Plants and Space Exploration: Observations from Some NASA Studies

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Human Life Support Requirements:

Inputs

	Daily Rqmt.	(% total mass)
Oxygen	0.83 kg	2.7%
Food	0.62 kg	2.0%
Water (drink and food prep.)	3.56 kg	11.4%
Water (hygiene, flush laundry, dishes)	26.0 kg	83.9%

TOTAL 31.0 kg

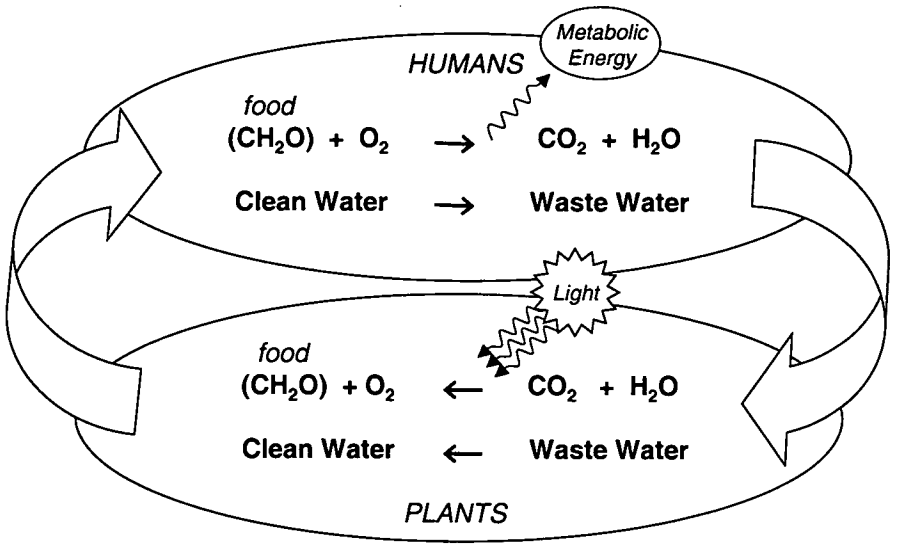
Outputs

	Daily	(% total mass)
Carbon dioxide	1.00 kg	3.2%
Metabolic solids	0.11 kg	0.35%
Water	29.95 kg	96.5%
(metabolic / urine		12.3%)
(hygiene / flush		24.7%)
(laundry / dish		55.7%)
(latent		3.6%)

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 Human Life Support



Plants and Life Support: Some Background

*Joseph Priestley (1772) **

- "...a sprig of mint in a glass jar continued growing for some months, I found that the air would neither extinguish a candle, nor was it at all inconvenient to a mouse"
- "plants thrive particularly well in air made obnoxious by the exhalations of animals (and humans)"

** Abstracted from E.I. Rabinowitch. 1945. Photosynthesis and Related Processes. Interscience Publ. Inc. NY.*

Plants and Life Support: Some Background

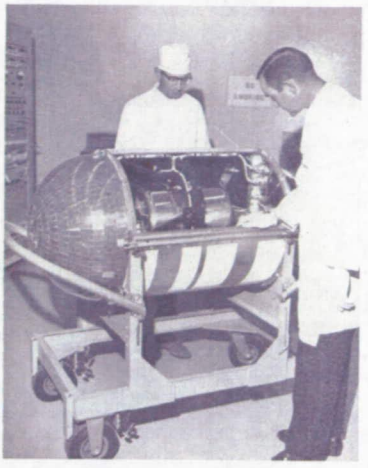
Early references:

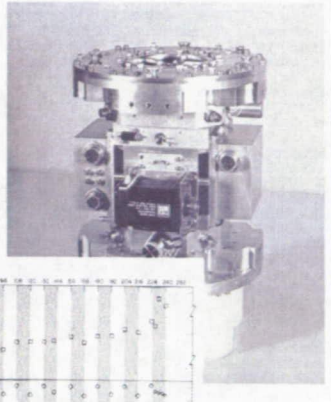
- Specht, H. 1952. Toxicology of travel in the aeropause. In: C.S. White and O.O. Benson (eds.) Physics and Medicine of the Upper Atmosphere, University of New Mexico Press, Albuquerque.
- Bowman, N.J. 1953. The food and atmosphere control problem on space vessels. II. The use of algae for food and atmospheric control. J. British Interplanetary Soc. 12:159-167.
- Myers, J. 1954. Basic remarks on the use of plants as biological gas exchanges in a closed system. J. Aviation Medicine. 25:407-411.

Early Studies Focused on Algae and Cyanobacteria *(1950s and 1960s)*

- *Chlorella pyrenoidosa* TX71105 (thermotolerant 39°C)
- Other photosynthetic organisms: *Anacystis, Synechocystis, Scenedesmus, Synechococcus, Spirulina*
- *Hydrogenomonas* for biomass production (with electrolysis)
- Development of culture systems (chemostats, turbidostats)
- Studies with animals (e.g., mice, monkeys) and humans

Early Plant Experiments in Space





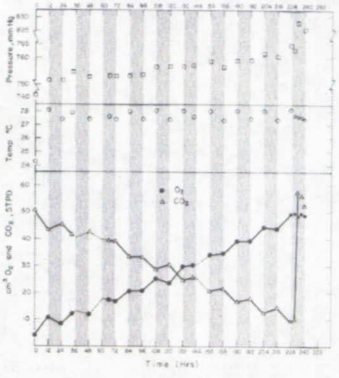
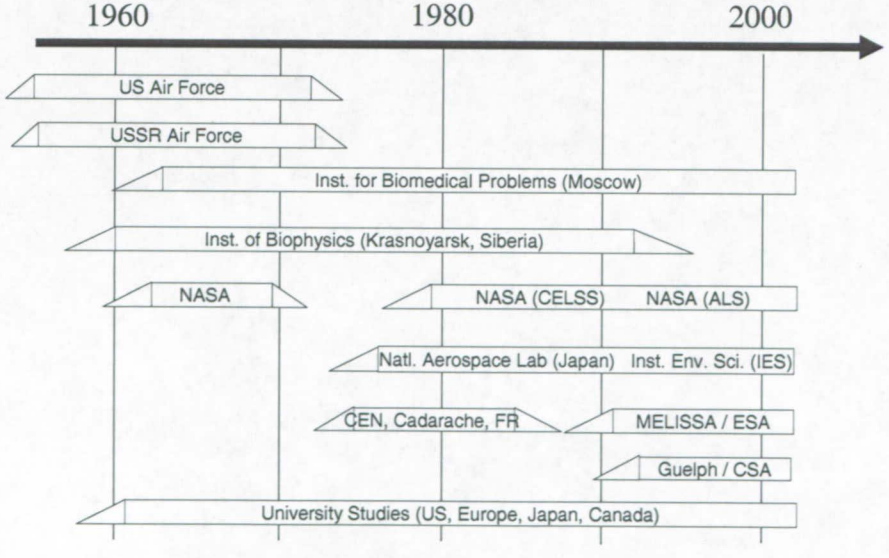


FIG. 11. Experimental apparatus mounted in OV1 satellite; note solar cell dome power system.

FIG. 10. Flight data: pressure, temperature, CO_2 and O_2

C.H.Ward, S.S. Wilks, and H.L. Craft. 1970. Dev. Indust. Microbiol. 11:276-295

Testing with Plants and Algae for Life Support



Testing with Higher Plants

(1980s and 1990s)

→ Horticulture for Space Missions

- Higher plants (crops) more acceptable as a food source
- Improved productivity of plants in controlled environment agriculture (CEA)
  - Hydroponic culture
  - HID Lighting
  - CO_2 enrichment
- Broad information base on agronomic spp.

Some Findings from NASA Testing

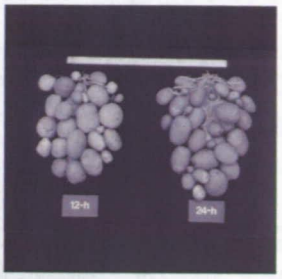
→ Recirculating Hydroponics with Crops:

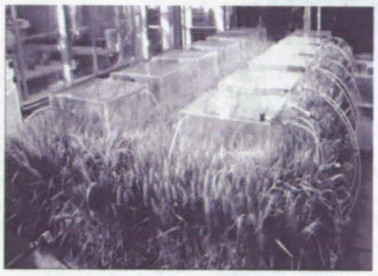
Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting

Some Findings from NASA Testing

→ High Yields from High Light and CO_2 Enrichment :

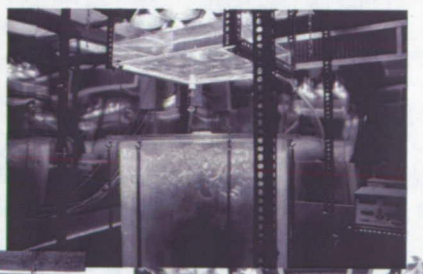
Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models

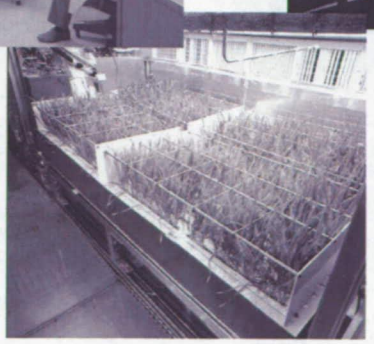


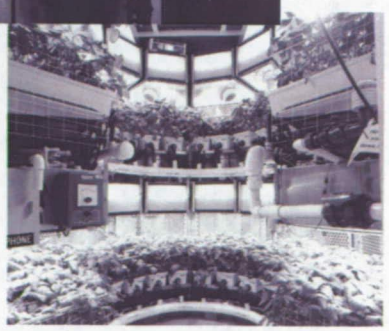


Some Findings from NASA Testing

→ Closed System Studies:

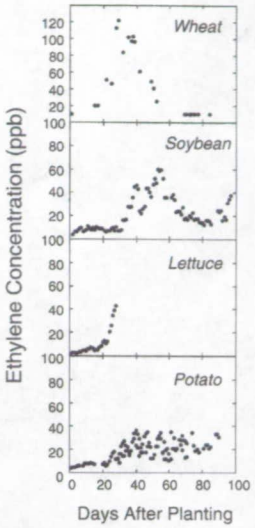


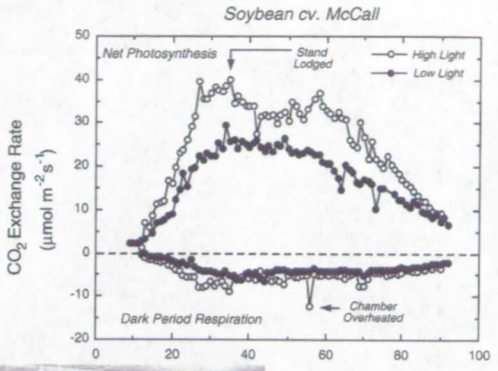




Some Findings from NASA Testing

→ Whole Canopy Gas Exchange:





Some Findings from NASA Testing

→ Cultivar Selection and Development :

<u>Several Universities:</u>
Cultivar Comparisons
(wheat, potato, soybean, lettuce, sweetpotato, tomato)

<u>Utah State Univ:</u>
Super Dwarf Wheat
Apogee Wheat
Perigee Wheat
Super Dwarf Rice

<u>Tuskegee Univ:</u>
ASP Sweetpotato

What Will it Take to Grow Plants for on Mars ?

Horticultural Challenges for Going To Mars:

Crop Physiology

⇒ *More Complete Environmental Response Data*

- Photosynthetic Photon Flux (PPF)
- Temperature
- Photoperiod
- Carbon Dioxide, Oxygen, Other Gases ?
- Atmospheric Pressure
- Mineral Nutrition

➢*Including Sub-Optimal Conditions*

Horticultural Challenges for Going to Mars:

Plant Breeding / Genetic Engineering

- Better Adapted Cultivars
  - High Nutritional Value
  - High Harvest Index
  - Dwarf Growth Habit
  - Tolerance to Space Settings:
    - Super-Elevated CO_2
    - Hypogravity
    - Electric Light Sources
  - Growth on Recycled Wastes (NH_4^+, Na^+)

Horticultural Challenges for Going to Mars:

Agricultural Engineering

- Improved Planting/Harvesting Approaches
  - ➢ Mechanization / Automation
- Improved Lighting Systems
  - More Efficient Electric Lamps
  - Light Collecting / Conduit Systems
  - Transparent / Inflatable Materials
- Improved Environmental Monitoring and Control
- Water Recycling and Nutrient Solution Mgmt.

Constraints for Crop Production on Mars:

("Economics" of Life Support)

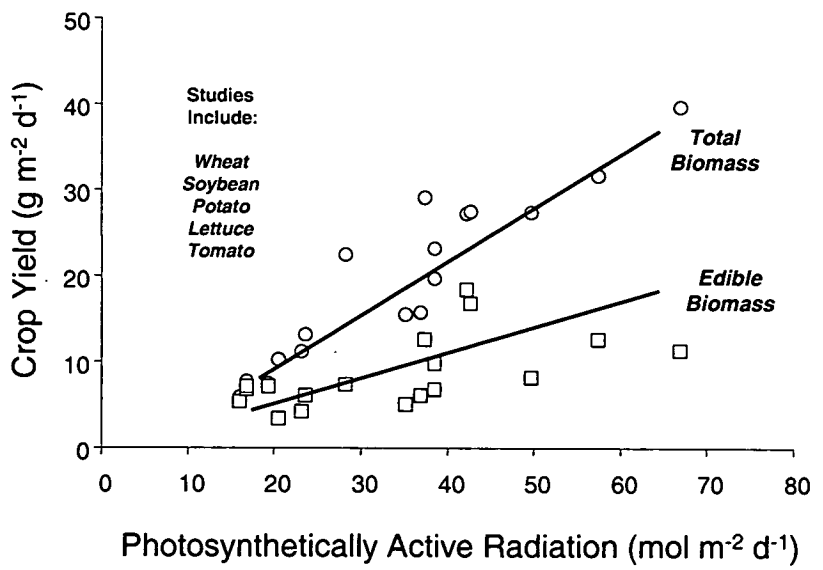
- Energy Requirements
- System Mass
- System Volume
- Crew Time
- System Reliability

} *These Apply for All Life Support Technologies*

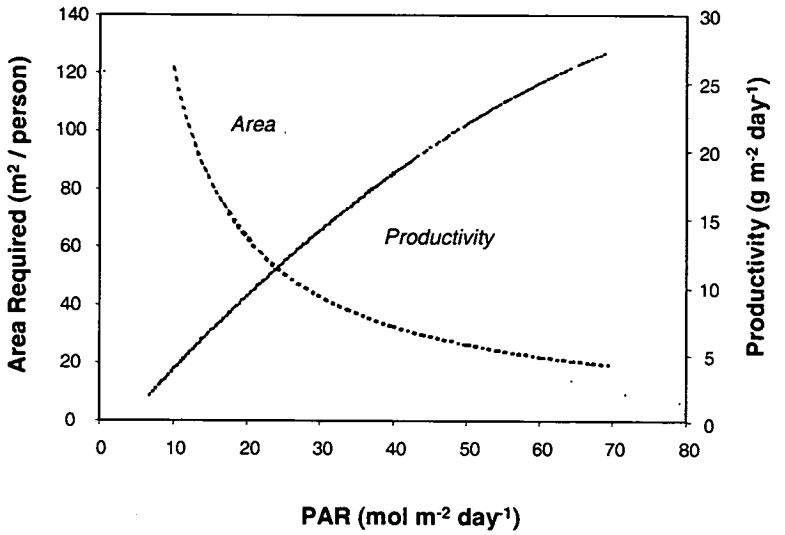
For Plants, Lighting Dominates These Costs !

Effect of Light on Crop Yield

(Data from NASA Biomass Production Chamber)



Effect of Light (PAR) on Productivity and Crop Area Requirements



Methods for Providing Plant Lighting

- Electric Lighting

  ⇒ *High Power Requirements*
  Finite Lamp Life
  Thermal Management

- Solar (Direct) Lighting

  ⇒ *Light Collectors and Conduits*
  Transparent Structures ("Greenhouses")

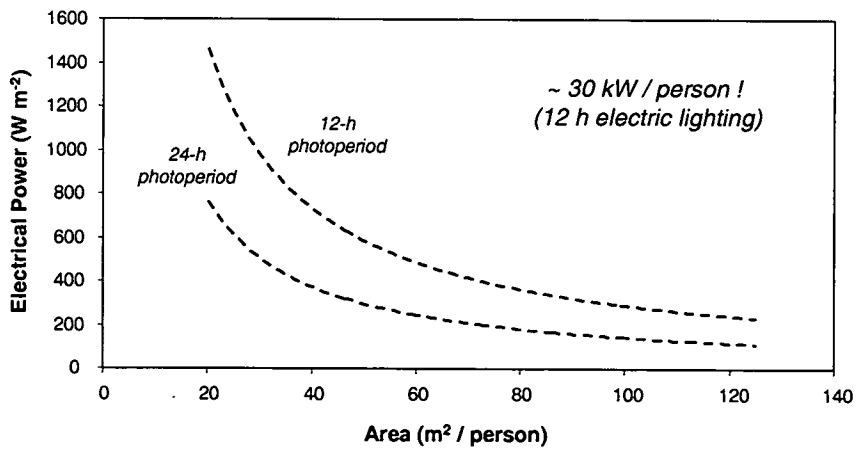
  ⇒ *Effects of Local Environment*
  - *distance from sun*
  - *photoperiod*
  - *dust storms (Mars)*

Electric Lamp Considerations

Lamp Type	Conversion* Efficiency	Lamp Life* (hrs)	Spectrum
Incandescent/Tungsten**	5-10%	2000	Intermd.
• Xenon	5-10%	2000	Broad
• Fluorescent***	20%	5,000	Broad
⇨ • LEDs (red)****	20%	100,000 ?	Narrow
• Metal Halide	25%	20,000	Broad
• High Pressure Sodium	30%	25,000	Intermd.
• Low Pressure Sodium	35%	25,000	Narrow
⇨ • Microwave Sulfur	35-40%+	?	Broad

* *Approximate values.*
** *Tungsten halogen lamps have broader spectrum.*
*** *For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.*
**** *Blue and green LEDs ~5 to 10% efficient.*

Required Electrical Power for Lighting vs. Area per Person



Assuming: 20% electrical conversion efficiency
4 kcal g^{-1} in harvested food
2500 kcal person^{-1} day^{-1}

⇒ ***Nuclear Power ?!***

Direct Solar Radiation Options

Earth Radiation:

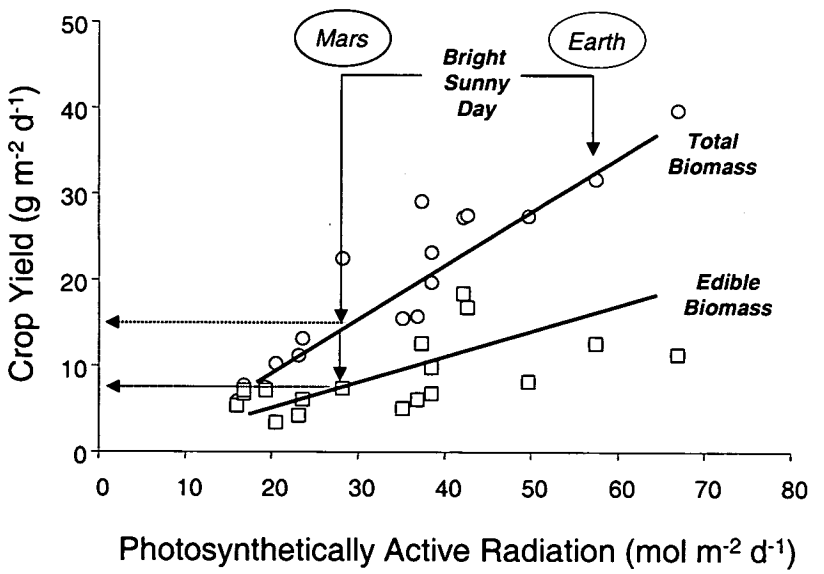
*- incident**	*~1350 W m^{-2} total* *~ 600 W m^{-2} PAR*
- daily PAR	*~15 MJ m^{-2} d^{-1} (~60 mol m^{-2} d^{-1})*

***Mars Radiation** (~44% of Earth's):*

*- incident**	*~ 600 W m^{-2} total* *~ 260 W m^{-2} PAR*
*- daily PAR***	*~ 7 MJ m^{-2} d^{-1} (~26 mol m^{-2} d^{-1})*

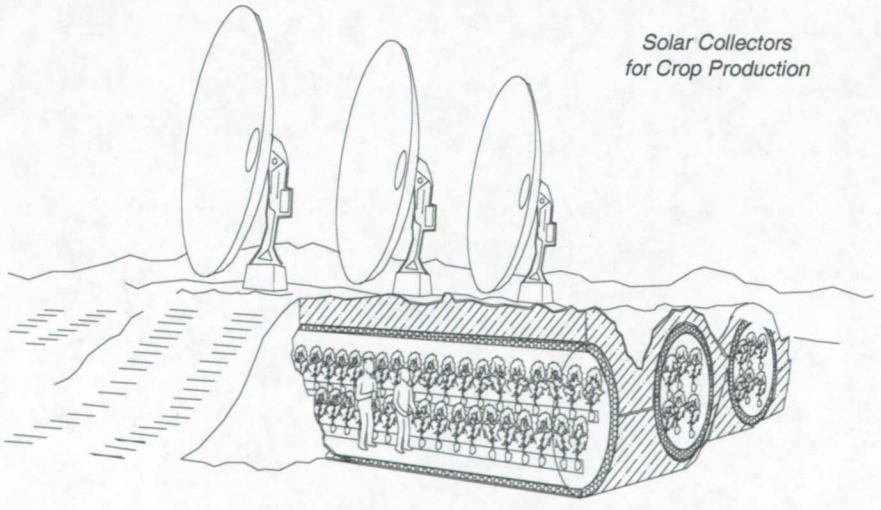
* *At outer edge of atmosphere*
** *Surface irradiance estimated from Landis (1996); values dependent on latitude, time of year, and weather*

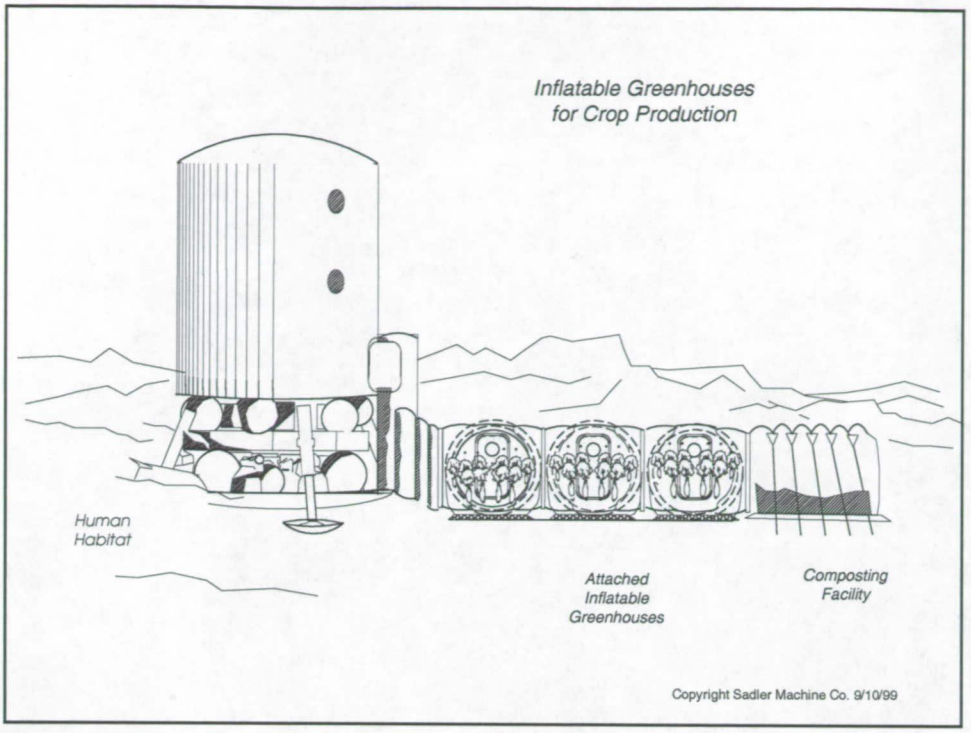
Crop Yield vs. Light

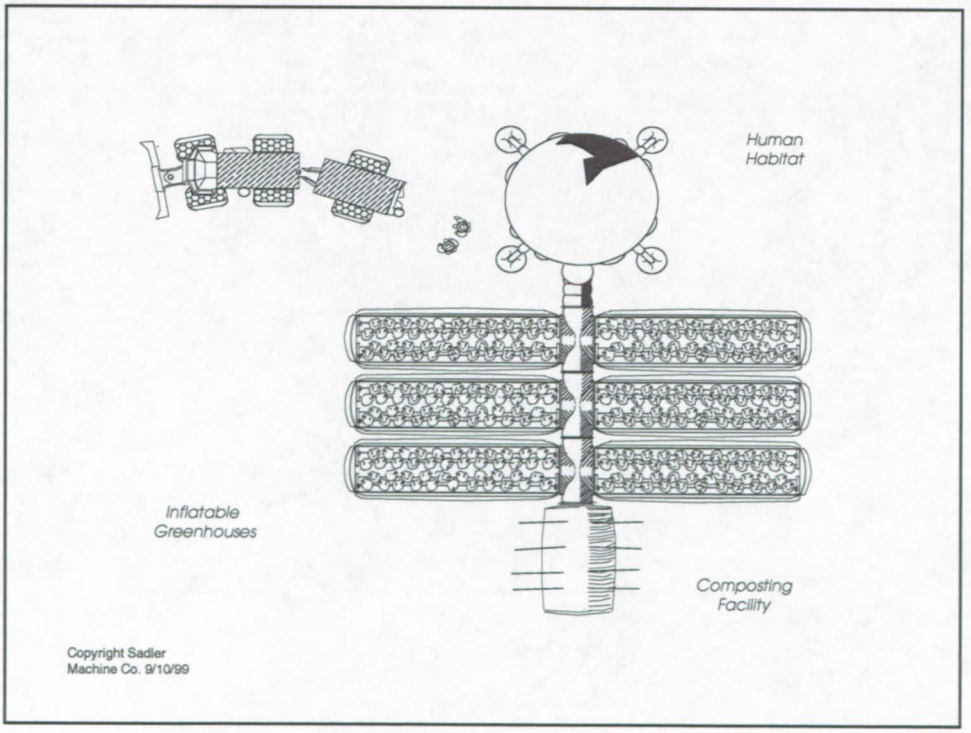


Can "Greenhouses" be Used on Mars ?

- Optimized Light Collection
  - Greenhouse Structural Design
  - Ancillary Collectors / Reflectors ?
- Thermal Management Challenges
- Materials Challenges:
  - Inflatable Systems (for reduced mass)
  - Resistance to Leakage
  - Resistance to UV
  - Temperature Tolerance




Inflatable Greenhouses
for Crop Production
Human
Habitat
Attached
Inflatable
Greenhouses
Composting
Facility
Copyright Sadler Machine Co. 9/10/99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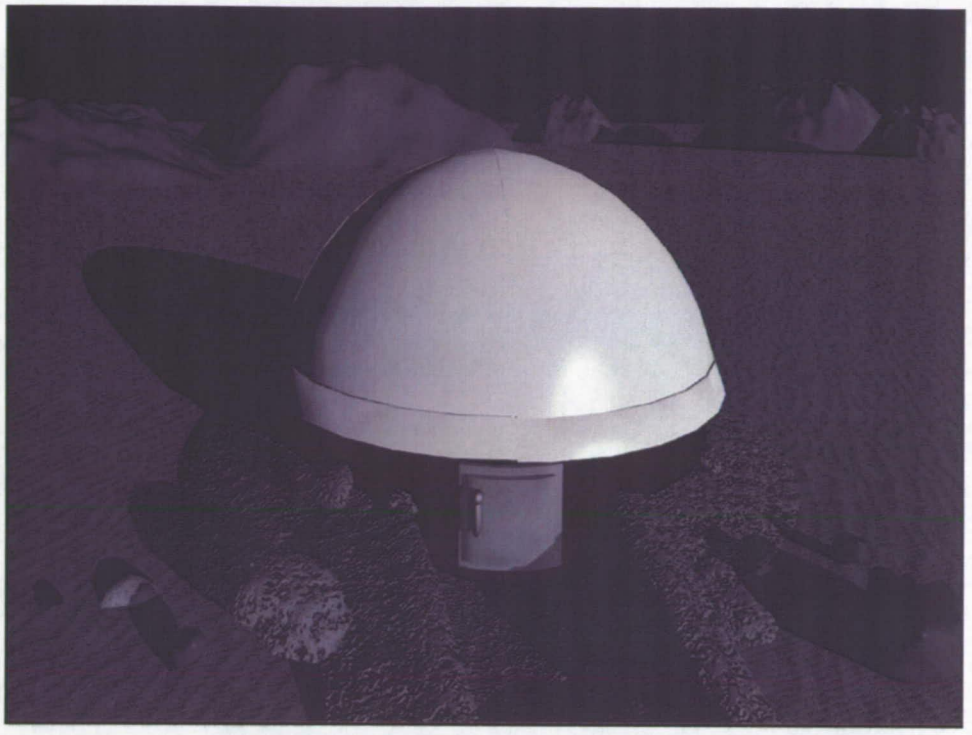
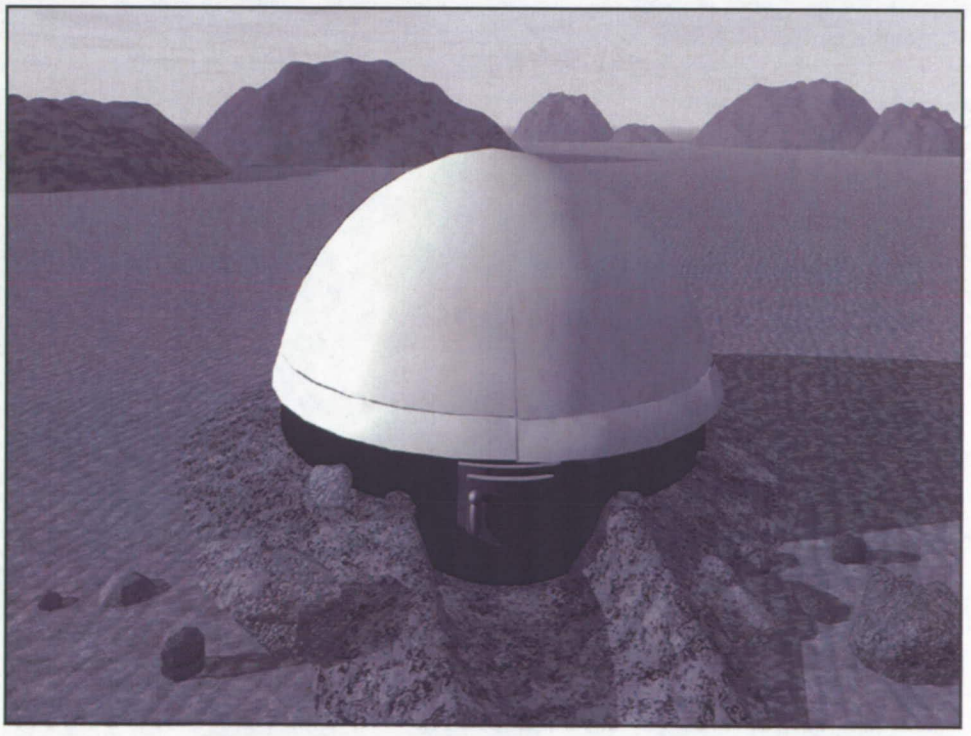
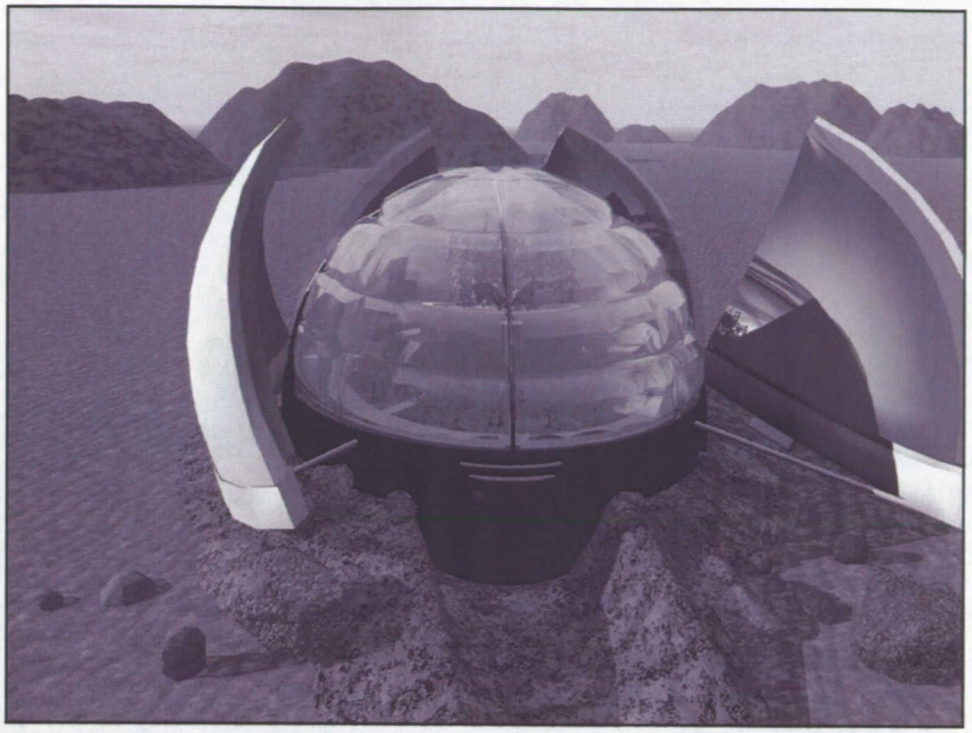
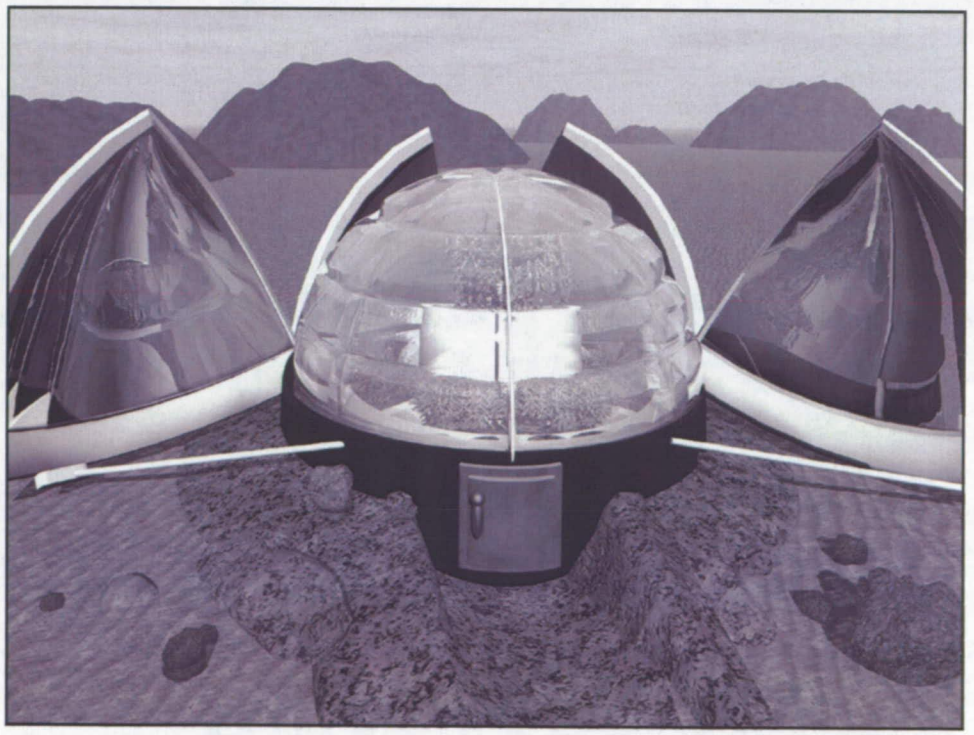








Can Low Pressures Be Used for Crop Production Systems ?

- Reduced Structural Mass
- Reduced Gas Leakage (and Resupply)
- Wider Selection for Transparent Materials

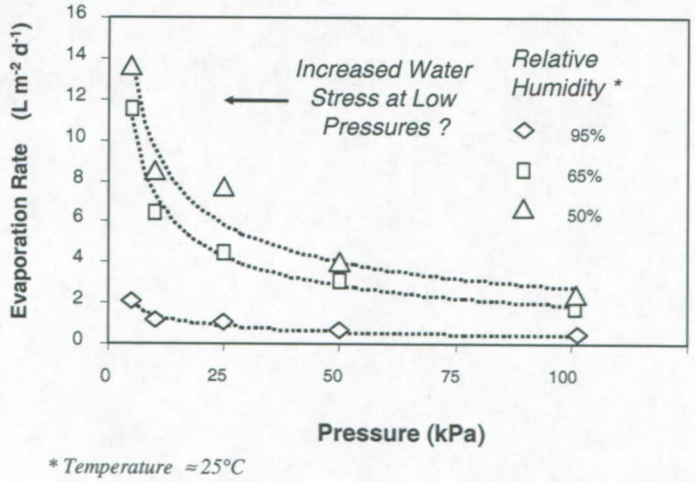
Previous Studies with Plants and Pressure

- Wright Patterson Air Base, USA (1960s)
- Siegel et al. (1962, 1963)
- Burg and Burg (1965)
- Gale (1972, 1973)
- Rule and Staby (1981)
- Andre and Richaud (1985); Andre and Massimino (1992)
- Musgrave et al. (1988)
- Daunicht and Brinkjans (1992, 1996)
- Ohta et al. (1993)
- Goto et al. (1995, 1996), Iwabuchi et al. (1996)
- Corey et al. (1996, 1997)

- *Studies Ongoing* : Texas A&M Univ. (USA)
  Kennedy Space Center, FL
  Univ. of Guelph (Canada)

Mars Deployable Greenhouse: A Pre-Prototype Design

Water Evaporation Rates vs. Pressure



* Temperature ≈ 25°C

A Minimum Atmosphere for Mars Greenhouses

- Total Pressure ($\geq$ 10 kPa ?)
- Oxygen > 5 kPa (?)
- Humidity ~ 40 to 90% (1.5 to 3.5 kPa)
- Carbon Dioxide ~0.1 kPa - 3 kPa (?)

➢ *Earth's Atmosphere : 101 kPa total, 21 kPa O_2, 0.04 kPa CO_2*

Human Tending of Low Pressure Gardens

- Acceptable limits of O_2 partial pressure
  - > 18 kPa (without breathing assistance)
- Acceptable limits of CO_2 partial pressure
  - Limited exposure to > 1 kPa

⇒ Greenhouse "EVAs" *(extravehicular activities)* ?

- Fire Safety Considerations
  - O_2 Partial Pressure, O_2 Percentage

Psychological Contributions of Plants

- Fresh Foods
  - *Colors*
  - *Texture*
  - *Flavor*
- Bright Light
- Aromas
- Gardening Activity

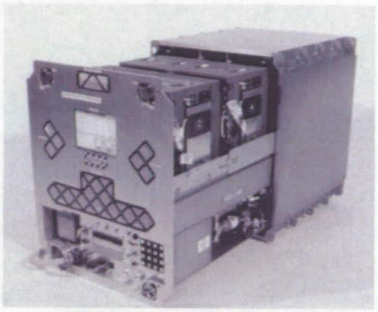
Current Testing for Spaceflight

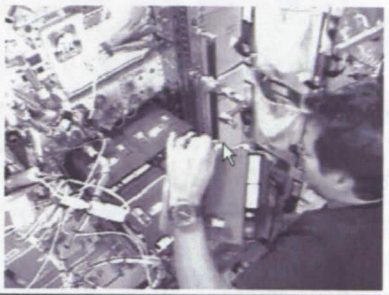
LED Lighting Systems

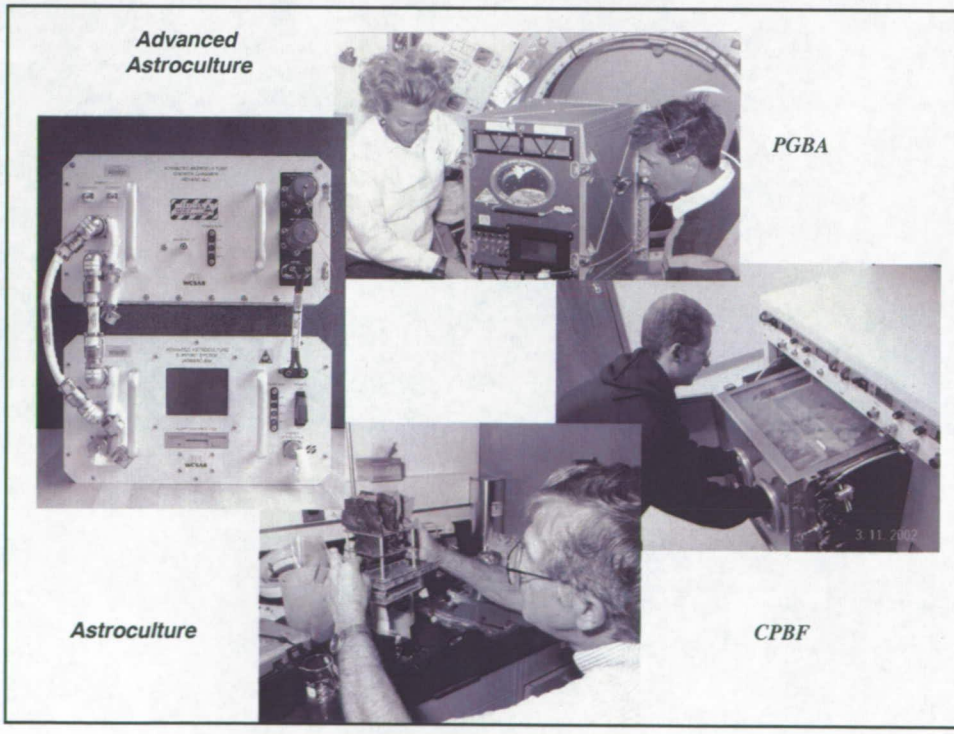
Watering Systems for Spaceflight

Candidate Crops

Spaceflight Chambers for Plant Tests



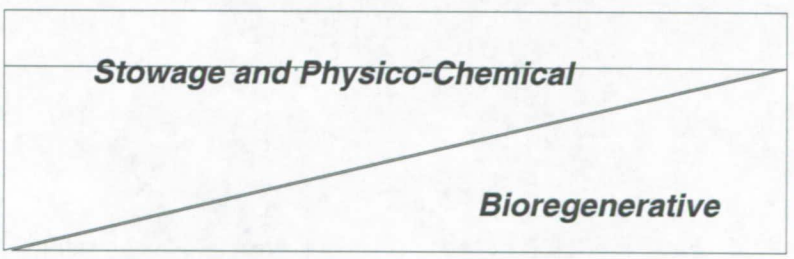


Horticulture for Space Missions

Mission	Plant Contribution	Comments
Intl. Space Station (ISS)	- Dietary Supplement	"Salad Machine" Electric Lighting
Mars Transit Vehicles	- Dietary Supplement - Water Processing?	Salad Machine Electric or Direct Lighting ?
Mars Surface (Near- Term)	- ~5-10% Food Prod. - Water Processing	Large Garden System Electric Lighting or Small Greenhouses
Mars Surface (Mid-Term)	- ~50% Food Prod - ~100% O_2 Production - Water Processing	Intermediate Greenhouse Suplmt. Electric Lighting
Mars Surface (Far-term)	- 90% Food Prod. - Plants for O_2 - Water Processing	Large Greenhouse Suplmt. Electric Lighting Nuclear Power ?

Role of Bioregenerative Life Support for Future Missions

Short Durations (early missions) ***Longer Durations*** ***Autonomous Colonies***



Plant Growing Area →

~1-5 m² total ***~10-25 m² / person*** ***~50 m² / person***

More Testing is Needed !

- *Unique Aspects of Space*
- *Multiple Crop Systems*
- *Sustained Production*
- *Reduction in System Costs*

A Priestley Experiment on Mars ? !

"Where perhaps sprigs of wheat, potatoes, lettuce and others will not at all be inconvenient to their human companions "