Plants for Human Life Support in Space

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David Robinson Memorial Lecture
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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***	

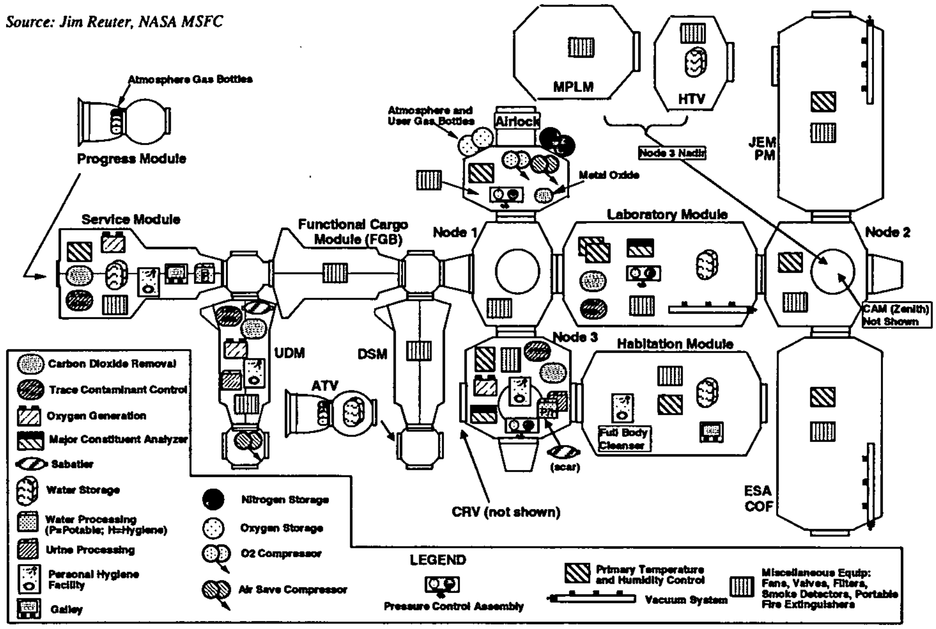
Outputs

	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.

International Space Station Life Support Hardware

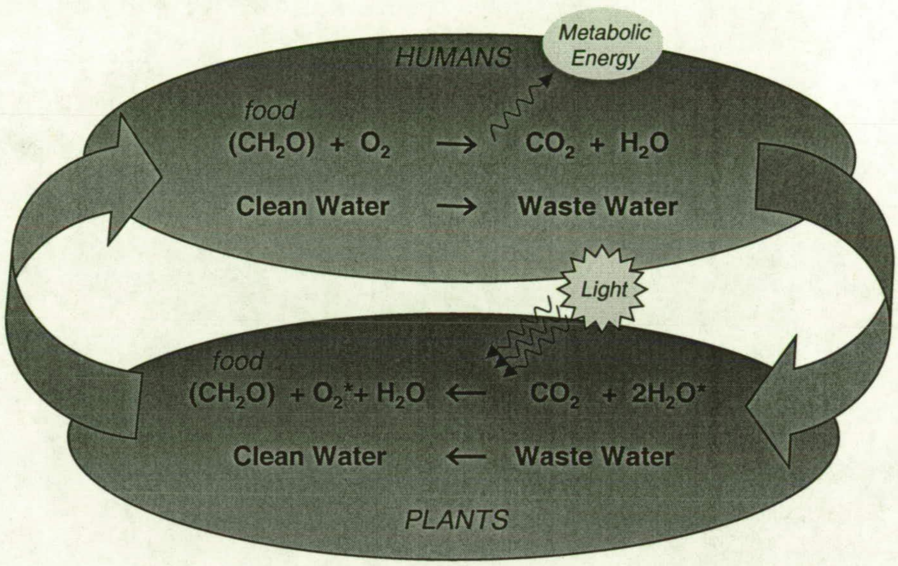
Source: Jim Reuter, NASA MSFC



Current Physico-Chemical System for Space Station Life Support

- Food—Stowage and Resupply
- Water—Stowage and Resupply
  - Some condensate recovery with multi-filtration; iodine and silver as disinfectants
- CO_2 Removal—Four-Bed Molecular Sieve
  - Water Vapor Recovered, CO_2 then vented overboard
  - Future—Add Sabatier Reduction System (requires H_2 and produces Water and Methane)
- O_2 Production—Electrolysis of Water
  - Potassium Perchlorate “Candles” as Back-up Supply
- Trace Contaminant Control—Carbon Filters and Catalytic Oxidation

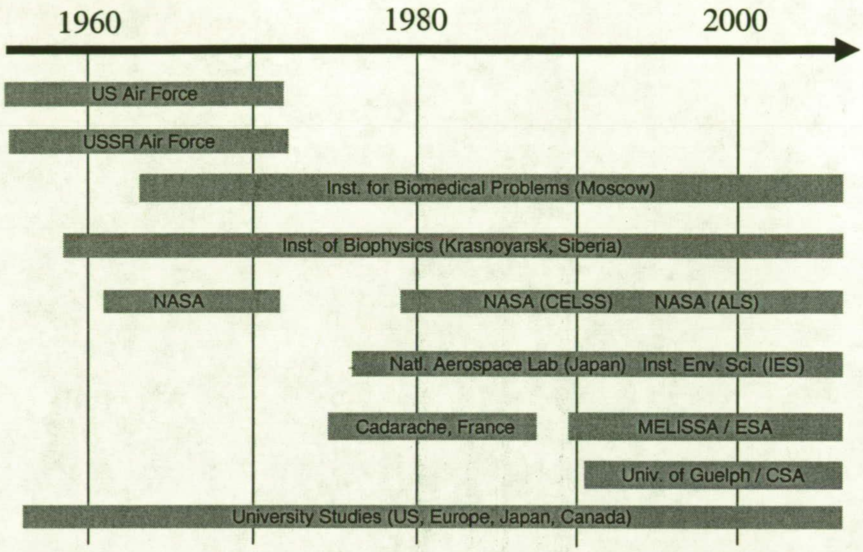
Bioregenerative Life Support using Plants



Plants for Life Support: *Some Early References*

- Tsiolkovsky, K.E. 1926. Exploration of space with rockets. Kaluga Press (in Russian).
- 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.

Life Support Testing with Plants and Algae



What Types of Plants Would be Needed?

- Crops--high yielding and nutritious
- High harvest index (edible / total biomass)
- Horticultural considerations
  - planting, harvesting, pollination, propagation
- Environmental considerations
  - photoperiod, temperature, mineral nutrition
- Processing requirements
- Dwarf or low growing types

Some Crops for Life Support-Complete Diet

Hoff, Howe, and Mitchell [a]	Salisbury and Clark [b]	Crops in Russian BIOS-3 Testing [c]	Crops in Japanese CEEF Testing [d]
Wheat	Wheat	Wheat	Rice
Potato	Rice	Potato	Soybean
Soybean	Sweetpotato	Carrot	Chinese Cabbage
Rice	Broccoli	Radish	Cucumber
Peanut	Kale	Beet	Snap Bean
Dry Bean	Lettuce	Nut Sedge	Daikon Radish
Tomato	Carrot	Onion	Komatsuna
Carrot	Rape Seed (Canola)	Cabbage	Leek
Chard	Soybean	Tomato	Lettuce
Cabbage	Peanut	Pea	Potato
	Chickpea	Dill	Pumpkin
	Lentil	Cucumber	Shungiku
	Tomato	Salad spp.	Tomato
	Onion		Pepper
	Chili Pepper		Spinach

[a] Hoff, Howe, and Mitchell (1982); [b] Salisbury and Clark (1996); [c] Gitelson and Okladnikov (1994)—diet also included supplemental animal protein and sugar; [d] Masuda et al. (2005)

Supplemental Crops for Early Missions--Incomplete Diet

Boeing Comp. (1962)[a]	NASA Vegetable Production Unit [b]	Chinese Space Agency [c]	South Pole Research Station [d]
Sweetpotato	Lettuce	Neilvnanyou Lettuce*	Red Oakleaf Lettuce
Tampala	Spinach	Dasusheng Lettuce*	Green Oakleaf Lettuce
Lettuce	Radish	Naichoutai Lettuce	Grand Rapids Lettuce
Chinese Cabbage	Cabbage	Dongfangkai Lettuce	Red Romaine Lettuce
Cabbage	Green Onion	Sijiyoumaicai Lettuce*	Green Romaine Lettuce
Cauliflower	Carrot	Sowthistle*	Cucumber
Kale	Tomato	Jingyou Rape	Tomato
Collards	Pepper	Daye Spinach	Pepper
Turnip	Strawberry	Quanneng Spinach	Cantaloupe
Swiss Chard	Herbs		Strawberry
Endive			Herbs
Dandelion			Radish
Radish			Sunflower
New Zeal. Spinach			Nasturtium
		* Selected for further study	

[a] Boeing Company (1962); [b] Wheeler and Strayer (1997); [c] Ain, Guo, Tang (2006); [d] Patterson et al. (2006)

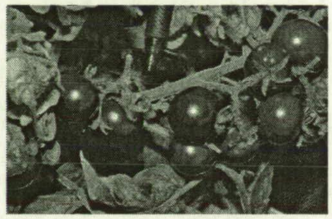
Cultivar Comparisons and Crop Breeding

Cultivar Comparisons :
Wheat, Potato, Lettuce
Soybean, Sweetpotato,
Tomato, Pepper
→

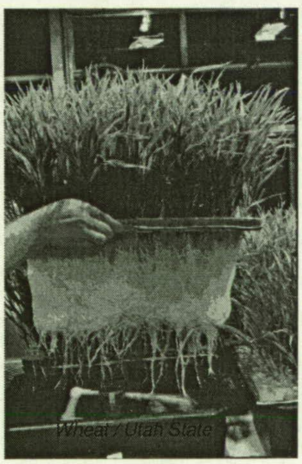
←
Plant Breeding
- Super Dwarf Wheat
- Apogee Wheat
- Perigee Wheat
- Super Dwarf Rice

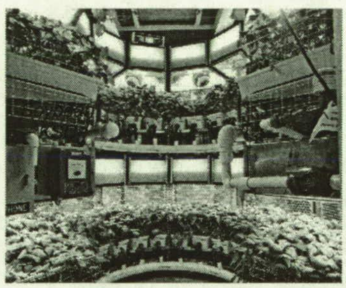
←
Genetic Engineering
Artificial Storage Protein Gene in Sweetpotato

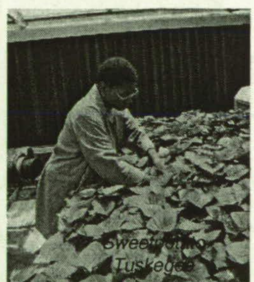
Dwarf Pepper ↑ and Tomato ↓



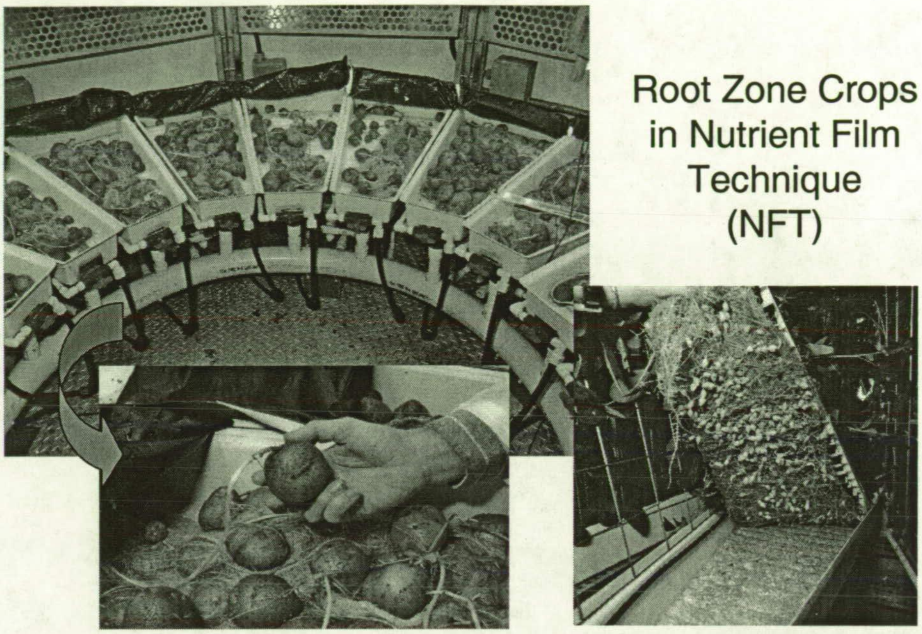
Recirculating Hydroponics with Crops







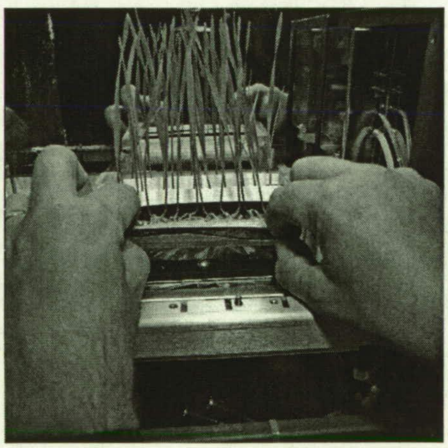
Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting



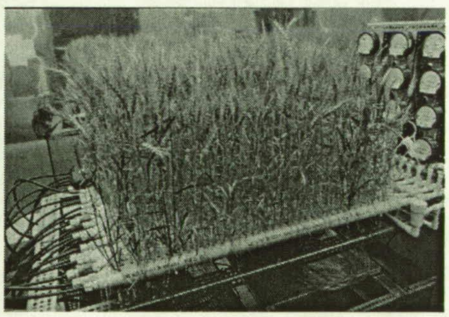
Root Zone Crops in Nutrient Film Technique (NFT)

Wheeler et al., 1990. Amer. Potato J. 67:177-187; Mackowiak et al. 1998. HortScience 33:650-651

Watering Systems for Weightlessness

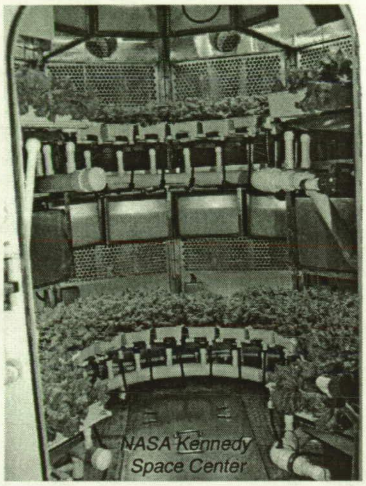


Porous Ceramic Tubes to Contain the Water

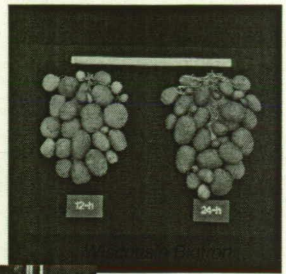


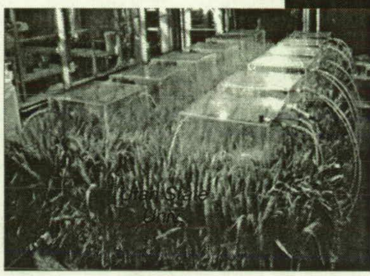
Wright et al. 1988. Trans. ASAE 31:440-446; Dreschel and Sager. 1989. HortScience 24:944-947.

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

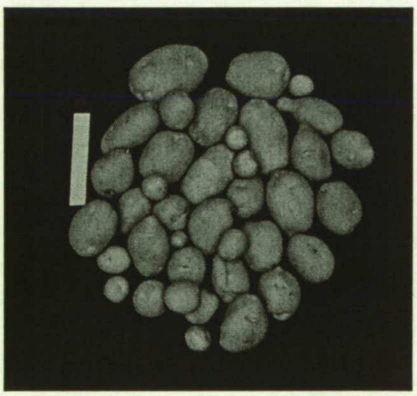


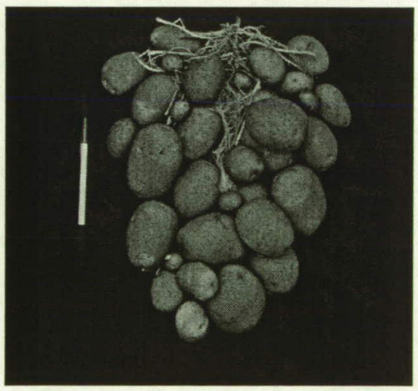


- Bubgee, B.G. and F.B. Salisbury. 1988. Plant Physiol. 88:869-878.
- Wheeler, R.M., T.W. Tibbitts, A.H. Fitzpatrick. 1991. Crop Science 31:1209-1213.

Upper Limits of Yield ?

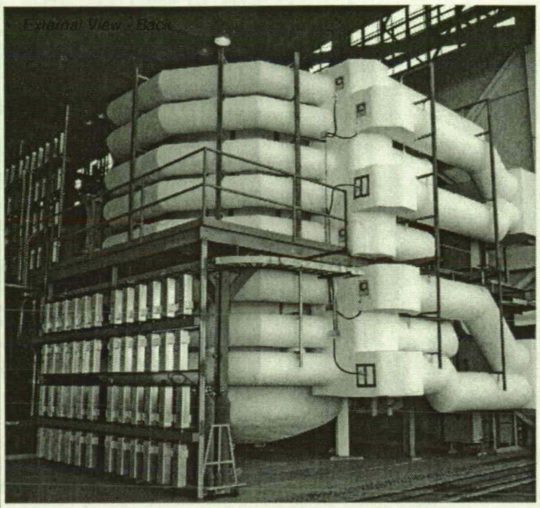
→ *Higher Yields Reduce the Amount of Planted Area*

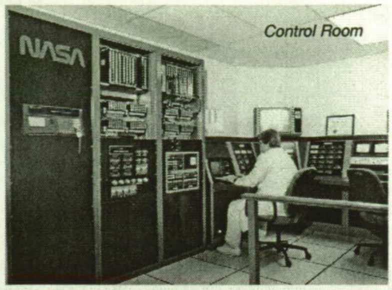


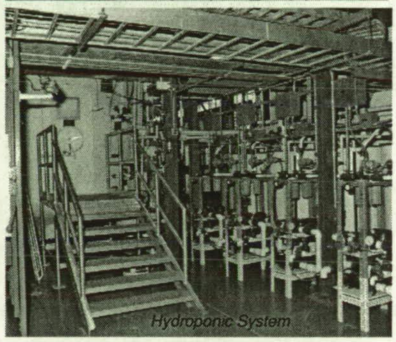


19.7 kg FM m^{-2} in 132 days = 197 t ha^{-1}

NASA's Biomass Production Chamber (BPC)

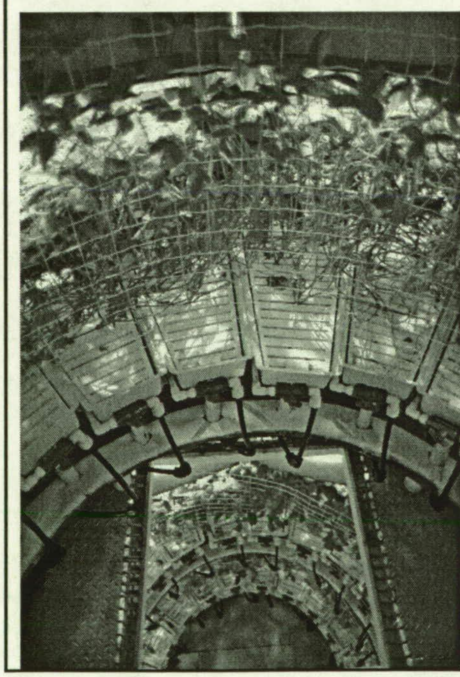




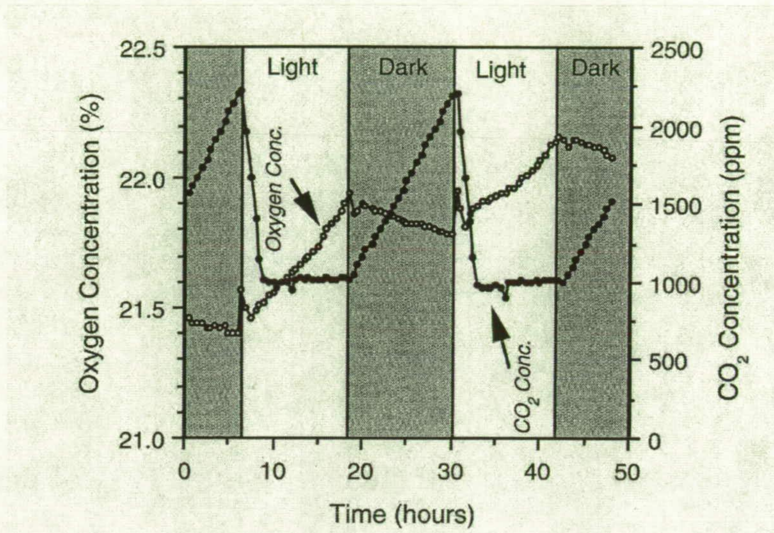


20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers

NASA's Biomass Production Chamber (BPC)

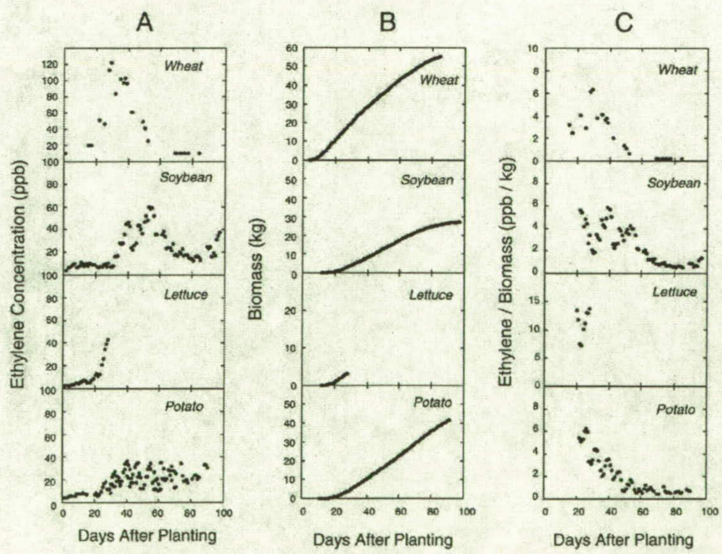


Canopy CO_2 Uptake / O_2 Production
(20 m² Soybean Stand)



Wheeler. 1996. *In:* H. Suge (*ed.*) Plants in Space Biology.

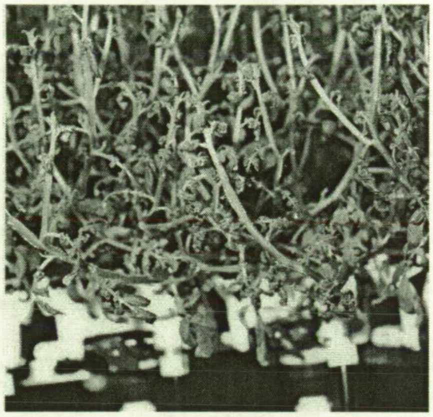
Canopy / Stand Ethylene Production



Wheeler et al. 2004. HortScience 39:1541-1545.

Ethylene in Closed Systems

Epinastic
Wheat Leaves
at ~120 ppb



Epinastic
Potato Leaves
at ~40 ppb

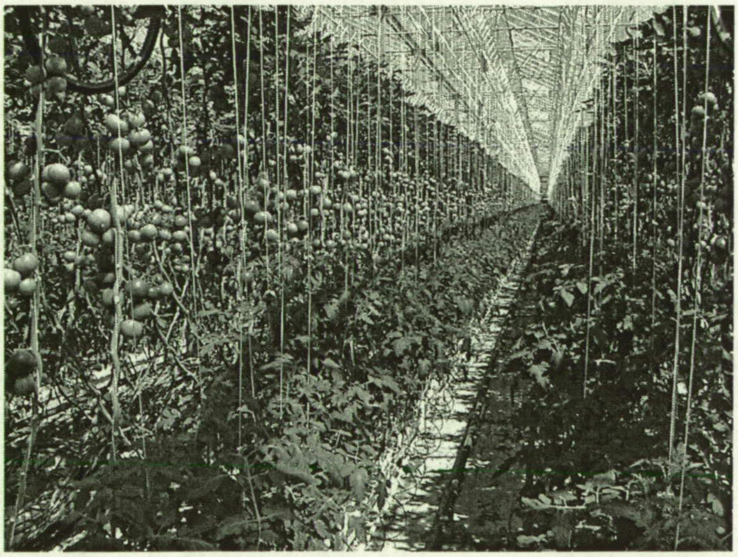
Challenges in Controlled Environment Crop Production

Maximum Space Utilization (floating raft hydroponics)

(Cornell Univ., New York, USA)

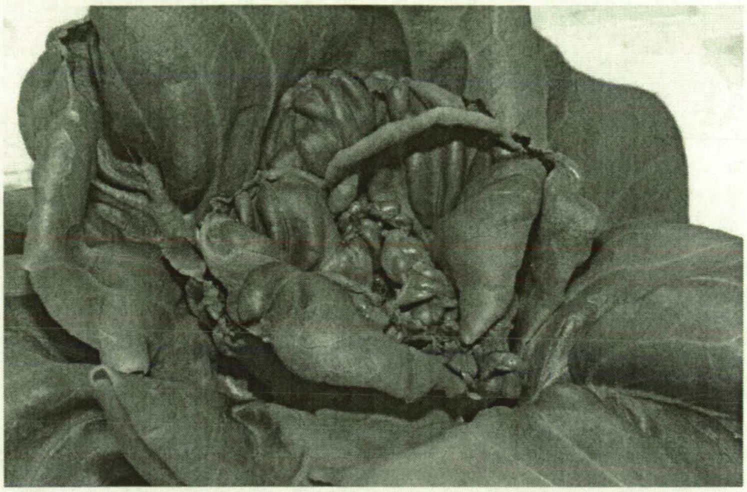
High-Yielding Systems with High Light

(Euro Fresh Corp., Wilcox, Arizona, USA)



Tomato yields up to 80 kg m^{-2} $year^{-1}$, $\approx$ 20 g DM m^{-2} day^{-1}

Plant Physiological Disorders--Leaf Tipburn



Lettuce cv. Flandria

Physiological Disorders--Blossom-End Rot

Pepper
cv. Fruit Basket

Physiological Disorders--Long Photoperiod Intolerance

Potato cv. Denali

Note: Upright, chlorotic leaves

Physiological Disorders--Oedema

Potato cv. Denali

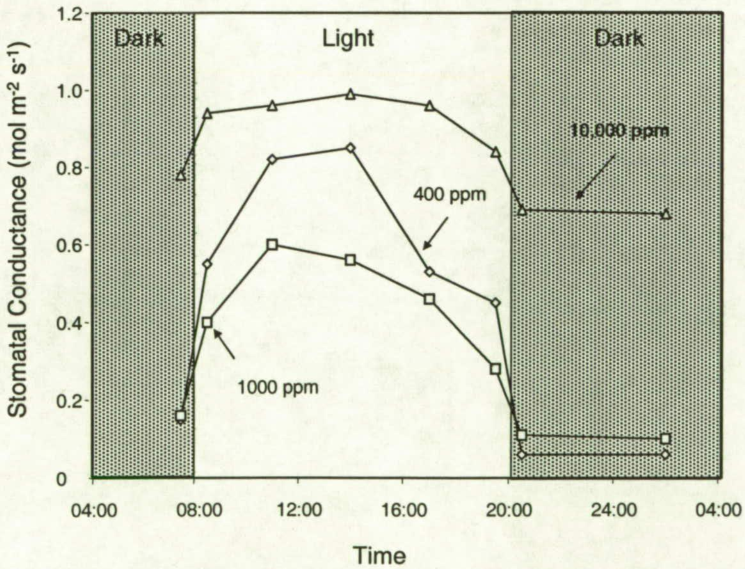
Physiological Disorders--Super-Elevated CO_2 Injury

Soybean-5000 ppm CO_2

Radish-10,000 ppm CO_2

- Wheeler, R.M., C.L. Mackowiak, L.M. Siegriest, J.C. Sager. 1993. J. Plant Physiol. 142:173-178.

CO_2 Effects on Stomata



Wheeler, R.M. 2006. Potato Res. (in press)

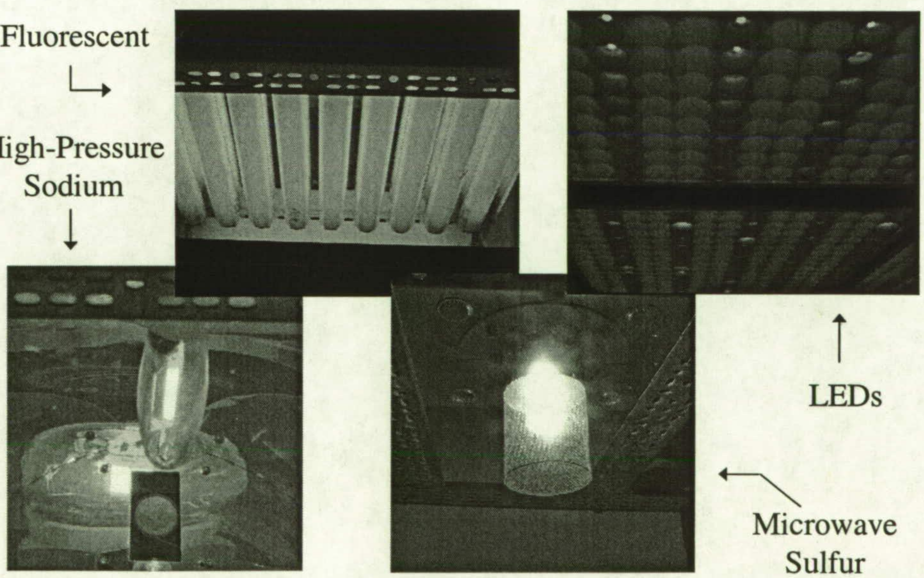
The Importance of Lighting

--Electric Lamp Options

Lamp Type	*Conversion* Efficiency*	*Lamp Life* (hrs)*	*Spectrum*
• Incandescent/Tungsten**	5-10%	2000	Intermd.
• Xenon	5-10%	2000	Broad
• Fluorescent***	20%	5,000-20,000	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.*

Electric Lighting Systems



LED Studies

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

Some References:

Bula et al. 1991. HortSci 26:203-205.

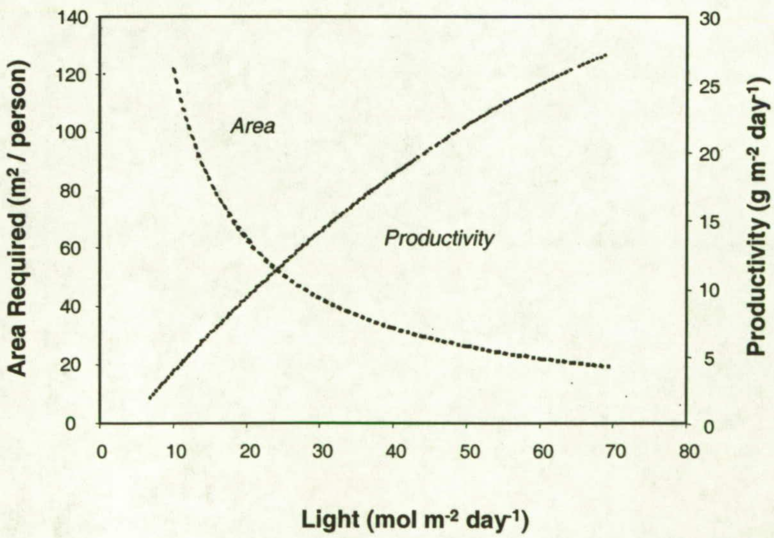
Barta et al. 1992. Adv. Space Res. 12(5):141-149.

Tennessen et al. 1994. Photosyn. Res. 39:85-92.

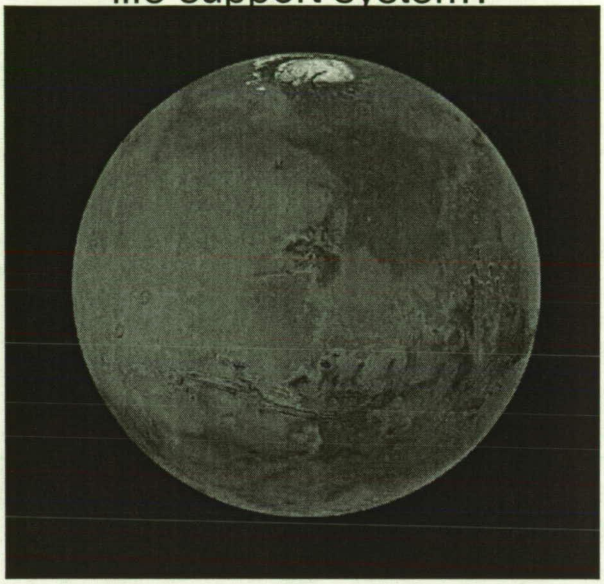
Goins et al. 1997. J. Exp. Botany 48:1407-1413.

Kim et al. 2004. Ann. Bot. 94:691-697

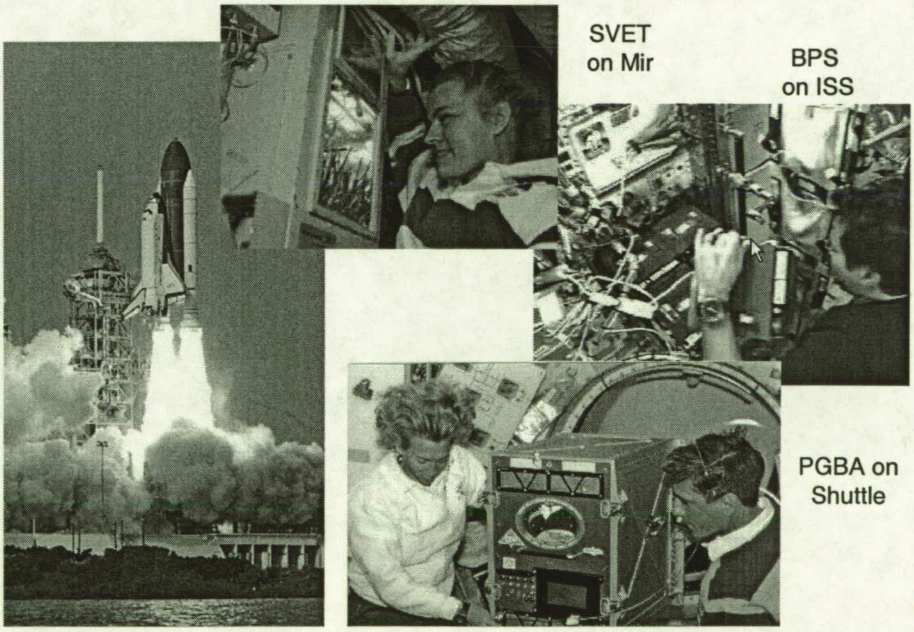
Light, Productivity, and Crop Area Requirements



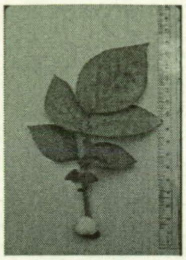
What will it take to achieve a plant-based life support system?

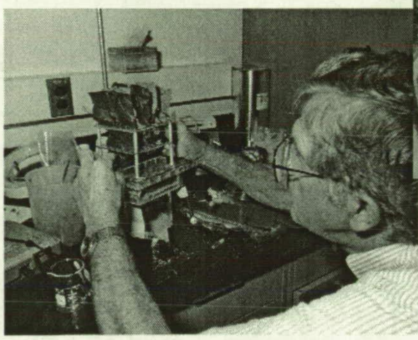


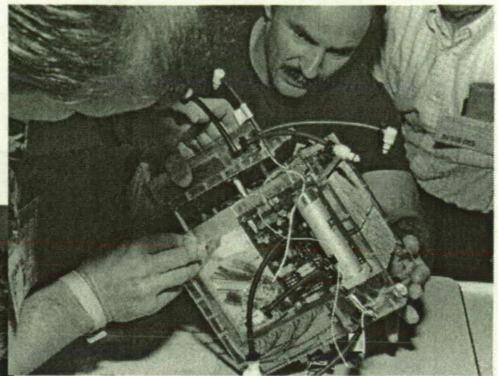
Start with Small Plant Chambers in Low-Earth Orbit



Potato Tubers Grown in Space

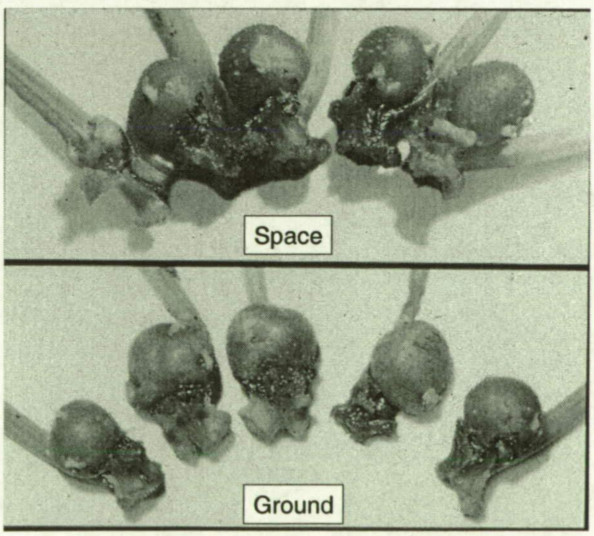






- STS-93 Shuttle Mission (1995)
- Five Leaf Cuttings in the Moist Arcillite
- 16 Days in Space
- Astroculture Plant Growth Unit

Space Environment Does Not Prevent Tuberization



Conduct a Demonstration on the International Space Station (ISS)

Russian Cosmonaut with
Mizuna Plants
(Chinese Cabbage)

Expand to a Production Oriented Design -- Such as the 3-Dimensional Phytoconveyor

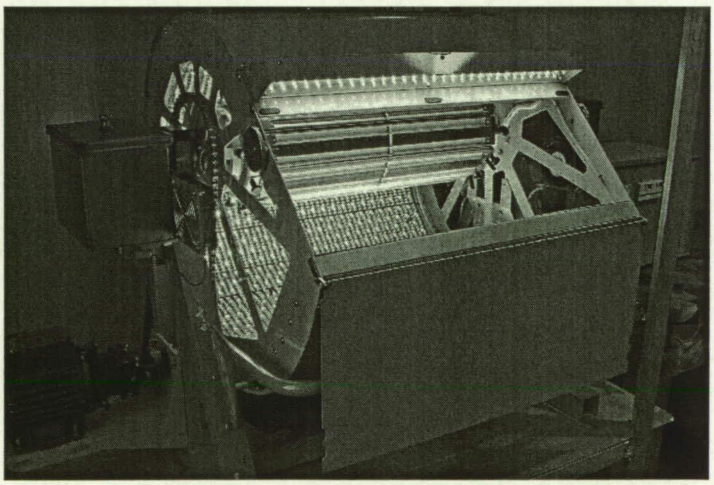
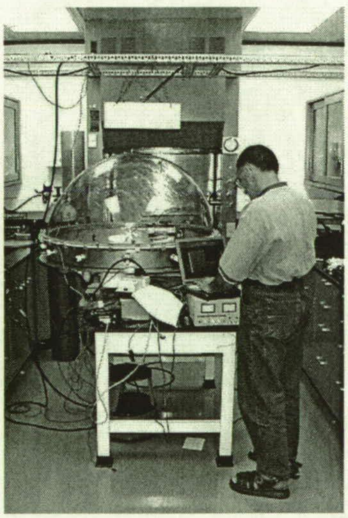


Photo Courtesy of Dr. Yuli Berkovitch, Inst. for Biomedical Problems, Moscow

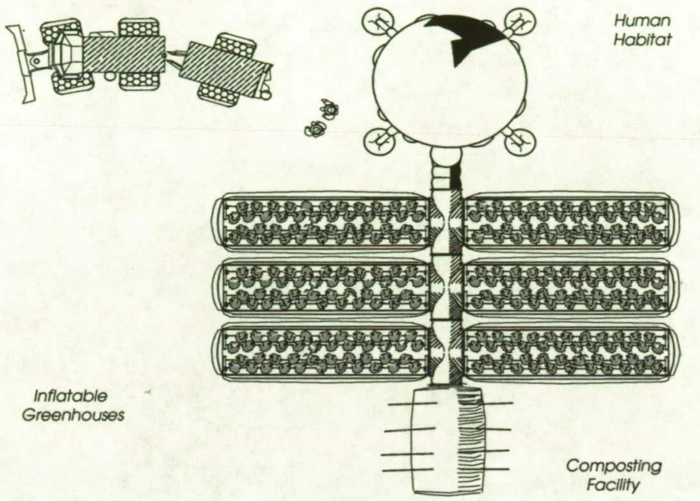
Use ISS Experience to Build a Vegetable Production Unit for "Transit Missions" to Mars

Test Planetary Surface Deployable Greenhouse Concepts

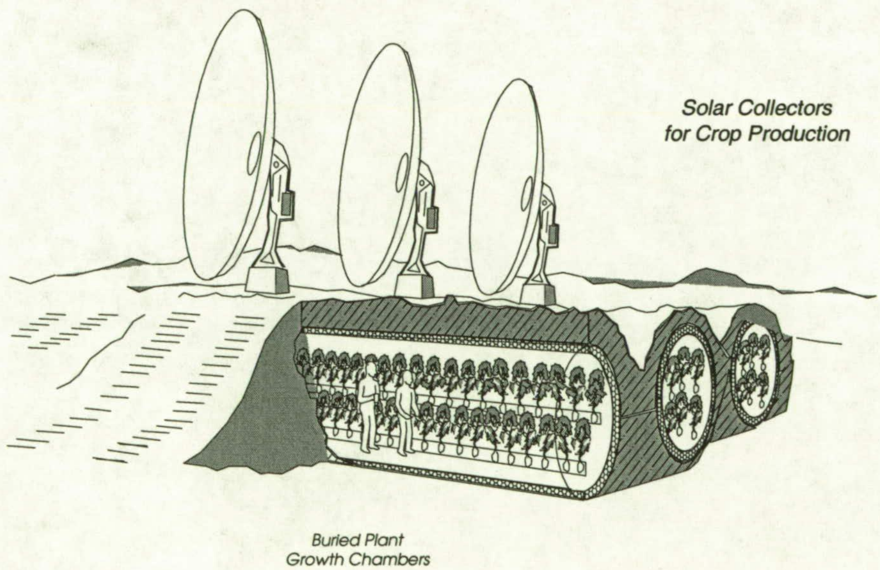
→ such as light weight inflatable structures



Multiple Inflatable Greenhouses for Life Support



Assess Shielded Structures for Radiation Protection



Conduct Human Testing with Plants in Closed Systems

- BIOS Studies-Krasnoyarsk, Siberia
- IMBP Studies-Moscow
- BPC Studies, NASA-Kennedy Space Center
- VPGC Studies, NASA-Johnson Space Center
- LMLSTP Studies, NASA-Johnson Space Cen.
- IES / CEEF, Rokkasho, Aomori, Japan

One Human and 11 m^2 of Wheat !

Terrestrial Testbeds South Pole Station Antarctica

Jenn Nelkin, Univ. of Arizona with US Senator John McCain

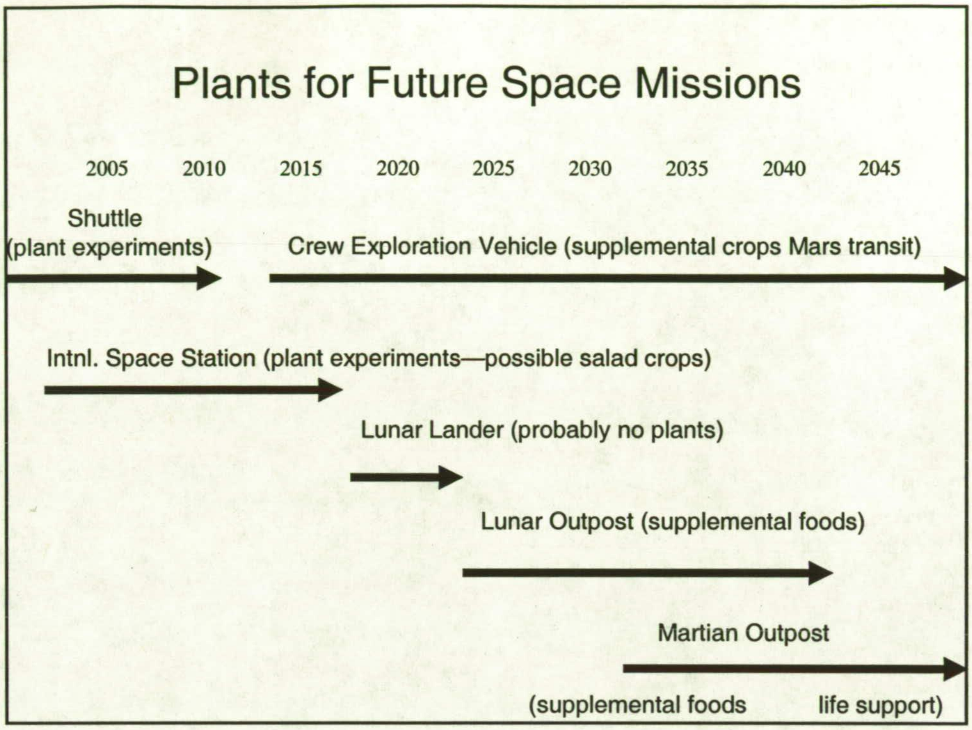
Constraints for Crop Production in Space:

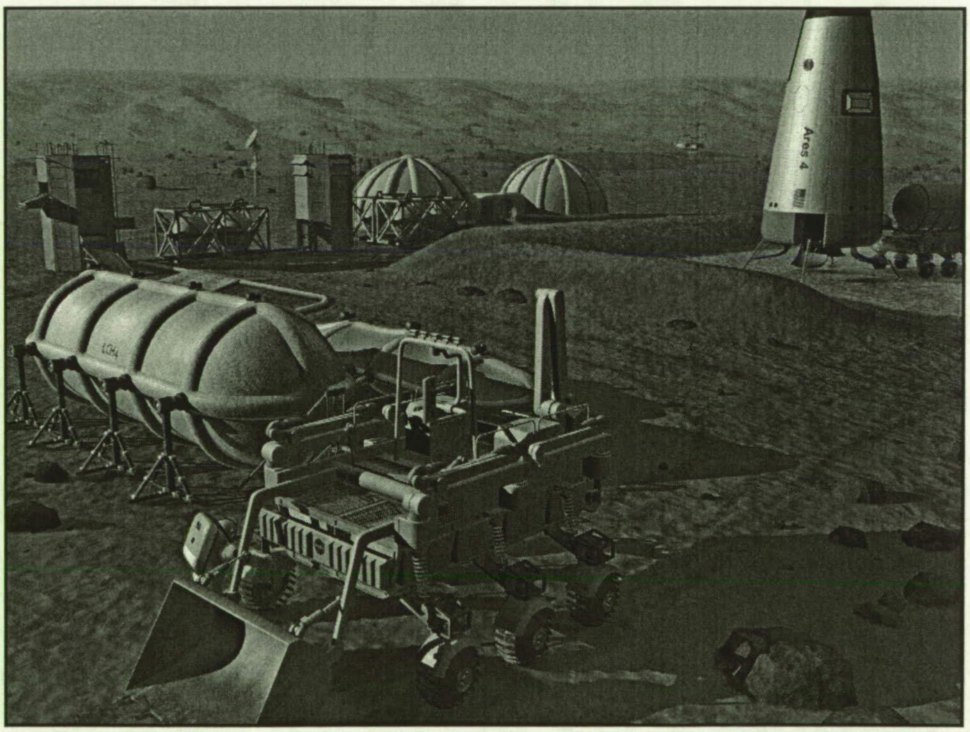
("Economics" of Life Support)

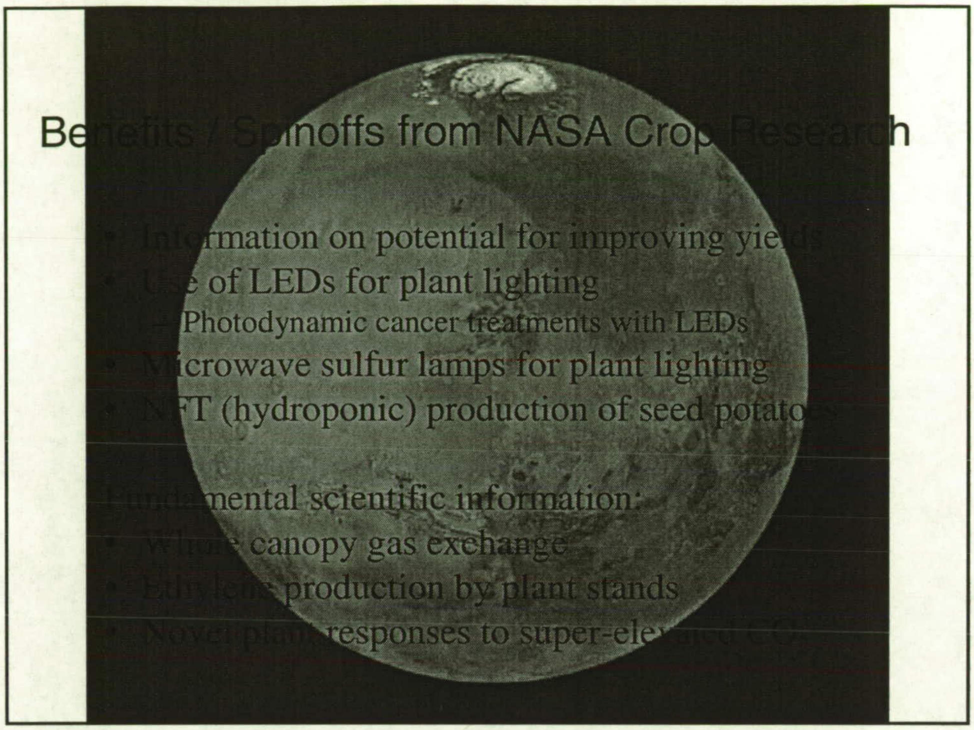
- Energy Requirements
- System Mass
- System Volume
- Crew Time
- System Reliability

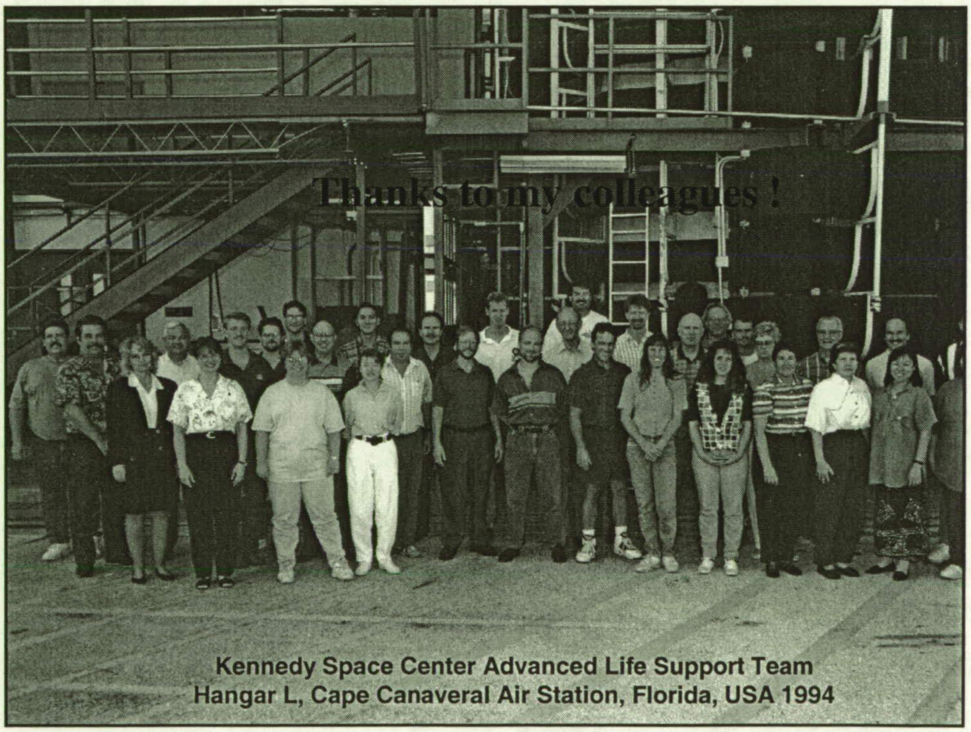
These apply for all life support technologies, including the use of plants

For Plants, Lighting Dominates These Costs !


Plants for Future Space Missions
2005 2010 2015 2020 2025 2030 2035 2040 2045
Shuttle
(plant experiments)
Crew Exploration Vehicle (supplemental crops Mars transit)
Intnl. Space Station (plant experiments—possible salad crops)
Lunar Lander (probably no plants)
Lunar Outpost (supplemental foods)
Martian Outpost
(supplemental foods
life support)


Ares 4


Benefits / Spinoffs from NASA Crop Research
• Information on potential for improving yields
• Use of LEDs for plant lighting
– Photodynamic cancer treatments with LEDs
• Microwave sulfur lamps for plant lighting
• NFT (hydroponic) production of seed potatoes
Fundamental scientific information:
• Whole canopy gas exchange
• Ethylene production by plant stands
• Novel plant responses to super-elevated CO_2


Thanks to my colleagues !
Kennedy Space Center Advanced Life Support Team
Hangar L, Cape Canaveral Air Station, Florida, USA 1994