

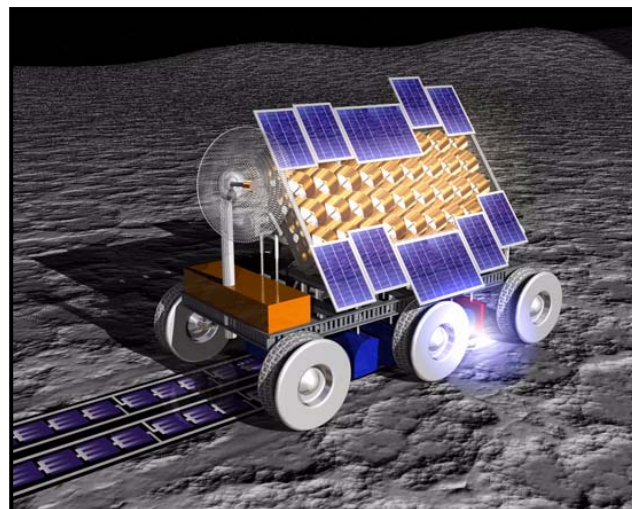
***In-Situ* Resource Utilization Lunar Solar Cell Manufacturing**

Energy is fundamental to nearly everything that humans would like to do in space, whether it is science, commercial development, or manned exploration. If indigenous energy sources can be developed, a wide range of possibilities emerge for subsequent space-based development. This picture is particularly true for the Moon where significant electric energy will be required for a number of lunar development scenarios; including science stations, lunar resource processing, and tourism. The Center for Advanced Materials, in collaboration with its research and industrial partners, is developing an approach to generate electrical energy on the Moon through the *in-situ* fabrication of thin film solar cells on the lunar surface. In supplying this electrical energy by *in-situ* fabricated solar cells, the costly transport and installation of an immense number of solar cells to support lunar energy needs will not be required. The fabrication of solar cells on the surface of the Moon can be accomplished by placing mobile solar cell fabricators on the Moon, which utilize lunar resources of the Moon to manufacture solar cells on location.

ISRU

The availability of significant electric power at the surface of the moon will be a principal driver defining the complexity of a lunar base. Proposals to generate power on the moon include both nuclear and solar (photovoltaic) systems. The main drawback to all of the approaches to date is that all of the mass for the power system must be transported from the earth to the moon. For a lunar base this could amount to over 40 metric tons to the moon for the utilization phase.

A more efficient, possibly synergistic, approach is to attempt to utilize the existing lunar resources to gen-



Autonomous solar-powered lunar photovoltaic cell production rover.

erate the power systems. The synergism occurs from the fact that there is an ultra-high vacuum environment on the surface of the moon, and there are materials present on the moon from which thin film solar cells could be made within this vacuum environment by direct evaporation.

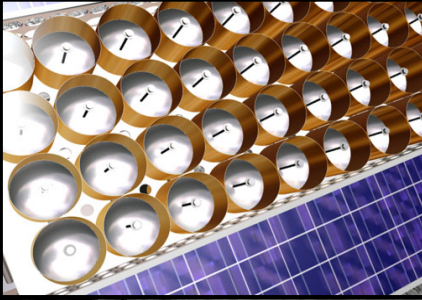
Technology

The ultra-high vacuum environment at the surface of the Moon allows for the vacuum deposition of thin film silicon solar cells directly on the lunar surface without the need for vacuum chambers. As a result, these solar cells can be fabricated through the integration of a regolith processing step that is robotically undertaken to extract the needed raw materials for solar cell growth, and a subsequent solar cell vacuum deposition process accomplished by an autonomous robotic rover that lays down continuous ribbons of solar cells directly on the lunar surface.

Crucial to the *in-situ* process is converting the lunar dust into a glassy substrate through heating. On Earth, silicon solar cells are not typically vacuum deposited on glass substrates, instead they are deposited in crystalline form on single crystal substrates. Vacuum deposition on glass is problematic, and when working cells are achieved, they typically have low efficiencies (~5-7%). This, however, may be acceptable for the lunar fabrication since more low efficiency solar cells can be fabricated on the Moon to give the required TOTAL power for lunar use; quality can be sacrificed for quantity.

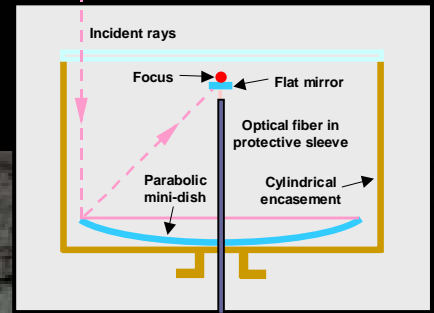
Compound	JSC-1 (%)	Apollo sample (%)
Silicon Oxide	47.71	47.3
Aluminum Oxide	15.02	17.8
Calcium Oxide	10.42	11.4
Iron Oxide	10.79	10.5
Magnesium Oxide	9.01	9.6
Titanium Oxide	1.59	1.6
Sodium Oxide	2.7	0.7
Potassium Oxide	0.82	0.6
Chromium Oxide	0.04	0.2
Manganese Oxide	0.18	0.1
Phosphorous Oxide	0.66	0.00

JSC-1 lunar regolith simulant and actual Apollo Program sample constituents.



Thermal Power

The rover utilizes solar thermal heating to prepare the Lunar regolith for substrate use. Small parabolic collectors concentrate sunlight to generate the 50 - 60 Watts/cm² needed to melt a thin layer (~0.4 cm) of the Moon's surface. Fiber optic light pipes direct the solar energy to heating elements located under, and shielded from, the rover's carriage structure.

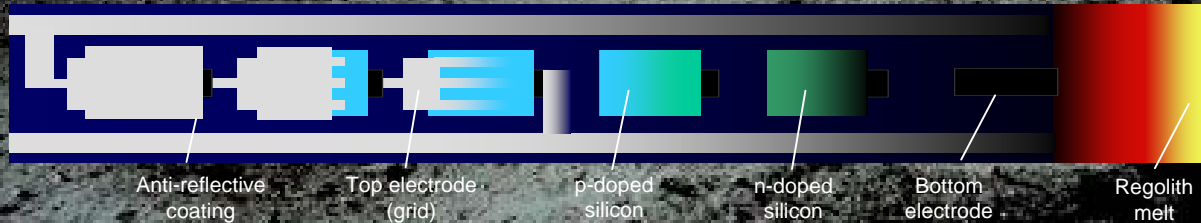
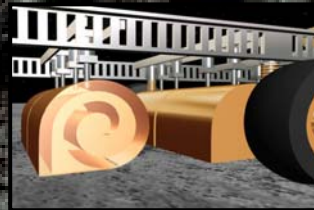
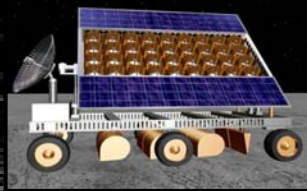


Fiber optics also supply heat energy to a series of evaporation furnaces beneath the rover. These source cells run at temperatures from 1000°C – 1500°C and deliver silicon and dopant metals to the growth region. Heating of individual evaporators is controlled by preferentially shuttering the solar collectors (see picture opposite side).

Solar panels provide systems and propulsive power. During growth operations, the rover moves across the lunar surface at approximately 1 meter/hour.

Sequenced shuttering of material evaporators combined with the rover's motion results in photovoltaic cell patterning, including interconnecting electrodes.

In CAM's laboratories, researchers have produced electrically insulating (>1 Megohm/cm) and mechanically compatible glassy substrates from JSC-1 lunar regolith simulant.



Evaporated regolith provides a highly transparent SiO₂-Al₂O₃ film to serve as an anti-reflective coating. Carefully designed paving patterns and cell segmenting allow for removal of under-performing components and maintenance of overall system continuity.

A small fleet of 150 kg rovers (roughly the size of an office desk) designed to clear and prepare the lunar surface, and then pave it with solar cells (20 cm X 30 cm) could robotically produce an array capable of supplying 100 kW for arriving manned missions.

Cost Analysis

A NAFCOM cost model was constructed to examine the cost effectiveness of fabricating solar cells on the Moon using lunar resources. The model assumes cell efficiency of 5%, and compares cost of manufacture using exclusively in-situ resources versus a hybrid approach where small quantities of high quality semiconductor material imported from earth.

Lunar Power Need (Mega Watts)	Si production on Moon (\$/Watt)	PV raw material from Earth (\$/Watt)
0.54	1,322	629
1.8	508	237
10	341	164
10,000	13.87	31.74

Assuming a material transportation cost of \$200,000/kg, the model indicates that the fabrication of solar cells on the moon, even when compared to ultra lightweight solar cells (0.5 – 1 kW/Kg) becomes cost effective in the MegaWatt range.



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