DRAFT

Life Support System Technologies for NASA Exploration Missions

Mike Ewert
Deputy Project Manager, Exploration Life Support Project
NASA Johnson Space Center

Army Research Office
Workshop on Base Camp Sustainability
September 12, 2007
Exploration Life Support
The Vision for Space Exploration

- Complete the International Space Station
The Vision for Space Exploration

• Safely fly the Space Shuttle until 2010
The Vision for Space Exploration

Develop and fly the Crew Exploration Vehicle no later than 2014
The Vision for Space Exploration

Return to the Moon no later than 2020
Human Life Support Requirements

Open-Loop Life Support System
Resupply Mass - 12,000 kg/person-year
(26,500 lbs/person-year)

- Water 89%
- Oxygen 2.5%
- Food (dry) 2.2%
  (Hydrated = 7%)
- Crew Supplies 2.1%
- Gases lost to space 2.1%
- Systems Maintenance 2.1%
## Challenge in Space

### Human Life Support Requirements For Exploration Missions

(25 kg/person-day)

<table>
<thead>
<tr>
<th>Consumables</th>
<th>Wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gases</strong></td>
<td><strong>Gases</strong></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>0.84</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td><strong>Water</strong></td>
</tr>
<tr>
<td>Drinking</td>
<td>Urine</td>
</tr>
<tr>
<td>1.62</td>
<td>1.50</td>
</tr>
<tr>
<td>Water content of food</td>
<td>Perspiration/respiration</td>
</tr>
<tr>
<td>1.15</td>
<td>2.28</td>
</tr>
<tr>
<td>Food preparation water</td>
<td>Fecal water</td>
</tr>
<tr>
<td>0.79</td>
<td>0.09</td>
</tr>
<tr>
<td>Shower and hand wash</td>
<td>Shower and hand wash</td>
</tr>
<tr>
<td>6.82</td>
<td>6.51</td>
</tr>
<tr>
<td>Clothes wash</td>
<td>Clothes wash</td>
</tr>
<tr>
<td>12.50</td>
<td>11.90</td>
</tr>
<tr>
<td>Urine flush</td>
<td>Urine flush</td>
</tr>
<tr>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Solids</strong></td>
<td><strong>Solids</strong></td>
</tr>
<tr>
<td>Food</td>
<td>Urine</td>
</tr>
<tr>
<td>0.62</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>Feces</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Perspiration</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Shower &amp; hand wash</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Clothes wash</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
</tr>
</tbody>
</table>
Loop Closure

- Desirable loop closure would minimize the supplied $O_2$ and $H_2O$ as well as recovery of resources from solid waste
- The solution is sensitive to
  - $O_2$ and $H_2O$ resources consumed (not recovered) by EVA (large driver)
  - Moisture content in delivered food
  - Recycling technologies in terms of % recovery
Exploration Life Support – Recycling & Closure

<table>
<thead>
<tr>
<th>Recovery = mass recycled/ 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>Closure = mass recycled &amp; used/ total resources needed</td>
<td></td>
<td></td>
<td></td>
</tr>
<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% (≤69%?) (^b)</td>
<td>≥ 97% (^c)</td>
</tr>
<tr>
<td>% Closure</td>
<td>~ 100% (^a)</td>
<td>~ 100% (^a)</td>
<td>~ 100%</td>
</tr>
<tr>
<td><strong>Water Recovery Systems</strong></td>
<td>Note: No EVA</td>
<td></td>
<td>93 - ~ 100% (^e)</td>
</tr>
<tr>
<td>% Recovery</td>
<td>~ 100%</td>
<td>93% (^d)</td>
<td></td>
</tr>
<tr>
<td>% Closure</td>
<td>~ 100%</td>
<td>63% (^a)</td>
<td></td>
</tr>
<tr>
<td><strong>Solid Waste Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Recovery (H₂O)</td>
<td>92% (^g)</td>
<td>0 %</td>
<td>90 to ~ 100 % (^f)</td>
</tr>
<tr>
<td>Volume Reduction (^h)</td>
<td>100:1 (^g)</td>
<td>0 %</td>
<td>10:1 to 100:1</td>
</tr>
<tr>
<td>Waste Stabilization</td>
<td>Yes (^g)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Clothing Laundry</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^a\) 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)

\(^b\) Up to 69% if a Sabatier reactor is implemented to perform CO₂ reduction

\[^{CO_2 + 4H_2 \rightarrow CH_4 + 2 H_2O + CO_2 \uparrow + H_2 \uparrow} \]

\(^c\) Complete CO₂ reduction to C and O₂ (assumes technology addition beyond Sabatier; e.g., Bosch reactor)

\(^d\) RISS Regenerative ECLSS

\(^e\) Add brine recovery to water or via solid waste system to recover additional water

\(^f\) Water Recovery

\(^g\) Only feces were incinerated, producing additional water

\(^h\) Reduced beyond hand compaction

8 May 2007; DHenninger/281-483-5034
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
# LMLSTP Phase II: Water Recovery System Requirements

<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>25.81</td>
<td>Totals, per person</td>
<td>27.35</td>
</tr>
<tr>
<td>Totals, crew of four</td>
<td>103.24</td>
<td>Totals, crew of four</td>
<td>109.40</td>
</tr>
</tbody>
</table>
**LMLSTP Phase II: Water Recovery System**

### Urine Treatment Subsystem
- Vapor Compression Distillation (VCD)

### Primary Treatment Subsystem
- Ultra Filtration/Reverse Osmosis (UF/RO)

### Post Processing Subsystem
- Volatile Removal Assembly (VRA)
- Ion Exchange & Activated Carbon Iodination

- Urine & Flush
- Chemicals

- Hygiene Water (Sink & Shower)
- Laundry
- Condensate

- Poitable Water Tanks

- Storage Tanks

- Brine Tank
LMLSTP Phase II Test Results: Water Recovery System Performance

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
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
## LMLSTP Phase III: Water Recovery System Requirements

<table>
<thead>
<tr>
<th>Water Use/Waste Water Source</th>
<th>Water Allotment (kg/crew of 4/day)</th>
<th>Waste Water Generation (kg/crew of 4/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laundry</td>
<td>50.00</td>
<td>47.64</td>
</tr>
<tr>
<td>Shower</td>
<td>25.44</td>
<td>23.72</td>
</tr>
<tr>
<td>Hand Wash</td>
<td>14.56</td>
<td>14.12</td>
</tr>
<tr>
<td>Oral Hygiene</td>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>Drinking</td>
<td>7.08</td>
<td>0.00</td>
</tr>
<tr>
<td>Food Preparation</td>
<td>2.72</td>
<td>0.00</td>
</tr>
<tr>
<td>Dish Washing</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Urine Flush</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Urine</td>
<td>0.00</td>
<td>7.64</td>
</tr>
<tr>
<td>Condensate</td>
<td>0.00</td>
<td>12.04</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>105.24</strong></td>
<td><strong>110.6</strong></td>
</tr>
</tbody>
</table>
LMLSTP Phase III: Water Recovery System

**Primary Treatment**
- Immobilized Cell Bioreactor (ICB)
- Trickling Filter Bioreactor (TFB)

**Secondary Treatment**
- Reverse Osmosis (RO)
- Air Evaporation Subsystem (AES)

**Post Processing**
- Ammonium Removal Subsystem
- Aqueous Phase Catalytic Oxidation (APCOS)
- Ultraviolet/Ion Exchange (UV/IC)
- Cold Sterilization (0.2 µm)
- Microbial Check Valve - Iodination (MCV)

- A total of 8797 liters of potable water was produced by the system (96.7 L/day)
- The starting volume of 878 L was cycled through the system 10 times
- With the inclusion of the AES, recovery of water was essentially 100%
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
Summary & 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.
Sustainability Assessment

- Resource Utilization
- Environmental Quality

Technologies

Applications

Benefits To JSC
Formation of the Sustainability Partnership at JSC

- Partnership established in 2004 between Engineering and Center Operations
  - “NASA...promotes technological advances that can result in spin-off technologies“
  - “NASA policy directives compel JSC to take action to reduce environmental impact”
  - “The purpose of the Sustainability Partnership is to bring forward, coordinate and advertise innovative sustainability ideas and projects and to share the responsibility for environmental sustainability at JSC.”
“We leave as we came, and God willing, as we shall return, with peace and hope for all mankind.”
— Eugene Cernan, Commander of the last Apollo mission

“As for the future, your task is not to foresee it, but to enable it.”
Antoine de-Saint-Exupery
Backup Information
NASA’s Response

• Administrator O’Keefe has endorsed an Environmental Management System (EMS) at NASA and committed us to Sustainability principles

• Federal Executive Orders Require:
  – Solid waste reduction of 35% between 1997 and 2010
  – Energy reductions of 20-35% between 1990 and 2010
  – Installation of solar energy systems
  – Greenhouse gas reduction of 30% between 1990 and 2010
  – Reduction of toxic chemicals by 40%
  – Phase out of ozone depleting substances
    Petroleum reduction of 20% between 1999 and 2005
Systems Engineering & Analysis Approach

- Ex. If energy saving lights and computers are used in a new building, the cooling system can be reduced, thus reducing the building volume, which saves more cooling and power.

- Devised 15 Environmental Sustainability Indicators for JSC:
  - **Air Pollution**: $SO_2$, $NO_x$, Particulates, Carbon, Ozone depleting substances
  - **Energy**: Electricity, Natural gas, Diesel, BTU/GSF, Non-renewable energy 

- Ex. If a refrigerant additive can save JSC 3 million kWh/yr in energy, it also reduces:
  - $SO_2$ by 4,900 kg/yr
  - $NO_x$ by 3,400 kg/yr
Future Technologies Considered

• Air
  – Advanced air monitors

• Agriculture & Food
  • Crop based foods requiring little energy

• Energy
  – Higher efficiency motors
  – Clean coal & carbon sequestration
  – Nuclear fusion
  – Solar (inc. lunar PV power)
  – Bio-fuels
  – Various energy storage options

• Fuel Cells
  – PEM
  – Regenerative
  – Fuel cell landscape cart & mower

• Sustainable Habitats
  – LED lighting

• Thermal Control
  – Micro-electromechanical systems (MEMS) cooling devices
  – Better refrigerants
  – High efficiency centrifugal chiller
  – Desiccant cooling systems
  – Solar powered refrigeration
  – Vacuum insulation
  – Refrigerator efficiency improvements

• Transportation
  – Fuel cell vehicles
  – Hypercar
  – Aerial vehicles

• Waste
  – Composting
  – Super-critical water oxidation
  – Disposable cup/utensil alternatives

• Water
  – Reuse for irrigation

Note: Those in blue were analyzed quantitatively
Recommendation: R&D Investment in

- Energy Efficient Habitability
  - Motors, computers, cooling, lighting, food preparation and storage, “green building”
- Waste Reduction/Reuse
- Water Purification/Reuse
- Renewable Energy Technologies
  - Solar
  - Regenerative fuel cells
- Electric vehicles
  - Fuel cell & solar powered

➢ We must move these from laboratory to daily life
Recommendation: Integrate Sustainability in Workplace

- Renewable Energy
  - Ex. Solar @ Mars field test site
- Energy Efficiency
  - Efficient air-conditioning
  - LED Stoplights
  - High reflectivity roofs
- Sustainable Buildings
- Alternative Fuel Vehicles
- Fuel Cell Cart for Landscaping

➢ Commercial & Experimental
Sustainability On Site (cont.)

• Sustainable Buildings
  – Astronaut Quarantine Facility was JSC’s first LEED Certification ("Green Building")
  – Several more are in development!
  – A Lawrence Berkeley study estimates “direct increase in office workers’ performance … between 0.5 and 5%.”

• Alternative Fuel Vehicles
  – JSC has several new electric carts
  – Would like to use compressed natural gas in existing vehicles
  – Brought fuel ethanol (E85) to JSC
Education & Outreach

• Trying to increase Employee Awareness of Environmental Sustainability Issues
  – Environmental Management System (EMS)
  – Learn from NASA’s Earth Science Enterprise
  – Began a Natural Step training class

• Promote Community Awareness
  – Display at public events
  – Form partnerships (e.g. City)
  – Education outreach
THERMAL CONTROL

WATER

AIR

SOLID WASTE MANAGEMENT
(RESOURCE RECOVERY)

RESEARCH AND TECHNOLOGY DEVELOPMENT

CROP PRODUCTION

FOOD PROCESSING
Lunar-Mars Life Support Test Project
Phase III 91-Day Test
September - December 1997

Biological Water Recovery System
Carbon Dioxide Reduction System
Carbon Dioxide Removal System
Oxygen Generation System
Trace Contaminant Control System
Solid Waste Incinerator
Phase III Crew (left to right, Nigel Packham, Laura Supra, John Lewis, Vickie Kloeris)

VPGC Wheat Harvest
Control Room