Modular Roving Planetary Habitat, Laboratory, and Base

Critical Design Review

April 19, 2004
Mission Statement

“Returning to the moon is an important step for our space program... The moon is home to abundant resources. Its soil contains raw materials that might be harvested and processed into rocket fuel or breathable air. We can use our time on the moon to develop and test new approaches and technologies and systems that will allow us to function in other, more challenging environments. The moon is a logical step toward further progress and achievement.”

~ President George W. Bush

- Restore human exploration to the moon, investigating a large portion of the lunar surface
- Maximize the search for natural lunar resources through a mobile base
- Develop the experience and the required technologies for extended human space travel
Program Overview

**Designed to meet externally applied constraints**

<table>
<thead>
<tr>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design/Manufacture</td>
<td>Test Systems</td>
<td>Launch Modules</td>
<td>Manned Missions (every 6 months)</td>
</tr>
</tbody>
</table>

- Launch small, autonomous, mobile modules with specialized purposes to the moon
- Assemble the modules into a complete base
- Send a crew of 4 to the assembled base to conduct experiments for 3 lunar day-night cycles (months)
- Disassemble base and send modules to next site of interest, up to 1000km away, over an unmanned period of 3 months
Science Objectives

• Study the effects of the lunar environment on life, especially long duration missions
  - Radiation
  - Skeletal system
  - Cardiovascular system
  - Muscle development and decay
  - Plant and animal biology
  - Nutrition and medical care
  - Crew dynamics
  - Human performance and adaptations

• Study the moon and its resources
  - Volcanic and impact history
  - Water ice and ore deposits as potential resources
  - Deep lunar composition
  - Environmental variations along the surface
Assembly Sites and Selection Criteria

- Approximately 1000 km apart
- Apollo site candidates
- Surveyor landing sites
- Ore deposits and useful elements
- Permanently shadowed regions
- Age and appeal of lunar structures

Sites
1) Marius
2) Flamsteed
3) Gassendi
4) Tycho
5) Meretus
6) Drygalski
7) Schrodinger
8) Minnaert
9) Mare Ingenii
10) Gagarin

http://geopubs.wr.usgs.gov/i-map/i2769/

Kevin Eisenhower
Module Types

- **6 Habitable Modules**
  - Size governed by launch vehicle payload size
  - Need 6 to achieve the necessary floor space and volume to accommodate a crew of 4 for 3 lunar sols

- **6 Chassis with all-wheel drive**
  - Provide locomotion for Habitable Modules
  - Equipped with transit connections to link vehicles in the transit phase

- **4 Power Modules with all-wheel drive**
  - Provides AC power to all modules
  - Equipped with navigation computers and leads during transit
Modularity – Transit Phase

- After each manned mission, MORPHLAB will disassemble and travel autonomously to a new base site
- Enables exploration and analysis of vast areas of the Lunar surface
- Transit configuration:
  - 1 Power Module,
  - 2 Habitable Modules, &
  - 2 Chassis Modules
- Science will be performed by the modules while traveling

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Modularity – Manned Base Phase

- Multiple base configurations possible
- Subsystems split between modules
Benefits of Modularity

• Modules are less massive than a large-scale structure
  – Can be launched on existing launch vehicles
  – Increased mobility

• Capable of traversing great distances
  – Multiple lunar base locations
  – Science may be performed while modules are in transit
  – Experiments may be subjected to long exposures to the lunar environment

• Feasible program expenditures
  – Allows for cost spreading over the program duration

• Utilizes a cost learning curve
Module Details

Habitable Module

Chassis Module

Power Module
Habitable Module
Habitable Module Overview

• Habitable modules:
  – provide the space where the crew will live and work while not out on EVA
  – two types of modules:
    • Habitable-Living (3 of 6)
    • Habitable-Science (other 3 of 6)

• This breakup
  – allows minimal disruption if the astronauts have different sleeping schedules
  – restricts lunar dust to the EVA areas

• Functions are distributed and redundant so that the failure of any one module will not disrupt normal activities (Level 1 requirements I3, I11)
Sizing Requirements

- All crew interfaces are sized to accommodate 95th percentile American males to 5th percentile Japanese females (Level 1 requirements L1, L2).
- The size of the modules is bounded by:
  - maximum radius of Delta IV-Heavy payload area – 4.5 m
  - minimum amount of room necessary for four people in the same module – 10.24 m²
- Habitable modules are 4.0 m in diameter, which gives 12.56 m² of floor space per module:
  - accounts for wires and pipes behind walls and furnishings
  - leaves enough open space in the modules to move about
  - keeps the module mass reasonable.
Habitable-Living Subtypes

- Both types include
  - Basement level radiation shelter sleeping areas
  - Two hatches, L-shape intersection

Crew quarters (2)

Galley (1)

- Androgynous Docking Mechanism
- Viewing Window
- Radiator
- N₂ Tanks
- O₂ Tanks
- H₂O Tanks
Habitable-Science Subtypes

EVA workspace (2)  Experiment area (1)

- Both types include
  - Basement level storage compartments
  - Three exits, T-shape intersection
# Radiation Environment

<table>
<thead>
<tr>
<th></th>
<th>Energy Level (MeV)</th>
<th>Flux (p/cm²-s)</th>
<th>Particles, Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Allen Belts</td>
<td>10⁻¹ – 10³</td>
<td>10² – 10¹⁰</td>
<td>Trapped p⁺, e⁻, Short-duration</td>
</tr>
<tr>
<td>GCR</td>
<td>10² – 10⁴, max 10¹¹</td>
<td>10⁻⁵ – 1, max ~2</td>
<td>85% p⁺, 13% He⁺, 2% HZE, Near-constant</td>
</tr>
<tr>
<td>SPE</td>
<td>10⁻¹⁻³, max ~10⁴</td>
<td>10⁻³ – 10⁴, max ~10⁶</td>
<td>96-99% p⁺, 1-3 days</td>
</tr>
</tbody>
</table>

Van Allen Belts
- Trapped Particles

Cislunar Space Radiation
- Solar Winds
- Galactic Cosmic Rays (GCRs)
- Solar Particle Events (SPEs)

Note: Drawing not to scale
# Necessity of Radiation Shielding

<table>
<thead>
<tr>
<th>Lifetime Limits: BFO dose (blood-forming organs), 5 cm depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>Male</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Female</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time interval</th>
<th>BFO dose limits</th>
<th>Dose Source</th>
<th>On Lunar Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 days</td>
<td>25 rem</td>
<td>SPE</td>
<td>200 rem</td>
</tr>
<tr>
<td>1 year</td>
<td>50 rem</td>
<td>GCR</td>
<td>30 rem/year</td>
</tr>
</tbody>
</table>

- SPE shielding is necessary
- From the Level 1 requirements (M1, M6, I1, L2, L5, L6, L7), shielding must prevent the radiation dose received from exceeding these levels for the habitable mission length.
• 5.7cm Polyethylene is used for SPE shielding
• 4mm Aluminum pressure hull helps block GCR
# Radiation Dose Breakdown

<table>
<thead>
<tr>
<th>Period</th>
<th>Total hours</th>
<th>Shielding (g/cm²)</th>
<th>Total dose (rem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Allen Belts both ways</td>
<td>--</td>
<td>--</td>
<td>2</td>
</tr>
<tr>
<td>EVAs</td>
<td>84</td>
<td>336</td>
<td>1.44</td>
</tr>
<tr>
<td>GCR asleep</td>
<td>84</td>
<td>672</td>
<td>1.33</td>
</tr>
<tr>
<td>GCR awake, no EVA</td>
<td>84</td>
<td>1008</td>
<td>4.31</td>
</tr>
<tr>
<td>DIPS (5 modules)</td>
<td>84</td>
<td>2016</td>
<td>1.03</td>
</tr>
<tr>
<td>GCR asleep</td>
<td>180</td>
<td>1440</td>
<td>2.85</td>
</tr>
<tr>
<td>EVAs</td>
<td>180</td>
<td>~3.5</td>
<td>0.01</td>
</tr>
<tr>
<td>SPE, August 1972 dosage</td>
<td>180</td>
<td>72</td>
<td>21.74</td>
</tr>
<tr>
<td>GCR awake</td>
<td>180</td>
<td>2805</td>
<td>11.99</td>
</tr>
<tr>
<td>DIPS (5 modules)</td>
<td>180</td>
<td>4320</td>
<td>2.2</td>
</tr>
<tr>
<td>Total dose 30 days</td>
<td>24.99 rem</td>
<td>Total dose 84+180 days</td>
<td>48.91 rem</td>
</tr>
</tbody>
</table>

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Cat McGhan
Radiation Shelter Sleeping Areas

- From the Level 1 requirements and trade studies:
  - Level 2 requirement L6: Radiation shielding capable of suitable protection against a solar flare must be internal to at least three habitable modules.
- Habitable-living basement level
- Split in half by a noise-muffling curtain for privacy
- Dual-purpose
- Emergency exit procedure:
  - Move curtain aside
  - Exit via second door
Radiation Shelter Specifics

- Shelter built into basement of Habitable-Living modules
  - Maximizes daytime living floor area
  - Minimizes mass consumption by doubling shelter as sleeping quarters
  - Basement also leaves room for storage and ECLSS systems

- High Density Polyethylene
  - Superior radiation protection per amount of mass compared to other materials
  - 0.057 m thickness based on radiation analysis
  - 568 kg total
Radiation Shelter Specifics

- Can accommodate two people each
- Two doors built into the top
- Internal Dimensions
  - Based on estimated necessary volume for 95th percentile American male to sleep comfortably (derived from L1 requirement)
  - 1.9 m long, 1.95 m wide, 0.8 m tall

Kevin Macko
Procedure for Impending SPE

• In the event of an impending SPE:
  – SOHO (SOlar and Heliospheric Observatory) or its successor will give 2-3 days notice of heightened activity
  – The astronauts will be informed by Mission Control and EVAs will be cancelled for the duration
  – Just before the event, SOHO and other Space Weather satellites will give a few hours notice
  – Astronauts will retreat to the shelter for the duration of the event

• The crew will be able to maintain contact with Mission Control via their laptops, and they will have access to whatever libraries and amusements that they can download from the NASA computers
Micrometeoroid Protection

- Micrometeoroids massive enough to cause damage are very rare: probability analysis is necessary
- NASA Human rating requirement: The program shall be designed such that the cumulative probability of safe crew return over the life of the program exceeds 0.99
- We will assume a desired 0.996 Probability of No Penetration (PNP) per mission - same as Apollo requirement

\[ F = \frac{-\ln(PNP)}{A \times t} \]

- \( F = 1.28 \times 10^{-4} \) hits/m\(^2\)-year
- \( A = 41.6 \) m\(^2\)
- \( Y = 0.75 \) years
Micrometeoroid Protection

- Micrometeoroid flux of $1.28 \times 10^{-4}$ hits/m$^2$-year is off this chart
- Data curve was graphically extended to this flux
- Critical micrometeoroid mass estimated to be $3 \times 10^{-4}$ grams

Micrometeoroid Protection

- Data based on heuristic from NASA Preferred Reliability Practices document on micrometeoroid protection (Practice No. PD-EC-1107)
- Assumed .5 mm spacing between MLI and aluminum pressure hull
- 4 mm Al skin chosen based on 13.3 km/s average lunar micrometeoroid velocity
Pressurized tanks must have a factor of safety of 3.0.
Rounded shape chosen to minimize stresses due to internal pressure.
Bottom is rounded to minimize pressure stress, but flattened to lay on chassis module correctly.
Pressure Hull Analysis

- 4 mm thick Al-2014 pressure hull
  - Stress concentrations around doors and windows are assumed to be handled by their frames
  - 2.8 margin of safety for hoop stress
- 2 mm thick bottom reinforcement
  - Where stresses are above 164 MPA with 4mm thickness
- Design based on FEA is conservative: stringers not included in pressure model

Finite element analysis with 57.2 kPa internal pressure applied
Internal Support Structure

- 3 critical loading scenarios considered
  - Launch: 6g’s axially, 2.5g’s laterally (based on Delta-IV-H payload planner’s guide)
  - Landing: 1 lunar g vertically and horizontally, on one leg
  - Hab/Science to Chassis attachment: 4 lunar g’s

- All elements made of titanium alloy with hollow circle cross-section
- Primary structure designed for 2.0 factor of safety based on S1 requirement

<table>
<thead>
<tr>
<th>Component</th>
<th>O.D.</th>
<th>I.D.</th>
<th>Mass</th>
<th>Max Design Stress</th>
<th>Margin of Safety</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Stringers</td>
<td>.030 m</td>
<td>.024 m</td>
<td>49 kg</td>
<td>394 MPa</td>
<td>.40</td>
<td>Compression</td>
</tr>
<tr>
<td>Circular Stringers</td>
<td>.033 m</td>
<td>.032 m</td>
<td>24 kg</td>
<td>524 MPa</td>
<td>.052</td>
<td>Bending</td>
</tr>
<tr>
<td>Elliptical Stringers</td>
<td>.018 m</td>
<td>.014 m</td>
<td>32 kg</td>
<td>542 MPa</td>
<td>.018</td>
<td>Bending</td>
</tr>
<tr>
<td>Circular Frames</td>
<td>.031 m</td>
<td>.026 m</td>
<td>157 kg</td>
<td>524 MPa</td>
<td>.052</td>
<td>Compression</td>
</tr>
</tbody>
</table>
Internal Support Structure

- **FEM Assumptions**
  - Door and window frames that intersect with internal structure will act as the stringers in reality
  - FEM analysis is conservative because skin is not included to take loads
  - Excessive load concentrations at joints can be ignored

- **Launch Loading**
  - Vertical stringers, circular frames, and upper circular stringers sized based on this scenario
  - Constrained at 4 connection points along bottom frame
  - 3700 kg vehicle mass distributed to structural connection points

Highest stress concentrations:
- 525 MPa
- 395 MPa
- 265 MPa
- 135 MPa
- 70 MPa
Internal Support Structure

- **Landing Loading**
  - Worst case – landing on one leg
  - Constrained at leg attachment points
  - Max stress: 179 MPa - no internal structural components sized for landing

- **Hab to Chassis Attachment**
  - 0.03 m fall onto chassis when landing legs are removed
  - Max stress: 542 MPa in lower elliptical stringers
### Additional Structural Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Max Design Stress (MPa)</th>
<th>Safety Factor</th>
<th>Margin of Safety</th>
<th>Mass (kg)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator Support Structure</td>
<td>Titanium Alloy</td>
<td>437</td>
<td>2</td>
<td>.26</td>
<td>21.2</td>
<td>Compression</td>
</tr>
<tr>
<td>Docking Mechanism Walkway</td>
<td>Aluminum 2014</td>
<td>174</td>
<td>2</td>
<td>.049</td>
<td>93</td>
<td>Bending</td>
</tr>
<tr>
<td>Radiation Shelter</td>
<td>Polyethylene</td>
<td>3.2</td>
<td>1.5</td>
<td>3.6</td>
<td>568</td>
<td>Bending</td>
</tr>
<tr>
<td>Oxygen Tank</td>
<td>Aluminum 2014</td>
<td>109</td>
<td>3</td>
<td>.003</td>
<td>65</td>
<td>Hoop Stress</td>
</tr>
<tr>
<td>Nitrogen Tank</td>
<td>Aluminum 2014</td>
<td>109</td>
<td>3</td>
<td>.003</td>
<td>58</td>
<td>Hoop Stress</td>
</tr>
</tbody>
</table>

- Safety factors based on S1 requirement
  - 2.0 for primary structures
  - 1.5 for secondary structures
  - 3.0 for pressure vessels
Floor Panel Requirements

- Composite sandwich panel used to sustain compressive and bending loads of floor items
- Level 1 requirements
  - S1: Factor of Safety = 2
  - S2: Non-negative MOS (Margin Of Safety) for launch loads (6g Earth)
- Total load of interior items
  - Must sustain launch loads
  - Assumed the load is distributed over entire panel
  - Future iterations will use composite laminate theory for more precise numbers
Floor Panel Design

Mass of Interior Items Estimated 876.1 kg

Skin: High Modulus Carbon Fiber-Epoxy
- 37 kg
- 0.13 cm thick

Core: Aluminum 5056 Honeycomb
- 37 kg/m³
- ¼ in. cell size
- 24 kg
- 7.24 cm thick

Total Panel:
61 kg
7.49 cm thick
0.98 cm max. deflection
# Floor Panel Deflection and Failure Modes

<table>
<thead>
<tr>
<th>Loading Effect</th>
<th>Effect Induced</th>
<th>Limit</th>
<th>MOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Deflection</td>
<td>0.98 cm</td>
<td>0.01 cm</td>
<td>0.02</td>
</tr>
<tr>
<td>Local Compressive Stress</td>
<td>11500 Pa</td>
<td>5.20 MPa</td>
<td>451.73</td>
</tr>
<tr>
<td>Skin Stress</td>
<td>59.5 MPa</td>
<td>GPa</td>
<td>19.83</td>
</tr>
<tr>
<td>Core Shear Stress</td>
<td>0.168 MPa</td>
<td>1.80 MPa</td>
<td>9.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential Failure Phenomenon</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-cell Buckling</td>
<td>20 GPa</td>
<td>1.24 GPa</td>
<td>12.44</td>
</tr>
<tr>
<td>Skin Wrinkling</td>
<td>1.33 GPa</td>
<td>1.24 GPa</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Buckling Stress
Window Requirements

- **Types:** Hatch and General Area
- **Level 1 Requirements**
  - **S1:** Factor of Safety = 3
  - **S2:** Nonnegative MOS in bending for launch loads (6g Earth)
  - **L2:** Adhere to NASA-STD-3000, delimiting the following:
    - minimum window diameters, minimum blunt impact (550N), height of windows, optical and manufacturing requirements, ionizing radiation protection (GCR), non-ionizing radiation protection (UV), safety precautions
  - **L8:** Must have emergency alternative access / bailout options
- **S2** met by using the window frame to channel launch loads around the window and into a stringer
- **L2** is met using a sunshade 4 mm thick of Aluminum 2014. Sun shade also protects crew from earth’s magnetic field
- **L8** is satisfied using hatches, where a porthole must be present to allow astronauts to see what is on the other side of the hatch
Window Assembly

• Material: Ceradyne Thermo-Sil® Ultra High Strength Fused Silica
  - radio wave, IR, microwave radiation transparent
  - low CTE ($0.5 \times 10^{-6}/^\circ\text{C}$)
  - high strength/weight ratio:
    - flexural strength ~ 55 MPa
    - density ~ 2020 kg/m$^3$
Window Assembly

• Differences from ISS windows:
  – Different pressure pane thickness from ISS
  – MORPHLAB uses 4 mm Aluminum 5056 sunshades over all windows

• Similarities to ISS windows:
  – Same debris pane thickness
  – Anti-reflective coating on outer surface of outer window pane
  – Blue-red reflective coating on inner surface of inner window pane to filter out IR and UV
  – Air tight seal between pressure panes
## Window Panes

<table>
<thead>
<tr>
<th>Pressure Pane</th>
<th>Hatch</th>
<th>General Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (cm)</td>
<td>20.3</td>
<td>50.8</td>
</tr>
<tr>
<td>Thickness (cm)</td>
<td>0.547</td>
<td>1.37</td>
</tr>
<tr>
<td>MOS</td>
<td>0.0100</td>
<td>0.0100</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.559</td>
<td>8.76</td>
</tr>
</tbody>
</table>

### Fused Silica Kick Pane

<table>
<thead>
<tr>
<th></th>
<th>Hatch</th>
<th>General Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (cm)</td>
<td>0.644</td>
<td>0.644</td>
</tr>
<tr>
<td>MOS</td>
<td>0.0182</td>
<td>0.0182</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.556</td>
<td>3.48</td>
</tr>
</tbody>
</table>

### Aluminum Sunshade

<table>
<thead>
<tr>
<th></th>
<th>Hatch</th>
<th>General Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (cm)</td>
<td>0.400</td>
<td>0.400</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.510</td>
<td>3.77</td>
</tr>
</tbody>
</table>

### Fused Silica Debris Pane

<table>
<thead>
<tr>
<th></th>
<th>Hatch</th>
<th>General Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (cm)</td>
<td>0.970</td>
<td>0.970</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.835</td>
<td>6.18</td>
</tr>
</tbody>
</table>
# Window Masses Per Module

<table>
<thead>
<tr>
<th>Description</th>
<th>Habitable-Living</th>
<th>Habitable-Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hatch Windows with Pressure Panes, Kick Pane, and Aluminum Sunshade</td>
<td>2</td>
<td>3*</td>
</tr>
<tr>
<td>Hatch Windows with Pressure Panes, Kick Pane, Aluminum Sunshade, and Debris Pane</td>
<td>0</td>
<td>1*</td>
</tr>
<tr>
<td>General Area Windows with Pressure Panes, Kick Pane, Aluminum Sunshade, and Debris Pane</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Total Window** Weight (kg)</td>
<td>35.3</td>
<td>9.57</td>
</tr>
</tbody>
</table>

* Walkways protect all hatch windows except outer EVA hatch window; only the outer EVA door’s window needs micrometeoroid and lunar dust protection during transit
** Total Window Weight excludes TBD window frames
Hatches & Docking

- Extendable mating ring on each inflatable tunnel
- Sliding interior doors
- inflatable tunnel

- Provides travel between modules in shirtsleeve environment
- Provides power, water, and air transfer between modules during base phase
- More details forthcoming
Chassis Overview

- Single universal chassis for all MORPHLAB applications
  - 4 power modules landed on Moon with chassis permanently attached
  - 6 Chassis Module landed on Lunar Surface
- 4 wheel drive / 4 wheel steering
- Total Mass = 1483kg
- Drive platform for Power Module and Habitable Module
- Utilizes 24 hour battery power source until mated with Power Module
- Capable of supporting 3700kg load during transit and base phase
- Can be directly landed on lunar surface with a payload of 2000kg
- .7m minimum ground clearance and 1.4m diameter wheel to meet Level 1 requirement: capability of traversing a .5m obstacle
Chassis Dimensions

Requirements:
Must be capable of traversing over a .5m boulder
Must fit within 4.5m dynamic envelope of Delta IV-H payload shroud

- Ground clearance = .7m
- Total Height = 1.7m
- Maximum width = 4.16m
- Closed Maximum length = 4.16m
- Open Maximum length = 7.6m
- Max wheelbase = 4.16m
- Max Wheel Stance (width between wheels) = 3.2m
- Total Structural Mass = 305kg
- Materials used include Aluminum 2014 & Titanium Alloy (Ti -10V 2Fe -3Al)
Chassis Expansion

Requirements:

• Must be capable of traversing a 20 deg. cross slope.
• Must be capable of traversing a 30 deg. Direct incline.
• All components of MORPHLAB shall be launched on Atlas V or Delta IV launching systems.
  - Launching on a Delta IV-H results in greatest payload in LEO, therefore, greatest landed mass on lunar surface.
  - To fit on Delta IV-H all components of MORPHLAB must fit inside 4.5m diameter dynamic envelope of a 5m payload shroud.

To meet these requirements the chassis was designed to be in a folded position during transit atop a Delta IV-H and to expand during lunar orbit to a greater wheelbase. The extended wheelbase of 4.16m is necessary to prevent tipping during 30 deg. direct incline.
Chassis Expansion

• Expansion accomplished by two equal length ‘spreading bars’ rotating about a ‘central pin’ to force two ‘sliding bars’ outward carrying with them the wheels and struts that are attached.

• The spread bars are both driven by a single electric motor with a geared connection to the bars.

• Once in final position the strut assembly is rigidly locked in place at the ends of the upper frame to prevent loads during landing and lunar surface transit to flow through the ‘spreading bars’.

• Expansion mechanism mass = 20kg.
Chassis Components

Transit Connections:
- Connect modules and provide power and data connections during transit configuration
- Initially stowed to fit in Delta IV-H payload
Chassis Components

Decent Beams (2):
- Aluminum 2014
- Mass of each = 5.8kg
- Critical Load During Lunar Decent each sustaining 3500N Maximum Stress = 81MPa
- Margin of Safety = 1.02
- Failure mode: bending

Launch Beams (2):
- Titanium Alloy Ti -10V-2Fe-3AL
- Mass of each = 53.7kg
- Critical Load During Delta IV-H main engine cutoff, max axial acceleration = 6g’s, max lateral acceleration = 2.5 g’s, supports maximum of 3500kg (including chassis)
- Margin of Safety = .23
- Failure mode: bending

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Jason Seabrease
Chassis Components

• Struts and axles affected by bending moments, compression, and tension.
• Compression, bending, and sheer forces most critical during lunar landing.
• Struts and axles also affected by dynamic loading during lunar transit and static loading during base configuration.
• Components sized to support 3500 kg above chassis during all transit and static cases and to support 3500 kg total for landing loads.
• All components finalized through Finite Element Analysis with ProMechanica.
Chassis Components

Struts and Axles:

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Material</th>
<th>Max Stress (MPa)</th>
<th>Margin Of Safety</th>
<th>length (m)</th>
<th>Outer Radius (mm)</th>
<th>Inner Radius (mm)</th>
<th>Total mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Strut</td>
<td>Ti Alloy</td>
<td>400</td>
<td>0.38</td>
<td>0.8</td>
<td>0.05</td>
<td>0.045</td>
<td>22.2</td>
</tr>
<tr>
<td>Angled strut 1</td>
<td>Ti Alloy</td>
<td>400</td>
<td>0.38</td>
<td>0.9</td>
<td>0.05</td>
<td>0.045</td>
<td>25.0</td>
</tr>
<tr>
<td>Angled strut 2</td>
<td>Ti Alloy</td>
<td>400</td>
<td>0.38</td>
<td>1.1</td>
<td>0.05</td>
<td>0.04</td>
<td>57.8</td>
</tr>
<tr>
<td>Wheel Axle</td>
<td>Ti Alloy</td>
<td>350</td>
<td>0.58</td>
<td>1.2</td>
<td>0.1</td>
<td>0.098</td>
<td>27.8</td>
</tr>
</tbody>
</table>

**Vertical Strut** (4) and **Angled Strut 1** (4): Critical loading during power module landing on lunar surface directly on wheels; worst case considered as landing directly on one wheel with all force acting in vertical direction. Failure due to combination of compression and bending.

**Angled Strut 2** (4) and **Wheel Axle** (4): Critical loading during power module landing on lunar surface directly on wheels; worst case considered as landing directly on one wheel with all force acting in chassis horizontal direction (first wheel touchdown with chassis perpendicular to lunar surface).
Wheel Design

- Requirement
  - MORPHLAB must overcome 0.5m obstacles.
  - Wheel must support the weight of power module during landing
  - Safety Factor = 2

- Assumptions
  - Axle constrain
  - Load = $g_{\text{lunar}} \times m_{\text{vehicle}}$
  - Wheel diameter = 1.4 m
  - Ti alloy

Constraints

$g_{\text{lunar}} m_{\text{vehicle}}$

357MPa

MS = 0.540 Mass = 37.4kg

Kevin Mako/Abraham Daiub
Motor / Gear

With a 20% margin:
- The wheels need 655.4 N-m torque on the Power module
- The wheels need 810.2 N-m torque on the Hab Life/Science modules
- The chosen motor is the MF0210050 from Emoteq Corporation

Chosen for:
- Decent torque output 305.7 N-m
- Low Mechanical time constant (time to get to 63.2% of max speed)
- Low weight 7.61 kg

- The torque is good, but a gear will need to be used to get the torque for the modules, thus a gear with a gear ratio of 3 to 1 is used

Picture of a MF0210 motor

www.emoteq.com
Braking System

• Derived Requirements
  – Stop while moving at maximum speed
    • Stopping distance < linkage bending tolerance
    • Stop full caravan assembly
  – Stopped on maximum slope
    • 30° longitudinal slope
    • One end sitting on 0.5 meter obstacle

• Electrohydraulic Disc Brakes (shuttle)
  – Less torque variation during stop vs. drum brakes
  – Benefits of carbon brakes vs. steel brakes
    • Lighter
    • Resistant to friction
    • Efficient whether hot or cold
    • Absorbs 2-3 times more heat
Braking System

Moving at 1 km/hr

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braking Force</td>
<td>236 N</td>
</tr>
<tr>
<td>Brake Torque</td>
<td>165 N-m</td>
</tr>
<tr>
<td>Stopping Time</td>
<td>0.091 s</td>
</tr>
<tr>
<td>Energy Dissipated</td>
<td>358 J</td>
</tr>
<tr>
<td>Average Power Dissipated</td>
<td>3920 W</td>
</tr>
</tbody>
</table>

Stopped on Slope

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braking Force</td>
<td>9110 N</td>
</tr>
<tr>
<td>Brake Torque</td>
<td>6370 N-m</td>
</tr>
</tbody>
</table>
Chassis / Habitable Interface

Requirements:

• Provide rigid connection between Habitable module and Chassis
• Transfer power between Chassis and Habitable module
• Prevent Dust from interfering with power connection

Blue cup fixed on 4 locations on bottom of Habitable Module Skin.

Yellow sleeve spring loaded and designed to prevent dust from collecting on power connection.

Sleeve is driven down inside larger sleeve to expose supporting cylinder and power connection probe

Power connection probe

Supporting cylinder

As Habitable Module descends it automatically aligns itself snugly on top of supporting cylinder and allows power probe to reach into plug internal to Habitable Module

Cylinder Diameter = 5 cm
Cylinder length = 8 cm
Max Compression = 128 MPa
Material = Al 2014
Margin of Safety = .2
Power Module Overview

Requirements:
- Supports a 5 year mission (M6)
- Capable of producing power during the lunar night (M1)
- Must not impose a health risk to the crew (M1, L7)
- Multiple power sources to accommodate potential module loss (I3, I4)
- Size must not impact MORPHLAB system mobility (M2)
- Additional Factors: low system mass, high reliability

Selected: Dynamic Isotope Power System (DIPS)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No Single-Point Failure Reliability</td>
<td>.9955</td>
</tr>
<tr>
<td>Thermal to Electric Efficiency</td>
<td>26%</td>
</tr>
<tr>
<td>Specific Power (with shielding)</td>
<td>12.6 W/kg</td>
</tr>
<tr>
<td>Total DIPS Mass (with shielding)</td>
<td>420 kg</td>
</tr>
<tr>
<td>Power Output</td>
<td>5.3 kWe</td>
</tr>
<tr>
<td>Number of Units</td>
<td>4</td>
</tr>
</tbody>
</table>
Power Module Components

- Avionics suite
- Robotic Arm (stowed configuration)
- DIPS
- Shadow Shield
- Radiator
- Heat Source

University of Maryland
CDR 04/19/04
Joe Cavaluzzi
**Heat Source:**

- **Half Life:** 88 years
- **Mass:** 95 kg
- **Thermal Output:** 20.3 kWt
- **EOL Thermal Output:** 19.5 kWt

(EOL: End of Life)

**Engine:**

<table>
<thead>
<tr>
<th>Qin</th>
<th>15.3 kWt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qout</td>
<td>5.5 kWt</td>
</tr>
<tr>
<td>Work Out</td>
<td>7.4 kW</td>
</tr>
<tr>
<td>TH</td>
<td>1300 K</td>
</tr>
<tr>
<td>TL</td>
<td>460 K</td>
</tr>
<tr>
<td>Carnot Eff.</td>
<td>64.3%</td>
</tr>
<tr>
<td>Actual Eff.</td>
<td>48.6%</td>
</tr>
</tbody>
</table>

**Alternator:**

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>72%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output</td>
<td>5.3 kWe</td>
</tr>
<tr>
<td>EOL Power Output</td>
<td>5.1 kWe</td>
</tr>
</tbody>
</table>

Total System Mass: 420 kg

Heat transfer into engine estimated as 75% efficient

PuO₂

Lithium Hydride Shadow Shield 200 kg (0.3 m³)

Radiator

Stirling Cycle Engine

Alternator

Power Out 5.3 kWe

Joe Cavaluzzi
Common Sub-Systems

Communications

Thermal Control Systems

External Lighting
• Modules will be insulated with Multilayer Insulation (MLI)
  – Thin layers of Mylar coated with aluminum separated by a vacuum
  – The Mylar has low-conductivity of .20 W/m*K so it effectively isolates
    the inner-workings of the module from the harsh lunar environment with
    fluctuations in temperature from 160K to 380K
  – During the lunar day and night, the assumption is there will be enough
    layers of MLI (ie. 10) to act adiabatically and therefore keep the ambient
    inside reference temperature at 298K
  – Moonshine and lunar albedo will not pose a heating problem to the
    module, even though it will “see” 380K at some points, because of the
    MLI and its adiabatic assumption
  – Aerogel will be used where heat leakage paths occur (ie. Panel seams,
    corners) because it insulates well (thermal cond.= .004 W/m*K) and has
    a density of 10 kg/m³
  – 10 layers @ .25 mm thickness implies volume of .14 m³ and with a
    density of 1420 kg/m³ gives a mass of 193 kg
• A vertical radiator atop a module on the lunar surface will “see” solar flux ($I_s$), moonshine (IR), and lunar albedo (alb) which means the environment temperature would be around 380K at the equator during lunar noon.

• Since the top of the module is 4.5m off the surface, a horizontal radiator will never “see” moonshine or lunar albedo. The only radiation it will “see” is from solar flux, where the worst case would be noon at the equator when the entire radiator is illuminated.

• There will be no solar flux at night or at the poles because of the sun’s incident angle of zero degrees to the radiator.
Radiator Sizing

- Ran thermal equilibrium analysis on horizontal radiator to find out what area was needed to dissipate the allotted heat per module
- Since lunar albedo and moonshine are not considered, the thermal equilibrium equation then becomes:

\[ I_s \alpha A_s + P_{int} = \alpha \delta A_R (T_{rad}^4 - T_{env}^4) \]  

1. \( I_s \) : Absorptivity (.08)
2. \( A_s \) : Projected Area Facing Sun
3. \( P_{int} \) : Internal Heat Dissipated \((Q_{in})\)
4. \( T_{rad} \) : Temperature of Radiator Surface
5. \( \alpha \) : Absorptivity (.08)
6. \( \delta \) : Emissivity (.92)
7. \( A_R \) : Total Radiative Area
8. \( \sigma \) : Stefan-Boltzman Constant \((5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)\)
9. \( T_{env} \) : Temperature of Environment \((4\text{K})\)

- Took case of sun directly overhead illuminating the whole area of the radiator with all energy needing to be dissipated through radiator. Therefore,

\[ A_R = A_s = A \]
Radiator Sizing Continued

- Taking the case of Lunar noon at the equator, the optical properties must have a low absorptivity as to minimize solar heating effects and high enough emissivity to radiate internal heat effectively (ie. \( \varepsilon = .92 \) and \( \alpha = .08 \))

<table>
<thead>
<tr>
<th></th>
<th>( Q_{\text{in}} ) (kW)</th>
<th>Rad Area (m²) ( ^\wedge )</th>
<th>Mass (kg)*</th>
<th>Dimensions (m³) ~</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitable Living</td>
<td>4.0</td>
<td>13.34</td>
<td>71</td>
<td>5.00 x 2.67 x .04</td>
</tr>
<tr>
<td>Habitable Science</td>
<td>2.3</td>
<td>7.67</td>
<td>41</td>
<td>2.77 x 2.77 x .04</td>
</tr>
<tr>
<td>Power Module</td>
<td>7</td>
<td>6</td>
<td>32</td>
<td>4.65 x 1.5 x .04</td>
</tr>
</tbody>
</table>

- \(^\wedge\) Assuming \( T_{\text{rad}} = 298\text{K} \), and therefore in thermal equilibrium with inner cabin
- * Assuming 5.3 kg/m² for one-sided, horizontal radiators from Lunar Base Handbook
- ~ Assuming .04 m for thickness of typical radiator
Using loop heat pipes (LHP) due to flexibility and fact that they dissipate more heat than conventional heat pipes. A benchmark of 1 loop heat pipe being able to dissipate 1.6 kW was used.

Habitable-Living Module has 4 LHP (two outer: 1350 kW/each, two inner: 650 kW/each) to handle lower night loads.

Habitable-Science Module has 4 LHP (two outer: 500 kW/each, two inner: 650 kW/each) to handle lower night loads as well.

<table>
<thead>
<tr>
<th></th>
<th>Volume (m³)</th>
<th>Q_{in} (kW) Low Level</th>
<th>Area (m²) Low Level</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitable Living</td>
<td>.51</td>
<td>1.3</td>
<td>3.16</td>
<td>10.18</td>
</tr>
<tr>
<td>Habitable Science</td>
<td>.29</td>
<td>1.3</td>
<td>3.16</td>
<td>4.51</td>
</tr>
</tbody>
</table>

Radiator Mass
Habitable Living Radiator

- Spring-loaded deployable joints
- Condensers
- Mass = 71 kg
- Aluminum Honeycomb backing
- MLI underside acts adiabatically
- Evaporators
- Reservoirs
- Low Conductance Mountings

$\alpha, \epsilon = .08, .92$

$T_{rad} = 298K$

$T_{rad} = 298K$

$Q_{in}$ via LHP

Deep Space = 4K

Matt Hughes

University of Maryland

CDR 04/19/04
Communication Capabilities

• Level 1 Requirements:
  – 10Mbps of bidirectional digital data
  – Two uplink channels HDTV
  – One downlink channel HDTV

• Derived Requirements:
  – EVA communications
    • Module – Rover
      – Main comms. with EVA
      – Send one HDTV to base
    • Module – Astronaut
      – Voice
      – Health monitoring
  – Inter-Module communications
    • Nominally use only wireless
    • Backup physical connection
    • Receive commands during transit
    • Processor/memory sharing during peak usage times
Bandwidth Requirements

- **HDTV Requirements**
  - Uncompressed single channel is 1.5Gbps
  - With MPEG-2 compression single channel is 19.4 Mbps
    - Internationally accepted industry standard
    - Depending on available bandwidth high quality compression up to 80Mbps
  - 4 – 8 standard video channels on single HDTV band
  - Two uplink – 40Mbps
  - One downlink – 20Mbps
- **Total Uplink** – 50Mbps
- **Total Downlink** – 30Mbps

- **Lunar Surface**
  - Bandwidth determined by
    - Rover – Module
    - EVA/Suit - Module
    - Module – Module
  - Inter-module communications used for computer interaction and communications between crew members
    - <1Mbps for voice comms
    - Remainder used for data transfer and video link

- **Total Uplink** – 60Mbps
- **Total Downlink** – 40Mbps
Halo Orbit

- Far side communications will be accomplished through satellites placed in halo orbits about the Earth-Moon L2 point
  - Number of satellites: 4
    - Placed in the same orbit with 90° phase offset
    - Provides two fault tolerance regardless of base or satellite location
  - Orbital parameters
    - Period: ~ 1 year
    - In-plane amplitudes:
      - 32,250 km in line with the Earth-Moon vector
      - 90,000 km normal to the Earth-Moon vector
    - Out-of-plane amplitude: 63,200 km
Halo Orbit Diagram

TO EARTH

L1
MOON
L2

45000km

TOP VIEW

MOON
L1
L2

ISOMETRIC

SIDE VIEW

38400km
25800km
6450km

VIEW FROM EARTH
## Moon – Earth Link Budgets

<table>
<thead>
<tr>
<th></th>
<th>Moon NS Hab-Earth</th>
<th>Moon NS Power-Earth</th>
<th>Moon FS Hab-Halo</th>
<th>Moon FS Power-Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diameter</strong></td>
<td>50 cm</td>
<td>10 cm</td>
<td>50 cm</td>
<td>10 cm</td>
</tr>
<tr>
<td><strong>Band</strong></td>
<td>Ka</td>
<td>Ka</td>
<td>Ka</td>
<td>Ka</td>
</tr>
<tr>
<td><strong>Transmit Bit Rate</strong></td>
<td>50 Mbps</td>
<td>10 Mbps</td>
<td>50 Mbps</td>
<td>10 Mbps</td>
</tr>
<tr>
<td><strong>Receive Bit Rate</strong></td>
<td>30 Mbps</td>
<td>10 Mbps</td>
<td>30 Mbps</td>
<td>10 Mbps</td>
</tr>
<tr>
<td><strong>Output Power</strong></td>
<td>1.2 W</td>
<td>4.0 W</td>
<td>4.0 W</td>
<td>11.4 W</td>
</tr>
<tr>
<td><strong>Link Margin</strong></td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
</tr>
</tbody>
</table>

NS – Near Side Module  
FS – Far Side  
Hab – Habitable  

Mike Naylor
## Lunar Surface Link Budgets

<table>
<thead>
<tr>
<th></th>
<th>Module-Module 20km range</th>
<th>Rover-Module 20km range</th>
<th>EVA Suit-Module 10km range</th>
<th>Total Module Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Omni-antenna</td>
<td>Omni-antenna</td>
<td>Omni-antenna</td>
<td>Omni-antenna</td>
</tr>
<tr>
<td>Band</td>
<td>UHF</td>
<td>UHF</td>
<td>UHF</td>
<td>UHF</td>
</tr>
<tr>
<td>Transmit Bit Rate</td>
<td>30 Mbps</td>
<td>30 Mbps</td>
<td>&lt;1 Mbps</td>
<td>60 Mbps</td>
</tr>
<tr>
<td>Receive Bit Rate</td>
<td>30 Mbps</td>
<td>10 Mbps</td>
<td>&lt;1 Mbps</td>
<td>40 Mbps</td>
</tr>
<tr>
<td>Output Power</td>
<td>N/A</td>
<td>18.2W (Rover only)</td>
<td>1 W</td>
<td>37.5 W</td>
</tr>
<tr>
<td>Link Margin</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
<td>3.0 dB</td>
</tr>
</tbody>
</table>
Radiation-Hardened Computers

- Level 1 Requirements
  - Shall be capable of reaching a TRL of 6 by the technology cut-off date of Jan. 1, 2010
    - TRL 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- Looked at 7 different radiation hardened (Rad-Hard) computers for trends
  - MASS
  - RAD750
  - SCS750
  - RHPPC
  - RHPCM
  - RAD6000
- Compared Rad-Hard vs. Commercial Off the Shelf (COTS) to identify technology gaps and trends:
  - Processor Speed
  - Bus Speed
  - Power Consumption
COTS vs Rad-Hard: Clock Speed

- Trends suggest a 5 year technology gap in clock speed between COTS and Rad-Hard
- By 2010 Rad-Hard Processor speed of 3400 MHz
• Bus speed is positively related to clock speed for COTS
• No correlation or trend could be established for Rad-Hard in 2010
Used COTS to establish a heuristic.
Rad-Hard plotted against heuristic as verification.

Max Power Consumption(W) = 0.0231(CS + BS [MHz]) - 0.9789

R² = 0.9308
# Rad-Hard Computer Mass

<table>
<thead>
<tr>
<th>Rad-Hard Computers</th>
<th>MHz</th>
<th>Power</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASS</td>
<td>N/A</td>
<td>11 W</td>
<td>&lt; 1 kg</td>
</tr>
<tr>
<td>RAD6000</td>
<td>25</td>
<td>7.5</td>
<td>0.849</td>
</tr>
<tr>
<td>RHPPC</td>
<td>100</td>
<td>11 W</td>
<td>1 kg</td>
</tr>
<tr>
<td>RHPMC(p)</td>
<td>120</td>
<td>11 W</td>
<td>1 kg</td>
</tr>
<tr>
<td>RAD750</td>
<td>166</td>
<td>10 W</td>
<td>.549 kg</td>
</tr>
<tr>
<td>RAD750***</td>
<td>200</td>
<td>10 W</td>
<td>1 kg</td>
</tr>
<tr>
<td>Proton100K</td>
<td>400</td>
<td>7-9 W</td>
<td>N/A</td>
</tr>
<tr>
<td>SCS750*</td>
<td>800</td>
<td>8-22 W</td>
<td>&lt; 1.5 kg</td>
</tr>
</tbody>
</table>

- As technology increases, performance increases, but also hardware is smaller and lighter, thus mass is relatively constant.
- We adopted a mass estimation above the current heaviest and highest performing Rad-Hard computer of 1.5 kg.
Rad-Hard Computer

• Conclusion: By 2010:

<table>
<thead>
<tr>
<th>Clock-Bus Speed</th>
<th>Power</th>
<th>Mass</th>
<th>SDRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3400-50 MHz</td>
<td>96 W</td>
<td>1.5 kg</td>
<td>256 MB</td>
</tr>
</tbody>
</table>

• Other Features:
  – Single Event Latchup immune
  – Single Event Upset rate 1E-6 upsets/day
  – Direct Memory Access Bus 1GB/s for data storage
  – Selectable processor speed and power consumption

• Open Items: Look into ThinkPad 760X, ThinkPad 755C, AP-101S
## Dual Computer Interface

<table>
<thead>
<tr>
<th>Module</th>
<th># of Computers</th>
<th>Landing</th>
<th>Base</th>
<th>Transit</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>Non-volatile memory card</td>
</tr>
<tr>
<td>Habitable Science</td>
<td>2 (1)</td>
<td>3</td>
<td>1-5</td>
<td>2</td>
<td>Solid state recorder</td>
</tr>
<tr>
<td>Habitable Living</td>
<td>1</td>
<td>3</td>
<td>3-4</td>
<td>2</td>
<td>Solid state recorder</td>
</tr>
<tr>
<td>Chassis</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>Non-volatile memory card</td>
</tr>
</tbody>
</table>

1 – Minimum processing power – sensor monitoring, basic communications  
3 – Medium processing power – GUI interfaces, full communications, calculations  
5 – High processing power – High rate data intake and analysis, autonomous tasks
Multi-Processor Issues

• Each module will be equipped with up to two computer systems that utilizes three CPUs each
  – Two of three processors used during healthy mode
  – Third processor monitors heartbeat of other two and takes control in the event of CPU failure

• Measures must be taken to ensure correct handling of all tasks
  – Tasks must have locks to ensure only one processor attempts it at a time
  – Local memory to perform current task
  – Shared memory to provide information to other processors about state of completed tasks
  – Memory backups for recovery on separate CPU/computer
CPU Monitoring

Each set of computers will need to be monitored on both a hardware and software level:

– Hardware monitoring
  • Voltages throughout system
  • Memory parity checking
  • CPU temperature
  • Clock/timer input sync

– Software monitoring
  • Unexpected results trigger diagnostics
  • Checksum calculation verification on memory contents
  • Extra diagnostics run during idle periods
  • All functions return status codes
  • Timeouts on all loops
  • Event logging
Computer System Fault Path

- Local Memory
  - Critical Systems
    - CPU A1
      - Shared Memory
        - Memory Backup
          - Non-Critical CPU 1
            - Heartbeat
            - CPU B1
              - Local Memory
          - Non-Critical CPU 2
            - Heartbeat
        - CPU A2
    - Local Memory

Mike Naylor
One CPU Failure...

- **CPU A1 FAULT**
- **Critical Systems**
- **Shared Memory**
- **Memory Backup**
- **CPU A2**
- **Non-Critical CPU 1**
- **Handle by CPU B1**
- **Wait for OK**
- **Recovery**
- **Heartbeat**
- **CPU B1**
- **Local Memory**

---

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Two CPU Failures...

- CPU A1 FAULT
- CPU A2 FAULT
- Shared Memory
- Memory Backup
- Non-Critical Not Monitored
- Non-Critical Not Monitored
- Wait for OK
- Recovery
- CPU B1
- Local Memory

Mike Naylor
External Lights

- Made from super bright LED’s (light emitting diodes)
- LED’s will be bundled into a “headlight” configuration consisting of 19 individual diodes
- The resulting bundle will be 3-4 times brighter than a standard headlight, with at least as much range (~.15 km)
External Lights

- LED used LEDW47-66-60-120 by Laser Optronix
- Each LED produces 13 candles of light
- Each LED weighs .037 kg which makes each bundle weighs .71 kg
- Each LED needs 4.56 W of power
- Lights will be used during travel phases for far side and night traversing
- Lights will be used during base phase for perimeter lighting for safety
External Lights

Two types of lights made from the bundles

Non-movable

Limited Movement lights

±125° ±125°

Limited Movement can also pitch up and down 35°
External Light Placement

Power module:
3 lights integrated with sensor suite

Power lights mounted with lidar suites

Lights mounted on Hab modules

Robonaut on wheels: (not pictured)
1 mounted light

Habitable module:
2 limited movement lights mounted on opposite sides

Rover (not pictured):
1 light mounted on a rotating mount

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Rob Winter
## Module Mass Breakdown

<table>
<thead>
<tr>
<th></th>
<th>Living / Life Support</th>
<th>Avionics</th>
<th>Structural</th>
<th>Descent / Landing</th>
<th>Power Systems</th>
<th>Science Instruments</th>
<th>Total</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Habitable Modules</strong></td>
<td>600 kg</td>
<td>100 kg</td>
<td>1410 kg</td>
<td>180 kg</td>
<td>120 kg</td>
<td>500 kg</td>
<td>2910 kg</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Living Specialized</strong></td>
<td>760 kg</td>
<td>100 kg</td>
<td>1950 kg</td>
<td>180 kg</td>
<td>120 kg</td>
<td></td>
<td>3100 kg</td>
<td>15%</td>
</tr>
</tbody>
</table>

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Kevin Eisenhower, Daniel  
Senai & Luke Twarek
Module Mass Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avionics</td>
<td>200</td>
</tr>
<tr>
<td>Structural</td>
<td>750</td>
</tr>
<tr>
<td>Drive System</td>
<td>650</td>
</tr>
<tr>
<td>Power Systems</td>
<td>240</td>
</tr>
<tr>
<td>2 Robotic Arms</td>
<td>150</td>
</tr>
<tr>
<td>Total</td>
<td>1980</td>
</tr>
<tr>
<td>Margin</td>
<td>46%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avionics</td>
<td>100</td>
</tr>
<tr>
<td>Structural</td>
<td>650</td>
</tr>
<tr>
<td>Transit Connections</td>
<td>200</td>
</tr>
<tr>
<td>Drive System</td>
<td>650</td>
</tr>
<tr>
<td>Power Systems</td>
<td>90</td>
</tr>
<tr>
<td>Total</td>
<td>1480</td>
</tr>
<tr>
<td>Margin</td>
<td>60%</td>
</tr>
</tbody>
</table>

Power Module
Chassis Module
Power Distribution

• Combination of AC and DC power
  – AC enables multiple base configurations while reducing switchgear
  – DC reduces development costs for electrical components by utilizing already developed components
  – Exact voltages and frequencies are still being determined to minimize power losses and reduce arcing potential
Power Connections & Distribution

Habitable Modules:
• AC/DC Rectifier
• Rechargeable Battery

Power Modules:
• DIPS
• AC/DC Rectifier

Chassis Modules:
• AC/DC Rectifier
• Rechargeable Battery

AC Power Source
Habitable Module Power Layout

CONNECTIONS TO OTHER MODULES

CONNECTIONS THROUGH DOCKING RINGS TO OTHER HABS (2 OR 3)

CHASSIS / HAB PERMANENT CONNECTION

AC/DC RECTIFIER

RECHARGEABLE BATTERY 24 HOUR CHARGE DURATION

LEGEND

AC POWER

DC POWER

COMPONENT

COMMUNICATIONS

OTHER DC SYSTEMS

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Chassis Module Power Layout

- Connections to other modules
  - Hard Transit Connection (2)
  - Base Connection Port (2)
  - Chassis / HAB Permanent Connection

- Wheel Motors

- Inverter / Battery Charger

- Rechargeable Battery 24 Hour Charge Duration

- Other AC Systems

- Other DC Systems

- Communications

Legend:
- AC Power
- DC Power
- Component
Unmanned Transit Phase

Vehicle Assembly

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Transit Phase Overview

• After each manned mission, MORPHLAB will disassemble and travel autonomously to a new base site.

• Enables the exploration and analysis of vast areas of the Lunar surface.

• Science will be performed by the modules while traveling.
Transit Phase Topics

- Transit assembly layouts
- Mapping satellites
- Position determination & obstacle avoidance
- Transit power budgets
- Transit connections
- Steering
- Module control scenarios & failure modes
- Science performed in transit
• 3 Vehicle Assemblies:
  – Each vehicle assembly consists of a power module and two habitable – chassis assemblies
  – The modules are joined through transit connections on the chassis
  – Power and data are transferred through the transit connections

Width: 4m
Length: 22.9m
Vehicle Assembly

- Vehicle assemblies can take different paths to the next base site, expanding the area covered for scientific exploration.

1 power module is dedicated to carry two lunar modules.

Width: 7.6m  Length: 7.0m

David Pullen
Mapping Satellite

- Current lunar topographical information
  - Clementine LIDAR mapping mission
    - Resolution
      - Vertical: 40 m
      - Horizontal: 100 m
    - Cross-track measurement spacing: 40 km
    - In-track measurement spacing: 1 – 2 km
    - Coverage limited to ± 60° latitude

- Photography
  - Lunar Orbiters
    - Photographed 95% of the surface
    - Resolution up to .3 m

- Derived requirements
  - Courses must be plotted prior to departure
  - Polar regions need to be analyzed for topography and water ice deposits
Mapping Satellite

- Specifications derived from Mars Global Surveyor (MGS)
  - MGS Narrow Angle Camera
    - Resolution: 1.4 m/pixel
    - Field of view (FOV) up to 2.9 km X 25.2 km
  - MGS LIDAR
    - Resolution
      - Vertical: 2 m
      - Horizontal: 160 m
    - 10 Hz sample rate

- Assumptions
  - Mission duration: 60 days
  - Circular Orbit
  - Tech capabilities scaled by 2x compared to MGS
  - Photographs
    - Taken on light side only
    - Resolution and FOV scaled linearly vs. altitude
  - LIDAR ranging
    - Taken on both sides
    - No across-track measurements
Mapping Mission Analysis

- Nominal mission duration: 60 days
- Altitude: 115 km
- Camera specs
  - Resolution: 20 cm
  - Field of View: 1.5 km x 15 km
- LIDAR specs
  - 20 Hz sample rate
  - Measurements:
    - In-track: 76 m
    - Cross-track: 15 km
Position Determination

- MORPHLAB must be capable of determining its position and attitude during its entire mission duration
  - This will be accomplished with:
    - Inertial mass units (IMU)
    - Star trackers
    - Communications with other modules and Earth
Position Determination

- Currently, IMUs and star trackers are used in many space applications for position and attitude determination
  - Current specifications will be sufficient to meet requirements
  - Specific systems used in MORPHLAB will be determined closer to the technology cutoff date

- Design constraints
  - Low Mass
  - High Reliability
Position Determination

Current IMU specifications

- Source: Ball Aerospace
- Mass: 1.4 kg
- Power requirement: 6 W
- Gyro
  - Range: +/- 200 deg/sec
  - Bias: +/- 1 deg/hr
- Accelerometer
  - Range: +/- 12 g’s
  - Bias: +/- 0.3 mg’s
  - Clock: 10MHz
  - Activation time: 5 sec
Position Determination

Current star tracker specifications

- Source: Ball Aerospace
- Mass: 2.5 kg
- Power requirements: 9W
- Angular accuracy: 40 arc sec
- Update rate: 10 Hz
- Field of view: 20° x 20°
- Catalog Size: 6000 stars
Obstacle Avoidance

• Level 1 requirements
  – MORPHLAB must be capable of traversing obstacles smaller than 0.5 m
  – MORPHLAB must be capable of traversing slopes up to 20° cross-slope or 30° direct slope

• Derived requirements
  – Sensors must be capable of resolving a 0.5 m obstacle at a distance of no less than 7 m away
  – Transits must be plotted prior to departure to ensure paths are free of large obstacles or slopes over the entire route
Obstacle Avoidance

- Rough course will be determined from Earth by analyzing mapping satellite data prior to mission start
- Small obstacles will be located and avoided in real-time using on-board sensor suites
  - Power module sensor systems
    - Laser imaging radar (LIDAR) – resolves obstacles regardless of lighting
    - Video cameras – provide visual images for teleoperation / supervisory control
  - All other modules will be controlled by the power modules via communications links
Obstacle Avoidance

- Power modules will have 3 complete sensor suites
  - Mounted on gimbals in rotating assemblies
    - Azimuth range of vision: 360°
    - Elevation range of vision: 180°
  - One sensor is located in the rear, dedicated to robotic arm operations
Obstacle Avoidance

• Current LIDAR specifications
  – Mass: 3.6 kg x 3 = 10.8 kg
  – Power requirement: 16 W x 3 = 48 W
  – Pulse duration: 8 ns
  – Measurement rate: 12 kHz
  – Distance range: 0 – 250 m
  – Accuracy: +/- 6 mm
  – Acquisition time: 2 sec

• Current video camera specifications
  – Mass: 0.3 kg x 3 = 0.9 kg
  – Power requirements: 3 W x 3 = 9 W
  – Image: 1024 x 1024 pixels
Obstacle Avoidance

• The following conditions must be known or monitored:
  – Situational awareness
    • State of own vehicle
      – Current speed / acceleration
      – Position on surface
      – Adherence to planned route
      – Reaction time of human or computer in control
    • State / model of nearby objects / environment
      – Location and classification of object
      – Patterns of transit hindering objects and lighting distortions
  – Processing and algorithms
    • What situation are we in?
    • How likely is a collision?
    • How dangerous is the situation?
    • Is an action needed?
Obstacle Avoidance

• System response
  – Human or on-board computer senses a transit hindering obstacle via sensor systems
  – Collision warnings
    • Audio and visual warning alert user of a likely collision
    • Vehicle comes to a stop
  – Collision avoidance
    • Steering and speed of vehicle altered to avoid obstacle
Operational Requirements

• **Level 1 requirements:**
  – Systems onboard MORPHLAB shall be capable of operating in any of the following control modes for any or all of the nominal mission segments:
    - On-board direct human control
    - Teleoperation
    - Supervisory control
    - On-board autonomous control

• **Derived requirements**
  – A human operator shall be able to take over the control of the vehicle from Earth and teleoperate if a critical situation arises (e.g. less than 0.01m from an approaching boulder larger than 0.5 m in height)
  – If an obstacle is observed, but the planned trajectory does not avoid the obstacle, supervisory control shall be implemented to avoid obstacle.
Teleoperation and Supervisory Control

- Some situations may arise that will force MORPHLAB out of autonomous control and into either supervisory or teleoperational control
- Supervisory – operation via preprogrammed sequence of events from Earth followed by the execution of these commands by MORPHLAB
  - Shall be implemented if MORPHLAB detects a potential problem that cannot currently be avoided via autonomous control
  - Reliant on accuracy of on-board computers
- Teleoperation – operation of MORPHLAB from Earth
  - Shall be implemented if MORPHLAB senses an unavoidable object
  - Ground user shall take over control, navigate around object, and return MORPHLAB to autonomous control
  - Reliant on accuracy of navigational equipment
- Teleoperation and supervisory control modeled from previous Earth, Mars and Lunar exploration missions: Dante II, NOMAD, Sojourner, Lunakhod
Transit Peak Power System

Li-Ion Battery Banks:

- Sized to provide 24 hours of standby power to an unmated module
- Under high system loads when modules are linked, battery resources can be pooled to meet peak power needs

Constant Power Output

Power Module: 5.3 kWe

Vehicle Assembly Peak Power

Habitable Science 12.6 kWhr

- Chassis 5.4 kWhr

Habitable Living 12.6 kWhr

- Chassis 5.4 kWhr

Maximum Power Output: 6.8 kWe (for 24 Hours)

Short Term Power

Habitable Module: 101 kg Li-Ion Bank
Chassis: 44 kg Li-Ion Bank
Vehicle Assembly Power Budget

**Vehicle Assembly System Average**

- **DIPS**: 5.3 kWe
- **Battery**: 1.5 kWe
- **Total**: 6.8 kWe

<table>
<thead>
<tr>
<th>System</th>
<th>Power (kWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotion</td>
<td>3 kWe</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>1 kWe</td>
</tr>
<tr>
<td>Avionics</td>
<td>1 kWe</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5 kWe</strong></td>
</tr>
</tbody>
</table>

**Vehicle Assembly System Peak**

- **Locomotion**: 4.2 kWe
- **Thermal Control**: 1.2 kWe
- **Avionics**: 1.3 kWe
- **Total**: 6.7 kWe

**Generated Power**

- **DIPS**: 5.3 kWe
- **Battery**: 1.5 kWe
- **Total**: 6.8 kWe

**System Peak**

- **Max Power Output**: Total
- **DIPS Power Output**: Total
Locomotion Resistive Forces

- Soil Compaction Resistance $R_c = \text{func.}(\text{wheel width, soil properties, wheel sinkage})$
- Bulldozing Resistance $R_b = \text{func.}(\text{wheel width, soil properties, terrain slope})$
- Rolling Resistance $R_r = \text{func.}(\text{soil properties, wheel loading})$
- Gravitational Resistance $R_g = \text{func.}(\text{wheel loading, terrain slope})$

**Forward Motion:**

Tractive Force $>\text{Motion Resistance}$

**Assumptions:**

- Maximum chassis wheel load $= 1962\ \text{N}$
- Maximum power module wheel load $= 1430\ \text{N}$
- Terrain slope will not exceed 30 degrees
- Rolling friction is estimated as 0.2 (comparable to firm sand)
Transit Power Usage

<table>
<thead>
<tr>
<th>Component</th>
<th>Max Power/Wheel</th>
<th>Max Motion Power (4 wheels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis</td>
<td>375 W</td>
<td>1.5 kWe</td>
</tr>
<tr>
<td>Power Module</td>
<td>300 W</td>
<td>1.2 kWe</td>
</tr>
<tr>
<td>Vehicle Assembly</td>
<td>-</td>
<td>4.2 kWe</td>
</tr>
</tbody>
</table>

- **0° - 16° slope:**
  - Transit Speed 1.2 - 1 km/h
- **16° - 30° slope:**
  - Transit Speed 1 - 0.7 km/h
Transit Connection

Ball joint rotates ± 45° left/right

Ball joint rotates ± 30° up/down

0.8 MPa

10,000N

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Turning Capabilities

- True Double-Ackerman Design:
  - Back Wheel/Front Wheel turn angle ratio of 1
- Turning radius for single module:
  - Wheelbase Length: 4.2m.
  - Wheelbase Width: 3.3m.
  - Wheel turn Angle: 30 deg.
  - TURN RADIUS = 4m
- Turn radius for single vehicle assembly:
  - Total vehicle length: 20m.
  - Total vehicle width: 3.3m.
  - Wheel turn Angle: 30 deg.
  - TURN RADIUS = 8m

Note: Figures not to scale
Steering Mechanism

- Modified rack-and-pinion system
- Four-wheel steering with independent motors
- Allows modules to rotate with no translation
- Lunar dust effect on steering is a major concern

Top
Note: Figure not drawn to scale
# Steering Mechanism

<table>
<thead>
<tr>
<th>Torque due to:</th>
<th>(N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Force ($F_z$)</td>
<td>-48</td>
</tr>
<tr>
<td>Lateral Force ($F_y$)</td>
<td>0*</td>
</tr>
<tr>
<td>Tractive Force ($F_x$)</td>
<td>50</td>
</tr>
<tr>
<td>Aligning Torque</td>
<td>30</td>
</tr>
<tr>
<td>Rolling Resistance Torque</td>
<td>0</td>
</tr>
<tr>
<td>Overturning Torque</td>
<td>0</td>
</tr>
<tr>
<td>Net Torque feedback to Steering System</td>
<td>20</td>
</tr>
</tbody>
</table>

* Assumed slow motion
Slope Traversal

- Level 1 Requirements
  - 30 degree direct slope
  - 20 degree cross slope
  - 0.5 meter obstacle

- Max direct angle: 36.8°
- Max cross angle: 28.7°
- Max C.G.: 2.80 m
Hang-Up Failure

- Vehicle ground clearance: 1.35 m
- Clearance Requirements
  - 30° direct slope
    - 0.542 m (up-slope to flat)
    - 1.10 m (up-slope to down-slope)
  - 20° cross slope
    - 0.2845 m (up-slope to flat)
    - 0.562 m (up-slope to down-slope)
Nose-In Failure

Vehicle overhang from wheel base < wheel radius
Nose-In Failure is not a concern

Emily Tai
Science in Transit

2 robotic arms on each power module:

- Capable of collecting and storing soil samples
- Equipped with soil analyzing instruments
- Vehicle assemblies may travel separate to sample more of the surface
- More details forthcoming
Intermission
Manned Base Assembly Phase
Base Phase Topics

- Science in base assembly
- Docking Mechanism
- Base power budget
- Crew Systems & ECLSS
- Logistics Module
- Interior layout
- Extra vehicular activity
- Lunar roving vehicle
Base Assembly Site

- Crew support equipment is supplied by a logistic depot, landed near the desired assembly site.
- The specific base location and configuration will be determined when MORPHLAB arrives.
- Assembly will be within 10km of the logistic depot.
- Astronauts land within 100m of the assembled base.
- Tele-operated lunar rovers pick up landed astronauts.
Base Assembly Overview

- Transit connections disconnect and modules reconfigure into a base
- While reconfiguring, batteries supply power to the habitable and chassis modules
- Once the modules are positioned correctly, the docking mechanisms extend and connect
Base Assembly Overview

- Power modules connect power cords to the chassis modules with the robotic arms.
- Power modules are driven 10m away from the base assembly to reduce radiation exposure to the crew from the DIPS.
- The modules are pressurized and computers are initialized to prepare for the arrival of the astronauts.
Module Overview

- 2 Habitable-Living: Crew Quarters
  - 2 docking hatches
  - Primary used as sleeping quarters
- 1 Habitable-Living: Galley
  - 2 docking hatches
  - Primary used as a galley
- 2 Habitable-Science: EVA
  - 1 EVA Airlock
  - 2 docking hatches
- 1 Habitable-Science
  - 3 docking hatches
Optimum Base Assembly

• Base Assembly Requirement
  – At least one habitable-science module is needed to provide all habitable-living modules with complete life support
  – Each module should have two routes to reach EVA airlocks for an emergency evacuation
    • Level 1 requirement L8: System shall provide for emergency alternative access and EVA "bailout" options

• Consideration for base assembly
  – Base assembly should be comfort for living and working on missions for astronauts
Base Assembly Configuration

- Primary Base Assembly
Base Assembly Configuration

- Optional Base Configuration
Assembly Site Selection Criteria

Level 1 Science Goals:
- Volcanic and impact history
- Deep lunar composition
- Environmental variations along the surface
- Water ice and ore deposits as potential resources

- Apollo landing site candidates
- Volcanic lava “tunnels” (rilles)
- Permanently shadowed regions
- Age of lunar structures
- Highland material
- Approximately 1000 km apart

- Ore deposits and useful elements:
  - Helium
  - Nitrogen
  - Oxygen
  - Carbon
  - Silicon
  - Thorium
  - KREEP* materials

* Potassium, Rare Earth Elements, Phosphorus

Solar cell production

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Kevin Eisenhower
### Assembly Site Selection

**Near Side**
1. Drygalski
2. Moretus
3. Rozhdestvenski
4. Nansen
5. Hermite
6. Schrodinger
7. Gassendi
8. Rima Bode II
9. Tycho
10. Rima Prinz I
11. Tsiolkovsky
12. Minnaert
13. Aristarchus
14. Alphonsus
15. Mare Ingenii
16. Marius
17. Flamsteed P
18. Mons Rumker
19. Lichtenberg
20. Censorinus
21. Mare Orientale
22. Apollo 13 site
23. Apollo 14 site
24. Gagarin
25. Copernicus

**Far Side**
10. Rima Prinz I
9. Tycho
8. Rima Bode II
7. Gassendi
6. Schrodinger
5. Hermite
4. Nansen
3. Rozhdestvenski
2. Moretus
1. Drygalski

*Site rankings done by trade study of goals, site criteria, and feasibility.

http://geopubs.wr.usgs.gov/i-map/i2769/
# Assembly Site Distances

<table>
<thead>
<tr>
<th>Assembly Site</th>
<th>Straight line distance between (km)</th>
<th>Estimated driving distance (km) (+ 30%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Marius Hills</td>
<td>515</td>
<td>670</td>
</tr>
<tr>
<td>2) Flamsteed Crater P</td>
<td>479</td>
<td>623</td>
</tr>
<tr>
<td>3) Gassendi Crater</td>
<td>966</td>
<td>1256</td>
</tr>
<tr>
<td>4) Tycho Crater</td>
<td>911</td>
<td>1184</td>
</tr>
<tr>
<td>5) Moretus Crater</td>
<td>553</td>
<td>719</td>
</tr>
<tr>
<td>6) Drygalski Crater</td>
<td>212</td>
<td>276</td>
</tr>
<tr>
<td>go through South Pole</td>
<td>546</td>
<td>710</td>
</tr>
<tr>
<td>7) Schrodinger Crater</td>
<td>562</td>
<td>731</td>
</tr>
<tr>
<td>8) Minnaert Crater</td>
<td>822</td>
<td>1069</td>
</tr>
<tr>
<td>9) Mare Ingenii</td>
<td>539</td>
<td>701</td>
</tr>
<tr>
<td>10) Gagarin Crater</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The largest distance is 1256 km.
1) Marius Hills
(51W, 11N)
- Steep volcanic hills
- Large amounts of silica
- Rilles nearby could be collapsed lava tunnels

2) Flamsteed Crater P
(43W, 4S)
- 1m thick regolith infers that it is young
- Surveyor 1 landing site
3) Gassendi Crater (38W, 19S)
- Contains ancient highland rocks
- Lunar transient phenomenon observations
- Most likely candidate for Apollo 18
4) Tycho Crater 
(12W, 42S)
- Rare materials
- Lunar transient 
phenomenon observations
- Crater still has rays infers 
that it is young
- Youngest known crater by 
current knowledge
- Surveyor 7 landing site
5) Moretus Crater (9W, 72S)
- Possibility of ice in permanently shadowed craters
6) Drygalski Crater (83S, 90W)
   - Possibility of ice in permanently shadowed craters
   - Areas of constant sunlight nearby (Malapert Mountains)
7) Schrodinger Crater (72S, 134W)
- Contains recent volcanic ejecta
- Second youngest impact basin
8) Minnaert Crater (67S, 171W)
- Strongest possibility of investigating lunar mantle
- Located within Aitken Basin
9) **Mare Ingenii**
(40S, 167W)
- High concentration of thorium
- Possibility of investigating lunar mantle
- Located within Aitken basin
10) Gagarin Crater (29S, 150W)

- Contains ancient highland rock
Geological Science Instruments

Level 1
- Potential water ice
- Ore deposits as potential resources
- Deep lunar composition
- Lunar volcanic and impact history
- Lunar dust and environmental changes

Level 2
- Mineral analysis
- Seismic instruments
- Soil collection
- Surveyor instrument retrieval
- Dust detecting instruments

Level 3
- Mini Thermal Emission spectrometer
- X-ray / Gamma-ray spectrometer
- Mossbauer spectrometer
- Integrated Dust/Soil Experiment mass spectrometer
- Passive Seismic Experiment Package
- Active Seismic Profiling Experiment

Robotic arms
- Scoop
- Hammer
- Rake
- Tongs
- Electric drill

Lunar Dust Detector

Kevin Eisenhower
# Soil Sample Collection

## Apollo Soil Collection Details

<table>
<thead>
<tr>
<th>Apollo</th>
<th>total rock mass (kg)</th>
<th># of rocks</th>
<th>largest rock returned (kg)</th>
<th>mission hours</th>
<th>EVA hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>21.6</td>
<td>68</td>
<td>5.6</td>
<td>195.5</td>
<td>2.25</td>
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<tr>
<td>12</td>
<td>34.3</td>
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<tr>
<td>14</td>
<td>42.3</td>
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<td>9.0</td>
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<td>9.5</td>
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<tr>
<td>15</td>
<td>77.3</td>
<td>370</td>
<td>9.7</td>
<td>67</td>
<td>18.5</td>
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<tr>
<td>16</td>
<td>95.7</td>
<td>731</td>
<td>11.7</td>
<td>71</td>
<td>20.25</td>
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<tr>
<td>17</td>
<td>110.5</td>
<td>741</td>
<td>3.6</td>
<td>75</td>
<td>22</td>
</tr>
</tbody>
</table>

## Average Values

- **avg EVA hours / mission hours**
- **average rock mass / EVA hour**
- **average rock # / EVA hour**

<table>
<thead>
<tr>
<th>Apollo</th>
<th>avg EVA hours / mission hours</th>
<th>average rock mass / EVA hour</th>
<th>average rock # / EVA hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0.012</td>
<td>9.6</td>
<td>30.2</td>
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<tr>
<td>12</td>
<td>0.238</td>
<td>4.6</td>
<td>9.2</td>
</tr>
<tr>
<td>14</td>
<td>0.284</td>
<td>4.5</td>
<td>15.8</td>
</tr>
<tr>
<td>15</td>
<td>0.276</td>
<td>4.2</td>
<td>20.0</td>
</tr>
<tr>
<td>16</td>
<td>0.285</td>
<td>4.7</td>
<td>36.1</td>
</tr>
<tr>
<td>17</td>
<td>0.293</td>
<td>5.0</td>
<td>33.7</td>
</tr>
<tr>
<td>average</td>
<td>0.275</td>
<td>4.6</td>
<td>23.0</td>
</tr>
</tbody>
</table>

**MORPHLAB manned mission**: 2160 hours (3 months)

**Total collected rock mass**: 600 kg

**Assumption:**
Collect at 1/4 th the rate of Apollo (larger stay times, and more time spent traveling in the rover)
Soil Sample Collection

Apollo Rock Samples

Want robotic arm capable of picking up 6 kg rock

Keep rocks for 7 days → 46 EVA hours (28% mission hours)

50 kg of rocks collected

+ 300 kg of rocks returned each mission (50% total collected)

= 350 kg total rock storage mass

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Kevin Eisenhower
Robotic Arm Capabilities

- Pick up and store soil samples
- Soil inspection
- External module inspection / maintenance
- Removal of descent engines
- Plugging in power cords

<table>
<thead>
<tr>
<th></th>
<th>mass (kg)</th>
<th>reach (m)</th>
<th>lift at extension (N)</th>
<th>min. temp. (deg C)</th>
<th>max temp. (deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranger Arm</td>
<td>77</td>
<td>1.35</td>
<td>133</td>
<td>-40</td>
<td>150</td>
</tr>
<tr>
<td>Requirements:</td>
<td>2</td>
<td>2</td>
<td>59</td>
<td>-173</td>
<td>127</td>
</tr>
</tbody>
</table>

- Different end effectors for each operation
- Modifications necessary (1m extensions, temperature)

http://ranger.ssl.umd.edu
Life Sciences: Level 1 and 2

- Crew dynamics
- Human performance, adaptations
- Skeletal system
- Muscle development/decay
- Cardiovascular system
- Nutrition and medical care
- Long term radiation exposure
- Plant biology in the lunar environment
- Questionnaires
- Foot/Ground Reaction System
- Ultrasound
- Gas Analyzer System for Metabolic Analysis Physiology (GASMAP)
- Ambulatory Data Acquisition System
- Portable Clinical Blood Analyzer (PCBA)
- EVARM system
- Advanced Astroculture™ Chamber
Life Sciences: Level 2

- Most of these systems have been used on the ISS. The reason for repetitions are:
  - Different gravitational environment
  - Find trends from mission to mission
  - Find a relationship between the Earth’s gravity, the Moon’s gravity, and microgravity; then educated predictions for other planetary gravities can be made
  - Enhance technology for medical care on Earth and future planetary bases
Racks

• Each science module will have one science rack

• These racks contain the instruments needed to perform various experiments

• The rack method makes it easy to change experiments & instruments from mission to mission

• Rack 1
  – PCBA (Portable Clinical Blood Analyzer)
  – The PCBA Cartridge Kit
  – PCBA Control Kit
  – EVARM system

• Rack 2
  – The Advanced Astroculture
  – Foot Ground Interface - Flight Cal Unit
  – Total Force - Foot Ground Interface
  – Lower Extremity Monitoring Suit
  – Ambulatory Data Acquisition System

• Rack 3
  – Ultrasound
  – GASMAP /calibration module
The objective of this study is to measure the impact of cultural and language background on space missions and to characterize changes over time in a number of important interpersonal factors, such as tension, cohesion, leadership role, and the relationship between space crews and monitoring personnel on Earth” (http://lsda.jsc.nasa.gov)

Questionnaires are submitted via computer back to Earth
• Bones have a steady decay, even with exercise.

• Muscle strength decreases significantly

• In lunar gravity, these numbers are not expected to be as drastic, but bone and muscle decay still need to be studied
Life Sciences: Level 2

Foot/Ground Reaction System

- Lower Extremity Monitoring Suit
- Total Force – Foot Ground Interface
- Foot Ground Interface – Flight Calibration Unit

- Measures the forces your legs and feet experience through a normal work day
- Mass: 46 kg

http://spaceflight.nasa.gov/station/science/experiments/fact_foot.html
Life Sciences: Level 2

Ultrasound

• 3D capability & real time 2D
• Respiratory Trace Display

• Total Mass: 86 kg

Applications:

– Echocardiography
– Abdominal (deep organ)
– Vascular, muscle, tendon, trans-cranial ultrasound

http://hrf.jsc.nasa.gov/ultrasound.htm
Life Sciences: Level 2

Gas Analyzer System for Metabolic Analysis Physiology (GASMAP)

- Study effects of reduced gravity on the musculoskeletal aspects of breathing during rest, heavy exercise, and deep breathing

- Measures volume, temp, frequency, pressure of inhaled & exhaled air
- To be used during exercise
- Total Mass: 244 kg

http://hrf.jsc.nasa.gov/gasmappics.htm
Life Sciences: Level 2

Portable Clinical Blood Analyzer (PCBA)

• Study red blood cell mass and production.

• Mass PCBA: 0.54 kg
• Mass Cartridge Kit: 0.27 kg

http://www.amedical.com/istat.html
• Provides convenient data acquisition and storage of data collected by physiological sensors (such as FOOT). It will measure core body temperature, blood pressure, respiration and other physiological responses.
Life Sciences: Level 2

EVARM System

- Mounted inside the EVA suit
- Worn on the head, torso and leg

- Records radiation over different parts of the body during an EVA

http://resources.yesican.yorku.ca/trek/radiation/final/index_EVARMS.html

Paula C. Herda
Life Sciences: Level 2

Advanced Astroculture™ (ADVASC)

- Autonomous & continuous care for the plant for an average 180 days.

- The top box contains the computer, electronics & other support systems
- The bottom box contains the controlled plant growth chamber and ancillary subsystems

- Growing Space
  - Shoot area: 486 cm²
  - Shoot height: 34.5 cm
  - Root area: 486 cm
  - Root height: 5 cm

- Mass: 4.4 kg

http://wcsar.engr.wisc.edu/advasc.html

Paula C. Herda
# Summary of Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Mass: kg</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOOT</td>
<td>46 kg</td>
<td>Batteries included 1.5 V dc</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>86 kg</td>
<td>Peak 1004 W</td>
</tr>
<tr>
<td>(GASMAP)</td>
<td>244 kg</td>
<td>Peak 270 W</td>
</tr>
<tr>
<td>(PCBA)</td>
<td>.81 kg</td>
<td>Two 9 volt batteries</td>
</tr>
<tr>
<td>EVARM system</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Questionnaires</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Astroculture™ Chamber</td>
<td>46.7</td>
<td>Peak 300 W</td>
</tr>
<tr>
<td>Ambulatory Data Acquisition System</td>
<td>2.31</td>
<td>AA batteries</td>
</tr>
<tr>
<td>Totals</td>
<td>426 kg</td>
<td>1574W</td>
</tr>
</tbody>
</table>
Habitat to Habitat Connections

- To fulfill requirement M5, that all nominal movement between modules be accomplished in shirtsleeve conditions, some form of pressurized mating tunnel is required.
- Space limitations in the launcher payload shroud dictated that this system be retractable.
- Mass limitations on the habitat modules dictated that this system be as light as possible.
- Concerns over tipping while in transit dictated that this system needed to be able to deploy and retract before and after each crewed mission segment.
Paramount Tunnel Tradeoffs

- Metallic vs. Composite
- Male/Female mating vs. Androgynous mating
- Layered pressure bladder vs. Abrasion cover
- Active terminal mating vs. Passive terminal mating
- Passive latch connection vs. Active bolt connection
- Doors: normally open vs. normally closed
Additional Tunnel Concerns

• To modularize the air and water purification systems
  – Airflow must be allowed between habitable sections
  – Piping for water transport would need to exist between habitable modules

• Power delivery between modules could not be accomplished using the mechanical chassis linkages during Base Assembly Phase
  – Cables for power transfer would need to exist between habitable modules
Extendable Tunnel

- Foldable composite (Kevlar-49) was chosen over a telescoping metal tube.
  - Mass savings of 8x
  - Lighter extension mechanism than a large telescoping structure
  - Less likely to puncture pressure bladder
- Layers will be held together at the ends by clamped aluminum hoops.
- Two lengths: 1 m and 0.5 m
- Mass of 1 m tunnel: 10 kg
- Mass of 0.5 m tunnel: 6 kg

***Outside (P = 0)***
- Kevlar-49 Cross-Weave Stiffness Layer
- MLI Layers
- PVC Pressure Bladder
- Nomex Cross-Weave Abrasion Layer

***Inside (P = 25.7 kPa)***
Mating Ring

- Androgynous mating system chosen over male/female system to maximize possible base configurations.
- Tunnel connected to mating ring via clamping mechanism with self-sealing o-rings to ensure pressure seal.
- Power and water piping connections located in ring
  - Hard dock seals piping
  - Piping runs inside or parallel to extension mechanism
- Total mass of mating ring: 80 kg
Hard Dock

- Antisymmetric nut/bolt configuration provides androgynous interface.
- Inner and outer hard connection points.
- 16 connections needed to ensure both two-fault tolerance and antisymmetry.
- Active bolt hard dock chosen due to 2x mass savings over passive latches.
- Spring-loaded dust covers ensure no particles get into threads when not in base assembly.

A-A Soft Dock

A-A Hard Dock

Luke Twarek
Pressure Seal

- After hard dock, PVC pressure seal bladder inflates in order to form a self-sealing pressure seal.
- In the event of a rupture in the bladder, the other pressure seal bladder can inflate to seal the leak.
- Spring-loaded dust cover prevents dust and UV radiation from degrading the PVC when not in base assembly.
- Pressurization lines carried with extension mechanism.
Extension Mechanism

- Exact mechanism has not yet been chosen, the candidates are:
  - Telescoping tube
    - Can also be used to transfer power and water
  - Rotators and beams
    - Can be used for precision alignment of mating rings
  - Extending beams
    - Easily adapted from chassis
Mating Sequence

- Initial alignment with chassis wheels
- Initial tunnel extension
- Terminal alignment via sensors
- Terminal tunnel extension
- Soft dock
- Extend bolts
- Hard dock
- Pressure seal inflation
- Pressure bladder inflation
- Exterior walkway deployment
- Doors open to circulate air
Base Peak Power System

Maximum Power Output: 20.4 kWe (for 24 hours) With 3 DIPS

MORPHLAB Net Battery Totals

- Mass: 870 kg
- Storage Capacity: 108 kWhr
- 24 Hour Discharge: 4.5 kWe

Power Module
- 5.3 kWe

Spare Power Module
- 5.3 kWe

Habitable Chassis
- 12.6 kWhr

24 Hour Chassis
- 5.4 kWhr

Science Chassis
- 5.4 kWhr

Living Chassis
- 5.4 kWhr

12.6 kWhr

Joe Cavaluzzi
Base Power Budget

<table>
<thead>
<tr>
<th>Generated Power</th>
<th>Base System Average</th>
<th>Base System Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIPS* 15.9 kWe</td>
<td>Crew Systems 6 kWe</td>
<td>Crew Systems 8 kWe</td>
</tr>
<tr>
<td>Battery 4.5 kWe</td>
<td>Avionics 2 kWe</td>
<td>Avionics 3 kWe</td>
</tr>
<tr>
<td>Total 20.4 kWe</td>
<td>House Keeping 1 kWe</td>
<td>House Keeping 1 kWe</td>
</tr>
<tr>
<td></td>
<td>Thermal Control 2 kWe</td>
<td>Thermal Control 3 kWe</td>
</tr>
<tr>
<td></td>
<td>Battery Recharge 0.5 kWe</td>
<td>Battery Recharge 1 kWe</td>
</tr>
<tr>
<td></td>
<td>Science 3.5 kWe</td>
<td>Science 4 kWe</td>
</tr>
<tr>
<td></td>
<td>Total 15 kWe</td>
<td>Total 20 kWe</td>
</tr>
</tbody>
</table>

*Output of 3 Power Modules

University of Maryland
CDR 04/19/04

Joe Cavaluzzi
Crew Systems

Design Constraints:

- All crew interfaces shall
  - Accommodate the 95th percentile American male to the 5th percentile Japanese female (L1)
  - Adhere to NASA STD-3000 (L2)

- For optimal performance on long duration missions
  - Minimum surface area = 61 m²
  - Min. ceiling clearance = 2.2 m
  - Min. interior volume = 135 m³

- Nominal mission consists of
  - 4 member crew (L4)
  - Capable of daily 2 person EVAs (L5)
  - Zero pre-breathe time for EVAs (L9)

- Emergency requirements
  - 180 day subsistence food stock (L6)
  - At least 2 IVA exits from each module
  - EVA bailout options (L8)

* IVA = Inter-Vehicular Activities
MORPHLAB vs. LMLSTP

• Lunar-Mars Life Support Test Project (LMLSTP)
  – NASA/Johnson Space Center project
  – 4 crew members spending 90 days in a closed-loop life support system habitat
  – Habitable Surface Area = 58.44 m²
  – Habitable Volume = 163.63 m³

• Total for MORPHLAB base configuration
  – Habitable Surface Area = 75.4 m²
  – Habitable Volume = 198 m³
Module Subtypes

Habitable-Living:

- **2 Crew quarters**
  - Sunken SPE-shielded beds
  - Sanitary systems, main level
- **1 Galley**
  - Food preparation area
  - Exercise area, lounge
  - Backup quarters (I3 & I11)
- **ECLSS systems**
  - Vapor Phase Catalytic Ammonia Removal
  - Multi-filtration
  - Supercritical Waste Oxidation

Habitable-Science:

- **2 EVA areas**
  - Main airlocks, dust removal
  - Repair area, tool storage
  - Durable experimentation area
- **1 Experiment area**
  - Finer specialized equipment
  - Backup galley (I3 & I11)
- **ECLSS systems**
  - Water Vapor Electrolysis
  - Electrochemical Depolarized Cells
  - Sabatier
  - Trace Contaminant Control
Atmosphere Selection

- Cabin pressure set at 57.1 kPa
  - Design Considerations:
    - Pressure low enough to allow R value under 1.6 (NASA standard)
    - Pressure high enough to allow for minimum fire risk
- 40% O2, 59% N2, 1% CO2
  - Calculations of partial pressures of each of the gas’ minimum and maximum levels for long duration exposure were used to determine this make-up
  - Levels for hyperoxia, hypoxia, CO2 toxicity, and fire prevention from NASA STD-3000 document
ECLSS – Overview

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>WVE</th>
<th>EDC</th>
<th>Sabatier</th>
<th>TCC</th>
<th>VAPCAR</th>
<th>MF</th>
<th>SCWO</th>
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</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>144.00</td>
<td>44.40</td>
<td>17.90</td>
<td>100.00</td>
<td>68.00</td>
<td>3.90</td>
<td>694.00</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>0.75</td>
<td>0.07</td>
<td>0.04</td>
<td>0.30</td>
<td>0.24</td>
<td>0.0012</td>
<td>2.12</td>
</tr>
<tr>
<td>Power Req. (kW)</td>
<td>1.60</td>
<td>0.15/0.11</td>
<td>0.05</td>
<td>0.15</td>
<td>0.10</td>
<td>0.0004</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Oxygen Generation: Water Vapor Electrolysis
Carbon Dioxide Removal: Electrochemical Depolarization Concentrator
Carbon Dioxide Reduction: Sabatier
Trace Contaminant Control: Trace Contaminant Control System
Water Distillation: Vapor Phase Catalytic Ammonia Removal
Water Filtration: MultiFiltration
Solid Waste Removal: Supercritical Water Oxidation

* All values for crew per day
ECLSS – Needs and Effluents

<table>
<thead>
<tr>
<th>Needs</th>
<th>Supply (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>3.36</td>
</tr>
<tr>
<td>Hygiene Water</td>
<td>101.6</td>
</tr>
<tr>
<td>Supply Water</td>
<td>9.48</td>
</tr>
<tr>
<td>Solids</td>
<td>2.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effluents</th>
<th>Product (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>4.00</td>
</tr>
<tr>
<td>Hygiene Water</td>
<td>101.6</td>
</tr>
<tr>
<td>Supply Water</td>
<td>6.00</td>
</tr>
<tr>
<td>Solids</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**Oxygen - Shortage of 0.40 kg per crew/day**
Water vapor Electrolysis produces 2.96 kg per crew/day while 3.36 kg is required.

**Hygiene Water – no shortage.**
Multifiltration produces 100% water resupply up to flow of 114 kg day ( > 101.6 kg )

**Supply Water – Shortage of 3.48 kg per crew/day**
Vapor Phase Catalytic Ammonia Removal System produces 100% water resupply up to flow of 13 kg/day (> 6 kg). 6.00 kg or supply water is recycled while 9.48 kg is required.

**Solids – 2.48 kg required per day**
Supercritical Waste Oxidation has 0% resupply flow rate. All solids needed must be provided using food.

* All values for crew per day
ECLSS – Interior Layouts

Habitat Module Basement – Science/EVA

- Water Vapor Electrolysis
- Sabatier
- Electrochemical Depolarization Concentrator
- Trace Contaminant Control

Habitat Module Basement – Living/Bed

- Vapor Phase Catalytic Ammonia Removal Multifiltration
- Supercritical Waste Oxidation
- Sleeping Quarters

Trap door from upstairs

Syed Hasan
ECLSS Flow Diagram

MORPHLAB CREW

Condensing Heat Exchanger

Electrochemical Depolarization Concentrator

overboard venting

cabin return

air return

cabin air

air

supercritical Water Oxidation

waste products

condensate

Vapor Phase Catalytic Ammonia Removal

urine

nitrogen

oxygen

Water Vapor Electrolysis

product water

hydrogen

overboard venting

Multifiltration

product water

waste water

MORPHLAB CREW SYSTEMS

Sabatier

carbon dioxide hydrogen

Trace Contaminant Control

Syed Hasan
Water and Waste Flow Diagrams

**WATER FLOW**

- VAP'CAR
- MF
- MORPHLAB CREW
- Oxygen production
- Condensate from atmosphere
- Waste water
- Urine

**WASTE FLOW**

- SCWO
- Non-recovered waste output
- Feces
- Garbage
- MORPHLAB CREW

Syed Hasan
# ECLSS - Summary

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Vapor Electrolysis</td>
<td>144.0</td>
</tr>
<tr>
<td>Electrochemical Depolarization Concentrator</td>
<td>44.4</td>
</tr>
<tr>
<td>Sabatier</td>
<td>17.9</td>
</tr>
<tr>
<td>Trace Contaminant Control System</td>
<td>100.0</td>
</tr>
<tr>
<td>Vapor Phase Catalytic Ammonia Removal</td>
<td>34.0</td>
</tr>
<tr>
<td>MultiFiltration</td>
<td>2.0</td>
</tr>
<tr>
<td>Supercritical Water Oxidation</td>
<td>347.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science/EVA</td>
<td>306.3</td>
</tr>
<tr>
<td>Living/Bed</td>
<td>383.0</td>
</tr>
</tbody>
</table>

Supply needed per mission (84 days):

<table>
<thead>
<tr>
<th>Product</th>
<th>Amount (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>33.6</td>
</tr>
<tr>
<td>Hygiene Water</td>
<td>0.0</td>
</tr>
<tr>
<td>Supply Water</td>
<td>292.3</td>
</tr>
<tr>
<td>Solids</td>
<td>208.3</td>
</tr>
</tbody>
</table>
Logistics Depot

- Will be launched before every mission containing re-supply of provisions
- Exterior of habitable module, with provisions in place of interior equipment
- First depot:
  - Supplies provisions for two months
  - Contains mobile Robonauts to perform maintenance throughout program
  - Contains two lunar rovers

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Logistics Depot 1</th>
<th>Logistics Depot 2-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen gas</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Oxygen tanks (6)</td>
<td>230</td>
<td>345</td>
</tr>
<tr>
<td>Nitrogen gas</td>
<td>36</td>
<td>53</td>
</tr>
<tr>
<td>Nitrogen tanks (6)</td>
<td>205</td>
<td>308</td>
</tr>
<tr>
<td>Water</td>
<td>195</td>
<td>292</td>
</tr>
<tr>
<td>Water tanks (6)</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>Food</td>
<td>139</td>
<td>208</td>
</tr>
<tr>
<td>Robonaut on wheels (2)</td>
<td>312</td>
<td>-</td>
</tr>
<tr>
<td>DC battery</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Landing legs</td>
<td>212</td>
<td>212</td>
</tr>
<tr>
<td>Science instruments</td>
<td>563</td>
<td>563</td>
</tr>
<tr>
<td>Hull</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>Lunar Rovers (2)</td>
<td>416</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2833</strong></td>
<td><strong>2542</strong></td>
</tr>
</tbody>
</table>

First mission - 56 days
Remaining missions - 84 days
Habitable-Living: Crew Quarters

*2 modules

docking mechanism

docking mechanism

desorption

shelter doors

radiation

Top View

desk

desk

chair

chair

stowage

stowage

sink & cabinet

shower

mirror

closet

closet

Jessica Seidel
Habitable-Living: Galley

Top View

docking mechanism

storage & exercise equipment

stowage

storage

docking mechanism

radiation shelter doors

table & 4 chairs

cabinets, microwave & counter

cabinets & counter

sink

refrigeration unit

shower

toilet

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Habitable-Science: EVA

Top View

- EMU Store
- airlock
- chair
- science rack 2
- storage
- docking mechanism
- TV
- stowage (3)
- storage
- docking mechanism

EMU boxes & storage

*2 modules

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Habitable-Science

- Top View
- Docking mechanism
- Storage
- Science rack 3
- Docking mechanism
- Refrigeration unit
- Cabinets, microwave & counter
- Sink
- Exercise equipment storage
- Cabinet & counter
- Extendable work table & 4 chairs
- Jessica Seidel
# Interior Acoustics

<table>
<thead>
<tr>
<th>Sound Pressure Level in dB</th>
<th>Duration</th>
<th>Performance Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-40</td>
<td>Continuous</td>
<td>No conversation interference</td>
</tr>
<tr>
<td>60-70</td>
<td>Continuous</td>
<td>Voices must be raised significantly; telephone use difficult</td>
</tr>
<tr>
<td>85</td>
<td>Long</td>
<td>Protective earwear must be worn</td>
</tr>
<tr>
<td>100</td>
<td>Sudden onset</td>
<td>Reflex response of tensing, grimacing, covering the ears, and urge to avoid or escape</td>
</tr>
<tr>
<td>114</td>
<td>Sudden onset</td>
<td>Pain in the ears</td>
</tr>
<tr>
<td>120</td>
<td>Continuous</td>
<td>Hearing loss occurs</td>
</tr>
<tr>
<td>150</td>
<td>2 minutes</td>
<td>Reduced visual acuity; chest wall vibrations; gag sensations; respiratory rhythm changes</td>
</tr>
<tr>
<td>167</td>
<td>Sudden onset</td>
<td>Human lethality</td>
</tr>
</tbody>
</table>
Computer User Interface

- Will be LCD flat panel, touch screen mounted on the walls in the habitable modules
  - Currently have 18” LCD touch screen panels that weigh less than 2kg
  - No external input devices reduces clutter inside module
- System of menus to browse different command options
  - Sensor monitoring
    - ECLSS
    - Power grid
    - Computer status
    - Communication status
  - Communications with Earth
  - Communications with other modules
  - EVA support
    - Communications with Astronauts
    - Tele-operation of rovers
  - Entertainment
Alerts for Sensor System

• Integrated sensors for
  – air and water composition
  – pressure levels
  – system integrity

• Monitoring Computer System (MCS)
  – sensors are all tied into it; tracks changes in the levels
  – issues commands to the appropriate system to make adjustments if optimal levels are not met
  – communicates problems to the crew via yellow and red alert alarms when problems occur
# System Levels – ECLSS

<table>
<thead>
<tr>
<th>System</th>
<th>Red, low</th>
<th>Nominal</th>
<th>Red, high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical Depolarized Concentrator</td>
<td>291K</td>
<td>--</td>
<td>297K</td>
</tr>
<tr>
<td>Sabatier</td>
<td>366.5K</td>
<td>700K</td>
<td>811K</td>
</tr>
<tr>
<td>Trace Contaminant Control</td>
<td></td>
<td>723K, 100kPa</td>
<td></td>
</tr>
<tr>
<td>Vapor Phase Catalytic Ammonia Removal</td>
<td></td>
<td>350K, 80kPa</td>
<td>723K, 200kPa</td>
</tr>
<tr>
<td>Multifiltration</td>
<td>289K, 70kPa</td>
<td>--</td>
<td>328K, 210kPa</td>
</tr>
<tr>
<td>Supercritical Water Oxidation</td>
<td>647K, 22.1MPa</td>
<td>923K, 25.3MPa</td>
<td>--</td>
</tr>
</tbody>
</table>

- Note: Yellow levels are 10% in from Red levels
System Levels – Atmosphere

- For internal working considerations only:

<table>
<thead>
<tr>
<th>Gas</th>
<th>Red, low</th>
<th>Yellow, low</th>
<th>Nominal</th>
<th>Yellow, high</th>
<th>Red, high</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2$</td>
<td>18.62kPa, 32.5%</td>
<td>21.38kPa, 37.3%</td>
<td>22.89kPa, 40%</td>
<td>34.48kPa, 60.2%</td>
<td>41.38kPa, 72.28%</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>--</td>
<td>--</td>
<td>0.4kPa, 0.69%</td>
<td>1.01kPa, 1.7%</td>
<td>3.54kPa, 3.5%</td>
</tr>
</tbody>
</table>

- For EVA considerations only:

<table>
<thead>
<tr>
<th>R-factor</th>
<th>Red, low $P_{\text{module}}$, high $N_2%$</th>
<th>Yellow, low $P_{\text{module}}$, high $N_2%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>52.41kPa, 63.5%</td>
<td>55.17kPa, 60.5%</td>
</tr>
<tr>
<td>1.4</td>
<td>55.17kPa, 65%</td>
<td>57.93kPa, 62%</td>
</tr>
<tr>
<td>1.6</td>
<td>60.69kPa, 68%</td>
<td>62.76kPa, 65%</td>
</tr>
</tbody>
</table>

- $P_{\text{suit}} = 25.7\text{kPa}$, $P_{\text{module}} = 57.2\text{kPa}$ nominal
- $O_2\% = 100\% - N_2\% - 1\% CO_2$
Other Monitoring

• Fire protection
  – minimal because of the atmospheric composition
  – fire extinguishers are present to put out small fires

• Health monitoring
  – occurs on a daily basis
  – is part of the exercise routine for data collection on the effects of a low-gravity environment on the human physiology
Crew Activity

- Crew Schedule Guidelines:
  - The crew may adjust the schedule to that day’s science
  - The following guidelines should be followed when adjusting daily schedule (L2)
    - Crew members must eat at least once every 7 hours
    - 2 hours delegated for exercise and recreation each day
    - 8 hours of sleep a day

- EVA rotation:
  - Two, two person teams will alternate daily EVAs
  - Teams will alternate crew members every week

Sample Crew Schedule:

<table>
<thead>
<tr>
<th>Daily schedule</th>
<th>Crewmember Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000 - 0600</td>
<td>Sleep</td>
</tr>
<tr>
<td>0600 - 0700</td>
<td>Hygiene/Breakfast</td>
</tr>
<tr>
<td>0700 - 0800</td>
<td>Daily Coordination</td>
</tr>
<tr>
<td>0800 - 1300</td>
<td>EVA/Tasks</td>
</tr>
<tr>
<td>1300 - 1400</td>
<td>Lunch</td>
</tr>
<tr>
<td>1400 - 1700</td>
<td>EVA/Tasks</td>
</tr>
<tr>
<td>1700 - 1900</td>
<td>Exercise &amp; Recreation</td>
</tr>
<tr>
<td>1900 - 2000</td>
<td>Dinner</td>
</tr>
<tr>
<td>2000 - 2100</td>
<td>Hygiene</td>
</tr>
<tr>
<td>2100 - 2200</td>
<td>Downtime</td>
</tr>
<tr>
<td>2200 - 2400</td>
<td>Sleep</td>
</tr>
</tbody>
</table>
Food & Water

- Level 1 requirements state that MORPHLAB must hold 180 days of food at a subsistence level in addition to the 90 days nominal mission supply (L1)

- Subsistence level will contain mostly EVA food bars & nutritional supplements, estimated weight=100kg

<table>
<thead>
<tr>
<th>Data based off ISS daily consumables</th>
<th>kg/person-day</th>
<th>Single manned mission requirement (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking water</td>
<td>1.6</td>
<td>576</td>
</tr>
<tr>
<td>In food water</td>
<td>1.15</td>
<td>414</td>
</tr>
<tr>
<td>Food preparation water</td>
<td>0.75</td>
<td>270</td>
</tr>
<tr>
<td>Food</td>
<td>0.62</td>
<td>223</td>
</tr>
</tbody>
</table>

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Nutrition

- NASA STD-3000 states crew member diet must meet FDA nutritional requirement standards (L2)
- Daily caloric intake based on weight in kg
  - Men
    - 18-30 years: kcal/day = 1.7 (15.3*Weight + 679)
    - 30+ years: kcal/day = 1.7 (11.6*Weight + 879)
    - Range: 2791.9 - 3716.3 kcal/day
  - Women
    - 18-30 years: kcal/day = 1.6 (14.7*Weight + 496)
    - 30+ years: kcal/day = 1.6 (8.7*Weight + 829)
    - Range: 1897.12 – 2244.8 kcal/day
- An additional 500 kcal/day should be added when an EVA occurs
# Nutrition

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Requirement</th>
<th>Nutrient</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein</td>
<td>12-15% total energy consumed</td>
<td>Biotin</td>
<td>100 µg</td>
</tr>
<tr>
<td>Carbohydrate</td>
<td>50-55% total energy consumed</td>
<td>Pantothenic Acid</td>
<td>5 mg</td>
</tr>
<tr>
<td>Fat</td>
<td>30-35% total energy consumed</td>
<td>Calcium</td>
<td>1000-1200 mg</td>
</tr>
<tr>
<td>Fluid</td>
<td>238-357 ml per MJ consumed</td>
<td>Phosphorus</td>
<td>1000-1200 mg</td>
</tr>
<tr>
<td>Vitamin A</td>
<td>1000 µg</td>
<td>Magnesium</td>
<td>350 mg</td>
</tr>
<tr>
<td>Vitamin D</td>
<td>10 µg</td>
<td>Sodium</td>
<td>1500-3500 mg</td>
</tr>
<tr>
<td>Vitamin E</td>
<td>20 mg</td>
<td>Potassium</td>
<td>3500 mg</td>
</tr>
<tr>
<td>Vitamin K</td>
<td>80 µg</td>
<td>Iron</td>
<td>10 mg</td>
</tr>
<tr>
<td>Vitamin C</td>
<td>100 mg</td>
<td>Copper</td>
<td>1.5-3.0 mg</td>
</tr>
<tr>
<td>Vitamin B&lt;sub&gt;12&lt;/sub&gt;</td>
<td>2 µg</td>
<td>Manganese</td>
<td>2.0-5.0 mg</td>
</tr>
<tr>
<td>Vitamin B&lt;sub&gt;6&lt;/sub&gt;</td>
<td>2 µg</td>
<td>Fluoride</td>
<td>4 mg</td>
</tr>
<tr>
<td>Thiamin</td>
<td>1.5 mg</td>
<td>Zinc</td>
<td>15 mg</td>
</tr>
<tr>
<td>Riboflavin</td>
<td>2 mg</td>
<td>Selenium</td>
<td>70 µg</td>
</tr>
<tr>
<td>Folate</td>
<td>400 µg</td>
<td>Iodine</td>
<td>150 µg</td>
</tr>
<tr>
<td>Niacin</td>
<td>20 mg</td>
<td>Chromium</td>
<td>100-200 µg</td>
</tr>
</tbody>
</table>

**ISS Daily Nutritional Recommendations**

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Food Storage

- Three levels of storage
  - Frozen: includes most entrees, vegetables, baked foods, grains, and desserts
  - Refrigerated: fresh-treated fruits and vegetables, extended-shelf-life refrigerated foods, dairy products
  - Ambient: thermostabilized, irradiated, aseptic-fill, shelf-stable natural-form foods, and rehydratable beverages

- 180 subsistence level kept on board at all times, split up evenly between modules
  - Diet will consists of EVA food bars and nutritional supplements

- Nominal manned mission food supply will be sent up via Logistics Depot before each manned mission
  - Food will be stored in 2 week supply containers
  - Containers will have straps so it can be carried onboard during the first EVA
## EMU Selection

<table>
<thead>
<tr>
<th></th>
<th>I-Suit</th>
<th>MK III</th>
<th>AX5</th>
<th>A7LB</th>
<th>Shuttle EMU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight- Suit</td>
<td>63.9 kg</td>
<td>67.5 kg</td>
<td>83.25 kg</td>
<td>22 kg</td>
<td>50 kg</td>
</tr>
<tr>
<td>Weight- PLSS</td>
<td>15 kg</td>
<td>15 kg</td>
<td>never fitted</td>
<td>26 kg</td>
<td>15 kg</td>
</tr>
<tr>
<td>Total Weight</td>
<td>78.9 kg</td>
<td>82.5 kg</td>
<td>83.25 kg</td>
<td>48 kg</td>
<td>65 kg</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>3.75 psi</td>
<td>8.3 psi, tested at 4.3 psi</td>
<td>8.3 psi</td>
<td>3.7 psi</td>
<td>4.3 psi</td>
</tr>
<tr>
<td>R value</td>
<td>1.3</td>
<td>1.14 (at 4.3 psi)</td>
<td>0.59</td>
<td>1.3</td>
<td>1.14</td>
</tr>
<tr>
<td>Suit type</td>
<td>Soft</td>
<td>Hybrid</td>
<td>Hard</td>
<td>Soft</td>
<td>Soft w. hard upper torso</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>ILC Dover</td>
<td>ILC Dover</td>
<td>NASA Ames</td>
<td>ILC Dover</td>
<td>ILC Dover</td>
</tr>
<tr>
<td>Entry</td>
<td>Waist</td>
<td>Back</td>
<td>Back</td>
<td>Waist</td>
<td>Waist</td>
</tr>
<tr>
<td>Storing</td>
<td>Bags</td>
<td>Hung</td>
<td>Hung</td>
<td>Bags</td>
<td>Bags &amp; Hung</td>
</tr>
<tr>
<td>Year developed</td>
<td>1998</td>
<td>1988</td>
<td>1980s</td>
<td>1970s</td>
<td>Late 1970s/ early 80s</td>
</tr>
</tbody>
</table>
EVA Support

• I- Suit
  – Manufactured by ILC- Dover
  – Soft bodies suit increases mobility and decreases weight
  – Waist entry
  – 8 suits for redundancy (I4)
    • 4 come up with crew, fitted specifically for them
    • 4 kept on board, general sizes with interchangeable section
  – 80 kg weight with Portable Life Support System (PLSS)
  – 8 hours of nominal breathing, 45 minutes of emergency life support
  – 25.7 kPa, 100% O₂ atmosphere
  – Zero pre-breathe (L9)
    • R value of 1.3

http://strangeblue.iwarp.com
spacesuits/ILC.html

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Emergency EVA Access

- Level 1, L8: System shall provide emergency access and EVA bailout alternatives
- Airlock connections between modules will serve as pressure doors in case of decompression and also as emergency bailout hatches
- Procedure for emergency egress:
  - Put on EVA suit
  - Make sure all doors are closed and sealed
  - Disengage umbilical walkway
  - Open hatch door to outside
  - Deploy flexible ‘rope’ ladder from floor and egress
Airlock

- 101 kg total mass
  - 50 kg structure
  - 22 kg inner door (pressure hatch)
  - 10 kg ladder
  - 14 kg pump
  - 5 kg tubing

- Accommodates one person in I-suit
  - 0.8 m x 0.8 m x 2.0 m high

- Depressurized and Re-pressurized
  - Most of airlock air pumped back into module before outer door is opened
  - Air shower from above when air returns to airlock
Airlock

- Pump similar to Dekker Vacuum Technologies DuraVane RVD007L
  - Chosen based on: mass, ultimate vacuum, speed to depressurize
  - 14 kg mass
  - 12 kPa ultimate vacuum
  - 0.2 m$^3$/min pumping speed, depressurizes airlock in 7 minutes
Lunar Roving Vehicle

• Level 1 requirements lead us to selection of a rover
  – MORPHLAB shall have daily EVAs by two astronauts (L5), and that they must be able to travel within a radius of 10 km from the base (M4)
    • A 10 km-radius circle is too much area for astronauts to explore on foot, so they need a rover
  – A rover will allow them to bring back soil and rock samples, as in the Level 1 requirements (M3)
  – The rover can be used to transport the astronauts from the landing vehicle to MORPHLAB (M5)
Lunar Roving Vehicle

• Based on Apollo Lunar Roving Vehicle
  – 208 kg mass
  – 3.1 m long, 1.8 m wide, 1.2 m high
  – Carries up to 490 kg payload including astronauts, samples, and equipment
  – Folds up to 0.85 m³ for storage
  – Top speed 14 km/h
  – Can go over obstacles 30.5 cm high, crevasses 70 cm wide
  – Travels on 25° slopes, parks on 35° slopes
  – Pitch and roll stability of ±45°

• Will have two modules to meet redundancy requirement (I3 & I11)
Lunar Roving Vehicle

- Original Apollo LRV batteries not acceptable
  - Two 36 V silver-zinc batteries
  - 78 hour lifetime

- MORPHLAB LRV will have rechargeable batteries
  - Two 36 V lithium ion
  - 112 W constant power
  - 11 kg mass
  - Rechargeable
    - Plug into habitat module (currently drawing least power)
    - Budgeted 200 Watts per hour to recharge in 8 hours

- Batteries aren’t sufficient for 3 month traverse, so the rovers are transported on the power modules
Lunar Roving Vehicle

• Payload Breakdown
  – 2 astronauts, 95 percentile American males: 197 kg
  – 2 Mark III Suits & PLSS: 148 kg
  – Lunar samples and soil instruments: 95 kg
  – Communication/control/camera equipment: 10 kg Total: 450 kg

• Speed is useful
  – 14 km/h for an 8-hour EVA gives 112 km of travel total
  – Can return from 10 km in 43 minutes if needed
Getting to the Moon
Getting to the Moon Topics

- $\Delta V$ Calculations
- Launch Options
- Multi-Stage System
- RCS
- Landing Autonomy
- Landing Zone
- Landing Legs
- Chassis Transit
ΔV Requirements

<table>
<thead>
<tr>
<th>Burn #</th>
<th>Burn Description</th>
<th>ΔV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LEO to LTO</td>
<td>3.14 km/s</td>
</tr>
<tr>
<td>2</td>
<td>LTO to LLO</td>
<td>.84 km/s</td>
</tr>
<tr>
<td>3</td>
<td>LLO to LD</td>
<td>.01 km/s</td>
</tr>
</tbody>
</table>

*NOTE: Not to Scale

LEO = Low Earth Orbit  
(alt = 185km, 28.5°)

LTO = Lunar Transfer Orbit  
(6560km X 386200km)

LLO = Low Lunar Orbit  
(alt = 50km)

LD = Lunar Descent  
(50km x 10km)
ΔV Requirements

<table>
<thead>
<tr>
<th>Burn #</th>
<th>Burn Description</th>
<th>ΔV</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Braking and Approach</td>
<td>1.88 km/s</td>
</tr>
<tr>
<td>5</td>
<td>Landing</td>
<td>0.26 km/s</td>
</tr>
</tbody>
</table>

Total ΔV = 6.13 km/s

*NOTE: Not to Scale

Russell Parker
Launch Vehicle Options

- **Level 1 Requirement:**
  
  *All components for MORPHLAB system installation and operation shall be designed for launch on the Atlas V, Delta IV Heavy*

- **LEO Mass: Delta IV vs. Atlas V**
  - Delta IV-H ~ 25,800 kg
  - Atlas V-551 ~ 20,000 kg

- **Delta IV-H 2\(^{nd}\) Stage to LEO vs. LTO.**
  - Mass after LTO insertion burn:
    - Delta IV to LEO 8350kg
    - Delta IV to LTO 12980kg

- **One Stage vs. Two Stages**
  - **Assuming:**
    - Payload (Landed Usable Mass)
      - One Stage 4200 kg
      - Two Stage 3800 kg

<table>
<thead>
<tr>
<th>Stage</th>
<th>Isp</th>
<th>Inert Mass Fraction</th>
<th>ΔV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st})</td>
<td>465</td>
<td>.01</td>
<td>5.87</td>
</tr>
<tr>
<td>2(^{nd})</td>
<td>350</td>
<td>.07</td>
<td>.26</td>
</tr>
</tbody>
</table>
Two Stage System

• Despite lower mass still going with a two stage system.
• Benefits:
  – Allows us to take advantage of a high Isp engine for majority of burns
  – Easily dispose of large propellant tanks and main engine
  – Decrease ground clearance (smaller landing legs)
  – Landing stage can be moved out of the way by Power Module dexterous arm. (largest mass = 45kg)

Lunar Transfer and Approach Stage
(First Stage)
$\Delta V = 5.87 \text{ km/s}$

Lunar Landing Stage
(Second Stage)
with Habitable module
$\Delta V = .26 \text{ km/s}$

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Lunar Transfer and Approach Stage

**LOX Tank**
- Propellant Mass: 15960 kg
- Tank Mass: 560 kg
- Insulation Mass: 50 kg
- Variable Density Multi-Layer Insulation to reduce boil off from radiation

**Modified Pratt and Whitney RL-10B-2**
- Isp: 465s
- Mass: 280 kg
- Thrust can be throttled

**LH2 Tank**
- Propellant Mass: 2720 kg
- Tank Mass: 550 kg
- Insulation Mass: 200 kg
- VD-MLI to reduce boil off from radiation

**Titanium Thrust Structure**
- Support loads of:
  - 6g’s vertical
  - 2.5g’s lateral
- Low Thermal Conductivity to decrease boil off
- Mass = 920kg
Structural Analysis

- Launch loads:
  - 6 g’s vertical
  - 2.5 g’s lateral

- Material comparison
  - Al ~ 1340kg
  - Titanium ~ 920 kg

<table>
<thead>
<tr>
<th>Truss Member</th>
<th>Dimension (m)</th>
<th>M.S.</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>0.350, 0.346, 4.31</td>
<td>0.013</td>
<td>Local Buckling</td>
</tr>
<tr>
<td>LOX</td>
<td>0.105, 0.100, 2.42</td>
<td>0.10</td>
<td>Compression</td>
</tr>
<tr>
<td>LOX Connect</td>
<td>0.300, 0.250, 0.30</td>
<td>2.7</td>
<td>Bending</td>
</tr>
<tr>
<td>LH₂</td>
<td>0.200, 0.198, 3.38</td>
<td>0.009</td>
<td>Euler Buckling</td>
</tr>
<tr>
<td>Module</td>
<td>0.200, 0.198, 3.40</td>
<td>0.25</td>
<td>Euler Buckling</td>
</tr>
</tbody>
</table>
Thermal Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Assumed Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>270 K</td>
</tr>
<tr>
<td>LOX Tank</td>
<td>80 K</td>
</tr>
<tr>
<td>LH₂ Tank</td>
<td>4 K</td>
</tr>
<tr>
<td>Module</td>
<td>270 K</td>
</tr>
</tbody>
</table>

- **Given:**
  - \(K_{Ti} = 6.7 \text{ W/m-K}\)
  - \(L_{O2} = 213 \text{ kJ/kg}\)
  - \(L_{H2} = 446 \text{ kJ/kg}\)

- **Boil Off**
  - \(LOX = 29.7\text{kg (.19\%)}\)
  - \(LH2 = 5.7\text{kg (.21\%)}\)

<table>
<thead>
<tr>
<th>Flow</th>
<th>Source</th>
<th>Sink</th>
<th>Area</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_{12})</td>
<td>Engine</td>
<td>LOX</td>
<td>.031 m²</td>
<td>16.2 W</td>
</tr>
<tr>
<td>(Q_{23})</td>
<td>LOX</td>
<td>LH₂</td>
<td>.007 m²</td>
<td>.13 W</td>
</tr>
<tr>
<td>(Q_{34})</td>
<td>Module</td>
<td>LH₂</td>
<td>.007 m²</td>
<td>3.24 W</td>
</tr>
<tr>
<td>(Q_{\text{radiation}})</td>
<td>Sun</td>
<td>LH₂</td>
<td>27.5 m²</td>
<td>2.10 W</td>
</tr>
<tr>
<td>(Q_{\text{radiation}})</td>
<td>Sun</td>
<td>LOX</td>
<td>14.0 m²</td>
<td>4.12 W</td>
</tr>
</tbody>
</table>
Descent Engine

- Descent Engine’s Responsibility
  - Hovering
    - Modules hovers for 60 seconds
    - During hovering the lunar surface will be surveyed
  - Landing
    - The engine used to carry the module within the designated landing zone
    - The engines are throttled to low thrust for soft landing on landing legs onto the lunar surface
  - Descent Engines Considered

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust(N)</th>
<th>Isp(sec)</th>
<th>length(m)</th>
<th>diameter(m)</th>
<th>gimbaled(deg)</th>
<th>mass(kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3K (DASA/EADS)</td>
<td>3500</td>
<td>352</td>
<td>1.03</td>
<td>0.53</td>
<td>no</td>
<td>14.5</td>
</tr>
<tr>
<td>OMV Variable Thrust Engine (TRW)</td>
<td>578</td>
<td>308</td>
<td>0.7005</td>
<td>0.2713</td>
<td>10-100</td>
<td>6.8</td>
</tr>
<tr>
<td>RS-28 (Rocketdyne)</td>
<td>2670</td>
<td>220</td>
<td>?</td>
<td>?</td>
<td>no</td>
<td>12.7</td>
</tr>
<tr>
<td>RS-21 (Rocketdyne)</td>
<td>1330</td>
<td>294</td>
<td>?</td>
<td>?</td>
<td>no</td>
<td>8.4</td>
</tr>
</tbody>
</table>
Landing Stage

**EADS S3K (6)**
- Isp: 350s
- Mass: 14.5 kg
- Full Throttle: 3500 N
- Thrust can be throttled

**MON3 Tank(2)**
- Propellant Mass: 72 kg/tank
- Tank Mass: 22.5 kg/tank

**MMH Tank(2)**
- Propellant Mass: 95 kg/tank
- Tank Mass: 45 kg/tank

**He Pressure Tank**
- Not shown on model.
- He and Tank Mass < 5 kg

**Support Structure**
- Still being determined.
- Conservative mass estimate of 150 kg.
Landing Engine Schematic

Pressure Fed System

- pressurized helium tank
- helium isolation valve
- pressure relief valve
- check valve
- fill/vent
- supply line
- S3K Engine
- MON3 Tank
- MMB Tank

University of Maryland
CDR 04/19/04
Tia Burley
Reaction Control

- Reaction Control System’s (RCS) Responsibility
  - Attitude control during orbital maneuvering
  - Small translation maneuvers
  - Assist descent engine with landing maneuvers

- Reaction Control Thrusters Considered

<table>
<thead>
<tr>
<th>Rocket Thrusters</th>
<th>Thrust(N)</th>
<th>Isp(sec)</th>
<th>length(m)</th>
<th>diameter(m)</th>
<th>throttled %</th>
<th>mass(kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHT 20 (EADS)</td>
<td>20</td>
<td>230</td>
<td>0.195</td>
<td>0.033</td>
<td>40-100</td>
<td>0.395</td>
</tr>
<tr>
<td>S22 (EADS)</td>
<td>22</td>
<td>290</td>
<td>0.212</td>
<td>0.055</td>
<td>?</td>
<td>0.65</td>
</tr>
<tr>
<td>R-1E (Marquardt)</td>
<td>110</td>
<td>280</td>
<td>0.279</td>
<td>0.15</td>
<td>60-140</td>
<td>3.7</td>
</tr>
<tr>
<td>MR-107 (Rocket Research)</td>
<td>178</td>
<td>236</td>
<td>0.218</td>
<td>0.066</td>
<td>28-140</td>
<td>0.885</td>
</tr>
</tbody>
</table>
Reaction Control System

- Assume RCS only necessary to prevent rotational drift during transit.
- RCS uses Kaiser Marquardt R-1E (68N) located on thrust structure at LOX connection and on Module

<table>
<thead>
<tr>
<th>Axis</th>
<th>Max T</th>
<th>Rotational Velocity</th>
<th>Allowable Drift</th>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>532 N-m</td>
<td>.01 °/s</td>
<td>+/- 5°</td>
<td>33s</td>
</tr>
<tr>
<td>Y</td>
<td>532N-m</td>
<td>.01 °/s</td>
<td>+/- 5°</td>
<td>33s</td>
</tr>
<tr>
<td>Z</td>
<td>268N-m</td>
<td>.01 °/s</td>
<td>+/- 5°</td>
<td>63s</td>
</tr>
</tbody>
</table>

- Total burn time + 50% Margin = 192s

After 1st Burn, approximate values:

- $I_{xx} = 1.62 \times 10^5 \text{kgm}^2$
- $I_{yy} = 1.62 \times 10^5 \text{kgm}^2$
- $I_{zz} = 4.2 \times 10^4 \text{kgm}^2$
- c.g. = 8.3 m (z-direction)
Reaction Control System

- Kaiser Marquardt R-1E
  - Variable Thrust (68N – 158N)
  - MMH/N₂O₄
  - Isp = 280s
  - Mass Flow Rate
    - MMH = .0354 kg/s
    - N₂O₄ = .0256 kg/s
  - Mass = 3.7 kg
- Mass Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>11 kg</td>
</tr>
<tr>
<td>Engines</td>
<td>118 kg</td>
</tr>
<tr>
<td>Tanks</td>
<td>2 kg</td>
</tr>
<tr>
<td>Structures</td>
<td>20 kg*</td>
</tr>
<tr>
<td>TOTAL</td>
<td>151 kg</td>
</tr>
</tbody>
</table>

*Structural Mass still being determined. 20kg is an approximation.
## Launch System Mass Summary

<table>
<thead>
<tr>
<th></th>
<th>Launch Transfer and Approach Stage</th>
<th>Landing Stage</th>
<th>Reaction Control System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine</strong></td>
<td>RL-10B-2</td>
<td>S3K (6)</td>
<td>R-1E (32)</td>
</tr>
<tr>
<td></td>
<td>280 kg</td>
<td>14.5 kg each</td>
<td>3.7 kg each</td>
</tr>
<tr>
<td><strong>Propellant</strong></td>
<td>LOX/LH2</td>
<td>MON3/MMH</td>
<td>N₂O₄/MMH</td>
</tr>
<tr>
<td></td>
<td>1350 kg</td>
<td>330 kg</td>
<td>11 kg</td>
</tr>
<tr>
<td><strong>Tanks and Insulation</strong></td>
<td>18675 kg</td>
<td>130 kg</td>
<td>2 kg</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>920 kg</td>
<td>150 kg</td>
<td>20 kg</td>
</tr>
</tbody>
</table>

Resultant available landed mass: **3700 kg**
Landing Requirements

- **Level 1 Requirements:**
  - Each MORPHLAB module shall be capable of successful landing and operations with any or all of the following conditions occurring simultaneously:
    - 10° slope, any direction
    - 0.5 m diameter boulder anywhere in landing footprint
    - residual vertical velocity 1 m/sec
    - residual horizontal velocity 0.5 m/sec
  - Landing systems onboard MORPHLAB modules shall be capable of operating in on-board autonomous control

- **Derived Requirements:**
  - Upon landing chassis, habitable module must connect to power module within 24 hours
Landing Determination

- Prior to descent
  - Mapping satellite will provide preliminary terrain analysis of 1.4m resolution to determine ideal landing zone of .10km
  - Ideal landing zone will be relatively flat, and have few terrestrial hazards, cliffs or craters which can disturb communications
  - Trajectory corrections will keep us in the target footprint of 100m with terrestrial hazards greater than 1.4m known

- Autonomous Descent
  - Power Modules:
    - LIDAR will distinguish objects down to .5m, determine slopes of >10 deg, determine any zone considered unsafe
  - Habitable and chassis modules:
    - Power modules guide to safe landing
Landing Order and Sensors

Power Module
1, 2, 3, 4

Chassis Modules
5, 6, 7, 8, 9, 10

Habitable Module
11, 12, 13, 14, 15, 16

Power Module Landing Sensors
- Visual Imager
- Lidar
- IMU
- Fault Protection

Chassis & Habitable Sensors
- Visual Imager
- IMU
- Fault Protection

John Albritton
Landing Footprint

- Upon touchdown, LIDAR rotates forward to be used as obstacle avoidance.
- Power modules reposition 100m apart in a diamond formation.
- The diamond area, .01km$^2$, will be scanned using LIDAR to construct a safe landing zone.
- If unsafe landing zone, power modules will reposition until safe area found.
Chassis Landing

- Power module determines chassis’s relative position and descent velocity through triangulation

- Power modules continuously update and communicate the data to the chassis module providing real time navigation and guidance

- Chassis module is guided and landed within the “Safe Zone”
Chassis Recovery

- After successful landing of chassis, power module retrieves the chassis
- In the retrieval process, the power module removes the landing engines first and then connects to chassis for power up.
- The power module along with connected chassis will return to the diamond formation waiting for the next chassis’s descent
- This retrieval process will occur for all 6 chassis
- Chassis and power connection must occur within 24 hours
Habitable Module Landing

- After All 6 chassis are successfully landed and connected, the habitable and science modules follow

- The habitable and science modules will land using the same exact process as the chassis.

- A power module-chassis module assembly will be sent to retrieve the habitable module
Chassis Recovery

- The power module will first remove the descent engines.
- The chassis will then be commanded to drive under the habitable module and establish a permanent connection.
- This connection also is required to take place within 24 hours.
- This process will repeat until all habitable modules have established permanent connections with the 6 chassis.
Landing Summary

• Power modules land using full sensor suite
• Chassis and habitable modules landing without LIDAR utilize navigation and guidance provided by the power modules
• Chassis and habitable modules must connect with power modules within 24 hours
• All retrieval processes are guided and commanded by the power modules
Landing Zone

- Landing zone is based upon Apollo actual off target data
- The data was then filtered
- A standard deviation and average value was then found
- Then a technology advancement reduction taken (30% off Apollo numbers)
- A new standard deviation and average were then calculated

<table>
<thead>
<tr>
<th>Mission</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 11</td>
<td>.068 km</td>
<td>.155 km</td>
</tr>
<tr>
<td>Apollo 12</td>
<td>.016 km</td>
<td>.155 km</td>
</tr>
<tr>
<td>Apollo 13</td>
<td>.054 km</td>
<td>.155 km</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>.055 km</td>
<td>.0406 km</td>
</tr>
<tr>
<td>Apollo 15</td>
<td>.055 km</td>
<td>.0204 km</td>
</tr>
<tr>
<td>Apollo 16</td>
<td>.021 km</td>
<td>.0406 km</td>
</tr>
<tr>
<td>Apollo 17</td>
<td>.020 km</td>
<td>.0204 km</td>
</tr>
<tr>
<td>Apollo 18</td>
<td>.016 km</td>
<td>.0204 km</td>
</tr>
</tbody>
</table>

Apollo Distances from Target Landing Site

- Apollo 11: 6.86 km (filtered)
- Apollo 15: .55 km (filtered)
- Apollo 16: .21 km
- Apollo 17: .20 km
- Apollo 12: .16 km
• The new Standard deviation and average were normalized and then applied to a normal distribution curve to find a .9990 probability of success.
• This value then applied to the average gives us the probability of .9990 of being within a circle of that radius of the target site.
• So, this leaves us with a landing zone with a circular radius of .109 km for the first module (power) to land in.

• Other modules will land close to the first one, due to landing beacons being placed after power module landing, allowing them to land within meters of the power module.
Landing Stability Analysis

• Level 1 Requirement
  – MORPHLAB modules must be able to land on a 10° slope with residual 1.0 m/s vertical and 0.5 m/s lateral velocities

• Assumptions
  – 2-D motion & rigid body dynamics
  – Collisions are perfectly inelastic
  – Habitable module modeled as a cylinder and power module modeled as a box

• Analysis
  – Energy req. for tipping = potential energy of center of gravity – kinetic energy of vehicle
Landing Stability Analysis

Case A
- No-failure of power or habitable module

Case B
- 7.30m = footprint of habitable module
- 2.28m = footprint of power module

Case C
- 7.10 = footprint of habitable module
- 2.22 = footprint of power module

Habitable module footprint = 7.60m → stable
Power module wheel base = 3.3m wide 4.2m long → stable
Design of Landing Legs for Habitable Module

- **Level 1 Requirement**
  - MORPHLAB modules must be able to land on 10° slope with residual 1.0 m/s vertical and 0.5 m/s lateral velocities

- **Assumptions**
  - 63 m/s² axial, 1.63 m/s² lateral
  - Loads through of CG carried by stringers
  - Footpad constrained 1.

1/16*landed mass
Acceleration vector
Constraint

Abraham Daiub
## Design of Landing Legs for Habitable Module

<table>
<thead>
<tr>
<th>Member</th>
<th>ID (m)</th>
<th>OD (m)</th>
<th>Length (m)</th>
<th>S.M.</th>
<th>Max. Stress (MPa)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Upper Strut</td>
<td>.128</td>
<td>.130</td>
<td>1.45</td>
<td>0.379</td>
<td>388</td>
<td>Euler Buckling</td>
</tr>
<tr>
<td>Primary Lower Strut</td>
<td>.118</td>
<td>.120</td>
<td>2.67</td>
<td>0.052</td>
<td>526</td>
<td>Local Buckling</td>
</tr>
<tr>
<td>Secondary Strut</td>
<td>.099</td>
<td>.100</td>
<td>0.722</td>
<td>0.196</td>
<td>290</td>
<td>Local Buckling</td>
</tr>
<tr>
<td>Foot-pad</td>
<td>0</td>
<td>.5</td>
<td>0.30</td>
<td>.25</td>
<td>874.2</td>
<td>Bending</td>
</tr>
</tbody>
</table>

- **Primary Upper Strut**
- **Primary Lower Strut**
- **Secondary Strut**
- **Foot-pad**

**Foot-pad**

**Primary Lower Strut**
Design of Landing Legs for Habitable Module

- Requirement
  - Absorb all kinetic energy with one load limiter
  - Residual velocity 1.0 m/s axial and 0.5 m/s lateral

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>1.40</td>
</tr>
<tr>
<td>Cross section (m²)</td>
<td>0.0129</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.342</td>
</tr>
</tbody>
</table>

Chassis During Transit to Moon

- Wheels retracted inward toward center of thrust structure to allow chassis to fit within dynamic envelop of Delta IV-H 5m payload fairing.

- Launch loads transferred two four points at ends of 2 chassis ‘launch beams.’

- Maximum load acted on chassis during transit and launch occur during Delta IV – H main engine cutoff. Axial acc. = 6g’s, later acc = 2.5g’s. Chassis capable of supporting 3500 kg (including itself) during transit and launch.
Chassis Landing

Maximum landed mass = 3500kg

Maximum impact deceleration designed for
= 6 lunar g’s

Max deceleration is a very conservative estimate
derived from our requirement that the maximum
residual velocity during landing cannot exceed
1m/s and assuming that the deceleration during
impact will not occur in less that 1/10th of a second.

Worst cases for struts and axles correspond to a power module initially
touching down with only one wheel.

Landing loads can act in all three directions and create greater stresses in each
member for different loading directions.

All cases closely examined and modeled using ProEngineer.

All structural member pass all worst case landing load conditions with
positive margins of safety.
Fault Tolerance

• Level 1 Requirements:
  – Loss of 1 module should not end mission
  – Loss of 2 modules should support crew until launch window occurs

• Fail Safe Mode losses:
  – 1 Habitable-Science module
  – 1 Habitable-Living module
  – 2 Power modules

• Survival Mode losses:
  – 2 Habitable-Living modules
  – 2 Habitable-Science modules
  – 3 Power modules
Fault Tolerance/Reliability

- NASA JSC - 28354 requires reliability of 0.99 for crew return
- All sub-systems will have to meet these reliability requirements by Jan. 1st 2010 with a NASA technology readiness level (TRL) of 6

R-Power Sys = 0.99988
R-Living Sys = 0.995
R-Science Sys = 0.995

R-Power
R-Power
R-Power
R-Power
R-Power = 0.989

R-Living
R-Living
R-Living

R-Science
R-Science

= Fail Safe Mode

Daniel Senai
Required Sub-System Reliabilities

<table>
<thead>
<tr>
<th>Sub-System</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Module</td>
<td>0.989</td>
</tr>
<tr>
<td>Chassis Module</td>
<td>0.9978</td>
</tr>
<tr>
<td>DIPS</td>
<td>0.9955</td>
</tr>
<tr>
<td>Avionics</td>
<td>0.9978</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.9978</td>
</tr>
<tr>
<td>Docking Mechanism</td>
<td>0.9819</td>
</tr>
<tr>
<td>ECLSS</td>
<td>0.9819</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.9819</td>
</tr>
<tr>
<td>Avionics</td>
<td>0.9819</td>
</tr>
</tbody>
</table>

Habitable-Living and Habitat-Science Modules = 0.930

<table>
<thead>
<tr>
<th>Sub-System</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Sub-systems</td>
<td>0.9819</td>
</tr>
<tr>
<td>Avionics</td>
<td>0.9819</td>
</tr>
<tr>
<td>Thermal</td>
<td>0.9819</td>
</tr>
<tr>
<td>ECLSS</td>
<td>0.9819</td>
</tr>
<tr>
<td>Docking Mechanism</td>
<td>0.9819</td>
</tr>
<tr>
<td>Drive System</td>
<td>0.9966</td>
</tr>
<tr>
<td>Steering System</td>
<td>0.9966</td>
</tr>
<tr>
<td>Suspension System</td>
<td>0.9966</td>
</tr>
<tr>
<td>Brake System</td>
<td>0.9966</td>
</tr>
<tr>
<td>Avionics</td>
<td>0.9966</td>
</tr>
<tr>
<td>Power Sub-systems</td>
<td>0.9966</td>
</tr>
<tr>
<td>Chassis Module</td>
<td>0.9978</td>
</tr>
</tbody>
</table>
### Timeline

<table>
<thead>
<tr>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design/Manufacture</td>
<td>Test Systems</td>
<td>Launch Modules</td>
<td>Manned Missions (every 6 months)</td>
</tr>
</tbody>
</table>

- **Historical Precedent:**
  - **Apollo:**
    - 5 years from program start to first test
    - 2 years from testing to first human launch
    - 7 years total time from program start to human launch
  - **Shuttle:**
    - 5 years from program start to first test
    - 4 years from testing to first human launch
    - 9 years total time from program start to human launch
Timeline

  - All landings are scheduled for local lunar dawn + 3 days
  - Launch #18 - #24 are launch windows built into the timeline in case a launch must be delayed and so that the manned missions will begin on schedule
  - LVs can be ready in 22 days, each launch is scheduled 28-30 days apart
  - Mapping satellites to be launched January 2011 to get 24 months of data and analysis about the lunar terrain
  - Communications satellites will be launched February 2017
Timeline

• 17 required launches before first human mission
  – Launches #1 - #4 will be the power modules
  – Launches #5 - #10 will be the chassis modules
  – Launches #11 - #16 will be the habitable modules
  – Launch #17 will be the first logistics depot
    • Each logistics depot will be launched one month before the next human arrival
Timeline

  - Each human mission will be 6 months apart starting June 5, 2015
    - Launch will be June 1, 2015
    - Level 1 Requirement: I10
      - System shall provide autonomous checkout and unambiguous evidence of functionality prior to committing the next human
    - The first 3 month mission will be unmanned for the first month and land the first crew at local dawn on the second
      - The human mission will be 2 months in order to stay on schedule
    - Approximately 14 days will be lost of program time when the missions change over to far side
## Timeline

<table>
<thead>
<tr>
<th>Site #</th>
<th>Land Day before</th>
<th>Full Moon</th>
<th>Land Day</th>
<th>Launch Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Full Moon *****</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>2-Jun-15</td>
<td>5-Jun-15</td>
<td>1-Jun-15</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>22-Apr-16</td>
<td>26-Apr-16</td>
<td>22-Apr-16</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>16-Oct-16</td>
<td>22-Oct-16</td>
<td>18-Oct-16</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>11-Apr-17</td>
<td>17-Apr-17</td>
<td>13-Apr-17</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>5-Oct-17</td>
<td>18-Oct-17</td>
<td>14-Oct-17</td>
</tr>
<tr>
<td><strong>Far Side</strong></td>
<td><strong>Land Day after</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>14</td>
<td>31-Mar-18</td>
<td>14-Apr-18</td>
<td>10-Apr-18</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>25-Sep-18</td>
<td>3-Oct-18</td>
<td>29-Sep-18</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>14-Sep-19</td>
<td>24-Sep-19</td>
<td>20-Sep-19</td>
</tr>
</tbody>
</table>
Timeline

• In the event that a mission must be delayed the column labeled “Land Day before/after Full Moon” will be used to get the new landing date

• This factor will land humans at local lunar dawn + 2 days

• All full moons from 2015 – 2020 are listed in the detailed timeline document
Cost Analysis

• Level I Requirements: $51.5 Billion budget
  – Spread over 15 years
  – Derived from projected NASA spending on a lunar exploration program

• Mass-based, vehicle-level cost estimating relationship
  – Non-recurring costs
  – Production costs with 80% learning curve
  – Constants differ for launch vehicle stage, liquid rocket engine, scientific instrument, unmanned planetary, manned spacecraft
# Production Costs

## Vehicle Assembly

<table>
<thead>
<tr>
<th>Component</th>
<th>Qty</th>
<th>Cost ($B04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Module</td>
<td>4</td>
<td>1.33</td>
</tr>
<tr>
<td>Habitable-Living</td>
<td>3</td>
<td>1.99</td>
</tr>
<tr>
<td>Habitable-Science</td>
<td>3</td>
<td>1.91</td>
</tr>
<tr>
<td>Chassis Module</td>
<td>6</td>
<td>1.26</td>
</tr>
<tr>
<td>Logistics Module 1</td>
<td>1</td>
<td>1.19</td>
</tr>
<tr>
<td>Logistics Modules (2-10)</td>
<td>9</td>
<td>1.99</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>9.67</td>
</tr>
</tbody>
</table>

## Launch Structure

<table>
<thead>
<tr>
<th>Component</th>
<th>Qty</th>
<th>Cost ($B04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust Structure</td>
<td>26</td>
<td>0.973</td>
</tr>
<tr>
<td>Engine</td>
<td>26</td>
<td>0.780</td>
</tr>
<tr>
<td>Small Engine</td>
<td>52</td>
<td>0.159</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.91</td>
</tr>
</tbody>
</table>

## Satellites

<table>
<thead>
<tr>
<th>Component</th>
<th>Qty</th>
<th>Cost ($M04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping</td>
<td>1</td>
<td>67</td>
</tr>
<tr>
<td>Communications</td>
<td>4</td>
<td>115</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>182</td>
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</tbody>
</table>
## Launch Costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Number Launches</th>
<th>LV</th>
<th>Cost ($B04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Module</td>
<td>4</td>
<td>Delta IV-Heavy</td>
<td>0.660</td>
</tr>
<tr>
<td>Habitable-Living Module</td>
<td>3</td>
<td>Delta IV-Heavy</td>
<td>0.495</td>
</tr>
<tr>
<td>Habitable-Science Module</td>
<td>3</td>
<td>Delta IV-Heavy</td>
<td>0.495</td>
</tr>
<tr>
<td>Chassis Module</td>
<td>6</td>
<td>Delta IV-Heavy</td>
<td>0.990</td>
</tr>
<tr>
<td>Logistics Module 1</td>
<td>1</td>
<td>Delta IV-Heavy</td>
<td>0.165</td>
</tr>
<tr>
<td>Logistics Modules 2-10</td>
<td>9</td>
<td>Delta IV-Heavy</td>
<td>1.49</td>
</tr>
<tr>
<td>Communication Satellites</td>
<td>1</td>
<td>Atlas V</td>
<td>0.122</td>
</tr>
<tr>
<td>Mapping Satellite</td>
<td>1</td>
<td>Atlas V</td>
<td>0.122</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>4.54</strong></td>
</tr>
</tbody>
</table>
# Wrap Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Percentage</th>
<th>Cost ($B04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Development</td>
<td>0.035</td>
<td>0.412</td>
</tr>
<tr>
<td>Phase A Conceptual Studies</td>
<td>0.0003</td>
<td>0.0353</td>
</tr>
<tr>
<td>Phase B Definition Studies</td>
<td>0.035</td>
<td>0.412</td>
</tr>
<tr>
<td>Program Support</td>
<td>0.15</td>
<td>1.77</td>
</tr>
<tr>
<td>Operations Capability Development</td>
<td>0.15</td>
<td>1.77</td>
</tr>
<tr>
<td>Launch and Landing</td>
<td>0.066</td>
<td>0.777</td>
</tr>
<tr>
<td>Program Management and Integration</td>
<td>0.10</td>
<td>1.18</td>
</tr>
<tr>
<td>Fees</td>
<td>0.10</td>
<td>1.18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.10</strong></td>
<td><strong>7.54</strong></td>
</tr>
</tbody>
</table>
## Cost Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost ($B04)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle production</td>
<td>9.67</td>
</tr>
<tr>
<td>Launch structure production</td>
<td>1.91</td>
</tr>
<tr>
<td>Satellite production</td>
<td>0.182</td>
</tr>
<tr>
<td>Launches</td>
<td>4.53</td>
</tr>
<tr>
<td>Wrap factors</td>
<td>7.52</td>
</tr>
<tr>
<td><strong>Total System Cost</strong></td>
<td><strong>23.8</strong></td>
</tr>
</tbody>
</table>

Allowable reserve factor: 0.537

Total budget with 0.4 reserve factor: $39.7 Billion
Cost Summary

Cost-Budget Comparison

Year/Phase


Dollars ($M2004)
Summary

- Designed to fulfill the goals of the President’s new space initiative
- Stepping stone for an Earth to Mars mission
- Design utilizes existing launch vehicle technologies
- Design has great advantages over a large-scale stationary lunar base
- Inexpensive program
Open Items

There are a few subsystems that either have yet to be determined or need the completion of detailed analysis, these systems are:

- Radiator for the power module
- Extension for docking mechanism
- Specific computing requirements
- Interior lighting layout
- Steering and suspension mechanism
- Lunar rover storage
Acknowledgments

• Our advisors, Dr. Dave Akin and Dr. Mary Bowden, for their help and support

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• Dr. Fourney and the University of Maryland’s Aerospace Engineering Department