Project Team

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Daniel Todaro
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Kristy Weber
Kyle Zittle
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

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

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
<th>Level 6</th>
<th>Cost</th>
<th>Risk (Lik.)</th>
<th>Risk (Sev.)</th>
<th>Risk (Overall)</th>
<th>TRL</th>
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<tbody>
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<td>3 Mission Planning</td>
<td>3.4 Crew System</td>
<td>3.4.1 Life Support System</td>
<td>3.4.1.1 Atm. Control</td>
<td>3.4.1.1.1 CO₂ Scrubbing</td>
<td>3.4.1.1.1.1 4BMS</td>
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<td>3.4.1.2.2 Multi-Filtration System</td>
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<td>3.4.1.2.3 Forward Osmosis Bag</td>
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</tbody>
</table>

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Brianna Brassard  
ENAE484 Critical Design Review  
29 April 2014
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 III
## Mission Science Objectives

### Primary Science Questions

| I | What is the asteroid’s composition & chemical history? |
| I | What are the physical & surface characteristics of the asteroid? |
| I | What is the deep space environment near 1 AU? |
| I | What volatiles exist & can be extracted from the asteroid? |
| II | What are the effects of long-term variable gravity on human physiology? |
| II | What are the effects of long-term variable gravity on microbial life? |
| II | 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

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

Phase I
- Structure I Launch
- Crew I Launch

Phase II
- Structure II Launch
- Crew IIA, IIB, IIC Launch
- Crew I, IIA, IIB Return

Phase III
- Structure III Launch
- Crew III Launch
- Crew IIC, III Return
Mission Timeline: Phase I

Phase I

DRO

Sep 2021: Structure I Launch

Jan 2022: Crew I Launch

Apr 2022: Structure II Launch

Aug 2022: Maneuver away from asteroid

2021: ARM deposits asteroid in DRO

Jan 2022: Rendezvous and Assembly

Feb – Jul 2022: Phase I crew rotation

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Mission Timeline: Phase II

DRO

Aug 2022: Crew IIA Launch, Crew I Return

Sep 2022 – Feb 2023: Phase IIA crew rotation

Aug 2022: Rendezvous and Assembly

Sep 2022 – Feb 2023: Phase II A crew rotation

Mar 2023: Crew IIB Launch, Crew IIA Return

Mar 2023 – Aug 2023: Phase IIB crew rotation

Sep 2023: Crew IIC Launch, Crew IIB Return

Sep 2023 – Feb 2024: Phase crew IIC rotation

Nov 2023: Structure III Launch

Douglas Klein

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Mission Timeline: Phase III

Phase III

DRO

Mar 2024: Crew III Launch, Crew IIC Return

Apr 2024 – Jan 2027: Phase III crew rotation

Jan 2027: Crew III Return

Mar 2024: Rendezvous and Assembly

ENAE484 Critical Design Review
29 April 2014
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:

  **Geocentric Inertial Frame**

  Mean radius: 70,000 km

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

<table>
<thead>
<tr>
<th>Classification</th>
<th>Primary Transfer $\Delta V$ [km/s]</th>
<th>Secondary Transfer $\Delta V$ [km/s]</th>
<th>SDRO Insertion $\Delta V$ [km/s]</th>
<th>Total $\Delta V$ [km/s]</th>
<th>Duration [days]</th>
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</thead>
<tbody>
<tr>
<td>Low Energy Cargo [1]</td>
<td>3.2</td>
<td>---</td>
<td>0.090</td>
<td>3.29</td>
<td>100.5</td>
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<td>High Energy Cargo [1]</td>
<td>3.14</td>
<td>0.67</td>
<td>0.075</td>
<td>3.88</td>
<td>32.5</td>
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<tr>
<td>High Energy Crew [2]</td>
<td>3.2</td>
<td>---</td>
<td>0.80</td>
<td>~4.00</td>
<td>~4</td>
</tr>
</tbody>
</table>


Note: “Primary/Secondary” Transfer $\Delta V$ is analogous to TLI burn for Apollo missions, and SDRO Insertion $\Delta V$ with LOI

- DRO/L1 $\rightarrow$ Earth Return Trajectory
  - Maximum Earth Atmospheric Entry Interface Velocity: $12 \text{ km/s}$ (Apollo)
  - Cislunar design space: Apollo limits will not be exceeded on reentry
  - No slow down needed; $0.5 \text{ km/s}$ 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 \(\Delta V\) gain from Earth’s rotation

<table>
<thead>
<tr>
<th>Launch Site</th>
<th>Latitude ((\phi))</th>
<th>Azimuth (A) Range</th>
<th>Minimum Inclination (i)</th>
<th>(\Delta V) gain [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape Canaveral</td>
<td>28.5°</td>
<td>35° - 120°</td>
<td>28.5°</td>
<td>409</td>
</tr>
<tr>
<td>Vandenberg</td>
<td>34.8°</td>
<td>158° - 201°</td>
<td>51°</td>
<td>-382</td>
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</tbody>
</table>
## Heavy Lift Launch Vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mass to LEO [kg]</th>
<th>Mass to TLI [kg]</th>
<th>Payload Fairing Diameter [m]</th>
<th>Payload Fairing Height [m]</th>
<th>Total Fairing Volume [m$^3$]</th>
<th>Cost per kg, LEO</th>
<th>Cost per m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS Block 1A</td>
<td>105,000</td>
<td>[1]</td>
<td>8.4</td>
<td>~25</td>
<td>~1400</td>
<td>$14,286</td>
<td>$1.071 M</td>
</tr>
<tr>
<td>Falcon Heavy</td>
<td>53,000</td>
<td>~16,000</td>
<td>4.6</td>
<td>11.4</td>
<td>~130</td>
<td>$7245</td>
<td>$2.954 M</td>
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<tr>
<td>Atlas V 551</td>
<td>18,500</td>
<td>~4000</td>
<td>5.4</td>
<td>26.5</td>
<td>~550</td>
<td>$5946</td>
<td>$0.2 M</td>
</tr>
<tr>
<td>Delta IV Heavy</td>
<td>20,500</td>
<td>~6000</td>
<td>5.0</td>
<td>19.8</td>
<td>~300</td>
<td>$6829</td>
<td>$0.467 M</td>
</tr>
</tbody>
</table>

**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 $\Delta V$ is approximately equal to GEO total $\Delta V$
- 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)
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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value [kg]</th>
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<tbody>
<tr>
<td>Habitat Dry Mass</td>
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</tr>
<tr>
<td>Habitat Propellant Mass</td>
<td>2000</td>
</tr>
<tr>
<td>Upper Stage Dry Mass</td>
<td>5250</td>
</tr>
<tr>
<td>Upper Stage Propellant Mass</td>
<td>45,750</td>
</tr>
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</table>

- 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.
• **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

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mass to LEO [kg]</th>
<th>Mass to SDRO (fast transfer) [kg]</th>
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</thead>
<tbody>
<tr>
<td>SLS Block 1A</td>
<td>105,000</td>
<td>45,000</td>
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<tr>
<td>Falcon Heavy</td>
<td>53,000</td>
<td>16,500</td>
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<tr>
<td>Atlas V 551</td>
<td>18,500</td>
<td>5000</td>
</tr>
<tr>
<td>Delta IV Heavy</td>
<td>20,500</td>
<td>6250</td>
</tr>
</tbody>
</table>

- 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
- Latching End Effectors

11 m
32 cm
Robotic Arm D-H Parameters

<table>
<thead>
<tr>
<th>i</th>
<th>$\alpha_i$ [°]</th>
<th>$a_i$ [m]</th>
<th>$d_i$ [m]</th>
<th>$\theta_i$ [°]</th>
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<td>2</td>
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<td>3</td>
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<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Stowed configuration  
Packed configuration
Robotic Arm Mobility

Power Data Grapple Fixture (PDGF)  Flight Releasable Grapple Fixture (FRGFF)
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

- 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 m³
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

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

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

<table>
<thead>
<tr>
<th>Safety Features</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurization</td>
<td>EVA space suit shall be protected in the event that it ruptures by over</td>
</tr>
<tr>
<td></td>
<td>pressurization due to failure of the pressure supply system</td>
</tr>
<tr>
<td>Sharp Edges and Protrusions</td>
<td>All structures which require EVA interface shall be designed to preclude</td>
</tr>
<tr>
<td></td>
<td>sharp edges and protrusions, or be covered to protect crewmembers critical</td>
</tr>
<tr>
<td></td>
<td>support system</td>
</tr>
</tbody>
</table>
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 m³
Spatial Requirements

Determining habitable volume needed

\[ \text{Habitable Volume} \left[ \text{m}^3/\text{person} \right] \approx 4.8827 \times \ln(\text{duration in days}) - 3.9113 \]

- For 1000 day mission: \(30 \text{ m}^3/\text{person}\)
- For 6 crew (1,000 day): \(179 \text{ m}^3\)

(Factors Impacting Habitable Volume Requirements: Results from the 2011 Habitable Volume Workshop. NASA/TM-2011-217352)
### Spatial Requirements (0g, 95th % American Male)

<table>
<thead>
<tr>
<th>Functions</th>
<th>Volume [m³]</th>
<th>Dimensions (H x L x W) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eating, sleeping, hand washing, personal office, radiation shelter, conference</td>
<td>2.69</td>
<td>2.06 x 1.06 x 1.23</td>
</tr>
<tr>
<td>Shaving, grooming, oral hygiene</td>
<td>2.34</td>
<td>2.16 x 0.88 x 1.23</td>
</tr>
<tr>
<td>General workstations, food preparation, partial body cleaning, and housekeeping</td>
<td>4.34</td>
<td>2.06 x 1.06 x 1.99</td>
</tr>
<tr>
<td>Body waste management facilities, ascent and descent, and spacecraft duty station</td>
<td>1.70</td>
<td>1.52 x 0.91 x 1.23</td>
</tr>
<tr>
<td>Dressing and EVA suiting area</td>
<td>6.35</td>
<td>2.20 x 1.45 x 1.99</td>
</tr>
<tr>
<td>Accessing stowage and personal locker</td>
<td>6.00</td>
<td>2.76 x 0.88 x 2.47</td>
</tr>
<tr>
<td>Treadmill with Vibration Isolation System</td>
<td>6.12</td>
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<tr>
<td>Cycle Ergometer with Vibration Isolation System</td>
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<tr>
<td>Egress, translation, passageways</td>
<td>2.55</td>
<td>0.70 x 2.96 x 1.23</td>
</tr>
<tr>
<td>Egress, translation, passageways (EVA suits)</td>
<td>4.64</td>
<td>0.84 x 3.26 x 1.69</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Activity</th>
<th>Volume per person [m³]</th>
<th>Number of persons</th>
<th>Volume for all crew [m³]</th>
<th>Volume with multi-spaces [m³]</th>
<th>Total volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Galley</strong></td>
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<tr>
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<tr>
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<tr>
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<tr>
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</table>

**Reminder:** 179 m³ using curve

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

<table>
<thead>
<tr>
<th>Activity</th>
<th>Area per person [m(^2)]</th>
<th>Number of persons</th>
<th>Area for all crew [m(^2)]</th>
<th>Area with multi-spaces [m(^2)]</th>
<th>Total area [m(^2)]</th>
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<tbody>
<tr>
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Source: Dimensions for 0g, Human Integration Design Handbook. NASA/SP-2010-3407
## Spatial Requirements

<table>
<thead>
<tr>
<th>Human Integration Design Handbook</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitable Volume Workshop</td>
<td>179</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage and equipment needed inside habitat for Phase III</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water and food</td>
<td>8</td>
</tr>
<tr>
<td>Personal storage</td>
<td>10</td>
</tr>
<tr>
<td>Trash</td>
<td>5</td>
</tr>
<tr>
<td>Life support equipment</td>
<td>27</td>
</tr>
<tr>
<td>TOTAL</td>
<td>50</td>
</tr>
</tbody>
</table>

~230 m³ needed inside the habitat
Habitat Design Requirements

• Fit into a SLS Block 1A fairing including launch displacement
• Interior volume of at least 230 m³
• 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

Balistic Limit Equations for Whipple Shield

- Normal Whipple Shield
- 0.104% Probability
- 0.02% Probability
- 0.001% Probability

![Graph showing ballistic limit equations for Whipple Shield with velocity on the x-axis and projectile critical diameter on the y-axis.](image)
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

<table>
<thead>
<tr>
<th>Missions</th>
<th>Dose to the BFO [cSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury-Gemini</td>
<td>0.05</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>0.114</td>
</tr>
<tr>
<td>SKYLAB 4 (84 days)</td>
<td>7.94</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>0.052</td>
</tr>
</tbody>
</table>

(Source: Adams, 2001)

1 Year Exposure Limits

(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

<table>
<thead>
<tr>
<th>Description</th>
<th>Habitat Wall</th>
<th>End Caps</th>
<th>SPE Shelter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Thickness [cm]</td>
<td>1.6</td>
<td>1.6 + 0.2*</td>
<td>0</td>
</tr>
<tr>
<td>Al Shielding Depth [g/cm²]</td>
<td>4.32</td>
<td>4.86</td>
<td>0</td>
</tr>
<tr>
<td>PE Equivalent of Al [g/cm²]</td>
<td>3</td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td><strong>PE Shielding Thickness [cm]</strong></td>
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<td>1.5</td>
<td>11</td>
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<tr>
<td><strong>PE Shielding Depth [g/cm²]</strong></td>
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<td>11</td>
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<tr>
<td><strong>Total Shielding Depth</strong> [g/cm²]</td>
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<td>16</td>
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<tr>
<td>Volume of PE [m³]</td>
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<td>3.5</td>
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<tr>
<td>Mass of PE [kg]</td>
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<td>1200</td>
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<tr>
<td><strong>Total Mass of PE [kg]</strong></td>
<td>6820</td>
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</tbody>
</table>

### 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

*~0.2 cm of floor thickness was added to end caps thickness

**Total shielding depth is equivalent to PE

* Density of Al = 2.7 g/cm³
* Density of PE = 1.0 g/cm³
* 1 g/cm² of PE = 1.4 g/cm² of Al
* Shielding depth = Thickness x Density
Radiation Dose Calculation

- 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

<table>
<thead>
<tr>
<th>Location</th>
<th>Time [days]</th>
<th>Dose [cSv]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelter</td>
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<tr>
<td>Habitat</td>
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<td>40</td>
</tr>
</tbody>
</table>

**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

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

(Source: Cucinotta, 2005)
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

- Water Storage
- Hygiene Facility
- Life Support
- Personal Storage
- Water Recycling Unit
- Berths
- Galley/Food Storage
Centralized Berth: Pod Hotel
Centralized Berth: Pod Hotel
Decentralized Berth: L-Configuration
Decentralized Berth: L-Configuration
Decentralized Berth: 3-Stack

Hygiene Facility

Berths
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

• 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

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

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

<table>
<thead>
<tr>
<th>Gastrointestinal</th>
<th>Central</th>
<th>Peripheral</th>
<th>Sopite-related</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sick stomach</td>
<td>Feeling faint-like</td>
<td>Sweating</td>
<td>Feeling annoyed/irritated</td>
</tr>
<tr>
<td>Feeling queasy</td>
<td>Feeling light-headed</td>
<td>Feeling clammy/cold sweat</td>
<td>Feeling drowsy</td>
</tr>
<tr>
<td>Feeling nauseated</td>
<td>Disorientation</td>
<td>Feeling hot/warm</td>
<td>Feeling tired/fatigued</td>
</tr>
<tr>
<td>Feeling like vomiting</td>
<td>Dizziness</td>
<td></td>
<td>Feeling uneasy</td>
</tr>
<tr>
<td></td>
<td>Feeling like spinning</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: “A Questionnaire for the Assessment of Multiple Dimensions of Motion Sickness”. National Institute of Health.
<table>
<thead>
<tr>
<th>TEST SUBJECT NUMBER</th>
<th>Not at all</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Severeley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt sick to my stomach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt faint-like</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt annoyed/irritated</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt sweaty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>I felt queasy</td>
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<td></td>
<td></td>
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<tr>
<td>I felt lightheaded</td>
<td></td>
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<td></td>
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<tr>
<td>I felt drowsy</td>
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<td></td>
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<tr>
<td>I felt clammy/cold sweat</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>I felt disoriented</td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>I felt tired/fatigued</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>I felt nauseated</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt hot/warm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt dizzy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt like I was spinning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt as if I may vomit</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt uneasy</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Irene Borillo Llorca

ENAE484 Critical Design Review
29 April 2014
Window Position Testing

• Results

Motion Sickness (MS) associated with position of windows in habitat

- Dimensions of MS
  - Total
  - Gastrointestinal
  - Central
  - Peripheral
  - Sopite-related

- % of MS

• 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

Irene Borillo Llorca

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29 April 2014
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 5/8” 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 $\sigma_{\text{max}} = \sigma_{\text{press}} + 24\text{MPa}$

Source: NASA TN D-7439
Habitat Floor Design

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

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Upper Floor</th>
<th>Lower Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of floor</td>
<td>15 mm</td>
<td>35 mm</td>
</tr>
<tr>
<td>Cell diameter</td>
<td>25 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>Crush strength</td>
<td>0.03 kg/mm²</td>
<td>0.03 kg/mm²</td>
</tr>
<tr>
<td>Cell density</td>
<td>20 kg/m³</td>
<td>20 kg/m³</td>
</tr>
<tr>
<td>Cell weight</td>
<td>15.08 kg</td>
<td>25.13 kg</td>
</tr>
<tr>
<td>Face area density</td>
<td>6.9 kg/m²</td>
<td>8.6 kg/m²</td>
</tr>
<tr>
<td>Total mass</td>
<td>361.9 kg</td>
<td>457.4 kg</td>
</tr>
</tbody>
</table>

Lower Floor Analysis

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

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

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

\[
q = 955 \text{ N/m}^2
\]

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

\[
\sigma = \frac{SFk_2qa^4}{2D}
\]

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>22.93</td>
<td>220</td>
<td>8.6</td>
<td>-2.12</td>
<td>4</td>
<td>0.887</td>
</tr>
</tbody>
</table>

Source: [http://www.roymech.co.uk/Useful_Tables/Mechanics/Plates.htm](http://www.roymech.co.uk/Useful_Tables/Mechanics/Plates.htm)
Upper Floor Analysis

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

\[
e' = \sqrt{1.6ro^2 + t^2} - 0.675t
\]
\[
\sigma = \frac{SFq\ln\left(\frac{a}{e'}\right)}{t^2}
\]
\[
\delta = \frac{SF(0.217)qa^2}{Et^3}
\]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>3.58</td>
<td>10.75</td>
<td>125</td>
<td>10.6</td>
<td>-2.36</td>
<td>4</td>
<td>0.695</td>
</tr>
</tbody>
</table>

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:
  - $A = 0.2140 \, \text{m}^2$
  - $V = 0.4534 \, \text{m}^3$
  - $I = 0.2142 \, \text{m}^4$
  - 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)
  - \( \sigma = \frac{P}{A} = \frac{(6 \times 9.8 \times 0.453 \times 2700)}{0.2140} = 0.336 \text{ MPa} \)
  - Assumption made that launch supports will counter lateral launch loads

- **Euler Buckling load** during launch
  - \( F = \frac{\pi \times L^2 \times E I}{(K L)^2} = \frac{((\pi \times L^2) \times (68.9E9) \times (0.214))}{(1 \times 2.11)^2} \)
  - \( F = 32.7e+09 \text{ N} \)
  - \( \sigma = \frac{P}{A} = 32.7e+09 / 0.2140 = 152.8 \text{ MPa} \)

- **Pressurization load** is 10.4psi
  - \( \sigma = \frac{P \times r}{t} = \frac{(71710 \times 0.85)}{0.01} = 6.095 \text{ MPa} \)
Photovoltaic/Communications Tower

- Truss structure designed to support 4 photovoltaic arrays and communications array

- Dimensions
  - Cross section of truss: 1 m²
  - 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 ($F_{\text{member}} = 28.5\, \text{kN}$)
- All horizontal and cross-members are zero-force members
- Maximum axial force on a member = 1.5 MPa
  - $\sigma = P/A = F_{\text{member}}/A = 28.5\, \text{kN}/0.0019\, \text{m}^2$
- Maximum Euler Buckling in member = 79.32 MPa
  - $\sigma = \pi \sqrt{2 \frac{E}{(l/r)^2}} = \left(\pi \sqrt{2}\right) \times (68.9e +09)/((2.25/0.0243)^2)$
Phase II
Phase II: Approach and Rendezvous
Phase II: Approach and Rendezvous
Phase II: Approach and Rendezvous
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

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

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
\[ L_{eff} = L \cos(\theta) \]
Stability Arm Design

E\(_{\text{ddot}}\) vs Mass

Length Stability Arms (m)

- 10
- 15
- 20
- 25
- 30
- 35
- 40
- 45
- 50

Unstable

Stable

Mass (kg)

E\(_{\text{ddot}}\)

0

-0.8

-1

0

0.2

0.4

0.6

Mass (kg)

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Jennifer King
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

<table>
<thead>
<tr>
<th></th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast Cable Mass (kg)</td>
<td>45100</td>
<td>70300</td>
</tr>
<tr>
<td>Ballast Cable Length (m)</td>
<td>59</td>
<td>54.5</td>
</tr>
<tr>
<td>Ix</td>
<td>1.8446e+06</td>
<td>2.0046e+06</td>
</tr>
<tr>
<td>Iy</td>
<td>3.2290e+08</td>
<td>4.5507e+08</td>
</tr>
<tr>
<td>Iz</td>
<td>3.2299e+08</td>
<td>4.5516e+08</td>
</tr>
<tr>
<td>Stability Ratio</td>
<td>-0.0464</td>
<td>-0.0427</td>
</tr>
</tbody>
</table>

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

\[ a_{\text{design}} = 9.81 \ \text{[m/s]} \]
\[ l_{\text{design}} = a_{\text{design}} / \omega^2 \]
\[ r_{\text{design}} = 2H_{\text{HabFloor}} - H_{\text{HabEndcap}} - r_{\text{Hub}} \]
\[ C_{\text{HabandSIM}} = (C_{\text{Hab}} \times M_{\text{Hab}} + C_{\text{SIM}} \times M_{\text{SIM}}) / (M_{\text{Hab}} + M_{\text{SIM}}) \]
\[ W_{\text{effective}} = (M_{\text{Hab}} + M_{\text{SIM}}) \times (\omega^2 \times C_{\text{HabandSIM}}) \]
\[ T_{\text{Wire}} = SF \times W_{\text{effective}} \times (1/6) \Rightarrow \text{sizing} - 1 \text{ [in.]} \text{ diameter and 2.5 [kg/m]} \]

\[ M_{\text{tunnel}} = l_{\text{design}} \times m_{\text{tunnel}} \quad \text{and} \quad M_{\text{Wire}} = l_{\text{design}} \times m_{\text{Wire}} \]

\[ M_{\text{WireSystem}} = M_{\text{Wire}} + 6M_{\text{motor}} \]
\[ M_{\text{Hybrid}} = M_{\text{WireSystem}} + m_{\text{tunnel}} \times 10 \]
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

\[ \frac{\partial C_G}{\partial C_{Gi}} = \frac{M_i}{\sum M_i} = M_{ratio_i} \]

\[ \partial C_G = M_{ratio_i} \times \partial C_{Gi} \]

\[ \partial C_{Gx} = \partial C_{Gi} \times M_{ratio_i} \]

\[ \partial C_{Gy} = \partial C_{Gi} \times M_{ratio_i} \]

\[ \partial C_{Gz} = \partial C_{Gi} \times M_{ratio_i} \]

Cody Toothaker

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# Moving Mass and Center of Mass: Results

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

*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)**

\[ SF \cdot P_{\text{buckling}} = c \cdot \pi \cdot r^2 \cdot E \cdot I / \ell^2 \]

Central Hub Support Beams:

\[
(1/8)(2)(30000)(10)(6) = (4)\pi \cdot r^2 \cdot (7 \cdot 10 \cdot 10 \cdot I_{\square}) / (3) \cdot \ell^2 \quad \Rightarrow \quad I_{\square} = 1.46 \cdot 10^6 \text{ [mm}^4]\]

Stability Arm Support Beams:

\[
(1/4)(2)(2000)(10)(6) = (4)\pi \cdot r^2 \cdot (7 \cdot 10 \cdot 10 \cdot (1/12 \cdot s^{\uparrow}4) / (L) \cdot \ell^2 \quad \Rightarrow \quad s^{\uparrow}4 / L \cdot \ell^2 = 2.61 \cdot 10^5 \text{ [mm}^4]\]

Hub Infrastructure Members:

\[
F_{\text{axial}} = 10 \cdot M_{\text{HabandSIM}} \quad F_1 = F_{\text{axial}} / \cos(45) \quad F_2 = F_{\text{axial}} \quad A_{\text{i}} = 2 \cdot F_1 / S_{\text{f}}
\]
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

<table>
<thead>
<tr>
<th>Ballast Structure</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Lift Upper Stage</td>
<td>11,900</td>
</tr>
<tr>
<td>Crew Launch Upper Stage</td>
<td>6660</td>
</tr>
<tr>
<td>Support Structure</td>
<td>8500</td>
</tr>
<tr>
<td>Phase I Ballast</td>
<td>N/A</td>
</tr>
<tr>
<td>Phase II Ballast</td>
<td>45,100</td>
</tr>
<tr>
<td>Phase III Ballast</td>
<td>70,300</td>
</tr>
</tbody>
</table>

- 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**

\[ F = M a_{\text{centrip}} \]

\[
d_1 = 7 \text{ m} \rightarrow \text{Height of Hub in } z\text{-direction}
\]

\[
d_o = 2 \text{ m} \rightarrow \text{Outer diameter of the tunnel section}
\]

\[
L = 50 \text{ m} \rightarrow \text{For } < 4 \text{ RPM spin rate}
\]
“Stewart” Wire Rope-Truss Analysis

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

\[
\cos(\varphi) = F/F_s \quad \rightarrow \quad F_s = F/\cos(\varphi)
\]

\[
\cos(\varphi) = dx/dl \quad \rightarrow \quad dx = dl*\cos(\varphi)
\]

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

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

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

\[
F = k_{eff}*dx \quad \rightarrow \quad F/dl = k_{eff} = k*\cos^2(\varphi)
\]

\[
k_{eff-spring}/k_{spring} = \cos^2(7.12^\circ) \quad \rightarrow \quad k_{eff-spring}/k_{spring} = 0.985
\]
Six wire rope pairs in parallel, each with \( k_{\text{eff}} \approx k \cdot \cos^2(\varphi) \)

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

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

\[ F = Ma_{\text{centrip}} \]
**“Stewart” Wire Rope-Truss Configuration**

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

<table>
<thead>
<tr>
<th>Weight [N/m]</th>
<th>Minimum Sheave Diameter [m]</th>
<th>Size of Outer Wires [m]</th>
<th>Modulus of Elasticity* [Gpa]</th>
<th>Strength** [Mpa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.89</td>
<td>0.457</td>
<td>0.0012</td>
<td>75.8</td>
<td>689.5</td>
</tr>
</tbody>
</table>

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

**Based on nominal area of rope [1]**

**Hub Side**

**Hole Coordinates:**

\[
\begin{align*}
H1 &= (0, 0, d_1) \\
H2 &= (0, d_1 \cos(30^\circ), -d_1 \sin(30^\circ)) \\
H3 &= (0, -d_1 \cos(30^\circ), -d_1 \sin(30^\circ)) \\
H4 &= (L, d_o \cos(270^\circ-\theta), d_o \sin(270^\circ-\theta)) \\
H5 &= (L, d_o \cos(150^\circ-\theta), d_o \sin(150^\circ-\theta)) \\
H6 &= (L, d_o \cos(30^\circ-\theta), d_o \sin(30^\circ-\theta))
\end{align*}
\]

**Rope Vectors**

\[
\begin{align*}
r_{15} &= H5 - H1 \\
r_{16} &= H6 - H1 \\
r_{24} &= H4 - H2 \\
r_{26} &= H6 - H2 \\
r_{35} &= H5 - H3 \\
r_{34} &= H4 - H3
\end{align*}
\]

**Habitat Side**
6 sheaves for each of the wire ropes, each sheave mount transmits 1/6\textsuperscript{th} the total weight to a pair of cables:

\[ 2T\cos(\phi) = \frac{W_{\text{hab}}}{6} \quad \Rightarrow \quad T_{\text{Nominal}} = \frac{W_{\text{hab}}}{12\cos(\phi)} \]

\[ \phi = \cos^{-1} \left[ \frac{\text{dot}(\mathbf{r}_{ij}, \mathbf{W}_{\text{hab}})}{|\mathbf{r}_{ij}| \cdot |\mathbf{W}_{\text{hab}}|} \right] \]

Tension is dependent on the angle, \( \phi \), between wire rope and force vector; The angle \( \phi \) changes with angle of rotation, \( \theta \), of habitat about the x-axis.
“Stewart” Wire Rope-Truss Tension

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

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

From geometry: 

$$ T_{\text{min}} = T(60^\circ) = \frac{\text{Total Weight}}{12 \times \cos(5.71^\circ)} = 73.8 \text{ kN} $$
“Stewart” Wire Rope-Truss Restoring Force

By virtue of the angled wire ropes in the Stewart Truss configuration, the system naturally restores itself to $\theta = 0^\circ$

Perturbations from the nominal ($\theta = 0^\circ$) condition produce a restoring force, tending the system back to $\theta = 0^\circ \rightarrow$ Stable Equilibrium
“Stewart” Wire Rope-Truss Analysis

• For large $\theta$, 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 $\theta$.

• 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, $\theta$.

• Real system cables will be actively controlled by motor and break system keeping all cables loaded.
**“Stewart” Wire Rope-Truss Stress Analysis**

\[ T_{\text{nominal}} = \frac{W_{\text{hab}}}{12 \cos(\phi)} \]

\[ \sigma_{\text{nominal, tension}} = \frac{T_{\text{nominal}}}{A_{\text{metal}}} \]

\[ \sigma_{\text{sheave bending}} = E_r \frac{d_w}{D} \]

\[ \sigma_{\text{total}} = \sigma_{\text{nominal, tension}} + \sigma_{\text{sheave bending}} \]

\[ T_{\text{nominal}} = \frac{90000[\text{kg}] \times 9.8[\text{m/s}^2]}{(12 \times \cos(7.12^\circ))} = 74071 \text{ N} \]

\[ \sigma_{\text{nominal, tension}} = \frac{T_{\text{nominal}}}{A_{\text{metal}}} = 74071 \text{ N} / 10.3 \text{ mm} \approx 284 \text{ MPa} \]

\[ \sigma_{\text{sheave bending}} = E_r \frac{d_w}{D} = 75.8 \text{ GPa} \times \frac{21 \text{ mm}}{457 \text{ mm}} \approx 3.49 \text{ MPa} \]

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

Ultimate Load \( = \) Limit Load \( \times \) SF \( = \) 287.49 MPa \( \times \) 2 \( = \) 574.98 MPa

Ultimate Margin of Safety \( = \) \( (689.5 - 574.98)/574.98 = 0.1992 \)

\( E_r \) = Elastic modulus of rope = 75.8 GPa

Strength = 689.5 MPa

\( d_{w[1]} \) = Outer wire diameter = \( d[\text{in}]/22 = 21 \text{ mm} \)

\( D_{[1]} \) = Min. sheave diameter = 18\( d_{w[\text{in}]} \) = 457 mm

\( A_{\text{metal}}[2] = 0.404*(d_{w[\text{in}]}^2) = 10.3 \text{ mm} \)

Safety Factor = 2
Sheave Design

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

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

\[ D = 457 \text{ mm} \]

\[ T_{\text{nom}} = 74 \text{ kN} \]

\[ T_{\text{nom}} = 74 \text{ kN} \]

Shear Strength (6061-T6) \( \approx 200 \text{ MPa} = \tau_{\text{pin}} \)

\[ UL = 2 \times T_{\text{nom}} \times SF = 148 \text{[kN]} \times 2 = 296 \text{[kN]} \]

\[ \tau_{\text{pin}} = \frac{UL}{(\pi \times d_{\text{pin}}^2)/4} \rightarrow d_{\text{pin}} = (\frac{UL}{(\tau_{\text{pin}} \times \pi/4)})^{1/2} \]

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

Bearing pressure of the cable in the sheave groove: \( p_{[1]} = \frac{2 \times T}{(d \times D)} \)

\[ p = \frac{2 \times 74071 \text{[N]}}{(25.4 \text{[mm]} \times 457 \text{[mm]})} = 12.8 \text{ MPa} \]

\[ \sigma_{b\_sheave} = \frac{2 \times T_{\text{nom}}}{(W_{\text{sheave}} \times d_{\text{pin}})} \quad \sigma_{b\_holder} = \frac{P}{(W_{\text{sheave}} \times d_{\text{pin}})} \]
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:

\[
gear\ ratio = \frac{\text{required torque}}{\text{motor torque}}
\]

\[
rpm = \frac{\text{power} \times 60 \times \text{efficiency}}{\text{motor torque}}
\]

\[
\text{retract speed} = \pi \times \text{bend diameter} \times rpm / 60 \times \text{gear ratio}
\]

\[
\text{time} = \frac{\text{length}}{\text{retract speed}}
\]

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

![Graph of torque vs. RPM]

Constant Power at 1466W
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%)
# Reference Gearbox – Compound Train

<table>
<thead>
<tr>
<th>Variable</th>
<th>Calculation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Torque</td>
<td></td>
<td>21 Nm</td>
</tr>
<tr>
<td>Motor RPM</td>
<td></td>
<td>3300 rpm</td>
</tr>
<tr>
<td>Required Torque</td>
<td></td>
<td>78000 Nm</td>
</tr>
<tr>
<td>Torque Ratio</td>
<td>Required Torque/Motor Torque</td>
<td>3714:1</td>
</tr>
<tr>
<td>Stages</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Gearset Ratio</td>
<td>$(\text{Torque Ratio})^\text{Stages}$</td>
<td>5.2</td>
</tr>
<tr>
<td>Pinion Teeth</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Gear Teeth</td>
<td>$\text{Pinion Teeth}(\text{Gearset Ratio})$ (approximate)</td>
<td>88</td>
</tr>
<tr>
<td>Train Ratio</td>
<td>$(\text{Gear Teeth}/\text{Pinion Teeth})^\text{Stages}$</td>
<td>3717:1</td>
</tr>
<tr>
<td>Base Efficiency</td>
<td></td>
<td>98%</td>
</tr>
<tr>
<td>Train Efficiency</td>
<td>$(\text{Base Efficiency})^\text{Stages}$</td>
<td>90.4%</td>
</tr>
<tr>
<td>Power Input</td>
<td>Total Power/Train Efficiency</td>
<td>19500W</td>
</tr>
</tbody>
</table>
Reference Gearbox – Mass Estimation

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

\[ \psi = 1 - \frac{V_{\text{machined}}}{V_{\text{solid}}} \]

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

Oliver Ortiz

ENAE484 Critical Design Review
29 April 2014
During Renovations
Current State
Current State

Oliver Ortiz

ENAE484 Critical Design Review
29 April 2014
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.”

Donald Gregorich
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: φ=8 m, h=3.5 m, 4:1 ellipsoidal end caps
  - Total mass: 13,100 kg
  - Total habitable volume: 176 m³
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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>200 [kN]</td>
</tr>
<tr>
<td>Torsion</td>
<td>400 [Nm]</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Component</th>
<th>Combined Mass [kg]</th>
<th>Margin of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>81</td>
<td>0.725</td>
</tr>
<tr>
<td>Horizontal</td>
<td>1719</td>
<td>0.015</td>
</tr>
<tr>
<td>Cross member</td>
<td>237</td>
<td>1.08</td>
</tr>
</tbody>
</table>
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

![Diagram of gravity gradient system]

<table>
<thead>
<tr>
<th>Gravity</th>
<th>Rotation Rate [RPM]</th>
<th>1st Floor [g]</th>
<th>1st Floor Edge [g]</th>
<th>2nd Floor [g]</th>
<th>2nd Floor Edge [g]</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar</td>
<td>1.59</td>
<td>0.16</td>
<td>0.16</td>
<td>0.17</td>
<td>0.17</td>
<td>3.77</td>
</tr>
<tr>
<td>Mars</td>
<td>2.41</td>
<td>0.36</td>
<td>0.37</td>
<td>0.38</td>
<td>0.38</td>
<td>3.77</td>
</tr>
<tr>
<td>Earth</td>
<td>3.91</td>
<td>0.96</td>
<td>0.96</td>
<td>1.00</td>
<td>1.00</td>
<td>3.77</td>
</tr>
</tbody>
</table>
Phase III Gravity Gradients

<table>
<thead>
<tr>
<th>Gravity</th>
<th>Rotation Rate [RPM]</th>
<th>1st Floor [g]</th>
<th>1st Floor Edge [g]</th>
<th>2nd Floor [g]</th>
<th>2nd Floor Edge [g]</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
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<td>Mars</td>
<td>2.41</td>
<td>0.36</td>
<td>0.37</td>
<td>0.38</td>
<td>0.38</td>
<td>3.77</td>
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</tbody>
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<thead>
<tr>
<th>SIM [g]</th>
<th>SIM Edge [g]</th>
<th>% Change</th>
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</thead>
<tbody>
<tr>
<td>0.41</td>
<td>0.41</td>
<td>9.42</td>
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</tbody>
</table>
Phase III Ballast Configuration

- 3 Heavy Lift Upper Stages
- 4 Crew Launch Upper Stages
- Mass: 70,300 kg
## Margin of Safety (i)

<table>
<thead>
<tr>
<th>Section</th>
<th>Part</th>
<th>Failure Type</th>
<th>SF</th>
<th>MoS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central Hub</strong></td>
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<td>Cyclic Loading Fatigue 1</td>
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<td>Stability Support</td>
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<tr>
<td><strong>Mars SIM</strong></td>
<td>Floor Supports</td>
<td>Bending Yield on Launch</td>
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<tr>
<td></td>
<td>Pressure Vessel</td>
<td>Pressurization Yield</td>
<td>2</td>
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<td>Structure</td>
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<td>Bending Yield</td>
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<td>Horizontal Member</td>
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<td>Cross Member</td>
<td>Torsion Yield</td>
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<td><strong>Comm Tower</strong></td>
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## Margin of Safety (ii)

<table>
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<td>Structure</td>
<td>Euler Buckling on Launch</td>
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<td>Cable Attachment</td>
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<td>Floor Supports</td>
<td>Bending Yield on Launch</td>
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<td>0.7867</td>
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<tr>
<td></td>
<td>Mars SIM Attachment</td>
<td>Bending Yield on Spinning</td>
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<td>2.370</td>
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<td>Pressure Vessel</td>
<td>Pressurization Yield</td>
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<td>4.405</td>
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<td></td>
<td>Floor 1</td>
<td>Bending Yield</td>
<td>1.5</td>
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<tr>
<td></td>
<td>Floor 2</td>
<td>Bending Yield</td>
<td>1.5</td>
<td>9.945</td>
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<tr>
<td>Ballast</td>
<td>Upper Stage</td>
<td>Bending Yield on Spinning</td>
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<td>0.3100</td>
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<td>Stewart System</td>
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<td>Ultimate Tension</td>
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<td>Periphery</td>
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<td></td>
<td></td>
<td>Pressurization Yield</td>
<td>2</td>
<td>21.64</td>
</tr>
</tbody>
</table>
Main Propulsion System

Requirements:

• Phase I
  ▪ Propulsion system shall be capable of a $\Delta V = 75 \ m/s$ 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

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

- 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

<table>
<thead>
<tr>
<th>Engine</th>
<th>Propellants</th>
<th>Thrust [N]</th>
<th>$I_{sp}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airbus 200 N Thruster</td>
<td>NTO and MMH</td>
<td>200</td>
<td>270</td>
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<tr>
<td>R-40B</td>
<td>NTO and MMH</td>
<td>4000</td>
<td>293</td>
</tr>
<tr>
<td>R-4D</td>
<td>NTO and MMH</td>
<td>490</td>
<td>315.5</td>
</tr>
</tbody>
</table>

- 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 $\Delta V = 0.0015 \ m/s$
• Total Pulses: 20,781
• TRL Level-9

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

<table>
<thead>
<tr>
<th>Engine</th>
<th>Propellant(s)</th>
<th>Thrust [N]</th>
<th>$I_{sp}$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airbus 200 N Thruster</td>
<td>NTO and MMH</td>
<td>200</td>
<td>270</td>
</tr>
<tr>
<td>R-1E</td>
<td>NTO and MMH</td>
<td>111</td>
<td>280</td>
</tr>
<tr>
<td>MRE-1.5</td>
<td>Hydrazine</td>
<td>86</td>
<td>228</td>
</tr>
<tr>
<td>Mr-107V</td>
<td>Hydrazine</td>
<td>220</td>
<td>229</td>
</tr>
</tbody>
</table>
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
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
  - \( \Delta m = I_{zz} \omega z m \downarrow T / 2L \cos(\theta \downarrow T) F_{T,\text{max}} \)

• Ballast
  - \( \Delta m = I_{zz} \omega z m \downarrow T / 2L \cos(\theta \downarrow T) F_{T,\text{max}} m \downarrow \text{Habitat} / m \downarrow \text{Ballast} \)

- \( I_{zz} \) = moment of inertia about z
- \( \omega z \) = change in angular velocity about z
- \( m \downarrow T \) = thruster mass flow rate
- \( L \) = distance between habitat/ballast and Hub
- \( \theta \downarrow T \) = thruster angle
- \( F_{T,\text{max}} \) = maximum thruster force
- \( m \downarrow \text{Habitat} \) = mass of habitat
- \( m \downarrow \text{Ballast} \) = mass of ballast
Phase I

• Maneuvers
  ▪ DRO orbit insertion

• Propellant mass
  ▪ $\Delta m = 1864.5\ kg$

• Taking chemical properties into account
  ▪ $\Delta m_{\text{Oxidizer}} = 1055\ kg$
  ▪ $\Delta m_{\text{Fuel}} = 640\ kg$

• Maximum volume for tanks
  ▪ $V_{\text{Oxidizer}} = .732\ m^3$
  ▪ $V_{\text{Fuel}} = .527\ m^3$
Phase II-Moon

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

<table>
<thead>
<tr>
<th>Structure</th>
<th>Required Propellant (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat</td>
<td>350 212 561</td>
</tr>
<tr>
<td>Ballast</td>
<td>285 172 457</td>
</tr>
</tbody>
</table>

**Graph:** Required Propellant per Structure-Lunar

- Blue: Total Mass Propellant
- Red: Oxidizer Mass
- Green: Fuel Mass

**Legend:**
- Habitat
- Ballast
Phase II-Mars

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

<table>
<thead>
<tr>
<th>Structure</th>
<th>Required Propellant (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitat</td>
<td>477</td>
</tr>
<tr>
<td>Ballast</td>
<td>378</td>
</tr>
</tbody>
</table>

- Total Mars Propellant
- Oxidizer Mass
- Fuel Mass
Phase II-Earth

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

![Required Propellant per Structure-Earth](image)

- Total Earth Propellant
- Oxidizer Mass
- Fuel Mass

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ENAE484 Critical Design Review
29 April 2014
Phase III

- Maneuvers
  - DRO orbit insertion
  - Spin to Mars gravity

![Graph showing required propellant per structure for Mars]

- Habitat:
  - Total Mars Propellant: 1659
  - Oxidizer Mass: 1033
  - Fuel Mass: 626

- Ballast:
  - Total Mars Propellant: 1405
  - Oxidizer Mass: 875
  - Fuel Mass: 530
Propellant Tanks

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Habitat/Ballast</td>
<td>1796</td>
<td>0.7114</td>
<td>920.5</td>
<td>0.7268</td>
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<tr>
<td>Central Hub</td>
<td>2587</td>
<td>2.939</td>
<td>12,090</td>
<td>3.527</td>
</tr>
</tbody>
</table>
Propellant Tanks

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

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Habitat/Ballast</td>
<td>2963</td>
<td>.6099</td>
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<tr>
<td>Central Hub</td>
<td>4267</td>
<td>2.959</td>
<td>12,300</td>
<td>3.551</td>
</tr>
</tbody>
</table>
Feed System

• Gas Pressure Regulated feed system using Helium

Feed System

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

<table>
<thead>
<tr>
<th>Placement</th>
<th>Max Pressurant Mass [kg]</th>
<th>Max Pressurant Volume [m³]</th>
<th>Pressurant Tank Mass [kg]</th>
<th>Pressurant Tank Volume [m³]</th>
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</thead>
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<tr>
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<td>118.5</td>
<td>2.909</td>
<td>4.073</td>
<td>3.491</td>
</tr>
</tbody>
</table>
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:

\[ \|h_1\| = \|h_2\| = h_0 \]

\[ \|\Delta h\| = h_0 \sqrt{2 - 2 \cos \theta} \]
• 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”)
• 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:

- Radiators: 2.75 m$^2$
- Heat Exchanger
- Internal Power: 28 kW
- Heater power
- Pumped Fluid Loop
- Aluminized Kapton Surface Coating
- Solar Radiation

Temperature: $292K < T < 300K$
The incident solar area changes as the habitat rotates about the Hub, keeping the temperature throughout the station in a state of dynamic equilibrium.
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:

$$\Delta T_5 = (I \cdot A \cdot \alpha - (Q_{\text{radiator}} + \sigma \epsilon A r (T_5^4 - T_{\text{env}}^4)) + \frac{(T_4 - T_5) k_{\text{alum}} A_r}{d_{\text{outer}}}) \frac{1}{(m_{\text{outer}} C_{\text{alum}}) \Delta t}$$

$$\Delta T_4 = \left( \frac{\sigma \epsilon_{\text{inner}} (A_3 - A_{\text{strut}}) T_3^4 - (A_4 - A_{\text{strut}}) T_4^4}{2 + \alpha_{\text{inner}}} \right) + \left( \frac{T_1 - T_4 k_{\text{alum}} A_{\text{strut}}}{d_{\text{inner}} + d_{\text{strut}}} \right) + \left( \frac{T_5 - T_4 k_{\text{alum}} A_r}{d_{\text{outer}}} \right) \frac{1}{(m_{\text{outer}} C_{\text{alum}}) \Delta t}$$
Thermal Simulation (continued)

Conduction through inner wall

\[
\Delta T_3 = \left( \frac{T_1 - T_3}{d_{\text{inner}}/k_{\text{Alum}}(A_1 - A_{\text{strut}}) + d_{\text{polyeth}}/k_{\text{polyeth}}(A_3 - A_{\text{strut}})} \right)
\]

Net inner radiative transfer

\[
\Delta T_3 = \left( \frac{T_1 - T_3}{d_{\text{inner}}/k_{\text{Alum}}(A_1 - A_{\text{strut}}) + d_{\text{polyeth}}/k_{\text{polyeth}}(A_3 - A_{\text{strut}})} \right) + \frac{\sigma \epsilon_{\text{inner}}((A_4 - A_{\text{strut}})T_4^4 - (A_3 - A_{\text{strut}})T_3^4)}{2 + \alpha_{\text{inner}}} \frac{(m_{\text{polyeth}}C_{\text{polyeth}})\Delta t}{d_{\text{inner}} + d_{\text{strut}}}
\]

Inner power added

\[
\Delta T_1 = (Q_{\text{heater}} + P_{\text{internal}}) + \frac{T_3 - T_1}{d_{\text{inner}}/k_{\text{Alum}}(A_1 - A_{\text{strut}}) + d_{\text{polyeth}}/k_{\text{polyeth}}(A_3 - A_{\text{strut}})}
\]

Conduction through inner wall

\[
\Delta T_1 = (Q_{\text{heater}} + P_{\text{internal}}) + \frac{T_3 - T_1}{d_{\text{inner}}/k_{\text{Alum}}(A_1 - A_{\text{strut}}) + d_{\text{polyeth}}/k_{\text{polyeth}}(A_3 - A_{\text{strut}})} + \frac{(T_4 - T_1)k_{\text{Alum}}A_{\text{strut}}}{d_{\text{inner}} + d_{\text{strut}}} \frac{(m_{\text{inner}}C_{\text{Alum}})\Delta t}{d_{\text{inner}} + d_{\text{strut}}}
\]

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Thermal Coating

- **Outer surface coating:**
  - 0.25 mm Kapton Film with aluminum backing
  - Emissivity: \(0.45\)
  - Absorptivity: \(0.31\)

- **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
To keep $T = 297 \, \text{K}$ 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 $\varepsilon_{\text{radiator}} = 0.9$
• Requires 4.4 kW of power removal

\[ P_{\text{out}} = A_{\text{rad}} \varepsilon_{\text{rad}} \sigma T_{\text{rad}}^4 \]

• Radiator cross sectional area of $= 2.75 \text{ m}^2$
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 \( kg/s \)

\[ P = (m \ \Delta p/\rho) = mg(h_2 - h_1) \]

• 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

Temperature Increase on Sunlit Side

Temperature Decrease on Dark Side

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29 April 2014
Thermal Control Flowchart

Measure temperature in habitat

High: T>297K
- Increase radiator pump power and shutoff heater
- Increase pump power of fluid loop

Low: T<297 K
- Retract radiator, increase radiator pump power and increase heater power
- lower pump power as desired

High: ΔT> 5K

High: ΔT< 5K
Eclipsing at 70,000 km DRO

*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

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</thead>
<tbody>
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<td>Average</td>
<td>Peak</td>
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<td>6200</td>
<td>6000</td>
<td>6700</td>
<td>6300</td>
</tr>
<tr>
<td>PPT</td>
<td>4000</td>
<td>8000</td>
<td>5000</td>
<td>10000</td>
<td>5500</td>
</tr>
<tr>
<td>Crew Systems</td>
<td>15000</td>
<td>18000</td>
<td>15000</td>
<td>18000</td>
<td>15000</td>
</tr>
<tr>
<td>LSM</td>
<td>1000</td>
<td>2000</td>
<td>11500</td>
<td>23000</td>
<td>11500</td>
</tr>
<tr>
<td>Science</td>
<td>2200</td>
<td>3000</td>
<td>4400</td>
<td>6000</td>
<td>6600</td>
</tr>
<tr>
<td>Mars SIM</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10000</td>
</tr>
<tr>
<td>Total</td>
<td>27200</td>
<td>37200</td>
<td>41900</td>
<td>63700</td>
<td>54900</td>
</tr>
</tbody>
</table>

Michael Shallcross

ENAE484 Critical Design Review

29 April 2014
Solar Cell Performance Comparison

- 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

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

**Gallium Arsenide Triple Junction Cell**

Each junction collects energy over a different range of the Solar spectrum.

---

Michael Shallcross

ENAE484 Critical Design Review
29 April 2014
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 m²
  - Total Cost = $25MM

- **PHASE 2:** 42 kW → 65 kW
  - Total Mass = 445 kg
  - Total Surface Area = 159 m²
  - Total Cost = $40MM

- **PHASE 3:** 55 kW → 85 kW
  - Total Mass = 582 kg
  - Total Surface Area = 208 m²
  - Total Cost = $52MM

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29 April 2014
Photovoltaic Location

• PHASE I
  - Located on Hab
  - Two arrays provide 104 m² 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: $\rho = 8930 \text{ kg/m}^3$  
  \[ \text{resistivity} = 1.7e-8 \Omega \cdot \text{m} \quad \varepsilon = 0.15 \]

\[ P = I^2R = I^2\left(\frac{\text{res} \cdot L}{Acs}\right) = \varepsilon \cdot \sigma \cdot As \cdot T^4 \]

\[ T = \left(\frac{I^2 \cdot \text{res} \cdot L}{Acs \cdot As \cdot \varepsilon \cdot \varepsilon \cdot \sigma}\right)^{1/4} \]

- 50 m of wire will have ~25 kg mass
- $\rho = 8930 \text{ kg/m}^3 = m/v = m/(\pi r^2)$
- $r=4.5 \text{ mm}$  
  Diameter = 9 mm  
  $R = 13 \text{ m}\Omega$
- $T_{\text{melt}} \text{ Cu} = 1356 \text{ K}$
- Insulated wire will be able to carry load without significant power loss

Space Mission Engineering: The New SMAD
### Power Management and Distribution

<table>
<thead>
<tr>
<th>Part</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSU</td>
<td>Receives power from array and maintains output voltage to setpoint by shunting/unshunting array strings.</td>
</tr>
<tr>
<td>DCSU</td>
<td>Used for power distribution, protection and fault isolation. Uses relays and switches to route primary power downstream.</td>
</tr>
<tr>
<td>MBSU</td>
<td>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.</td>
</tr>
<tr>
<td>DDCU</td>
<td>Responsible for DC power conversion (acts as transformer) for 160 VDC to 120VDC, which is the prescribed voltage for all users.</td>
</tr>
<tr>
<td>BCDU</td>
<td>Provides charge and discharge control of electricity from batteries.</td>
</tr>
</tbody>
</table>

**Diagram:**
- **PV Array**
  - Sequential Shunt Unit (SSU)
  - DC Switching Unit (DCSU)
  - Battery Charge / Discharge Unit (BCDU)
  - Main Bus Switching Unit (MBSU)
  - DC-DC Converter Unit (DDCU)
  - Batteries
  - Fuel Cells
  - To Users/Loads
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>27.2</td>
<td>4.1</td>
<td>8</td>
<td>330</td>
</tr>
<tr>
<td>II</td>
<td>42.0</td>
<td>4.1</td>
<td>8</td>
<td>508</td>
</tr>
<tr>
<td>III</td>
<td>55.0</td>
<td>4.1</td>
<td>8</td>
<td>665</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy Density (W-hr/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel Cadmium</td>
<td>40</td>
</tr>
<tr>
<td>Nickel Metal Hydride</td>
<td>60</td>
</tr>
<tr>
<td>Nickel Hydrogen</td>
<td>60</td>
</tr>
<tr>
<td>Silver-zinc</td>
<td>100</td>
</tr>
<tr>
<td>Lithium Ion</td>
<td>120</td>
</tr>
<tr>
<td>Lithium Polymer</td>
<td>180</td>
</tr>
</tbody>
</table>

### Energy Density Chart

![Specific Energy Density Chart](chart.png)

- **Material**: Nickel Cadmium, Nickel Metal Hydride, Nickel Hydrogen, Silver-zinc, Lithium Ion, Lithium Polymer

- **Energy Density**: Ranges from 40 to 180 W-hr/kg.
Lithium-Ion Batteries

- 120 W-hr/kg:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Energy Requirement [kW-hr]</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>330</td>
<td>2750</td>
</tr>
<tr>
<td>II</td>
<td>508</td>
<td>4233</td>
</tr>
<tr>
<td>III</td>
<td>665</td>
<td>5542</td>
</tr>
</tbody>
</table>

- 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 $3.11 \times 10^6$ 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)

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Mass Required [kg]</th>
<th>Density [kg/m$^3$]</th>
<th>Al Tank Diameter [m]*</th>
<th>Container Mass [kg]*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas. $H_2$</td>
<td>30</td>
<td>0.082</td>
<td>1.4</td>
<td>632</td>
</tr>
<tr>
<td>Gas. $O_2$</td>
<td>200</td>
<td>1.308</td>
<td>0.98</td>
<td>360</td>
</tr>
</tbody>
</table>

*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:

\[
    m = \frac{E \cdot \rho}{k \cdot \sigma}
\]

<table>
<thead>
<tr>
<th>Shape</th>
<th>K factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laval disk</td>
<td>1</td>
</tr>
<tr>
<td>Solid disk</td>
<td>0.606</td>
</tr>
<tr>
<td>Thick rim</td>
<td>0.305</td>
</tr>
<tr>
<td>Thin rim</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Flywheels

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

- For 660 kW-hr:

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

- 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 electrolyzer 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

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

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

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Code Type</th>
<th>$\text{BER}_{\text{des}} = 10^{-6}$</th>
<th>$\text{BER}_{\text{des}} = 10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$E_b/N_0$ [dB]</td>
<td>$E_b/N_0$ [dB]</td>
</tr>
<tr>
<td>BPSK</td>
<td>Uncoded</td>
<td>10.5</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>Hamming (7,4)</td>
<td>7.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>RS (31,16)</td>
<td>4.5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Turbo</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>QPSK</td>
<td>Uncoded</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Hamming (7,4)</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>RS (31,16)</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Turbo</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>8QAM</td>
<td>Uncoded</td>
<td>12.5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Hamming (7,4)</td>
<td>9.5</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>RS (31,16)</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Turbo</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th></th>
<th>TX Diameter [m]</th>
<th>RX Diameter [m]</th>
<th>Eb/N0 Received [dB]</th>
<th>Eb/N0 Required [dB]</th>
<th>BER [dB]</th>
<th>Data Rate [bytes/sec]</th>
<th>Link Margin [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ka-band</strong></td>
<td>11</td>
<td>1</td>
<td>31.31</td>
<td>9.73</td>
<td>-50</td>
<td>10 MB/s</td>
<td>21.58</td>
</tr>
<tr>
<td><strong>S-band</strong></td>
<td>11</td>
<td>1</td>
<td>19.17</td>
<td>9.73</td>
<td>-50</td>
<td>1 MB/s</td>
<td>19.17</td>
</tr>
<tr>
<td><strong>VHF</strong></td>
<td>Yagi</td>
<td>Yagi</td>
<td>23.37</td>
<td>9.73</td>
<td>-50</td>
<td>100 kB/s</td>
<td>13.64</td>
</tr>
<tr>
<td><strong>UHF</strong></td>
<td>Yagi</td>
<td>Yagi</td>
<td>21.92</td>
<td>9.73</td>
<td>-50</td>
<td>100 kB/s</td>
<td>12.19</td>
</tr>
</tbody>
</table>

**RED:** Nominal mode for data transmission
## Link Margin Analysis (Downlink to Earth)

<table>
<thead>
<tr>
<th></th>
<th>TX Diameter [m]</th>
<th>RX Diameter [m]</th>
<th>Eb/N0 Received [dB]</th>
<th>Eb/N0 Required [dB]</th>
<th>BER [dB]</th>
<th>Data Rate [bytes/sec]</th>
<th>Link Margin [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ka-band</strong></td>
<td>1</td>
<td>11</td>
<td>26.54</td>
<td>9.73</td>
<td>-50</td>
<td>10 MB/s</td>
<td>16.81</td>
</tr>
<tr>
<td><strong>S-band</strong></td>
<td>1</td>
<td>11</td>
<td>15.19</td>
<td>9.73</td>
<td>-50</td>
<td>1 MB/s</td>
<td>5.45</td>
</tr>
<tr>
<td><strong>VHF</strong></td>
<td>Yagi</td>
<td>Yagi</td>
<td>28.60</td>
<td>9.73</td>
<td>-50</td>
<td>100 kB/s</td>
<td>18.87</td>
</tr>
<tr>
<td><strong>UHF</strong></td>
<td>Yagi</td>
<td>Yagi</td>
<td>21.92</td>
<td>9.73</td>
<td>-50</td>
<td>100 kB/s</td>
<td>8.96</td>
</tr>
</tbody>
</table>

RED: Nominal mode for data transmission
## Modes of Communication

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

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

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

<table>
<thead>
<tr>
<th>Moment of Inertia (kg-m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{xx}$ 3.435x10⁶</td>
</tr>
<tr>
<td>$I_{yy}$ 7.302x10⁵</td>
</tr>
<tr>
<td>$I_{zz}$ 7.700x10⁵</td>
</tr>
</tbody>
</table>

• 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:

<table>
<thead>
<tr>
<th></th>
<th>Total Mass (kg)</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Wheels</td>
<td>2085.7*</td>
<td>125.1</td>
</tr>
<tr>
<td>Propellant</td>
<td>2919</td>
<td>144</td>
</tr>
</tbody>
</table>

*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

System Computer

Desired Attitude

Control Laws

Real Time Attitude Estimate

Definitive Attitude Determination Software

Attitude Measurement

Attitude Sensors
- IMU
- Sun sensors
- Star trackers

Control Command

Attitude Actuators
- Thrusters
- Reaction Wheels

Control Torque

Spacecraft Dynamics

Internal/External Disturbances

Adapted from Space Mission Engineering: The New SMAD

Jennifer King
ENAE484 Critical Design Review
29 April 2014
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 computer 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 m³
Use Case Diagram

Space Habitat Cabin Atmosphere Control System

Command Center

Crew Member

Monitor Atmosphere Condition

Outputs CO₂

Inputs O₂

Increases Temperature

Remove CO₂

Regenerate O₂

Maintain Temperature

Outside environment
Block Definition Diagram

Atmosphere Control System

**4 Bed Molecular Sieve (4BMS)**
- Power: watts
- Volume: m³ [unit = cubicMetre]
- Weight: kg [unit = kilogram]

**Sabatier Reaction System**
- Power: watts
- Volume: m³ [unit = cubicMetre]
- Weight: kg [unit = kilogram]

**Advance Carbon Formation Reaction System (ACRS)**
- Power: watts
- Volume: m³ [unit = cubicMetre]
- Weight: kg [unit = kilogram]

**Tanks**
- Volume: m³ [unit = cubicMetre]
- Weight: kg [unit = kilogram]

**Power Supply**
- Power: watts

**Sensors**
- **O₂ Reading**
- **N₂ Reading**
- **CO₂ Reading**

**Solar panels**

**Temperature and Humidity Control System (THC)**
- Power: watts
- Volume: m³ [unit = cubicMetre]
- Weight: kg [unit = kilogram]
BDD for O₂ Regeneration

```
<<block>>
Atmosphere System CO₂ Removal and O₂ Regeneration
<<constraints>>
mass1 : MassBalance
power1 : PowerBalance
volume1 : VolumeBalance
MMOS : MassMOS
PMOS : PowerMOS
Vmos : VolumeMOS

weight : kilogram
Weight_MOS : Real
Power_MOS : Real
Volume_MOS : Real
power : watt
volume : cubicMetre
crew : Real

<<constraint>>
MassBalance
constraints
\{m=(m1+m2+m3)\times crew\}
parameters
m : kilogram
m1 : kilogram
m2 : kilogram
m3 : kilogram
crew : Real

<<constraint>>
PowerBalance
constraints
\{w=(w1+w2+w3)\times crew\}
parameters
w : watt
w1 : watt
w2 : watt
w3 : watt
crew : Real

<<constraint>>
VolumeBalance
constraints
\{v=(v1+v2+v3)\times crew\}
parameters
v : cubicMetre
v1 : cubicMetre
v2 : cubicMetre
v3 : cubicMetre
crew : Real
```
Mass, Volume, Power Requirements

- **MassReq**
  - **Id**: 4
  - **Text**: The total mass for each component must satisfy the requirement to remove the CO₂ for a crew of 6.

- **PowerReq**
  - **Id**: 5
  - **Text**: The total power for each component must be sufficient to remove the CO₂ for a crew of 6.

- **VolumeReq**
  - **Id**: 6
  - **Text**: The total volume for each component must satisfy the requirement to remove the CO₂ for a crew of 6.

- **MassMOS**
  - **Constraints**: \( \text{mos} = \left( \frac{30^{\text{crew}} + 91^{\text{crew}} + 60^{\text{crew}}}{30^{\text{crew}} + 91^{\text{crew}} + 60^{\text{crew}}} \right) \)
  - **Parameters**: \( \text{mos} : \text{Real} \), \( \text{crew} : \text{Real} \), \( \text{actual} : \text{kilogram} \)

- **PowerMOS**
  - **Constraints**: \( \text{mos} = \left( \frac{170^{\text{crew}} + 260^{\text{crew}} + 130^{\text{crew}}}{170^{\text{crew}} + 260^{\text{crew}} + 130^{\text{crew}}} \right) \)
  - **Parameters**: \( \text{mos} : \text{Real} \), \( \text{crew} : \text{Real} \), \( \text{actual} : \text{watt} \)

- **VolumeMOS**
  - **Constraints**: \( \text{mos} = \left( \frac{0.11^{\text{crew}} + 3^{\text{crew}} + 0.1^{\text{crew}}}{0.11^{\text{crew}} + 3^{\text{crew}} + 0.1^{\text{crew}}} \right) \)
  - **Parameters**: \( \text{mos} : \text{Real} \), \( \text{crew} : \text{Real} \), \( \text{actual} : \text{cubicMetre} \)
O₂ Regeneration Activity diagram

Values to Remove CO₂ for a crew of 6

<table>
<thead>
<tr>
<th>System</th>
<th>Power [W]</th>
<th>Weight [kg]</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Removal/O₂ Regeneration</td>
<td>4032</td>
<td>1303</td>
<td>23</td>
</tr>
</tbody>
</table>

- The table shows the total amount of power, weight, and volume the CO₂ removal / O₂ regeneration system will have.
- A 1.2 margin of safety is applied to account for exercise and EVA days.
Atmosphere Requirement Diagram

**Atmosphere Control**
- **Id**: "4.1.4"  
  **Text**: ""

**Safety**
- **Id**: "4.1.4 2.1"  
  **Text**: "Occurs when you have insufficient oxygen pressure in the alveolar. Saturation < 90%"

**Hypoxic Zone**
- **Id**: "4.1.4 2.2"  
  **Text**: "Must have enough power to support all the atmosphere components"

**Oxygen Toxicity**
- **Id**: "4.1.4 2.2"  
  **Text**: "Must have enough power to support all the atmosphere components"

**Performance**
- **Id**: "4.1.4 .1"  
  **Text**: ""Must have enough power to support all the atmosphere components"

**Power**
- **Id**: "4.1.1"  
  **Text**: "The components used must have high technology readiness levels."

**Reliability**
- **Id**: "4.1.1"  
  **Text**: "The components used must have high technology readiness levels."

**Sound/Speech**
- **Id**: "4.1.4 2.4"  
  **Text**: "Pressure lower than 69 Kpa will result in degradation of crew member’s ability to understand speech transmitted through the atmosphere form sound source."

**Fire Contingency**
- **Id**: "4.1.4 2.3"  
  **Text**: "NASA’s requires that O2 percentage be less than 30% due to fire concern."
Determining $O_2$ Percentage

![Graph showing fraction of Hb saturation vs. pO2 in mmHg.](image)

**Graph Details:**
- **Oxygen Dissociation Curve**
- **Standard Sea Level**

**Regression Analysis:**
- **X:** 99.72  
  **Y:** 0.962
- **X:** 4.605  
  **Y:** 3.178

---

**Graph 2:**
- **Log(Y/(1-Y)) vs. log(pO2) in mmHg**
- **Linear Regression Curve**
- **Fitted line**

---

**Notes:**
- Samuel Garay
- ENAE484 Critical Design Review
- 29 April 2014
### Pressure and O₂ Trade Study

<table>
<thead>
<tr>
<th>Cabin Pressure [kPa]</th>
<th>%O₂</th>
<th>O₂ Pressure Felt in the Alveolar (PaO₂) [kPa/mmHg]</th>
<th>Saturation%</th>
<th>PaO₂ at (SSL) – PaO₂ in cabin [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>*101.32</td>
<td>21</td>
<td>13.3/99.7</td>
<td>96.2</td>
<td>0</td>
</tr>
<tr>
<td>62</td>
<td>30</td>
<td>10.4/78.4</td>
<td>93.87</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>72</strong></td>
<td><strong>30</strong></td>
<td><strong>13.4/101</strong></td>
<td><strong>96.3</strong></td>
<td><strong>-0.1</strong></td>
</tr>
<tr>
<td>54</td>
<td>32</td>
<td>9/67.5</td>
<td>91.82</td>
<td>4.3</td>
</tr>
<tr>
<td>34.47</td>
<td>80</td>
<td>18.9/141.36</td>
<td>97.4</td>
<td>-5.6</td>
</tr>
</tbody>
</table>

- A cabin Pressure of 72 kPa and a 30% O₂ 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.

<table>
<thead>
<tr>
<th></th>
<th>Mass [kg]</th>
<th>Volume [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_2$/O$_2$ tanks for EVA</td>
<td>89</td>
<td>0.8</td>
</tr>
<tr>
<td>N$_2$/N$_2$ tanks for EVA</td>
<td>208.3</td>
<td>2.13</td>
</tr>
<tr>
<td>O$_2$/O$_2$ tanks for Mars SIM</td>
<td>52</td>
<td>0.47</td>
</tr>
<tr>
<td>N$_2$/N$_2$ tanks for Mars SIM</td>
<td>121.3</td>
<td>1.09</td>
</tr>
<tr>
<td>Total</td>
<td>470.6</td>
<td>4.49</td>
</tr>
<tr>
<td></td>
<td>Duration</td>
<td>Mass [kg]</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Food</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase I</td>
<td>30 Days</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>6 Months</td>
<td>1241</td>
</tr>
<tr>
<td>Phase II</td>
<td>Three 6 Month Missions at Different Gravities</td>
<td>1862 for each</td>
</tr>
<tr>
<td>Phase III</td>
<td>1000 Days</td>
<td>11,140</td>
</tr>
<tr>
<td><strong>Refrigerator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>All Duration</td>
<td>67.75</td>
</tr>
<tr>
<td><strong>Microwave Oven</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase I,II,III</td>
<td>All Duration</td>
<td>11.34</td>
</tr>
<tr>
<td><strong>Galley Sink</strong></td>
<td></td>
<td>27.22</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Food Regeneration Based on Data from NASA Ames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [kg]</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Food Regeneration</td>
</tr>
</tbody>
</table>
# Hygiene Mass and Volume Estimates

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

- **Toilet-Liquid Waste**

<table>
<thead>
<tr>
<th></th>
<th>Mass [kg]</th>
<th>Volume [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Urinal</td>
<td>9.435</td>
<td>0.089</td>
</tr>
<tr>
<td>Urine Collection Module</td>
<td>9.253</td>
<td>0.043</td>
</tr>
</tbody>
</table>

- **Solid Waste**

<table>
<thead>
<tr>
<th></th>
<th>Mass [kg]</th>
<th>Volume [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Collection Module</td>
<td>64.9</td>
<td>0.48</td>
</tr>
</tbody>
</table>

- **Shower**

<table>
<thead>
<tr>
<th></th>
<th>Mass [kg]</th>
<th>Volume [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower with Fixed Nozzle</td>
<td>43.32</td>
<td>0.97</td>
</tr>
<tr>
<td>Whole Body Shower</td>
<td>150.6</td>
<td>3.11</td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Waste Containers</th>
<th>Description</th>
<th>Acceptability for Hazardous Waste</th>
<th>Usable Volume [m³]</th>
<th>Unit Mass Empty [kg]</th>
<th>Unit Mass (Full) [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Trash Bag (KBO-M)</td>
<td>Used for wet or dry trash</td>
<td>Yes</td>
<td>0.03</td>
<td>0.79</td>
<td>8</td>
</tr>
<tr>
<td>Solid Waste Container (KTO)</td>
<td>Used for solid and biological waste</td>
<td>Yes</td>
<td>0.04</td>
<td>3.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Container for Water/Urine (EDV)</td>
<td>Used for urine and wastewater collection</td>
<td>No</td>
<td>0.02</td>
<td>5.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Food Waste Bag</td>
<td>Used to replace table scraps and wet items</td>
<td>No</td>
<td>2.6*10^-3</td>
<td>0.06</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Source:** Management Plan for Waste Collection and Disposal. NASA/SSP 50481B
## Waste Containers (ii)

<table>
<thead>
<tr>
<th>Waste Containers</th>
<th>Description</th>
<th>Acceptability for Hazardous Waste</th>
<th>Usable Volume [m³]</th>
<th>Unit Mass Empty [kg]</th>
<th>Unit Mass (Full) [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharps Container</td>
<td>Used to dispose sharp objects</td>
<td>Yes</td>
<td>2.4*10^{-3}</td>
<td>0.39</td>
<td>1.36</td>
</tr>
<tr>
<td>Plastic Waste Bag</td>
<td>Used for non sharp hazardous waste</td>
<td>Yes</td>
<td>0.11</td>
<td>0.05</td>
<td>TBD</td>
</tr>
<tr>
<td>Fecal Collection Assembly (Apollo Bag)</td>
<td>Used as contingency bag for solid human waste</td>
<td>No</td>
<td>2*10^{-4}</td>
<td>0.06</td>
<td>TBD</td>
</tr>
<tr>
<td>Contingency Urine Collection Device (CUCD)</td>
<td>Used as a contingency bag for liquid human waste</td>
<td>No</td>
<td>5*10^{-4}</td>
<td>0.03</td>
<td>TBD</td>
</tr>
</tbody>
</table>

*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 \(67 \text{ kg/m}^3\) (average density estimate based on data from MARPOL study and Skylab)

• Trash generation rate of \(1.83 \text{ kg/crew member/day}\)

• 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 m³

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

<table>
<thead>
<tr>
<th>Items</th>
<th>Volume Required [m³] for Mission Duration, 6 crew</th>
<th>Stowage Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td>15.25</td>
<td>16.13</td>
</tr>
<tr>
<td>Hygiene Products</td>
<td>2.24</td>
<td>3</td>
</tr>
<tr>
<td>Clothes</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Personal Equipment</td>
<td>3.78</td>
<td>3.8</td>
</tr>
<tr>
<td>Trash</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Exercise Equipment</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Workstation</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
## Water Consumption

<table>
<thead>
<tr>
<th>Phase</th>
<th>Drinking (Regular Day) [kg/person/day]</th>
<th>Drinking (EVA day) [kg/person/day]</th>
<th>Food Prep [kg/person/day]</th>
<th>Hygiene [kg/person/day]</th>
<th>Clothes Washing [kg/week]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>2</td>
<td>4</td>
<td>0.75</td>
<td>4-7</td>
<td>38</td>
</tr>
<tr>
<td>Phase II</td>
<td>3</td>
<td>5</td>
<td>0.75</td>
<td>4-7</td>
<td>38</td>
</tr>
<tr>
<td>Phase III</td>
<td>3</td>
<td>5</td>
<td>0.75</td>
<td>4-7</td>
<td>38</td>
</tr>
</tbody>
</table>

- 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 m³
    • Power: 350 W
Total Water Budget

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

<table>
<thead>
<tr>
<th>Phase</th>
<th>Water lost from system [kg]</th>
<th>Nominal water required [kg]</th>
<th>Contingency Supply [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I (4 crew, 180 days)</td>
<td>470</td>
<td>575</td>
<td>470</td>
</tr>
<tr>
<td>Phase II (6 crew, 180 days)</td>
<td>720</td>
<td>920</td>
<td>875</td>
</tr>
<tr>
<td>Phase III (6 crew, 1000 days)</td>
<td>4115</td>
<td>4315</td>
<td>875</td>
</tr>
</tbody>
</table>

- 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

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

**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

<table>
<thead>
<tr>
<th>Exercising Machine</th>
<th>Body Volume Needed for Operation for 0g ([\text{m}^3])</th>
<th>Mass ([\text{kg}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVIS</td>
<td>6.12</td>
<td>180</td>
</tr>
<tr>
<td>CEVIS</td>
<td>1.70</td>
<td>27</td>
</tr>
</tbody>
</table>

*(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

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configurations</td>
<td><strong>i.e. Constellation space suit</strong> EVAs in microgravity and terrestrial</td>
</tr>
<tr>
<td>Operating pressure</td>
<td><strong>i.e. Extravehicular Mobility Unit (EMU)</strong> 10.4 psi to 4 psi → Denitrogenation with pure oxygen = 40 min inside suit</td>
</tr>
<tr>
<td>Air composition</td>
<td></td>
</tr>
<tr>
<td>Mobility</td>
<td></td>
</tr>
<tr>
<td>Donning</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td></td>
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</tbody>
</table>
Space Suits Contd.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service life</td>
<td>Long shelf life at least 8 years</td>
</tr>
<tr>
<td>Radiation shielding</td>
<td>6 hours of EVAs during each week</td>
</tr>
<tr>
<td>Propulsion unit</td>
<td>\textit{i.e. Manned Maneuvering Unit (MMU)}</td>
</tr>
<tr>
<td>Dust mitigation</td>
<td>On legs, arms and chest</td>
</tr>
</tbody>
</table>

Space suit meeting all requirements does not exist $\rightarrow$ need to develop a new one
Space Suits

• Constellation Single Suit System Architecture

Sensor Overview

<table>
<thead>
<tr>
<th>ADCS</th>
<th>CS</th>
<th>PPT</th>
<th>LSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star Tracker</td>
<td>Water</td>
<td>Temperature</td>
<td>Strain Gauges</td>
</tr>
<tr>
<td>Sun Sensor</td>
<td>Atmosphere</td>
<td>Tank Levels</td>
<td>Inductive Wire Integrity</td>
</tr>
<tr>
<td>IMUs</td>
<td>Radiation</td>
<td>Thruster State</td>
<td>Cameras</td>
</tr>
<tr>
<td></td>
<td>Smoke</td>
<td>Battery Level</td>
<td></td>
</tr>
</tbody>
</table>
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
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
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
## Sensors Total Budget

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

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

**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 mission success and risk to crew safety
• Analyzed before and after mitigation and contingency efforts

<table>
<thead>
<tr>
<th>risk level</th>
<th>insignificant</th>
<th>minor</th>
<th>moderate</th>
<th>severe</th>
<th>catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almost Certain</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Likely</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Possible</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Unlikely</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Rare</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
### Risk Analysis Matrix

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

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

<table>
<thead>
<tr>
<th>Category</th>
<th>Event</th>
<th>Unmitigated Risk Level (Mission)</th>
<th>Unmitigated Risk Level (Crew)</th>
<th>Mitigation Measures</th>
<th>Primary Contingency</th>
<th>Mitigated Risk Level (Mission)</th>
<th>Mitigated Risk Level (Crew)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics Failure</td>
<td>Pressure Sensor</td>
<td>3</td>
<td>3</td>
<td>Secondary Sensors</td>
<td>Repair / disable if possible</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>CO₂ Sensor</td>
<td>3</td>
<td>3</td>
<td>Secondary Sensors</td>
<td>Repair / disable if possible</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Smoke Detector</td>
<td>3</td>
<td>3</td>
<td>Secondary Detectors</td>
<td>Repair / disable if possible</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Nitrogen Sensor</td>
<td>3</td>
<td>3</td>
<td>Secondary Sensors</td>
<td>Repair / disable if possible</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Inertial Measurement Unit</td>
<td>4</td>
<td>3</td>
<td>Control System identifying malfunction</td>
<td>Repair / shut down faulty IMU</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manual override / shutoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal Equilibrium Sensor</td>
<td>4</td>
<td>4</td>
<td>Manual override accessible to crew</td>
<td>Repair / disable if possible</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Secondary Sensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Star Tracker</td>
<td>4</td>
<td>2</td>
<td>Backup Star Trackers</td>
<td>Repair / recalibrate tracker</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Battery Combustion</td>
<td>4</td>
<td>3</td>
<td>Fire Extinguishers accessible to crew</td>
<td>Extinguish battery fire</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Back-up batteries accessible to crew</td>
<td>Replace battery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Communications</td>
<td>4</td>
<td>2</td>
<td>Backup communications system</td>
<td>Diagnose problem, repair</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Communications system ground training</td>
<td>Use backup system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Communications Pointing</td>
<td>4</td>
<td>2</td>
<td>Backup pointing motor</td>
<td>EVA to repair / replace assembly</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EVA to repair</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar Panel</td>
<td>4</td>
<td>4</td>
<td>Excess power capabilities allowing for repair/replacement time</td>
<td>Limit power usage to critical systems</td>
<td>3</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Independent radiator control</td>
<td>Repair / replace if possible</td>
<td></td>
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<tr>
<td></td>
<td>Radiator Control</td>
<td>4</td>
<td>4</td>
<td>Manual override of radiator automation</td>
<td>Manually override radiator operation combination</td>
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<td>Sun Sensor</td>
<td>4</td>
<td>2</td>
<td>Redundant sensors (8)</td>
<td>Repair / recalibrate tracker</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>EVA</td>
<td>Suit Rupture</td>
<td>3</td>
<td>5</td>
<td>Two personnel minimum on EVA</td>
<td>Return to Hab Airlock immediately</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Disconnect from Station</td>
<td>3</td>
<td>5</td>
<td>Two personnel minimum on EVA</td>
<td>Use RCS pack to return to station / retrieve disconnected astronaut</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>One RCS pack minimum on EVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cable connect points on external structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radio Failure</td>
<td>2</td>
<td>3</td>
<td>Simulation testing</td>
<td>Return to Hab Airlock immediately</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Category</td>
<td>Event</td>
<td>Unmitigated Risk Level (Mission)</td>
<td>Unmitigated Risk Level (Crew)</td>
<td>Mitigation Measures</td>
<td>Primary Contingency</td>
<td>Mitigated Risk Level (Mission)</td>
<td>Mitigated Risk Level (Crew)</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------------</td>
<td>----------------------------------</td>
<td>-------------------------------</td>
<td>---------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>--------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Life Support Failure</td>
<td>Four Bed Molecular Sieve</td>
<td>3</td>
<td>4</td>
<td>Crew-accessible replacements</td>
<td>Replace faulty sieves</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Multi-Filtration System</td>
<td>3</td>
<td>4</td>
<td>Crew-accessible replacements</td>
<td>Repair / replace filters</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(Water)</td>
<td></td>
<td></td>
<td>Water quality testing kits accessible to crew</td>
<td>Repair / replace components</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Sabatier Reaction</td>
<td>3</td>
<td>3</td>
<td>Replacement components accessible to crew</td>
<td>Repair / replace components</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Advanced Carbon-Formation</td>
<td>3</td>
<td>3</td>
<td>Replacement components accessible to crew</td>
<td>Repair / replace components</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Reaction System</td>
<td></td>
<td></td>
<td>Replacement components accessible to crew</td>
<td>Repair / replace components</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Vapor Compression Distillation</td>
<td>3</td>
<td>4</td>
<td>Replacement components accessible to crew</td>
<td>Crew-accessible replacements</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Forward Osmosis Bags</td>
<td>2</td>
<td>3</td>
<td>Crew-accessible replacements</td>
<td>Forward Osmosis secondary system</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Waste Collection (Space Toilet)</td>
<td>2</td>
<td>3</td>
<td>Contingency waste bags accessible to crew</td>
<td>Replace faulty bags</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Natural</td>
<td>Solar Particle Event</td>
<td>3</td>
<td>4</td>
<td>Periods of inhabitance planned for low solar activity periods</td>
<td>Move crew into most heavily shielded area ASAP</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Meteoroid Contact</td>
<td>4</td>
<td>4</td>
<td>Dedicated foreign object sensors for station course intersection</td>
<td>Move crew into most heavily shielded area ASAP</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
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

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

<table>
<thead>
<tr>
<th>Item</th>
<th>A</th>
<th>B</th>
<th>M</th>
<th>Cost ($M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>13.89</td>
<td>0.55</td>
<td>750</td>
<td>529.65</td>
</tr>
<tr>
<td>Liquid Rocket Engine</td>
<td>34.97</td>
<td>0.55</td>
<td>2 &amp; 4.31</td>
<td>2780.38</td>
</tr>
<tr>
<td>Science Instrument</td>
<td>2.235</td>
<td>0.5</td>
<td>150</td>
<td>27.37</td>
</tr>
<tr>
<td>In Space Habitat</td>
<td>1457.7</td>
<td>0.0856</td>
<td>21577</td>
<td>3424.98</td>
</tr>
</tbody>
</table>
# Cost Drivers

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost ($M)</th>
<th>Costing Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrusters</td>
<td>2780</td>
<td>CER</td>
</tr>
<tr>
<td>Launch Vehicle(s)</td>
<td>5175</td>
<td>Industry Data</td>
</tr>
<tr>
<td>Habitat</td>
<td>3424</td>
<td>CER</td>
</tr>
<tr>
<td>Hub</td>
<td>2084</td>
<td>Material Cost &amp; Development</td>
</tr>
<tr>
<td>MARS SIM</td>
<td>2250</td>
<td>CER</td>
</tr>
</tbody>
</table>
Budget Breakdown by Department

- Avionics
- CS
- PPT
- LSM
- MPA

% of Total Budget
Cost over Timeline of Project

- Before Phase I
- Phase I
- Phase II
- "Phase III"
- Refurbishment

Cost ($M)

0 2000 4000 6000 8000 10000 12000

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
  - \( \sigma\downarrow \theta = \frac{pr}{t} \)
  - \( t\downarrow min = 2.08 \ mm \)
- 4:1 Ellipsoidal End cap
  - \( (\sigma\downarrow \theta)\downarrow max = 1.42*\frac{pr}{t} \)
  - \( t\downarrow min = 2.95 \ mm \)
- 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

\[ F = \pi^2 \frac{EI}{(KL)^2} \]

- Applying constraints and safety factor
  \[ I_{\text{min}} = 9.02 \times 10^{-6} \]
- With cross-section and geometric constraints thickness of beam was determined
  \[ t_{\text{min}} = 0.130 \text{ m} \]
  \[ A_{\text{min}} = 0.0065 \text{ m}^2 \]
Horizontal Stringer Design

- Bottom stringer design
- Load = 62.5 KN per member
- Safety Factor: 2
- \( \sigma_{\text{max}} = \frac{My_{\text{min}}}{I_{\text{x}}} \)
- Applying constraints
  - \( h_{\text{min}} = .143 \, m \)
- Floor stringer design
- Floor Bending Load = 15.6 KN
- \( \sigma_{\text{max}} = \frac{My_{\text{min}}}{I_{\text{x}}} \)
- Applying constraints
  - \( h_{\text{min}} = .140 \, m \)
Cable System Connection

- Bending Load = 500 KN per member
- Safety Factor: 2
- $\sigma_max = \frac{My_{\text{min}}}{I_{x}}$
- Using I-Beam cross-section to strengthen against beaming
- $I_{x}/y_{\text{min}} = 0.0036 \text{ m}^3$
- I-beam Dimensions:
  - d = 163.83 mm
  - h = 82.3 mm
  - b = 204.3 mm
  - t = 91.92 mm
Power Appendix

PV Sizing Equations:

\[ P_{array} = \frac{P_{e} \cdot T_{e}}{X_{e}} + \frac{P_{d} \cdot T_{d}}{X_{d}} \]

\[ P_{array} = \frac{P_{d}}{X_{d}} \]

- \( P_{d} \) = Power during daylight (average set per phase by demand)
- \( T_{d} \) = Time during daylight per orbit
- \( X_{d} \) = Path efficiency from arrays to loads (Use 0.85 – industry standard)
- \( P_{e} \) = Power during eclipse
- \( T_{e} \) = Time during eclipse per orbit (Treat as zero since eclipse so infrequent)
- \( X_{e} \) = Path efficiency from arrays through batteries to loads

- \( I \) = Solar Flux Constant at 1 AU = 1364 W/m²
- 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

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Purpose</th>
<th>Qty</th>
<th>Dimensions Each [cm]</th>
<th>Mass Each [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequential Shunt Unit (SSU)</td>
<td>Receives power from array and maintains output voltage to setpoint by shunting/unshunting array strings.</td>
<td>4-8</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>DC Switching Unit (DCSU)</td>
<td>Used for power distribution, protection and fault isolation. Uses relays and switches to route primary power downstream.</td>
<td>4</td>
<td>71.1x101.6x30.5</td>
<td>108</td>
</tr>
<tr>
<td>DC to DC Converter Unit (DDCU)</td>
<td>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.</td>
<td>4</td>
<td>173x64x36</td>
<td>67</td>
</tr>
<tr>
<td>Main Bus Switching Unit (MBSU)</td>
<td>Responsible for DC power conversion (acts as transformer) for 160 VDC to 120VDC, which is the prescribed voltage for all users.</td>
<td>4</td>
<td>71.1x101.6x30.5</td>
<td>100</td>
</tr>
<tr>
<td>Battery Charge/Discharge Unit (BCDU)</td>
<td>Provides charge and discharge control of electricity from batteries.</td>
<td>4</td>
<td>71.1x101.6x30.5</td>
<td>107</td>
</tr>
<tr>
<td>Remote Power Controller Module (RPCM)</td>
<td>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</td>
<td>92</td>
<td>17x20x9</td>
<td>5</td>
</tr>
</tbody>
</table>

### Power Transfer Devices

ENAE484 Critical Design Review  
29 April 2014

UNIVERSITY OF MARYLAND
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:

\[ p_{[1]} = \frac{2T}{(dD)} \]

\[ p = \frac{2(74071 \text{ [N]})}{(25.4 \text{ [mm]} \times 457 \text{ [mm]})} = 12.8 \text{ MPa} \]

\[ S_u = 1.8483 \times 10^6 \]
• 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

Required Propellant per Structure-Moon

<table>
<thead>
<tr>
<th>Structure</th>
<th>Habitat</th>
<th>Ballast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Propellant (Total Moon Propellant)</td>
<td>1388</td>
<td>1192</td>
</tr>
<tr>
<td>Required Propellant (Oxidizer Mass)</td>
<td>864</td>
<td>742</td>
</tr>
<tr>
<td>Required Propellant (Fuel Mass)</td>
<td>524</td>
<td>450</td>
</tr>
</tbody>
</table>

Total Moon Propellant

Oxidizer Mass

Fuel Mass
Appendix Slides

Graph 1: Probability of Bit Error vs. $E_b/N_0$
- Uncoded BPSK
- RS (31,16)
- Uncoded QPSK
- RS (31,16)
- Uncoded 8QAM
- RS (31,16)

Graph 2: Bit-Error Rate
- 1 iteration
- 2 iterations
- 3 iterations
- 4 iterations
- 10 iterations

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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.
References


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References


References (cont)


References (cont)


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