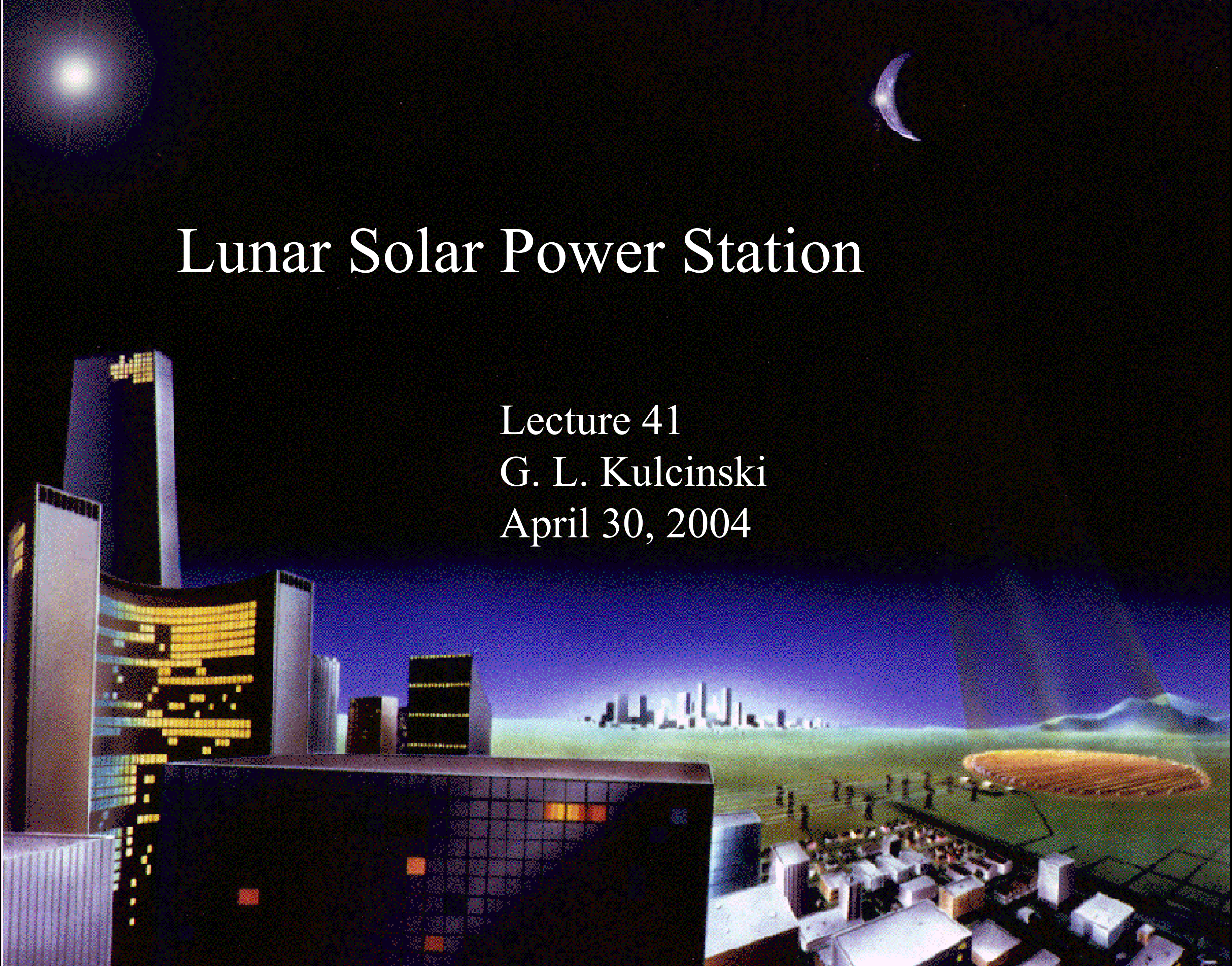


Lunar Solar Power Station

Lecture 41
G. L. Kulcinski
April 30, 2004

Why Are We Interested in a Lunar Based Solar Power System (LSPS)?

- General Features of Extraterrestrial Solar Power Systems
  - The Sun is a dependable energy source that supplies high quality energy
  - Concept utilizes passive and low mass equipment to collect and generate electricity
  - Can be operated while repairs are made

Why Are We Interested in a Lunar Based Solar Power System (LSPS)? (cont.)

- Why the Moon vs. GEO?
  - Stable and predicable platform (low gravity, no wind, few moonquakes)
  - The Moon contains all the materials needed for solar cells and structures (reduces transportation over SPS)
  - Less intrusive than GEO positioning
  - Improved worker safety

Solar Energy From Space

Solar Power Satellites

- Pioneered by Peter Glaser
- Originally proposed 1968
- Subjected to scrutiny by NASA, DOE, and National Academy of Sciences

Lunar Power System

- Pioneered by David Criswell
- Originally proposed 1985
- Subjected to analysis by NASA and U. of Houston

Selected Recent Lunar Solar Power References by David Criswell

- Criswell, D. R. (2002 Oct.) Lunar solar power (LSP) System-Driven human development of the Moon and the resource-rich exploration of the inner solar system, IAA-02-IAA 13.2.07, 6pp., International Astronautics Federation and World Space Congress, Houston, TX

- Criswell, D. R. (2002 Oct.) Accelerating 21st century economic growth by implementation of the Lunar Solar Power (LSP) System, IAF-02-R.3.04, 6pp., International Astronautics Federation and World Space Congress, Houston, TX

- Criswell, D. R. (2002 Oct.) Development and commercialization of the Lunar Solar Power (LSP) System, IAA-02-IAA 1.2.04, 6pp., International Astronautics Federation and World Space Congress, Houston, TX

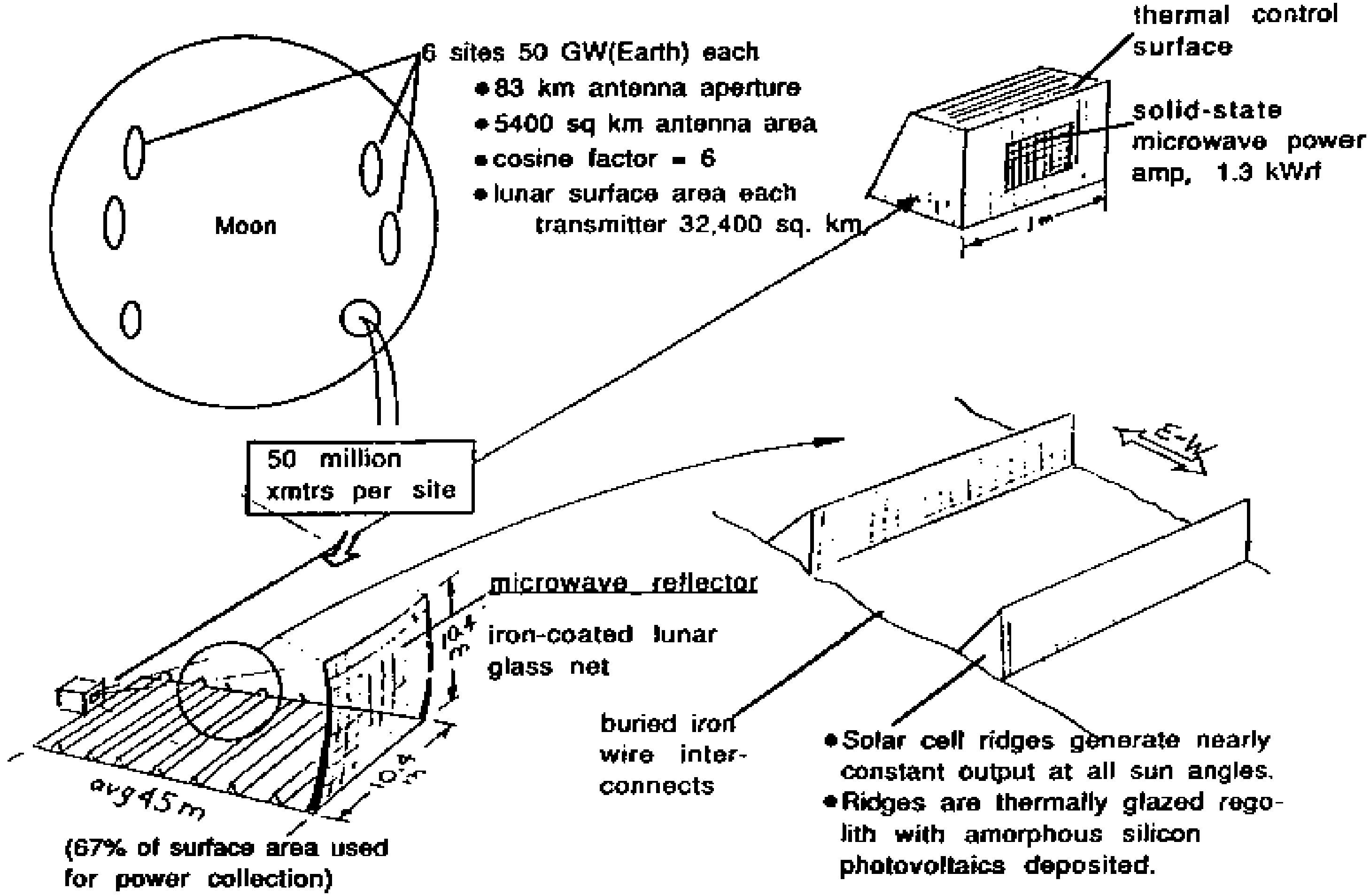
- Martin Hoffert, Ken Calderia, Gregory Benford, David R. Criswell, Christopher Green, Howard Herzog, Atul K. Jain, Haroon S. Kheshgi, Klaus S. Lackner, John S. Lewis, H. Douglas Lightfoot, Wallace Manheimer, John C. Mankins, Michael E. Mauel, L. John Perkins, Michael E. Schlesinger, Tyler Volk, and Tom M. L. Wigley (2002 November 1) Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet, Science, Vol. 298, 981 – 987.

- Martin Hoffert, Ken Calderia, Gregory Benford, David R. Criswell, Christopher Green, Howard Herzog, Atul K. Jain, Haroon S. Kheshgi, Klaus S. Lackner, John S. Lewis, H. Douglas Lightfoot, Wallace Manheimer, John C. Mankins, Michael E. Mauel, L. John Perkins, Michael E. Schlesinger, Tyler Volk, and Tom M. L. Wigley (2003 April 25) Response – Existing technologies can contribute, Science, Vol. 300, 582 – 583. Also see 581-582.

- Criswell, D. R. (2003 December, Invited), Lunar Solar Power System: A return to the Moon?, IEEE Potentials, 20 – 25, 4 photographs, 4 figures.

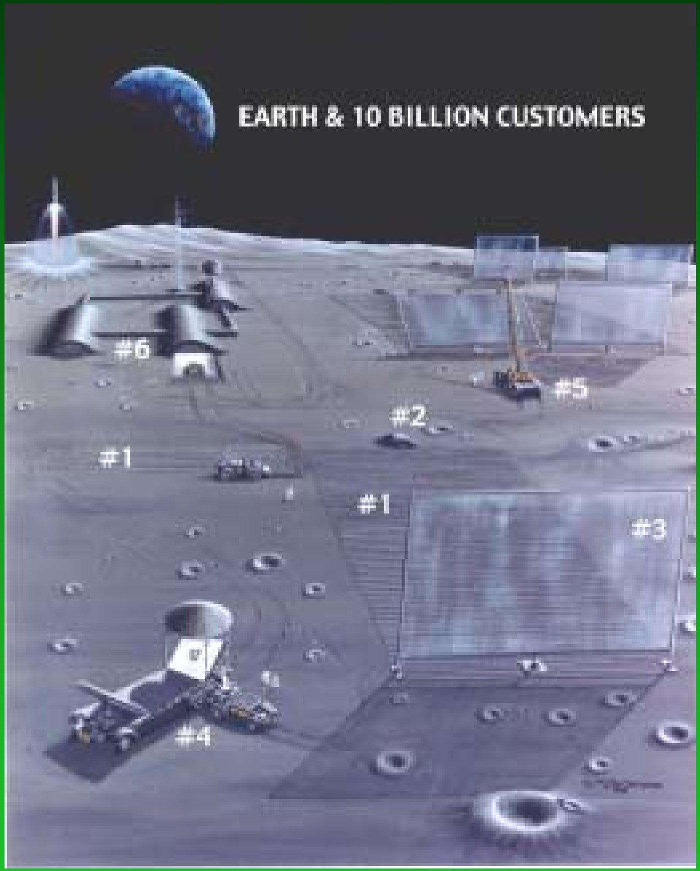
- Criswell, D. R. (2004 - now on sale) Lunar Solar Power, in The Encyclopedia of Energy (editor in chief – C. J. Cleveland, managing editor – R. Matsumura), paper #226, manuscript 38pp, 3 tables, 5 figures, Academic Press, Elsiever.

Lunar Power System Concept



After Woodcock, 1989

DEMONSTRATION LSP BASE



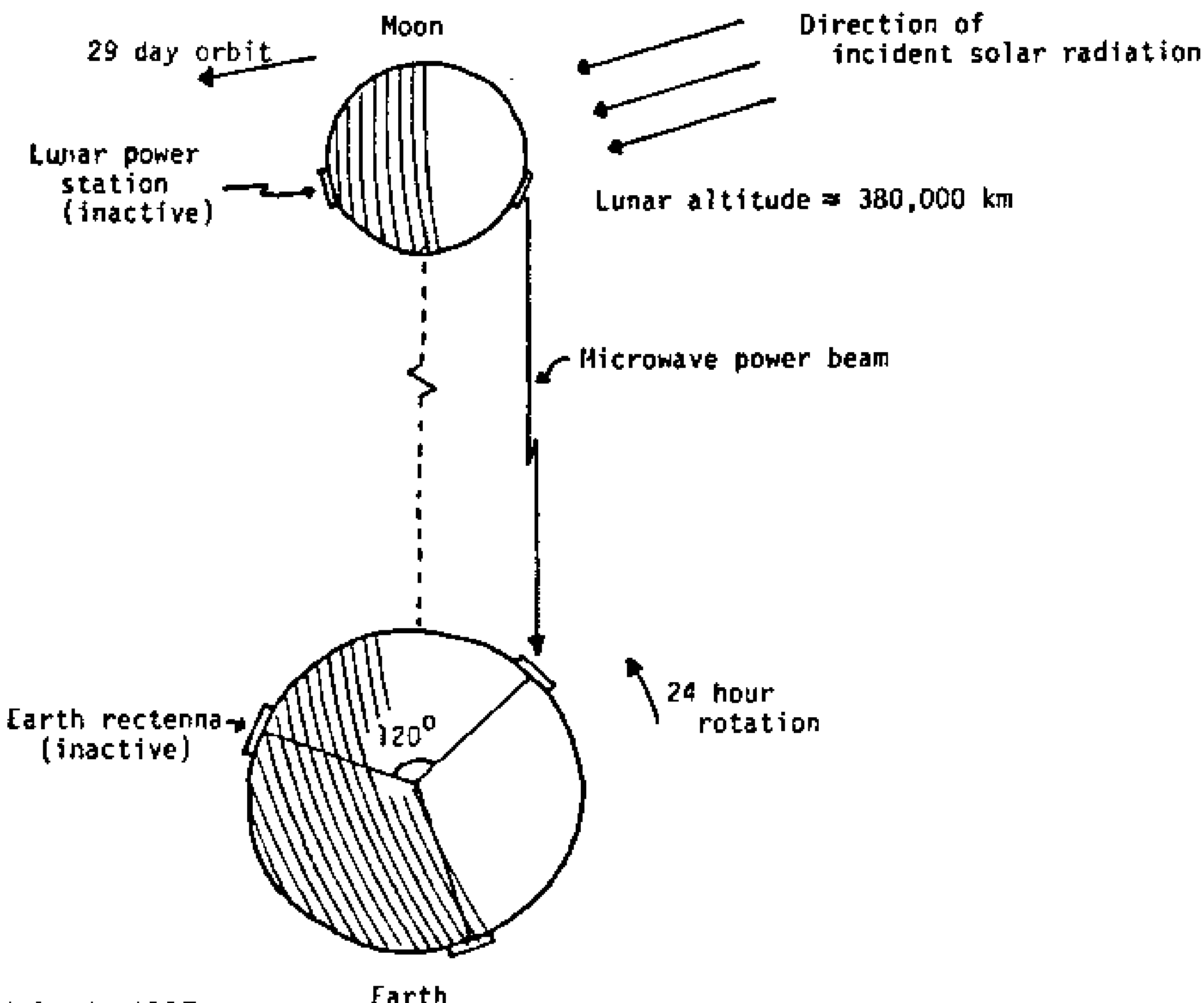
Harvesting the Moon

- EARTH IS FIXED IN SKY
- BASE IS COMPOSED OF POWER PLOTS
- POWER PLOT - BASIC UNIT
  - #1 Solar arrays, buried wiring
  - #2 Microwave transmitters
  - #3 Reflectors form a large lens as seen from Earth
- #1, 2, & 3 ARE MADE FROM LUNAR MATERIALS BY #4, 5, & 6 PRODUCTION EQUIPMENT

Concerns About the LSPS

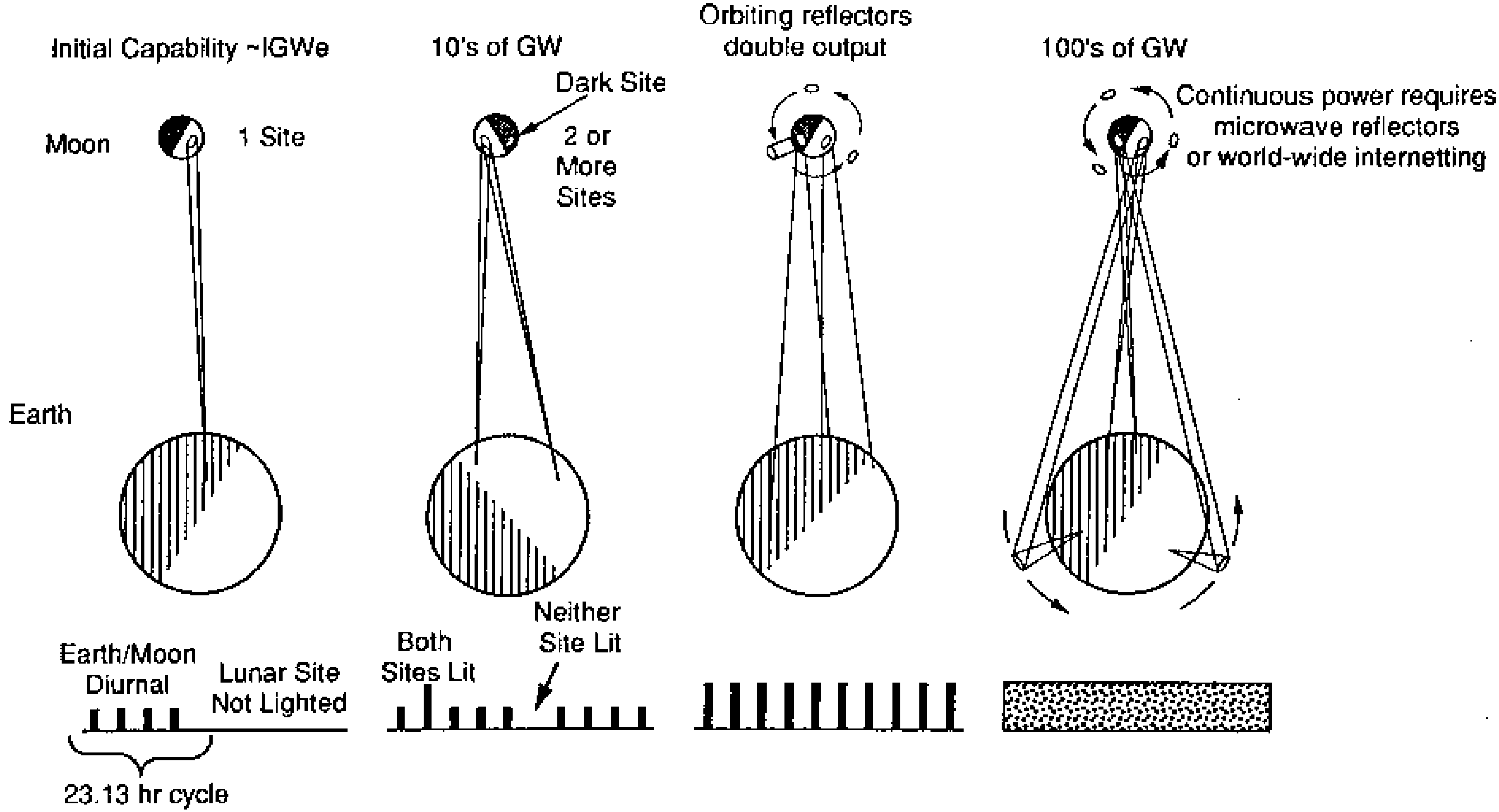
- Lunar base only receives solar energy 50% of the time (need multiple collection bases)
- Rotation of the Earth means multiple receiving stations are required
- Fixed collectors do not collect optimum solar flux
- Si cells are about 1/3 the efficiency of GaAs cells
- Larger transmitting distance requires bigger transmitting antenna

The Rotation of the Moon and Earth Requires Multiple Collection and Receiving Units



After Kerwin and Arndt, 1985

Evolution of Lunar Power System to Continuous Baseload Power Requires Auxiliary Reflectors at Earth and Moon



After Woodcock, 1989

The Collection Area of a Lunar Power System Must be Much larger Than That for a SPS

- Factor of 2 because of day/night cycle
- Factor of 2 because of fixed oblique solar incidence angle
- Factor of 3 because Si converters are 1/3 the efficiency of GaAs.

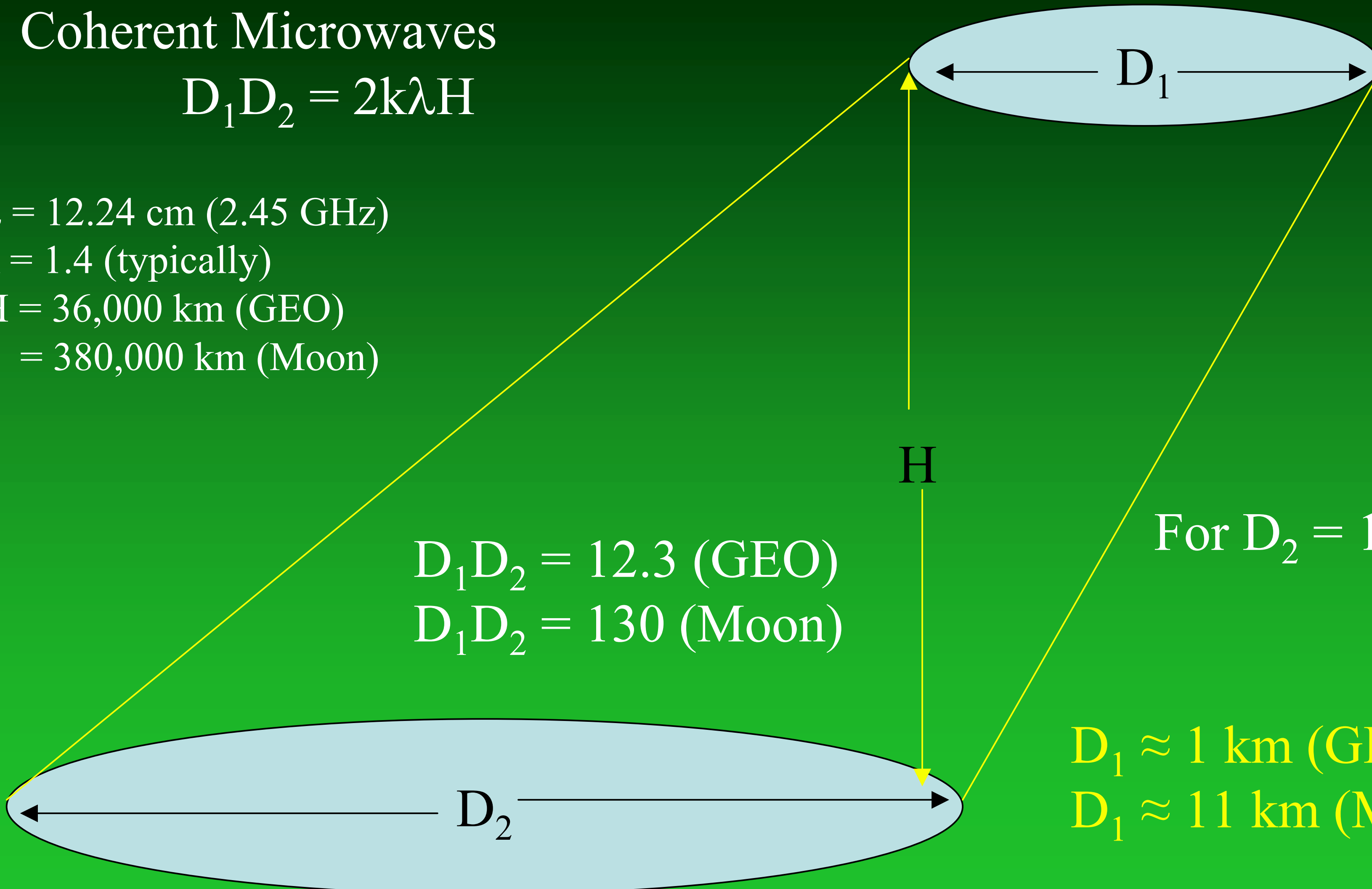
The total area of LSPS is ≈ 12 times that of a SPS

Transmitting Antenna Sizing Criteria

Coherent Microwaves

$$D_1 D_2 = 2k\lambda H$$

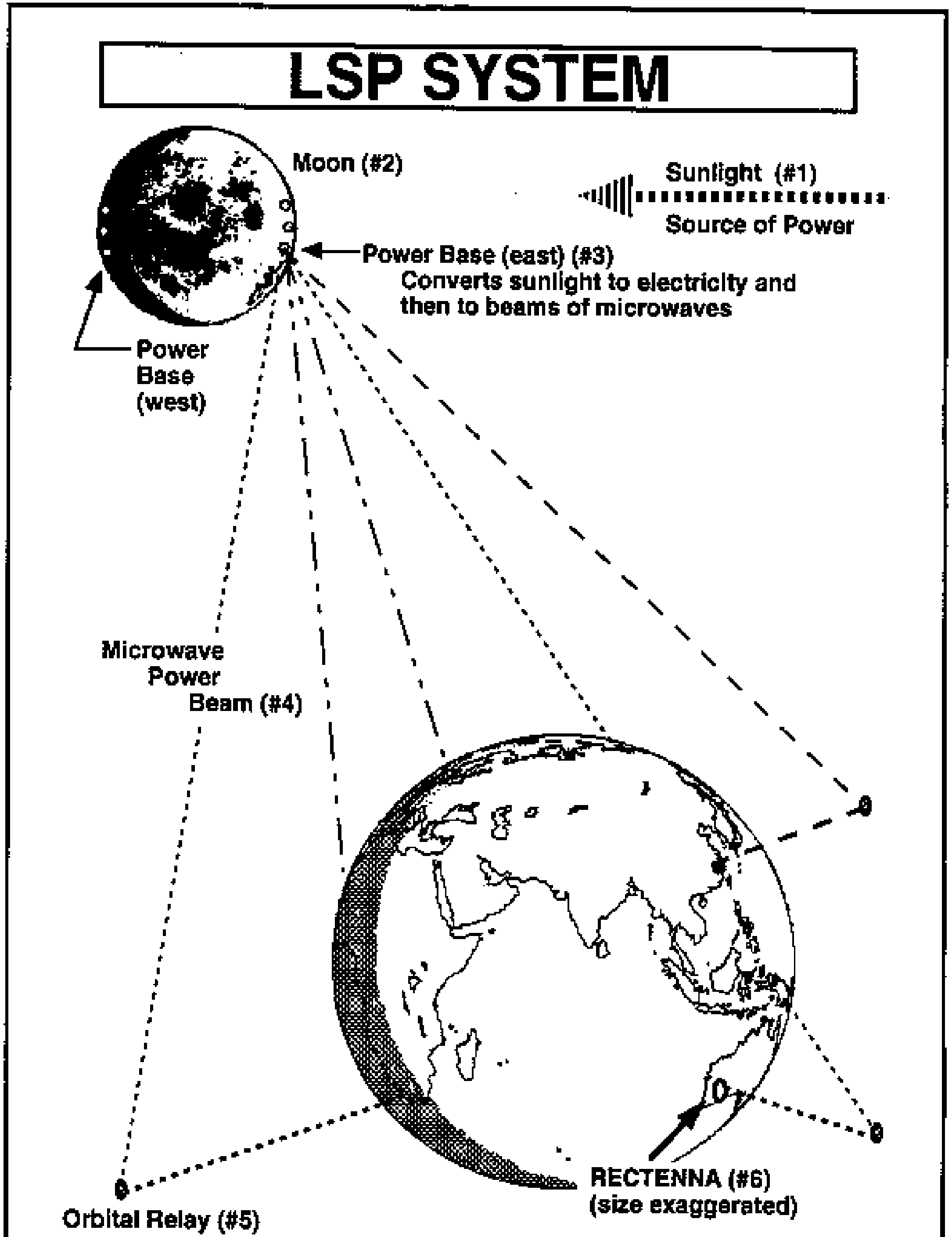
λ = 12.24 cm (2.45 GHz)
k = 1.4 (typically)
H = 36,000 km (GEO)
= 380,000 km (Moon)



$D_1 D_2 = 12.3$ (GEO)
$D_1 D_2 = 130$ (Moon)

For $D_2 = 12$ km

$D_1 \approx 1$ km (GEO)
$D_1 \approx 11$ km (Moon)



LSP SYSTEM
Moon (#2)
Sunlight (#1)
Source of Power
Power Base (east) (#3)
Converts sunlight to electricity and
then to beams of microwaves
Power
Base
(west)
Microwave
Power
Beam (#4)
Orbital Relay (#5)
RECTENNA (#6)
(size exaggerated)

EARTH'S MOON & LSP POWER BASES

Harvested Moon

Ref: David Criswell

- MOON WITH BASES
  - Receives 13,000 TWs
  - Bases built using known lunar materials in known environment
- 10 POWER BASE PAIRS
  - Always face the Earth
  - Beam ~20 – 30 TWe to Earth

Lunar Solar Power Reference Design- 20,000 GW_e-(Criswell 1996)

World Installed capacity -1999-3,180 Gwe

Illumination of one cell (geometry)	32%
Fill factor (ground cell area/base area)	20%
Solar cell efficiency	10%
Collection efficiency	90%
Electricity to microwave	85%
Transmission to Earth	73%
Earth atmosphere transmission	98%
Rectenna collection efficiency	89%
Microwave power conditioning	88%
Electric grid conditioning	97%
Overall efficiency for 1,368 W/m^2 (electricity to Earth grid/lunar solar watt)	0.266%

Lunar Solar Power Reference Design- 20,000 GW_e- (Criswell 1996)- Continued

- For a 0.266% overall efficiency and to produce 20,000 GW_e, one would need to cover 15.3% of the lunar surface.
- Number of bases required would be 12 (pairs)

Lunar Solar Power Reference Design- 20,000 GW_e- (Criswell 1996)- Continued

• Total regolith handled	2 billion tons/y
• Lunar equipment mining processing support	 12, 739 tons 428,481 tons 48,171 tons
• Transport to Space from Earth (ave. for 10y ramp-up) from Earth (parts, consumables, > 10 y) from the Moon (LO mirrors)	 70,314 tons/y 172,687 tons/y 336,181 tons/y
• People on the Moon in LLO in LEO	 5,000 395 486

Lunar Solar Power Reference Design- 20,000 GW_e-(Criswell 1996)- Continued

• Costs ($1995 billions)	
Space	4,926
Earth (mainly rectennas)	17,040
Total	21,966
• Capital Costs	1,098 $\$/kW_e$

It is Claimed That the Total Mass Investment for Electricity from Lunar Solar Energy is Less Than for Terrestrial Solar Energy Systems

	$Tons/GW_e$
Terrestrial Thermal Power Systems	310,000
Terrestrial Photovoltaic	430,000
Lunar Solar power System	52,000

After Criswell and Thompson, 1996

MASS & COST PROJECTIONS

- 20 TWe BY 2050 & 1,000 TWe-y BY 2070
  - 90% local manufacturing & tele-operation from Earth
  - $1 \cdot 10^5$ km^2 of reflective rectennas on Earth (0.8 T$)*

TOTAL MASS TO MOON (tonnes)	
Micro-manufacturing	24,361
Hot Forming	10,313
Beneficiation	3,212
Habitats, shops, mobile units	22,085
Chemical Refining	2,469
Gather & eject to orbit	438
Excavation	80
Cold Assembly	28
TOTAL	62,915
PEOPLE (6 month tours)	
Moon	436
Lunar Orbit	59
Earth Orbit	63
LUNAR & SPACE COST (2000$)	0.8 T$
***ENGINEERING COST (¢/kWe-h)**	**0.1**

- COST DISTRIBUTION
  - ~75% first 30 years
  - ~12 years breakeven
- TOTAL REVENUE ~80 T$ @ 1 ¢/kWe-h
- REVENUE NOT INCLUDED
  - Clean energy premium
  - Rectenna area dual-use

Ref: David Criswell, 2001

How Would You Fabricate Solar Cells On the Moon?

Utilize Lunar Resources to Fabricate Solar Cells on the Moon

- **Moon's Surface is an Ultra-High Vacuum**
  - **~ 10^{-10} Torr (day)**
  - **Use vacuum deposition to make thin film solar cells**
- **Elements Required for Silicon-based Thin Film Solar Cells are Present on the Moon**
  - **Silicon**
  - **Iron**
  - **Titanium Oxide**
  - **Calcium**
  - **Aluminum**

Reference:A. Ignatiev, U. Of Houston

Utilization of Lunar Resources - ISRU

- **Past Interest in Lunar Resource Utilization was the Extraction of Oxygen**

  - Waste Products were:

  . Silicon
  . Iron
  . TiO_2
  . Etc

  - These Waste Products can be used as Raw Materials for Solar Cell Fabrication….

Reference:A. Ignatiev, U. Of Houston

Carbothermal Reduction of Anorthite

Step 1. $4\ CH_4 \xrightarrow{1400^oC} 4\ C + 8\ H_2$

Step 2. $CaAl_2Si_2O_8 + 4\ C \xrightarrow{1650^oC} CaO + Al_2O_3 + 2\ Si + 4\ CO$

(anorthite)

m.p. 1521^oC

Step 3. $4\ CO + 12\ H_2 \xrightarrow[250^oC]{Ni\ Catalyst} 4\ CH_4 + 4\ H_2O$

Step 4. $4\ H_2O$ + electrolysis $\xrightarrow{75^oC} 4\ H_2 + 2\ O_2$

- **Closed cyclic process yielding both OXYGEN and SILICON:**

$CaAl_2Si_2O_8 \text{ ------> } CaO + Al_2O_3 + 2\ Si + 2\ O_2$

Reference: A. Ignatiev, U. Of Houston

Carbon Compounds Can Also be Used to Extract Oxygen, Fe, & TiO_2 from Lunar Illmenite

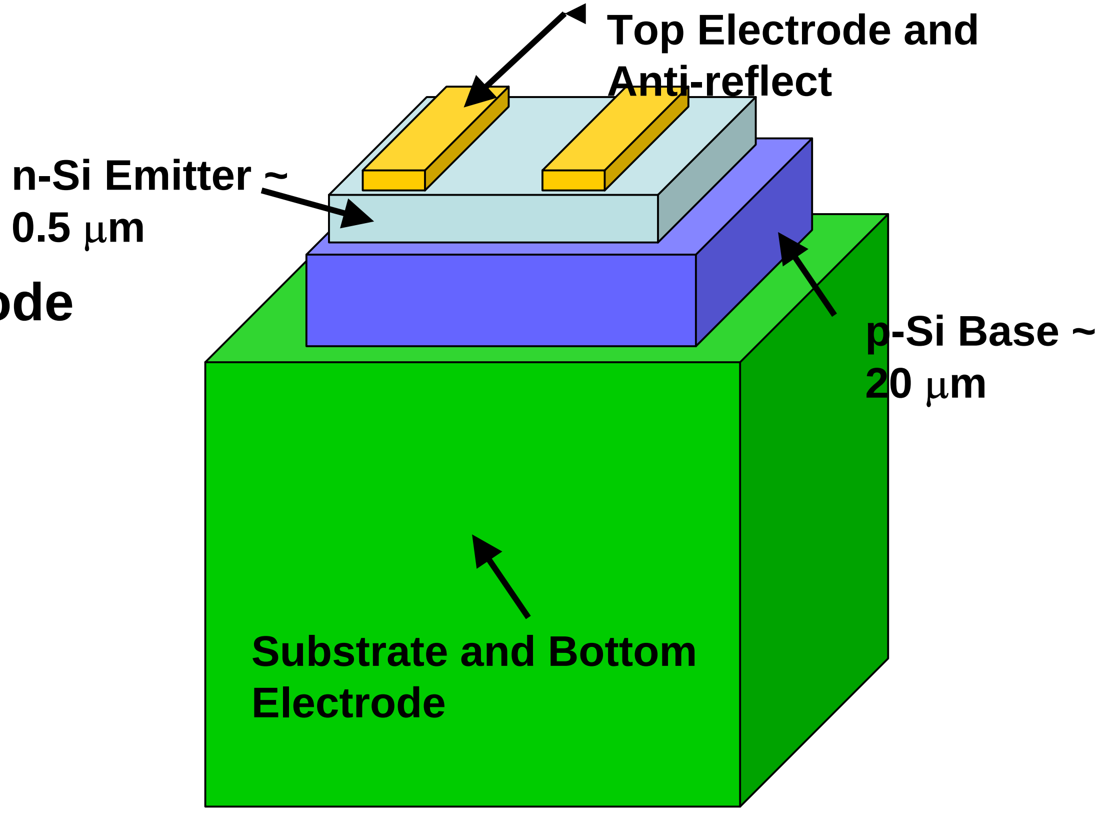
- Carbon Monoxide Cycle
  - $FeTiO_3 + CO$ <--> $Fe + TiO_2 + CO_2$
  - $2\ CO_2$ <--> $2\ CO + O_2$

- Methane Cycle
  - $FeTiO_3 + CH_4$ <--> $Fe + TiO_2 + CO + 2H_2$
  - $2\ CO + 6H_2$ <--> $2\ CH_4 + 2\ H_2O$
    - $2\ H_2O$ <--> $2H_2 + O_2$

⇒ **Yields iron for interconnect and TiO_2 for antireflect**

Fabrication of Thin Film Silicon Solar Cells on the Moon

- **Needs**
  - Substrate
  - Bottom electrode
  - p-n junction
  - Top patterned electrode
  - Antireflection layer
  - Interconnection of individual cells



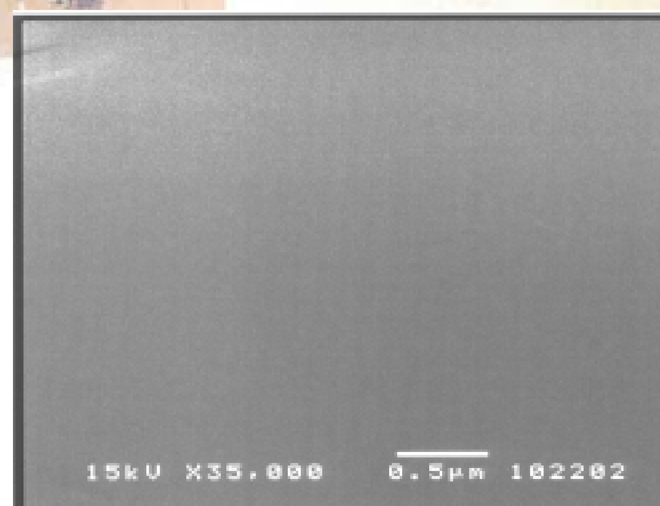
Reference:A. Ignatiev, U. Of Houston

Substrate

- **Use Lunar Regolith Simulant**
  - **Fine powder (<100 μm)**
  - **softens around 1300^{o}C**
  - **highly viscous state**
  - **some gas evolution**

  - **Melts around 1500^{o}C**
  - **less viscous**
  - **surface smoothes to be very flat**
  - **high resistivity > 2MΩ-cm**

  - **Excellent solar cell substrate**



Reference:A. Ignatiev, U. Of Houston

Solar Cell Fabrication Tool

- **Mechanized Solar Cell Growth Facility - Crawler**

  - ~ 150 - 200 kg

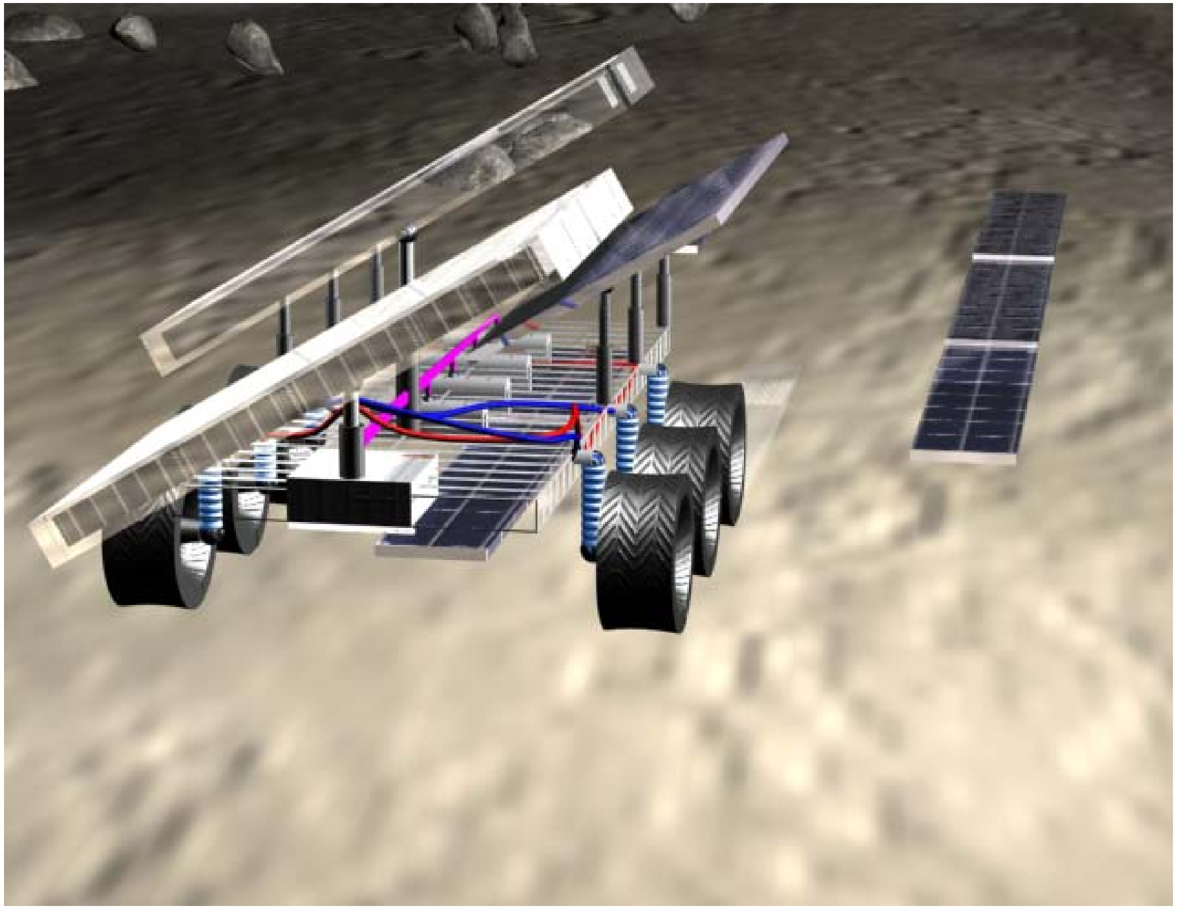
  - Multiple parabolic concentrator collectors - slow tracking

  - Solar panels for power

  - Continuous lay-out of cells on lunar surface

  - Remotely controlled

Reference:A. Ignatiev, U. Of Houston

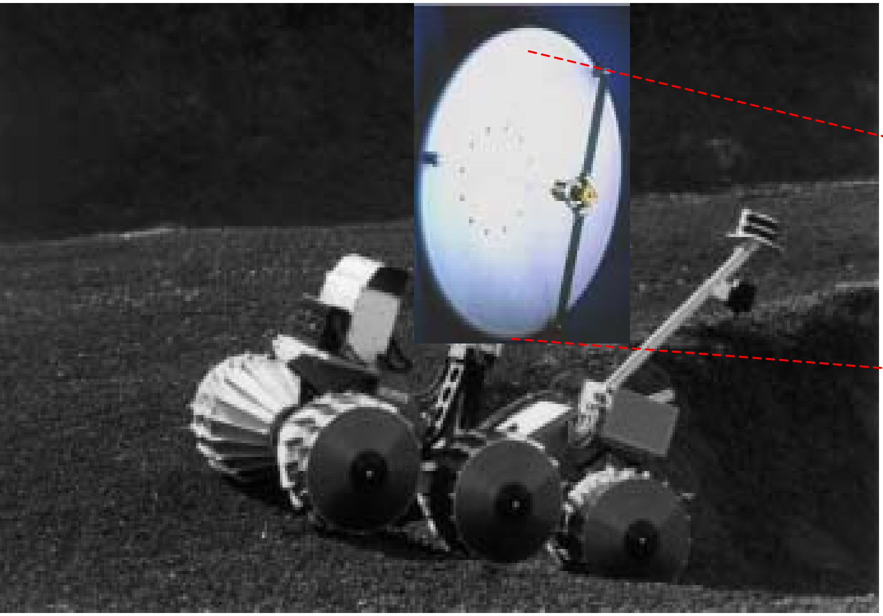


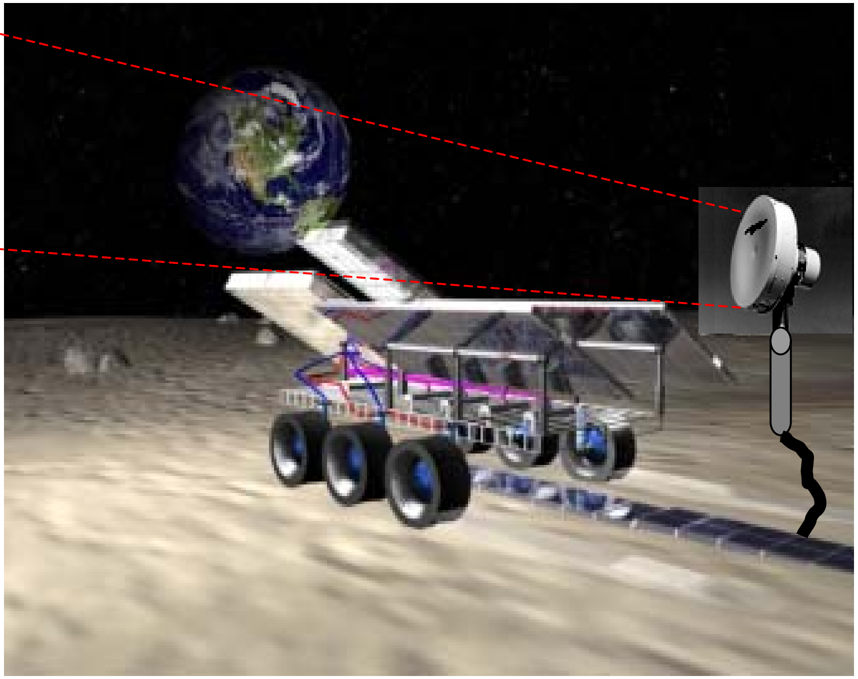
Lunar Solar Cell Fabricator/Crawler

Reference:A. Ignatiev, U. Of Houston

Distributed Energy on the Moon

Lunar Solar Cell Fabrication

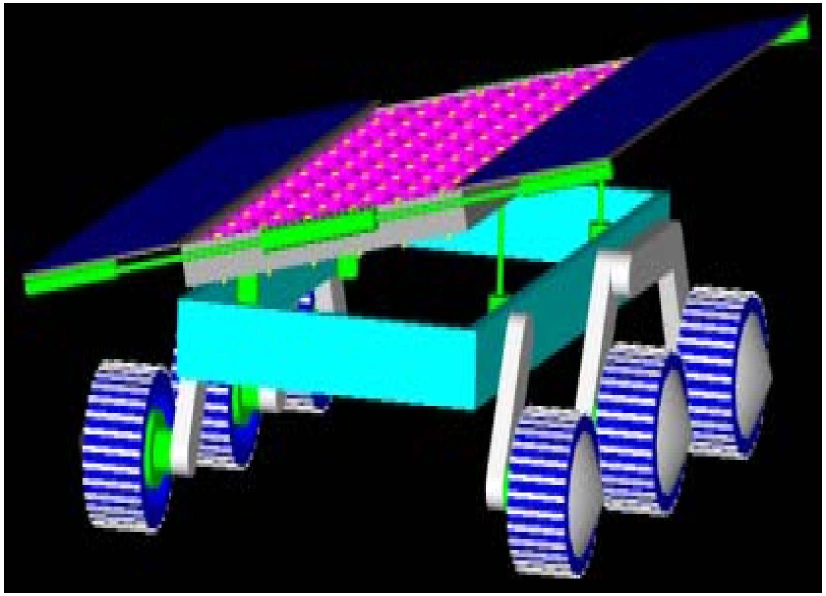




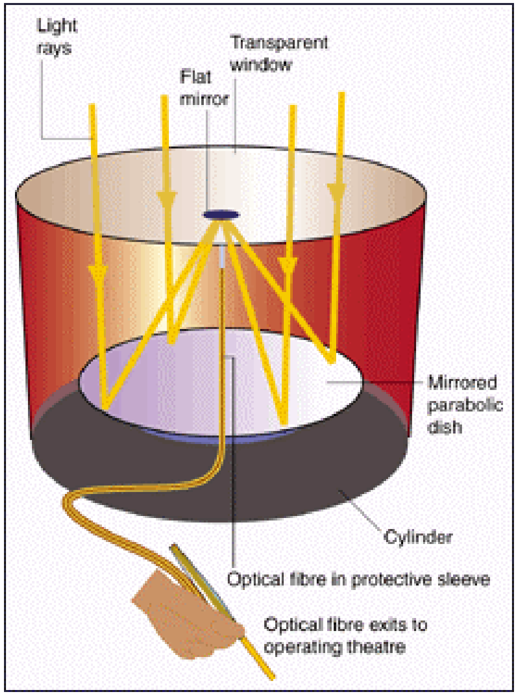
Lunar Power Beaming

Reference:A. Ignatiev, U. Of Houston

Cell Fabrication Facility with Parabolic Concentrators in Conjunction with Fiber Optics



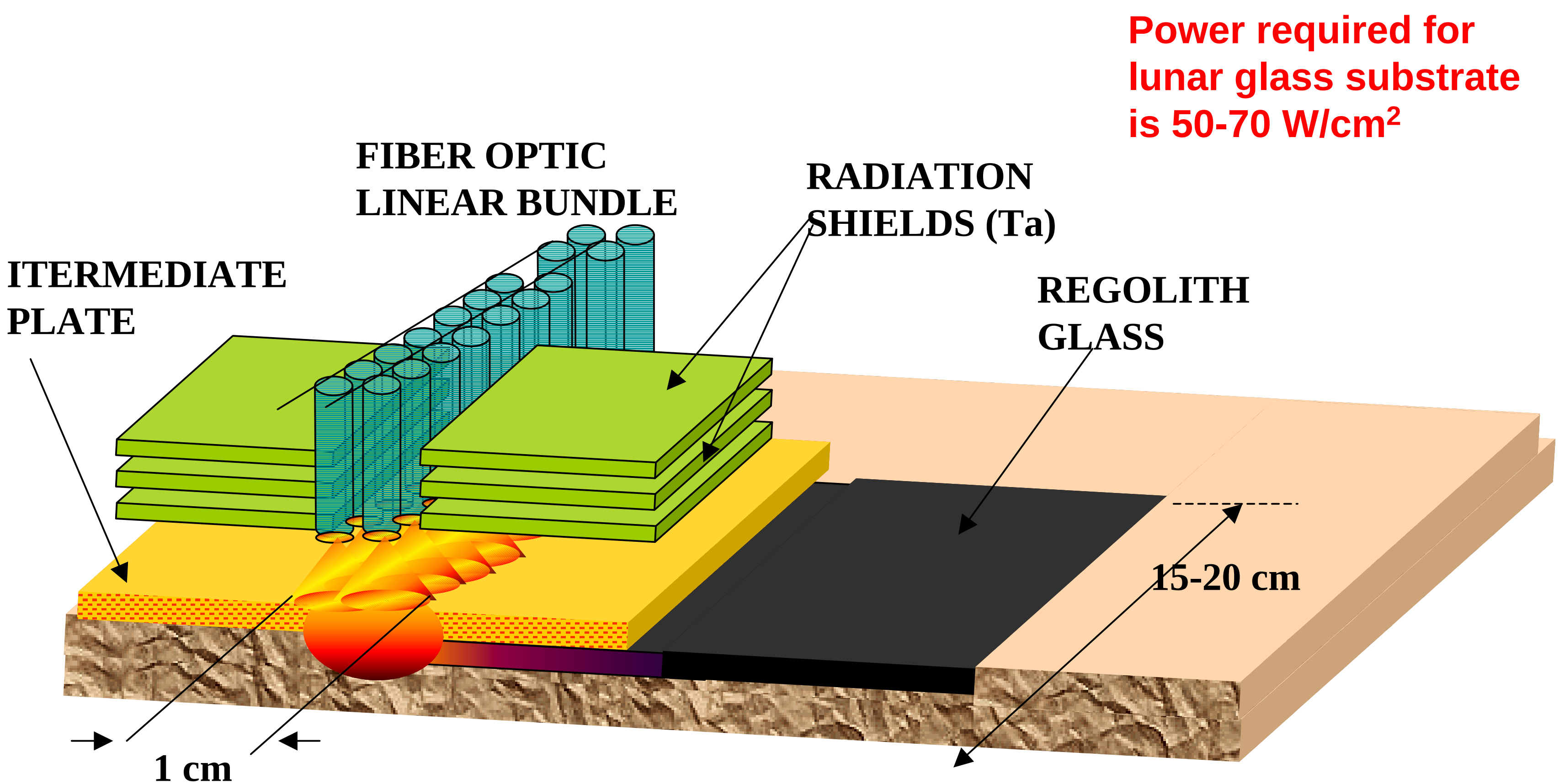
Mechanized Solar Cell Fab Facility



Solar Concentrator (Nakamura)

Reference:A. Ignatiev, U. Of Houston

Solar Thermal Lunar Regolith Melting



Reference:A. Ignatiev, U. Of Houston

Fabrication of Solar Cells on the Surface of the Moon from Lunar Regolith

- 1 m^2/hr
- Fabricate ~ 65 W per hr @ 5%
- Assume 35% uptime (total ~3060 hrs/yr)
- Fabricate ~200 kW/yr capacity
- Require ~ 180 kg of raw materials/yr
- Continuous Cell Replacement – Self Replicating System
  - Assume limited cell lifetime
    - . Radiation damage
    - . Particle damage

→ Make More Solar Cells

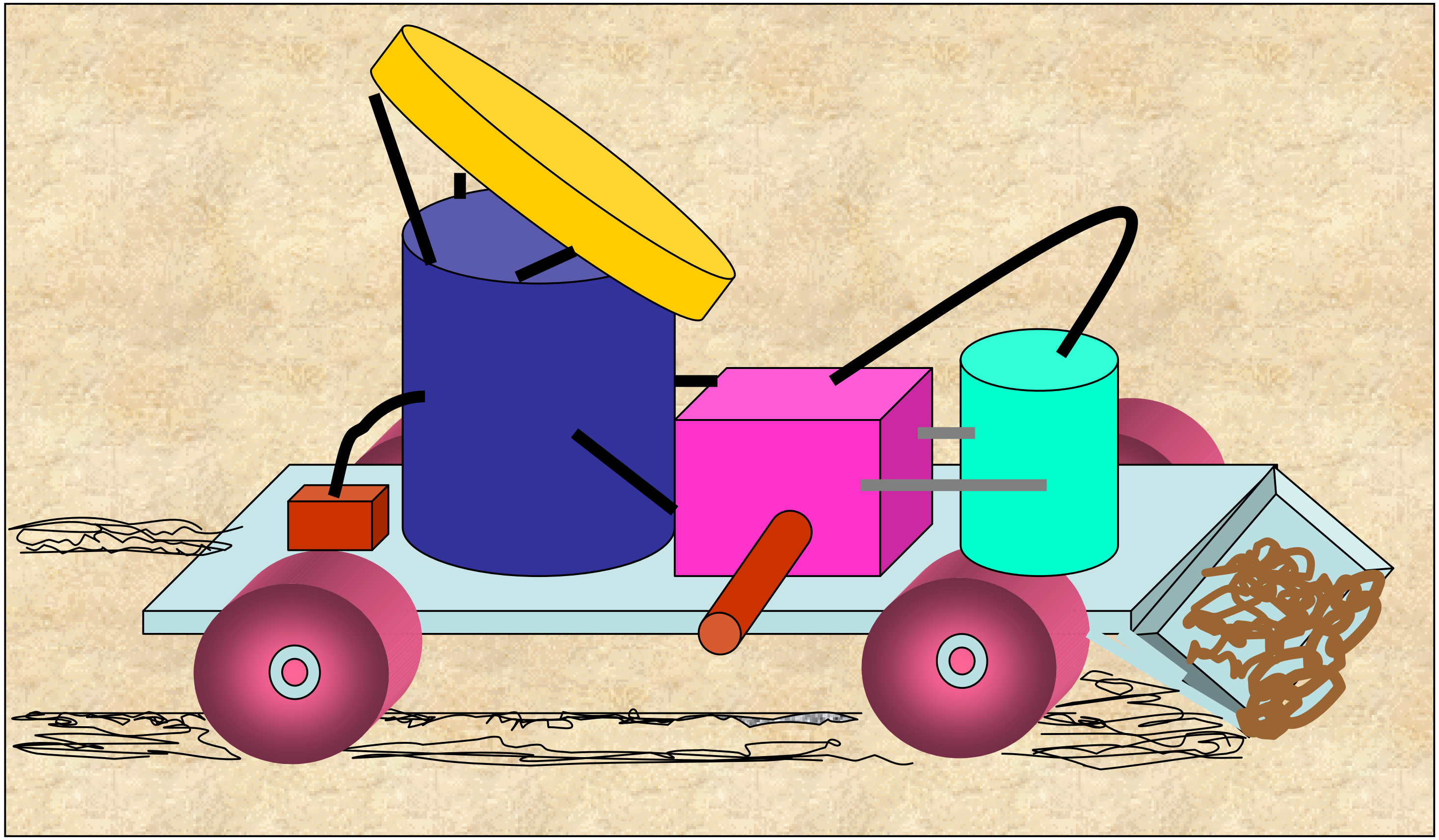
Reference:A. Ignatiev, U. Of Houston

Regolith Materials Extraction for Production of Solar Cells on the Surface of the Moon

- **Mechanized Regolith Processing Rover/Crawler**
  - **~ 200 - 300 kg**
  - **Regolith scoop**
  - **Solar thermal and electric heat (connect to solar cell field)**
  - **Recycle volatiles**
  - **Transfer oxygen**
  - **Feed solar cell production rover(s)**
    - **. ~ 10 kg reactor $\Rightarrow$ ~180kg product/yr**
    - **. Small support rover to feed cell fabricators**
  - **Possible secondary purification required**
    - **. Vacuum purify**

Reference:A. Ignatiev, U. Of Houston

Lunar Regolith Processing Rover



Reference:A. Ignatiev, U. Of Houston

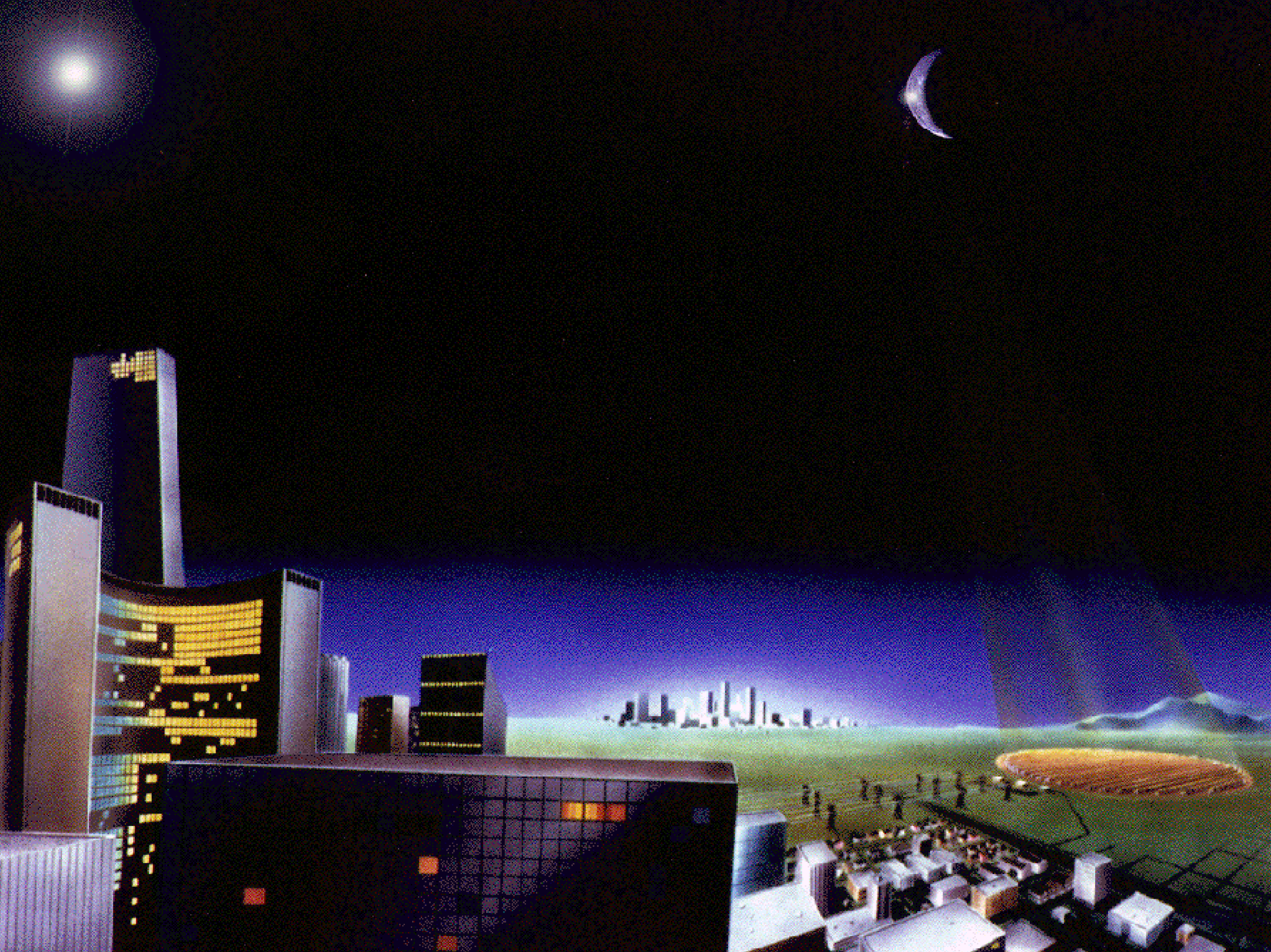
Production of Solar Cells on the Surface of the Moon from Lunar Regolith

- **Ultra-high Vacuum on Lunar Surface Allows for Direct Thin Film Solar Cell Production**
  - **Less Mass to the Moon**
  - **Lunar Resources can be Utilized for Cell Production**
  - **Trade-off Cell Efficiency with Quantity**
  - **Multiple Facilities can be Utilized**

- **Industrial Scale Power Generation and Power Grid on the Moon**

  . 10 Rovers $\Rightarrow$ from 2 to 4 MW/year
  . 100 Rovers $\Rightarrow$ Up to 40 MW/year

Reference:A. Ignatiev, U. Of Houston



Conclusions-LSPS

- The Lunar Solar Power Satellite would require a return to the Moon on a significant scale.
- The LSPS would make sense if it produced most of the projected electricity use in the World (i. e., small systems would not be favored).
- A major factor in the ultimate COE from the LSPS will be the launch costs from Earth and these have to drop significantly.