Solar Cell Development on the Moon for Lunar Solar Power

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A NASA Research Partnership Center

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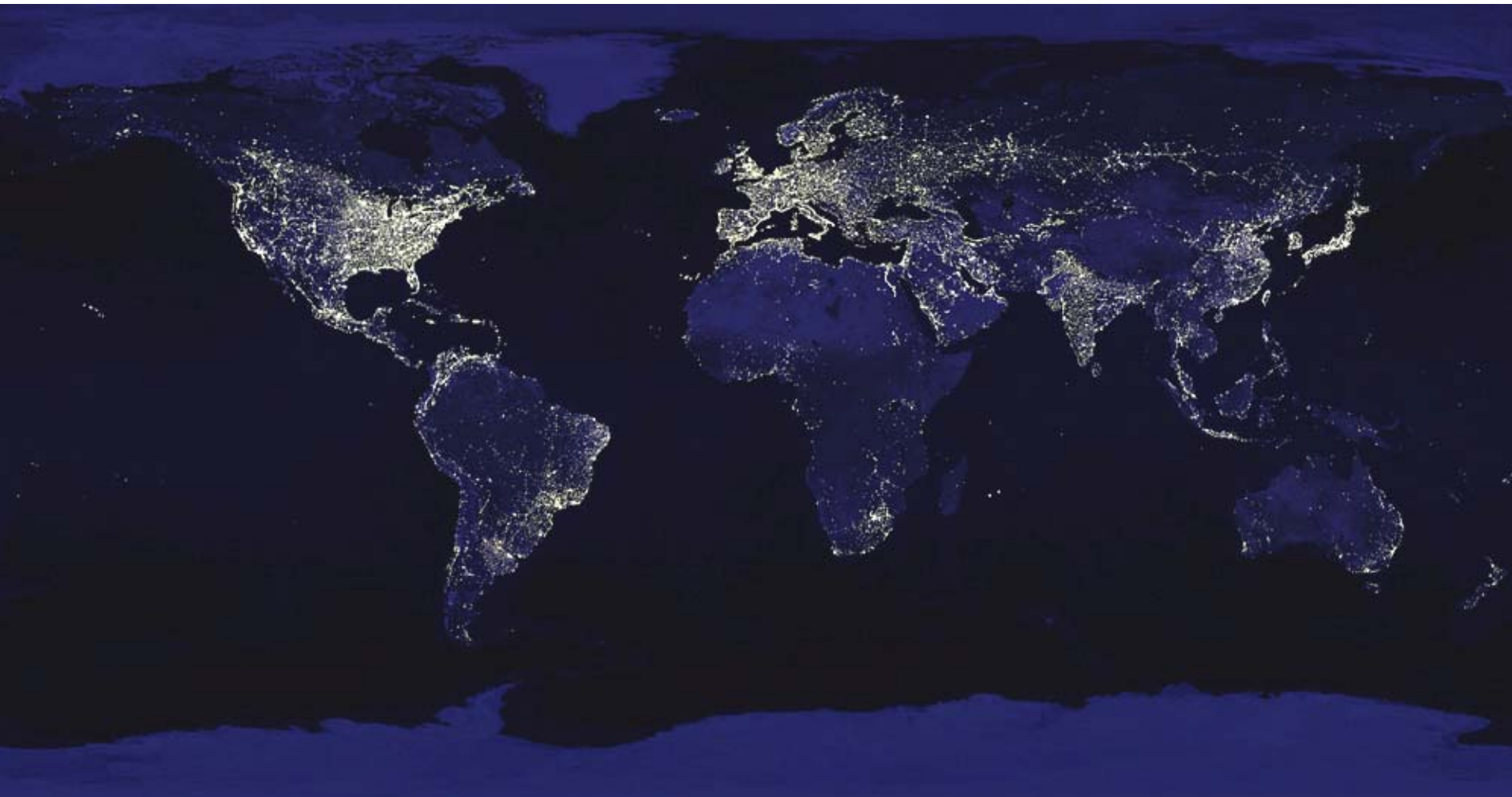
World Electrical Energy Use



Major Critical Need on Earth

1. Electrical Energy

Most Critical Needs in Space

1. Electrical Energy
2. Electrical Energy
3. Electrical Energy

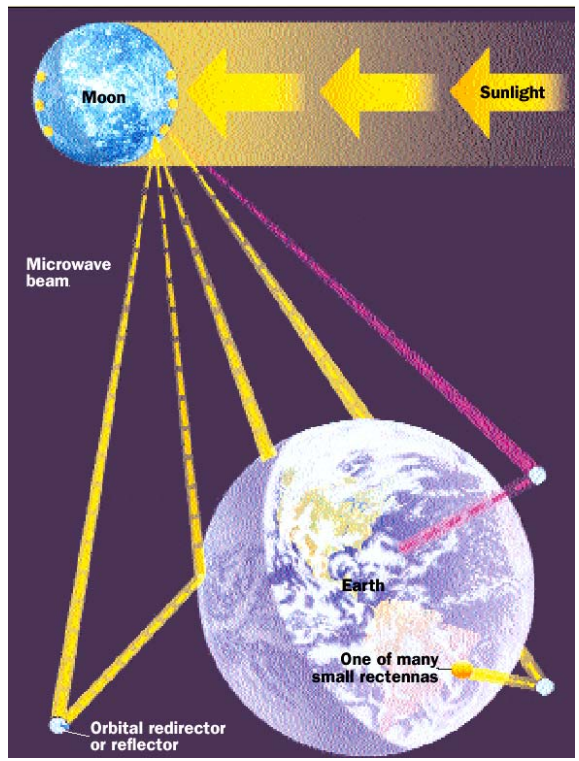
Use of Space Generated Electrical Energy

- **In Space: Energy Rich Environment**
  - **Exploration**
  - **Colonization**

- **Earth Benefits**
  - **Space Solar Power**
    - **Moon – Natural Satellite**

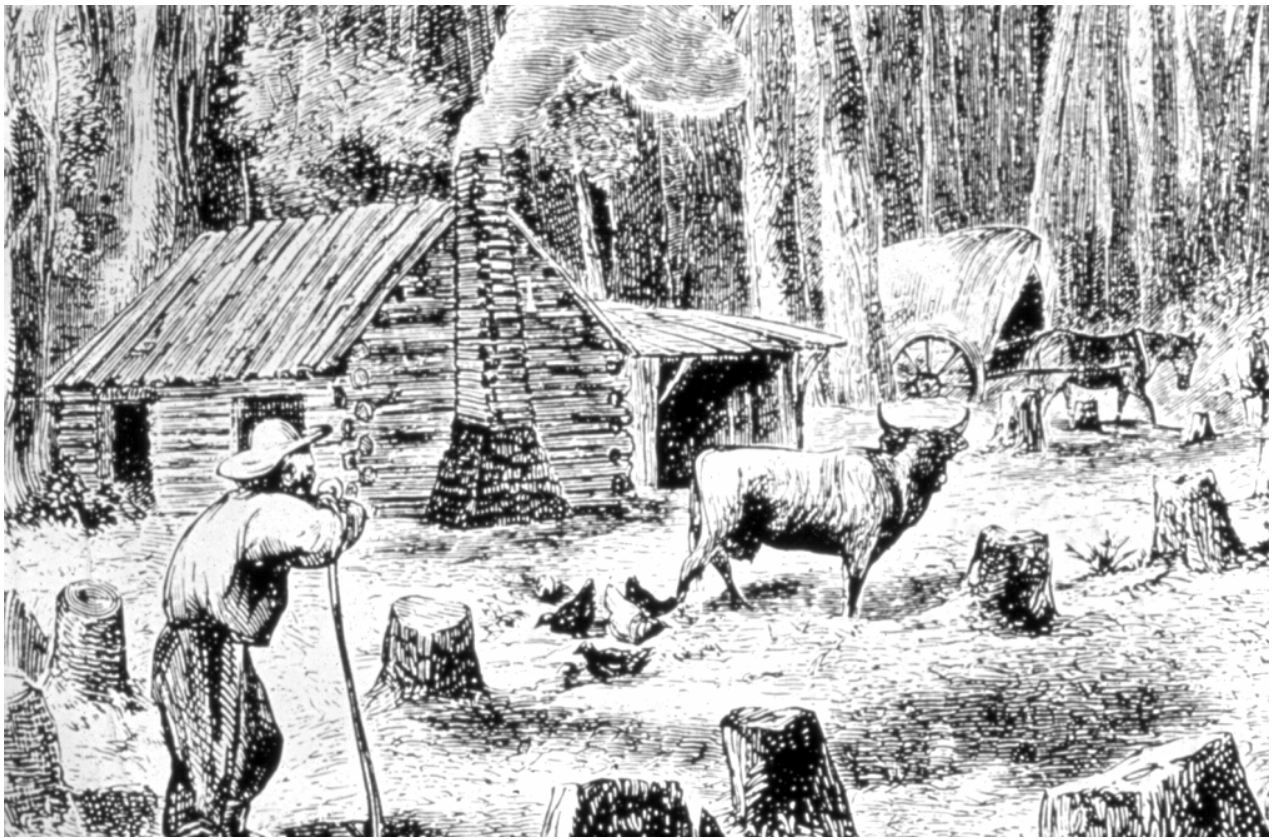
The Moon as a Solar Power Satellite

- **Identified First by Criswell and Waldron**
- **Less Mass to the Moon**
- **More Direct Logistics – Stand on Solid Ground**
- ***In situ* Resource Utilization**
- **Always Has One Face Toward Earth**
- **Use Relay Satellites**
- **Microwave Power Beam**



The Moon as a Solar Power Satellite

- How to Establish the Moon as an SPS ?
- Focus Initially on Small Scale Lunar Solar Power System
  - Accelerate Technologies to Larger Scale
- Don't Bring EVERYTHING to the Moon
  - Use the Resource there – "Live Off the Land"



Living off the Land: **Use Resources Present - Just Bring Tools**

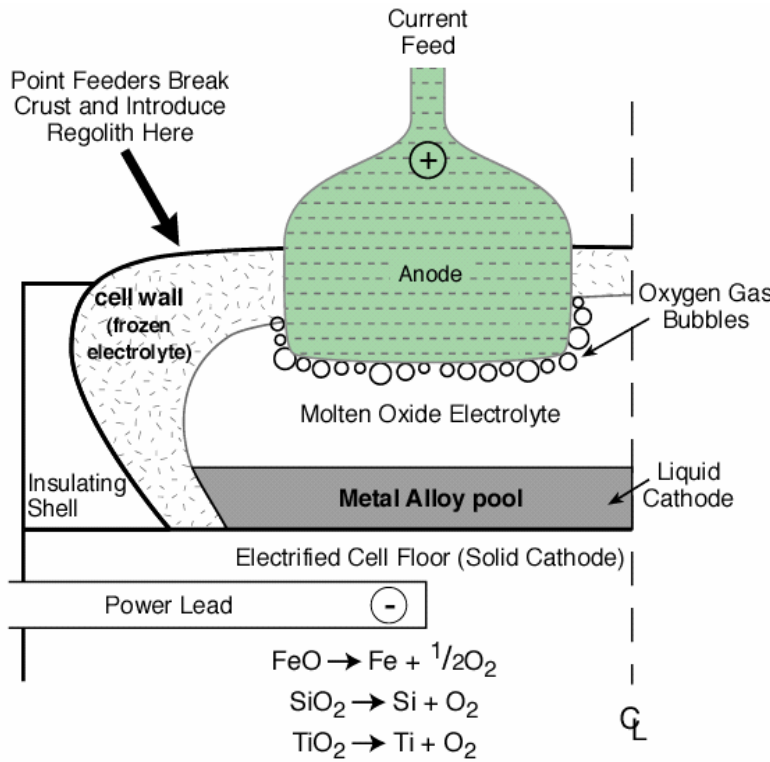
Do This in Space : In-Situ Resource Utilization (ISRU)

Generation of Electrical Energy 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**

Chemical Reduction of Regolith for Silicon Solar Cell Raw Materials

- **Silicon Extraction / Metals Extraction**
  - Carbothermal Reduction
  - Hydrogen Reduction
  - Fluorine Reduction
  - Electrochemical Reduction
  - etc. – Identify Best for Lunar Environment

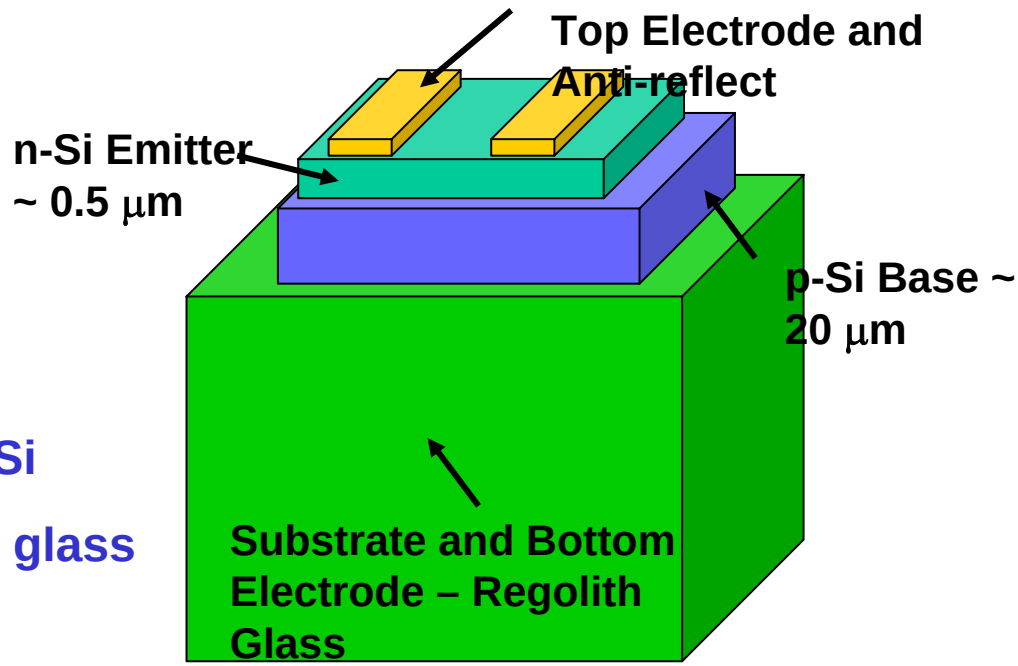


Need Adequate Quality of Silicon

Make Solar Cells On the Moon !

Fabrication of Thin Film Silicon Solar Cells on the Moon

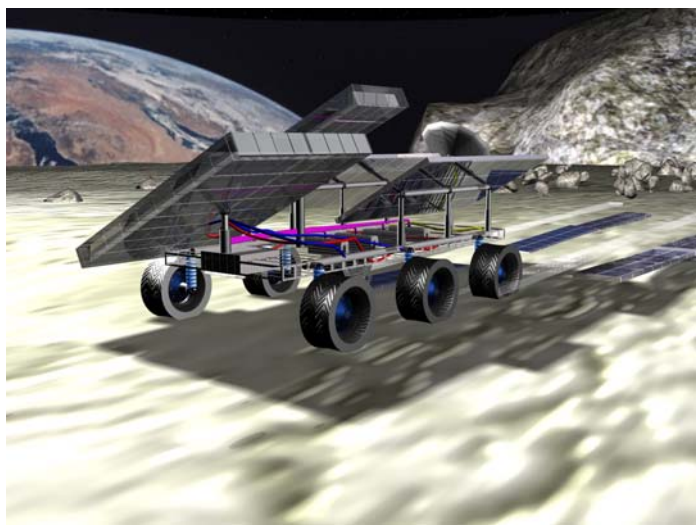
- Microcystalline Si Cells
  - Low efficiency ~5 - 8%
  - Make many cells
- Needs
  - Substrate – regolith glass
  - Bottom electrode – Al, FeSi
  - Si p-n junction – dopant
  - Top patterned electrode – FeSi
  - Antireflection layer – regolith glass
  - Interconnection of individual cells – FeSi, Fe



→ Need a Deposition/Fabrication Tool

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

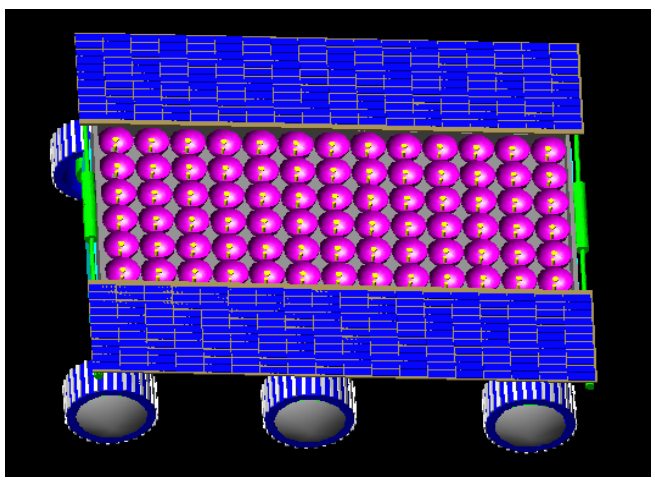
- **Mechanized Solar Cell Growth Facility – Cell Paver**
  - **~ 150 - 200 kg**
  - **Evaporation energy from solar thermal collectors**
  - **PV panels for motive/control power**
  - **Continuous lay-out of cells on lunar surface**
  - **Remotely controlled**

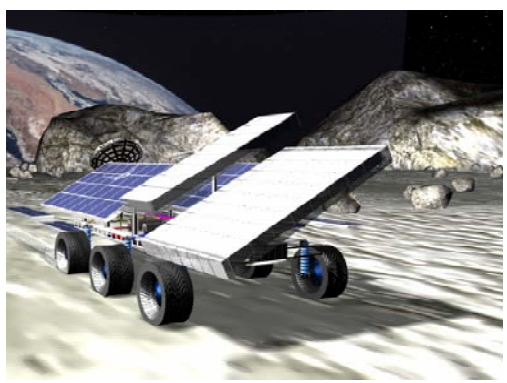


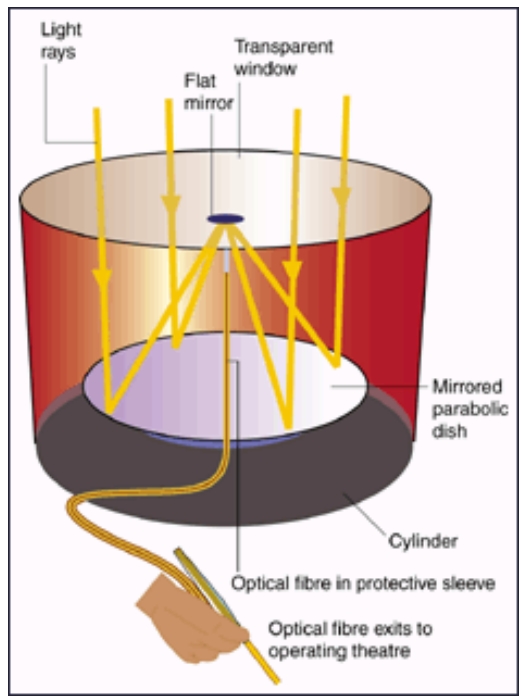
Initially Take the Raw Materials to the Moon - BOOTSTRAP

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

- **Parabolic Concentrators in Conjunction with Fiber Optics**
- **Solar Energy for:**
  - **Melting of Regolith into Glass**
  - **Evaporation of Silicon and Metals**



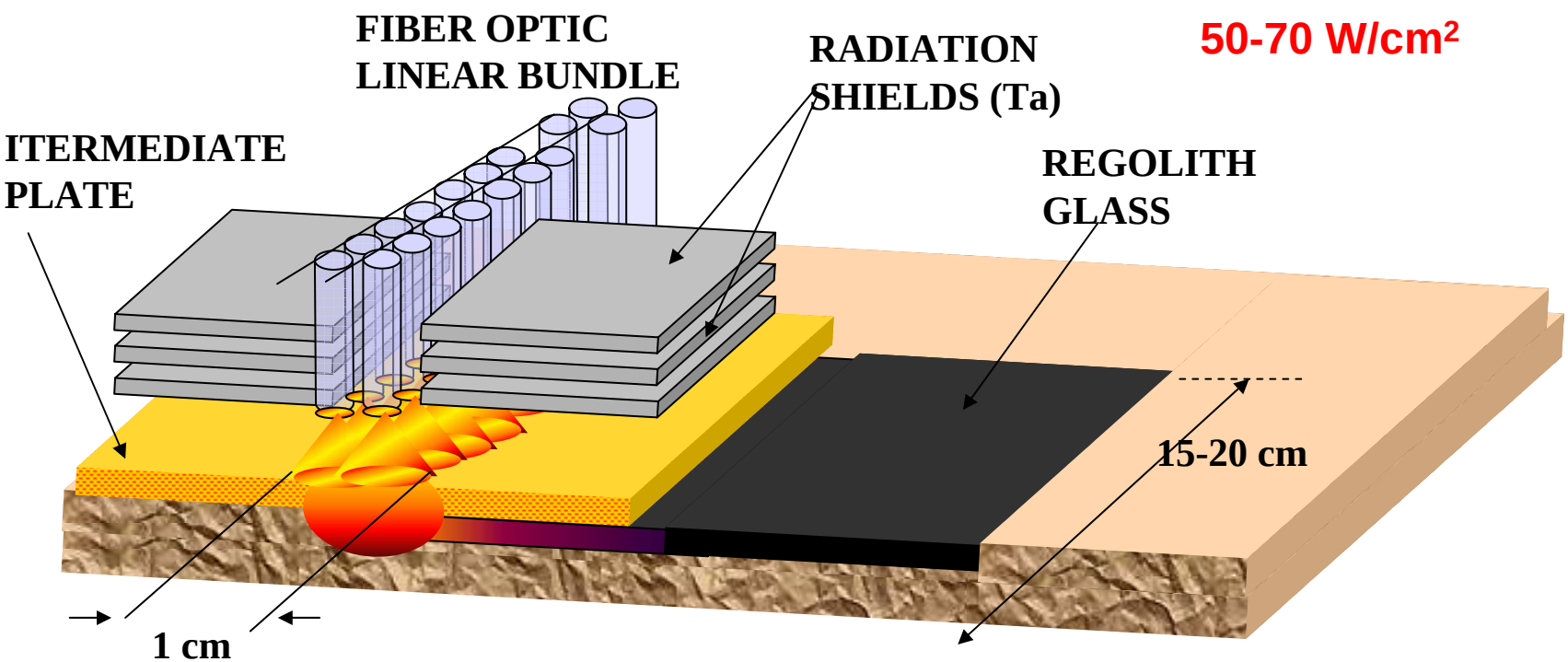




Solar Thermal Lunar Regolith Melting

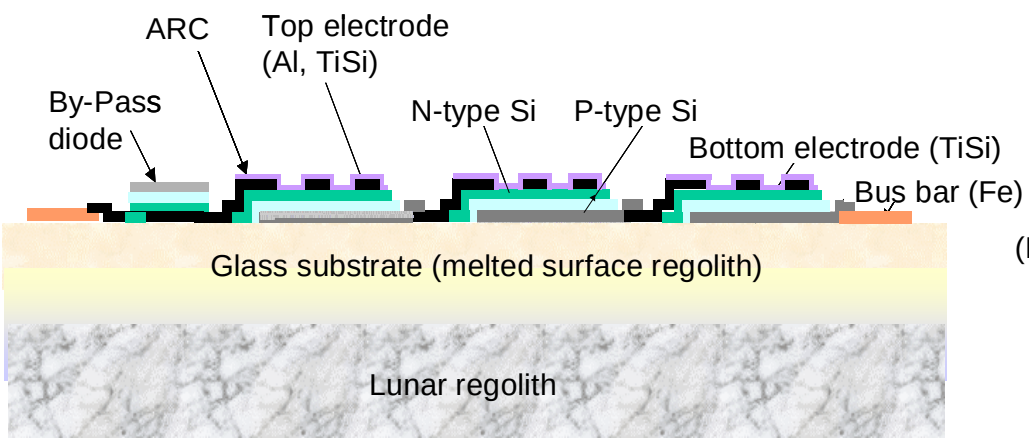
Power required to melt lunar glass substrate:

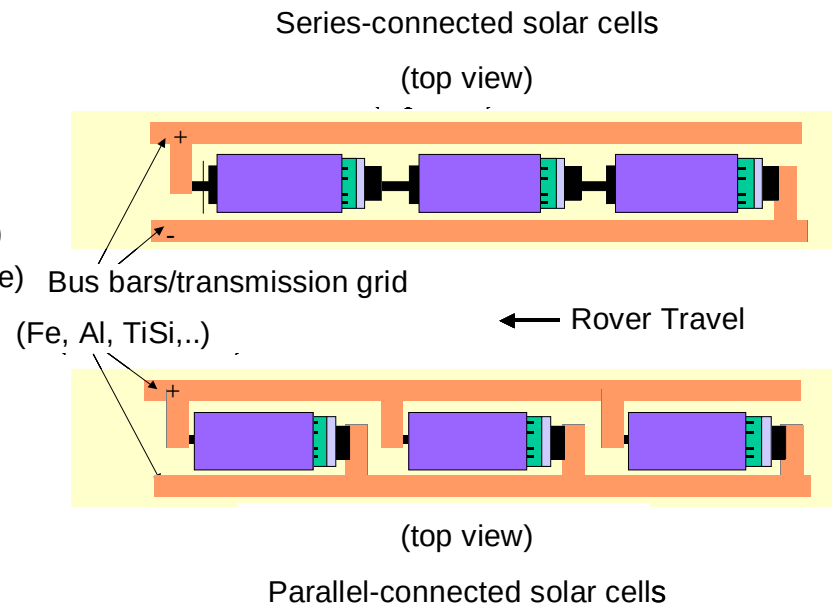
50-70 W/cm^2



Lunar Solar Cell Interconnection

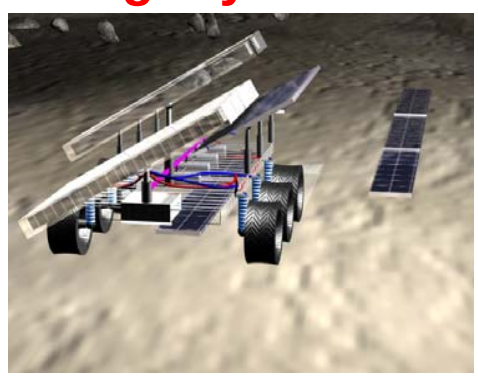
- **Stair-step interconnection**
- **Serial connections for ~ 100V**
- **Cell groups fabricated for ~ 5 A**





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

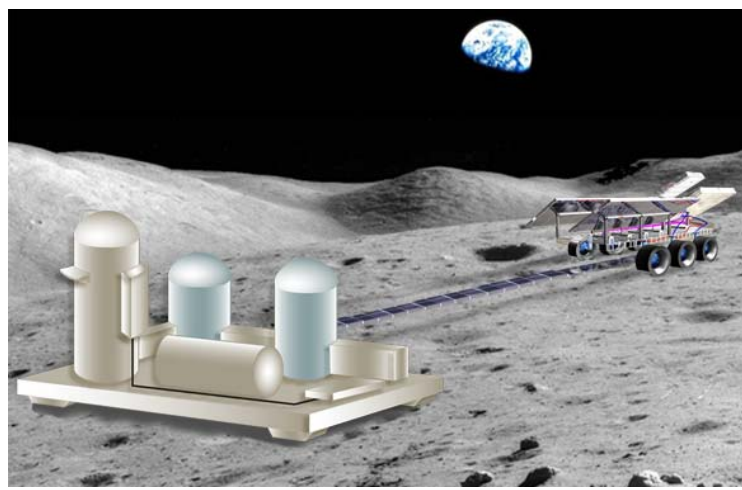
- 1 m^2/hr (prototype facility)
- Fabricate ~ 65W/hr @ 5% and AM0 (~1400 W/m^2)
- Assume 35% uptime (~3060 hrs/yr)
- Fabricate ~200kW/yr capacity
- Require ~ 100kg of raw materials (Si)/yr
- Continuous Cell Replacement – 'Self Replicating' System
  - Assume limited cell lifetime
    - . Radiation damage
    - . Particle damage



→ Make More Solar Cells

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

- **Regolith Processing Facility: Si and Metals Extractor**
  - **~ 150 kg**
  - **Regolith scoop**
  - **Solar thermal and electric heat (connect to solar cell field)**
  - **Recycle electrolyte (electrochemical reduction)**
  - **Transfer oxygen and volatiles**
  - **Feed solar Cell Paver(s)**
    - **~ 10 kg reactor ⇒ ~150kg/yr @ 500W**
    - **Small Support Rover to feed Cell Pavers**
  - **Possible secondary purification required**
    - **Vacuum purify**



Production of Solar Cells on the Surface of the Moon

- **Ultra-high Vacuum on Lunar Surface Allows for Direct Thin Film Solar Cell Production on the Moon**
  - **Less Mass (cost) to the Moon – 1 MW @ < 1/10 Cost**
  - **Lunar Resources Utilized for Cell Production**
  - **Trade-off Cell Efficiency with Quantity**
- **Industrial Scale Power Generation and Power Grid on the Moon**
  - **10 Rovers ⇒ from 2 to 4 MW/year**
  - **100 Rovers ⇒ Up to 40 MW/year**
  - **1,000 Larger Scale Rovers ⇒ Up to 2 GW/year**

Lunar Solar Cell Cost Projection

	Power Scenarios			
	540 kW	1,500 kW	8,000 kW	10,000,000 kW
Development cost ($/kg)	$100,000,000	$100,000,000	$180,000,000	$20,000,000,000
Transportation cost ($/kg)	$57,000,000	$57,000,000	$114,000,000	$11,400,000,000
Operations cost	$12,000,000	$40,000,000	$80,000,000	$800,000,000
Total cost	$169,000,000	$197,000,000	$374,000,000	$32,400,000,000
Total power kW-hr	2,365,200	15,636,600	290,569,200	348,683,040,000
Unit cost $/kW-hr	$71.45	$12.60	$1.28	$0.11
Unit cost $/W	$313	$131	$46.75	$3.24

NAFCOM

$0.50

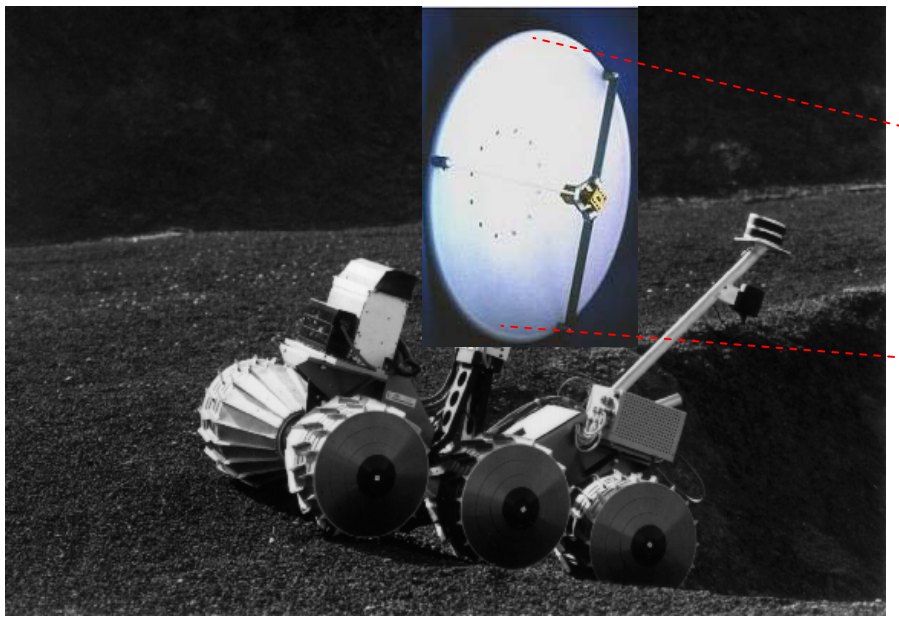
→ **May be Cost-Effective for Large Production**

Production of Solar Cells on the Surface of the Moon for Lunar Use

- **Direct Fabrication on the Surface in Equatorial Regions**
  - **Lunar Base**
  - **Propellants**
  - **He^3 mining**
  - **Tourism**
  - **Radio Astronomy**
  - **Optical Astronomy**
  - **Asteroid Mitigation**

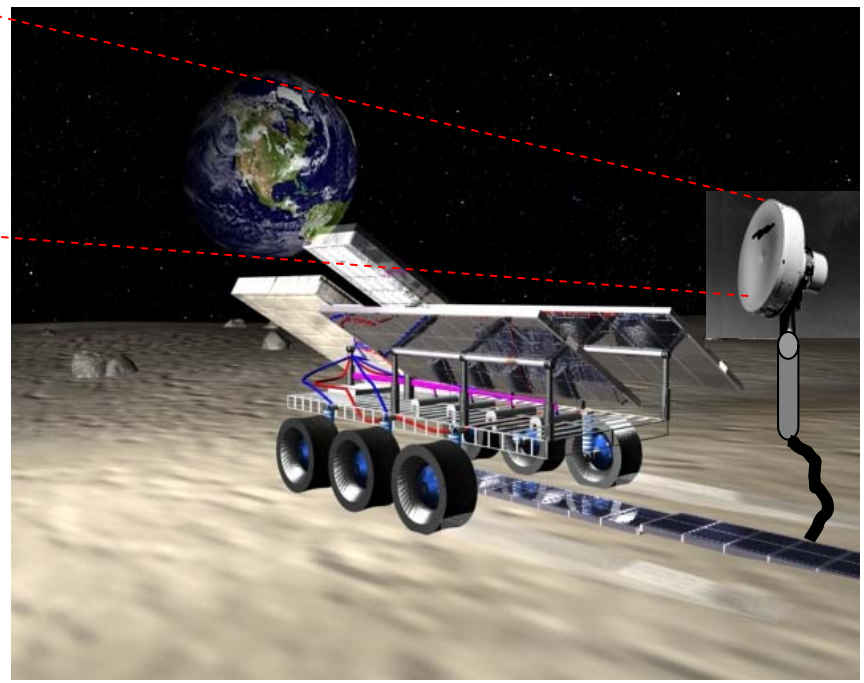
- **South Pole**
  - **Possible water mining/electrolysis**
    - **Circumferentially cover mountain peak**
      - **Nearly continual sunlight**
    - **Fabricate on 'inclinable' lunar glass substrates**

Distributed Energy on the Moon



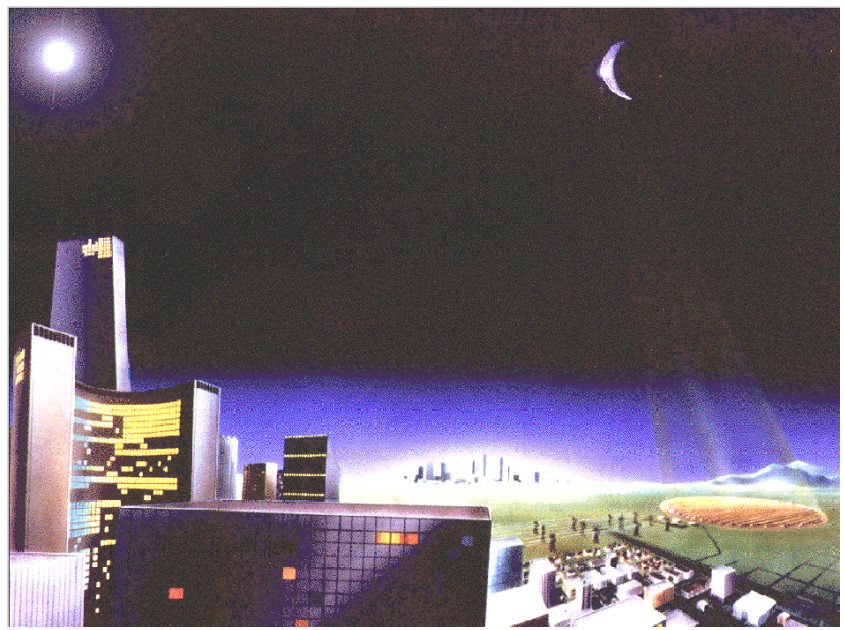
Lunar Power Beaming

Fabricated Lunar Solar Cell Grid



Production of Solar Cells on the Surface of the Moon for an SSPS

(from Criswell)



- Fabricate GW-TW Capacity of Solar Cells on Moon
- Fabricate Thin Film Rectennas and Thin Film Transistor Back-plane Converters/Amplifiers
- Microwave Power Beaming from Moon

Collaborators/Contributors:

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