NASA’s Contributions to Controlled Environment Agriculture

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EVOLVABLE MARS CAMPAIGN
A Pioneering Approach to Exploration

EARTH RELIANT
- International Space Station
- Orion Crewed Spacecraft
- Asteroid Redirect Vehicle
- Space Launch System 70 mt
- Space Launch System 130 mt
- Commercial Cargo & Crew

PROVEN GROUND
- ROBOTIC LUNAR SURFACE
- Global Exploration Roadmap
- Initial Transit Habitation
- SEP Cube
- DISTANT RETROGRADE LUNAR ORBIT

EARTH INDEPENDENT
- MARS SURFACE
- Mars Cargo Pre-Deployment
- PHOBOS
- DEIMOS
- MAVEN

THE TRADE SPACE
Across the Board
- Solar Electric Propulsion
- In-Situ Resource Utilization (ISRU)
- Robotic Precursors
- Human/Robotic Interactions
- Partnership Coordination
- Exploration and Science Activities

Cislunar Trades
- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades
- Split versus monolithic habitat
- Cargo pre-deployment
- Mars vicinity activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses
### Human Life Support Requirements:

#### Inputs

<table>
<thead>
<tr>
<th>Daily Rqmt.</th>
<th>(% total mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.83 kg 2.7%</td>
</tr>
<tr>
<td>Food</td>
<td>0.62 kg 2.0%</td>
</tr>
<tr>
<td>Water</td>
<td>3.56 kg 11.4%</td>
</tr>
<tr>
<td>(drink and food prep.)</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>26.0 kg 83.9%</td>
</tr>
<tr>
<td>(hygiene, flush laundry, dishes)</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL 31.0 kg**

#### Outputs

<table>
<thead>
<tr>
<th>Daily Rqmt.</th>
<th>(% total mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1.00 kg 3.2%</td>
</tr>
<tr>
<td>Metabolic solids</td>
<td>0.11 kg 0.35%</td>
</tr>
<tr>
<td>Water</td>
<td>29.95 kg 96.5%</td>
</tr>
<tr>
<td>(metabolic / urine 12.3%)</td>
<td></td>
</tr>
<tr>
<td>(hygiene / flush 24.7%)</td>
<td></td>
</tr>
<tr>
<td>(laundry / dish 55.7%)</td>
<td></td>
</tr>
<tr>
<td>(latent 3.6%)</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL 31.0 kg**

Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document

Food assumed to be dry except for chemically-bound water.
Plants for Life Support!

**HUMANS**

Food

$(\text{CH}_2\text{O}) + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$

Clean Water → Waste Water

Metabolic Energy

**PLANTS**

Food

$(\text{CH}_2\text{O}) + \text{O}_2 + \text{H}_2\text{O} \leftarrow \text{CO}_2 + 2\text{H}_2\text{O}^*$

Clean Water ← Waste Water

Light
**NASA’s Bioregenerative Life Support Testing**

<table>
<thead>
<tr>
<th>Year</th>
<th>Program</th>
<th>Universities</th>
<th>Ames</th>
<th>Kennedy</th>
<th>Johnson</th>
<th>Small Companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>CELSS Program</td>
<td>Wheat (Utah State)</td>
<td>Algae</td>
<td>Large, Closed System</td>
<td>Solid Media</td>
<td>SBIRs—Sensors, LEDs, Zeolite, BPS, VEGGIE, Aeroponics, Solar Conc., HELIAC</td>
</tr>
<tr>
<td>1990</td>
<td>ALS / ELS Program</td>
<td>Gas Ex./Ethylene (Utah State)</td>
<td>Closed Systems</td>
<td>NFT</td>
<td>Pressure Human / Integration</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>LSHS Program</td>
<td>MIR Wheat (Utah St.)</td>
<td>STS-73 Potato Leaves</td>
<td>Lighting</td>
<td>BIO-Plex</td>
<td></td>
</tr>
</tbody>
</table>

**Facilities and Technologies**
- **Habitat Demo Unit**
- **Plant Atrium (KSC)**
- **ISS VEGGIE**
- **Lunar Greenhouse (Arizona)**
- **Advanced Plant Habitat ISS**
- **ISS Mizuna Utah St./KSC**
- **Hypobaria (TAMU)**
- **ISS Wheat Expmt**
- **Never Completed**
- **LEDs (Purdue)**
- **BPS, VEGGIE, Aeroponics, Solar Conc., HELIAC**
Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat)
- High harvest index (edible / total biomass)
- Horticultural considerations
  - planting, watering, harvesting, pollination, propagation
- Environmental considerations
  - lighting, temperature, mineral nutrition, CO₂
- Processing requirements
- Dwarf or low growing types
# Some Crops for Life Support

<table>
<thead>
<tr>
<th>Tibbitts and Alford (^a)</th>
<th>Hoff, Howe, and Mitchell (^b)</th>
<th>Salisbury and Clark (^c)</th>
<th>Crops Used in BIOS-3 Testing (^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Wheat</td>
<td>Wheat</td>
<td>Wheat</td>
</tr>
<tr>
<td>Soybean</td>
<td>Potato</td>
<td>Rice</td>
<td>Potato</td>
</tr>
<tr>
<td>Potato</td>
<td>Soybean</td>
<td>Sweetpotato</td>
<td>Carrot</td>
</tr>
<tr>
<td>Lettuce</td>
<td>Rice</td>
<td>Kale</td>
<td>Radish</td>
</tr>
<tr>
<td>Sugar Beet</td>
<td>Peanut</td>
<td>Broccoli</td>
<td>Beet</td>
</tr>
<tr>
<td>Pea</td>
<td>Dry Bean</td>
<td>Lettuce</td>
<td>Nut Sedge</td>
</tr>
<tr>
<td>Taro</td>
<td>Tomato</td>
<td>Carrot</td>
<td>Onion</td>
</tr>
<tr>
<td>Winged Bean</td>
<td>Carrot</td>
<td>Rape Seed (Canola)</td>
<td>Cabbage</td>
</tr>
<tr>
<td>Broccoli</td>
<td>Chard</td>
<td>Soybean</td>
<td>Tomato</td>
</tr>
<tr>
<td>Onion</td>
<td>Cabbage</td>
<td>Peanut</td>
<td>Pea</td>
</tr>
<tr>
<td>Strawberry</td>
<td></td>
<td>Chickpea</td>
<td>Dill</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lentil</td>
<td>Cucumber</td>
</tr>
</tbody>
</table>

\(^a\) Tibbitts and Alford (1982); \(^b\) Hoff, Howe, and Mitchell (1982); \(^c\) Salisbury and Clark (1996); \(^d\) Gitelson and Okladnikov (1994)—diet also included supplemental animal protein and sugar.
Targeted Crop Selection and Breeding for Space at Utah State University

Selection of Existing Rice Genotypes

Targeted Wheat Breeding

‘Apogee’ Wheat  ‘Perigee’ Wheat
Water and Nutrients for Growing Crops

Recirculating Hydroponics

Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting

Root Zone Crops in Nutrient Film Technique (NFT)

Evapotranspiration from Plant Stand (potato)

Fig. 7

High Yields from NASA Sponsored Studies

Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce - Exceeded Commercial Yield Models

Canopy CO$_2$ Uptake / O$_2$ Production
(20 m$^2$ Soybean Stand)

**CO₂ Exchange Rates of Soybean Stands**

![Graph showing CO₂ exchange rates over time](image)

- **Photosynthesis**
- **Night Respiration**
- **Canopy Lodged**
- **High Temp Event**
- **Harvest**
- **815 µmol m⁻² s⁻¹ (HPS Lamps)**
- **477 µmol m⁻² s⁻¹ (MH Lamps)**

Wheeler et al., 2004. EcoEngineering.
Ethylene Gas in Closed Systems

Epinastic Wheat Leaves at ~120 ppb

Epinastic Potato Leaves at ~40 ppb

(Wheeler et al., 2004 HortScience)
NASA’s Biomass Production Chamber (BPC)
Early Vertical Agriculture!

20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers
NASA’s Biomass Production Chamber (BPC) …an early example of a Vertical Agriculture Systems
Wheat
*(Triticum aestivum)*

planting ➔ harvest
Soybean
(Glycine max)
Lettuce

(Lactuca sativa)
Potato
(Solanum tuberosum)
Automation Technologies for CEA

ALSARM Robot in NASA Biomass Production Chamber
Electrical Power for BPC

- 96 400-W HPS lamps with dimming ballasts
- Two 30 kW blowers (400 m$^3$ min$^{-1}$)
- Two 15-ton (52 kW) chillers for cooling
- 100 kW water heater for air re-heating

→ Not designed for energy efficiency!!
## Electric Lamp Options for Lighting

<table>
<thead>
<tr>
<th>Lamp Type</th>
<th>Conversion* Efficiency</th>
<th>Lamp Life* (hrs)</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent/Tungsten**</td>
<td>5-10%</td>
<td>2000</td>
<td>Intermd.</td>
</tr>
<tr>
<td>Xenon</td>
<td>5-10%</td>
<td>2000</td>
<td>Broad</td>
</tr>
<tr>
<td>Fluorescent***</td>
<td>20%</td>
<td>5,000-20,000</td>
<td>Broad</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>25%</td>
<td>20,000</td>
<td>Broad</td>
</tr>
<tr>
<td>High Pressure Sodium</td>
<td>30-35%</td>
<td>25,000</td>
<td>Intermd.</td>
</tr>
<tr>
<td>Low Pressure Sodium</td>
<td>35%</td>
<td>25,000</td>
<td>Narrow</td>
</tr>
<tr>
<td>Microwave / RF Sulfur</td>
<td>35-40%+</td>
<td>?</td>
<td>Broad</td>
</tr>
<tr>
<td>LEDs (red and blue)****</td>
<td>&gt;40%</td>
<td>100,000 ?</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

* Approximate values.

** Tungsten halogen lamps have broader spectrum.

*** For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.

**** State-of-Art Blue and Red LEDs most efficient.
LED Studies

Red...photosynthesis
Blue...photomorphogenesis
Green...human vision

North American Patent for Using LEDs to Grow Plants Developed with NASA Funding at University of Wisconsin – WCSAR!
Solar Collector / Fiber Optics For Plant Lighting

2 m² of collectors on solar tracking drive (NASA KSC)

Up to 400 W light delivered to chamber (40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.

Nakamura et al. 2010. Habitation
The Importance of Light for Crop Yield

Photosynthetically Active Radiation (mol m$^{-2}$ d$^{-1}$)

Crop Yield (g m$^{-2}$ d$^{-1}$)

Includes:
- Wheat (4)
- Soybean (4)
- Potato (4)
- Lettuce (3)
- Tomato (2)

Solar Collectors for Crop Production

Buried Plant Growth Chambers

Sadler and Giacomelli, 2002
University of Arizona Lunar / Mars Greenhouse
Hypobaric Testing with Plants

Testing at:
NASA KSC
Univ. of Guelph
Texas A&M =>
Univ. of Florida
Lettuce, radish, and wheat plants exposed to rapid pressure drop (27 days old)
NASA's HDU at Desert Test Site

Habitat Demonstration Unit (HDU) Test 2011

Human Habitats and Crops for Supplemental Food

Plant Atrium or Growing Shelf

Habitat Demonstration Unit (HDU) Test 2012
Some other Benefits of Plants in Space

- Fresh Foods
- Colors
- Texture
- Flavor
- Nutrients
- Bright Light
- Aromas
- Gardening Activity
Plant Chamber at US South Pole Station

Plants and Human Well-Being
Current Plant Testing on the International Space Station—VEGGIE Plant Chamber
Overexpression of FT flowering gene in plums (USDA researchers) resulted in dwarf growth habit and early flowering.
Sequential Development for Space Agriculture

VEGGIE 0.15 m$^2$

"Salad Machine" Growth Unit (2.0 m$^2$)

MPLM or Cygnus-like Module (10 m$^2$)

Surface System Food Production Module (20 m$^2$)
Agriculture in Space

As we explore sustainable living for space, we will learn more about sustainable living on Earth.
Some Lessons Learned from NASA CEA Research

- 20-25 m² of crops could provide all the O₂ for one person, and 40-50 m² all of the food (dietary calories)
- Better adapted crops are needed—short growth, high harvest index, improved nutrition—Use genetic engineering?
- Lighting is key to sustaining high yields
- CEA systems require large quantities of water (e.g., 50 L m⁻²) and this water must be recycled.
- Up to 90 kg of fertilizer would needed per person per year, emphasizing the need for recycling nutrients.
- Plants can provide psychological benefits to humans—this needs further study.
- The use of agriculture for space life support will likely evolve sequential, as mission infrastructures expand.
Effect of Light (PAR) on Productivity and Crop Area Requirements

- Area Required (m² / person) vs. Light or PAR (mol m⁻² day⁻¹)
- Productivity (g m⁻² day⁻¹) vs. Light or PAR (mol m⁻² day⁻¹)
Figure 11: The daily integrated total, direct, and diffuse PPF versus latitude and Martian Sol for two Mars years. The labeled sols correspond to the start of each season on Mars. For example, sol 150 corresponds to the Northern Autumnal equinox.
Phase Change of Water

Temperature (°C) vs. Pressure (kPa)

- **Vapour**
- **Liquid**

**Triple Point of Water**
- 0.01°C and 0.6 kPa

**Plants Held Here for 30 min**

0 2 4 6 8 10 12 14 16 18 20 22 24

0 2 4 6 8 10 12 14 16 18 20 22 24

0 20 40 60