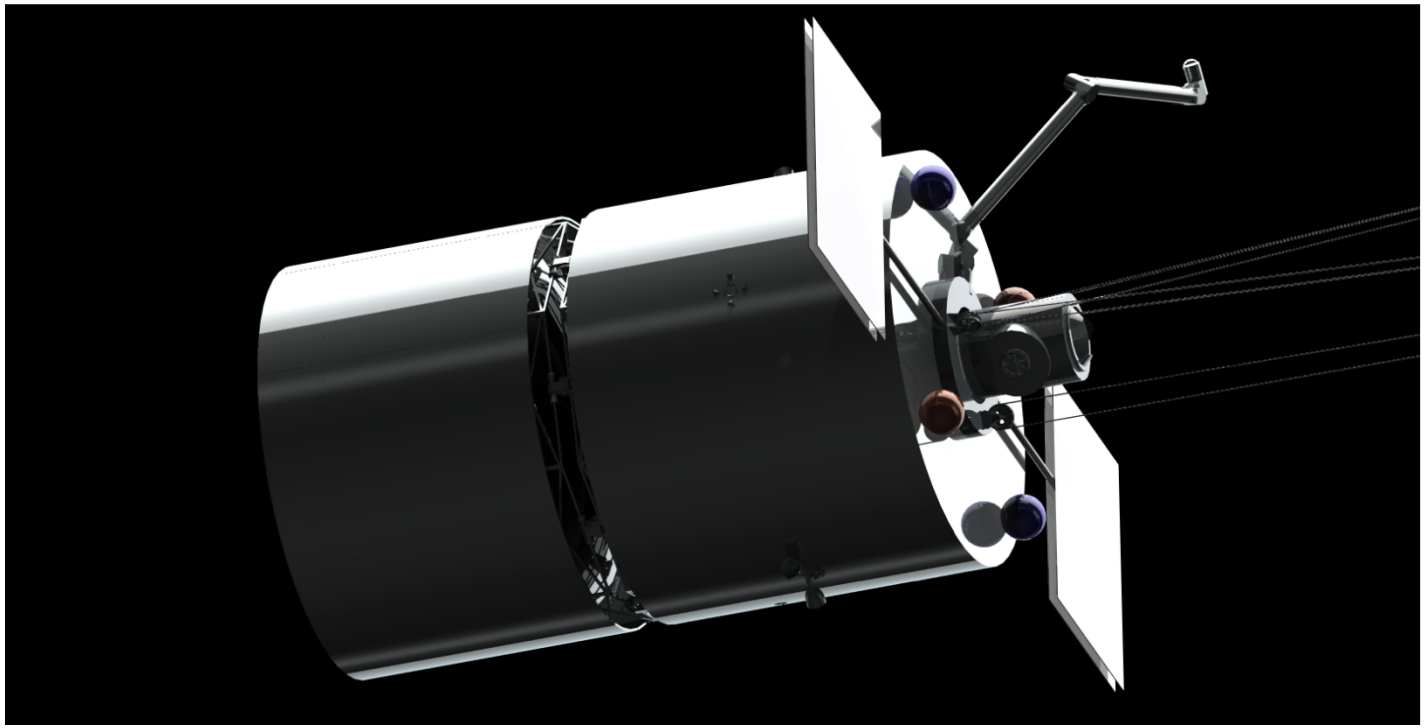
- Hypothesis: standard 1ft ladder rung spacing is based on human body geometry more than human strength and weight
- If true, scaling rung spacing with gravity level might be detrimental to ease of traversal
- Requirements for traversing with cargo must also be investigated

INTERMISSION

Phase III



Phase III: Addition of Mars SIM to Habitat



Mars Surface Imitation Module (SIM)

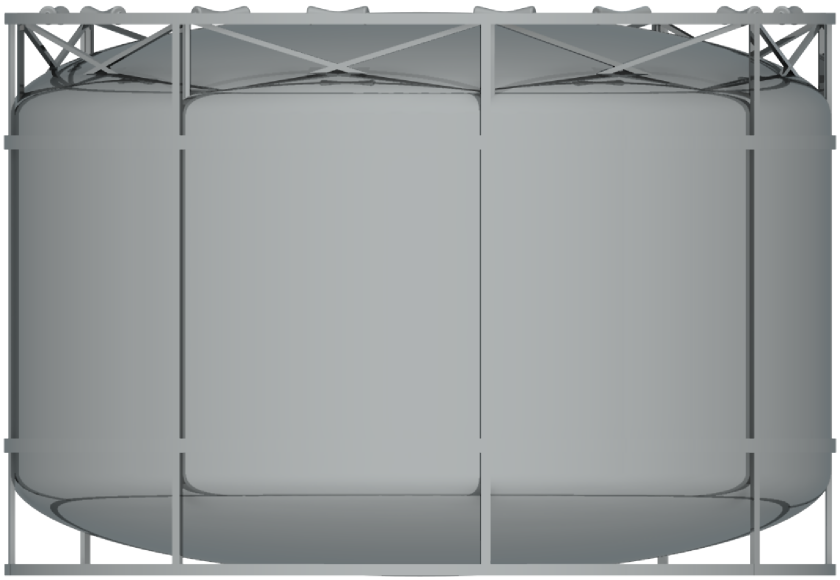
- Additional structure launched and attached to complete Phase III requirements
- Share life support, thermal, and power systems with habitat
- Independent reaction control system and propulsion tanks
- Capable for shirt-sleeved transfer between habitat and staging area

Mars SIM Usage

- Full EVA simulation for two astronauts
- Mars SIM will be pressurized to Mars pressure
  - Mars pressure: 600 Pa
- Mars SIM gravity: 4.06 $m/s2$
  - Mars gravity: 3.71 $m/s2$
- Airlock and ready room area provides additional storage for consumables
- Specifications:
  - Dimensions: ø=8 m, h=3.5 m, 4:1 ellipsoidal end caps
  - Total mass: 13,100 kg
  - Total habitable volume: 176 m^3

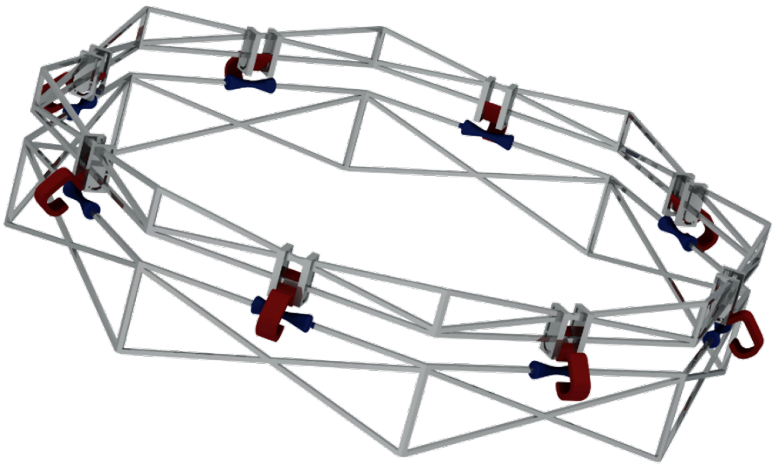
Structural Layout

- Main structure will be the same specifications as the habitat, but with a single floor, 3.5 m in height
- Truss at top with attachment mechanism to interface with habitat
- Total structure mass: 12,080 kg



Attachment Mechanism

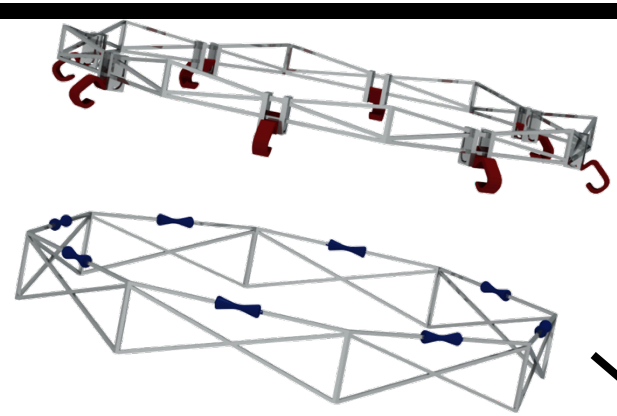
- IDSS is not robust enough to be sole point of contact
- 8 additional mechanical attachments engage after IDSS soft/hard captures



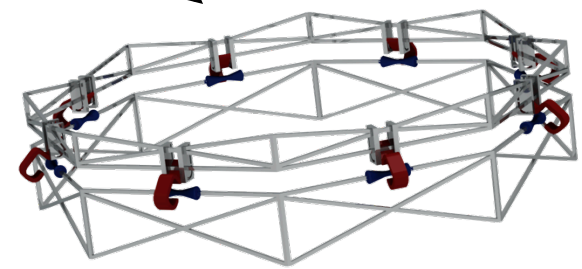
Axial	200 [kN]
Torsion	400 [Nm]

Attachment Process

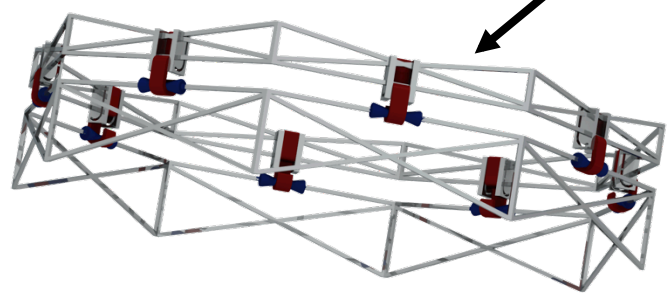
On approach, active side deploys



IDSS soft capture/hard capture systems engage



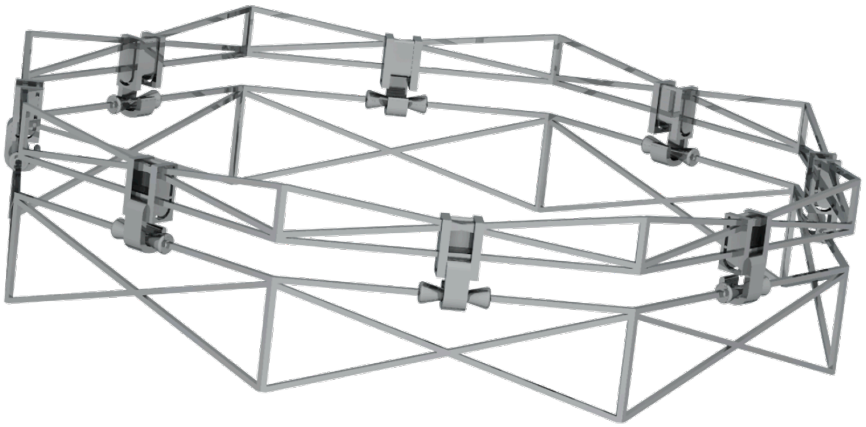
Active side retracts, completing structural connection



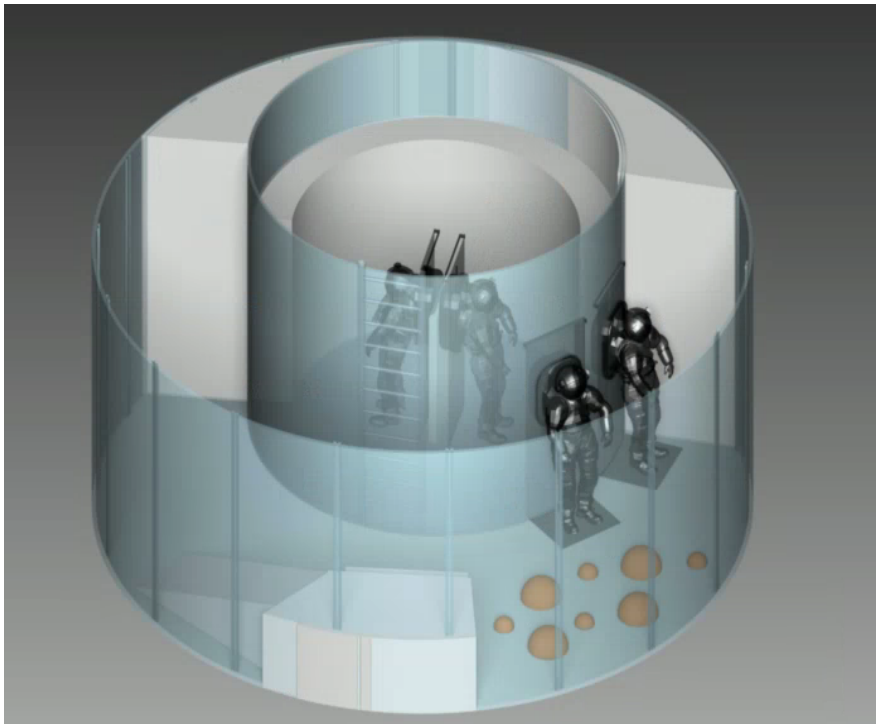
Attachment Inter-webbing

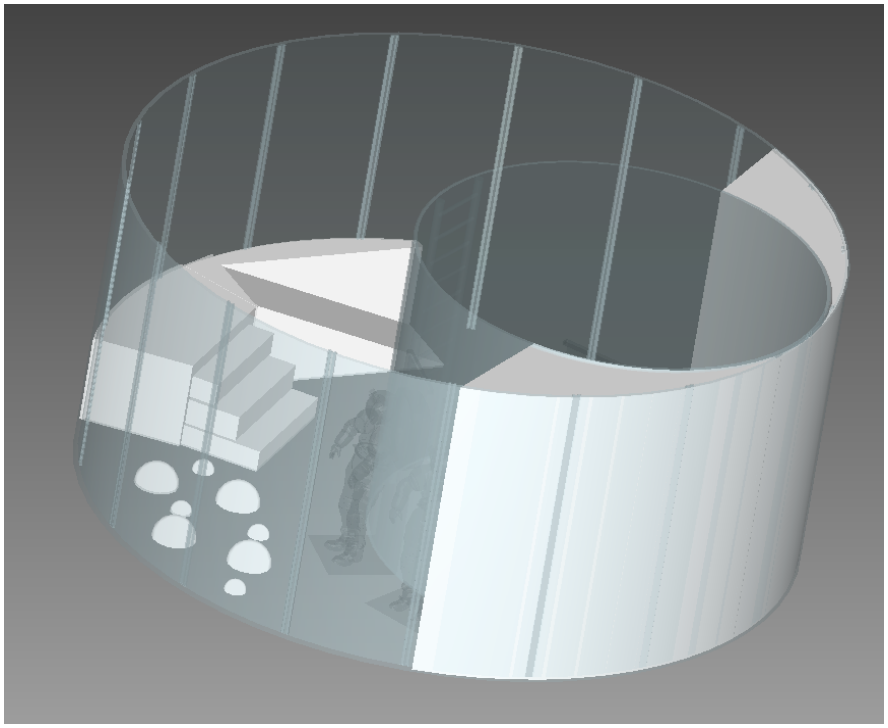
- Transmits loads from SIM to attachment system
- Safety factor = 2

Component	Combined Mass [kg]	Margin of Safety
Axial	81	0.725
Horizontal	1719	0.015
Cross member	237	1.08



Mars SIM Internal Layout





Activity Simulations (i)

- General mobility tests such as walking and jumping
- Interactions with ladders, stairs, ramps and other potential lander ingress/egress configurations

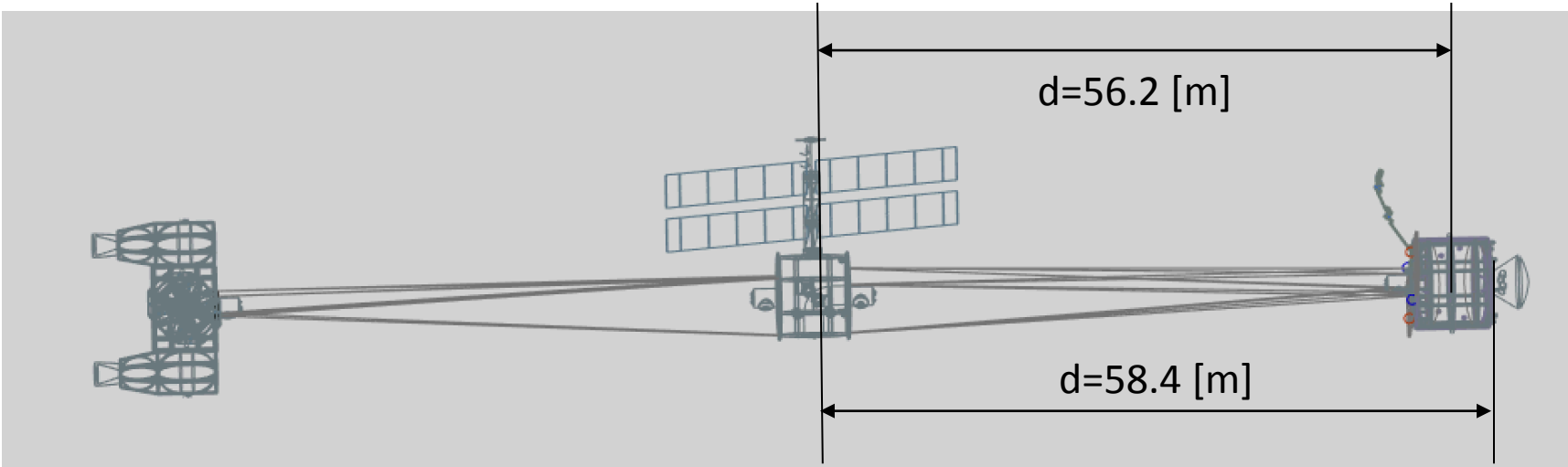
Activity Simulations (ii)

- Rock yard
  - Recycled rubber rocks
    - 4 boulders (158 kg)
    - 100 small rock of varying size (32 kg)
- Sample collection
  - Used rakes, tongs, and scoops on the Moon
  - Gnomon
    - Gimbaled stadia rod mounted on a tripod
    - Shows reflectivity, sun angle, colors, and estimates object sizes
  - Optimize for use on Mars
- Transport and handling of materials
  - Sample bags and storage boxes
    - Optimize for use on Mars

Additional Experiments

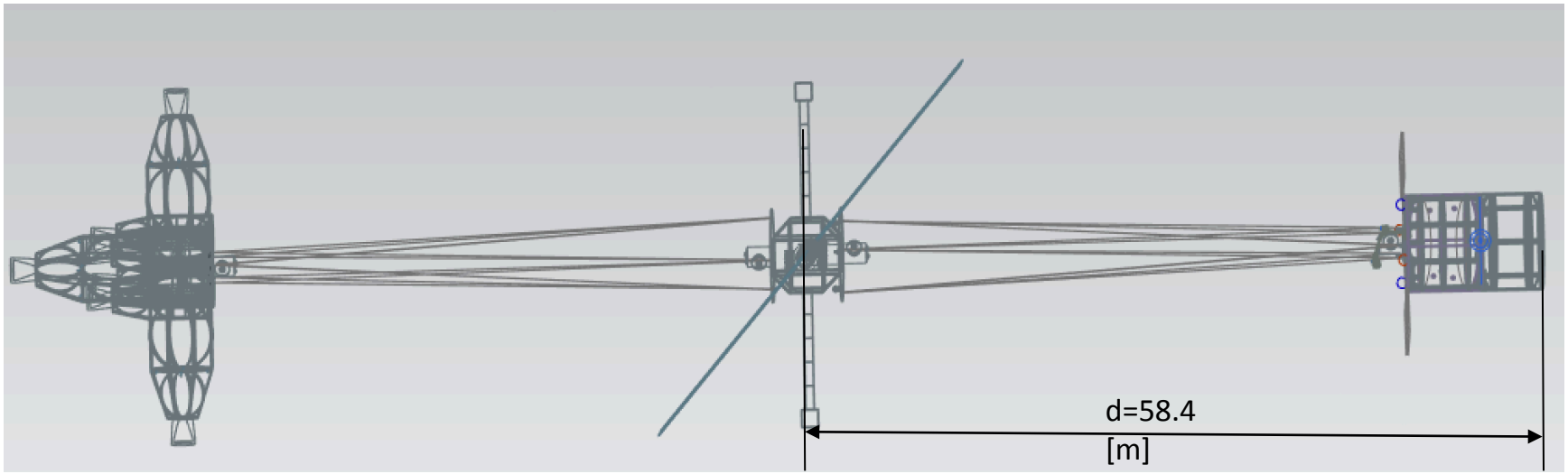
- Simple construction tasks
  - Modular design
  - Reconfigure structure to have different experiments
  - Emergency portable EVA shelters
- Suit ports
- Operations in varying wind speeds
- Operations in varying levels of lighting

Phase II Gravity Gradients



Gravity	Rotation Rate [RPM]	1st Floor [g]	1st Floor Edge [g]	2nd Floor [g]	2nd Floor Edge [g]	% Change
Lunar	1.59	0.16	0.16	0.17	0.17	3.77
Mars	2.41	0.36	0.37	0.38	0.38	3.77
Earth	3.91	0.96	0.96	1.00	1.00	3.77

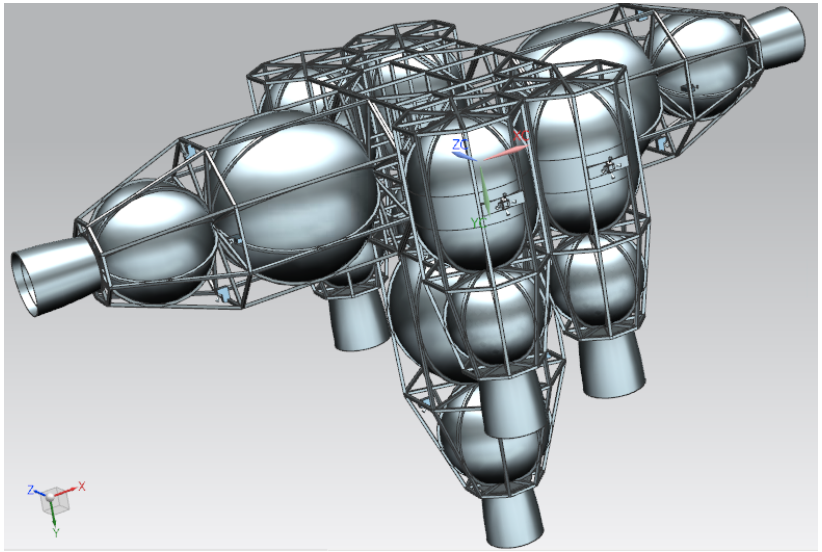
Phase III Gravity Gradients

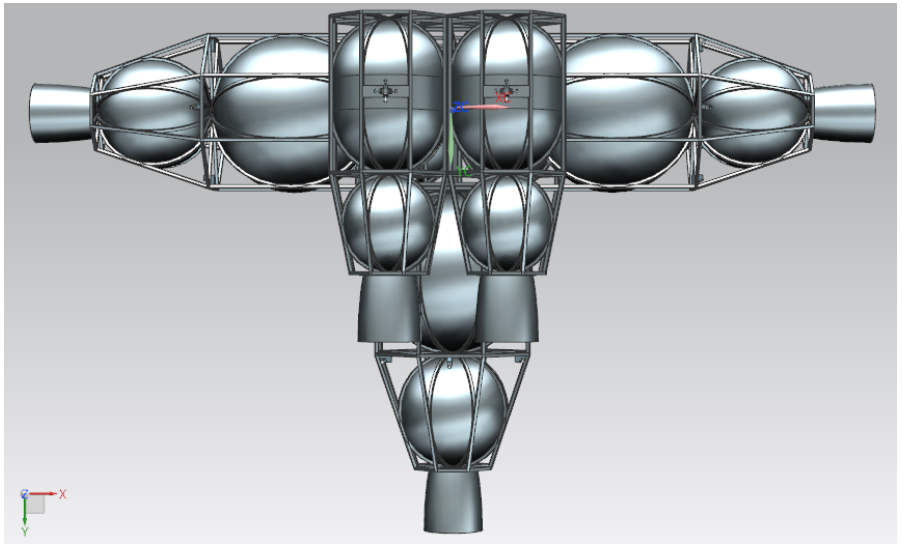


Gravity	Rotation Rate [RPM]	1st Floor [g]	1st Floor Edge [g]	2nd Floor [g]	2nd Floor Edge [g]	% Change
Mars	2.41	0.36	0.37	0.38	0.38	3.77

SIM [g]	SIM Edge [g]	% Change
0.41	0.41	9.42

Phase III Ballast Configuration





- 3 Heavy Lift Upper Stages
- 4 Crew Launch Upper Stages
- Mass: 70,300 kg

Margin of Safety (i)

Section	Part	Failure Type	SF	MoS
Central Hub	Primary Members	Cyclic Loading Fatigue 1	2	0.1188
		Cyclic Loading Fatigue 2	2	49.34
	Secondary Members	Cyclic Loading Fatigue 1	2	0.0548
		Cyclic Loading Fatigue 2	2	175.9
	Vertical Support	Euler Buckling on Launch	2	0.0281
	Stability Support	Euler Buckling on Launch	2	0.2719
Mars SIM	Floor Supports	Bending Yield on Launch	2	0.7867
	Pressure Vessel	Pressurization Yield	2	4.404
	Structure	Euler Buckling on Launch	2	1.040
Inter-webbing	Axial Member	Bending Yield	2	0.7250
	Horizontal Member	Axial Yield	2	0.0150
	Cross Member	Torsion Yield	2	1.080
Comm Tower	Axial Member	Axial Yield	2	91
	Axial Member	Euler Buckling on Launch	1.5	1.32

Margin of Safety (ii)

Section	Part	Failure Type	SF	MoS
Habitat	Structure	Euler Buckling on Launch	2	1.04
	Cable Attachment	Bending Yield on Spinning	2	0.7778
	Floor Supports	Bending Yield on Launch	2	0.7867
	Mars SIM Attachment	Bending Yield on Spinning	2	2.370
	Pressure Vessel	Pressurization Yield	2	4.405
	Floor 1	Bending Yield	1.5	13.29
	Floor 2	Bending Yield	1.5	9.945
Ballast	Upper Stage	Bending Yield on Spinning	1.5	0.3100
Stewart System	Wire Rope	Ultimate Tension	2	0.1992
Periphery	Airlock	Launch Loads	2	409
		Euler Buckling	1.5	0.2042
		Pressurization Yield	2	21.64

Main Propulsion System

Requirements:

- Phase I
  - Propulsion system shall be capable of a ΔV = 75 m/s with a precision of 5 m/s
- Phase II/III
  - Propulsion system shall be capable of spinning the habitat up to or down from Earth gravity in less than 1 hour
  - Propulsion system shall be able to adjust rotation rate at least 10 times per day (16,000 total) by pulsing or throttling

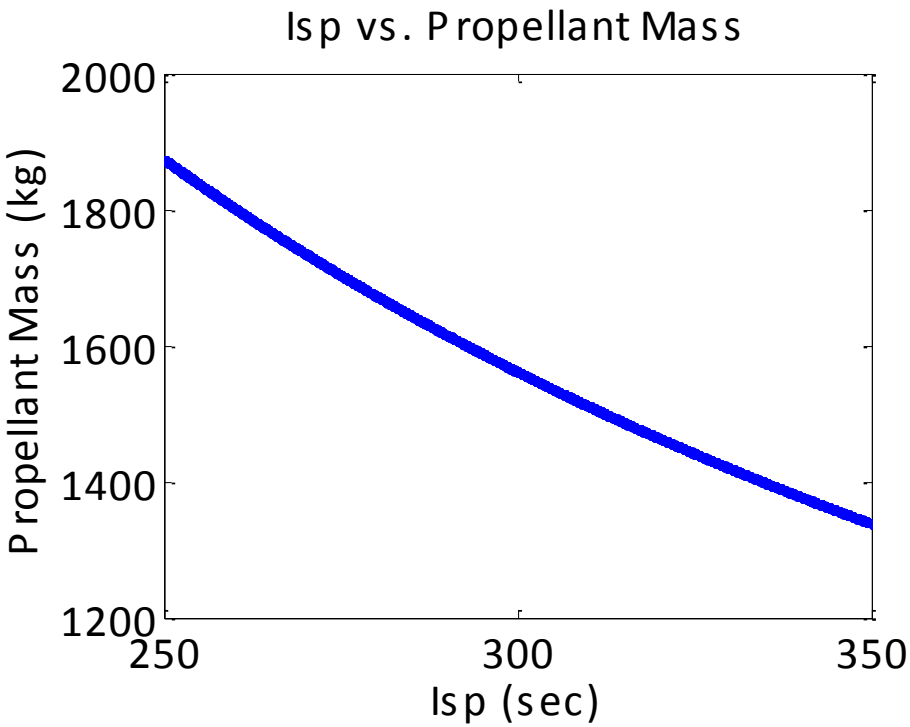
Propellant Options

Propellant	I_{sp} range [s]	Thrust Range [N]
Cold Gas	50 – 179	0.05 – 5
Monopropellant	220 – 260	0.19 – 3000
Bipropellant	280 – 350	10 – 110,000
Electric	300 – 4000	0.01 – 2
Solid	280-305	30,000 – 81,000

- Solid propellant is unfeasible due to throttling requirement
- Electric propulsion would take 5 days to spin up/down
- Cold gas would require 2900 kg of propellant and 2.5 days for spin up/down
- Monopropellant would require 2000 kg of propellant for spin up/down

Bipropellant Thrusters

Engine	Propellants	Thrust [N]	I_{sp} [s]
Airbus 200 N Thruster	NTO and MMH	200	270
R-40B	NTO and MMH	4000	293
R-4D	**NTO and MMH**	**490**	**315.5**



- Apogee style bipropellant engines were not considered due to their limited lifetime

Aerojet R-4D Thruster

Specifications:

- Mass: 4.31 kg
- Nominal mixture ratio: 1.65
- Thrust: 490 N
- I_{sp}: 315.5 s
- Max power: 46 W
- Flow rate: 158 gm/s
- Minimum impulse bit: 15.6 N-s
  - Minimum ΔV= 0.0015 m/s
- Total Pulses: 20,781
- TRL Level-9

Digital image. Aerojet Rocketdyne. Web. 27 Apr. 2014. <https://www.rocket.com/propulsion-systems/bipropellant-rockets>.

Secondary Propulsion System

Requirements:

- Phase I
  - Propulsion system shall be capable of acting as RCS for Hab
- Phase II/III
  - Propulsion system shall serve as back-up system for spin up/down as well as attitude control
    - Shall be capable of providing a slew rate of 0.2˚ per hour
    - Shall be capable of use 100 time a day (160,000 total)

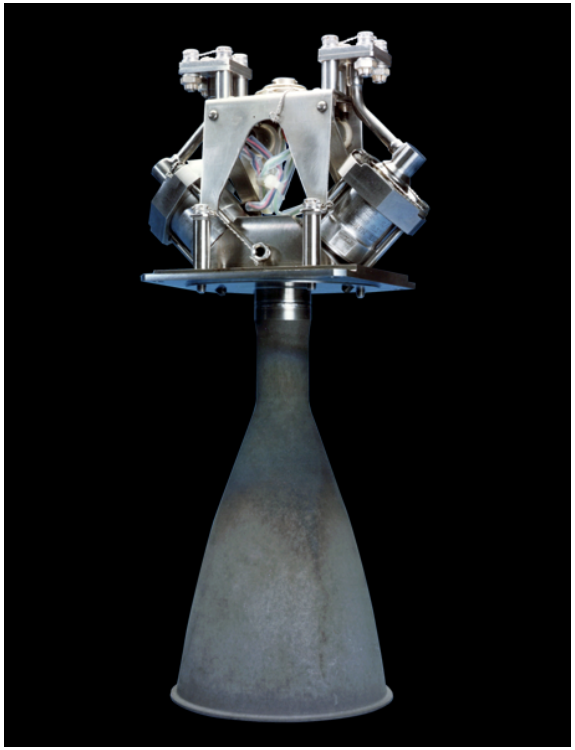
Secondary Thrusters

Engine	Propellant(s)	Thrust [N]	I_{sp} [s]
Airbus 200 N Thruster	NTO and MMH	200	270
R-1E	**NTO and MMH**	**111**	**280**
MRE-1.5	Hydrazine	86	228
Mr-107V	Hydrazine	220	229

Aerojet R-1E Thruster

Specifications:

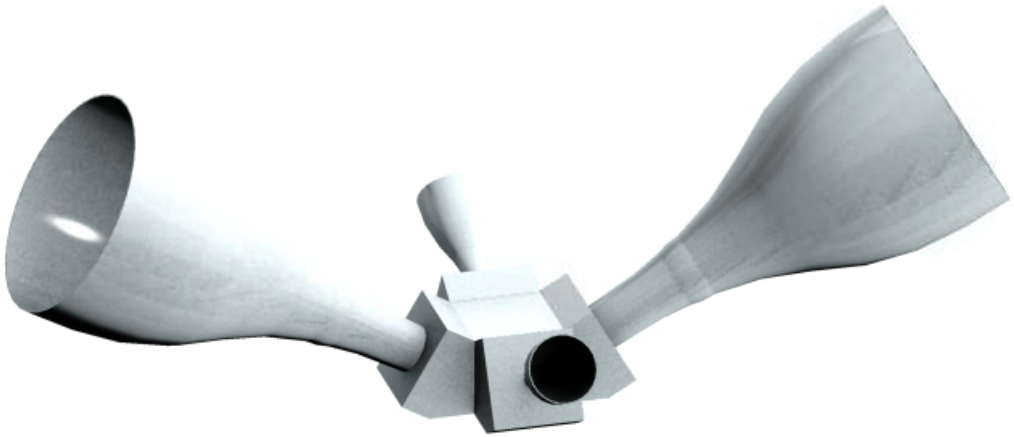
- Mass: 2 kg
- Nominal mixture ratio: 1.65
- Thrust: 110 N
- I_{sp}: 280 s
- Max power: 36 W
- Flow rate: 40.4 gm/s
- Minimum impulse bit: 0.89 N-s
- Total Pulses: 330,000
- TRL Level-9



Digital image. Aerojet Rocketdyne. Web. 27 Apr. 2014. <https://www.rocket.com/propulsion-systems/bipropellant-rockets>.

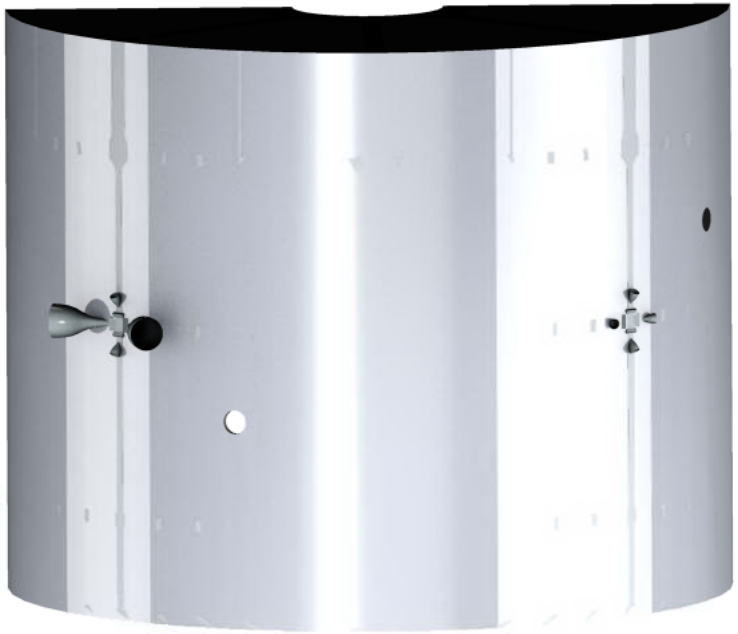
Thruster Quads

- Thrusters shall be used as part of thruster block or quad
- 12 total quads on the station (8 w/o Mars SIM)
- 6 shall consist of 4 R-1E thrusters (Control Quad)
- 6 shall consist of 2 R-1E and 2 R-4D thrusters (Spin Quad)
- Angled away from the structure 30˚ to reduce plume impingement effects and to ensure 2-fault tolerance



Quad Placement

- 4 quads each on the habitat, ballast, and Mars SIM
- Control quads shall be located on the y faces
- Spin quads shall be located on the z faces
  - R-4E Thrusters shall be directed in the ± x direction
- Any two thruster quads can fail and be compensated by the others



Propellant Mass Estimates

- Habitat
  - $\Delta m = I_{zz} * \omega_z * m_T / 2 * L * \cos(\theta_T) * F_{T,max}$
- Ballast
  - $\Delta m = I_{zz} * \omega_z * m_T / 2 * L * \cos(\theta_T) * F_{T,max}$ $m_{Habitat} / m_{Ballast}$

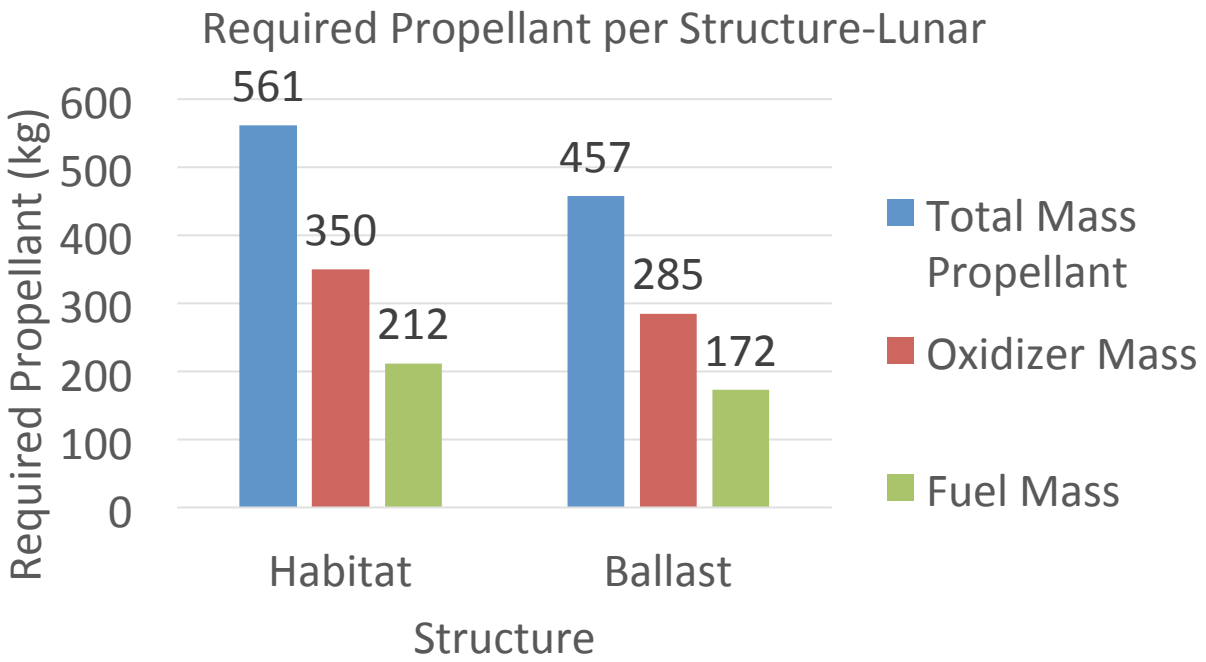
- I_{zz} =moment of inertia about z
- ω_z =change in angular velocity about z
- m_T =thruster mass flow rate
- L=distance between habitat/ballast and Hub
- θ_T =thruster angle
- $F_{T,max}$ =maximum thruster force
- $m_{Habitat}$ =mass of habitat
- $m_{Ballast}$ =mass of ballast

Phase I

- Maneuvers
  - DRO orbit insertion
- Propellant mass
  - $\Delta m = 1864.5\ kg$
- Taking chemical properties into account
  - $\Delta m_{Oxidizer} = 1055\ kg$
  - $\Delta m_{Fuel} = 640\ kg$
- Maximum volume for tanks
  - $V_{Oxidizer} = .732\ m^3$
  - $V_{Fuel} = .527\ m^3$

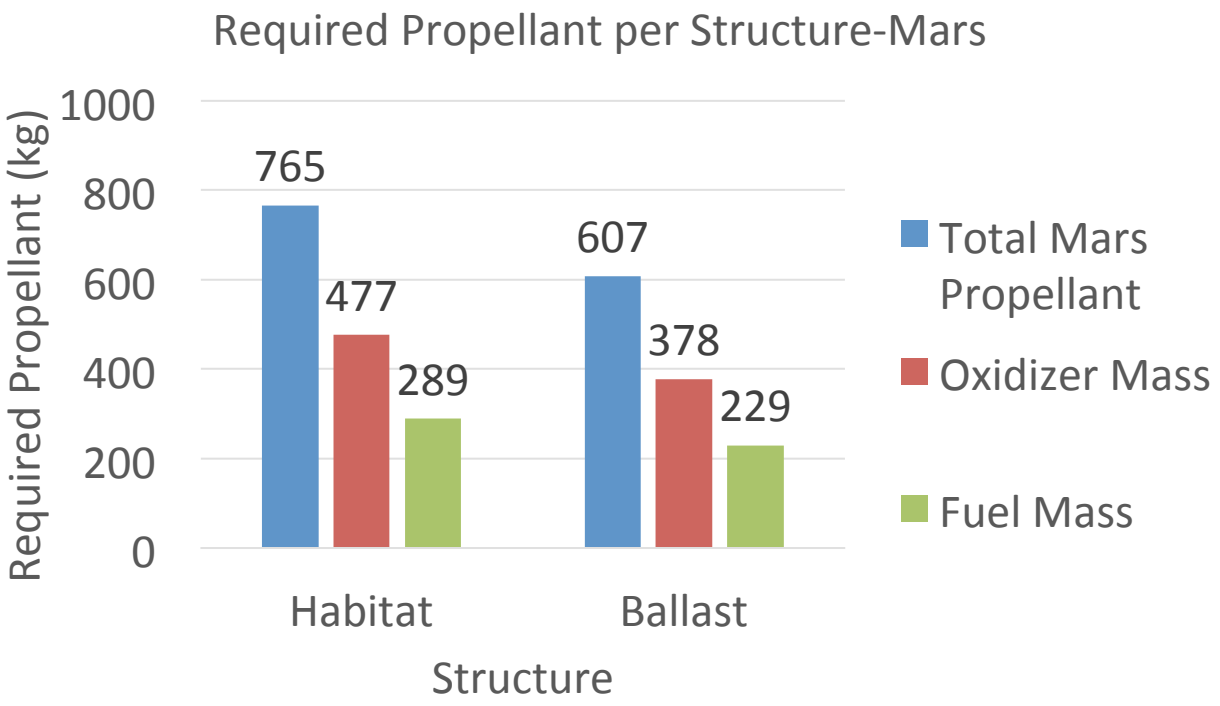
Phase II-Moon

- Maneuvers
  - DRO orbit insertion
  - Separate spins to Moon, Mars, Earth gravity levels



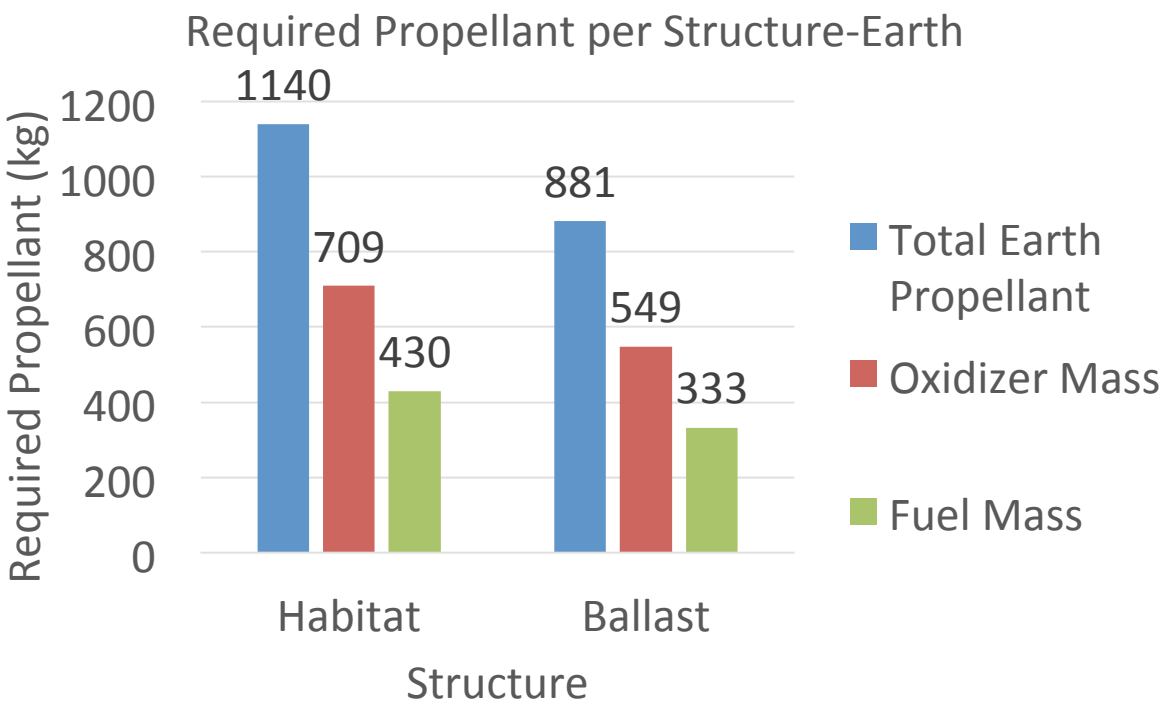
Phase II-Mars

- Maneuvers
  - DRO orbit insertion
  - Separate spins to Moon, Mars, Earth gravity levels



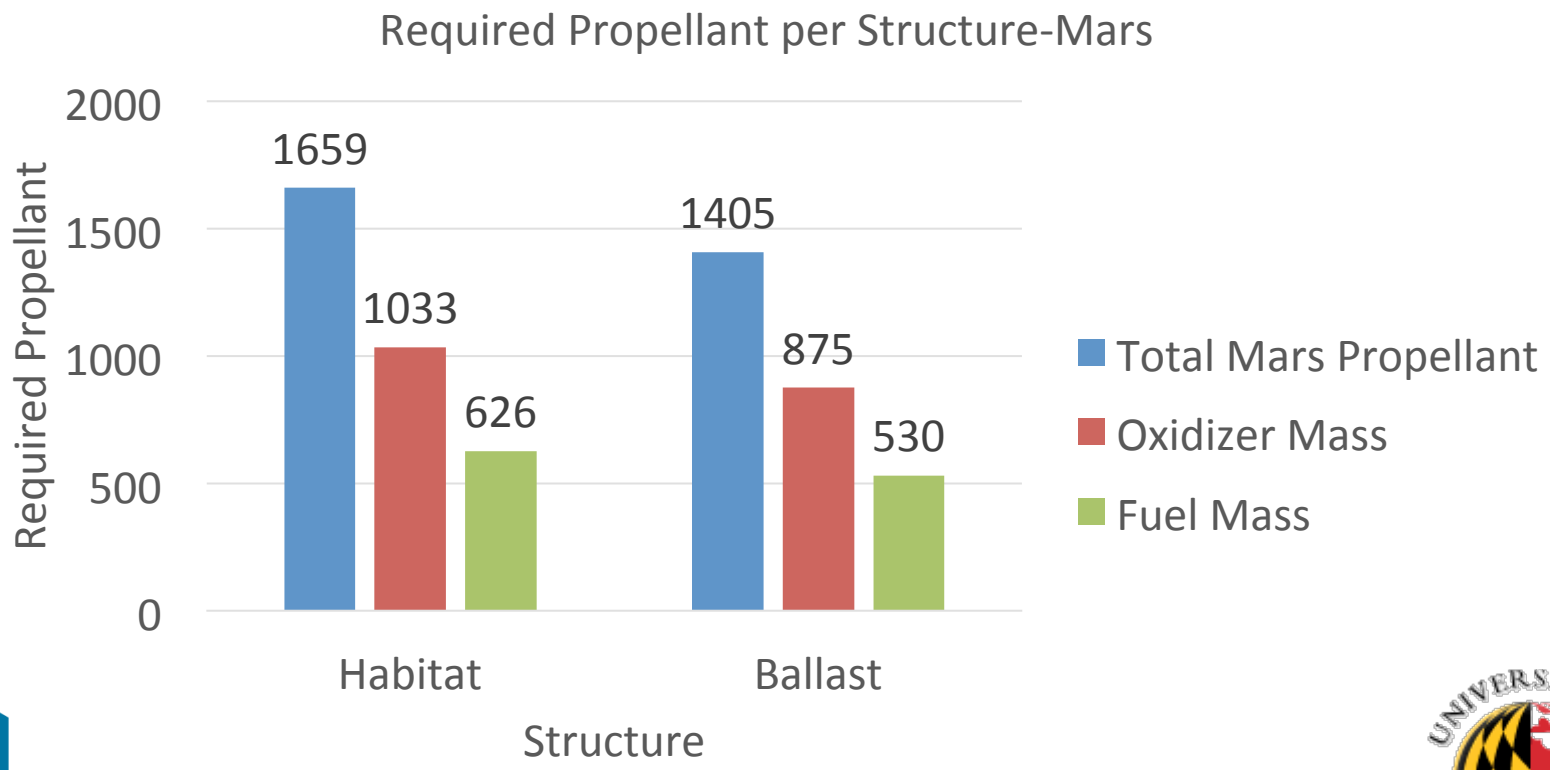
Phase II-Earth

- Maneuvers
  - DRO orbit insertion
  - Separate spins to Moon, Mars, Earth gravity levels



Phase III

- Maneuvers
  - DRO orbit insertion
  - Spin to Mars gravity



Propellant Tanks

- Fuel Tanks
  - Aluminum 6061-T6
  - Tank Pressure: 1.93 MPa

Placement	Max Fuel Mass [kg]	Max Fuel Volume [m^3]	Tank Mass [kg]	Tank Volume [m^3]
Habitat/Ballast	1796	0.7114	920.5	0.7268
Central Hub	2587	2.939	12,090	3.527

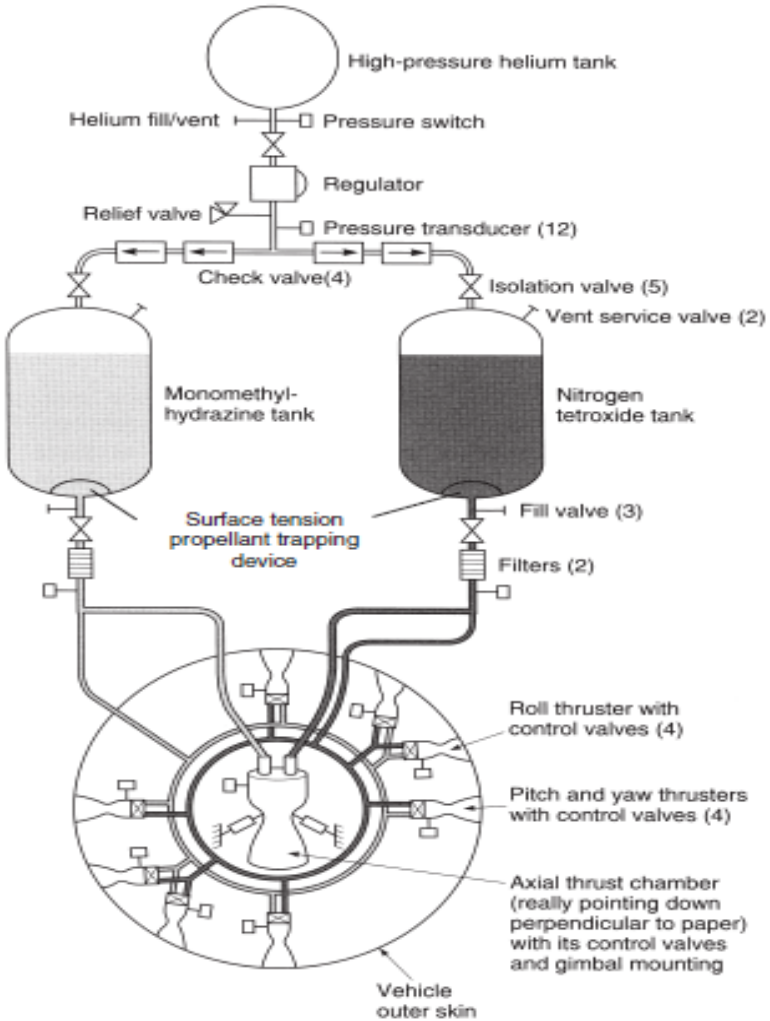
Propellant Tanks

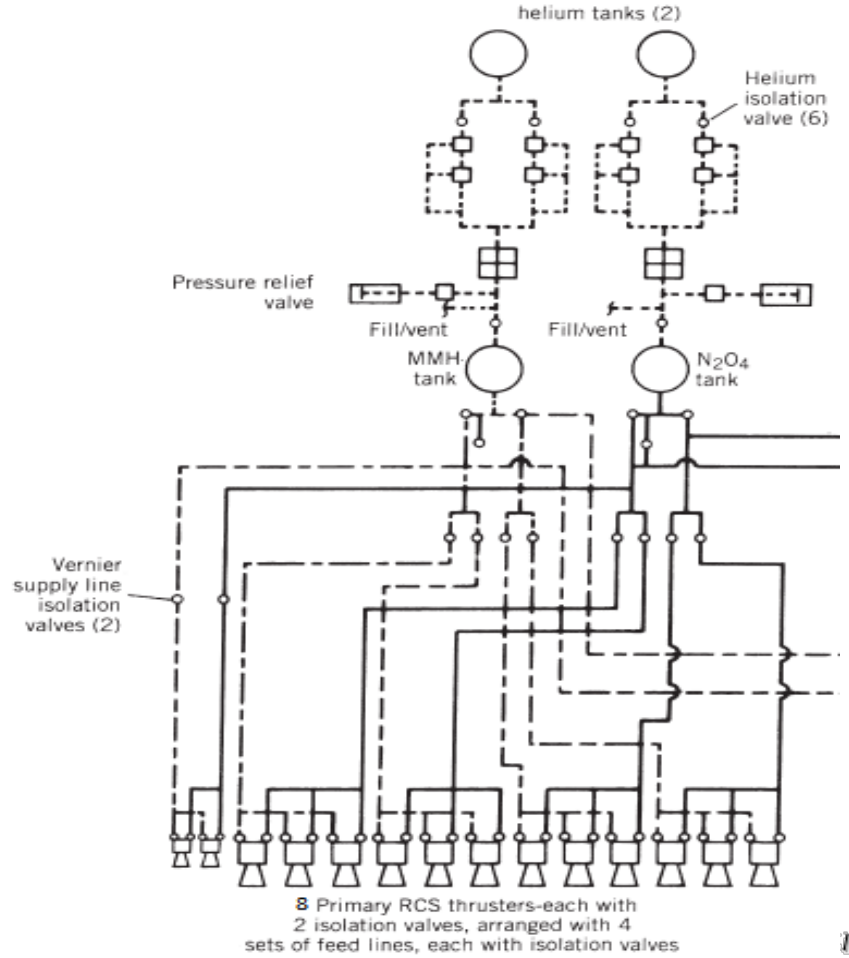
- Oxidizer Tanks
  - Aluminum 6061-T6
  - Tank Pressure: 1.93 MPa

Placement	Max NTO Mass [kg]	Max NTO Volume [m^3]	Tank Mass [kg]	Tank Volume [m^3]
Habitat/Ballast	2963	.6099	927.3	0.7319
Central Hub	4267	2.959	12,300	3.551

Feed System

- Gas Pressure Regulated feed system using Helium





Sutton, George P., and Oscar Biblarz. *Rocket Propulsion Elements*. Hoboken, NJ: Wiley, 2010. Print.

Feed System

- Helium Tanks
  - Aluminum 6061-T6
  - Tank Pressure: 24.8 MPa

Placement	Max Pressurant Mass [kg]	Max Pressurant Volume [m^3]	Pressurant Tank Mass [kg]	Pressurant Tank Volume [m^3]
Habitat	43	1.056	1.647	1.267
Central Hub	118.5	2.909	4.073	3.491

Feed System

- Fuel Lines
  - Stainless steel
  - Length of 6.25 m to each thruster
- Valves
  - Start/Stop Valves
  - Isolation Valves
  - Pressure Relief Valves

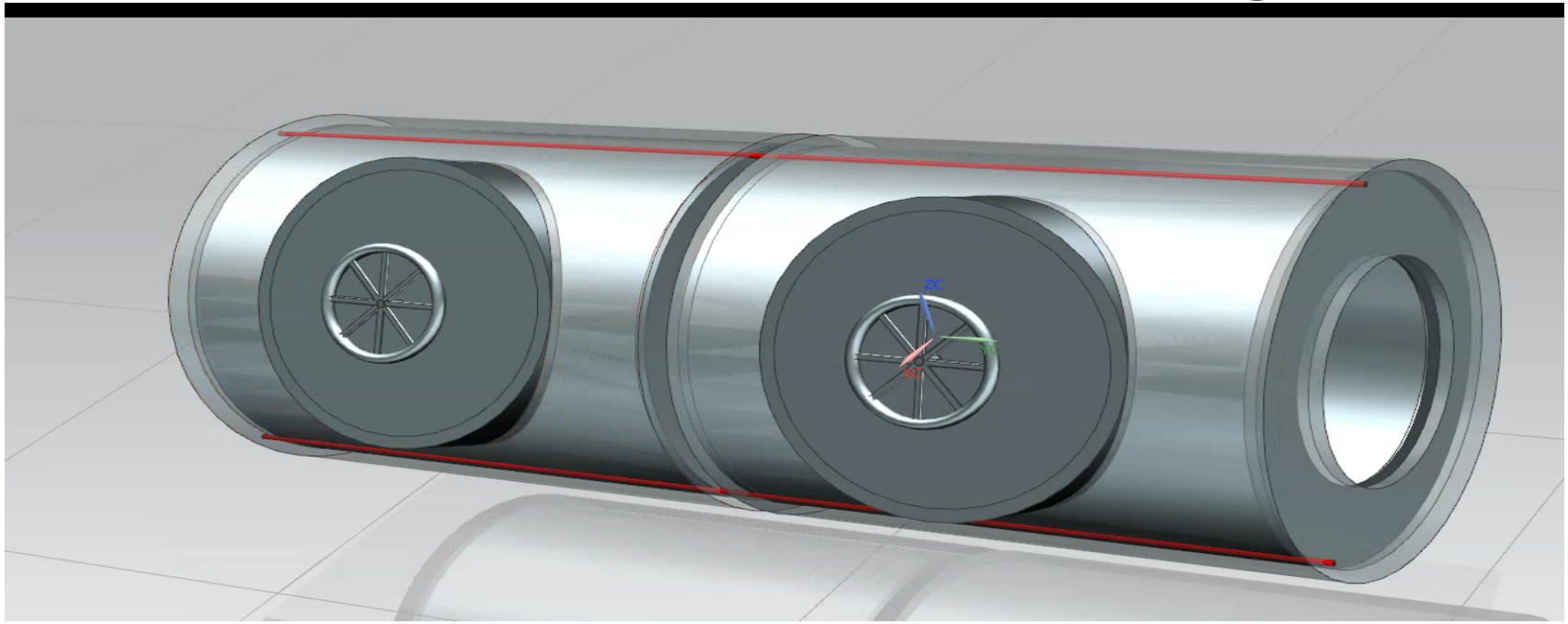
Feed System

- Safety Provisions
  - Isolation Valves
  - Burst Diaphragms
  - Vibration Monitors
  - Sniff Devices
  - Filters

Refueling Overview

- Our system requires refueling due to tank size, mass, and launch constraints
- Refill tanks for both fuel and oxidizer
- Two types of refueling:
  - Intra-vehicular
    - Hub to Habitat/Ballast
  - Inter-vehicular
    - External System to Polus
- Intra-Vehicular Refueling:
  - Done only when spun down
  - Mass of tanks on the Habitat and Ballast should be as small as possible due to several constraints including mass and fairing size
  - There needs to be enough propellant in tanks for a spin down as well as contingency
  - Due to these constraints we must spin down before we change gravities to refuel

Intra-Vehicular Refueling



- Pipes are constructed on the rigid structures between the Hub and the Habitat/Ballast
- They will connect with a male/female locking mechanism
- Sensors for this mechanism include:
  - Conductivity sensors
  - Pressure transducers

Inter-Vehicular Refueling

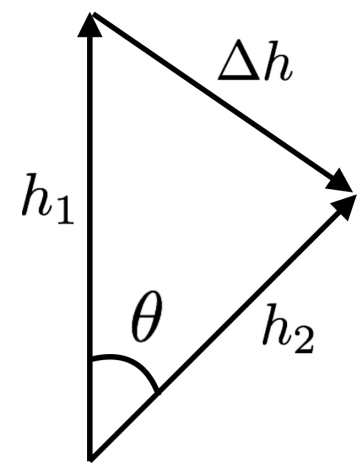
- Phase I
  - The propellant needed for this phase will be carried up with the Habitat in its tanks
- Phase II
  - The propellant needed for this phase will be carried up by the Hub and Ballast
- Phase III
  - The Oxidizer mass required is 2963 kg and the Fuel mass is 1796 kg. These masses both include the propellant mass needed for the SDRO orbit insertion and the rotations in this phase.
  - Dragon cargo capsule has been sized to carry 6000 kg of propellant.
  - IDSS has a planned capability to integrate fuel umbilical through the docking interface which we will use to refuel the station

Orientation & Pointing

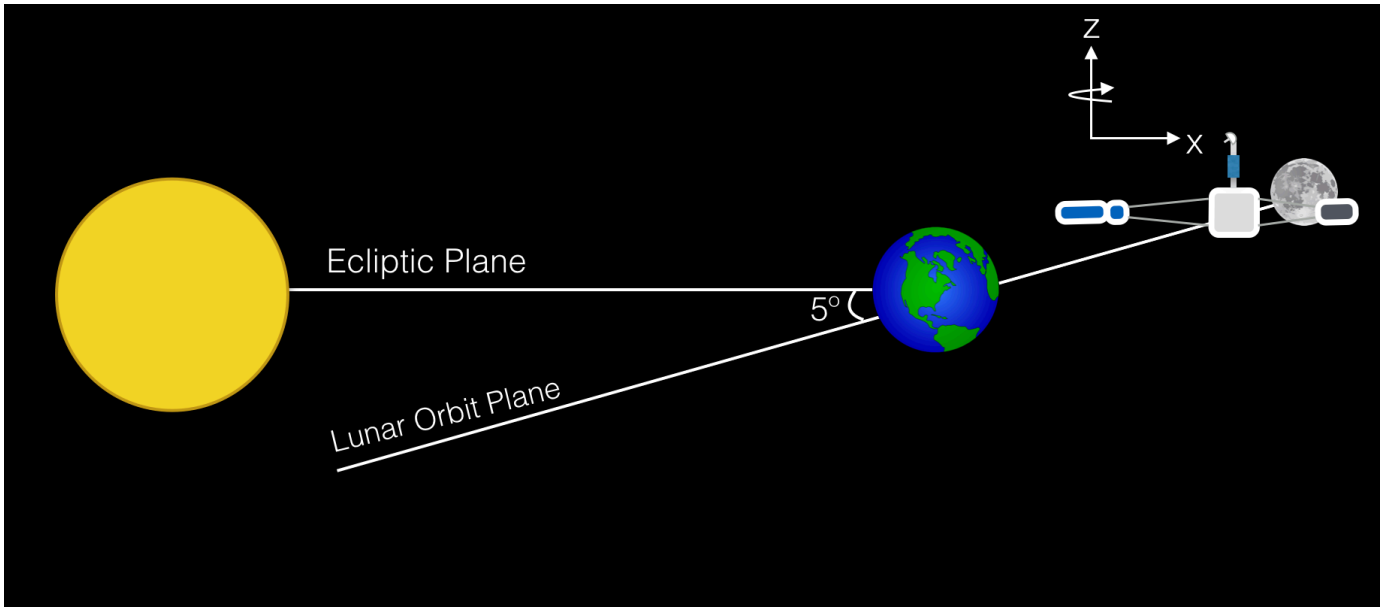
- Factors to consider:
  - Thermal equilibrium of the habitat
  - Solar panel exposure to sunlight
  - Polus/Earth communications
  - Operational objectives (EVAs, etc.)
    - Relative orientation of Polus/asteroid
  - Phase II/III angular momentum
    - Rotation plane changes are costly!
    - To change the direction of the habitat's angular momentum vector:

$$\|h_1\| = \|h_2\| = h_0$$

$$\|\Delta h\| = h_0\sqrt{2 - 2\cos\theta}$$

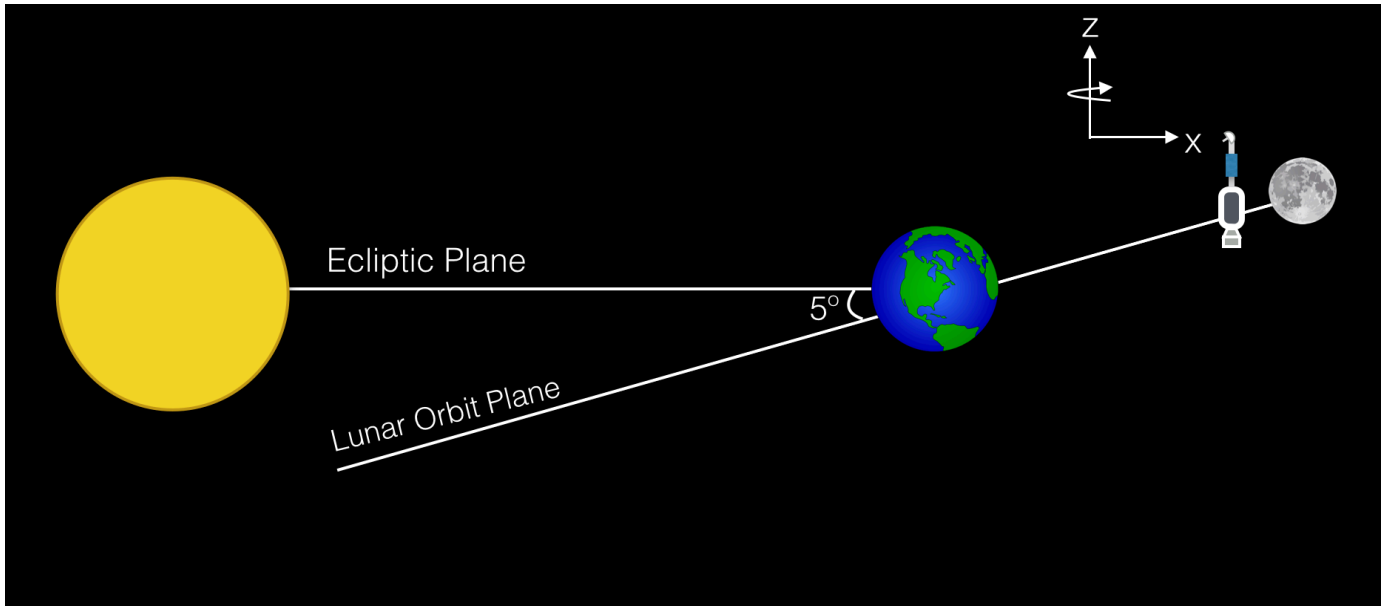


Orientation & Pointing: Phases II & III



- Advantages of rotation in the ecliptic plane:
  - No beta joint needed, alpha joint rotates once per sidereal year
  - No changes to angular momentum vector required
  - Minimal antenna pointing (+/− 5°)
  - Thermal homogeneity (no "hot side")

Orientation & Pointing: Phase I

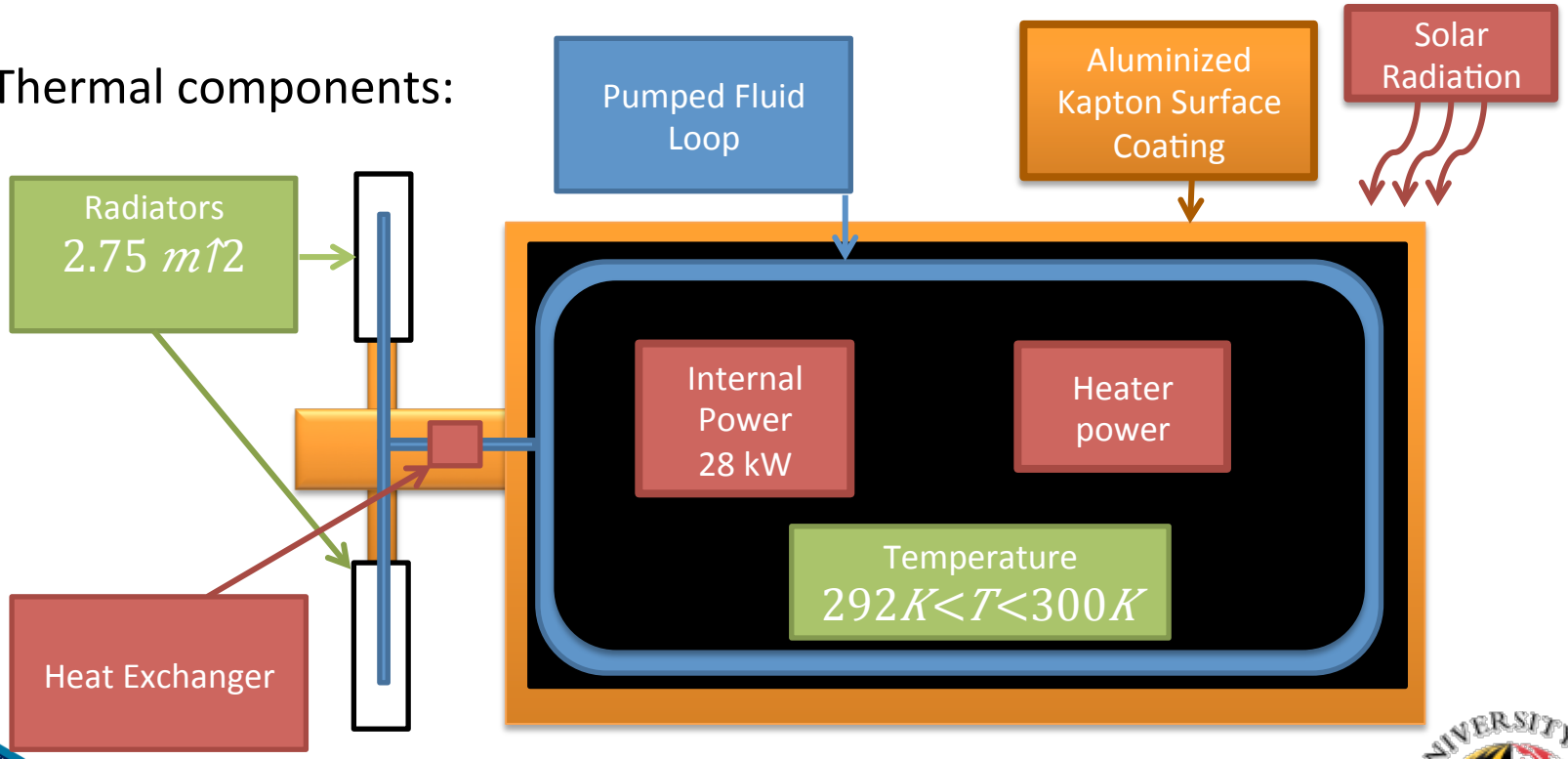


- Nominal rotation plane also chosen as ecliptic
  - No beta joint, same antenna/panel configuration
  - Everything above alpha joint moved to the Hub in Phase II, III
  - Apollo-esque "Barbecue Roll" to assist thermal homogeneity

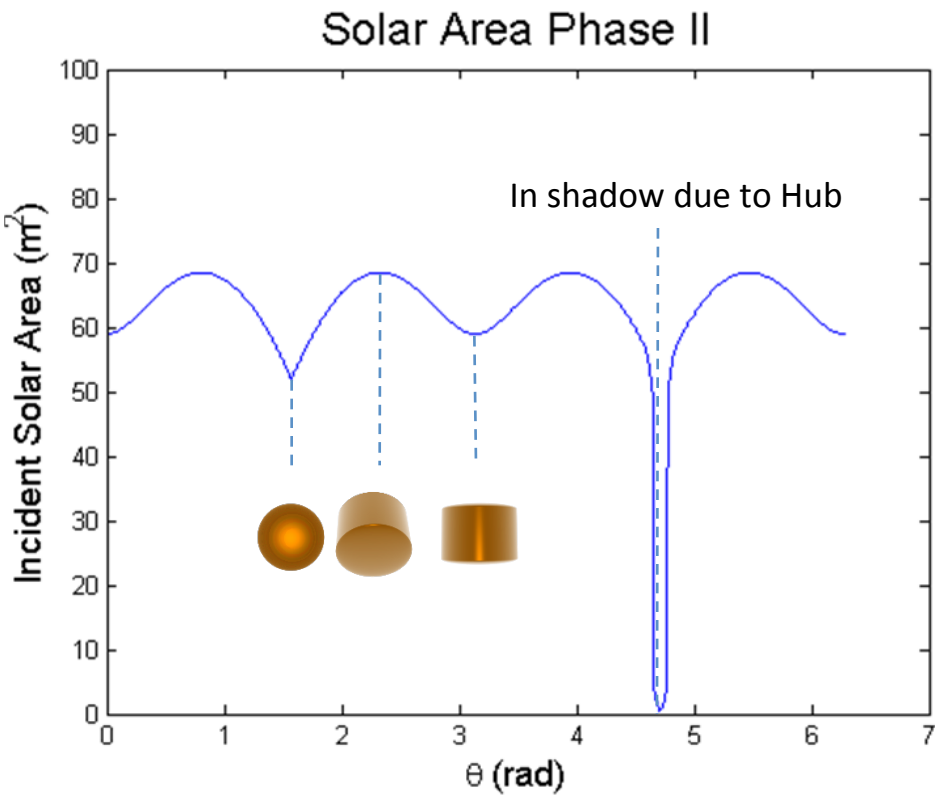
Thermal Overview

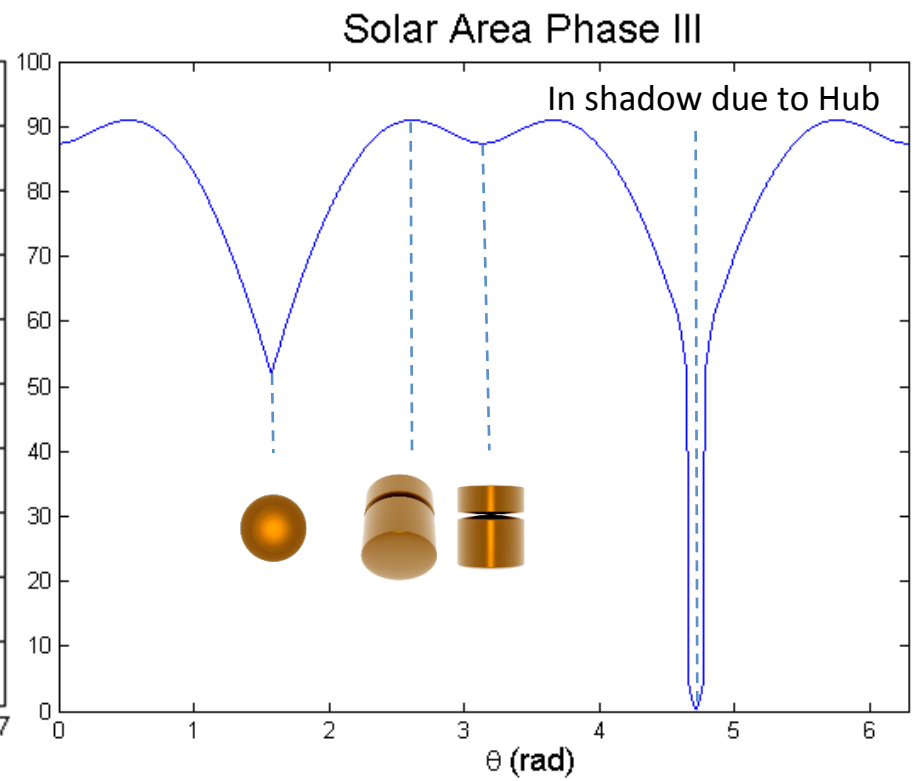
- Temperature needs to be within the bounds for the duration of the mission
- This requires a system that will work for all three phases and all rotation rates
- The system has to account for near-complete sunlight and for eclipse phases

Thermal components:



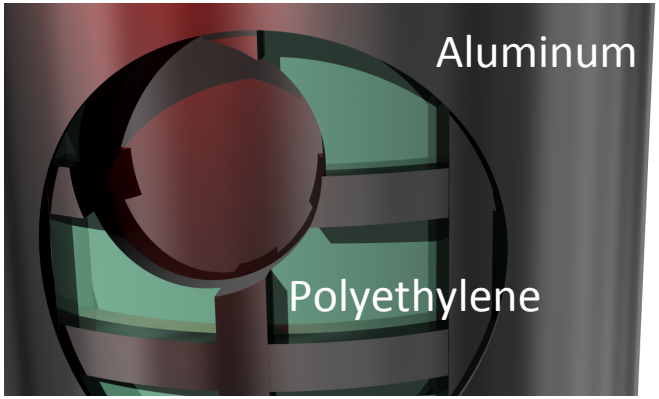
Solar Heating Area

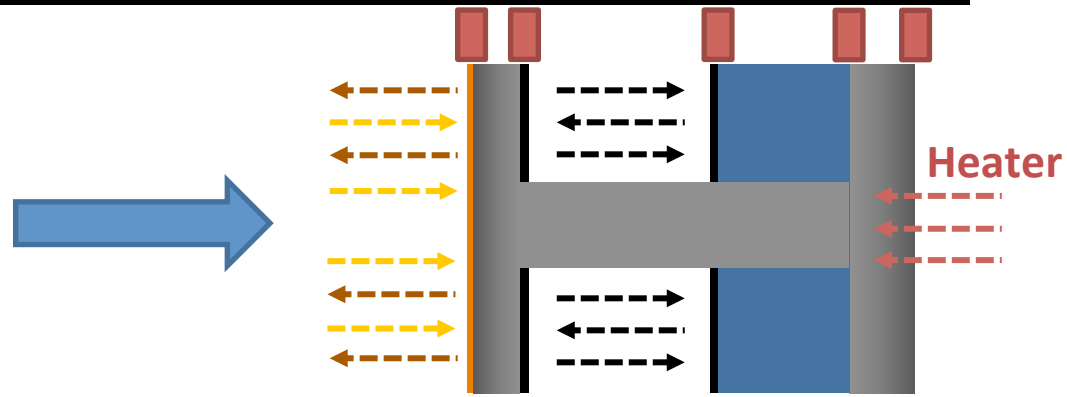




The incident solar area changes as the habitat rotates about the Hub, keeping the temperature throughout the station in a state of dynamic equilibrium

Thermal Simulation: Wall Heat Transfer



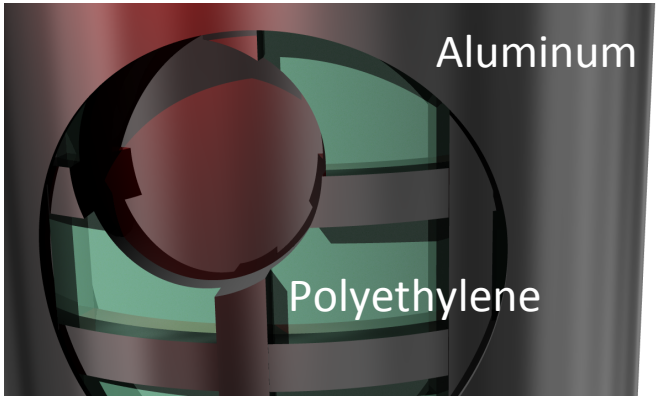


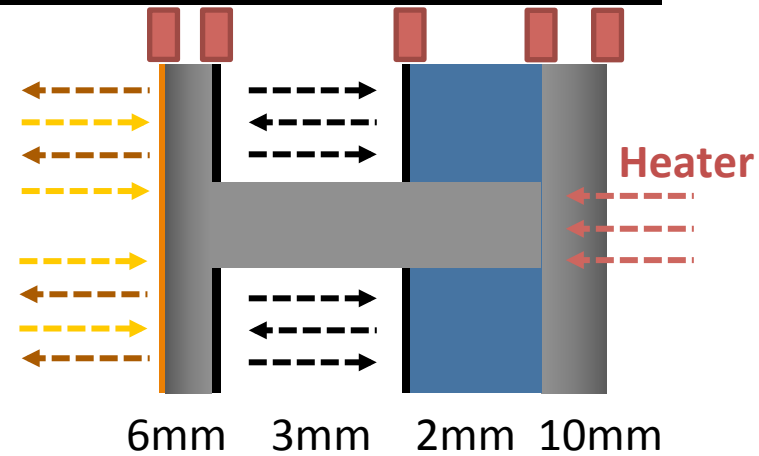
For the simulation, the temperature at five different locations within the whipple shield was iterated over time ($T_{i+1} = T_i + \Delta T$) using the following algorithm:

$$\Delta T_5 = \Big(\overbrace{I_s A_s \alpha}^{\text{Radiation into habitat}} - \overbrace{\left(Q_{radiator} + \sigma \epsilon A_r (T_5^4 - T_{env}^4)\right)}^{\text{Radiation out of habitat}} + \overbrace{\frac{(T_4 - T_5) k_{alum} A_r}{d_{outer}}}^{\text{Conduction through outer wall}}\Big) / (m_{outer} C_{alum}) \Delta t$$

$$\Delta T_4 = \Big(\overbrace{\frac{\sigma \epsilon_{inner} \left((A_3 - A_{strut}) T_3^4 - (A_4 - A_{strut}) T_4^4\right)}{(2 + alpha_{inner})}}^{\text{Net inner radiative transfer}} + \overbrace{\frac{(T_1 - T_4) k_{alum} Astrut}{d_{inner} + d_{strut}}}^{\text{Conduction through strut}} + \overbrace{\frac{(T_5 - T_4) k_{alum} A_r}{d_{outer}}}^{\text{Conduction through outer wall}}\Big) / (m_{outer} C_{alum}) \Delta t$$

Thermal Simulation (continued)





$$\Delta T_3 = \Bigg(\overbrace{\frac{T_1 - T3}{\left(\frac{d_{inner}}{k_{alum}(A_1 - A_{strut})} + \frac{d_{polyeth}}{k_{polyeth}(A_3 - A_{strut})} \right)}}^{\text{Conduction through inner wall}} + \overbrace{\frac{\sigma \epsilon_{inner}\left((A_4 - A_{strut}) T_4^4 - (A_3 - A_{strut}) T_3^4 \right)}{2 + alpha_{inner}}}^{\text{Net inner radiative transfer}} \Bigg) / (m_{polyeth} C_{polyeth}) \Delta t$$

$$\Delta T_1 = \Bigg(\overbrace{Q_{heater} + P_{internal}}^{\text{Inner power added}} + \overbrace{\frac{T_3 - T_1}{\left(\frac{d_{inner}}{k_{alum}(A_1 - A_{strut})} + \frac{d_{polyeth}}{k_{polyeth}(A_3 - A_{strut})} \right)}}^{\text{Conduction through inner wall}} + \overbrace{\frac{(T_4 - T_1) k_{alum} A_{strut}}{d_{inner} + d_{strut}}}^{\text{Conduction through strut}} \Bigg) / (m_{inner} C_{alum}) \Delta t$$

Thermal Coating

- Outer surface coating:
  - 0.25 mm Kapton Film with aluminum backing
  - emissivity: 0.45
  - absorptivity: 0.31

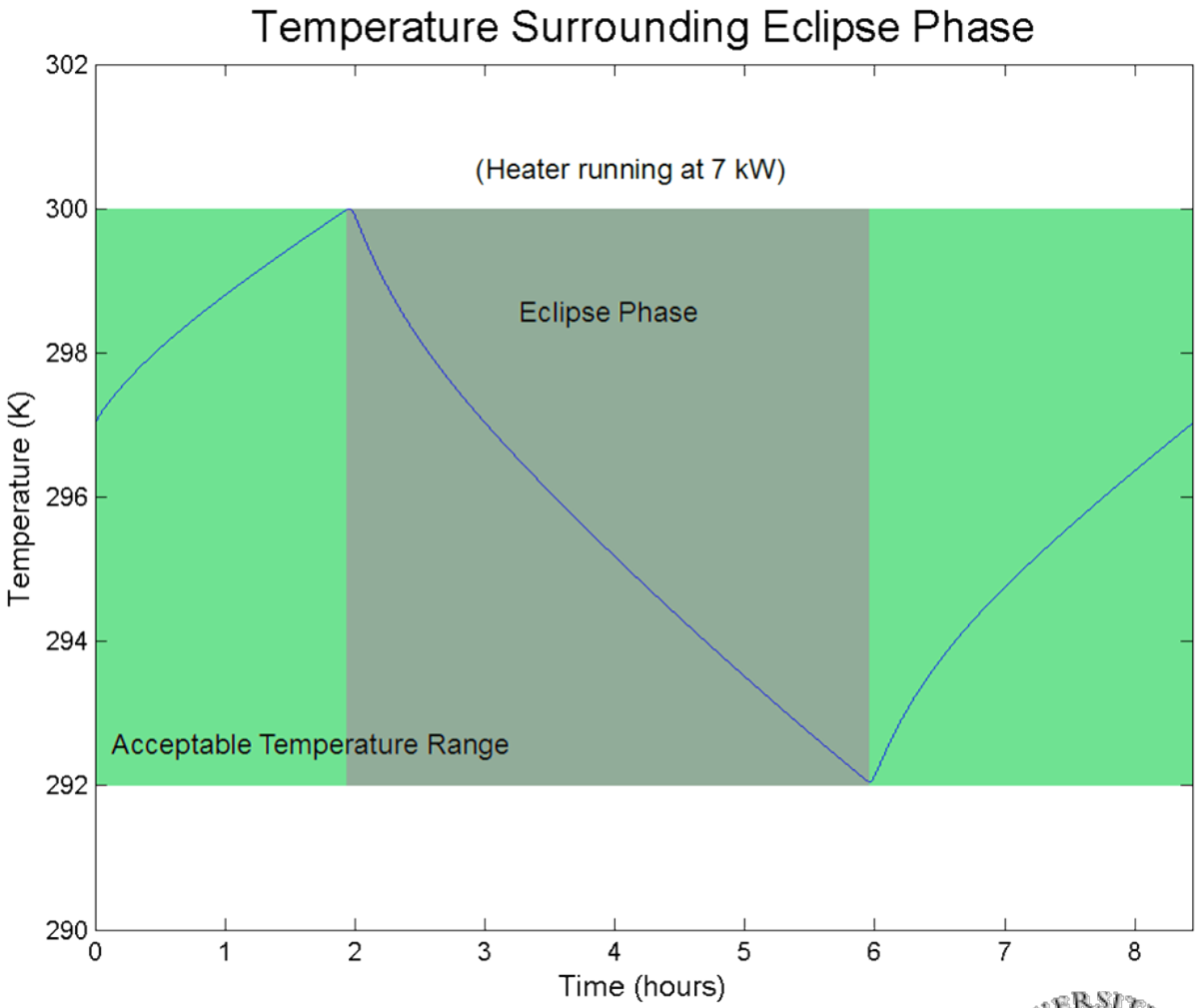
(Kapton Film Sample)

- Inner surfaces coating:
  - GSFC Black Paint 313-1
  - emissivity: 0.96
  - absorptivity: 0.86

- With these coatings, the heat that needs to be removed via the radiators during the 1 g case is 4.4 kW, and the heat that needs to be added during the eclipse phase is 7 kW

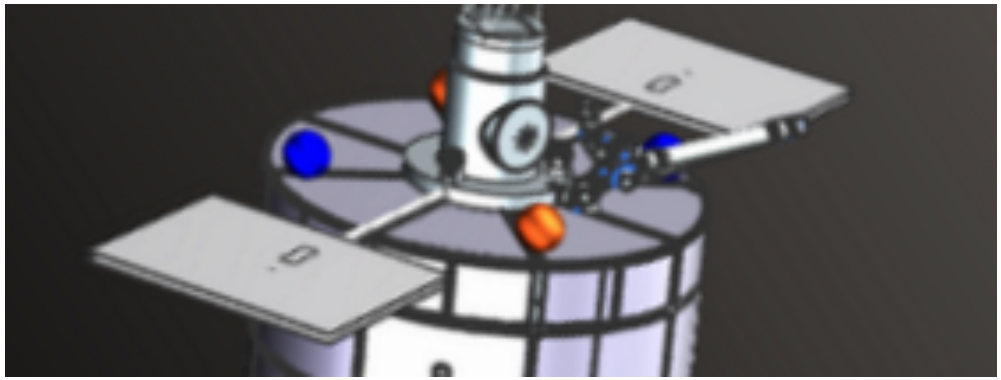
Eclipse Phase

- To keep T = 297 K during eclipse phase, 30,000 W of heater power is required
- Instead, heater is run at its maximum rating of 7 kW for the 8 hours surrounding eclipse
- Radiator panels are retracted/deployed over the 2 hour periods
- Temperature varies within the 8 K range – negligible effect on crew comfort



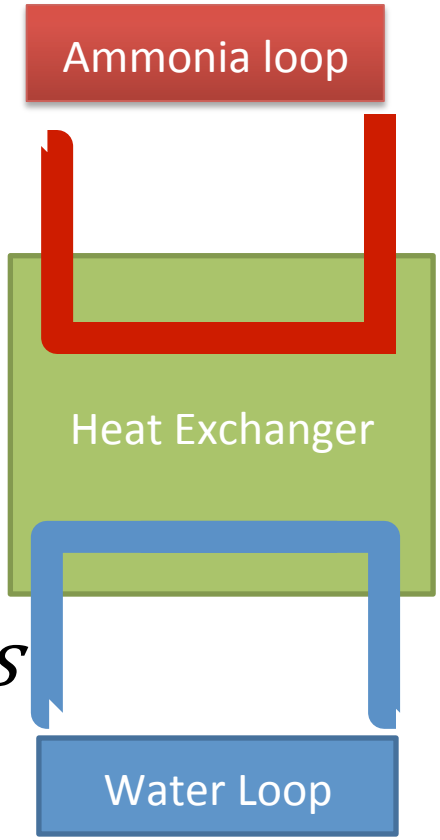
Radiator

- 2 radiators on booms extended off strut
- Coated in White paint $\varepsilon_{radiator} = 0.9$
- Requires 4.4 kW of power removal
- $P_{out} = A_{rad}\, \varepsilon_{rad}\, \sigma T_{rad}^4$
- Radiator cross sectional area of $= 2.75\ m^2$



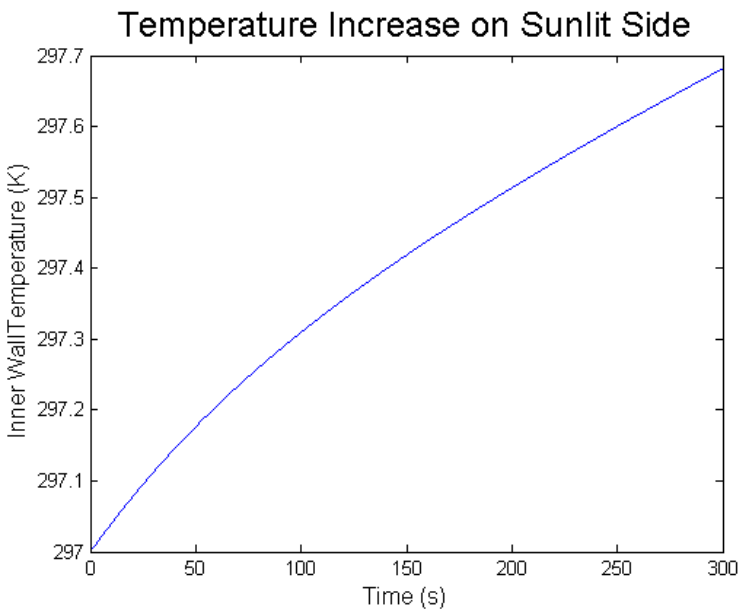
Pumped Fluid Loop

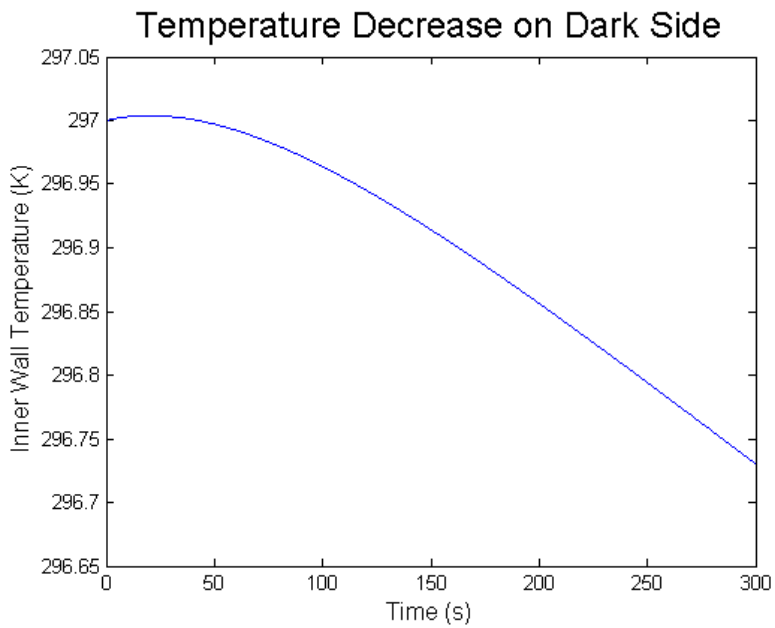
- The pumped water will equilibrate the temperature on the inside of the habitat
- Ammonia used for the radiator
- $Q = m\, c \Delta T$
- Maximum water mass flow rate: 0.32 kg/s
- $P = (m\, \Delta p / \rho) = m\, g (h_2 - h_1)$
- Maximum power water pump : $200\ W$
- Maximum ammonia Mass flow rate: 0.71 kg/s
- Maximum power radiator pump : $300\ W$



Thermal Control in 0g case

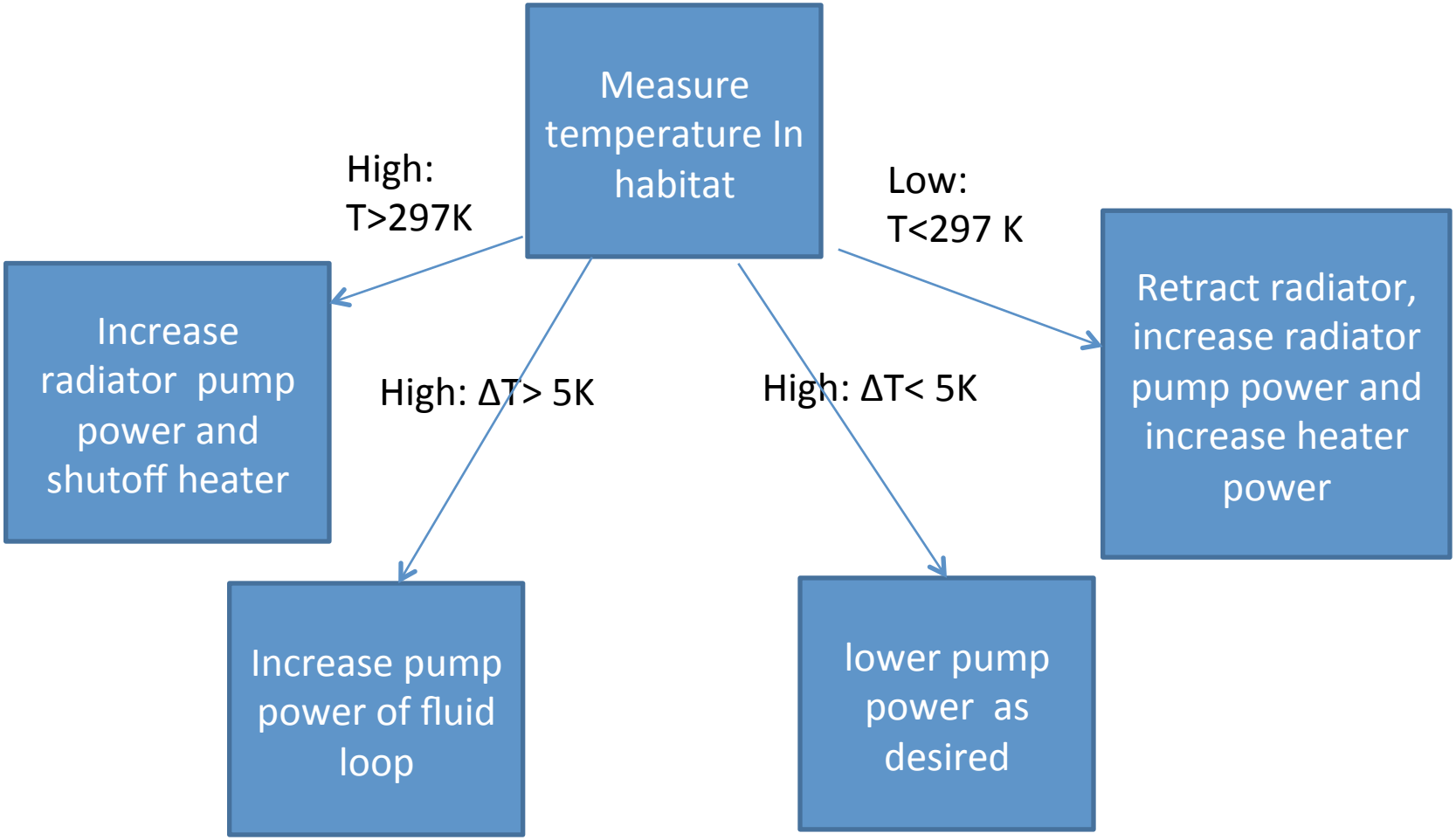
- A Barbecue roll with a 10 min period results in temperature difference from side to side of 2K



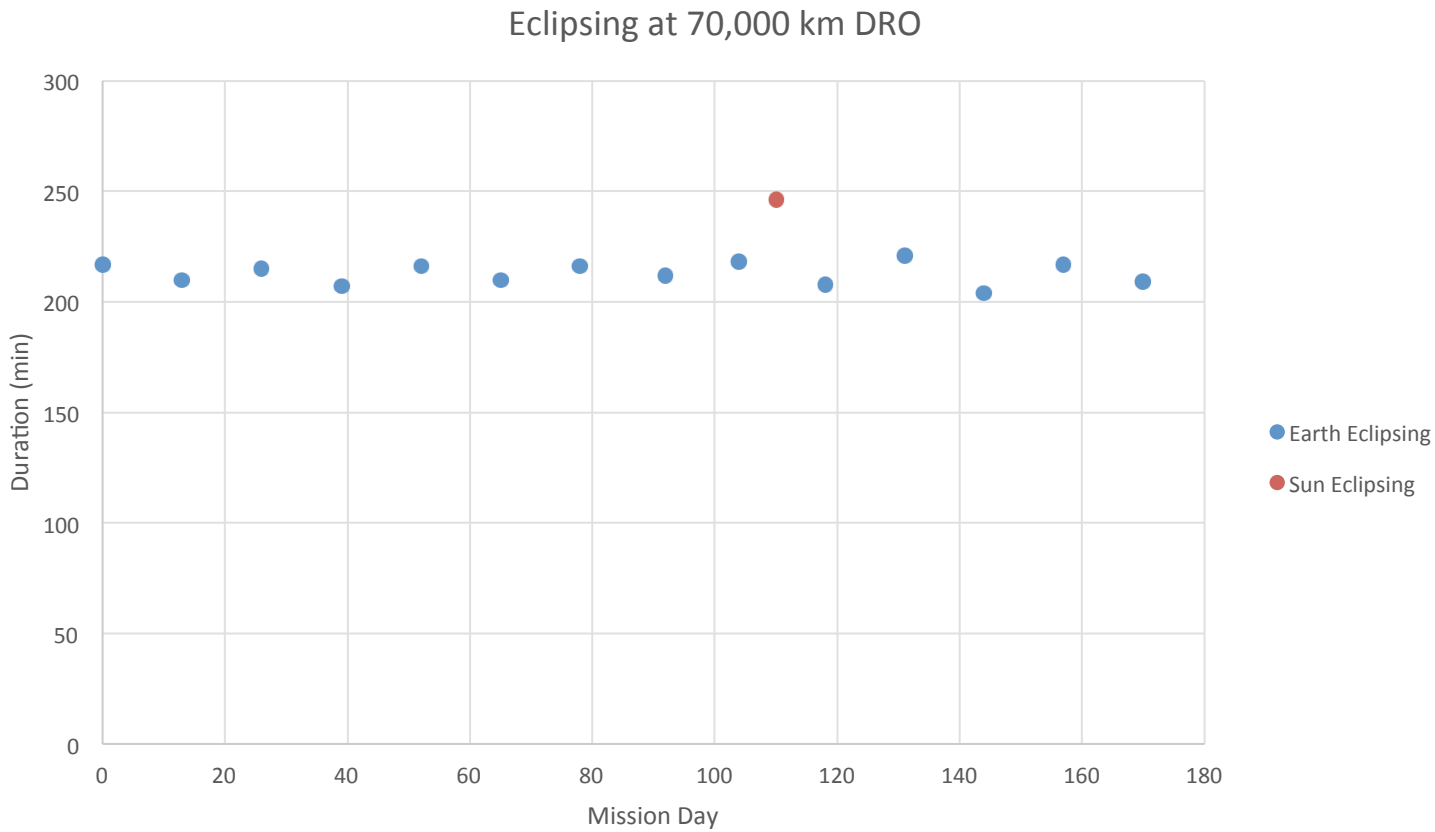


- Requires 3 kW of power removal through radiators

Thermal Control Flowchart



Eclipsing



*Data from Daniel R. Adamo "A Stable Home For Redirected Asteroids (And More?): Selenocentric Distant Retrograde Orbits (SDROs) "

Nominal mission from July to December 2013

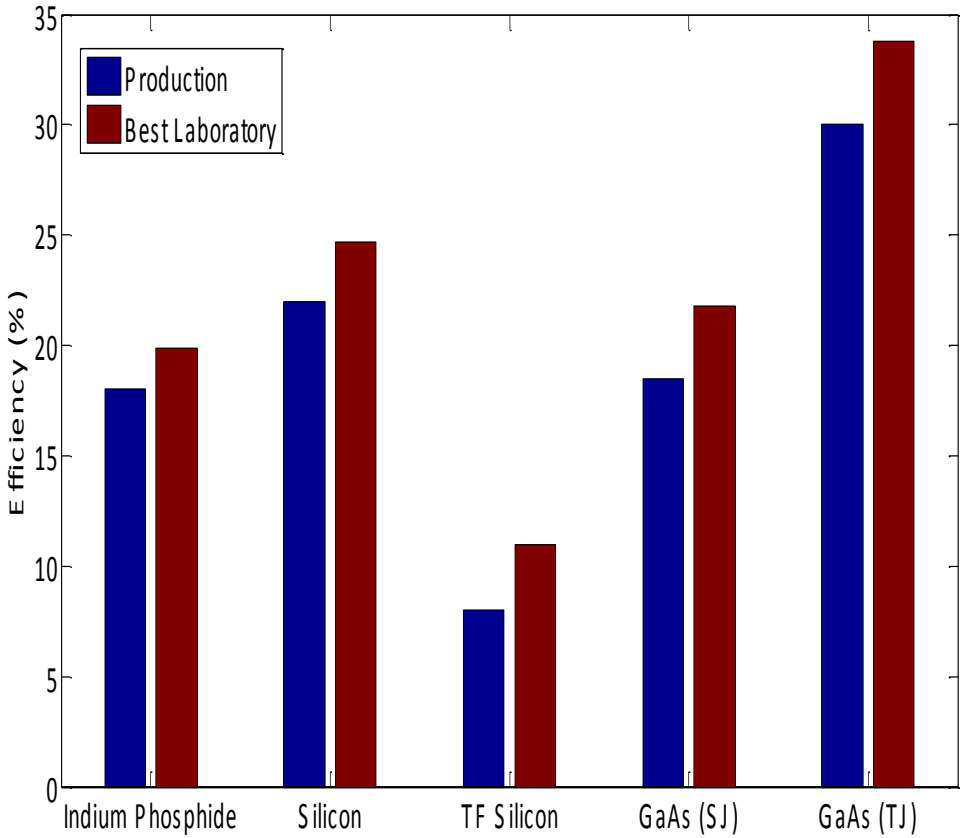
Eclipsing

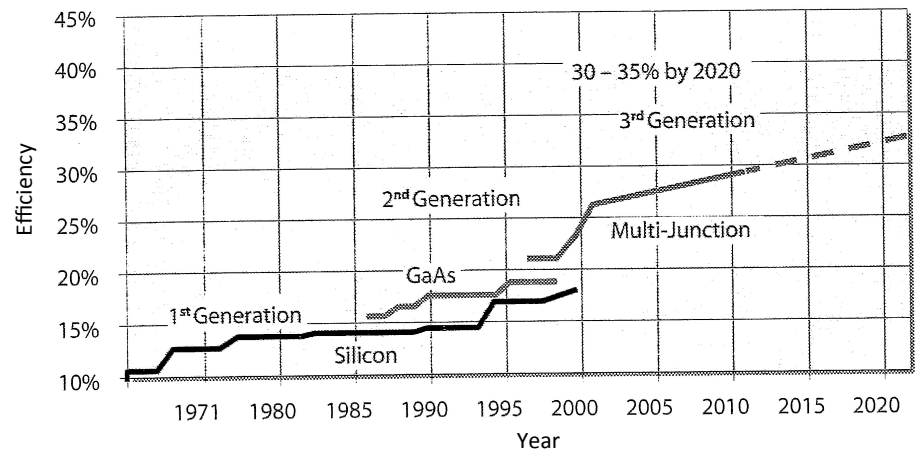
- Using data from a 170 day mission at a DRO radius of about 70,000 km, the Earth was eclipsed every 13 days for 207-221 min and the sun only once for 246 min
- This is the desired stable orbit to support the ARM in Phase I and will also have much less eclipsing than a DRO with a smaller radius
- A radius of 12,500 km resulted in eclipses of ~90 min every 2-3 days

Power Budget

Source	Phase I [W]		Phase II [W]		Phase III [W]	
	Average	Peak	Average	Peak	Average	Peak
Avionics	5000	6200	6000	6700	6300	7000
PPT	4000	8000	5000	10000	5500	11000
Crew Systems	15000	18000	15000	18000	15000	18000
LSM	1000	2000	11500	23000	11500	23000
Science	2200	3000	4400	6000	6600	9000
Mars SIM	N/A	N/A	N/A	N/A	10000	12000
Total	27200	37200	41900	63700	54900	80000

Solar Cell Performance Comparison





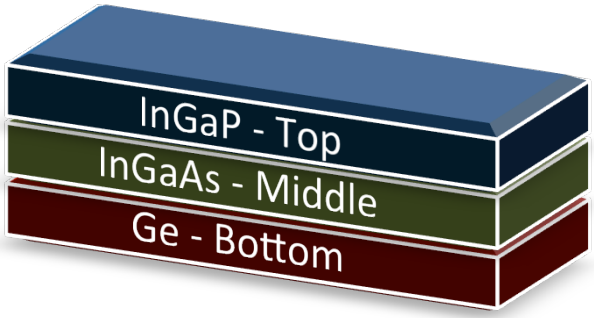
Efficiency projections found in: *Wertz, James R., et al. Space Mission Engineering: The New SMAD*

- Multi-Junction Gallium Arsenide (GaAs) outperforms other available solar cell technology
- Efficiency projections show MJ GaAs efficiency between 30-35 % by 2020

Comparison of GaAs Cell Technologies

Technology	Efficiency	Specific Area [W/m²]	Specific Mass [W/kg]	Specific Cost [$/W]
GaAs (Single Junction)	18.5 %	252	94	852
GaAs (Multi Junction)	22.6 %	308	110	695
GaAs (Improved MJ)	26 %	354	128	617
GaAs (Ultra MJ)	28 %	382	139	617
GaAs (MJ 2020 Projection)	30 %	410	146	617

Tunnel Junctions

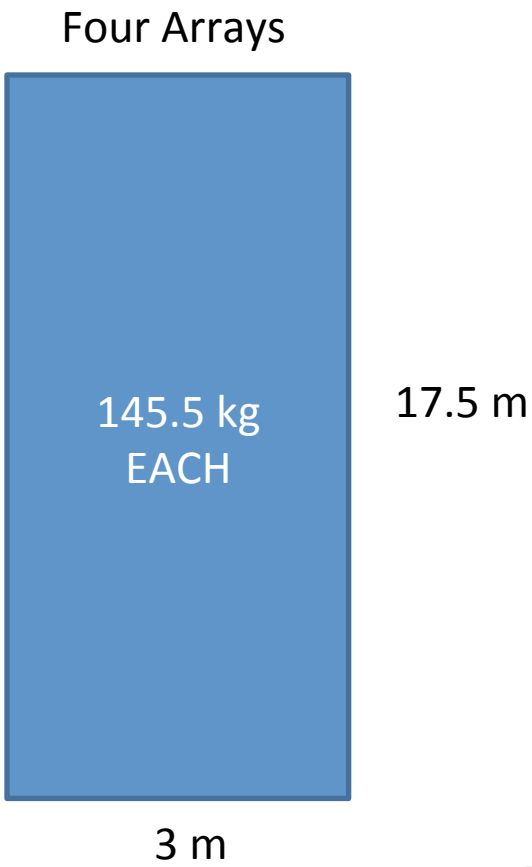


Gallium Arsenide Triple Junction Cell
Each junction collects energy over a different range of the Solar spectrum

Photovoltaic Sizing

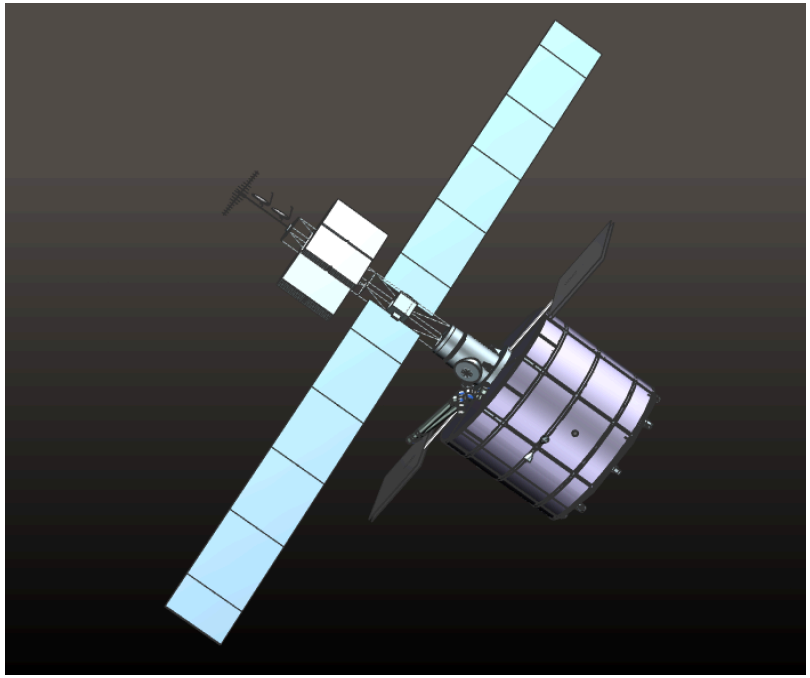
- Solar cells can expect up to 30% degradation over 10-15 year lifespan
- Shall design for EOL assuming 30% margin

- PHASE I: 27 kW → 41 kW
  - Total Mass = 281 kg
  - Total Surface Area = 100 m^2
  - Total Cost = $25MM
- PHASE 2: 42 kW → 65 kW
  - Total Mass = 445 kg
  - Total Surface Area = 159 m^2
  - Total Cost = $40MM
- PHASE 3: 55 kW → 85 kW
  - Total Mass = 582 kg
  - Total Surface Area = 208 m^2
  - Total Cost = $52MM



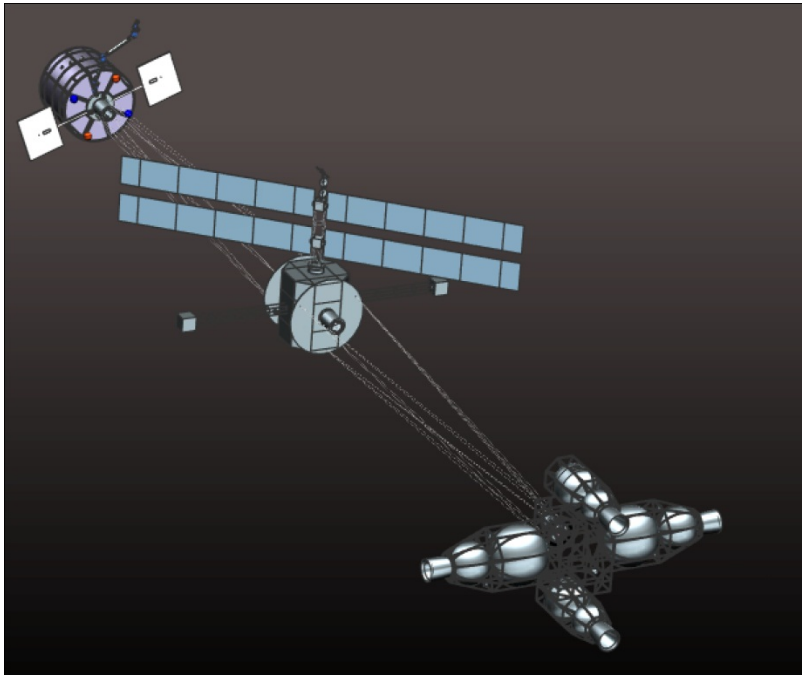
Photovoltaic Location

- PHASE I



- Located on Hab
- Two arrays provide 104 m^2 and 42.6 kW - enough power for Phase I

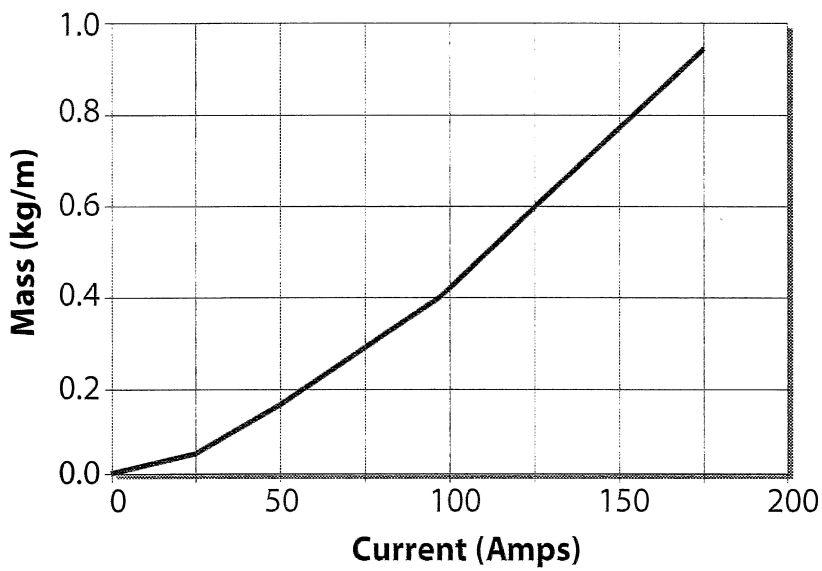
- PHASE II/III



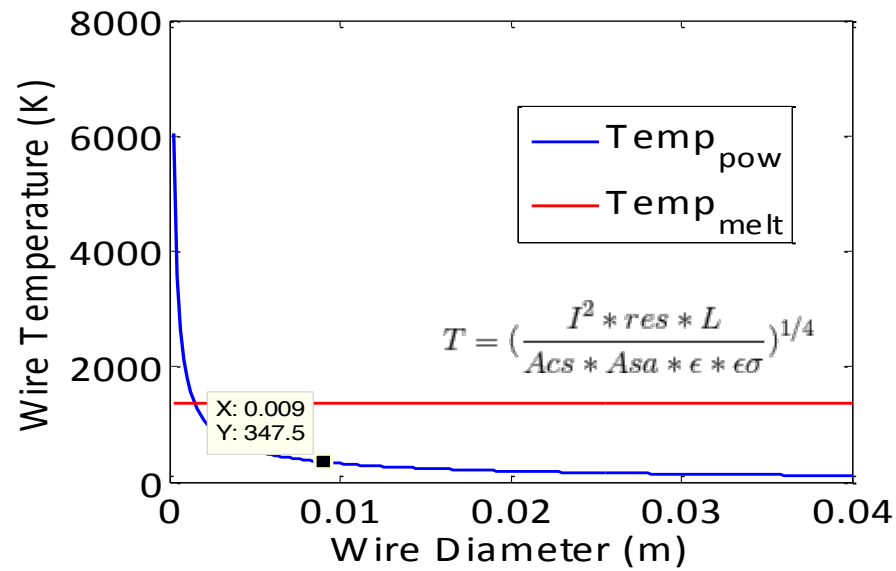
- Located on Hub
- Retractable power lines extending from Hub when spun up
- One primary bundle and one back-up bundle

Power Transfer

- Each PV Wing provides 13.75 kW and up to 115 Amps through carrier lines
- Annealed Cu: *ρ = 8930 kg/m³* *resistivity = 1.7e-8 Ω-m* *ε = 0.15*



$$P = I^2R = I^2(\frac{res * L}{Acs}) = \epsilon * \sigma * As * T^4$$

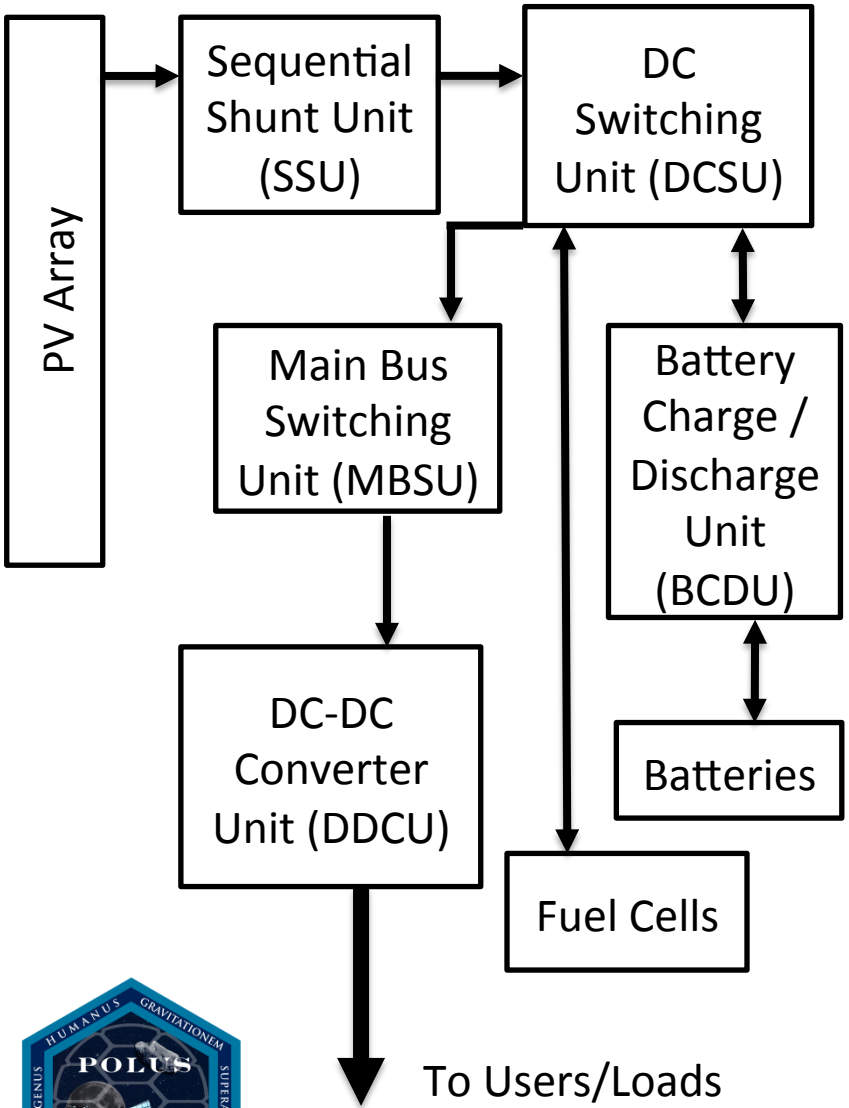


- 50 m of wire will have ~25 kg mass
- ρ = 8930 kg/m³ = m/v = m/(πr²)
- r=4.5 mm Diameter = 9 mm R = 13mΩ

- T_{melt} Cu = 1356 K
- Insulated wire will be able to carry load without significant power loss

Source: Wire Mass vs. Current found in *Wertz, James R., et al. Space Mission Engineering: The New SMAD*

Power Management and Distribution



Part	Purpose
SSU	Receives power from array and maintains output voltage to setpoint by shunting/ unshunting array strings.
DCSU	Used for power distribution, protection and fault isolation. Uses relays and switches to route primary power downstream.
MBSU	Distributes primary power from the power channels to the DDCUs and other loads. Able to "cross-tie" primary power channels in case of power failure.
DDCU	Responsible for DC power conversion (acts as transformer) for 160 VDC to 120VDC, which is the prescribed voltage for all users.
BCDU	Provides charge and discharge control of electricity from batteries.

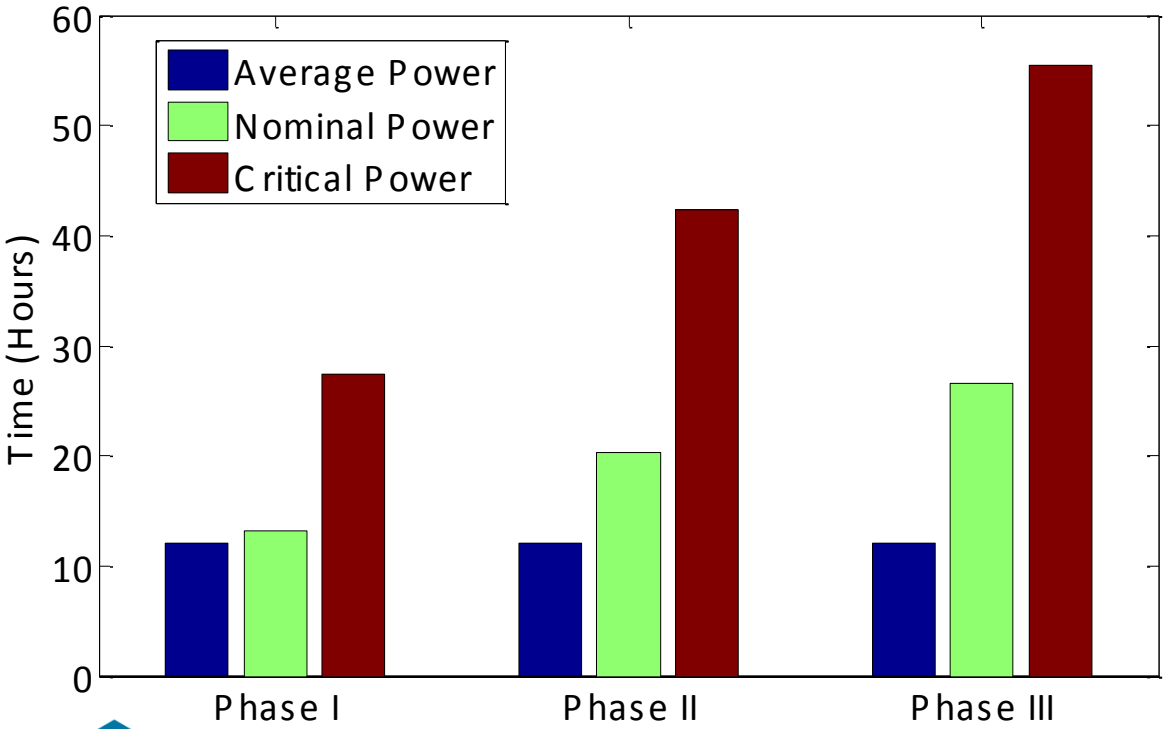
Energy Storage

- Habitat will be eclipsed every six months for approximately 4.1 hours
- Shall provide energy storage to keep systems running when photovoltaics are eclipsed

Phase	Avg. Power [kW]	Time Per Eclipse [hours]	Contingency Time [hours]	Total Energy Storage [kW-hr]
I	27.2	4.1	8	330
II	42.0	4.1	8	508
III	55.0	4.1	8	665

Energy Storage

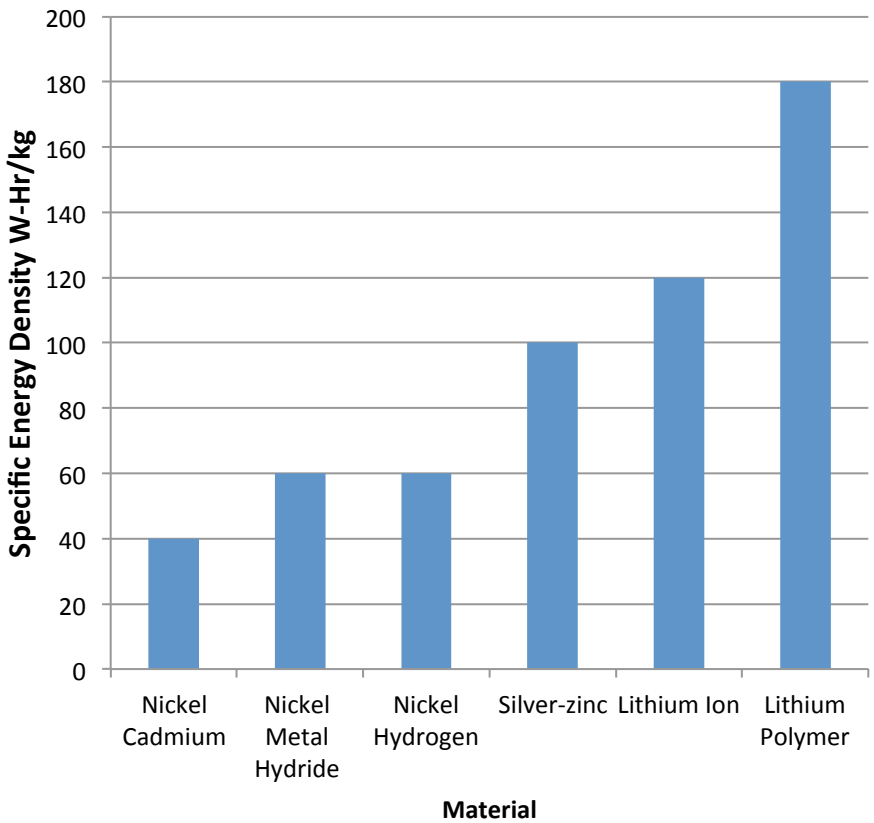
- Designing for average power during eclipse with 8 hour contingency allows broad range of energy storage capabilities



- Average power allows systems to run as normal
- Nominal power (25 kW) allows essential systems and some non-essential systems to operate
- Critical power (12kW) allows only essential life support and communications

Batteries

Material	Energy Density (W-hr/kg)
Nickel Cadmium	40
Nickel Metal Hydride	60
Nickel Hydrogen	60
Silver-zinc	100
Lithium Ion	120
Lithium Polymer	180



Lithium-Ion Batteries

- 120 W-hr/kg:

Phase	Energy Requirement [kW-hr]	Mass [kg]
I	330	2750
II	508	4233
III	665	5542

- High reliability/experienced with energy storage in space applications
- 15 year mission life expectancy
  - Less frequency of eclipse may extend the lifetime of the batteries
- Installed primary and redundant heaters to maintain at operational temperatures: 268K – 308K (-5°C – 35°C)
- Designed to withstand $3.11*10^{6}$ rads of radiation

Regenerative Fuel Cells

- Capable of 275 W-h/kg (plus reactants)
- 15 minute startup time and 24,000 hour life expectancy
- Gaseous H_2 and O_2 are used for reactants
  - No cryogenics required to liquefy
  - Relatively small operation time keeps reactants and pressurized storage tank mass low
  - Water byproduct is converted back to H_2 and O_2
- Total Mass: 3620 kg
  - Includes Reactor (2400 kg), reactants (230 kg) and tanks (992 kg)

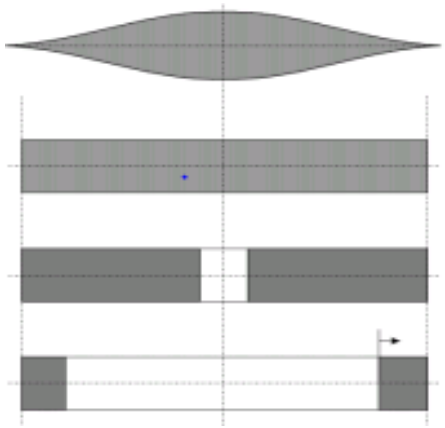
Reactant	Mass Required [kg]	Density [kg/m^3]	Al Tank Diameter [m]*	Container Mass [kg]*
Gas. H_2	30	0.082	1.4	632
Gas. O_2	200	1.308	0.98	360
*4 cm tank thickness/200 atm				

Flywheels

- Low TRL/not yet proven for space flight
- High risk: High RPM's can cause extensive damage if there is a structural failure
- Most effective when power is drawn over a short amount of time
- If flywheels can be proven for space flight, they can provide a higher energy density alternative to batteries
- Shape Factor:

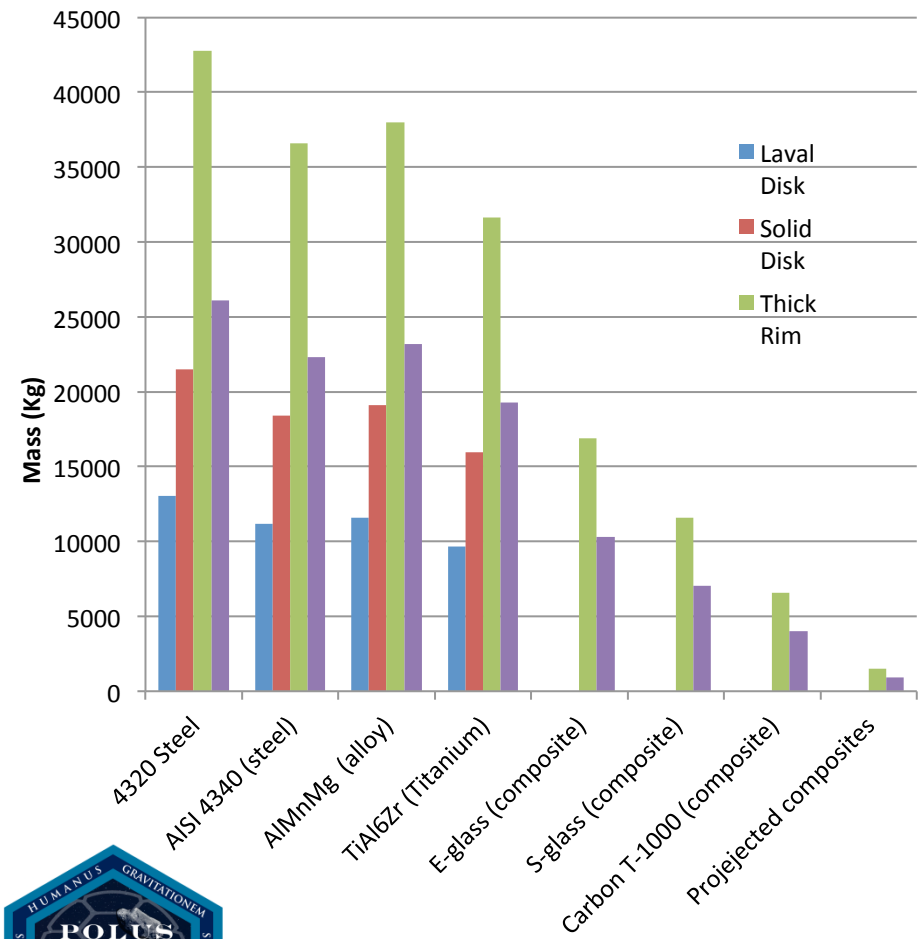
$$m = \frac{E * \rho}{k * \sigma}$$

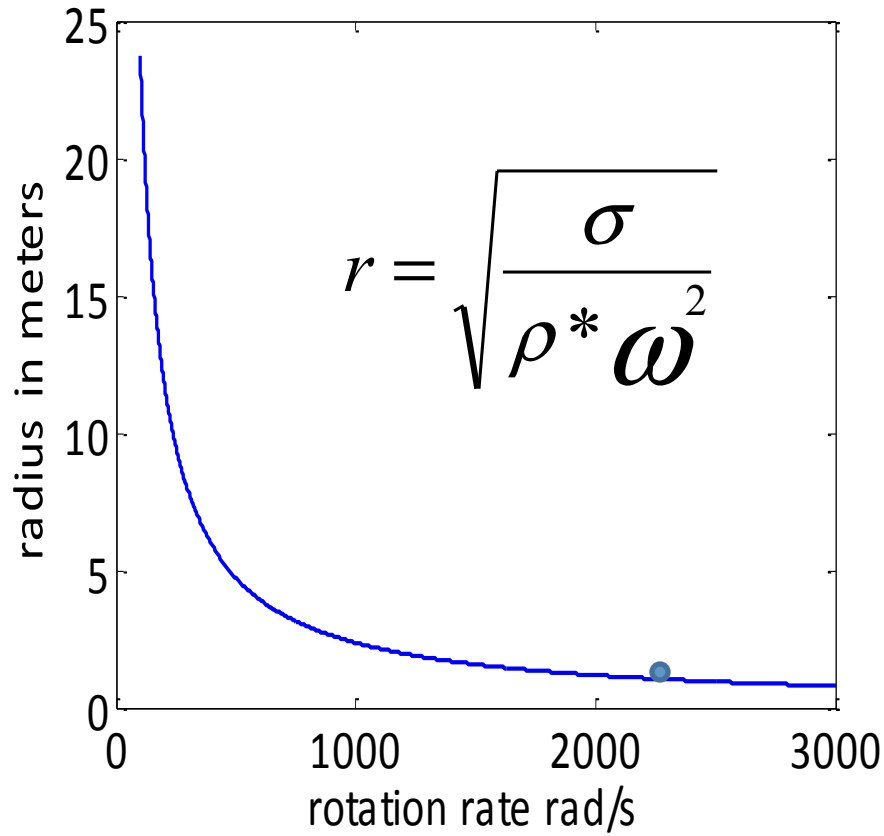
Shape	K factor
Laval disk	1
Solid disk	0.606
Thick rim	0.305
Thin rim	0.5



Flywheels

- Thin Rim Composite with 1 m radius at 22,000 rpm = 916 kg





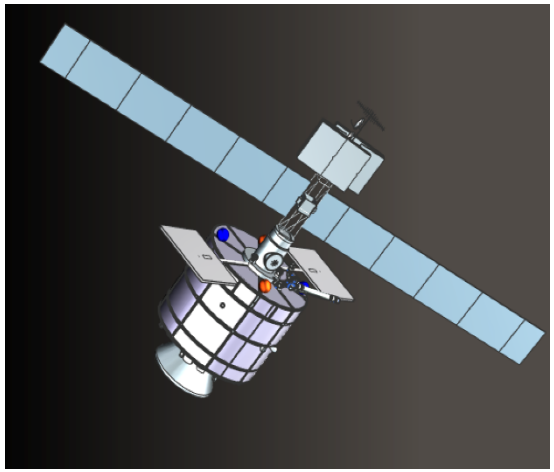
Energy Storage

- For 660 kW-hr:

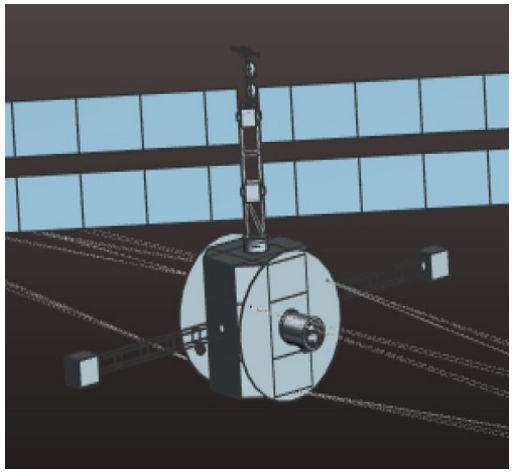
Regenerative Fuel Cell	Lithium Ion Battery	Flywheels
3620 kg Total Mass • **0.275 kW-hr/kg + 1220 kg reactants plus storage**	5500 kg Total Mass • 0.120 kW-hr/kg • ~35% more mass than fuel cells	1000 kg Total Mass • 1 m radius • 22,000 rpm • Short duration
TRL 4-5	TRL 9+	TRL 4
Risk: Moderate (Compressed H2)	Risk: Moderate (Combustion of Li-Ion Cells)	Risk: Low

- Can expect Regenerative Fuel Cells or reliable Li-Ion or Li-Polymer batteries with similar specific energy [275 W-hr/kg] to be viable by 2020

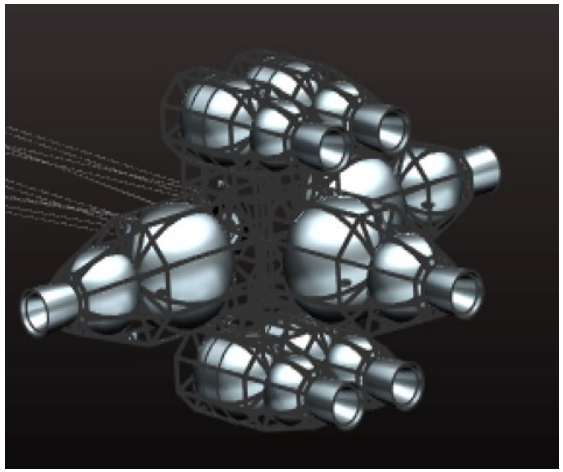
Energy Storage



- Regenerative Fuel Cell with reactants and electolyzer located at Habitat for Phase I/II/III
- 3600 kg



- Li-Ion battery located at Hub for cable motor contingency
- 15 minute startup time for fuel cells eliminates their use for emergency reel in
- 350 kg: Provides full motor power (21 kW) for two hours



- Li-Ion battery located at the Ballast for contingency in case power lines fail
- 50 kg provides thruster power for two hours

Communications Requirements

- Support constant communication with minimal dead zone/blackout scenarios
  - Communications tower must have line of sight unblocked by Hab or ballast (as much as possible)
- Nominal required Tx/Rx rates from data budget
  - 1 MBps for low-bandwidth
  - 10 MBps for high-bandwidth

Communications Networks

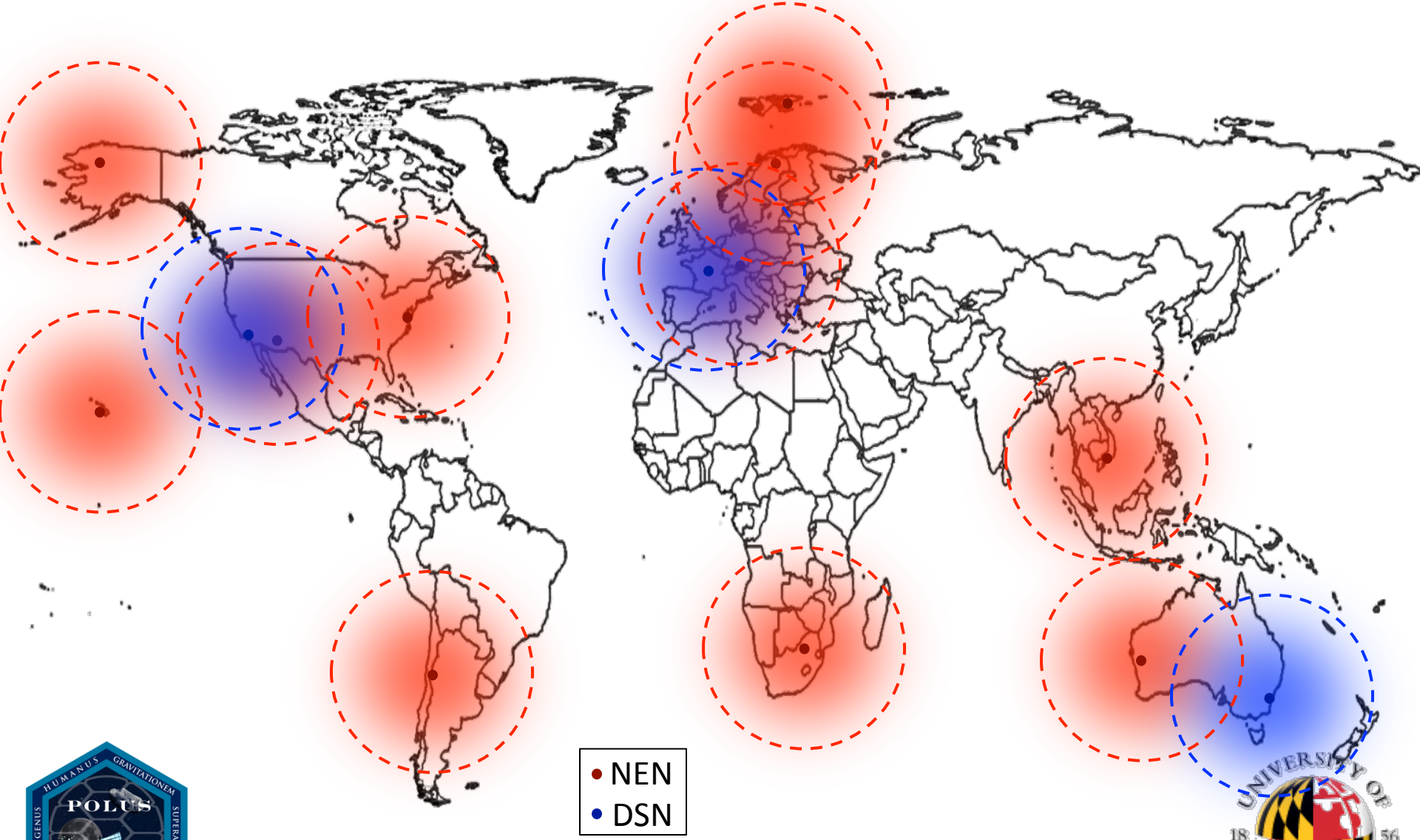
- S-band DSN ground antennas
  - 26 m antennas (Goldstone, Madrid, and Canberra)
- S-band NEN ground antennas
  - Antennas of sizes ranging from 11-18 m in Virginia, Norway, Alaska, Hawaii, Australia, Chile, New Mexico, Malaysia, South Africa, Sweden, and Germany
- UHF/VHF ground antennas
  - VHF: Wallops Ground Station (VA), White Sands Complex (NM)
  - UHF: Merrit Island Launch Annex (FL), Ponce de Leon Tracking Station (FL)

DSN & NEN Ground Antenna Specifications

Location	Diameter [m]	Tx Freq [MHz]	EIRP [dBWi]	Rx Freq [MHz]	G/T [dB/K]
Goldstone	26	2110-2120	129	2270-2300	30
Canberra					
Madrid					
Norway	11, 13	2025-2120	68	2200-2400	24.45
Alaska					23.5
Hawaii	13				
Australia					
Virginia	11.3		66		23.63
Chile	12		68	2200-2300	23
Sweden	13		70		
Germany	15		78		26.7
New Mexico	18		80		29

Sources: *Large Antennas of the Deep Space Network*, *Near Earth Network (NEN) Users' Guide*

DSN & NEN Ground Antenna Locations



Data Compression

- Standards defined by Consultative Committee for Space Data Systems (CCSDS)
- Lossless compression for telemetry, crew health data, and audio feeds
  - Preprocessor and Adaptive Entropy Encoder
  - Rice's adaptive coding technique
- Lossy compression adequate for video feeds

Bit Error Rate Analysis

Modulation	Code Type	$BER_{des} = 10^{-6}$	$BER_{des} = 10^{-5}$
		E_b/N_0 [dB]	E_b/N_0 [dB]
BPSK	Uncoded	10.5	9.5
	Hamming (7,4)	7.5	6.5
	RS (31,16)	4.5	4
	Turbo	**1**	**0.8**
QPSK	Uncoded	11	10
	Hamming (7,4)	8	7
	RS (31,16)	5.5	5
	Turbo	N/A	N/A
8QAM	Uncoded	12.5	12
	Hamming (7,4)	9.5	8.5
	RS (31,16)	7	6.5
	Turbo	N/A	N/A

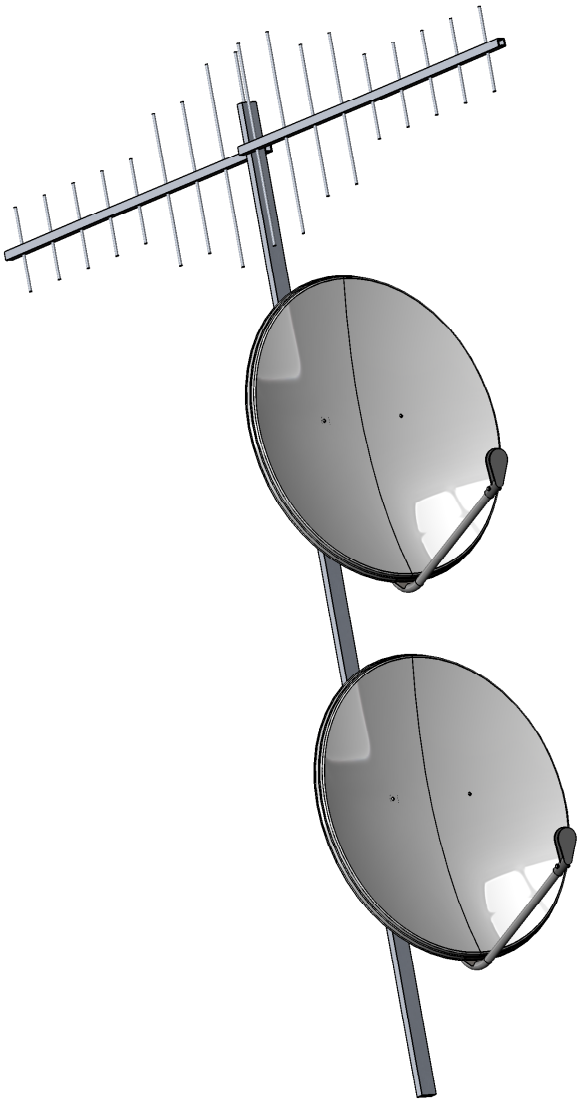
Source: *Investigation of Hamming, Reed-Solomon, and Turbo Forward Error Correcting Codes*

Data Encoding

- Viable options are Hamming, Reed-Solomon, and turbo
- Based on requirements, turbo is the best option
  - Better for long distance and low power communication
  - Achieves a low BER at a low SNR
  - Recursive Systematic Convolutional (RSC) encoders

Antenna Structure

- Top of boom: dual band yagi for UHF/VHF comms
- Middle: Ka-band dish
- Bottom: S-band dish



Link Margin Analysis (Uplink to Habitat)

	TX Diameter [m]	RX Diameter [m]	Eb/N0 Recieved [dB]	Eb/N0 Required [dB]	BER [dB]	Data Rate [bytes/sec]	Link Margin [dB]
Ka-band	11	1	31.31	9.73	-50	10 MB/s	21.58
S-band	11	1	19.17	9.73	-50	1 MB/s	19.17
VHF	Yagi	Yagi	23.37	9.73	-50	100 kB/s	13.64
UHF	Yagi	Yagi	21.92	9.73	-50	100 kB/s	12.19

RED: Nominal mode for data transmission

Link Margin Analysis (Downlink to Earth)

	TX Diameter [m]	RX Diameter [m]	Eb/N0 Recieved [dB]	Eb/N0 Required [dB]	BER [dB]	Data Rate [bytes/sec]	Link Margin [dB]
Ka-band	1	11	26.54	9.73	-50	10 MB/s	16.81
S-band	1	11	15.19	9.73	-50	1 MB/s	5.45
VHF	Yagi	Yagi	28.60	9.73	-50	100 kB/s	18.87
UHF	Yagi	Yagi	21.92	9.73	-50	100 kB/s	8.96

RED: Nominal mode for data transmission

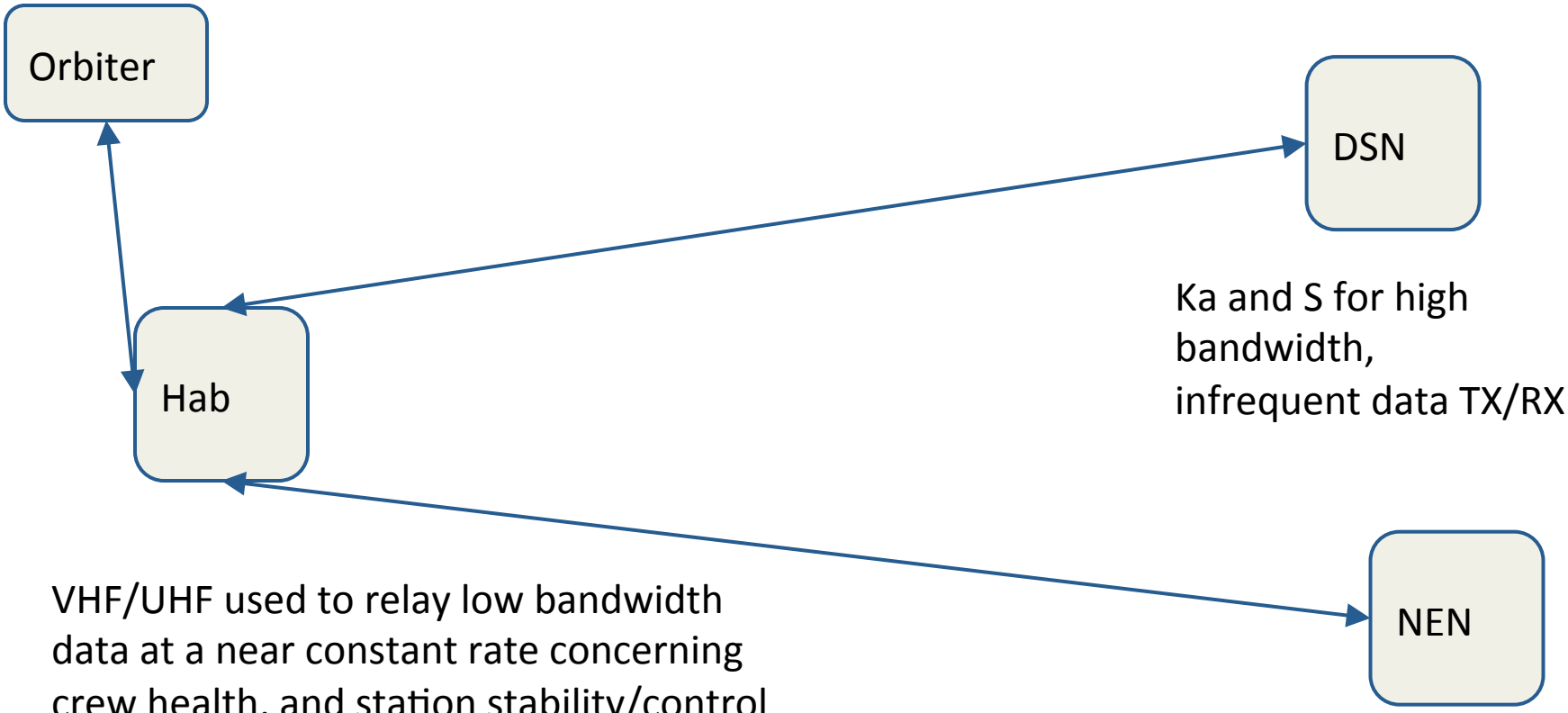
Modes of Communication

Direction	Data Rate	Antenna Type	Link Margin [dB]
Uplink to Hab	100 kb/sec	UHF-Yagi	12.19
Uplink to Hab	1 MB/sec	S-band Dish	19.17
Downlink to Earth	100 kb/sec	VHF-Yagi	18.87
Downlink to Earth	10 MB/sec	Ka-band Dish	16.81
Hab to Orbitor	10 MB/sec	VHF-Yagi	79.17
Orbitor to Hab	10 MB/sec	UHF-Yagi	67.71

Modes of Communication

1. Use VHF/UHF to send/receive vital information (astronaut health, atmosphere and structure stability) at a minutely rate (low bandwidth ~100 kB/s)
2. Ka-band used to transmit HD video feed (high bandwidth ~10 MB/s)

Communications Architecture



Ka and S for high bandwidth, infrequent data TX/RX

VHF/UHF used to relay low bandwidth data at a near constant rate concerning crew health, and station stability/control

Also used for communications with orbiter

Communications Backup

- Spare yagi, S, and Ka antenna to be kept on board habitat
- Best case: all antennas fully functional
- Worst case: only yagi or one dish; low bandwidth data rate sufficient to allow for repairs to be made as necessary to dysfunctional equipment

ADCS Reaction Wheels

- Requirements (Phase I):
  - Maintain .1 rev/min around x-axis
  - Slew 0.02 deg/s around y, z-axes

	Moment of Inertia (kg-m^2)
I_{xx}	3.435×10^6
I_{yy}	7.302×10^5
I_{zz}	7.700×10^5

- 0.5 m diameter, Graphite Aluminum
- 2000 RPM
  - Max rate of 3000 RPM
- Housed in 0.55x0.55x0.3 case
  - 6061-Aluminum
- Outer Rim: 0.02x0.1 m
- Inner Disc: 0.02x0.02 m

- Spin up time: 20.8s
  - Motor provides 10 N-m
- Mass: 20.6 kg
- Housing Mass: 32.1 kg
- Power Required: 41.7 W

- Total Mass (4 wheels+Motors): 250.8 kg
- Total Power (3 wheels): 125.1 W

ADCS Trade

Phase I:

	Total Mass (kg)	Total Power (W)
Reaction Wheels	**2085.7***	**125.1**
Propellant	2919	144

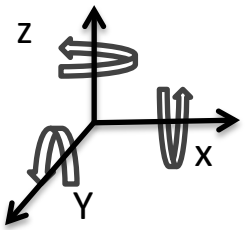
*Assumes propellant mass needed to de-saturate every 90 days

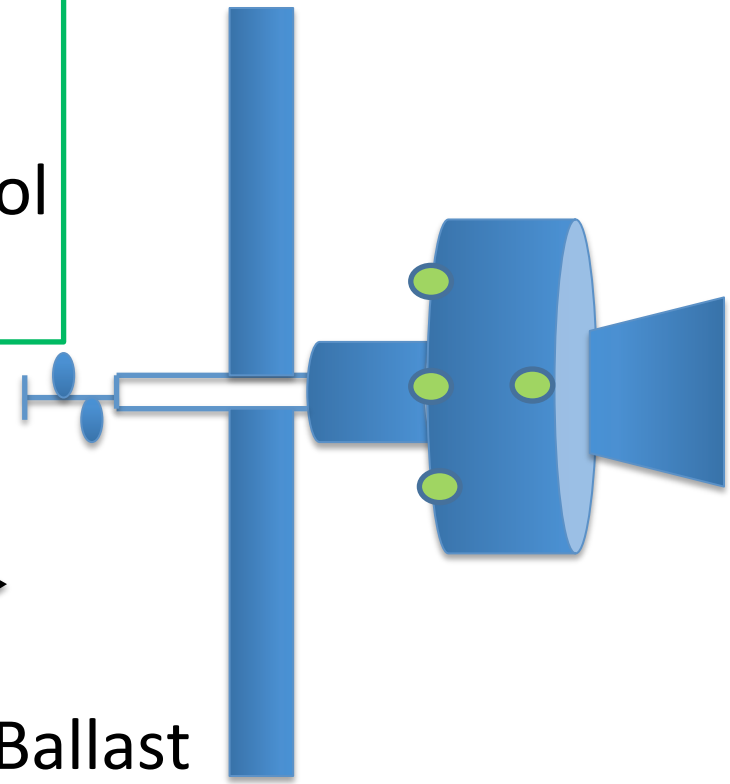
Phase II & III:

- Wheels already available
  - No added mass or cost of propellant

Reaction Wheel Placement

- Phase I:
  - All on Habitat
  - Three axes rotational control
  - 4th wheel as contingency

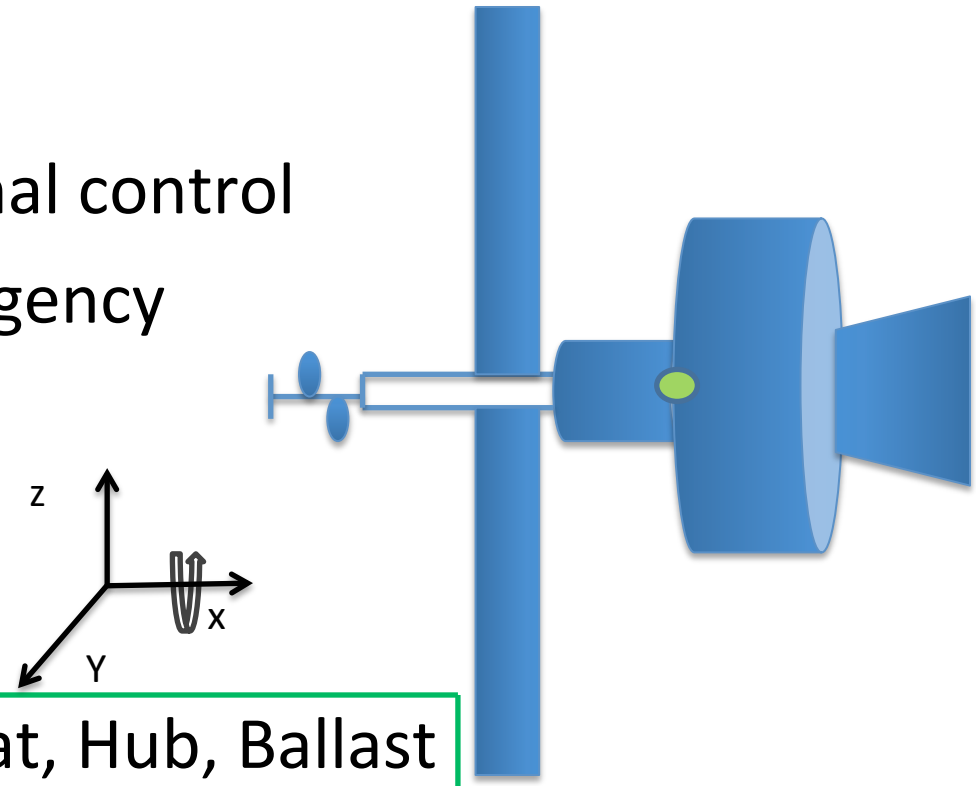




- Phase II & III:
  - One each on Habitat, Hub, Ballast
  - Prevents twisting around x-axis for all three cases

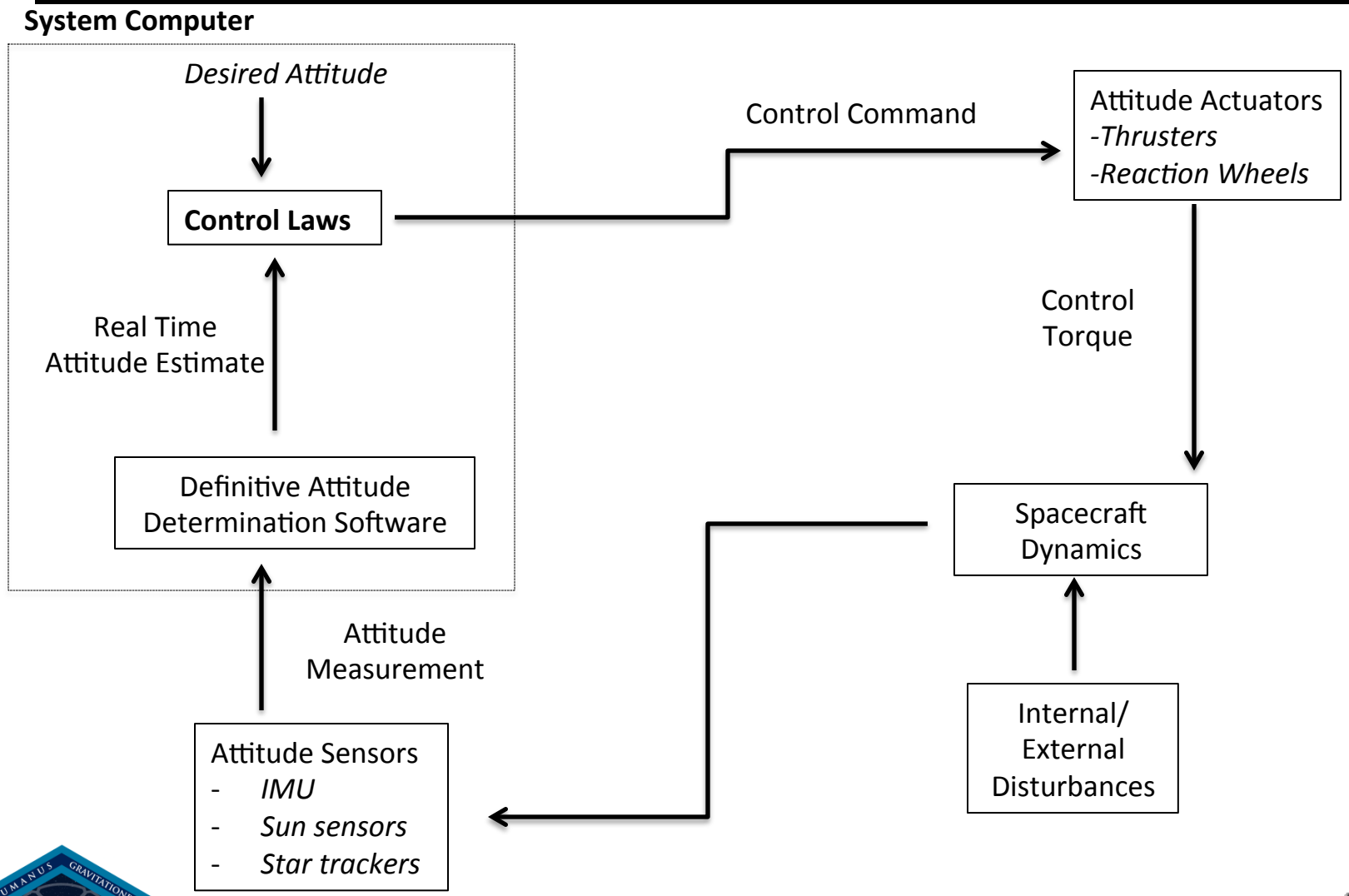
Reaction Wheel Placement

- Phase I:
  - All on Habitat
  - Three axes rotational control
  - 4th wheel as contingency



- Phase II & III:
  - One each on Habitat, Hub, Ballast
  - Prevents twisting around x-axis for all three cases

ADCS System



Adapted from Space Mission Engineering: The New SMAD

GNC

- Requirements:
  - Maintain DRO
  - Achieve and maintain a safety ellipse 'orbit' around the asteroid
- Sensors utilized
  - IMUs
  - Star Trackers
  - Sun sensors
- The flight computer will take sensor data and implement a control algorithm to complete requirements of the Polus mission

3 Fault Tolerant Design Option

Five total computers.
- Four on, one on standby

→

One of four fails/outputs incorrect result
- Decision will be correct because three computers are correct

→

Three computers that can be trusted
- Another fails, but two are still correct

→

Turn on fifth computer.
- Three computers on and voting.

→

Can tolerate one more complete failure and still have correct result

- System has flight heritage
  - Used on Space Shuttle
- Allows for voting even after 2 faults
- No subsystem requires flight computers to make mission critical decisions that must be immediate and voted on.

2 Fault Tolerant Design Option

Four computers available
- Will use three computers with one on standby

If one computers fails, turn on standby computer
- Three computers are in use

In case of another failure, two computers available
- Cannot vote, but will know if computers output different results

- This system is 2 fault tolerant, but does not allow for voting after 1 fault

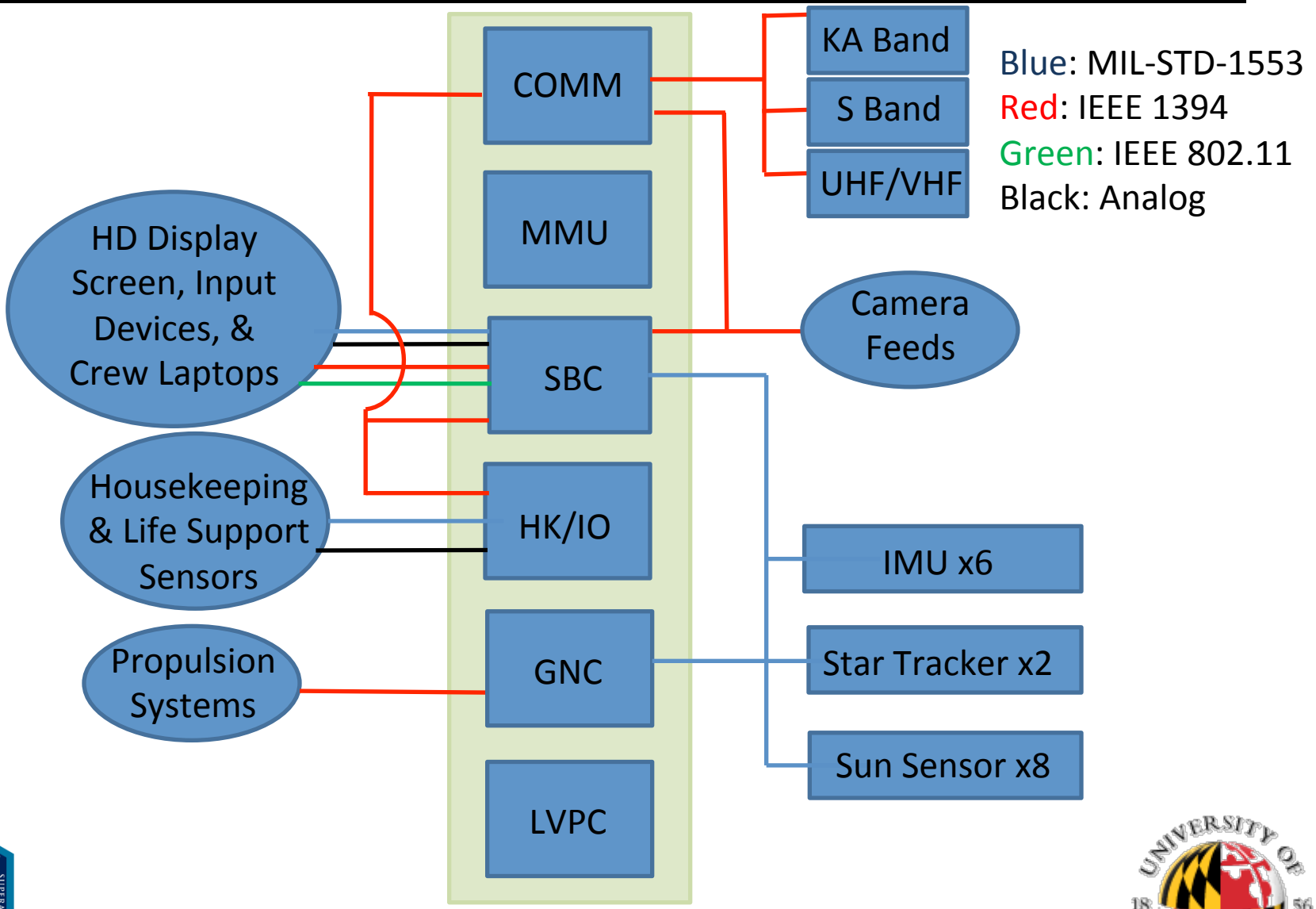
Fault Tolerant Computer

- Error detection and correction (EDAC)
  - Reed-Solomon error correction
  - Random Access Memory (RAM) Scrubbing
- Watchdog Timer
  - Prevent time-outs
- Confirmation Flags
  - Check for spurious interrupts
- Counter
  - Check for missed interrupts
- Redundant status register check
  - Check for incorrectly prioritized interrupts
- Cyclic Redundancy Check (CRC) Checksum
  - Check for read only memory (ROM) corruption
- Safe mode
- Self-test Programs

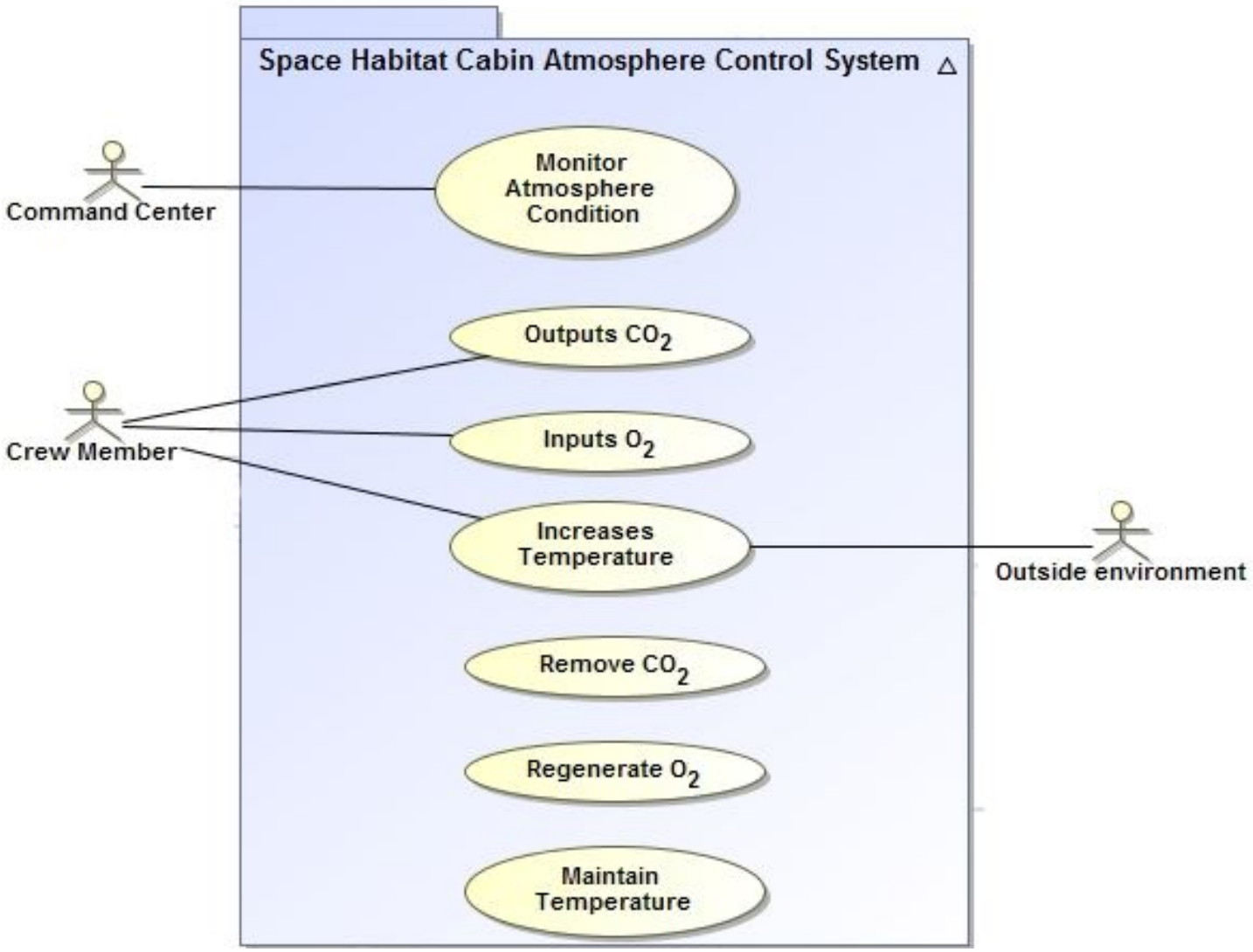
Command and Data Handling (C&DH)

- MIL-STD-1553 (Ethernet)
  - TRL 9
  - 1 Mbps
  - Low error rate of 1 word fault per 10 million words
  - Dual-redundant architecture
  - Transformer coupling
    - Better impedance matching, higher noise rejection characteristics
    - Prevents a terminal fault or stub impedance mismatch from affecting the entire bus
- IEEE 1394 (FireWire)
  - TRL 9
  - 800 Mbps
- IEEE 802.11 (Wi-Fi)
  - TRL 9
  - 11 Mbps
- Mass memory unit – Solid State Recorder
  - Memory on the order of Tbs
  - Power: 100 W Mass: 20 kg Volume: 0.0375 m^3

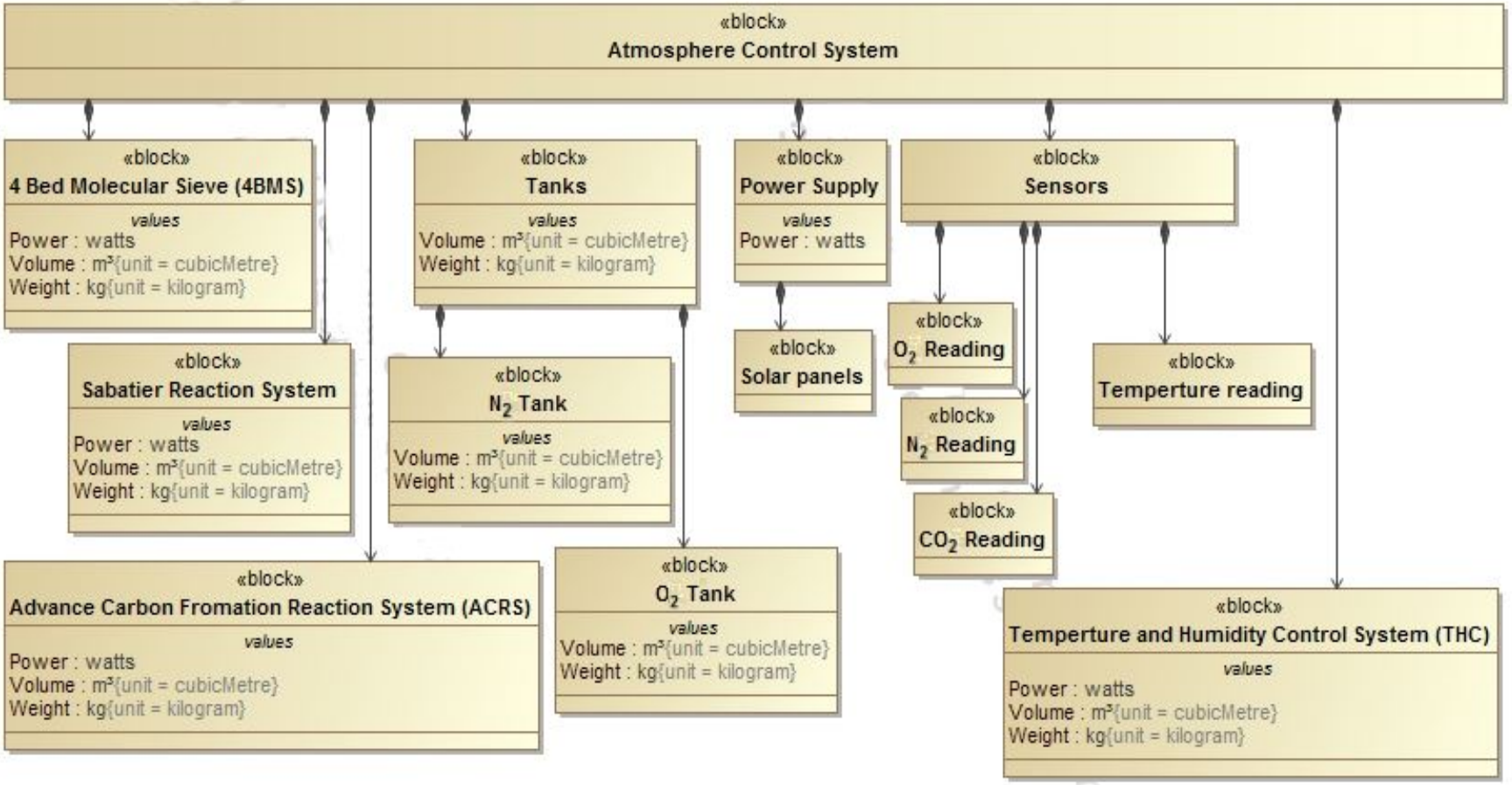
POLUS Avionics System Block Diagram



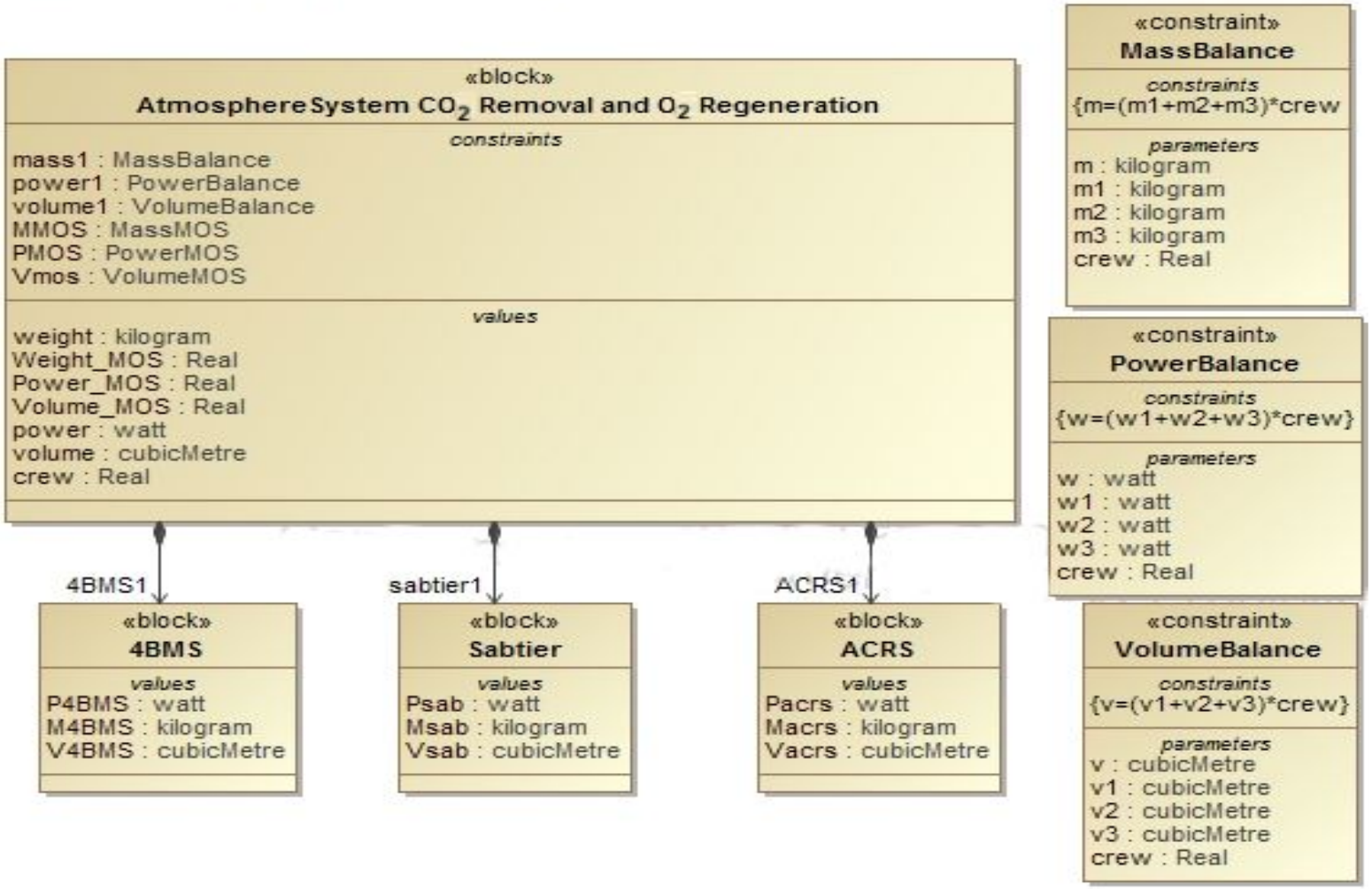
Use Case Diagram



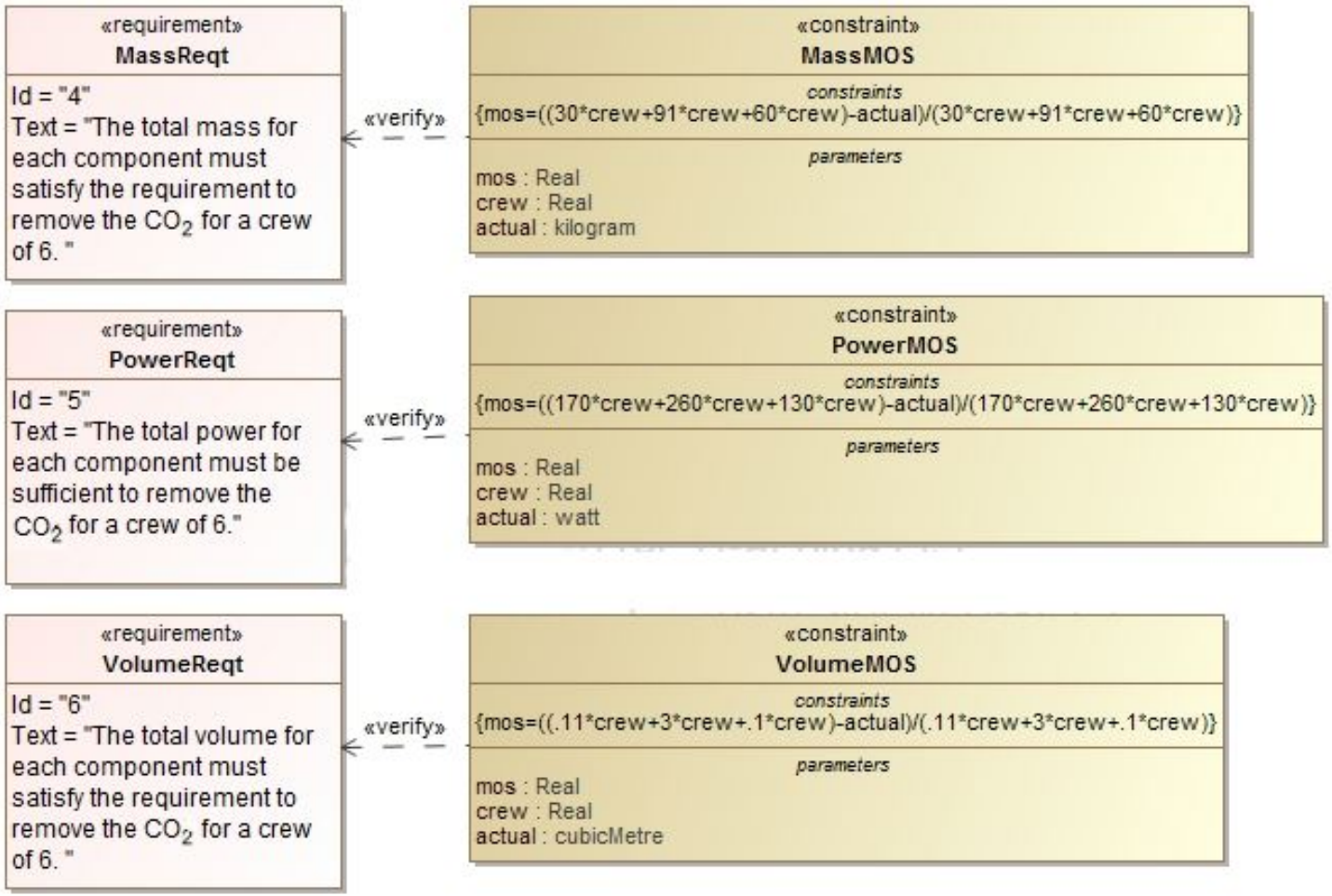
Block Definition Diagram



BDD for O_2 Regeneration



Mass, Volume, Power Requirements

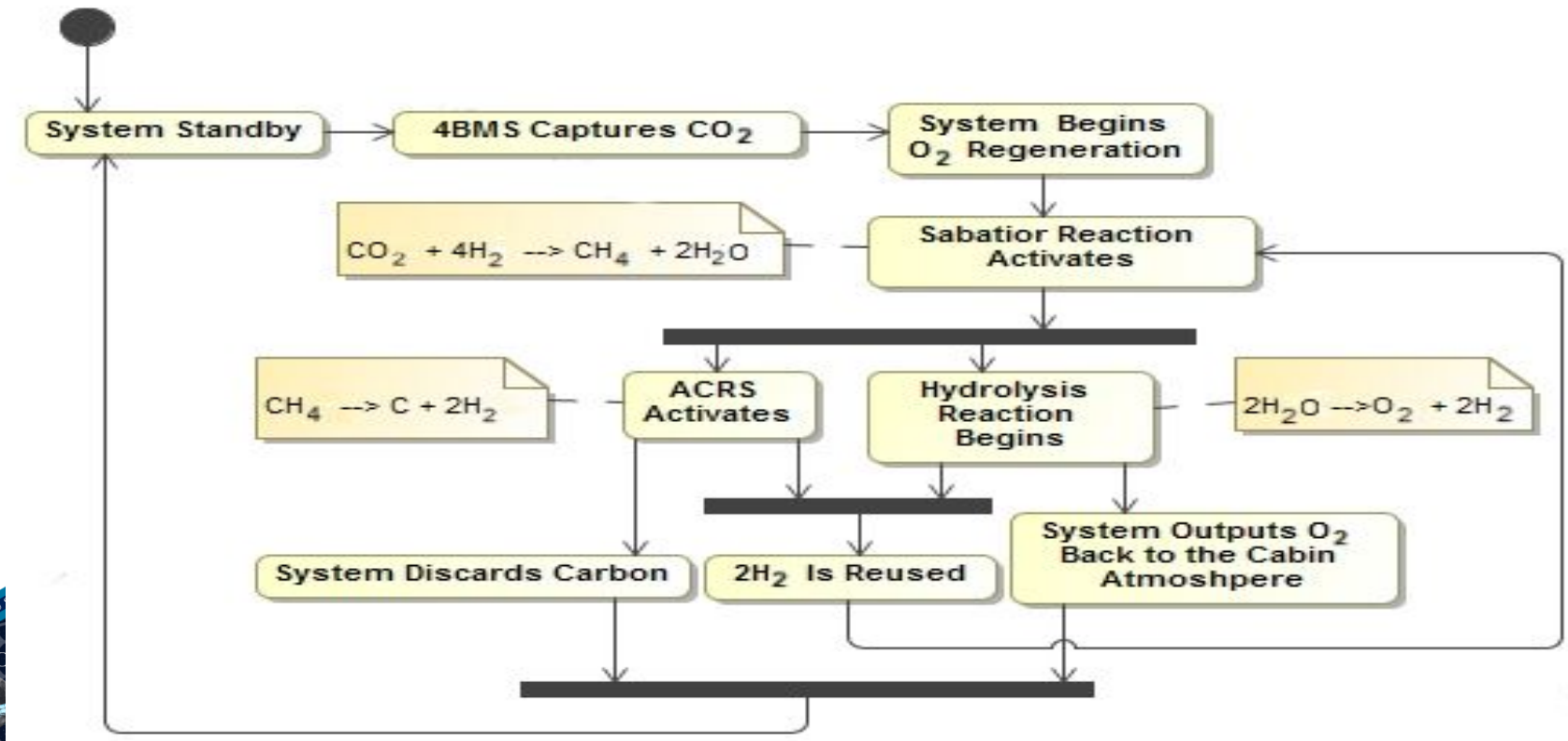


O_2 Regeneration Activity diagram

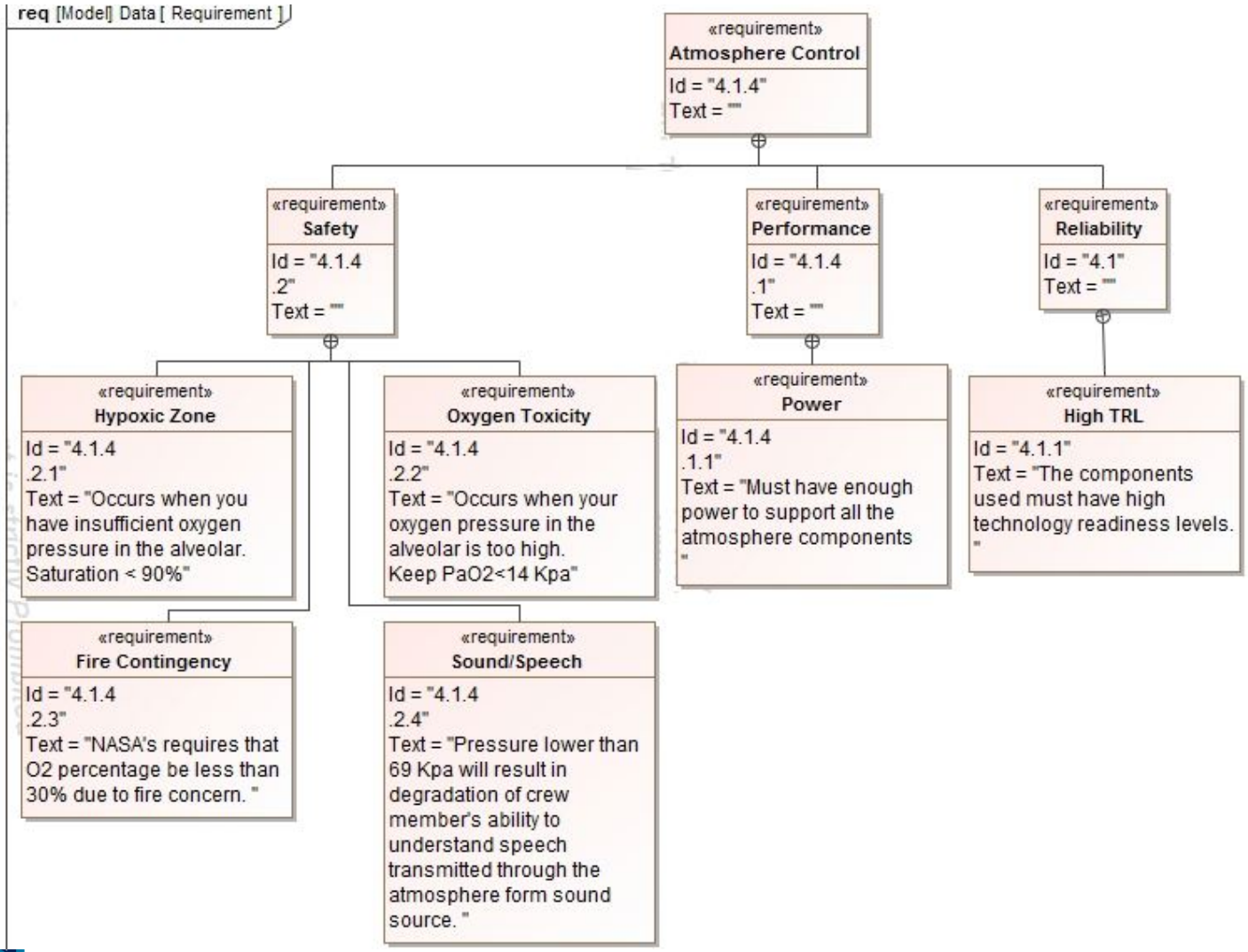
Values to Remove CO_2 for a crew of 6

System	Power [W]	Weight [kg]	Volume [m^3]
CO_2 Removal/O_2 Regeneration	4032	1303	23

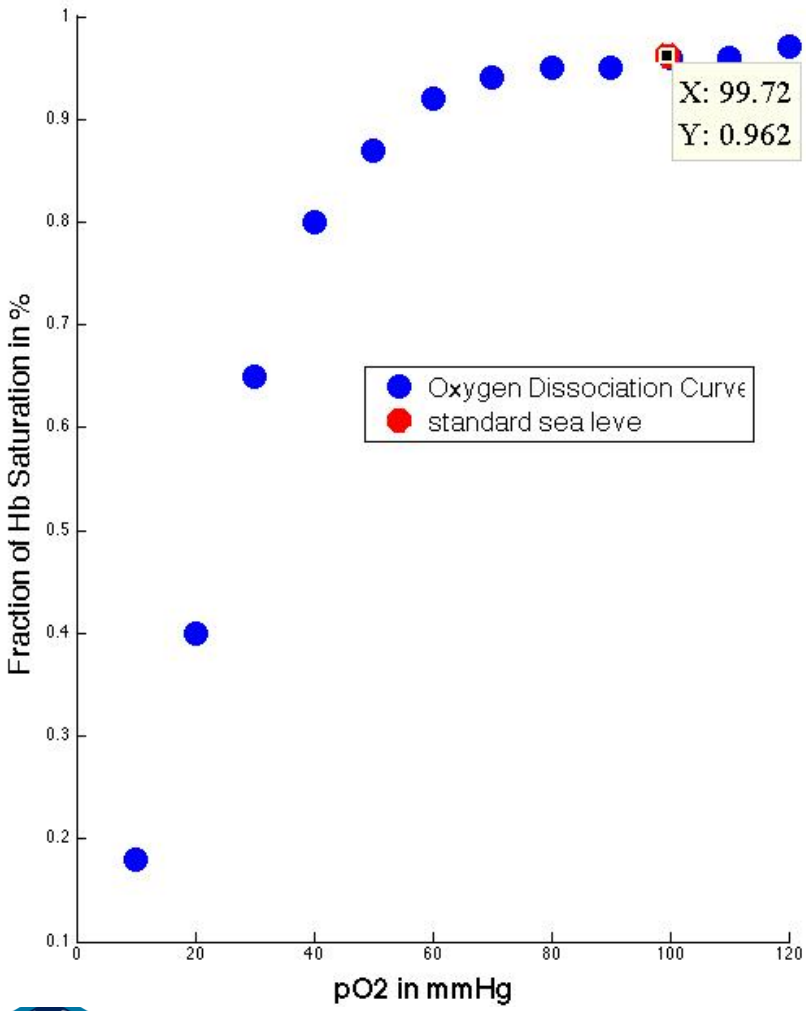
- The table shows the total amount of power, weight, and volume the CO_2 removal / O_2 regeneration system will have.
- A 1.2 margin of safety is applied to account for exercise and EVA days.

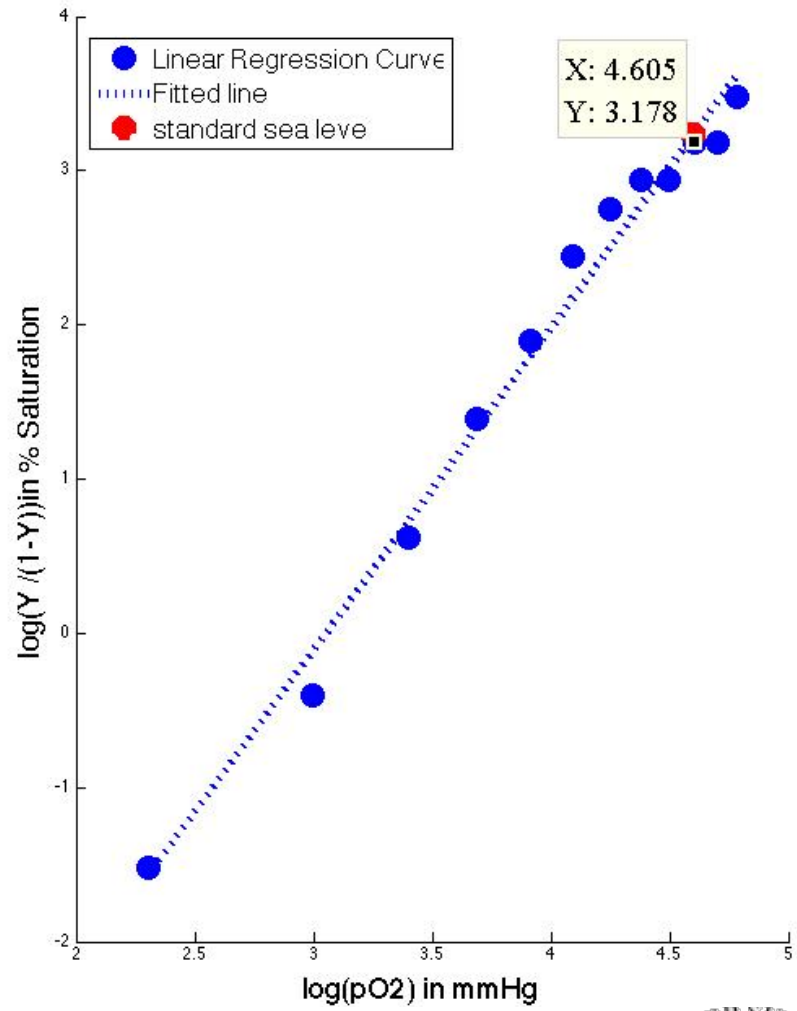


Atmosphere Requirement Diagram



Determining O_2 Percentage





Pressure and O_2 Trade Study

Cabin Pressure [kPa]	$\%O_2$	O2 Pressure Felt in the Alveolar (PaO_2) [kPa/mmHg]	Saturation%	PaO_2 at (SSL) – PaO_2 in cabin [kPa]
*101.32	21	13.3/99.7	96.2	0
62	30	10.4/78.4	93.87	2.9
72	**30**	**13.4/101**	**96.3**	**-0.1**
54	32	9/67.5	91.82	4.3
34.47	80	18.9/141.36	97.4	-5.6

- A cabin Pressure of 72 kPa and a 30% O_2 satisfies all of our requirements
- No denitrogenation will be required

O_2 and N_2 Tanks

- The airlock will be depressurized to 1 kPa and the remainder of the air will be vented out
- The largest airlock has a volume of 55.7 m^3. At cabin atmosphere condition the air in the airlock mass sums to 47.17 kg. When depressurized to 1 kPa about 1.4% of the air mass will remain and be vented off
- 0.7 kg (0.49 kg of N_2 and 0.21 kg of O_2) of air will be lost per depressurization
- There will be resupply of N_2 and O_2 to support up to 250 EVA (1 EVA per week) for the duration of the mission
- For contingency purposes there will be enough N_2 and O_2 to pressurize Mars SIM

	Mass [kg]	Volume [m^3]
O_2/O_2 tanks for EVA	89	0.8
N_2/N_2 tanks for EVA	208.3	2.13
O_2/O_2 tanks for Mars SIM	52	0.47
N_2/N_2 tanks for Mars SIM	121.3	1.09
Total	470.6	4.49

Galley Mass and Volume Estimates

		Duration	Mass [kg]	Volume [m³]
Food	Phase I	30 Days	207	0.31
		6 Months	1241	1.83
	Phase II	Three 6 Month Missions at Different Gravities	1862 for each	2.75 for each
	Phase III	1000 Days	11,140	16.13
Refrigerator	Phase I,II,III	All Duration	67.75	0.72
Microwave Oven			11.34	0.043
Galley Sink			27.22	0.377

Food Regeneration

- Food regeneration is difficult for missions less than 5 years
- The food produced by food regeneration would provide less than 1% of the crew's food energy

Food Regeneration Based on Data from NASA Ames				
	Mass [kg]	Volume [m^3]	Power [kW]	Total Meals Produced in 6 Months
Food Regeneration	1218	12.36	13	12.86

Hygiene Mass and Volume Estimates

	Mass [kg]	Volume [m^3]
Toilet-Liquid Waste	9.25	0.043
Toilet-Solid Waste	64.9	0.481
Shower	43.32	0.97
Washcloth	0.23 per cloth	$4.4*10^{-4}$ per cloth
Personal Hygiene Items (Phase I– 30 Days)	10.77	0.034
Personal Hygiene Items (Phase I–6 Months)	64.61	0.207
Personal Hygiene Items (Phase II- Three 6 Month Missions at Different Gravities)	96.9 for each	0.309 for each
Personal Hygiene Items (Phase III-1000 Days)	538.4	1.72
Hygiene Cleansing Station	11.9	0.099

Shower and Toilet

- Toilet-Liquid Waste

	Mass [kg]	Volume [m^3]
Aperture Urinal	9.435	0.089
Urine Collection Module	**9.253**	**0.043**

- Solid Waste

	Mass [kg]	Volume [m^3]
Fecal Collection Module	**64.9**	**0.48**

- Shower

	Mass [kg]	Volume [m^3]
Shower with Fixed Nozzle	**43.32**	**0.97**
Whole Body Shower	150.6	3.11

Types of Waste

- Waste can be categorized into the following:
  - Crew common trash
    - Wet/dry used or expired consumables
    - Hygiene products
    - Food waste
    - Human waste
  - Hardware trash
    - Used, defective, expired hardware
  - Hazardous waste
    - Batteries, biological/biomedical, sharps, chemical, and radioactive

Containment and Handling

- All waste containers will include labeling identifying trash type
- Hazardous waste container will be labeled accordingly with identification of all included hazards: battery, biological, sharps, chemical, radioactive
- Nonhazardous waste label will indicate either wet or dry status

Waste Containers (i)

Waste Containers	Description	Acceptability for Hazardous Waste	Usable Volume [m^3]	Unit Mass Empty [kg]	Unit Mass (Full) [kg]
Soft Trash Bag (KBO-M)	Used for wet or dry trash	Yes	0.03	0.79	8
Solid Waste Container (KTO)	Used for solid and biological waste	Yes	0.04	3.5	11.5
Container for Water/Urine (EDV)	Used for urine and wastewater collection	No	0.02	5.5	26.5
Food Waste Bag	Used to replace table scraps and wet items	No	$2.6*10^{-3}$	0.06	0.9

Source: Management Plan for Waste Collection and Disposal. NASA/SSP 50481B

Waste Containers (ii)

Waste Containers	Description	Acceptability for Hazardous Waste	Usable Volume [m^3]	Unit Mass Empty [kg]	Unit Mass (Full) [kg]
Sharps Container	Used to dispose sharp objects	Yes	$2.4*10^{-3}$	0.39	1.36
Plastic Waste Bag	Used for non sharp hazardous waste	Yes	0.11	0.05	TBD
Fecal Collection Assembly (Apollo Bag)	Used as contingency bag for solid human waste	No	$2*10^{-4}$	0.06	TBD
Contingency Urine Collection Device (CUCD)	Used as a contingency bag for liquid human waste	No	$5*10^{-4}$	0.03	TBD

Source: Management Plan for Waste Collection and Disposal. NASA/SSP 50481B

Trash Disposal

- Trash receptacles located within the habitat will use manual compaction methods for storage and removal of waste
- Trash receptacles will have a manual compaction trash density of **67 kg/m^3** (average density estimate based on data from MARPOL study and Skylab)
- Trash generation rate of **1.83 kg/crew member/ day**
- CTB's of varying sizes will be used as a means of temporary storage for compacted trash

Solid Waste Recycle Methods

- High Efficiency High Output Plastic Melt Waste Compactor (HEHO-PMWC)
  - Dimension: 0.46m W x 0.55m H x 0.48m D
  - Mass: 59 kg
  - Compaction chamber volume: 0.045 m^3
- PMWC uses heat and compaction to sterilize, reduce and encapsulate volume of trash
  - Volume reduction factor of 11:1
  - Produces an 40.6 X 2.5 cm square tile of hard plastic, which may be utilized for shielding
  - Chamber sized to support 11 kg trash per day
    - Operates 3 times per day with 3-4 kg per batch
    - Trash accumulation for 6 crew per day = 10.98 kg

Clothes Estimate

Clothing	Mass [kg]	Change rate for 0g (days)	Change rate for 1g (days)	Change rate for partial gravity (days)	Amount required for 0g (180 days, 6 crew) [kg]	Amount required for 1g (180 days, 6 crew) [kg]	Amount required for partial gravity (180 days, 6 crew) [kg]	Amount required for partial gravity (1000 days, 6 crew) [kg]
Shorts	0.48	10	2	3	51.84	259.2	172.8	961.8
Pants	0.62	10	2	3	67.2	334.8	223.2	1242.6
T-shirt	0.17	10	2	3	18.36	91.8	61.2	340.8
Socks	0.06	2	1	1	32.4	64.8	64.8	360
Underwear	0.065	2	1	1	35.1	70.2	70.2	390
Exercise shirt	0.135	3	1	1	48.6	145.8	145.8	810
Exercise shorts	0.0992	3	1	1	35.7	107.4	107.4	595.2
Total					**289.2**	**1074**	**845.4**	**4700**

Laundry System

- Advanced Microgravity Compatible, Integrated Laundry System (AMCIL)
  - Uses two phase water / water vapor system to allow good agitation of clothes during wash and rinse cycle
  - Drying achieved through microwave assisted vacuum drying and "jet" air flow
  - Fully operational in microgravity and partial gravity (Lunar, Mars)
  - Currently in development by UMPQUA Research Company
- Partial gravity simulation of 1000 days
  - Initial amount of clothes = 140.9 kg (1 month's worth)
  - Wash rate = once per week
  - Mass of water required to wash every week for 1000 days = 418 kg
  - Mass of typical washing machine: 80 kg
  - Total mass for 1000 days of partial gravity = **638.9 kg**

Stowage

- Stowage will be based on volume estimates of various items

Items	Volume Required [m^3] for Mission Duration, 6 crew	Stowage Volume [m^3]
Food	15.25	16.13
Hygiene Products	2.24	3
Clothes	3	3
Personal Equipment	3.78	3.8
Trash	5	5
Exercise Equipment	1.2	1.2
Workstation	2	2

Water Consumption

	Drinking (Regular Day) [kg/person/day]	Drinking (EVA day) [kg/person/day]	Food Prep [kg/person/day]	Hygiene [kg/person/day]	Clothes Washing [kg/week]
Phase I	2	4	0.75	4-7	38
Phase II	3	5	0.75	4-7	38
Phase III	3	5	0.75	4-7	38

- Non-regenerative system would require more than 55,000 kg water for 1000 day mission

Water Regeneration

- Water Processing Unit (WPU) inside habitat
  - Vapor Compression Distiller (VCD)
    - Processes urine and grey water
  - Filtration system
    - Filters remove large particles
    - Multi-filtration beds remove impurities
    - Catalytic oxidation reaction removes volatile organic compounds and kills bacteria and viruses
  - Specifications
    - Mass: 350 kg
    - Volume: 2 m^3
    - Power: 350 W

Total Water Budget

- Recycling efficiency 93%
  - Losses due to solid waste moisture, untreatable urine brine, moisture in leaked air

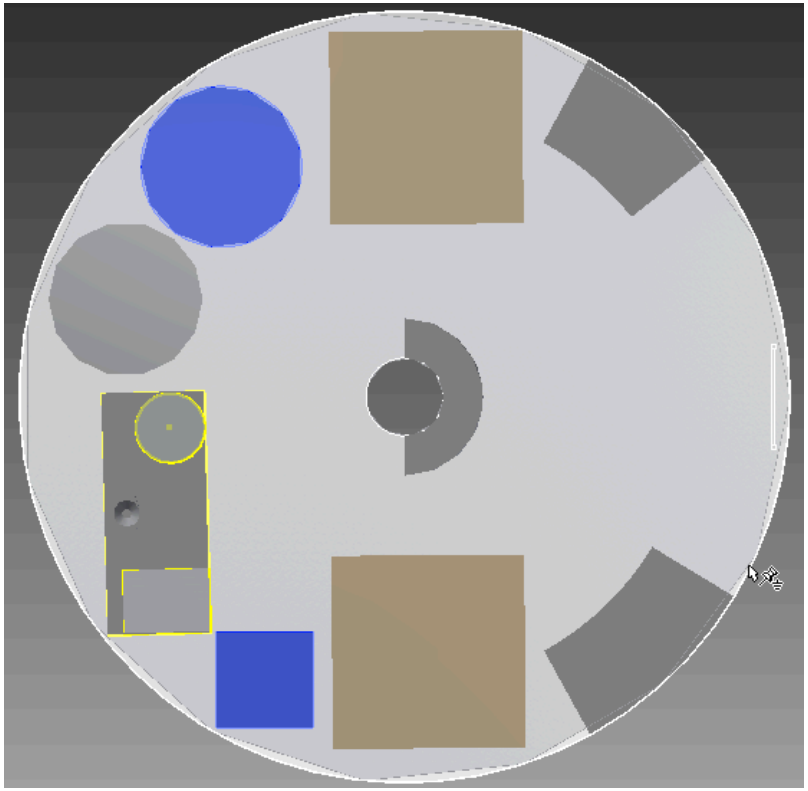
	Water lost from system [kg]	Nominal water required [kg]	Contingency Supply [kg]
Phase I (4 crew, 180 days)	470	575	470
Phase II (6 crew, 180 days)	720	920	875
Phase III (6 crew, 1000 days)	4115	4315	875

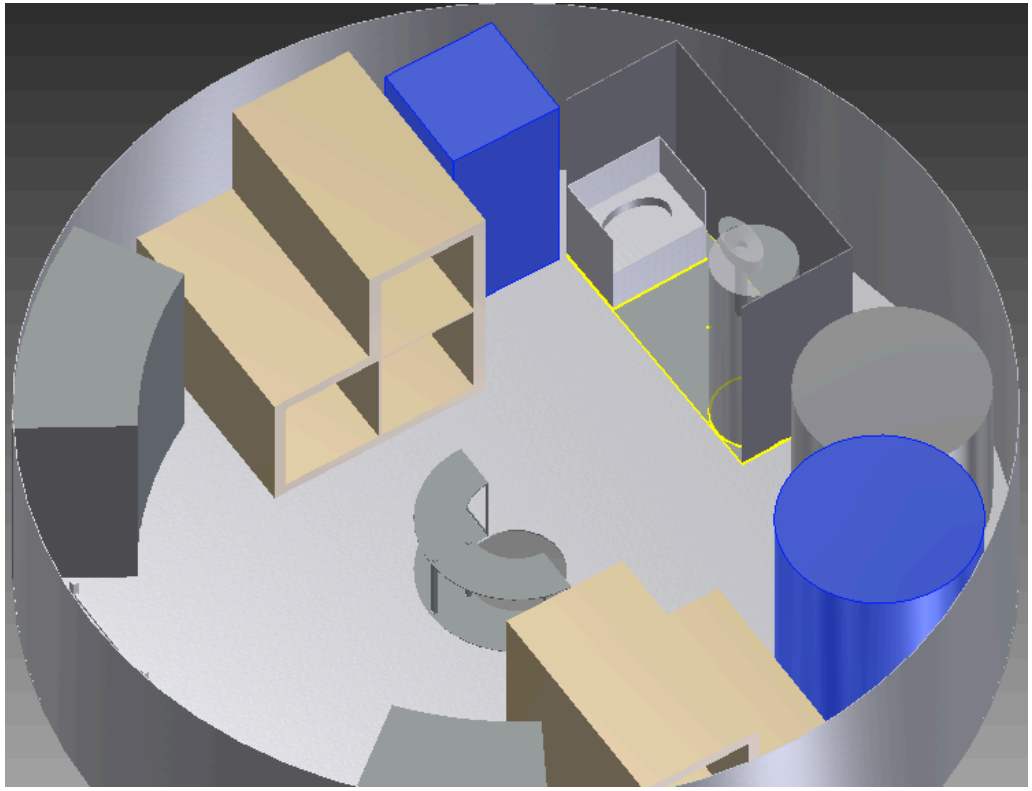
  - Contingency supply includes reserve water for 30 days and 5 EVA events

Water Storage

- One 4400 L tank inside habitat next to WPU
  - Stores potable water
  - Spigot for ambient temperature water
  - Spigot for hot water at 322.2 K (49° C)
  - Gauges indicate water quantity and temperature
- One 900 L tank in Mars SIM storage area
  - Stores Phase III contingency water
- One 250 L tank part of WPU
  - Stores used water and urine before processing
- Water pumped from resupply vehicle into tank
  - Pump requires 1.5 kW power
  - Takes 16 minutes to transfer 4000 L

Water Regeneration Location





Water Processing Unit and Main Tank shown in blue

Fire Detection & Suppression

- Smoke detectors
  - Alert crew to presence of fire
  - Located in each separate area of the station
- Portable breathing apparatuses
  - Provide 15 minutes emergency oxygen
  - 1 for each crew member on each level of habitat
  - 3 in Mars SIM
  - 3 in center Hub
- Fire extinguishers
  - Fine Water Mist technology
  - Located in each separate area of the station
- Flame retardant fabrics

Exercise

Exercise Requirements	TVIS	RED	CEVIS	EVA HW
Aerobic/Anaerobic training	XXX	X	XXX	
Neuromotor conditioning (coordination, muscle tone)	XXX			
Axial high-impact skeletal loading	XXX			
Stregth/endurance training of postural muscles	XX	XXX	X	
Skeletal muscle strength/endurance training	X	XXX	X	
Axial high-strain skeletal loading		XXX		
EVA arm exercise training		XX	XXX	
EVA handgrip strength training				XXX
EVA 2-hr prebreathe exercise countermeasure			XXX	
Aerobic/Anaerobic fitness assessment	X		XXX	
EVA arm ergometry assessment			XXX	

Note: Number of X's indicates effectiveness

TVIS: Treadmill Vibration Isolation System
RED: Resistive Exercise Device
CEVIS: Cycle Ergometer Vibration Isolation System
EVA HW: Handgrip equipment

(ISS Exercise Countermeasures. Johnson Space Center)

Exercise

Exercising Machine	Body Volume Needed for Operation for 0g [m^3]	Mass [kg]
TVIS	6.12	180
CEVIS	1.70	27

(Human Integration Design Handbook. NASA/SP-2010-3407)

- Most complete exercising machine: CEVIS
  - Can be used in all gravitational cases
  - It supports:
    - Science activities
    - Pre-breathe extravehicular activities (EVA)
    - Periodic fitness evaluations (PFE)
    - Pre-landing fitness evaluations
- To complement:
  - TVIS
    - Can adjust the Series Bungee System so that it is operational in all gravitational cases
  - Resistance bands
    - For strengthening body in a dynamic and easy way when in partial gravity and microgravity
  - Exercise Hand Grips
    - To increase hand dexterity for EVA performance

ALL EXERCISE EQUIPMENT CAN BE USED IN ALL GRAVITATIONAL FIELDS

Space Suits

	Requirement	Comments
Configurations	1 for Intravehicular Activities (IVA); 1 for Extravehicular Activities (EVA)	*i.e. Constellation space suit* EVAs in microgravity and terrestrial
Operating pressure	4 psi	*i.e. Extravehicular Mobility Unit (EMU)* 10.4 psi to 4 psi → Denitrogenation with pure oxygen = 40 min inside suit
Air composition	100% O_2	
Mobility	Compatible with EVA and IVA missions	
Donning	< 5 minutes when emergency	Including preparation and connection to the vehicle
Mass	IVA configuration: < 40 kg EVA configuration: < 70 kg	Fully suited (with all the life support systems)

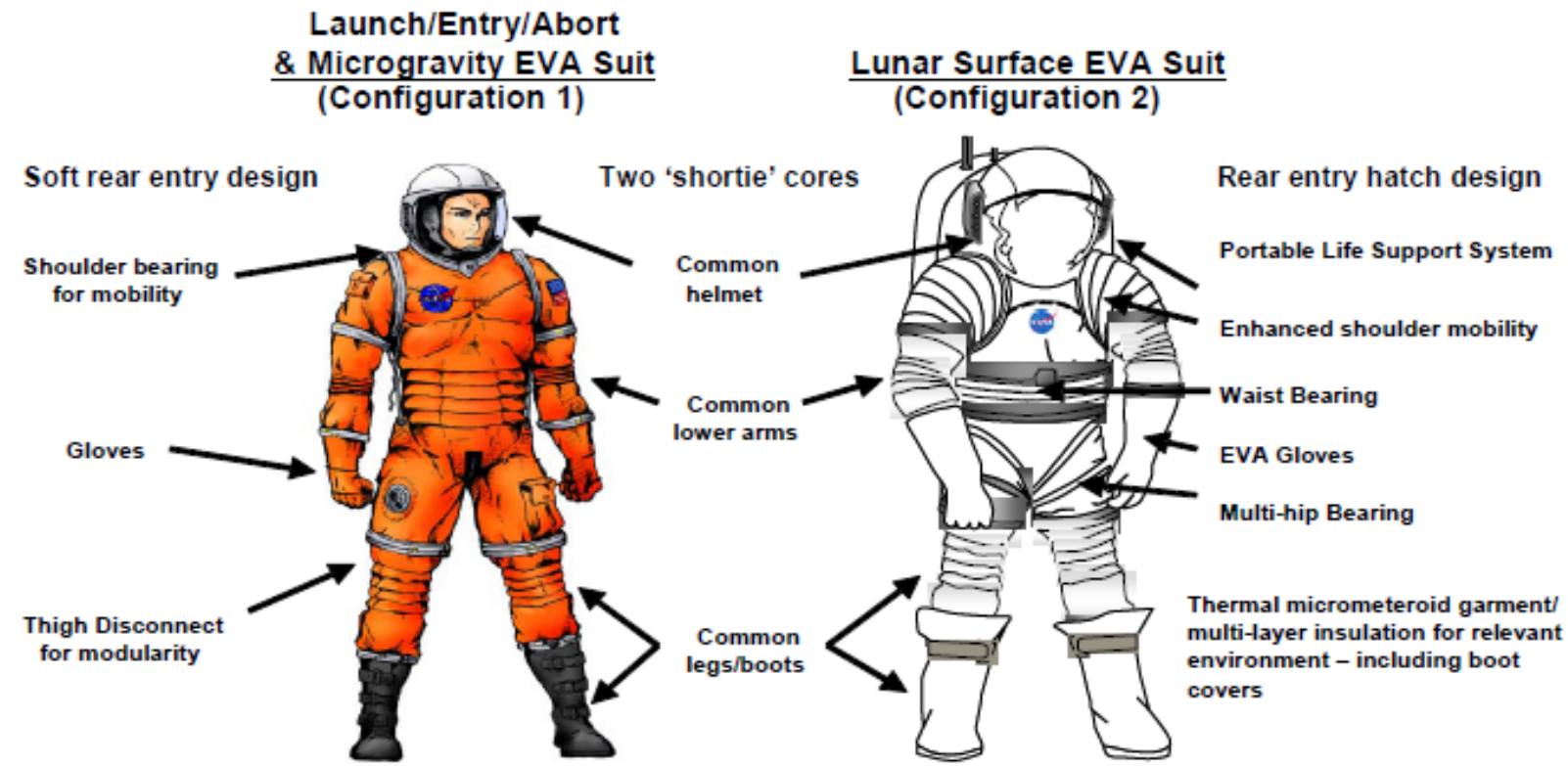
Space Suits Contd.

	Requirement	Comments
Service life	Equivalent to 3 year mission (using it every day)	Long shelf life at least 8 years
Radiation shielding	Protection for EVA missions (including simulations in Mars SIM)	6 hours of EVAs during each week
Propulsion unit	Compatible with system that allows astronauts to perform untethered EVAs	*i.e. Manned Maneuvering Unit (MMU)*
Dust mitigation	Electrodynamic Dust Shield attached to fabric	On legs, arms and chest

Space suit meeting all requirements does not exist → need to develop a new one

Space Suits

- Constellation Single Suit System Architecture



***Overall EVA System architecture approach - modular, reconfigurable, component-based architecture that meets various mission objectives**

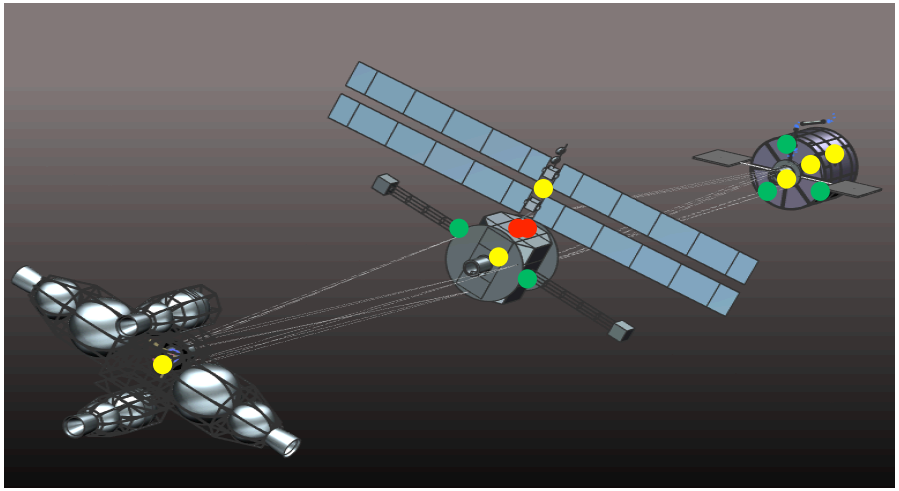
(Constellation Space Suit System Contract Award Announcement. NASA Exploration Systems Mission Directorate 2008)

Sensor Overview

ADCS	CS	PPT	LSM
Star Tracker	Water	Temperature	Strain Gauges
Sun Sensor	Atmosphere	Tank Levels	Inductive Wire Integrity
IMUs	Radiation	Thruster State	Cameras
	Smoke	Battery Level	

ADCS Sensors

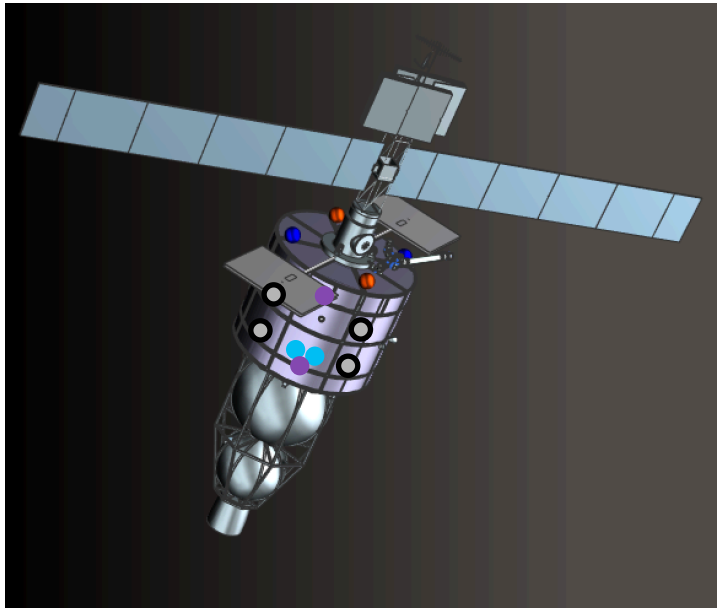
- Inertial Measurement Units (IMUs)
  - Provides system velocity and acceleration
  - Accuracy: <0.1 degree/hour
- Star trackers
  - Provide orientation of the station
  - Accuracy: 0.025 degree accuracy
- Sun sensors
  - Determine sun location
  - Accuracy: <1 degree



- IMUs
- Star Trackers
- Sun Sensors

Crew Systems

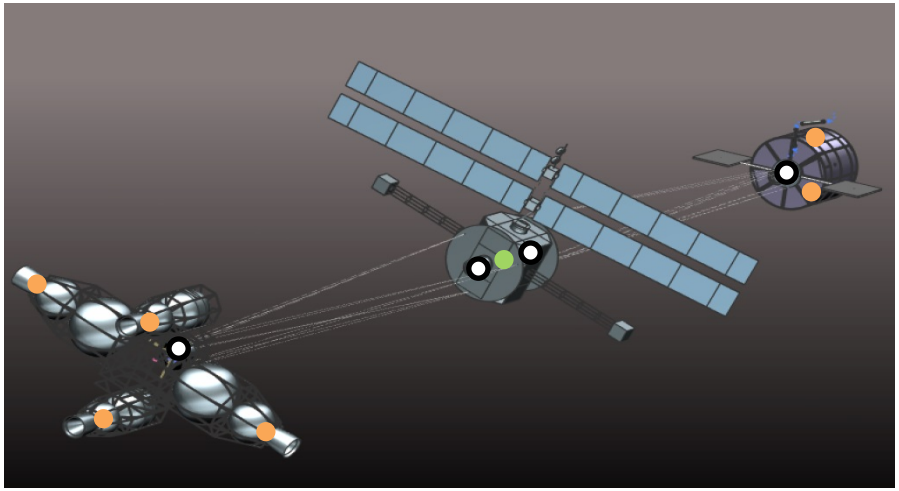
- Water Volume & Quality
  - Monitor water quality and quantity
  - Sensitivity to 1 mg/L of contaminants, 10 mL of water
- Radiation
  - Measure radiation received by crew and equipment
  - Accuracy: 1 mSv
- Smoke Detectors
  - Detect smoke particles in 0g and 1g



- Water
- Radiation
- Smoke

Power, Propulsion, and Thermal

- Comprised of:
  - Temperature
    - Accuracy: 0.5 deg C
  - Pressure
    - Accuracy: 100 Pa
  - Thruster state
  - Battery level
    - Accuracy: 1%
  - Conductive pipe sensors

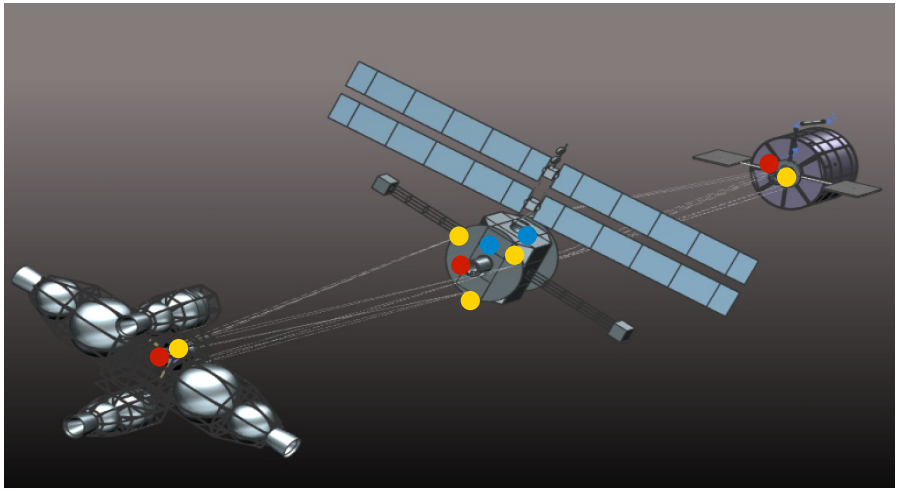


Temperature and Pressure will be distributed over the entire structure

- Thruster State
- Battery Level
- Conductive Pipe

Loads, Structures, and Mechanisms

- Comprised of:
  - Strain gauges
  - Conductive wire integrity
  - Cameras
- Objective:
  - Provide a visual and quantitative cable health monitor



- Strain Gauges
- Conductive Sensors
- Cameras

Sensors Total Budget

Sensor	Quantity	Sample Rate [Hz]	Throughput each [KIPS]	Data rate each [Kb/sec]	Power each [W]	Mass each [kg]
IMU	6	10	9	57	20	2
Star Tracker	2	0.01	1	0.25	10	3
Sun Sensor	8	1	2	0.1875	0.3	0.1
Water	4	0.1	-	-	10	1.5
Air	36	1	-	-	1.7	0.11
Radiation	2	0.1	-	-	0.84	2
Smoke	6	1	-	-	2	0.5
Thrusters	30	2	0.07	0.08	0.01	0.01
Temperature	50	1	-	-	1	0.01
Cameras	4	20	-	50	60	0.5
Total	**-**	**-**	**76**	**560**	**490**	**38.6**

Phase Based Sensor Budget

System Total	Phase I	Phase II	Phase III
Mass:	27 kg	35 kg	39 kg
Power:	368 W	450 W	490 W
Throughput:	46 KIPS	65 KIPS	76 KIPS
Data rate:	176 Kb/sec	439 Kb/sec	560 Kb/sec
Memory Required:	5.4 Gb	13.3 Gb	17 Gb
Total Cost:	1.5M	2.2M	2.5 M

**Phases are cumulative

Further Considerations

- Smoke detector challenges
  - Location
  - Particle size
- Cable monitoring considerations
- Data storage sizing
- Antenna interference

Risk Analysis

- Rating matrix based on combination of likelihood and severity of event
- Divided between risk to <u>mission success</u> and risk to <u>crew safety</u>
- Analyzed <u>before</u> and <u>after</u> mitigation and contingency efforts

Risk Analysis Evaluation					
	Insignificant	Minor	Moderate	Severe	Catastrophic
Almost Certain	3	4	4	5	5
Likely	3	3	4	4	5
Possible	2	3	3	4	5
Unlikely	2	3	3	3	4
Rare	1	2	3	3	4

Risk Analysis Matrix

Category	Event	Unmitigated Risk Level (Mission)	Unmitigated Risk Level (Crew)	Mitigation Measures	Primary Contingency	Mitigated Risk Level (Mission)	Mitigated Risk Level (Crew)
Structure Failure	Main Structure (Phase I)	5	3	Pre-Launch Stress/Vibration Testing	Attempt to repair	3	3
	Main Structure (Phase II and III)	5	5		Contingency repairs launch	3	4
	Hab Airlock (Phase I, EVA)	5	5	Astronauts on EVA carry necessary repair tools	Detach DragonRider for EVA pick-up	3	3
	Hab Airlock (Phase I, non-EVA)	4	3	Simulation testing	Access Airlock for repairs by detaching DragonRider, EVA from DragonRider	3	3
	Hab Airlock (Phase II and III, EVA)	5	5	DragonRider able to detach for EVA pick-up	Attempt external repairs Detach DragonRider for EVA pick-up and re-docking to Hab	3	3
	Hab Airlock (Phase II and III, non-EVA)	5	5	Able to use Mars SIM as detachable airlock in case of emergency	Attempt repairs, EVA if necessary	3	3
	Habitat Pressure Vessel (Phase I)	5	5	Simulation testing	Evacuate to DragonRider	4	4
	Habitat Pressure Vessel (Phase II and III)	5	5	Simulation testing	Evacuate to DragonRider	4	4
	Central Hub (occupied)	4	5	Simulation testing	Evacuate to DragonRider	4	4
	Central Hub (unoccupied)	4	3	Develop remote undocking/docking for DragonRider	Re-dock DragonRider with Hab (detach Mars SIM if necessary)	3	3
	Mars SIM (occupied)	3	4	Astronauts already in EVA suits	Return to Hab immediately Assess damage, conduct repairs if possible	2	3
	Mars SIM (unoccupied)	3	2	Airtight bulkhead between Hab and Mars SIM Mars SIM detachable after spin-down	Assess damage, conduct repairs if possible	2	1
	Ballast (rotating, spin-down component)	5	5	Develop remote undocking/docking for DragonRider	Detach Hab from Hub, stabilize and redock with DragonRider if possible	4	4
	Ballast (rotating, non-spin-down component)	4	4	Rigorous stress analysis before launch	Spin down, reel in to conduct repairs	3	3
	Ballast (nonrotating)	3	3	Robot arm available for repairs	Conduct EVA repairs	2	3

Risk Analysis Matrix

Category	Event	Unmitigated Risk Level (Mission)	Unmitigated Risk Level (Crew)	Mitigation Measures	Primary Contingency	Mitigated Risk Level (Mission)	Mitigated Risk Level (Crew)
Hardware Failure	Airtight Bulkhead Seal	3	3	Access to both sides of bulkheads and repair materials	Attempt repairs	2	2
	Insulation	2	3	Ground testing	Repair if possible	1	2
	Cables	5	5	Three fault tolerant Cable redundancy Cable replacements accessible for repairs Repair crew on standby for repairs mission	Reel in, spin down, conduct repairs / maintenance	3	3
	RCS	4	2	Thruster redundancy	EVA to repair (if necessary)	2	3
	Cable Winches (nonrotating)	4	3	Crew conducts winch test before spin-up	EVA to repair / replace winch	2	3
	Cable Winches (rotating)	5	4	Crew conducts winch test before spin-up	Spin down, reel in to conduct repairs	4	4
	Electrodynamic Dust Shield	3	2	Dust VCA serves as secondary system	Conduct repairs if possible	2	1
	Dust VCA	3	2	HEPA filter removes atmospheric contaminants	Conduct repairs if possible	2	1
Assembly	Radiator / Solar Array Unfold	5	4	Use of robot arm to identify / fix problems	Assemble with robot arm	3	3
	Hab / Hub Cables						
	Ballast / Hub Cables						
	Ballast			NBR Lab manual assembly rehearsal	EVA from Hab Airlock (manual assembly)		
	Communications Tower						
	Hab / Mars SIM						
Docking	Failure to dock DragonRider	5	4	Rehearsal of Hab Airlock boarding	EVA from DragonRider to repair or board	3	3
	Failure to dock DragonRider (Phase II and III)	3	2	Simulation of secondary docking	Use secondary docking point on hab	2	2
	Failure to dock Mars SIM	4	2	Robot arm available for realignment	EVA if necessary to align / redock	3	3
Leaks (to Space)	Propellant Leak	4	2	Emergency cutoff valve(s)	EVA to repair	3	3
	Radiator Coolant Leak	4	2	Emergency cutoff valve(s)	EVA to repair	3	3
	Water Leak	4	4	Emergency cutoff valve(s)	EVA to repair	3	3
	Nitrogen Leak	3	3	Emergency cutoff valve(s)	EVA to repair	2	3
	Major Atmosphere Leak	5	5	Oxygen masks accessible to crew Airtight bulkheads	Evacuate area, attempt repairs Seal bulkheads	4	4

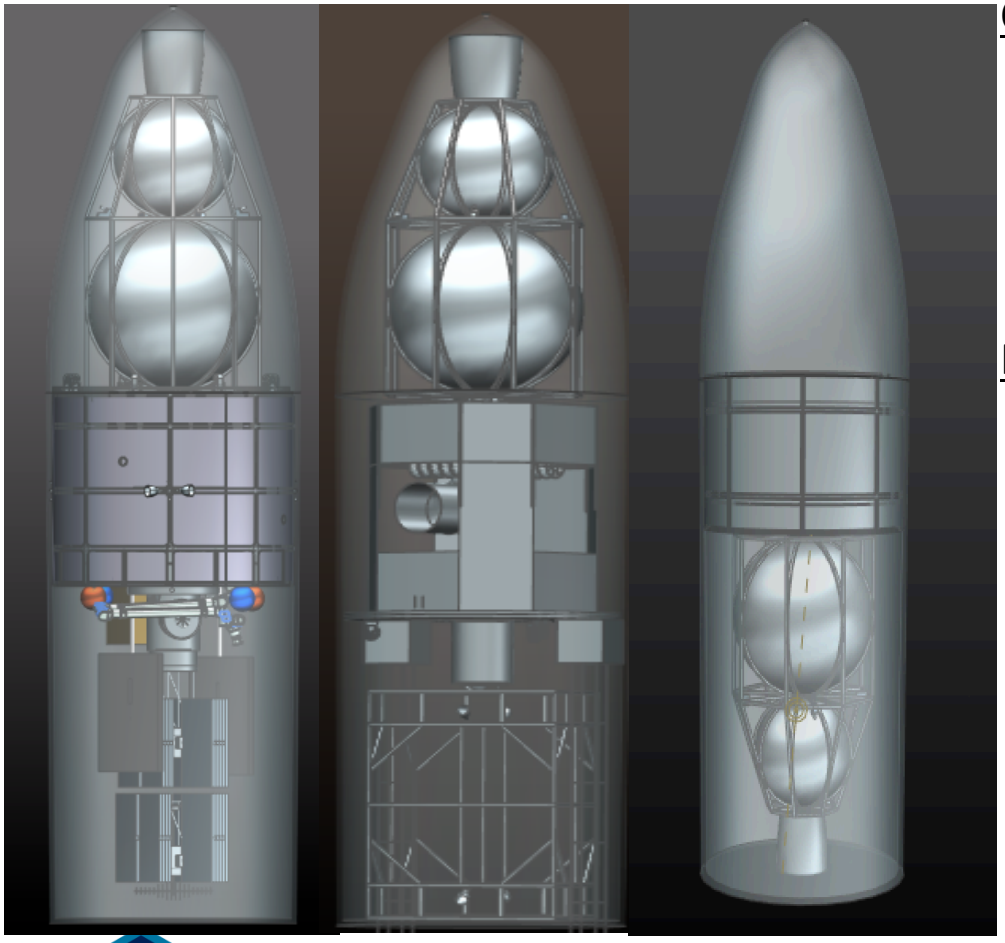
Risk Analysis Matrix

Category	Event	Unmitigated Risk Level (Mission)	Unmitigated Risk Level (Crew)	Mitigation Measures	Primary Contingency	Mitigated Risk Level (Mission)	Mitigated Risk Level (Crew)
Electronics Failure	Pressure Sensor	3	3	Secondary Sensors	Repair / disable if possible	1	2
	CO/CO_2 Sensor	3	3	Secondary Sensors		1	2
	Smoke Detector	3	3	Secondary Detectors		1	2
	Nitrogen Sensor	3	3	Secondary Sensors		1	2
	Inertial Measurement Unit	4	3	IMU Redundancy Control System identifying malfunction Manual override / shutoff	Repair / shut down faulty IMU	2	2
	Thermal Equilibrium Sensor	4	4	Manual override accessible to crew Secondary Sensors	Repair / disable if possible	1	2
	Star Tracker	4	2	Backup Star Trackers	Repair / recalibrate tracker	3	1
	Battery Combustion	4	3	Fire Extinguishers accessible to crew Back-up batteries accessible to crew	Extinguish battery fire Replace battery	2	2
	Communications	4	2	Backup communications system Communications system ground training	Diagnose problem, repair Use backup system	2	1
	Communications Pointing	4	2	Backup pointing motor	EVA to repair / replace assembly	3	3
	Solar Panel	4	4	Excess power capabilities allowing for repair/replacement time	EVA to repair Limit power usage to critical systems	3	3
	Radiator Control	4	4	Independent radiator control Manual override of radiator automation	Repair / replace if possible Manually override radiator operation combination	3	3
	Sun Sensor	4	2	Redundant sensors (8)	Repair / recalibrate tracker	3	1
EVA	Suit Rupture	3	5	Simulation testing Two personnel minimum on EVA	Return to Hab Airlock immediately	2	3
	Disconnect from Station	3	5	Simulation testing Two personnel minimum on EVA One RCS pack minimum on EVA Cable connect points on external structure	Use RCS pack to return to station / retrieve disconnected astronaut	2	3
	Radio Failure	2	3	Simulation testing Two personnel minimum on EVA	Return to Hab Airlock immediately	2	2

Risk Analysis Matrix

Category	Event	Unmitigated Risk Level (Mission)	Unmitigated Risk Level (Crew)	Mitigation Measures	Primary Contingency	Mitigated Risk Level (Mission)	Mitigated Risk Level (Crew)
Life Support Failure	Four Bed Molecular Sieve	3	4	Crew-accessible replacements	Replace faulty sieves	2	2
	Multi-Filtration System (Water)	3	4	Crew-accessible replacements Water quality testing kits accessible to crew	Repair / replace filters	2	2
	Sabatier Reaction	3	3	Replacement components accessible to crew	Repair / replace components	2	2
	Advanced Carbon-Formation Reaction System	3	3	Replacement components accessible to crew	Repair / replace components	2	2
	Vapor Compression Distillation	3	4	Replacement components accessible to crew	Repair / replace components	2	2
	Forward Osmosis Bags	2	3	Crew-accessible replacements Forward Osmosis secondary system	Replace faulty bags	2	1
	Waste Collection (Space Toilet)	2	3	Contingency waste bags accessible to crew	Repair toilet if possible Use contingency waste bags	2	1
Natural	Solar Particle Event	3	4	Periods of inhabitance planned for low solar activity periods	Move crew into most heavily shielded area ASAP	3	4
	Meteoroid Contact	4	4	Dedicated foreign object sensors for station course intersection	Move crew into most heavily shielded area ASAP	4	3

Volume Budget



Constraint for structural launches: **NASA SLS**

Cylindrical Section:

8.5 [m] Inner Diameter

125 [m] Height

Total volume of fairing: 1400 m³

Major items

Robotic Arm: 6 m³

Asteroid Orbiter: 10 m³

Communications/Power Tower: 6.75 m³

Hub: 183 m³

Mars SIM: 176 m³

Habitat volume required (internal): 230 m³

Habitat total volume: **281.5 m³** ✓

Mass Budget

- Constraint for structural launches: 45,000 kg
  - After 12,000 kg devoted to upper stage structure
- Major items
  - Phase I: Habitat, Robotic Arm, Asteroid Orbiter
  - Phase II: Hub, Ballast, Cables and Winches
  - Phase III: Mars SIM, Ballast, Crew Resupply
- Total mass
  - Phase I: 42,500 kg
  - Phase II: 41,000 kg
  - Phase III: 37,600 kg

Cost Estimating Relations

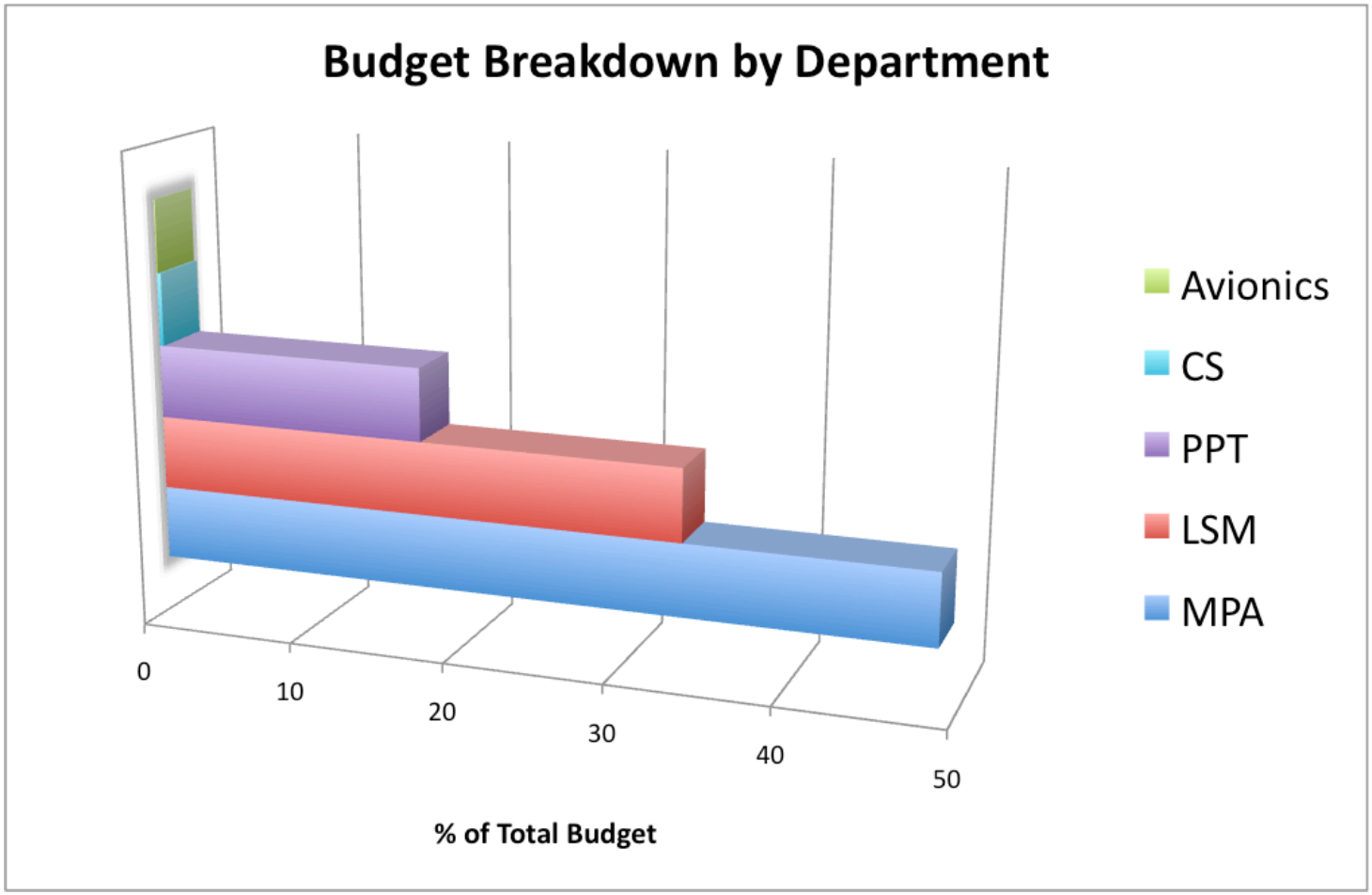
$$C(\$M) = a[m_{inert}(kg)]^b$$

Item	A	B	M	Cost ($M)
Satellite	13.89	0.55	750	529.65
Liquid Rocket Engine	34.97	0.55	2 & 4.31	2780.38
Science Instrument	2.235	0.5	150	27.37
In Space Habitat	1457.7	0.0856	21577	3424.98

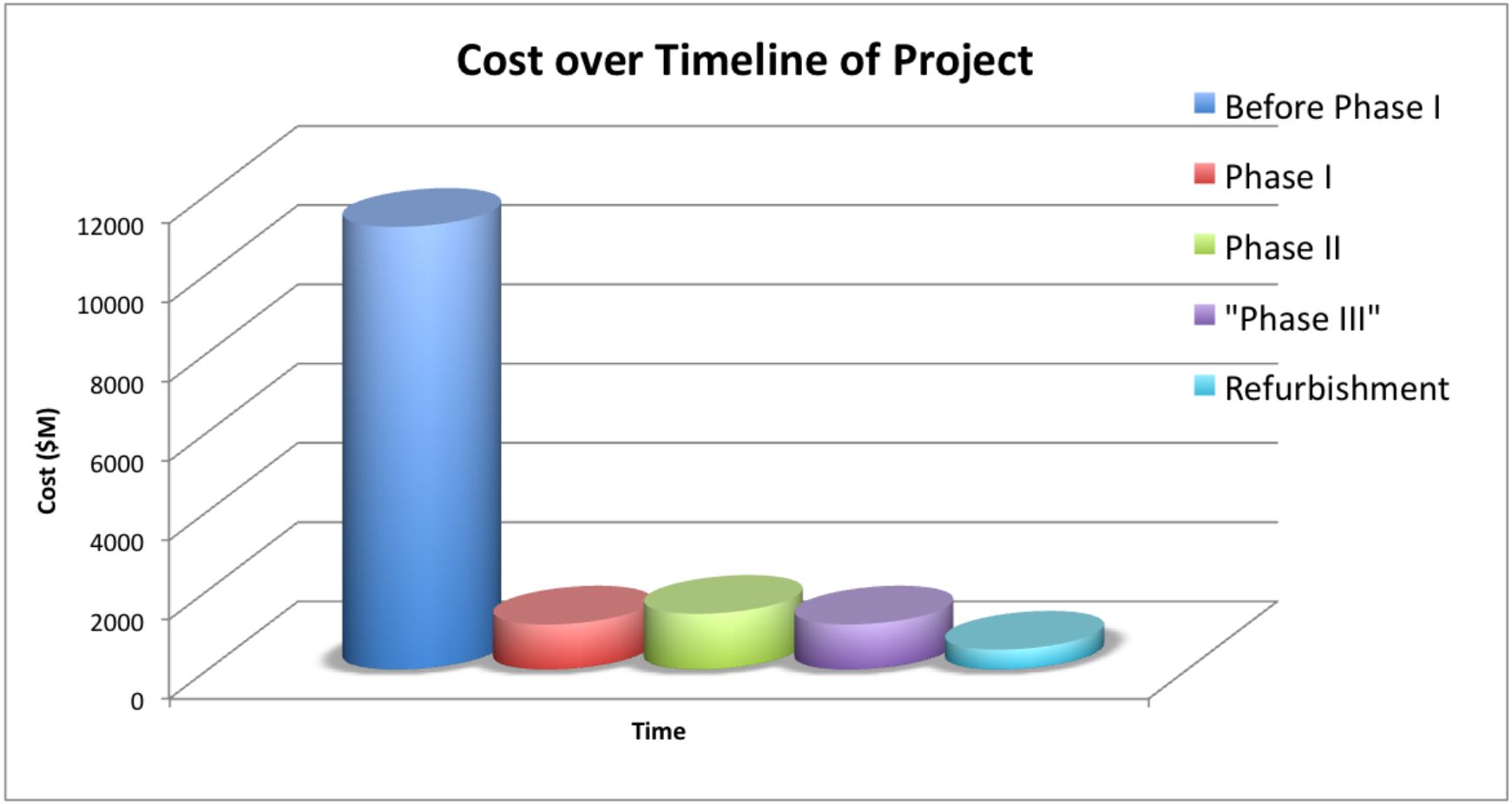
Cost Drivers

Item	Cost ($M)	Costing Method
Thrusters	2780	CER
Launch Vehicle(s)	5175	Industry Data
Habitat	3424	CER
Hub	2084	Material Cost & Development
MARS SIM	2250	CER

Budget


Budget Breakdown by Department
0
10
20
30
40
50
% of Total Budget
Avionics
CS
PPT
LSM
MPA

Cost


Cost over Timeline of Project
Before Phase I
Phase I
Phase II
"Phase III"
Refurbishment
Cost ($M)
12000
10000
8000
6000
4000
2000
0
Time

Cost

- **Max Budget:** $30B
  - Annual $3B max startup costs (10 years)
- **Estimated Total Budget :** $21.29B
- **Proposed Launch:** 2021
  - 7 years development time
  - 3 launch years
  - Post-2024 maintenance (<$1B)

Summary

- Polus supports NASA and the President Obama's goal of sending humans to an asteroid by 2025
- Would provide invaluable data never before collected:
  - Long-term survivability in deep space
  - Effects of changing gravity levels
  - Feasibility of artificial gravity habitats for exploration
- Has the potential to greatly reduce risk of Mars missions planned for the 2030s due to unknown factors

"Genus Humanus Gravitationem Superat"

Thank you for your time

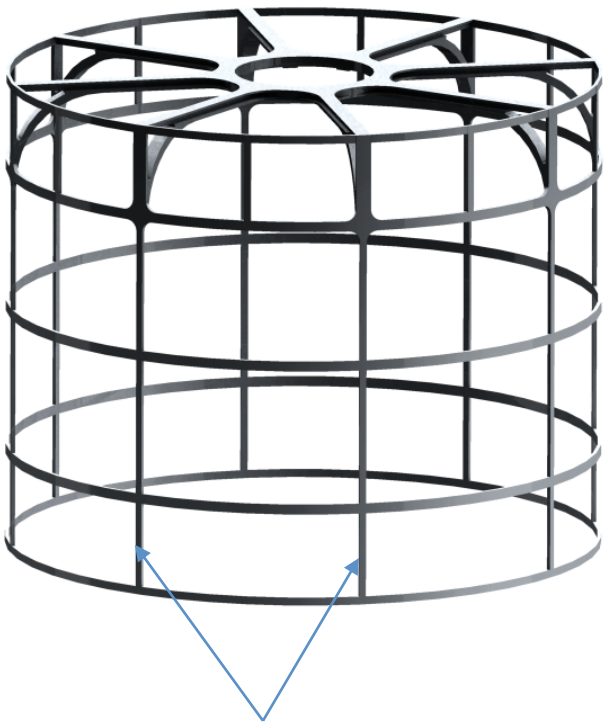
Appendix

Pressure Vessel

- Internal pressure: 10.4 psi
- Internal radius: 4 m
- Safety Factor: 2
- Cylindrical Section
- $\sigma\downarrow\theta = pr/t$
- $t\downarrow min = 2.08\ mm$
- 4:1 Ellipsoidal End cap
- $(\sigma\downarrow\theta)\downarrow max = 1.42 * pr/t$
- $t\downarrow min = 2.95\ mm$
- Source: Strength of Pressure Vessel with Ellipsoidal Heads

Axial Members

- Habitat Launch Mass: 41637.12 kg
- Axial Acceleration: 6 g's
- Axial Loading: 2.50 GN
- Analysis determined buckling would be the primary failure mode
- $F=\pi^2 EI/(KL)^2$
- Applying constraints and safety factor
- $I_{min}=9.02*10^{-6}$
- With cross-section and geometric constraints thickness of beam was determined
- $t_{min}=.130\ m$
- $A_{min}=.0065\ m^2$



Horizontal Stringer Design

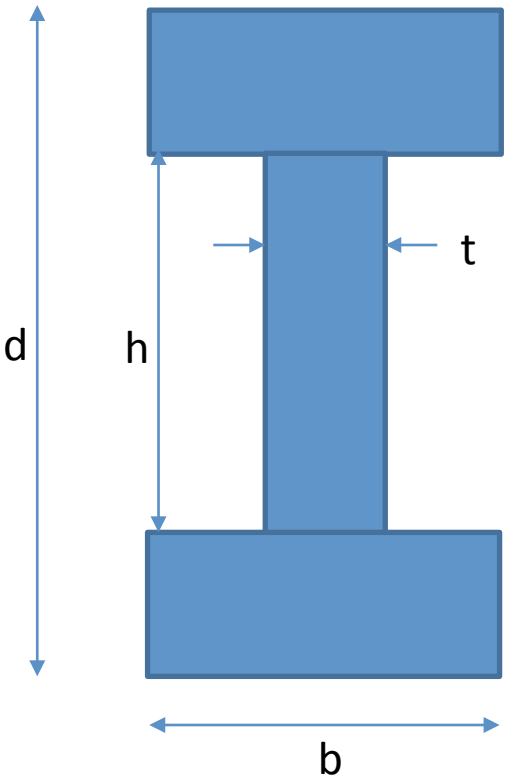
- Bottom stringer design
- Load = 62.5 KN per member
- Safety Factor: 2
- $\sigma_{max} = M y_{min} / I_x$
- Applying constraints
- $h_{min} = .143\ m$
- Floor stringer design
- Floor Bending Load = 15.6 KN
- $\sigma_{max} = M y_{min} / I_x$
- Applying constraints
- $h_{min} = .140\ m$

Bottom stringer

Floor stringers

Cable System Connection

- Bending Load = 500 KN per member
- Safety Factor: 2
- $\sigma_{max} = M y_{min} / I_x$
- Using I-Beam cross-section to strengthen against beaming
- $I_x / y_{min} = 0.0036\ m^3$
- I-beam Dimensions:
  - d= 163.83 mm
  - h= 82.3 mm
  - b= 204.3 mm
  - t= 91.92 mm



Power Appendix

PV Sizing Equations:

$$Parray = \frac{\frac{Pe*Te}{Xe} + \frac{Pd*Td}{Xd}}{Td} \longrightarrow Parray = \frac{Pd}{Xd}$$

- Pd = Power during daylight (average set per phase by demand)
- Td = Time during daylight per orbit
- Xd = Path efficiency from arrays to loads (Use 0.85 – industry standard)
- Pe = Power during eclipse
- Te = Time during eclipse per orbit (Treat as zero since eclipse so infrequent)
- Xe = Path efficiency from arrays through batteries to loads

- I = Solar Flux Constant at 1 AU = 1364 W/m^2
- Array specific area = 1364 * efficiency
- Array specific mass from density conversion factor (2.8) found in: *Wertz, James R., et al. Space Mission Engineering: The New SMAD*

Power Appendix

Instrument	Purpose	Qty	Dimensions Each [cm]	Mass Each [kg]
Sequential Shunt Unit (SSU)	Receives power from array and maintains output voltage to setpoint by shunting/unshunting array strings.	4-8	?	?
DC Switching Unit (DCSU)	Used for power distribution, protection and fault isolation. Uses relays and switches to route primary power downstream.	4	71.1x101.6x30.5	108
DC to DC Converter Unit (DDCU)	Distributes primary power from the power channels to the DDCUs and other loads. Able to "cross-tie" primary power channels in case of power failure.	4	173x64x36	67
Main Bus Switching Unit (MBSU)	Responsible for DC power conversion (acts as transformer) for 160 VDC to 120VDC, which is the prescribed voltage for all users.	4	71.1x101.6x30.5	100
Battery Charge/ Discharge Unit (BCDU)	Provides charge and discharge control of electricity from batteries.	4	71.1x101.6x30.5	107
Remote Power Controller Module (RPCM)	Interface between Power Supply and all other equipment on board. Essentially a multi-channel, high power circuit breaker used to control the distribution of secondary power to downstream loads and to protect against downstream faults	92	17x20x9	5

Power Transfer Devices

Wire Rope and Sheave Wear Analysis

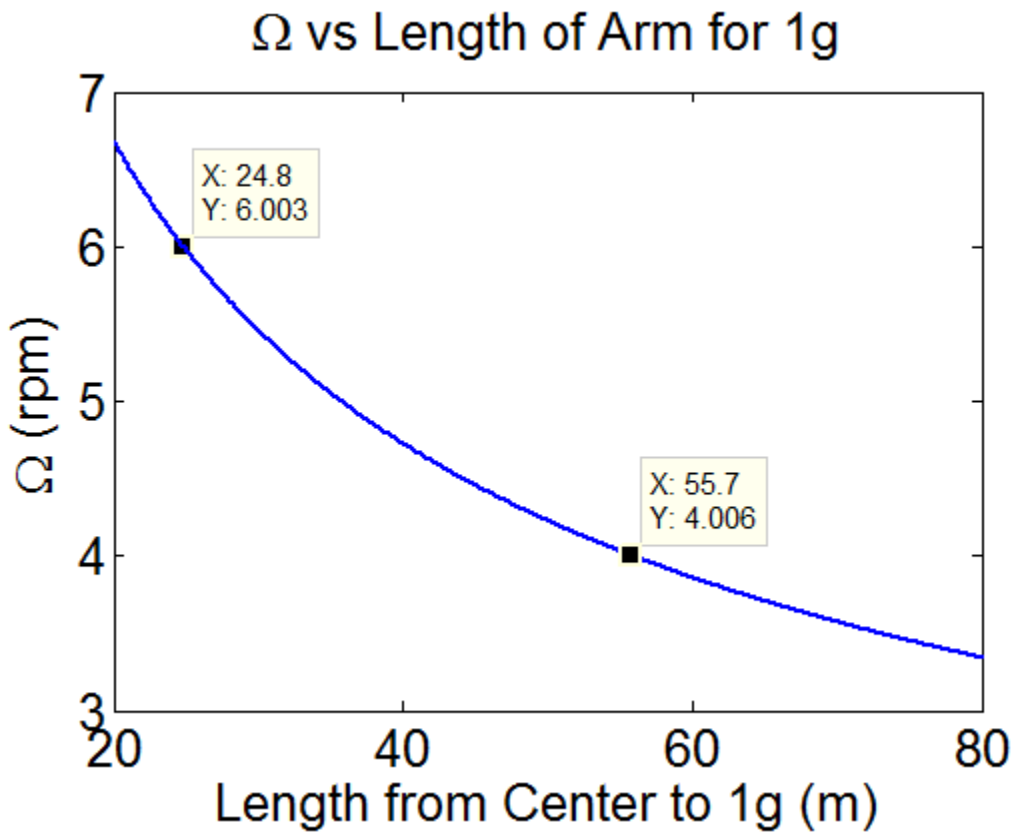
- The amount of wear to the wire rope in a sheave depends on bearing pressure of the cable in the sheave groove:

$$p_{[1]}=2T/(dD)$$

$$p=2(74071\ [N])/(25.4\ [mm]*457\ [mm])=12.8\ MPa$$

$$S_u=1.8483*10^6$$

Spin Rate/Arm Length Sizing

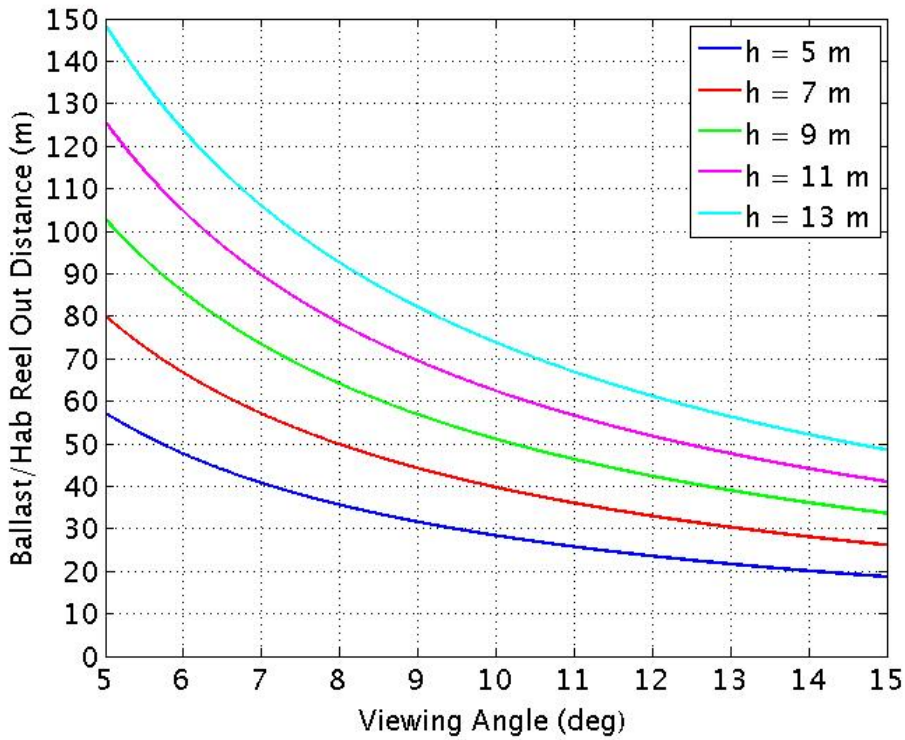


Rotation Frequency [rpm]	Arm Length [m]
4	55.8
6	24.8

- Focused on the range 4-6 rpm (comfort range)
- Although 6 rpm would reduce the arm length by 50%, we decided to go on the lower end of the comfort range at 4 rpm.

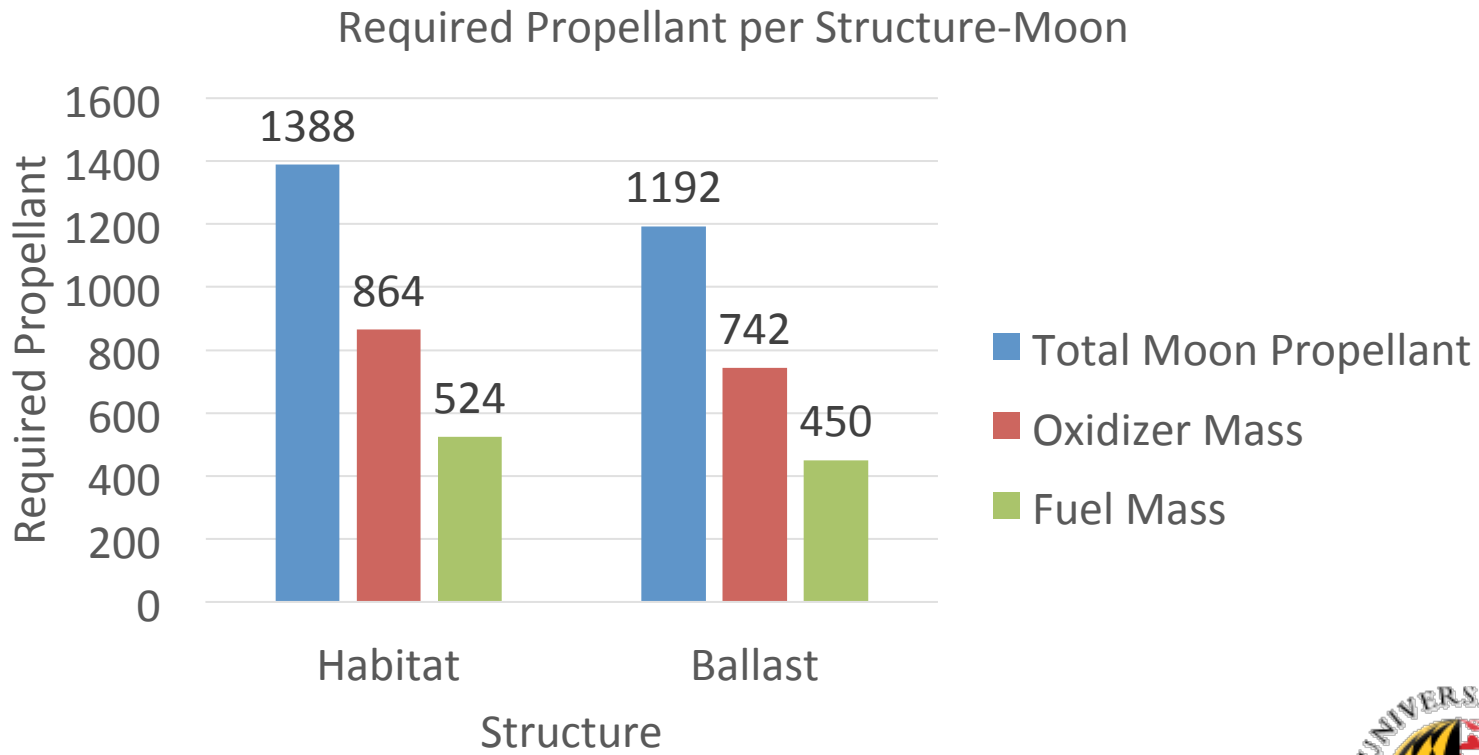
Communications Tower Height

- Required viewing angle for dish is 5°
  - Based on inclination of Moon's orbit
- For a tower height of 9 m, maximum reel-out distance is 102.9 m

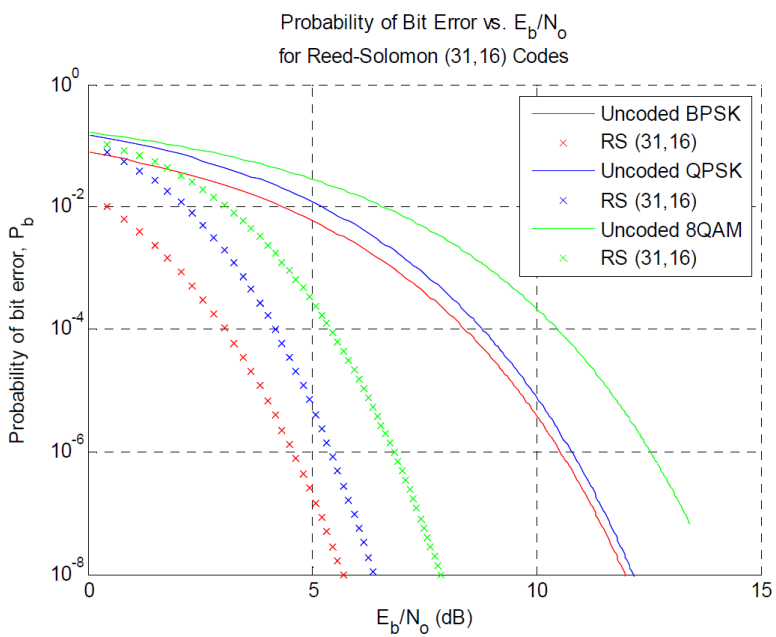


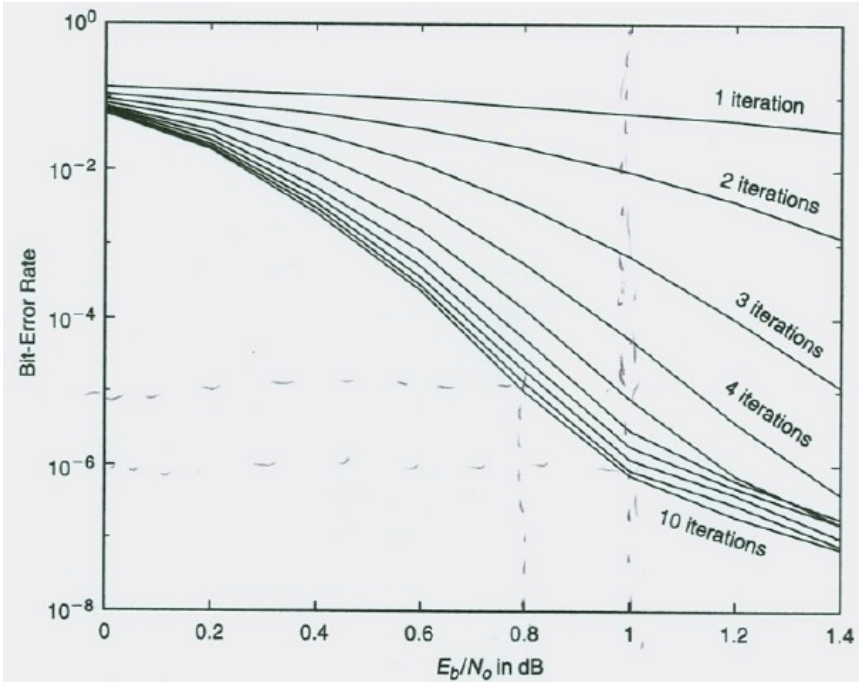
Phase III B

- Maneuvers
  - DRO orbit insertion
  - Spin to Moon, then Mars, then Moon gravity



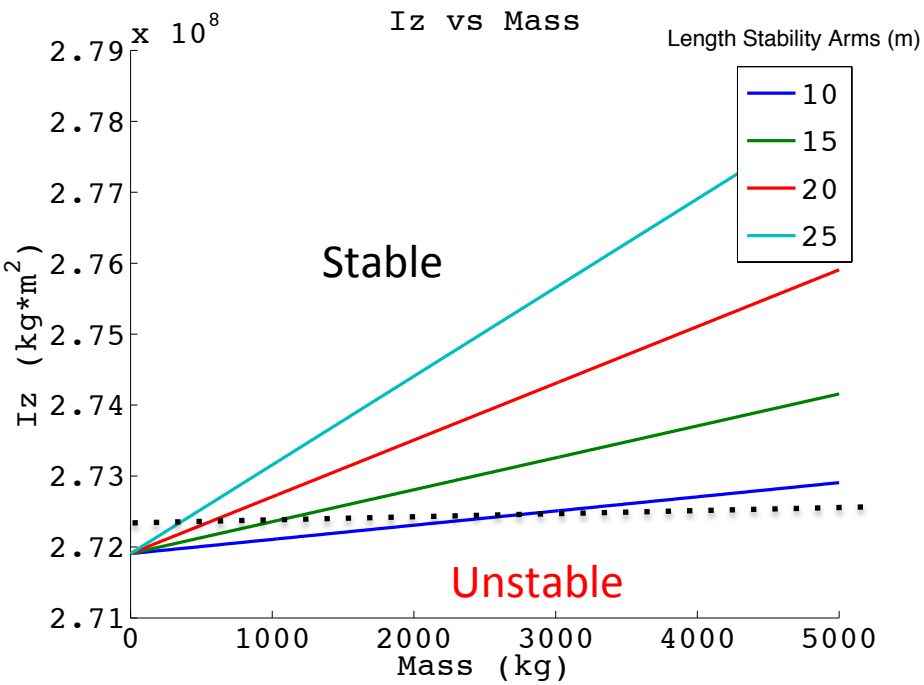
Appendix Slides



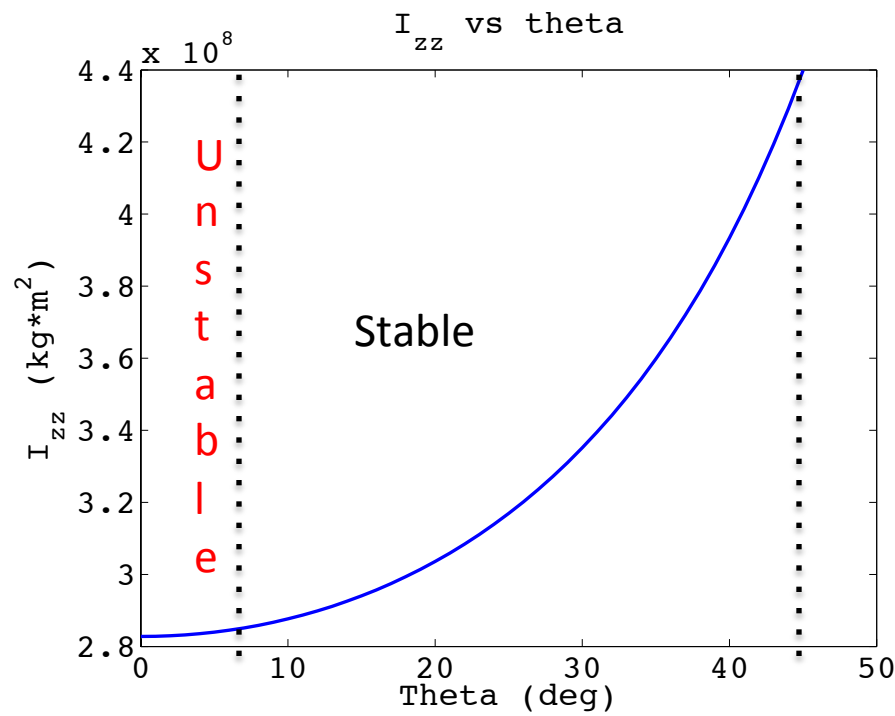


Comparing Iz

2 Arm



3 Arm



MOI in the z-direction is higher for the any angle configuration of the 3 arm case than any of the feasible 2 arm cases

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