North American Position: Lighting Technologies for Energy Limited Environments

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- **Controlled Environment Agriculture is by its nature energy limited**
- **"Space" is an extreme example**

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Greenhouse gasses:

- United States emits about 25 percent of the gases that produce global warming
- About 82% is from burning fossil fuels to generate electricity and to power our cars
- Annual per capita emissions:
  - United States-6.6 tons
  - Australia-6.5 tons
  - Canada-6.0
  - Netherlands-4.2 tons
  - Germany-3.7 tons
  - United Kingdom-3.2 tons
  - Japan-2.9 tons
- Lighting accounts for about 85% of energy costs, including heat removal from sources in CEA

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Energy Policy and the Kyoto Accord:

- **United States Energy Policy**
  - Develop new sources
  - Develop new technologies
  - Increase conservation
- **Why did the US pull out of the Kyoto Accord?**
  - George Bush thinks it unfair to the United States, as it leaves out developing countries, and would lead to higher energy prices in the United States
  - President Bush wants technology to play a role in cutting pollution and improved conservation
  - "The treaty is based upon flawed ideas. Research data on climate change do not show that human use of hydrocarbons is harmful. To the contrary, there is good evidence that increased atmospheric carbon dioxide is environmentally helpful." Dr. Frederick Seitz, president emeritus of Rockefeller University and a past president of the U.S. National Academy of Sciences

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Controlled Environment Lighting Systems

- Electrical demand-85%
- Thermal load-85%
- System mass-31%

System Components

- Source
  - Electrical conversion efficiency
- Distribution
  - Delivery efficiency of the PAR from source to canopy
- Receiver (plant canopy)
  - Absorption of the PAR by the photosynthetic pigments

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System Components

- Source
  - Electrical conversion efficiency
    - energy at the wall to PAR
- Distribution
  - Delivery efficiency of the PAR from source to canopy
    - photons from the source to the plant

- Receiver (plant canopy)
  - Absorption of the PAR by the photosynthetic pigments
    - spectral efficiency of the photons in exciting the photosynthetic pigments

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Lighting Efficiency Data

Parameter	Low	Nominal	High	Comments
Light Conversion Efficiency	0.1	0.3	0.5	Proportion of power turned into PPF
Light Delivery Efficiency	0.3	0.6	0.8	Proportion of PPF delivered to canopy
Overall Light Delivery Efficiency	0.03	0.2	0.4	Source to canopy

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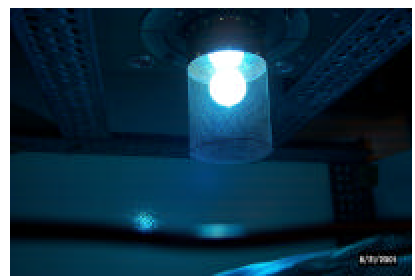
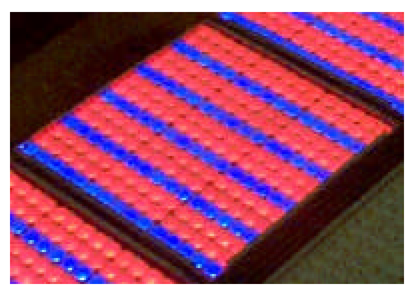
Sources



- **Sulphur lamp (microwave)**
- **Best conversion efficiency**
- **Uniform broad-spectrum**
- **Output dimmeable**
- **Point source requires distribution system**



- **LEDs**
- **Small mass and volume**
- **Limited thermal radiation**
- **Plants in close proximity**
- **Particularly suited for space**

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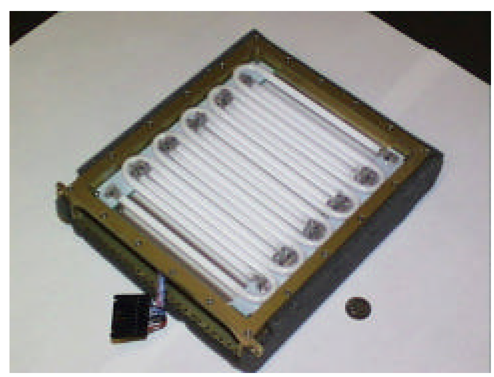
Sources (continued)

•Solar
•High thermal radiation
•P-P variable

•Fluorescent lamps
•Uniform distribution
•Thermal radiation load
•Efficient configuration



•HID lamps
•High efficiency
•High thermal radiation
•Non-point

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Lamp Characteristics:

Lamp Type	Conversion* Efficiency	Lamp Life* *(hrs)*	Spectrum
Incandescent	5-15%	~2000	Broad (-)
Xenon	5-10%	~5000	Broad
Fluorescent	~20%	~5,000	Broad
LEDs	~20%	>100,000	Narrow
Metal Halide	~25%	~20,000	Broad
High Pres. Sodium	30-35%	~20,000	Broad (-)
Low Pressure Sodium	~ 35%	~20,000	Narrow
Sulfur (Microwave)	35-50%	> 20,000	Broad

**** Approximate values***

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Distribution

- •Water jacketed lamps
- •Diffusers
- •Luminaires
- •Hybrid sources
- •Fibre optics / light pipes

Receiver (plant canopy)

- •Spectral distribution of source
- •Excitation of the photosynthetic pigments
- •Spacing of the crop for maximum area coverage
- •Geometry of the plant canopy for optimum interception

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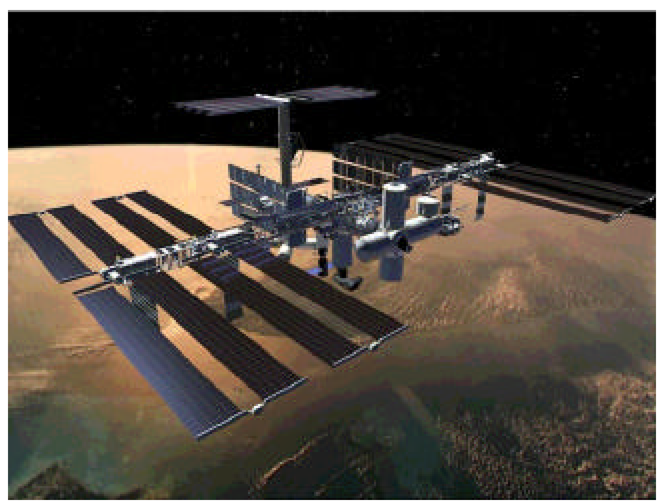
Energy Limits in Space Environments

Mid-deck lockers
- single-120W
- double-240W



ISS Express rack-1000W

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Design Challenges for Space Applications

•Low conversion efficiency and high Equivalent System Mass are more critical in the transit and Mars scenarios than on Earth

•Poor transport and distribution efficiency to the plant / crops

•Improvement of crop productivity and development through more efficient light delivery, interception, and photosynthesis (e.g. spacing and developmental physiology)

•New technologies must be developed and existing technologies improved

•The high energy demand to provide for biomass production is the primary obstacle to developing feasible bioregenerative system