Waste, Nutrition, and Bioregeneration

- Details of waste collection and remediation
- Current food systems
- Future food requirements
- Bioregenerative life support
Waste Management Compartment
Shuttle Toilet Training
ISS Waste and Hygiene Compartment
ISS Waste and Hygiene Compartment
ISS Toilet Operations
ISS Waste Collection System

- Compactor
- Thigh Bar
- Yoke Assembly
- Foot Restraint
- Seat
- Urinal Hose
- Urine Diverter Valve
- Fecal Canister
Fluidized Bed Incinerator Combustor
Commode and Vacuum Subassy
Urinal Subassembly Schematic
Toilet Consumables, Packaged and Not

Fecal Canister
Dry Wipes
Toilet Tissue

20 Defecations Worth Of Waste Consumables
Wet wipes
Gloves
Solid Waste Management - Functions

- Volume Reduction – Recovers habitable volume and reduces ESM. Achieved by compaction, particle size reduction, and/or mineralization.
- Drying/Water Recovery – Water recovery increases system closure, reduces ESM and provides stabilization/safening.
- Clothes Washing/Recovery – Enables reuse rather than disposal of clothing and decreases ESM for extended missions.
- Mineralization - Transformation of waste to its elemental components – provides significantly increased stabilization/safening and volume reduction and can increase system closure via resource recovery. Reduces ESM.
- Containment – Controls risk of crew/planetary contact with wastes and by-products. Achieved by containers, procedures, or isolation. Satisfies planetary protection protocols.
- Disposal – Decreases internal mass (propulsion costs) and volume by transfer to interplanetary space or planetary surface. Container ejection must avoid negative impacts with the spacecraft in space or harmful effect on a planetary surface.
- Particle Size Reduction – Numerous waste processing technologies require size reduction of particles to facilitate efficient operation. Feedstock size requirements are technology specific.
- Resource Recovery – Key requirement for life support systems approaching self-sufficiency. Resources recovered include water, clothes, CO₂, other materials and plant nutrients. Technology attributes depend on the resource to be recovered. Reduces ESM.

from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
Solid Waste Management Technologies

Technologies for Each Function

- Volume Reduction – Plastic heat melt compactor (ratio of 10 to 1 reduction), particle size reduction, and/or mineralization technologies.
- Clothes Washing – Micro/hypo gravity washer that minimizes water and soap usage.
- Mineralization – Incineration, hydrothermal oxidation, pyrolysis, composting (biological)
- Containment – Long duration (>200 years) containment systems (containers, procedures, or isolation).
- Disposal – Proper systems to facilitate disposal in interplanetary space and on planetary surfaces.
- Particle Size Reduction – Grinding, cutting and shredding technologies that function in micro/hypo-gravity.
- Resource Recovery – Drying systems, pyrolytic systems, oxidation systems, clothes washing systems.

from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
Solid Waste Management

### Potential ESM Savings via Enhanced Waste Management Operations

**Current ISS vs. ALS Technologies for a Mars Exploration Mission (600 days)**

<table>
<thead>
<tr>
<th>Item</th>
<th>ISS ESM</th>
<th>ALS ESM</th>
<th>Delta</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste (clothing, feces, food packaging, scraps, etc.)</td>
<td>3,933</td>
<td>1,000</td>
<td>2,933</td>
<td>assume containers for ISS - processor for ALS</td>
</tr>
<tr>
<td>Safener - e.g. container vs. mineralizer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Disposal on Mars surface</td>
<td>5,899</td>
<td>1,000</td>
<td>4,899</td>
<td>savings on return propulsion</td>
</tr>
<tr>
<td>Water in feces and waste</td>
<td>2,000</td>
<td>500</td>
<td>1,500</td>
<td>water saving vs. cost</td>
</tr>
<tr>
<td>Clothing</td>
<td>6,780</td>
<td>1,200</td>
<td>5,579</td>
<td>clothes washer</td>
</tr>
<tr>
<td>Compaction</td>
<td>3,000</td>
<td>1,000</td>
<td>2,000</td>
<td>assume crewed vol=200 kg/m^3, ISS is 1/2 compact by handed</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>17,679</td>
<td>3,700</td>
<td>13,978</td>
<td></td>
</tr>
</tbody>
</table>

From Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
## ISS Consumables Budget

<table>
<thead>
<tr>
<th>Consumable</th>
<th>Design Load (kg/person-day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.85</td>
</tr>
<tr>
<td>Water (drinking)</td>
<td>1.6</td>
</tr>
<tr>
<td>Water (in food)</td>
<td>1.15</td>
</tr>
<tr>
<td>Water (clothes and dishes)</td>
<td>17.9</td>
</tr>
<tr>
<td>Water (sanitary)</td>
<td>7.3</td>
</tr>
<tr>
<td>Water (food prep)</td>
<td>0.75</td>
</tr>
<tr>
<td>Food solids</td>
<td>0.62</td>
</tr>
</tbody>
</table>
ISS Food Preparation
Top 10 Favorite Space Foods (Discovery TV)

- Japanese Takeout
- Swedish Meatballs (Rachael Ray)
- Yogurt
- Chicken Soup
- Tortillas
- Shrimp Cocktail
- Hot Sauce
- M&Ms
- Dried produce
- “Appetizing Appetizer”
Top 10 Least Favorite Space Foods

- Freeze-Dried Ice Cream
- Graham Crackers
- Chips
- Sliced Bread
- Tube and Cubed Foods
- Pizza
- Cheesecake
- Carbonated Soda
- Fish Vera Cruz
- Brussel Sprouts
Food Management System

- Food Management System Tasks and Functions
  - Provide Stored Food System with a 3 – 5 year shelf life at ambient temperatures
    - Food Packaging
    - Food Preservation
    - Stored Food Stowage
  - Processed Food System Development
    - Crop and Stored Commodities Stowage
    - Process Crops and Stored Commodities
    - Processed Ingredient Stowage
  - Menu Development – food preparation in the galley using stored food system and processed foods
    - Food Preparation
    - Meets Nutritional Needs of Crew
    - Food Stowage

- Why necessary
  - The development of an advanced food system will enable support of humans beyond Low Earth Orbit (LEO).
  - Food must be safe, nutritious and acceptable to maintain crew health and well being throughout the entire mission
    - Food has a psychosocial element in addition to the nutrition
    - Crew performance and well-being dependent on a high quality food system
  - Food processing will provide the crew with a variety of fresh and nutritious foods

from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
Stored Food System Overview

Stored Food System

Justification/Rationale
- Stored food system needed for transit mission and early lunar/planetary missions
- Stored food system will supplement planetary processed food system
- Improved barrier packaging will provide required shelf life
- Emerging preservation technologies will provide improved nutrition and acceptability

3 - 5 year shelf life
- Safe
- Nutritious
- Acceptable
- Minimize mass

Food packaging materials
- Low mass
- High barrier
- Easily processed as waste

Preservation technologies
- Safe
- Nutritious
- Acceptable

Food stowage
- Environmental conditions to maximize shelf life
- Inventory control to easily locate food items

Competing Technologies:
- None

Complementary Technologies:
- Current packaging materials used in retorted products

GAPS:
- High barrier, non-metallized packaging materials
- Biodegradable and reusable packaging materials

Emerging thermal and non-thermal technologies
- Product development of ~175 items
- Confirm shelf life including effect of radiation

GAPS:
- Inventory management
- Storage conditions for non-retorted items

from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
Processed Food System Overview

Justification/Rationale
- Processed food system will augment stored food system by increasing variety and acceptability and improving nutrition
- Food processing will provide food system closure and increase self sufficiency
- Food processing will decrease amount of stored food necessary for a mission

Competing Technologies:
- None

Competing Technologies:
- None

Competing Technologies:
- None

GAPS:
- Determine products to produce from crops
- Determine crop “gold standard” for each crop
- Storage conditions for bulk ingredients and harvested crops

GAPS:
- Development of ~30 pieces of equipment to TRL 6
- Determine effects of reduced G and atmospheric pressure on processing

GAPS:
- Processing procedures (HACCP) using prototype equipment
- Clean-up procedures for each process (HACCP)

from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
Meal Preparation Overview

from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004
**Food Management Challenges**

- **What is the current state of the art?**
  - NASA
  - The current ISS food system is not adequate for mission longer than one year. The Food Management System approach includes a stored food system with increased shelf life, variety and acceptability, and processing systems that process raw food commodities into edible ingredients.
    - Food preservation
      - On Shuttle and ISS, the food system has a shelf life of 12 months for the freeze dried and natural form foods.
      - Thermostabilized and irradiated foods have a shelf life of 3 years
    - Food packaging
      - MRE pouch used for thermostabilized and irradiated foods has a high barrier to water and oxygen due to the aluminum layer (foil). However, it is dense and hard to process by solid waste processing team.
      - Poly material used for freeze dried foods and natural form foods has poor barrier materials and is overwrapped with a foil pouch for ISS
  - Food industry
    - The food industry does not require a 3 – 5 year shelf life
    - The focus of the food industry on barrier properties is less on barrier needs and more on packaging material clarity.
    - Miniaturized and multifunctional food processing equipment is not readily available

*from Barty, “NASA ESTSI Technical Interchange Meeting” December 2004*
Lunar-Mars Life Support Test Project

Phase I: 15-day, 1-Person Test
March 1995

Phase II: 30-day, 4-Person Test - June 1996
Phase IIA ISS: 60-day, 4-Person Test - January 1997
Phase III: 90-day, 4-Person Test - September 19, 1997

ARO Workshop on Base Camp Sustainability, September 2007
## Life Support Recycling and Closure

<table>
<thead>
<tr>
<th>Recovery, Resources Available</th>
<th>91-Day LMLSTP Phase 3 Test</th>
<th>ISS (complete)</th>
<th>Mars Technology Projections</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Revitalization Systems</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Recovery from CO₂</td>
<td>56%</td>
<td>0% (≤99%?)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>≥ 97%&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>% Closure</td>
<td>~100%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>~100%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>~100%</td>
</tr>
<tr>
<td><strong>Water Recovery Systems</strong></td>
<td>Note: No EVA</td>
<td>93%&lt;sup&gt;d&lt;/sup&gt;</td>
<td>93 - ~100%&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>% Recovery</td>
<td>~100%</td>
<td>63%&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>% Closure</td>
<td>~100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solid Waste Management</strong></td>
<td></td>
<td>0%</td>
<td>90 to ~100%&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>% Recovery (H₂O)</td>
<td>92%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Volume Reduction&lt;sup&gt;h&lt;/sup&gt;</td>
<td>100:1&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0%</td>
<td>10:1 to 100:1</td>
</tr>
<tr>
<td>Waste Stabilization</td>
<td>Yes&lt;sup&gt;g&lt;/sup&gt;</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Clothing Laundry</td>
<td>Yes&lt;sup&gt;g&lt;/sup&gt;</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

<sup>a</sup> Recycled wastewater was/will be electrolyzed; thus O₂ is not re-supplied (hit to water closure, but some made up with water in stored food).

<sup>b</sup> Up to 69% if a Sabatier reactor is implemented to perform CO₂ reduction: \( \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} + \text{CO}_2 + \text{H}_2 \)

<sup>c</sup> Complete CO₂ reduction to C and O₂ (assumes technology addition beyond Sabatier; e.g., Bosch reactor).

<sup>d</sup> RISS Regenerative ECLSS

<sup>e</sup> Add brine recovery to water or via solid waste system to recover additional water

<sup>f</sup> Water Recovery

<sup>g</sup> Only feces were incinerated, producing additional water

<sup>h</sup> Reduced beyond hand compaction

---


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LMLSTP Phase II Water Recovery

<table>
<thead>
<tr>
<th>Water Requirement (kg/person/day)</th>
<th>kg</th>
<th>Wastes Generated (kg/person/day)</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower water</td>
<td>6.36</td>
<td>Waste shower water</td>
<td>5.93</td>
</tr>
<tr>
<td>Hand wash</td>
<td>3.64</td>
<td>Waste hand wash</td>
<td>3.53</td>
</tr>
<tr>
<td>Clothes wash</td>
<td>12.50</td>
<td>Waste clothes wash</td>
<td>11.91</td>
</tr>
<tr>
<td>Urine flush</td>
<td>0.50</td>
<td>Urine flush</td>
<td>0.50</td>
</tr>
<tr>
<td>Food preparation water</td>
<td>0.68</td>
<td>Feces (solid)</td>
<td>0.03</td>
</tr>
<tr>
<td>Drinking water</td>
<td>1.77</td>
<td>Fecal water</td>
<td>0.09</td>
</tr>
<tr>
<td>Oral hygiene water</td>
<td>0.36</td>
<td>Sweat solids</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Urine</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Urine solids</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waste oral hygiene</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Condensate</td>
<td>3.01</td>
</tr>
<tr>
<td>Totals, per person</td>
<td><strong>25.81</strong></td>
<td>Totals, per person</td>
<td><strong>27.35</strong></td>
</tr>
<tr>
<td>Totals, crew of four</td>
<td><strong>103.24</strong></td>
<td>Totals, crew of four</td>
<td><strong>109.40</strong></td>
</tr>
</tbody>
</table>

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### LMLSTP Phase II Water Results

#### Subsystem Performance Over the 30-day test:

- **Urine Treatment Subsystem: Vapor Compression Distillation (VCD)**
  - Mass of urine and flush water processed: 182 kg
  - Mass of processed water produced: 179 kg
  - Water recovery rate for the subsystem: 98.5%

- **Primary Treatment Subsystem: Ultra Filtration/Reverse Osmosis (UF/RO)**
  - Mass of water processed: 3,090 kg
  - Mass of purified water produced: 2,957 kg
  - Water recovery rate for the subsystem: 95%

*Brines generated by both VCD and UF/RO over the 30 day test totaled ≈136 kg.*

- **Expected Quantities based on Nominal Human Requirements**
  - Urine and flush water (4 crew * 30 d * 2.47 kg) = 296 kg
  - Wastewater (4 crew * 30 d * 24.88 kg) = 2986 kg

---


ARO Workshop on Base Camp Sustainability, September 2007
LMLSTP Phase III Overview

- 4 crew members for 91 days
- Demonstrated an integration of advanced regenerative biological and physicochemical (P/C) technologies for life support.
- Two chamber facilities were interconnected
- **Air revitalization System**
  - Higher plants compliment P/C systems
- **Water Recovery System**
  - Microbial cell bioreactors were used for the primary treatment step
- **Food System**
  - The stored food system was supplemented with wheat grain for bread and fresh lettuce grown in situ
- **Waste Management System** (Demonstrations)
  - Inclination of human feces
  - Biodegradation of plant inedible materials

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LMLSTP Phase III Waste Management

Biological Degradation of Inedible Biomass and Recovery of Nutrient Salts

- ½ of the wheat’s inedible biomass was mineralized using a stirred tank aerobic bioreactor.
- Recovered nutrient salts were returned to the plant growth systems.
- Wheat grown using recovered nutrient salts showed no difference in productivity compared to controls.
- Average degradation of total solids: 45% (≈ 26 kg biomass was treated)
- Average salt recovery: 80%.

Incineration of Human Feces and Recovery of Carbon Dioxide

- Human feces (8.2 kg total) were incinerated in a fluidized bed incinerator.
- Carbon dioxide exhaust was injected into the wheat chamber after treatment for trace contaminants.

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LMLSTP Lessons Learned

- The Lunar Mars Life Support Test series successfully demonstrated integration and operation of advanced technologies for closed-loop life support systems, including physicochemical and biological subsystems.
- Increased closure was obtained when targeted technologies, such as brine dewatering subsystems, were added to further process life support system byproducts to recover resources.
- Physicochemical and biological systems can be integrated satisfactorily to achieve desired levels of closure.
- Imbalances between system components, such as differences in metabolic quotients between human crews and plants, must be addressed.
- Each subsystem or component that is added to increase closure will likely have added costs, ranging from initial launch mass, power, thermal, crew time, byproducts, etc., that must be factored into break even analysis.
- Achieving life support system closure while maintaining control of total mass and system complexity will be a challenge.

ARO Workshop on Base Camp Sustainability, September 2007
An Independent Assessment of the Technical Feasibility of the Mars One Mission Plan

Updated Analysis

Sydney Do, Koki Ho, Samuel Schreiner, Andrew Owens, Olivier de Weck
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology


FISO Telecon 02-11-15
Objective Space: Mission Endurance vs Crew Size

- State of the Art
  - Early Space Stations
    - Salyut
    - Mir
    - Skylab
  - ISS
  - NASA DRA5
  - South Pole Station
  - USS Parche Submarine
  - Aquarius Underwater Lab
  - STS
  - Early Crewed Vehicles
    - Gemini
    - Apollo
    - Vostok
    - Mercury
    - Voskhod

- Self Sustained Presence
  - Stanford Torus [10,000 people “indefinitely”]
  - Mars Settlement

- Space Missions
- Terrestrial Missions
### Classes of Space Habitation Mission Modes

<table>
<thead>
<tr>
<th>Fixed Crew</th>
<th>Increasing Crew</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No EVA</strong></td>
<td><strong>Terrarium Mode</strong></td>
</tr>
<tr>
<td><img src="image1.png" alt="Crew in a Can" /> (Inspiration Mars)</td>
<td><img src="image2.png" alt="Terrarium Mode" /> (Stanford Torus ie. Space Hotel)</td>
</tr>
<tr>
<td><strong>Exploration Mode</strong></td>
<td><strong>Colonization Mode</strong></td>
</tr>
<tr>
<td><img src="image3.png" alt="Exploration Mode" /> (Mars DRA 5.0, CxP Lunar Outpost)</td>
<td><img src="image4.png" alt="Colonization Mode" /> (Mars One)</td>
</tr>
</tbody>
</table>

---

*MIT Massachusetts Institute of Technology*

---

*4*
Timeline for Mars Studies

1950
- The Mars Project, W. von Braun
- Can we Get to Mars? W. von Braun
- The Exploration of Mars W. Ley & W. von Braun
- Conceptual Design for a Manned Mars Vehicle, P. Bono
- Capability of the Saturn V To Support Planetary Exploration, G.R. Woodcock

1960
- Study of Manned Nuclear-Rocket Missions To Mars, S. Himmel, et al
- Electromagnetic Launching As a Major Contribution to Spaceflight, A. C. Clarke
- Collier’s W. von Braun

1970
- Study of Conjunction Class Manned Mars Trips Douglas Missile & Space
- Manned Mars Exploration, NASA
- Study of NERVA-Electric Manned Mars, E. Stuhlinger, et al
- EMPIRE, Study of Early Manned Interplanetary Missions, Ford Aeronautics
- A Study of Early Interplanetary Missions, General Dynamics

1980
- America at the Threshold SEI Synthesis Group
- The Mars Transit System, B. Aldrin
- Exploration Tech Studies, Office of Explor., NASA
- Report on the 90-Day Study on Human Exploration, NASA
- The Viking Results-The Case for Man on Mars, R. Clark
- A Case for Mars: Concept Devlpnt for Mars Research

1990
- ExPC Mars Program Study, NASA
- The Moon as a Way station for Planetary Exploration, M. Duke
- Combination Lander All-Up Mission, NASA
- Three Magnum Split Mission, NASA

2000
- Dual Landers Presentation NASA (B. Drake)
- (2) Design Reference Mission 4.0, Bimodal and SEP, NASA
- Design Reference Mission 3.0, NASA
- Design Reference Mission 1.0, NASA
- The Li Transportation Node, N. Lemke
- Mars Direct: A Simple, Robust..., R. Zubrin

**Bold type represents selected studies

**A Comparison of Transportation Systems for Human Missions to Mars, AIAA 2004-3834

Mars One Mission Overview

Summary:
Gradual colonization of Mars via successive four-person, one-way missions to Mars starting in 2024

Mission Design Philosophy:
1. Permanent settlement
2. Maximize ISRU
3. All power from solar
4. Exploit currently available technology
5. International mission

Claim:
“No new major developments or inventions are needed to make the mission plan a reality. Each stage of Mars One mission plan employs existing, validated and available technology.”
Habitation Module
- Functional ECLS model based on NASA JSC BioSim
- Captures resource interaction between EVA, ECLS, and Biomass Production
- Plant model based on NASA Modified Energy Cascade Models

ISRU Module
- Sizing models for:
  - Soil processor oven (H$_2$O extraction)
  - Atmosphere processor (N$_2$ extraction)
- Based on conceptual ISRU designs

Sparing Module
- Models systems as a Semi-Markov Process (SMP) to determine no. of spares to ensure >99% probability of having enough spares to repair all failures over the mission lifetime
- Random failure modeled by exponential distributions based on part MTBF and LL
ISS Life Support Technologies
NASA Bio-PLEX Program

- NASA program initiated ~1988 to develop an integrated biological life support system / habitation testbed
- Three test phases planned: 425 day, 120 day, and 240 day tests
- Program funding cancelled in 2002

For more info, see: SAE 972342, SAE 1999-01-2186
Mars One Baseline: Food is 100% locally grown

Diet Planning:
- Caloric budget: 3040.1 Calories/Crew Member/day
- Target diet: 68% carbs, 12% protein, 20% fat
- Determine growth area via optimization:

\[
\begin{align*}
\min & \quad w_1 \sum_{i=1}^{9} x_i + w_2 \sigma(x) \\
\text{s.t.} & \quad \sum_{i=1}^{9} c_i r_i x_i \geq 2067.2 \quad \text{Meet minimum carb req.} \\
& \quad \sum_{i=1}^{9} p_i r_i x_i \geq 364.8 \quad \text{Meet minimum protein req.} \\
& \quad \sum_{i=1}^{9} f_i r_i x_i \geq 270.2 \quad \text{Meet minimum fat req.} \\
& \quad x_i \geq 0 \quad \text{for } i = 1, \ldots, 9 \quad \text{All areas are positive}
\end{align*}
\]

Selected Crop Growth Areas:

<table>
<thead>
<tr>
<th>Crop</th>
<th>Growth Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Bean</td>
<td>-</td>
</tr>
<tr>
<td>Lettuce</td>
<td>-</td>
</tr>
<tr>
<td>Peanut</td>
<td>72.7</td>
</tr>
<tr>
<td>Rice</td>
<td>-</td>
</tr>
<tr>
<td>Soybean</td>
<td>39.7</td>
</tr>
<tr>
<td>Sweet Potato</td>
<td>9.81</td>
</tr>
<tr>
<td>Tomato</td>
<td>-</td>
</tr>
<tr>
<td>Wheat</td>
<td>72.5</td>
</tr>
<tr>
<td>White Potato</td>
<td>4.99</td>
</tr>
<tr>
<td><strong>Total Growth Area (m²)</strong></td>
<td><strong>199.7</strong></td>
</tr>
</tbody>
</table>

Mars One claim: 50 m² for 12 crew

Calculated requirements:
- ~200 m² of plant shelf area for 4 crew
- 875 LED lighting systems
- 22000 L of nutrient solution
Mars One Baseline

Mars One Baseline with Resized Plant Growth System

Legend
- Technologies
- Stores / Tanks
- Grey Zones

Atmosphere Control and Supply
- PCA: Pressure Control Assembly
- PPRV: Positive Pressure Relief Valve
- IMV: Intermodule Ventilation Fan
- OGA: Oxygen Generation Assembly

Temperature and Humidity Control
- CCAA: Common Cabin Air Assembly (contains Condensing Heat Exchanger and Intermodule Ventilation Fan)

Air Revitalization
- CDRA: Carbon Dioxide Removal Assembly
- ORA: Oxygen Removal Assembly
- CRA: Carbon Dioxide Reduction Assembly

Water Recovery
- UPA: Urine Processor Assembly
- WPA: Water Processor Assembly
- PWD: Potable Water Dispenser

Waste Management
- WHC: Waste and Hygiene Compartment

Inflatable Unit
- Biomass Production System (BPS)
- Crew Quarters
- Wardroom
- Exercise Equipment
- Laboratory

Cargo Unit
- Life Support Unit
- Living Unit
- Airlock
- ILSRU

Food
- Spares
- Waste
Mars One Baseline

Mars One Baseline with Resized Plant Growth System

Legend
- Grey: Technologies
- Grey: Stores / Tanks / Zones

Atmosphere Control and Supply
- PCA: Pressure Control Assembly
- PPRV: Positive Pressure Relief Valve
- IMV: Intermediate Ventilation Fan
- CGA: Oxygen Generation Assembly

Temperature and Humidity Control
- CCAA: Common Cabin Air Assembly (contains Condensing Heat Exchanger and Intramodule Ventilation Fan)

Air Revitalization
- CDRA: Carbon Dioxide Removal Assembly
- CRA: Oxygen Removal Assembly
- CRA: Carbon Dioxide Reduction Assembly

Water Recovery
- UPA: Urine Processor Assembly
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Diagram of Mars One Baseline with Resized Plant Growth System
- Inflatable Unit
- Biomass Production System (BPS)
- Crew Quarters
- Wardroom
- Exercise Equipment
- Laboratory
- Access Aisles
- Nutrient Solution Store
- Lighting Zones
- Shoot Zones
- Root Zones
- Access Aisles
- Nutrient Solution Store
- Cargo Unit
- Life Support Unit
- Living Unit
- Life Support Unit
- Cargo Unit
Simulation Result:
- Crop death occurs at Day 12-19 due to insufficient CO₂.
- With CO₂ injection system incorporated, fire safety threshold exceeded at Day 43, and first crew fatality at Day 45 due to suffocation from too low ppO₂.

Cause:
- Crops produce too much O₂ (rises as crops reach maturity).
- PCA vents gases and introduces N₂ to maintain atmospheric composition.
- This continues until N₂ store is depleted on Day 42.
- Plants continue to produce O₂, raising O₂ molar fraction above fire safety threshold.
- Lack of N₂ causes module leakage to dominate, reducing total pressure, and ppO₂ below hypoxic threshold.

Finding:
- Peak N₂ depletion of 360 moles/day, requires an ISRU system that is 1.1 mT and 5 m³ (>45% and >20% of lander capacity, respectively) → prohibitively large system.
Simulation Case 1 – BPS Case: Oxygen Removal Assembly with BPS

- Place crops in their own plant growth chamber
- Install a "CO₂ Injector" to sustain crops
- Install an "Oxygen Removal Assembly" (ORA) → (Contradicts the "validated technology" claim)
  - Selectively removes excess O₂ from the atmosphere
  - Sends excess O₂ to a high pressure tank via a compressor, for use during EVA

Baseline
Simulation Case 1 – BPS Case: Oxygen Removal Assembly with BPS

- Place crops in their own plant growth chamber
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  - Selectively removes excess O₂ from the atmosphere
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BPS Case
Simulation Case 1

Legend
- Technologies
- Stores / Tanks
- Grey Zones

Atmosphere Control and Supply
PCA: Pressure Control Assembly
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Waste Management
WHC: Waste and Hygiene Compartment

Cargo Unit  Life Support Unit  Living Unit  Life Support Unit  Cargo Unit
Simulation Case 2 – SF Case: Zero Plant Growth / All Carried Food

ISS Baseline – all carried food – no plant growth

Baseline

Legend

Conveyor: Flow

Baseline

Added

Processor

Baseline

Store

Added

Dry

Waste

Stored

Crew

Food

Potable

Water

Dirty

Water

Grey

Water

Food Processing System

Biomass

Biomass Production System

Growth Lighting System
Simulation Case 2 – SF Case: Zero Plant Growth / All Carried Food

ISS Baseline – all carried food – no plant growth

SF Case

Legend

- Baseline Store
- Added Store
- Baseline Processor
- Added Processor

Consumable Flow
- Gas
- Water
- Solid
- Power
- Added Flow
Findings:

- ECLS Spares dominates in later campaigns because spares are needed to sustain the current crew, as well as the total crew and equipment that is already on the surface.
- Crossover point in resupply mass occurs at 6th crew, when resupplied food requirement exceeds ORA, CO₂ injector and LED spares requirements of BPS.
**Observation:** For a fixed probability of having sufficient spares to sustain the mission, doubling MTBF reduces spares requirement by only 2-4% since enough spares need to be provided for all potential failures (random and life limited) – specific failed components are not known a priori.
Launch Demands for First 5 Crews

<table>
<thead>
<tr>
<th>Mission</th>
<th>Predeployment Launch Requirement</th>
<th>Crew 1 Launch Requirement</th>
<th>Crew 2 Launch Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars One Claim</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Case 1 (BPS)</td>
<td>14</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Case 2 (No BPS)</td>
<td>10</td>
<td>18</td>
<td>19</td>
</tr>
</tbody>
</table>
Analysis Summary

Issue 1
- **Mars One:** "In total there will about 50m² available for plant growth... There will be sufficient plant production capacity to feed about three crews of four"
- **Finding:** 50m² is insufficient. 200m²+ of plant growth area is required to feed four people
- **Recommendation/Action:** Implement at least 200m² of plant growth into habitat

Issue 2
- **Mars One Design:** Crops share the same working volume as that of the crew
- **Finding 1:** Excess O₂ production by crops creates a fire hazard which when dealt with using existing ISS technologies, leads to depletion of N₂ stores, leading to crew suffocation
- **Finding 2:** Making up this N₂ depletion with ISRU will result in a prohibitively large system
- **Recommendation/Action:**
  - If plants are grown, grow them in a separate plant growth chamber and include an O₂ removal system (never before developed for flight) to recover O₂ for later use

Issue 3
- **Mars One:** "Each stage of Mars One mission plan employs existing, validated and available technology"
- **Finding 1:** Based on existing resupply logistics practices, the spares requirement will grow over time, thereby increasing the mission cost over time
- **Finding 2:** "There are some fundamental issues that need to be resolved concerning additive manufacturing and its utilization for terrestrial purposes before a space-based application can be derived" [REF: http://www.nap.edu/catalog.php?record_id=18871]
Summary and Conclusions

Additional Findings

- ISRU is an attractive option (spares mass requirement is 8% of consumables mass produced), but TRL is needs to be improved.
- ISRU and ECLS spares requirements increase significantly as a settlement grows – after 260 months on the Martian surface, spares makes up 55% of the resupply mass.
- The Mars One stated launch requirements are overly optimistic:
  - 10-14 Falcon Heavy launches required for predeployment ($3B-$4.2B)
  - 21-24 Falcon Heavy launches required to supply the 3rd crew ($6.3B-$7.2B)

Note:

- This analysis focused only on the impact of habitation, ECLS, and ISRU on spares and space logistics requirements. Several other subsystems such as communications and power need to be included for a complete analysis.

Recommendations

- Focus investment into increasing ECLS reliability and increasing ISRU TRL.
- Work on reducing launch costs.
- Investigate in-situ manufacturing capability to reduce spares resupply requirements.