The Lunar Mars Life Support Test Project

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26 May 2016
Background
NASA’s Large Scale Bioregenerative Life Support Tests

KSC’s Biomass Production Chamber
• Large-scale closed crop testing
• Control system development
• Evaluation of robotic arm (Florida State)
• Wastewater processing by crops
• Trace gas evolution & microbial ecology

JSC’s Large Scale Human-In-The-Loop Testing
• Large-scale crop testing
• Human test subjects
• Closed atmosphere
• Integration of physicochemical and biological technologies
Lunar Mars Life Support Test Project (LMLSTP)

Four tests with human test subjects were performed between 1995 and 1998 at NASA's Johnson Space Center.

<table>
<thead>
<tr>
<th>Test</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase IIA</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>15 days</td>
<td>30 days</td>
<td>60 days</td>
<td>91 days</td>
</tr>
<tr>
<td>Crew</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Types of Systems</td>
<td>Biological (Wheat)</td>
<td>Physicochemical (Advanced)</td>
<td>Physicochemical (ISS Regenerative ECLSS)</td>
<td>Integrated Physicochemical &amp; Biological (Advanced)</td>
</tr>
<tr>
<td>Full Closure</td>
<td>Air</td>
<td>Air &amp; Water</td>
<td>Air &amp; Water</td>
<td>Air &amp; Water</td>
</tr>
<tr>
<td>Partial Closure</td>
<td>Water, Food &amp; Waste</td>
<td>Food &amp; Waste</td>
<td>Food &amp; Waste</td>
<td>Food &amp; Waste</td>
</tr>
<tr>
<td>Open Loop</td>
<td>Water, Food &amp; Waste</td>
<td>Food &amp; Waste</td>
<td>Food &amp; Waste</td>
<td></td>
</tr>
</tbody>
</table>
Lunar Mars Life Support Test Project
Phase I: 15-day, 1-Person Test

Test Facility
- 2.7 m wide by 2.4 m tall atmospherically sealed with 2 compartments – 19.2 m³ (crew cabin) & 27 m³ (growth chamber).
- Growth chamber section outfitted with a hydroponic growing system for wheat.
- Leak rate <2% volume per day
The growth chamber was expected to exceed the carbon dioxide removal capacity and oxygen production requirement for one person during the 15 day period selected for the test (shaded).

Curve derived from Bugbee and Salisbury “Exploring the Limits of Crop Productivity”
Three methods for controlling atmospheric CO₂ and O₂ were demonstrated. Physicochemical (P/C) systems were used to correct for imbalances between crew respiration and crop photosynthesis (PSₙ) was regulated directly.

<table>
<thead>
<tr>
<th>Method of Control</th>
<th>Integrated P/C &amp; Biological</th>
<th>Environmental Regulation of PSₙ</th>
<th>Environmental Regulation of PSₙ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days of Test</td>
<td>1-6</td>
<td>7-12</td>
<td>13-15</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td>Maximum</td>
<td>Limited by Light Intensity</td>
<td>Limited by CO₂ Availability</td>
</tr>
<tr>
<td>Description</td>
<td>P/C Systems Correct Imbalance</td>
<td>Crop CO₂ Assimilation Matched to Crew CO₂ Output Respiration</td>
<td></td>
</tr>
<tr>
<td>Photosynthetic Photon Flux (Light Level)</td>
<td>Fixed Intensity</td>
<td>Intensity Adjusted Continuously to Maintain Cabin [CO₂]</td>
<td>Fixed Intensity</td>
</tr>
<tr>
<td>Supplemental CO₂ Injection</td>
<td>Inject to maintain cabin [CO₂]</td>
<td></td>
<td>Contingency Only</td>
</tr>
<tr>
<td>P/C O₂ Scrubber</td>
<td>Remove O₂ to maintain cabin [O₂]</td>
<td></td>
<td>Contingency Only</td>
</tr>
</tbody>
</table>
Demonstrated three control strategies

1. Full light, CO₂ injected to maintain [CO₂] setpoint
2. Light dimmed to maintain [CO₂] setpoint
3. No automated control; light at intermediate setpoint; CO₂ limited to crew member respiration
Daily removal of atmospheric carbon dioxide by the wheat crop over its life cycle

![Graph showing daily carbon dioxide removal](image)
LMLSTP Phase I Test Results
Oxygen Concentration in the Cabin Atmosphere

- During the first control period, $O_2$ production by the wheat exceeded the crew member’s respiration requirement. Physicochemical (P/C) systems were used to remove excess $O_2$ and maintained concentrations below a critical level.
- During the 2nd and 3rd control periods, net photosynthesis ($PS_n$) was matched to the crew member’s $CO_2$ output and cabin $[O_2]$ slowly fell.
LMLSTP Phase I Test Results
Ethylene Concentration in the Cabin Atmosphere

![Graph showing ethylene concentration over days from seeding with markers for growth chamber and air lock entries.](image)
LMLSTP Phase I Test Results

Evapotranspiration

Evapotranspiration (L m⁻² d⁻¹)

Days from seeding

15-day Human Test

Side A

Side B
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)**
  - Incineration of human feces
  - Biodegradation of plant inedible materials
The 11.2 m² growth chamber was divided into 2 sides, A and B, each with a separate hydroponic system.

- Side A: standard hydroponic nutrient solution formula
- Side B: nutrients derived from inedible biomass

Each side had 4 growing zones. After the chamber was fully planted, wheat was harvested and re-planted in a staged, serial fashion, in increments of ¼ of the planted area, approximately every 20 days.
LMLSTP Phase III:
Predicted atmosphere revitalization with batch cropping

Atmosphere revitalization predicted from CO₂ assimilation from “Apogee” Wheat grown at a PAR level of 1500 µm⁻² s⁻¹ and a 24 hr photoperiod, given that all four quarters of the growth chamber were planted and harvested sequentially at the same time.
Atmosphere revitalization predicted from CO$_2$ assimilation from “Apogee” Wheat grown at a PAR level of 1500 $\mu$m$^{-2}$ s$^{-1}$ and a 24 hr photoperiod.
**LMLSTP Phase III: Waste Management System Demonstrations**

**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.
- 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.
LMLSTP Phase III Results:
Actual Air Revitalization (CO₂ Removal) vs Predicted

![Graph showing actual vs predicted air revitalization over test days.]

### Test Deviations & Anomalies
- To reduce test costs, the last quarter of chamber (A2B4) was not replanted.
- Crop nutrient management was inadequate:
  - the first crops planted took up excessive amounts of K & P.
  - this resulted in nutrient deficiency stress in later crops, with secondary affects on growth, yield and resistance to disease organisms.
  - an opportunistic Fusarium infection was observed in stressed plants.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Actual Planting</th>
<th>Harvesting</th>
<th>Schedule Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4B2</td>
<td>18 78 80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3B1</td>
<td>38 39 82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2B4</td>
<td>58 86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1B3</td>
<td>79 81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LMLSTP Phase III Results:
Wheat Yield

Yield By Staged Crop

<table>
<thead>
<tr>
<th>Date Seeded</th>
<th>7/23/97</th>
<th>7/23/97</th>
<th>7/23/97</th>
<th>8/1/97</th>
<th>8/27/97</th>
<th>10/1/97</th>
<th>10/1/97</th>
<th>10/1/97</th>
<th>10/1/97</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Biomass (kg)</td>
<td>18</td>
<td>38</td>
<td>58</td>
<td>79</td>
<td>78</td>
<td>39</td>
<td>86</td>
<td>82</td>
<td>81</td>
</tr>
</tbody>
</table>

White numbers in bars: Age at harvest

Harvested grain was introduced into the Human Chamber to make bread. Fresh bread was baked every 5 days.

Yield By Nutrient Source

<table>
<thead>
<tr>
<th>Nutrient Source</th>
<th>Mean Grain Yield (kg)</th>
<th>Mean Grain Yield (kg m⁻²)</th>
<th>Harvest Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side A (Pure Salts)</td>
<td>10.48</td>
<td>1.87</td>
<td>36.5</td>
</tr>
<tr>
<td>Side B (Biologically Recovered Salts)</td>
<td>11.4</td>
<td>2.03</td>
<td>38.8</td>
</tr>
<tr>
<td>Total Chamber</td>
<td>21.88</td>
<td>1.95</td>
<td>37.7</td>
</tr>
</tbody>
</table>
LMLSTP Phase III Results: Lettuce Production System

• Lettuce was grown in a small growth chamber located within the crew living space.

• The chamber contained a 0.22 m² growing area illuminated with light emitting diodes (LEDs) providing 189 \( \mu \text{mol s}^{-1} \text{ m}^{-2} \) photosynthetic photon flux.

• Sequentially planted every 11 days, with 8 harvests during the 91 day-test, 4 plants per harvest.

• Average shoot fresh mass per plant was 157 g (5.5 oz) at an average of 31.5 days from seeding.

• Average Harvest Index
  
  69% Amount Consumed/Total
  83% Shoot/Total

• Average daily rate of make-up water use was 3.18 L m\(^{-2}\) d\(^{-1}\) for 64.5 total liters.
Prime Farmland?