NASA Plant Research for Life Support in Space

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IPSAM, June 2017, Limerick
## Human Life Support Requirements:

### Inputs

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

**TOTAL** 31.0 kg

### Outputs

<table>
<thead>
<tr>
<th></th>
<th>Daily</th>
<th>(% total mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1.00 kg</td>
<td>3.2%</td>
</tr>
<tr>
<td>Metabolic solids</td>
<td>0.11 kg</td>
<td>0.35%</td>
</tr>
<tr>
<td>Water (metabolic / urine)</td>
<td>29.95 kg</td>
<td>96.5%</td>
</tr>
<tr>
<td>(hygiene / flush)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(laundry / dish)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(latent)</td>
<td></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: Jim Reuter, NASA MSFC
Plants for “Bioregenerative” Life Support

**HUMANS**

Food

(CH₂O) + O₂ → CO₂ + H₂O

Clean Water → Waste Water

Metabolic Energy

**PLANTS**

Food

(CH₂O) + O₂ + H₂O ↔ CO₂ + 2H₂O*

Clean Water ↔ Waste Water

Light
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, micronutrients)
- High harvest index (edible / total biomass)
- Horticultural requirements
  - planting, watering, harvesting, pollination, propagation
- Environmental requirements
  - 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>Russian 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>Rice</td>
<td>Radish</td>
</tr>
<tr>
<td>Sweetpotato</td>
<td>Peanut</td>
<td>Sweetpotato</td>
<td>Beet</td>
</tr>
<tr>
<td>Peanut</td>
<td>Dry Bean</td>
<td>Broccoli</td>
<td>Nut Sedge</td>
</tr>
<tr>
<td>Rice</td>
<td>Tomato</td>
<td>Kale</td>
<td>Onion</td>
</tr>
<tr>
<td>Sugar Beet</td>
<td>Carrot</td>
<td>Lettuce</td>
<td>Cabbage</td>
</tr>
<tr>
<td>Pea</td>
<td>Canola</td>
<td>Carrot</td>
<td>Tomato</td>
</tr>
<tr>
<td>Taro</td>
<td>Soybean</td>
<td>Canola</td>
<td>Pea</td>
</tr>
<tr>
<td>Winged Bean</td>
<td>Peanut</td>
<td>Soybean</td>
<td>Dill</td>
</tr>
<tr>
<td>Broccoli</td>
<td>Dry Bean</td>
<td>Peanut</td>
<td>Cucumber</td>
</tr>
<tr>
<td>Onion</td>
<td>Tomato</td>
<td>Chickpea</td>
<td>Salad spp.</td>
</tr>
<tr>
<td>Strawberry</td>
<td>Chard</td>
<td>Lentil</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cabbage</td>
<td>Tomato</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Onion</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chili Pepper</td>
<td></td>
</tr>
</tbody>
</table>

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$^a$ 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.
Crop Selection and Breeding for Space

*(Utah State University)*

Selection of Existing Rice Genotypes

Wheat Breeding for Short Growth and High Harvest Index

‘Apogee’ Wheat  ‘Perigee’ Wheat
Genetic Engineering Tools

Overexpression of FT flowering gene in plums (USDA researchers) resulted in dwarf growth habit and early flowering
Water and Nutrients for Growing Crops
Recirculating Hydroponics

Wheat / Utah State

Soybean
KSC

Sweetpotato
Tuskegee

Rice / Purdue

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

Water Use (L m$^{-2}$ d$^{-1}$)

Days After Planting

Second Study
865 μmol m$^{-2}$ s$^{-1}$ PAR

First Study
655 μmol m$^{-2}$ s$^{-1}$ PAR

Water, Nutrient, and pH Control

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)

CO$_2$ Exchange Rates of Soybean Stands

Wheeler et al., 2004. EcoEngineering.
Effect of CO₂ Concentration on Photosynthesis (potato)

Similar results for wheat and soybean

Optimal Concentration

**CO₂ Exchange Rate (μmol m⁻² s⁻¹)**

**CO₂ Compensation Point**

**CO₂ Comp. Point**

**CO₂ (μmol mol⁻¹)**

**CO₂ (μmol mol⁻¹)**

**y = 0.15 x - 14.6**

**R² = 0.99**

(97)

Canopy / Stand Ethylene Production

Wheeler et al. 2004. HortScience
Ethylene 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

Control Room

Hydroponic System
NASA’s Biomass Production Chamber (BPC)
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 Lighting Considerations

<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 (white)</td>
<td>30-40%</td>
<td>50,000 ?</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.
Light Emitting Diodes (LEDs)

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

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

2 m² of collectors on solar tracking drive (NASA Kennedy Space Center, Florida)

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

Nakamura et al. 2010. Habitation
Photosynthetically Active Radiation (mol m\(^{-2}\) d\(^{-1}\))

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

Total Biomass

Edible Biomass

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

Light and Crop Yield

Solar Collectors for Crop Production

Buried Plant Growth Chambers

Inflatable Greenhouses

Composting Facility

Human Habitat

University of Arizona Lunar / Mars Greenhouse
Deployable Mars Greenhouse - Low Pressure Systems
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.
Hypobaric Testing with Plants

Testing at:
NASA KSC
Univ. of Guelph
Texas A&M Univ. ⇒
Univ. of Florida
Lettuce, radish, and wheat plants exposed to rapid pressure drop (27 days old)
Phase Change of Water

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

**Plants Held Here for 30 min**

**Vapour**

**Liquid**

Temperature (°C) vs. Pressure (kPa) graph.
Some other Benefits of Plants in Space

- Fresh Foods to Augment the Diet
  - Colors
  - Texture
  - Flavor
  - Nutrients
- Bright Light
- Aromas
- Gardening Activity
Testing Crops in Human Habitats

Habitat Demonstration Unit (HDU) Test 2011

Plant Atrium or Growing Shelf

NASA's HDU at Desert Test Site

HDU Test 2012
Plant Testing on the International Space Station—VEGGIE Plant Chamber
Sequential Development for Space Agriculture

VEGGIE 0.15 m²

“Salad Machine” Growth Unit (2.0 m²)

Surface System Food Production Module (20 m²)

MPLM or Cygnus-like Module (10 m³)
Some Lessons Learned from NASA CEA Research

- 20-25 $m^2$ of crops could provide all the $O_2$ for one person, and 40-50 $m^2$ all of the food (dietary energy).
- 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., 5 L $m^{-2} d^{-1}$) 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 plants for life support will likely evolve sequential, starting with small, supplemental food production and expanding for future missions.
Plants and Living in Space

As we explore sustainable living for space, we will learn more about sustainable living on Earth.
One of our Kennedy Space Center Researchers!

Michelle McKeon-Bennett, 2004, Space Life Science Laboratory, KSC, Florida
Effect of Light 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)**

The graph shows the relationship between the area required for crops and productivity as a function of light or PAR (photosynthetically active radiation) in mol m⁻² day⁻¹. The area required decreases as the light or PAR increases, while productivity increases with higher light or PAR levels.