Plants for Space Travel

Raymond M. Wheeler

NASA Exploration Research and Technology Directorate
Kennedy Space Center, Florida, USA

Plants Beyond Limits
Nov. 10, 2017
University of Central Florida
## 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</td>
</tr>
<tr>
<td>Food</td>
<td>0.62 kg</td>
</tr>
<tr>
<td>Water (drink and food prep.)</td>
<td>3.56 kg</td>
</tr>
<tr>
<td>Water (hygiene, flush laundry, dishes)</td>
<td>26.0 kg</td>
</tr>
</tbody>
</table>

**TOTAL 31.0 kg**

### Outputs

<table>
<thead>
<tr>
<th>Daily</th>
<th>(% total mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1.00 kg</td>
</tr>
<tr>
<td>Metabolic solids</td>
<td>0.11 kg</td>
</tr>
<tr>
<td>Water (metabolic / urine)</td>
<td>29.95 kg</td>
</tr>
<tr>
<td>(hygiene / flush)</td>
<td></td>
</tr>
<tr>
<td>(laundry / dish)</td>
<td></td>
</tr>
<tr>
<td>(latent)</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.
International Space Station Life Support Systems

Source: Reuter and Reysa, 2001
Plants for “Bioregenerative” Life Support

HUMANS

food

(CH₂O) + O₂ \rightarrow CO₂ + H₂O

Clean Water \rightarrow Waste Water

Metabolic Energy

Light

PLANTS

(CH₂O) + O₂* + H₂O \rightarrow CO₂ + 2H₂O*

Clean Water \leftrightarrow Waste Water

Inedible Biomass
Life Support Options for Different Missions

Short Duration Missions

Longer Durations

Autonomous Colonies

Stowage and Physico-Chemical

Bioregenerative

Role of Plants:

Supplemental Food
0.5 – 5 m² plant area

“More” Food, Partial \( \text{O}_2, \text{CO}_2 \) removal
5 – 25 m² plant area

Most Food, All \( \text{O}_2, \text{All CO}_2 \) removal
25 – 50 m² plant area
Bioregenerative Life Support Testing Around the World

1960
- US Military
- USSR Military

1980
- Russia - Inst. for Biomedical Problems - IMPB (Moscow)
- Russia - Inst. of Biophysics - IBP (Krasnoyarsk, Siberia)
- US NASA
- NASA (CELSS)  NASA (ALS)  NASA (LSHS)  AES/HDU
- Japan Aerosp. Lab.; Inst. Env. Sci. (IES); JAXA Chofu
- France Cadarache
- European Space Agency MELISSA

2000
- University Studies (US, Europe, Japan, Canada)
- Canada Univ. Guelph / CSA
- China Natl. Space Ag.
Crop Considerations for Space

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

<table>
<thead>
<tr>
<th>Hoff, Howe, and Mitchell (NASA)(^a)</th>
<th>Salisbury and Clark (NASA)(^b)</th>
<th>Crops Used in BIOS-3 (Russia)(^c)</th>
<th>Tako et al CEEF (Japan)(^d)</th>
<th>Waters et al. (ESA / Canada)(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Wheat</td>
<td>Wheat</td>
<td>Rice</td>
<td>Lettuce</td>
</tr>
<tr>
<td>Potato</td>
<td>Rice</td>
<td>Potato</td>
<td>Soybean</td>
<td>Wheat</td>
</tr>
<tr>
<td>Soybean</td>
<td>Sweetpotato</td>
<td>Carrot</td>
<td>Peanut</td>
<td>Potato</td>
</tr>
<tr>
<td>Rice</td>
<td>Broccoli</td>
<td>Radish</td>
<td>Sweetpotato</td>
<td>Tomato</td>
</tr>
<tr>
<td>Peanut</td>
<td>Kale</td>
<td>Beet</td>
<td>Sugar Beet</td>
<td>Carrot</td>
</tr>
<tr>
<td>Dry Bean</td>
<td>Lettuce</td>
<td>Nut Sedge</td>
<td>Beet</td>
<td>Tomato</td>
</tr>
<tr>
<td>Tomato</td>
<td>Carrot</td>
<td>Onion</td>
<td>Beet</td>
<td>Spinach</td>
</tr>
<tr>
<td>Carrot</td>
<td>Canola</td>
<td>Cabbage</td>
<td>Nut Sedge</td>
<td>Shungiku</td>
</tr>
<tr>
<td>Chard</td>
<td>Soybean</td>
<td>Tomato</td>
<td>Cucumber</td>
<td>Chinese Cabbage</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Peanut</td>
<td>Pea</td>
<td>Dill</td>
<td>Pea</td>
</tr>
<tr>
<td></td>
<td>Sweetpotato</td>
<td>Salad spp.</td>
<td>Cucumber</td>
<td>Onion/Leek</td>
</tr>
<tr>
<td></td>
<td>Kale</td>
<td></td>
<td></td>
<td>Komatsuna</td>
</tr>
<tr>
<td></td>
<td>Lettuce</td>
<td></td>
<td></td>
<td>Pepper</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Onion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chili Pepper</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Hoff, Howe, and Mitchell (1982); \(^b\) Salisbury and Clark (1996); \(^c\) Gitelson and Okladnikov (1994).

\(^d\) Tako et al. (2010); \(^e\) Waters et al. (2002)
Targeted Crop Selection and Breeding for Space at Utah State University

Selection of Existing Rice Genotypes

Targeted Wheat Breeding

‘Apogee’ Wheat  ‘Perigee’ Wheat
Overexpression of FT flowering gene in plums (ARS researchers) resulted in dwarf growth habit and early flowering.
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

Time (days)

CO₂ Exchange Rate (µmol m⁻² s⁻¹)

Photosynthesis

Canopy Lodged

815 µmol m⁻² s⁻¹ HPS Lamps

477 µmol m⁻² s⁻¹ MH Lamps

Harvest

Night Respiration

High Temp Event

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!*

External View - Back

- 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
# 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>50,000</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

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

2 m$^2$ of collectors on solar tracking drive (NASA KSC)

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)

Total Biomass

Edible Biomass

Earth and Mars comparison, with bright sunny day highlighted.
Solar Collectors for Crop Production

Buried Plant Growth Chambers

Sadler and Giacomelli, 2002
Life Sup. Biosphere Sci.
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.
University of Arizona Lunar / Mars Greenhouse
Deployable Mars Greenhouse - Low Pressure Systems
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)
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**

Human Habitats and Crops for Supplemental Food

Habitat Demonstration Unit (HDU) Test 2011

NASA’s HDU at Desert Test Site

HDU Test 2012
Current Plant Testing on the International Space Station—VEGGIE Plant Chamber

Passive Capillary Watering
Watering Systems for Weightlessness -- Special Challenges

Porous Ceramic Tubes to Contain the Water

Dreschel and Sager. 1989. HortScience

Porous Ceramic to Sub-irrigate Growing Media
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—Biophilia Concept? (E.O. Wilson)
Sequential Development for Space Agriculture

VEGGIE 0.15 m$^2$

“Salad Machine” Growth Unit (2.0 m$^2$)

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

MPLM or Cygnus-like Module (10 m$^2$)
NASA “Salad” Crops for Near Term Missions

- “Pick-and-Eat” Fresh Food for ISS
  - Lettuce
  - Chinese Cabbage
  - Mizuna
  - Dwarf Tomato
  - Dwarf Pepper

Technologies from “Space” Agriculture

LEDs for growing plants--patented through NASA funded center at Univ. of Wisconsin, ca. 1990

Potatoes in NFT at NASA KSC 1992, and at commercial “seed potato” facility (Sklarczyk Farms, MI) 2016
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.