

NASA Technical Memorandum 102102

# Lunar Production of Solar Cells

Geoffrey A. Landis  
*Lewis Research Center*  
*Cleveland, Ohio*

and

Maria Antonietta Perino  
*Aeritalia*  
*Space Systems Group, Research*  
*Torino-Corso Marche, Italy*

Corrected Copy

Prepared for the  
9th Biennial SSI/Princeton Conference on Space Manufacturing  
sponsored by Space Studies Institute  
Princeton, New Jersey, May 10-13, 1989



(NASA-TM-102102) LUNAR PRODUCTION OF SOLAR  
CELLS (NASA. Lewis Research Center) 18 p  
CSCL 03B

N89-27619

Unclas  
G3/91 0224998

# **LUNAR PRODUCTION OF SOLAR CELLS**

Geoffrey A. Landis\*  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

and

Maria Antonietta Perino  
Aeritalia  
Space Systems Group, Research  
10146 Torino-Corso Marche, Italy

## ***Abstract***

The feasibility of manufacturing of solar cells on the moon for spacecraft applications is examined. Because of the much lower escape velocity, there is a great advantage in lunar manufacture of solar cells compared to Earth manufacture. Silicon is abundant on the moon, and new refining methods allow it to be reduced and purified without extensive reliance on materials unavailable on the moon. Silicon and amorphous silicon solar cells could be manufactured on the moon for use in space. Concepts for production of a baseline amorphous silicon cell is discussed, and specific power levels calculated for cells designed for both lunar and Earth manufacture.

*\*National Research Council—NASA Research Associate.*

## **1. Introduction**

A first step toward realization of a lunar manufacturing base is to identify near-term products that could be manufactured on the moon for cost-effective use on-site and elsewhere. In this paper we discuss manufacture of photovoltaic solar arrays as one such product.

A lunar base is projected to require 100 kW to 1 MW or more of power, and a mining and manufacturing facility considerably more. It is a natural assumption to require that a manufacturing facility produce from locally available materials the solar arrays for its own expansion in a "bootstrap" process. Once it is accepted that a lunar base may manufacture its own power source, it is a straightforward extrapolation to the lunar production of solar arrays for other uses, taking advantage of the greatly reduced transportation costs due to the lower escape velocity of the moon.

The widely discussed manned Mars mission, for example, could require 1 MW or more. Transportation costs alone for a Mars power source could be on the order of a billion dollars. While these costs can be projected to decrease with the future availability of advanced launch systems and use of in-situ propellant production, the possible economic gains are nevertheless extremely large. This is a strong incentive for seeking ways of lowering transportation costs for the solar arrays. One route to doing this is to increase the array (and storage system) power to weight ratio ("specific power"). Another possibility is to manufacture the arrays in space.

## **2. Lunar Photovoltaic Arrays**

Most current plans for a lunar base assume that the base will include an industrial facility, primarily to produce oxygen for propulsion systems by reduction of the lunar soil [1]. A second product for such a facility could be solar arrays. While the primary user of lunar-produced solar cells would undoubtedly be the lunar base itself, there would be many markets. Figure 1 shows some of these possible uses of lunar produced photovoltaics, including solar-electric propulsion for orbital transfer vehicles and for solar system exploration, and power systems for geosynchronous Earth orbit (GEO) and low Earth orbit (LEO) satellites.

Use of lunar-manufactured solar cells for high-power solar-electric propulsion is an especially attractive option. Recent proposals for a manned Mars mission [2], for example, propose an unmanned, electric-propulsion cargo vehicle to ferry supplies to Mars orbit in advance of the crew on a low-thrust orbit. The power system for the electric propulsion is a 5 MW nuclear generator, which could be replaced with lunar-manufactured thin-film solar cells for a considerable savings in required weight to orbit. For a "sprint" mission, a high-power electric propulsion vehicles of 200 MW power and a specific impulse of 20,000 sec could make the round-trip to Mars as short as 7.5 months [2]. Solar-electric transport vehicles would also greatly reduce the required mass for servicing the lunar base itself. B.G. Logan [3], for example, proposes a 6 MW Manned Lunar Shuttle powered by a pulsed plasma gun,

estimating that this could halve the transport costs, even for relatively modest specific power solar arrays.

Use of lunar material has also been widely proposed for manufacture of solar cells for satellite solar power stations [4].

The cost of transportation from the Earth's surface to orbit and beyond can be quite high. Figure 2, for example, shows the cost of delivering conventional and advanced power systems to orbit, the moon, and Mars, using cost estimates typical of current technology space boosters. For example, a one-megawatt power system delivered to Mars could have transportation costs alone in the ten to hundred billion dollar range. While these costs are likely to be decreased with advanced transportation, they are likely to remain high.

The advantage of lunar manufacture is that the escape velocity is only 22% that of the Earth. Table 1-A shows the  $\Delta V$  (velocity increment) needed to achieve various destinations from the Earth's surface and from the moon. The payload fraction decreases exponentially with the delta-V, and a much higher fraction of the lift-off mass can be useful payload, as shown in table 1-B, which shows the theoretical maximum fraction of lift-off mass which can achieve the listed orbit if launched from the Earth's surface, compared to launched from the moon. (Actual rockets never achieve these values; typically only 1-2% of the mass of a rocket launched from the Earth is useful payload.) Even to low Earth orbit, five times the payload can be delivered if launched from the moon than if launched from the Earth's surface. For the commercially valuable geosynchronous orbit, almost nine times the payload can be delivered. This is a strong leverage factor for lunar manufacture.

The design criteria for lunar manufactured solar cells depends on the mission. The most important criteria for most missions are maximum power/weight ratio (specific power) and minimum usage of materials transported from Earth. For use on the lunar surface, specific power is not an important criterion.

### **3. Lunar Materials**

#### *3.1 Materials Availability*

Silicon is not only one of the most abundant elements on the Earth, it is also present in great quantity in the lunar soil.

Table 2 shows the lunar abundance of materials important for production of solar cells [5]. While high-efficiency solar cells can be made from a wide variety of semiconductors, lunar material scarcity rules out production of indium phosphide, gallium arsenide, copper indium selenide, or cadmium telluride solar cells. (Note, however, that the lunar surface has to date only been superficially examined, and that the possibility exists of mineral deposits with much greater concentrations than those listed here). The available semiconductor material is clearly silicon. Candidate solar cell types are crystalline silicon and amorphous silicon.

Production of the structural elements of the array is also important,

than those listed here). The available semiconductor material is clearly silicon. Candidate solar cell types are crystalline silicon and amorphous silicon.

Production of the structural elements of the array is also important, and in fact contributes more than half of the total mass of the finished array. Materials for producing structural elements are available on the moon [4,6]. Aluminum is a major constituent of the lunar soil, and titanium is also available in varying amounts depending on location. Nearly pure nickel-iron can be obtained by magnetic separation of the small (1-2%) amounts of meteoric material from the soil. Glass fiber can be manufactured from readily available lunar silica for use in composites [7,8].

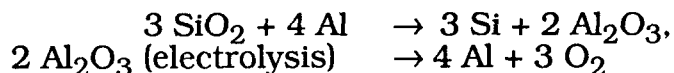
We further note that for a solar-powered moonbase it may also be important to manufacture from locally available materials a storage system to provide power for the 14-day lunar night. This is discussed in more detail in reference [9].

### 3.2 Silicon Production

Although silicon is abundant (second most abundant element, after oxygen, in the lunar crust), typically hydrogen, carbon, and halogens are required for existing technologies of refining and purification, although it is reasonable to expect that a process sequence adapted to lunar conditions may minimize usage of these materials. Calculations show that if recycling efficiency is good, transportation of these materials from Earth will not be a limiting factor.

The most common soil material is anorthite,  $\text{CaAl}_2\text{Si}_2\text{O}_8$ , which can be considered to be a mixture of calcium, aluminum, and silicon oxides:  $\text{CaO} + \text{Al}_2\text{O}_3 + 2\text{SiO}_2$ . In the literature several methods are proposed to process extraterrestrial ores, but none have been tested in situ. The primary criteria for the process selection are low power requirement and low requirement for non-lunar materials. Other important criteria include the end products provided, the process complexity, and suitability for manufacturing under 1/6 G.

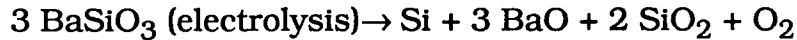
Processes considered include fluoroacid leaching, vapor phase pyrolysis [10], carbothermal processing, and slag electrolysis. For the candidate process we considered aluminum reduction followed by electrolysis to recover the aluminum, as shown by the following reaction:



This process has been developed and demonstrated by Keller and co-workers at EMEC corporation [11]. The aluminum acts simultaneously as a reducing agent for the silicon dioxide and as a solvent for the silicon that has been formed, which can subsequently be crystallized out of the solution in a nearly pure form by cooling. Because the reduction is exothermic, the reaction vessel needs to be heated externally only during the initial phase of melting of the slag and the beginning of the reaction.

An alternative process is electroreduction from an alkaline-earth oxide melt, which has been demonstrated by DeMattei, Elwell, and Feigelson at

Stanford [12], as shown in the reaction:



This has the disadvantage that the flux metal, barium, is not available on the moon. It is possible that other metals can be used. This is not a problem as long as the material recycling efficiency is high.

The silicon obtained must be purified for use in semiconductor devices. A candidate process for purification is by float-zone recrystallization, where the silicon rod is melted in a zone that passes along the length of the rod. Impurities are segregated to the end of the material. This process is slow, but has the advantage of zero materials consumption.

For crystalline silicon, assuming 17.5% efficiency, 65  $\mu$  thick cells, and 65% utilization of the silicon refined, 1000 kg/yr of silicon is required for a production rate of 1 MW/year. This is small amount compared to the processing of 12,000 metric tons/yr of lunar soil required for the 1,000 ton/yr lunar oxygen production envisioned in the lunar base/Mars evolution scenario [2]. We thus conclude that it is indeed reasonable to expect that even large-scale photovoltaic manufacturing can be considered to require no additional mining facilities.

### 3.3 Synthesis of Silane

If the solar cells are to be amorphous silicon cells made by the standard plasma deposition process, the silicon must be manufactured into silane ( $\text{SiH}_4$ ) gas. There are many different process sequences currently used for manufacture of silane [13]. We need to evaluate these methods considering availability of materials on the moon. All of the reactions involve materials which are not available on the moon. It is therefore important that the recycling efficiency of the process be high. The largest scale process, developed by Union Carbide [14,15], converts powdered, 98% metallurgical grade silicons to trichlorosilane at 500°C in a fluid-bed reactor and then successively disproportionates the trichlorosilane to an end product of silane according to the following sequence of reactions:



The intermediate reaction products are recycled. Metallic impurities in the initial metallurgical grade silicon are converted to chlorides and settle out in the first distillation step. For maximum recycling efficiency, these should be electrolyzed to recover the chlorine for reuse.

It should be noted that the actual mass of material to be manufactured

is not very large. If the cell manufacturing line is to produce amorphous silicon cells, for example, at 10% efficiency, the actual silane used in producing the two micron thick active layer is only 25 kg per year for a one megawatt/yr production line. If the production line capacity is increased to ten megawatts/year to produce panels for base expansion, solar-electric propulsion for a Mars mission, and for powering satellites in GEO, the requirement for silane, including waste, could be around 300 kg/year. By Earth production standards, this would be considered a laboratory-scale production level--there are at least 14 silane manufacturing plants worldwide with production rates over one ton/year [13].

#### **4. Solar Cells**

Primary considerations for the choice of a production process are (1) Low use of Earth-supplied materials, including reactants, etchant, and replacement parts; (2) low labor requirements, (3) energy efficiency, and (4) low mass equipment. As part of consideration (3), it is important to minimize the amount of silicon required, since the major part of the energy expenditure needed in manufacture comes from the silicon refining process. It is also useful to distinguish processes requiring only heat, which can be obtained by a relatively simple solar furnace, from processes requiring electrical power.

##### *4.1 Crystalline Silicon*

Typical crystalline silicon solar cells have an efficiency of about 15% under the space illumination of 1.35 kW/m<sup>2</sup>. The best cells made have an efficiency of 19%. The main problem with conventional crystalline silicon is the low power to weight ratio due to the thickness of the silicon substrate. This may be solved by use of ultra-thin cells using light-trapping techniques to increase the effective optical absorption [16]. Calculations indicate that such cells also have greatly improved radiation tolerance.

Another possibility for increasing specific power is to use light-weight concentrator elements. For space use, a concentrator system does not require great structural strength. A low concentration system made from 1.5 micron thick aluminized plastic with a support structure of equally low mass could improve specific power by a factor of nearly ten. The design has an advantage of a large acceptance angle compared to high-concentration systems, thus not requiring high-precision pointing, and allowing one-axis tracking. For Mars operation, where winds can reach speeds imposing dynamic loading roughly the same as a 25 MPH terrestrial wind, either stiffer arrays, or ones which could be stowed in high wind conditions, would be required.

The candidate process sequence is designed to take maximum advantage of the lunar environment. Silicon purification by (chloro)- silane distillation as discussed above should be avoided in the interest of simplifying the process and minimizing dependence on imported materials. Instead, the required purification process could be done by

multiple vacuum float-zone refining. This step would be followed by single-crystal growth, also by the float-zone process. Since float-zone processing is done in a solar oven, the process is not energy intensive. The boule is then sawed to the desired cross-section followed by wafer slicing, thinning, and surface etching to form the substrate silicon wafers. Silicon removed during the sawing and slicing operations would be re-melted and reused; nevertheless, a considerable amount of silicon is likely to be wasted. While the assumed utilization of 65% may be optimistic by current practice, it is likely that a process designed to minimize waste could do considerably better.

Solar cells would be formed on the substrate wafers by ion-implantation using a non-mass analyzed, solid source implanter [17], followed by annealing in a solar furnace, back-surface deposition of aluminum for a back-surface field and back contact; deposition of Al front contacts; and finally by vacuum evaporation of the  $\text{TiO}_2$  AR coating. The cell manufacturing process is followed by bonding the cells to a lunar-manufactured coverglass with silicone adhesive (which may have to be imported) and interconnection of the cells into an array.

Major disadvantages of crystalline silicon for lunar manufacture are the complexity of the process, the mass of the processing equipment needed, and the comparatively high usage of refined silicon.

#### 4.2 Amorphous Si:H

Amorphous silicon solar cells have efficiencies of 5-6% AMO, with ~10% likely for the near term [18]. The advantage of amorphous silicon cells is that the active thickness may be as low as 1-2 microns, thus requiring very little use of refined silicon. The disadvantage is the comparatively low efficiencies and the yet-unsolved problem of light-induced degradation. Preliminary studies suggest that amorphous silicon cells are more radiation tolerant than single crystal silicon, by a factor of 3 for electron irradiation, and by as much as a factor of 50 for proton irradiation [18,19]. Further, it may be possible to remove radiation damage by annealing at temperatures of 200° C or less [20].

An advantage of amorphous silicon is that, in principle, the process sequence can be made extremely simple.

While the silicon is readily available, hydrogen would have to be imported from earth. As 2-10 atomic percent of the composition of amorphous silicon, it is a negligible weight percentage, so this will not be a major problem. Dopants for a-Si typically are boron (diborane) and phosphorus (phosphine). The boron would have to be imported; this is also a small component. It also may be possible to dope the material with aluminum. Current technology amorphous silicon cells use indium-tin oxide, tin oxide, or cadmium sulfide for a transparent conductive surface layer. If material is not to be imported for the front contact, a possible substitute is zinc oxide, a highly transparent semiconductor. This would require refining zinc from the low (0.03%) concentration present. If this is not possible, it would be possible to use a very thin layer of aluminum.

Most projected high power/weight amorphous silicon arrays use polymer films (e.g., Kapton, Tedlar) as substrates. The absence of hydrogen



and carbon on the moon will require these to be brought from Earth. If specific power is not an issue (*e.g.*, if the arrays are to be used on the moon), cells could be fabricated on glass (possibly silica or alumina), which is easily available from lunar material.

For uses where specific power is important (*e.g.*, arrays which will be used elsewhere, for example for SEPS missions or for a Mars base), a likely substrate would be a thin metal foil. Production of amorphous silicon cells has been demonstrated on 7.5 to 25 micron electroformed nickel sheets, or stainless-steel sheets thinned by etching [20]. Iron is a major component of the lunar crust; very thin steel sheets (density 7.9 gr/cm<sup>3</sup>) would be an available substrate. Nickel is not easily available in the bulk soil, but can probably be refined from meteoric material magnetically separated from the soil.

A much better substrate would be thin aluminum or titanium, since the density is much lower (2.7 and 4.5 gr/cm<sup>3</sup> respectively). Use of such substrates is unproven.

One advantage to the moon as a location for an amorphous silicon manufacturing site is the presence of a good vacuum. Ambient pressure on the moon is in the range of 10<sup>6</sup> molecules/cm<sup>3</sup>. While exhaust from the transport spacecraft and leakage from the habitat will degrade the ambient high-vacuum environment somewhat, the pressure is still expected to be at most in the range of 10<sup>-9</sup> torr [21]. Since existing amorphous silicon processes have base pressures in the mid- to low- 10<sup>-6</sup> torr range, this is an excellent production environment.

#### 4.3 a-Si Cell Production

An advantage of amorphous silicon is the base of production experience in large-scale, semi-automated factories. The world output of amorphous silicon solar cells is 10-15 MW/yr, with additional production facilities under construction.

Amorphous silicon cells are currently made by a plasma process at 0.1 to 1 torr. Glow-discharge processing seems to give the best results. Typical deposition conditions are summarized in table 3 [22]. Three a-Si deposition chambers, a chamber for the deposition of the transparent conductor and one for deposition of the metal contacts, plus a loading chamber and an unloading chamber are required. In the roll-to-roll process [23], a flexible substrate is passed sequentially through chambers which deposit the p, i, and n amorphous silicon layers and the transparent conductor. In the continuous multichamber in-line system, the solar cell is deposited on a substrate, *e.g.*, glass, which need not be flexible.

For a typical production output of 1.5 MW per year, the production equipment for such a line on Earth would occupy about 750 m<sup>2</sup> of floor space, with a volume of about 230 m<sup>3</sup> and a total mass of 45,000 kg [24]. However, it must be noted that typical production processes are not optimized to minimize the equipment mass.

The lunar vacuum ambient will simplify the production process, since the vacuum chamber can be omitted. The process will require an enclosure to prevent the gas from leaking out into the lunar vacuum, but this can be light, since the pressure is negligible. It will also be necessary

to collect and compress the "waste" gas to recycle the hydrogen. This is done with vacuum pumps acting as compressors. The reaction chamber itself can be made extremely light in weight. The irreducible mass elements are the three RF generators, 50 kg each, the seven vacuum turbopumps, 30 kg each (450 l/min), and a primary pump to back the turbopumps, 250 kg (200 m<sup>3</sup>/hr). The total mass for this is about 600 kg. Likely other elements could increase this total by a factor of two or three. Provision of automated machinery would be likely to increase this yet further.

We also note that an alternative process sequence for lunar manufacture of amorphous silicon cells, based on vacuum evaporation using solar concentrators followed by hydrogenation of the material as a separate step, has been proposed by Fang [25]. While this process to date has only produced cells of comparatively low efficiency [26], there are no known mechanisms that prevent efficiencies from advancing to levels comparable to other technologies. If higher efficiencies can be obtained, the process proposed by Fang has an advantage over the plasma process discussed above in that the silane manufacturing process is unnecessary.

#### *4.4 a-Si Mass and Specific Power*

Amorphous Si cells are not yet proven in space. In the near term, a-Si will likely not reach efficiencies high enough to be competitive in low Earth orbit, where drag is an important factor. For cells to be used on the moon, weight is not a particular issue. For this application amorphous silicon is very likely the best technology. For other uses, it is worthwhile to make an approximate calculation to determine whether high specific power can be reached despite comparatively low efficiency.

The baseline cell considered was that of Mrig and Jackson [27], modified for lunar materials by replacing tin oxide by zinc oxide, and assumed to be deposited on a 25 micron thick Kapton substrate. It has been suggested [12,13] that an amorphous silicon array may require little or no coverglass, since the radiation damage is low, especially if the array is periodically annealed. This is likely optimistic, and applications such as Mars surface power will certainly require some protection to avoid abrasion by dust. Silica covers could easily be manufactured from materials available on the moon. The array weight, shown in table 4-A, is calculated both with and without a silica cover.

If the cell has an efficiency of 5%, a very conservative assumption, this translates to a uncovered cell specific power of 1700 W/kg. Since the Earth-manufactured substrate is 88% of the total cell mass; clearly there is no significant weight advantage to manufacturing such a cell on the moon. Addition of the cover reduces the specific power by a factor of four.

For a cell manufactured from all lunar materials, a lunar-manufactured steel substrate is substituted for the Kapton. This greatly increases the mass. A 25 micron steel substrate weighs 200 gr/m<sup>2</sup>, leading to a specific power (again assuming 5% efficiency) at the cell level of 350 W/kg without cover, or 220 with.

Despite the low efficiency assumed, even with the glass covers the cell specific power is competitive with baseline single crystal silicon cells. Cell

specific power is only one factor in the overall array specific power, and the structural mass of the array is also a consideration. In general this should be expected to scale with the cell mass.

Table 4B shows cell-level mass for a more advanced cell. Here we assumed a thinner substrate can be used, as well as slight reductions in the cell thickness (primarily the back contact). The thinnest Kapton currently available from Dupont is 7 micron. Tensile strength is 30,000 PSI, more than adequate for stretching out the array.

For this case the substrate is 80% of the total mass. For the advanced cell we assume a lower-mass and an efficiency increase to 10%, which is typical of the best single-junction cells currently made in the laboratory. Considerably higher performance is predicted for advanced structures. The cell-level specific power is 9880 W/kg without cover, or 1900 W/kg with a thin (25 micron) cover. For a cell from all lunar materials, a 7.5 micron steel substrate weighs 60 gr/m<sup>2</sup>, leading to a cell specific power of 2200 W/kg without cover or 1100 W/kg with the 25 micron cover.

## **5. Conclusions**

Solar cells manufactured on the moon could significantly reduce the cost of transportation of power systems to space destinations, including the moon, Mars, Earth orbit, and transfer orbits. Silicon is abundant on the moon, and refining processes have been demonstrated which do not depend on extensive use of reactants imported from Earth. Because of the lower requirements for refined silicon, the amorphous silicon process is preferred, despite lower efficiencies. Calculations show that specific power of amorphous silicon cells can be adequate for most uses.

Production of structural elements for the arrays, such as struts, frames, beams, *etc.*, is also an important part of the array manufacturing process, although not discussed in depth here, as is production of the substrates.

Assuming mining operations already in place on the moon for other purposes, such as oxygen extraction, production of silicon for lunar photovoltaic arrays is not a major difficulty. Lunar-produced photovoltaics are likely to be a practical product only if the predicted demand for power in space is large, at a minimum several megawatts per year. Such requirements are likely if there is a vigorous human presence in space, if solar-electric propulsion vehicles become a significant fraction of the in-space transportation system, or if satellite solar power systems become a power source for terrestrial power.

## 6. References

- (1) *Lunar Bases and Space Activities in the 21st Century Symposium*, 5-7 April 1988, Houston, TX.
- (2) NASA Office of Exploration, *Exploration Studies Technical Report FY 1988, Vol. 1*, NASA Technical Memorandum 4075, 21-22 (Dec. 1988).
- (3) B.G. Logan, "Initiative for the 21st Century: Advanced Space Power and Propulsion Based on Lasers," presented at NASA Lewis April 25-26, 1988; Lawrence Livermore Laboratory preprint UCRL-98520.
- (4) G.E. Maryniak and B. Tillotson, "Design of a Solar Power Satellite for Construction from Lunar Materials," *Space Power* 7, No. 1, 27-36 (1988).
- (5) Representative data from: G.H. Morrison *et al.*, "Multielement analysis of Lunar Soil and Rocks" *Science* Vol. 167 (special issue on Apollo 11 results), 505-507 (1970); *Apollo Preliminary Science Report* (Apollo 11 through Apollo 17); *Proc. 9th Lunar and Planetary Science Conf.*, Pergamon Press (1978); and D. Caulkins, "Raw Materials for Space Manufacturing," *J. Brit. Interplanetary Soc.*, 30, 314-316.
- (6) D. Bhogeswara Rao *et al.*, "Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen and Nonterrestrial Sources," *Space Resources and Space Settlements*, NASA SP-428, 257-288 (1979).
- (7) D. Ho and L.E. Sobon, "Extraterrestrial Fiberglass Production Using Solar Energy," *Space Resources and Space Settlements*, NASA SP-428, 225-232 (1979).
- (8) R.J. Williams, "Mining and Beneficiation of Lunar Ores," *Space Resources and Space Settlements*, NASA SP-428, 225-232 (1979).
- (9) G.A. Landis, "Solar Power for the Lunar Night," *9th Biennial Princeton/SSI Conf. on Space Manufacturing* (1989); to be published in *Space Manufacturing 8* (AIAA, 1989).
- (10) D.R. Sparks, "Vacuum Reduction of Extraterrestrial Silicates," *J. Spacecraft* 25 (2), 187-189 (1988).
- (10) D.L. Anthony *et al.*, "Dry Extraction of Silicon and Aluminum from Lunar Ores," Paper No. LBS-88-066, *Lunar Bases and Space Activities in the 21st Century Symposium*, 5-7 April 1988, Houston, TX.
- (11) R.C. DeMattei, D. Elwell, and R.S. Feigelson, "Electrodeposition of Silicon at Temperatures above its Melting Point," *J. Electrochem. Soc.*, 128, 8, 1712-1714 (1981).
- (12) P.A. Taylor, "Silane: Manufacture and Applications," *Solid State Technology*, July 1987.
- (13) J.H. Lorentz, "The Silicon Challenge," *Proc. Flat-Plate Solar Array Workshop on the Science of Silicon Material Preparation*, Aug 23025, 1982, DOE/JPL-1012-81.
- (14) Union Carbide, "Feasibility of the Silane Process for Producing Semiconductor Grade Silicon," Final Report, June 1979, DOE/JPL Contract 954334.
- (15) G.A. Landis, "Thin, Light-Trapping Silicon Solar Cells for Space," *20th IEEE Photovoltaic Specialists Conference*, Las Vegas, NV, 708-712 (1988).
- (16) A.J. Armini, S.J. Bunker, and M.B. Spitzer, "Non-Mass Analyzed Ion Implantation Equipment for High Volume Solar Cell Production," *16th*

*IEEE Photovoltaic Specialists Conference*, 895-899 (1982).

(17) G.A. Landis, S.G. Bailey and D.J. Flood, "Advances in Thin-Film Solar Cells for Lightweight Space Photovoltaic Power," *NASA Tech. Memo. TM-102017* (1989); to appear in *Space Power*, Vol. 8 (1989).

(18) J.J. Hanek *et al.*, *Space Photovoltaic Research and Technology 1986*, NASA CP-2475, 99-110 (1986); C.F. Gay *et al.*, *17th IEEE Photovoltaic Specialists Conference*, 151-154 (1984).

(19) C.E. Byvik *et al.*, *17th IEEE Photovoltaic Specialists Conference*, 155-160 (1984).

(20) G.A. Landis, "Degradation of the Lunar Vacuum by a Moon Base," submitted to *Acta Astronautica* (1988).

(21) M.A. Perino, "Introduzione Alle Celle Fotovoltaiche", A.I.T. SG-NT-AI-065, Sept. 1987; see also M.A. Perino, "Celle Solari in Silicio Amorfo Idrogenato," A.I.T. SG-PL-AI-040, Oct. 1986.

(22) A. Madan, "GSI's Continuous Multichamber Approach for Mass Production of Amorphous Silicon Solar Cells," *Proc. 1987 Amorphous Silicon Subcontractors' Review Meeting*, Palo Alto, CA Jan 26-27, 1987.

(23) A. Madan, private communication (1989).

(24) P.H. Fang, "A Lunar Solar Cell Production Plant," *Solar Cells*, 25, 31-37 (1988).

(25) P.H. Fang *et al.*, "Combined Microcrystal and Amorphous Silicon Solar Cells," *Appl. Phys. Lett.* 41 (4), 365 (1982).

(26) L. Mrig and B. Jackson, *Amorphous Silicon Conceptual Design and Cost Estimate*, SERI technical report SERI-RR-216-2668, Aug. 1985.

#### *Acknowledgements*

An earlier version of this paper was presented at the 20th IEEE Photovoltaic Specialists Conference in Las Vegas, NV, September 1988.

The authors would like to thank Dr. A. Madan of Glasstech Solar, Inc, for information concerning amorphous silicon deposition systems, and Maria Antonietta Perino would like to acknowledge the International Space University - Commercial Operations Group for discussions on the utilization of amorphous silicon solar cells for a moon base power supply.

**Table 1-A:  $\Delta V$  in km/sec  
(minimum velocity change needed to launch payload)**

To:	From:	
	Earth	Moon
L.E.O.	9.3	3.3
G.E.O.	11.9	3.2
Moon	13.6	-
Mars transfer orbit	13.6	5.2

**Table 1-B: Theoretical Maximum Payload Fraction  
(in percent)**

To:	From:	
	Earth	Moon
L.E.O.	9.8	43*
G.E.O.	5.1	45
Moon	3.3	100
Mars transfer orbit	3.3	27

Calculated using  $V_{\text{exhaust}}=4$  km/sec  
( $H_2/O_2$  propellant).  
\*assumes aerobraking at perigee.

**Table 2:  
Abundance of Elements in the Lunar Crust and Soil**

*Major Constituents:  
maximum concentrations in percent*

Oxygen	45
Silicon	28
Iron	18
Al	14
Mg	11
Ca	9
S	0.3
P	0.2

*Other components of interest (ppm)*

Germanium	450	Boron	24
Zinc	300	Copper	18
Carbon	200	Gallium	8
Arsenic	<100	Sn	<10
Hydrogen	70	Se, Cd	<1
Tellurium	60		

*Abundances listed are peak concentrations found in rocks or soil from Apollo missions.*

**Table 3: Glow-discharge processing of a-Si**

Gas	$SiH_4$ (pure or in $H_2$ or Ar) <i>(other constituents such as <math>SiF_4</math> also sometimes added)</i>
Pressure	0.1 to 10 Torr
Substrate temperature	200 - 300° C
Discharge power	4 W
Gas effusion velocity	20 - 30 sccm
n dopant gas	$PH_3$
p dopant gas	$B_2H_6$

**Table 4: Specific Power of Thin-Film Cells**

**A: Baseline**

Cell Element	Matl.	T ( $\mu$ )	$\rho$ ( $\text{gr}/\text{cm}^3$ )	M ( $\text{gr}/\text{m}^2$ )
AR Coating	TiO <sub>2</sub>	0.95	4.3	0.4
TCO	ZnO	0.1	5.6	0.6
$\alpha$ -Si	Si	0.54	2.3	1.2
<u>Back Contact</u>	<u>Al</u>	<u>1.0</u>	<u>2.7</u>	<u>2.7</u>
<i>total cell</i>		2.59		4.9
<u>Substrate</u>	<u>Kapton</u>	<u>25.</u>	<u>1.4</u>	<u>35.5</u>
<i>total, cell plus substrate</i>				40.4

Cover            SiO<sub>2</sub>    50    2.6    125

efficiency: 5% (AMO):  
 specific power (excluding array structure):  
 1700 W/kg without cover;  
 410 W/kg with cover

**Cell made from all-lunar materials:**

cell		2.59		4.9
<u>substrate</u>	<u>steel</u>	<u>25.</u>	<u>7.9</u>	<u>200</u>
<i>total, cell plus substrate</i>				205

Cover            SiO<sub>2</sub>    50    2.6    125

efficiency: 5% (AMO):  
 specific power (excluding array structure):  
 350 W/kg without cover;  
 220 W/kg with cover

**B: Advanced Cells**

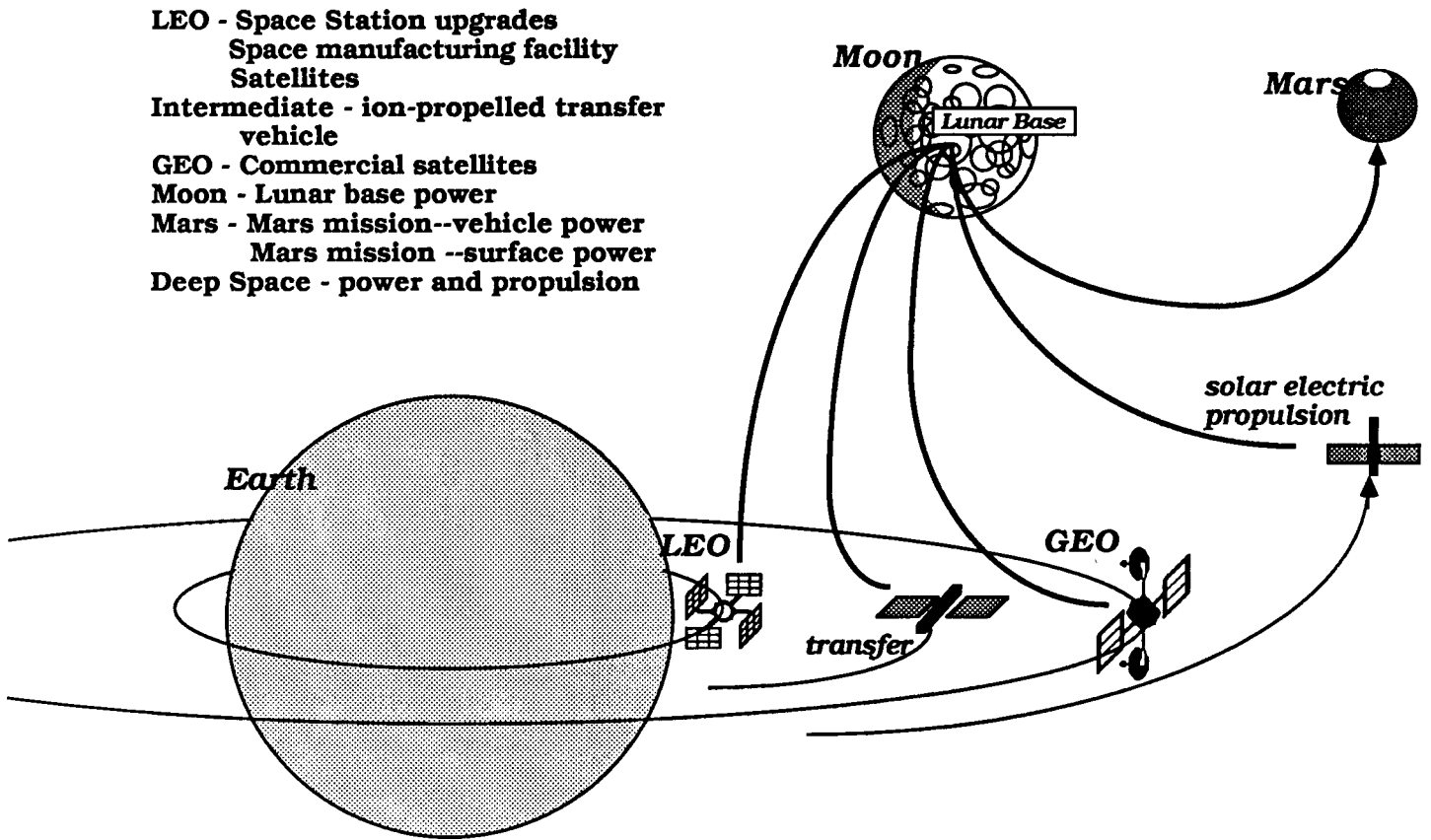
Cell Element	Material	M ( $\text{gr}/\text{m}^2$ )
cell	1.9 $\mu$ $\alpha$ -Si	2.7
<u>substrate</u>	<u>7<math>\mu</math> Kapton</u>	<u>10.8</u>
<i>total</i>		13.7

efficiency: 10% (AMO); specific power:  
 9900 W/kg without cover;  
 1900 W/kg with

**All-lunar materials:**

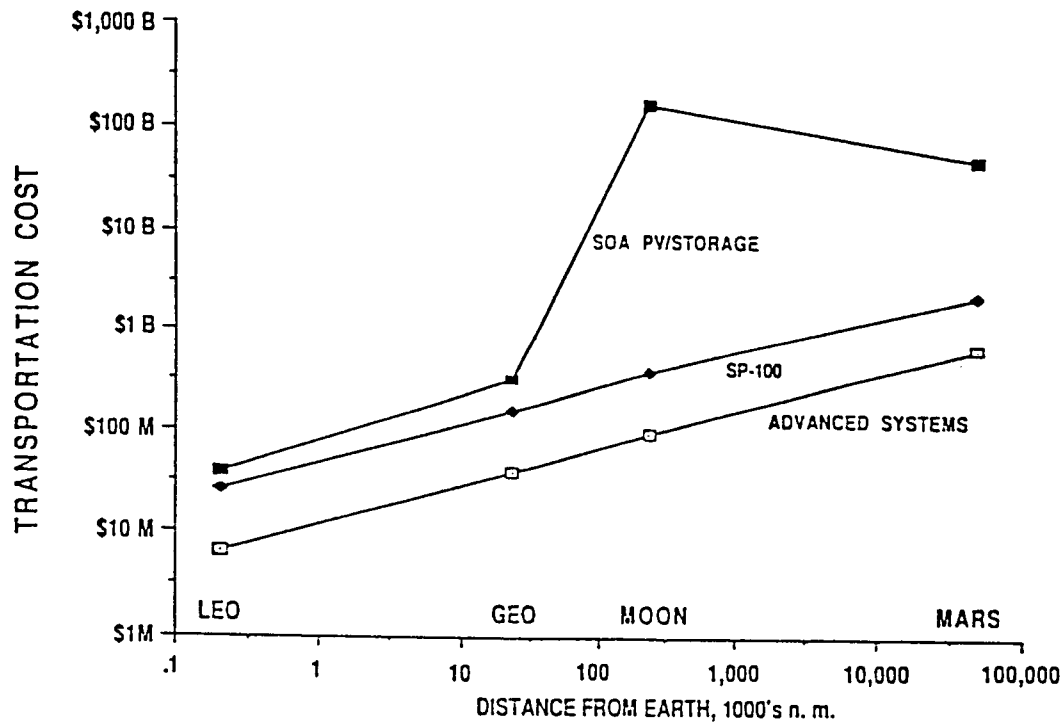
cell	1.9 $\mu$ $\alpha$ -Si	2.7
<u>substrate</u>	<u>7.5<math>\mu</math> steel</u>	<u>60</u>
<i>total</i>		62.7

efficiency: 10% (AMO):  
 specific power 2200 W/kg without cover  
 with 25 $\mu$  glass cover: 1100 W/kg



**Figure 1:**  
 Uses for Lunar Manufactured Photovoltaic Arrays





**Figure 2:**

Estimated transportation costs of delivery of 100 kW of electrical power to orbit, moon, and Mars using current technology boosters. Shown is state of the art (SOA) photovoltaic technology and storage, SP-100 nuclear power system, and a representative future technology "advanced" power system. The high cost of PV/storage for the moon is due to the mass of the storage required for the lunar night.



# Report Documentation Page

1. Report No. NASA TM-102102 Corrected Copy		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Lunar Production of Solar Cells				5. Report Date	
				6. Performing Organization Code	
7. Author(s) Goeffrey A. Landis and Maria Antonietta Perino				8. Performing Organization Report No. E-4866	
				10. Work Unit No. 506-41-11	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for the 9th Biennial SSI/Princeton Conference on Space Manufacturing sponsored by the Space Studies Institute, Princeton, New Jersey, May 10-13, 1989. Goeffrey A. Landis, National Research Council-NASA Research Associate; Maria Antonietta Perino, Aeritalia, Space Systems Group, Research, 10146 Torino-Corso Marche, Italy.					
16. Abstract The feasibility of manufacturing of solar cells on the moon for spacecraft applications is examined. Because of the much lower escape velocity, there is a great advantage in lunar manufacture of solar cells compared to Earth manufacture. Silicon is abundant on the moon, and new refining methods allow it to be reduced and purified without extensive reliance on materials unavailable on the moon. Silicon and amorphous silicon solar cells could be manufactured on the moon for use in space. Concepts for production of a baseline amorphous silicon cell is discussed, and specific power levels calculated for cells designed for both lunar and Earth manufacture.					
17. Key Words (Suggested by Author(s)) Moon base Lunar exploration Space industrialization Solar cells			18. Distribution Statement Unclassified - Unlimited Subject Category 91		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No of pages 18	22. Price* A03