

NIAC PROGRAM – Final Report

"New Architecture for Space Solar Power Systems: Fabrication of Silicon solar Cells Using In-Situ Resources"

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1.0 WORK PLAN

- Task 1. Selections of Typical Locations for Solar Cells Production on the Moon
- Task 2. Definition of Available Raw Materials on the Moon and Definition of Chemical/Electrochemical Processes for Extraction of Solar cell Materials
- Task 3. Definition of Production Process for Solar Cell Arrays on the Surface of the Moon
- Task 4. Performance Modeling for Assessing Cost/Benefit Ratio for the Power System Concept
- Task 5. Definition of Potential Applications to Mars
- Task 6. Identification of Key Tasks and Customers for Phase II of the Program

2.0 Summary of Accomplishments

- a. Lunar mare regolith simulant can be melted to produce a suitable substrate for solar cell deposition.
- b. Ferrosilicon can be produced by carbothermal reduction of lunar simulant; however, a purification stage is required either before or after reduction in order to produce silicon of appropriate purity.
- c. Lunar anorthite and anorthite-rich rocks are very refractory and must be raised to very high temperatures (>2000°C) before they begin to react. In addition, anorthite-rich melts are very viscous. This has two implications: (1) reaction rates with carbon are slow; and (2) anorthite-rich melts will not flow readily to make a good substrate for silicon PV production. This suggests that the crawler concept may not be applicable to lunar highlands terrains.
- d. The amount of lunar products required to produce 1 m² of silicon PV cells is about 50 g; approximately 180 kg/yr of lunar materials is required if a single crawler operates for 3500 hours (useful lunar daytime) depositing 1 m²/hr.

- e. A spreadsheet model has been constructed to show the advantage of producing silicon PV cells on the Moon compared to bringing them from Earth.
- f. A complete PV array production system will include several subsystems: raw materials production system; PV cell emplacement “crawler”; utility subsystem that transports raw materials from the materials production to the cell emplacement subsystem. Additional subsystems may be required for connecting the PV power system and distributing the power and for maintenance and repair of the arrays.

3.0 Detailed Accomplishments by Task

Task 1. Selections of Typical Locations for Solar Cells Production on the Moon

The capability of solar cell fabrication from *in-situ* materials directly on the lunar surface offers the potential to support a wide variety of activities. The principal site-related constraints associated with the concept are:

- (1) The latitude of the site, which may constrain the technique by which solar cells are applied directly to the surface or the expected efficiency of the system. At equatorial latitudes, solar cells may be applied to a flat surface for reasonable efficiency, however, in moving to higher latitudes, the cosine loss from a flat surface increases and it is desirable to tilt the array ever more toward the sun. The angle of repose of the lunar regolith limits such tilting to about 30° from horizontal.
- (2) The surface topography, which likewise can affect the application technique and the efficiency of the system. Large flat areas are preferred, though E-W-striking slopes tilted toward the equator are suitable at non-equatorial latitudes. Rugged terrain represents a problem for very large arrays, but the impact history of the Moon has produced relatively flat and smooth terrain at the kilometer scale in both lunar Mare and highland terrain.
- (3) The composition of the underlying material affects the process in two ways. First, the melting temperature of the regolith varies from about 1150°C on Mare basalt surfaces to over 1500°C on highland anorthositic terrain, which will affect the scale of the solar concentrators required for vacuum evaporation. Furthermore, whereas basaltic melts are relatively low viscosity and can flow to form a smooth surface, while the viscosity of the anorthositic material may prevent the formation of a smooth surface unless very high temperature is achieved. Second, the availability of raw materials for efficient production of silicon, iron, titanium dioxide and doping materials will differ from site to site. In addition, the mineralogical form determines the resource processing techniques that can be used. Three geochemical terrain types are found on the lunar near side. The lunar maria are filled with basaltic volcanic rocks, rich in iron, titanium and silicon. The lunar highlands are anorthositic (rich in calcium feldspar) in which calcium, aluminum and silicon are abundant, but iron and titanium are not. A third terrain, called the Procellarum KREEP terrain, contains material

ejected by the Imbrium Basin event that is richer in potassium, rare earth elements, and phosphorus, as well as thorium and other elements than the other two terrains. In order to have access to all needed elements, the best locations may be those where there is access to all three types of materials.

- (4) The nature of the use to which energy will be put to use will have a first-order effect on the process, because it may be associated with a special purpose that requires a particular location on the Moon. The ability to transmit energy from one place to another on the Moon will be limited, at least in the beginning phases of installation of a system, so energy systems would best be located near the point of use and a technique that could be applied anywhere would be favored. Concepts for lunar energy grids have been proposed (Schrunk et al, 1999), but require a large user base to be cost-effective.

Three sites are considered in this study: Each of them would be useful sites for early robotic and human exploration. They differ in that they could best support different long term activities and therefore suggest somewhat different development scenarios. These three sites are:

1. An equatorial site, located at about 33.1° E. This site is suitable for a permanently habitable human outpost, observing the Earth and space, and conducting routine lunar surface operations. It is chosen because of its special attributes as a location for a lunar electromagnetic launcher facility.
2. An equatorial site located at the east limb of the Moon. This site is compatible with a human lunar outpost, for access to the far side for observational purposes, and for its potential use as a site for a lunar power system, beaming power to Earth.
3. A site near the lunar South Pole, on the near side of the Moon (85°S). This could be a location for a human outpost with Mars analog characteristics, and where access to lunar polar ice may be available as the basis for a propellant export system.

Site 1. Equatorial site 0°, 33.1° E.

This site is chosen because it could be the best location for an electromagnetic launcher designed to transfer lunar materials from the Moon to the Earth-Moon L-2 Lagrangian Point. Heppenheimer showed that payloads launched on the same trajectory from the Moon by an electromagnetic launcher located at this point would have very small dispersion with respect to launch velocity variations at the L-2 point where packets would be collected by a “mass catcher”. This would mean that no terminal propulsion system would be needed, significantly improving the performance of the system.

The site is located in the southern region of Mare Tranquillitatis, close to some hills of highlands materials probably excavated by Mare Nectaris. The Mare portions are flat, with a relatively thick regolith, as this mare is among the older lunar maria. It is underlain by basaltic rock similar to that of the Apollo 11 sample collection. These have relatively high titanium content, due to the presence of the mineral ilmenite (FeTiO₃) in the basalts. The hills represent a variety of highlands units, some of which are ejecta from the Imbrium basin event. Iron and titanium maps produced from Clementine imagery show that both iron/titanium-rich and iron/titanium-poor

materials are present in these hills, as well as materials with signatures of the lunar geochemical component known as KREEP, which has much higher contents of Potassium, Rare Earth Elements, Phosphorus, Thorium and other elements than typically found in either highlands or mare rocks. Due to its elevated titanium content, relatively high concentrations of ^3He may be found in the regolith.

In addition to its potential value as a locale for accessing a wide variety of resources, this location would be a candidate for intensive geological study to address the question of the makeup of the early lunar crust. The successive ejecta blankets from several major impact events that occurred in the period 3.8 – 3.9 billion years ago probably sampled different depths in the original lunar crust. To unravel this history would require substantial on-site investigation, best supported by a long-term human outpost. Being an equatorial site, an Earth-observing system could be located here, capable of monitoring the Earth's magnetosphere.

Site 2. Equatorial Limb site (0° , 90°E) – Mare Smythii

A Mare Smythii site was proposed for a human outpost on the Moon by Spudis and Hood in 1988 because of several factors, including: ease of communications and operations; access to the far side for microwave- and radio-astronomy, a rich assemblage of accessible field localities for addressing the problems of lunar origin and history, and access to a wide variety of materials for resource processing. They suggested that an outpost located at 0° , 90°E , within the mare basalts would be supported by a communications station at 0° , 81°E , about 270 km from the outpost, where continuous line of sight to the Earth can be maintained. The radio-telescope facility would be located about 330 km to the east of the outpost, where the Earth could never be seen. This location could become a prime location for a Lunar Power System array, but would require an additional outpost at the West limb of the Moon.

The geochemical properties of the Mare Smythii region were examined by the orbital data from the Apollo, which were interpreted by Spudis and Hood, among others, to indicate that a wide variety of materials exist there. These include high-titanium basalts, possibly high-titanium pyroclastic glasses in dark mantle deposits, anorthositic debris, and KREEP-rich basalts. Most of the materials other than the mare basalts are found in mixed deposits and breccias that probably will require some degree of mineral separation to be made useful for resource purposes. Local transport of materials over distances of about 200km would be required to bring this variety of raw materials to a central processing plant.

Site 3 Lunar South Pole (180° , 85°S)

The lunar poles have been of interest for many years as a potential site for human outposts, because of their potential to provide a more constant thermal environment, with opportunities for straightforward engineering solutions to overcome barriers to the 14-day night experienced everywhere else on the Moon. The recent results of Clementine and Lunar Prospector missions have demonstrated that there are places where within a few kilometers it should be possible to station solar energy collectors, one of which is always illuminated (with the exception of periods of total lunar eclipse), so that a lunar outpost could readily receive solar energy at all times. In addition, there is evidence that there are increased concentrations of hydrogen and possibly ice

deposits in areas that are in permanent shadow. Access to both permanent sunlight and permanent shadow have many interesting potentials, for example, the placement of large infrared telescopes within a permanently shadowed, permanently cold crater, or even the thermo-electric generation of electricity by placing one end of a thermocouple in the cold, the other in a sunlit hot area. For human outposts, the surface thermal environment is colder, but varies over a smaller range than that at the equator, and similar to thermal environments encountered on Mars. Recently, Schrank et al have described a lunar power and communication grid that grows outward from a pole. The selected site is on the top of a mountain that rises several kilometers above the surrounding regions (Cornell reference) to the north and south at 85°S latitude. In addition to access to sunlight, the mountaintop is high enough that it is always in direct view of the Earth, making continuous communications possible. And, the south-facing side of the mountain is forever shielded from Earth and may be a location for an radio-telescope. Later radio telescopes may be located on the lunar far side, within 300 km of this location on the Moon. If a space transportation node is established in an Earth-Moon libration point, it is possible to depart from or arrive at the Moon at practically any time.

The material of which the mountain is made appears to be anorthositic, lying on the perimeter of the South Pole – Aitken Basin, the largest, oldest impact basin on the Moon. Geologically, a base at this location would have access to terrain that probably represents the earliest lunar crust. It would also be located within 100 km of some of the most extensively shadowed regions of the South Pole, in fact, local permanent shadow is certainly found at the foot of the mountain, within 15-20 km. Detailed study of the regolith within the permanent shadow would be possible from this location, and if ice or strongly enriched hydrogen deposits are located, this could become a prime site for commercial resource extraction.

For the specific production of silicon PV arrays, the site is very rich in aluminum but deficient in iron. It may be possible to obtain iron by extracting small quantities of meteoritic metal that exist everywhere on the Moon and which can be easily extracted by magnetic concentration. Silicon is abundant and silicon extracted directly from anorthite may be of sufficient quality that PV cells can be produced directly. Titanium is in rather low abundance in this region of the Moon, so SiO₂ may be the material of choice for antireflective coatings.

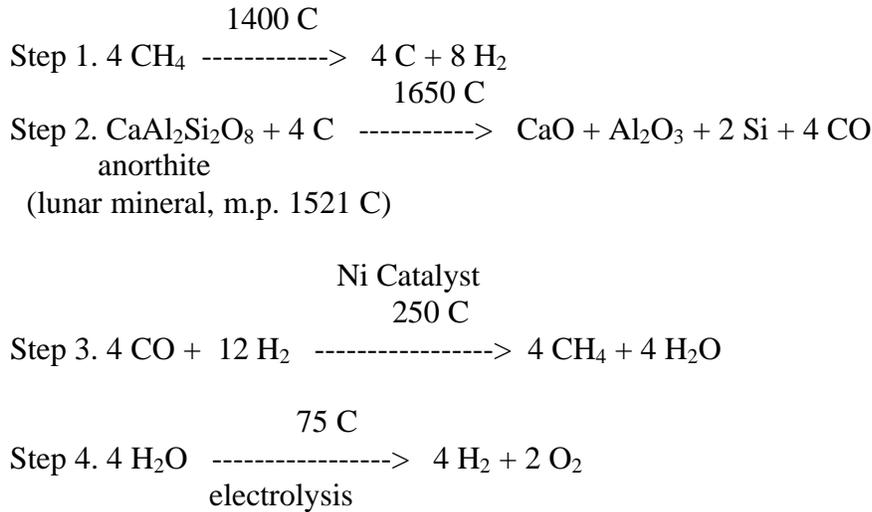
Task 2. Definition of Available Raw Materials on the Moon and Definition of Chemical/Electrochemical Processes for Extraction of Solar cell Materials

1. Chemistry

The Hydrothermal Reduction Process is not applicable to the production of silicon on the Moon as hydrogen cannot reduce silica to silicon at practically attainable temperatures. The Carbothermal Reduction Process is applicable to the production of silicon as carbon does reduce silica to silicon at 1650 C. A closed cycle process is required to reduce resupply from Earth. Resupply must be not more than 5% by weight, including chemical reagents, once the plant has been set up.

It should be noted that several other processes have been proposed for the preparation of silicon on the Moon, e.g., magma electrolysis and fluorine extraction. None of these processes are as mature as the Carbothermal Reduction Process.

Closed Cyclic Process for Preparation of Silicon on the Moon: (Oxygen is also prepared as a useful byproduct).



Resulting simplified chemical process:



As the focus of this program is to demonstrate the preparation of PV grade silicon from lunar simulant, i.e., JSC-1 and anorthite, the reduction chemistry will be simplified by using graphite as the source of carbon in place of methane, Step 2.

2. Engineering

Step 1. Load the reactor (a high performance Al_2O_3 crucible) with the required amounts of JSC-1 (or Anorthite) and graphite. Place the reactor in the high temperature furnace. Raise the reactor temperature to 1650°C at a controlled rate of 1.0 to $1.5^\circ\text{C}/\text{min}$ so as to prevent thermal stress cracking of the crucible. Monitor the composition of the product gas using VPC. Start to cool the reactor at the same controlled rate when the amount of CO in the product gas approaches zero.

Step 2. When the reactor reaches ambient temperature, remove it from the furnace and separate it from the solid product mix. Determine the physical and chemical composition of the product and the interface between the reactor wall and product. The metallic and slag phases may separate fairly cleanly. The interface zone will provide information about reactor life.

Step 3. We do not expect the silicon produced by the reduction reaction to be PV grade. Two methods of purification are being considered at this time, physical and chemical.

3. Physical Separation By Distillation

The major metallic components obtained on the reduction of JSC-1 will be silicon and iron. Only silicon will be obtained on the reduction of anorthite. The physical separation of silicon from iron may be obtained by vacuum distillation and/or physical vapor deposition. The difference between the boiling points between silicon and iron is 192.3 °C (@ 1.0 atm) which should be large enough to obtain good separation.

Table 1. Separation of Metals from Slag by Vacuum Distillation

Metal Oxide	Density g/cm ³	Melting Point C	Boiling Point C
TiO ₂	4.23	1857	3660 (as TiO)
Al ₂ O ₃	3.5-3.9	2018	(2980)
MgO	3.58	2825	3260
CaO	3.25	2927	3500
Si	2.33	1455	2680
Fe	7.86	1537	2872

Table 2. Comparison of the Chemical Compositions of JSC-1 (Lunar Regolith Simulant) and Anorthite (Lunar Mineral Simulant) in weight %.

Oxide	JSC-1	Anorthite
SiO ₂	47.1	43.198
TiO ₂	1.58	
Al ₂ O ₃	15.02	36.657
Fe ₂ O ₃ *	3.44	
FeO	7.35	
MgO	9.01	
CaO	10.42	20.161
Na ₂ O	2.70	
K ₂ O	0.82	
MnO	0.18	
Cr ₂ O ₃	0.04	
P ₂ O ₅	0.66	
LOI	0.71	
H ₂ O	-----	-----
Totals	99.65	99.996

*All of the iron oxide on the Moon is FeO.

4. Experimental Data on Carbothemal Reduction

Both JSC-1 simulant and anorthite were separately mixed with graphitic carbon and reduced at 1650 °C in a high temperature Ar flow furnace. The mixtures were put in yttria crucibles, and processed for a period of ~ 3 hrs at temperature. The anorthite processing resulted in a broken crucible even under the 1.5 – 2 °C/min heat up and cool down times used in the experiment. The reduced mass was found to be hard, dense, and dark gray in color.

The JSC-1 processing resulted in no breakage of the crucible, however, the extracted processed material was sponge-like in appearance, and dark gray. Both the JSC-1 and the anorthite samples were seen to impregnate the crucible walls, with less effect in the case of JSC-1.

The reduced JSC-1 and anorthite samples were characterized by scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), electron probe microanalysis (EPMA), and electron backscattering analysis. Several samples of reduced anorthite and reduced JSC-1 were investigated.

REDUCED ANORTHITE

SEM micrographs of small pieces of reduced anorthite revealed relatively rough particle surface with areas that looked like cleavage planes (Fig. 1). The more planar areas were populated with large numbers of small particles of size ~ 10 μm (Fig. 2).

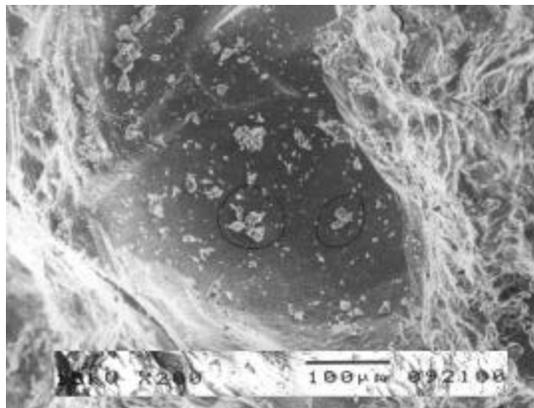


Figure 1. SEM micrograph of a region of the surface of a reduced anorthite sample indicating a rough sample surface morphology with particulate structure in planar regions.

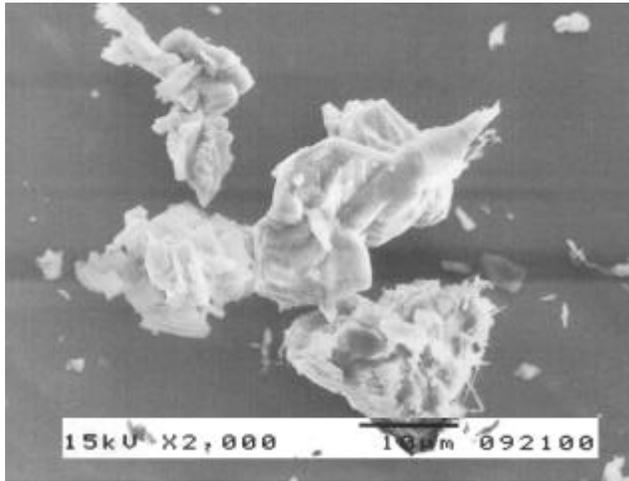


Figure 2. SEM micrograph of a region of the surface of a reduced anorthite sample indicating one of the particles in a planar regions. The particle is principally Si.

EDS measurements indicated that the particles were principally Al and Si with some Ca, while the background was mainly Al and Ca as can be seen in Figures 3 and 4. Elements of atomic number lower than sodium could not be seen by EDS due to the presence of a Be window between the detector and the sample, hence, it could not be determined if the samples were metallic or oxides.

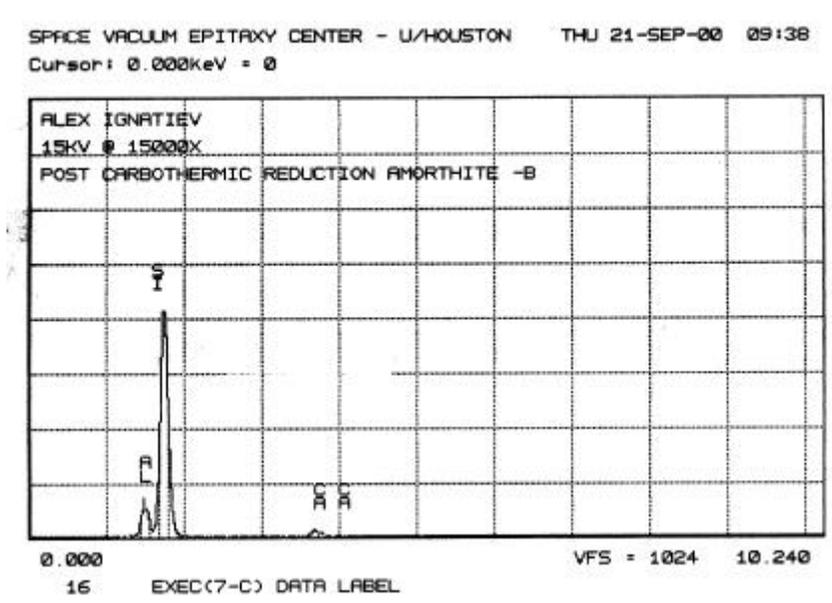


Figure 3. EDS measurement of one of the particles on the surface of a reduced anorthite sample indicating principally Si composition.

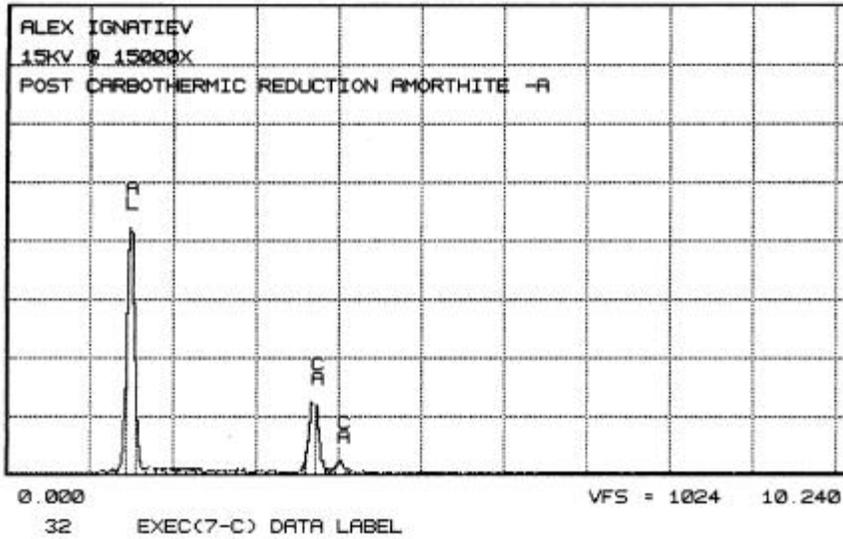


Figure 4. EDS measurement of the background area of a reduced anorthite sample indicating principally Al and Ca composition – EPMA data indicated the Al and Ca to be oxidized.

EPMA was applied to the sample with the following composition result:

Table 3. EPMA Analysis of the small particles on the surface of the sample

Element	Atomic %
Si	40
Al	11
Ca	4
O	44

Table 4. EPMA Analysis of the general sample background –

Element	Atomic %
Si	0
Al	30
Ca	7
O	63

These composition results are accurate only to about 15-20% since the analyzed samples did not have flat surfaces. None the less, it is clear that all of the processed material was oxidized to a

great extent. As such, it would not be suitable in its present state as a source of elemental material for thin film evaporation.

It should be noted that processing in the vacuum environment of the lunar surface would minimize or eliminate the oxidation that has been noted here in the initially processed material. Further effort is required to effectively answer this question.

REDUCED JSC-1

SEM micrographs of reduced JSC-1 revealed microstructure quite different from that of the processed anorthite. The sample surface was rougher than that of the anorthite sample, and had a large number of nodules imbedded in it (Figure 5). EPMA identified the nodules as an unoxidized FeSi alloy. Analysis of the remainder of the background material indicated a principal background of magnesium-aluminum spinel with additional small particles of CaMgAlSiO.

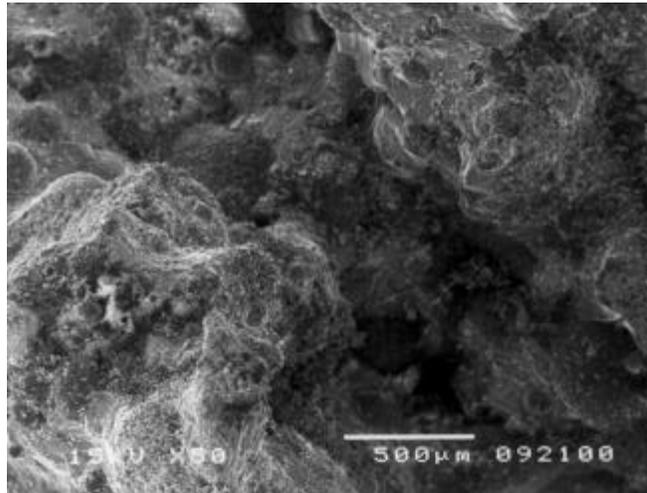


Figure 5. SEM micrograph of a region of the surface of a reduced JSC-1 sample indicating a large amount of surface morphology with nodular structure

EPMA results for the JSC-1 nodules, general background, and small particles are as follows:

Table 5. EPMA Analysis of the Nodules.

Element	Atomic %
Si	48
Fe	52

Table 6. EPMA Analysis of the Small Particles.

Element	Atomic %
Si	24
Al	6
Mg	9
Ca	21
O	40

Table 7. EPMA Analysis of the General sample background.

Element	Atomic %
Si	0
Al	21
Mg	11
Ca	0
O	68

It should be noted that these processed materials indicate that oxidation is occurring in the material as soon as it is exposed to the air atmosphere. As a result, care needs to be taken to prevent atmospheric exposure for the processed samples. This will be further studied to identify a process that would minimize or eliminate oxidation. However, as noted previously the observed oxidation will probably not be a problem on the surface of the Moon since the Moon has an excellent vacuum environment.

5. Results

The reduction with graphite of the anorthite and the JSC-1 samples is not fully complete. Both unreduced and additionally oxidized materials are present, with separation of silicon bearing species from the slag only in the case of the nodules found in reduced JSC-1. Those nodules are ~ 50-50 Fe-Si, and may be used for silicon extraction through the preferential evaporation of silicon in lunar vacuum. At the melting point of iron (1537 C) the vapor pressure of silicon is nearly 100 times that of iron – this indicates that successful vacuum distillation can be done to extract purified silicon from the lunar regolith.

Further improvement of the carbothermal reduction process is projected through the use of methane gas as the carbon source for the reduction. The use of methane may reduce the negative effects of the high viscosity of melted regolith, and allow for a more uniform distribution of carbon throughout the melt reducing the limitations of solid/liquid state diffusion.

Task 3. Definition of Production Process for Solar Cell Arrays on the Surface of the Moon

1. Solar Cell Construction

The silicon solar cell to be fabricated on the surface of the Moon would be simple p-n junction cell with melted regolith used as the substrate, silicon plus p-dopant evaporated in the first layer, and silicon plus n-dopant evaporated in the second layer. Bottom and top electrodes would be evaporated through contact masks to allow for both the cell surface transparency, and bottom and top contact interconnectivity for serial cell connection. A model of a Lunar silicon solar cell is given in Figure 6.

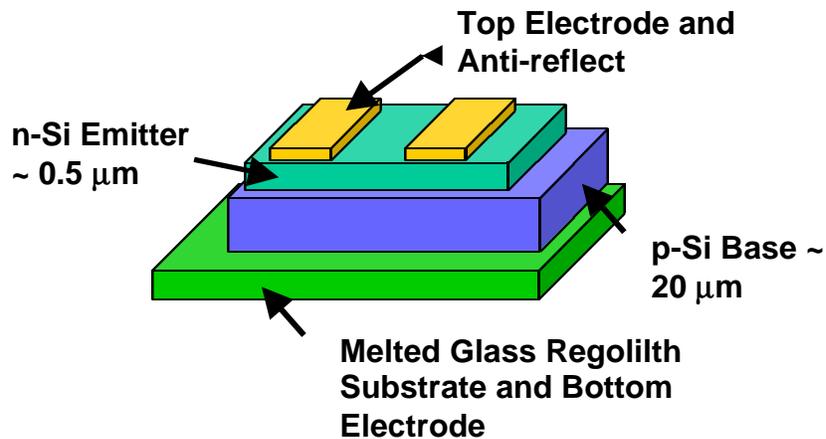


Figure 6. Proposed lunar silicon solar cell design.

The connectivity of the cells would yield a serially connected array with modules set at ~100V and 10A outputs. Serial connectivity through thin film evaporation is shown in Figure 7.

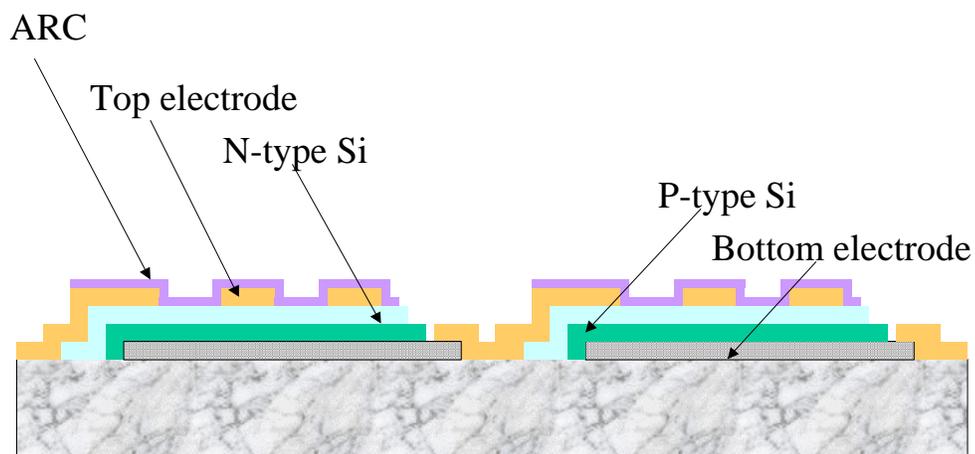


Figure 7. Serial connectivity for the fabricated cells showing the bottom electrode of one cell connected to the top electrode of the neighboring cell.

2. Vacuum Deposition Modeling

The modeling of vacuum deposition of solar cells on the moon has been conducted. Vapor pressures at temperature and resultant flux rates of evaporants have been calculated for predictions of vapor fluxes needed to deposit microns of silicon-based material on the moon.

The modeling has yielded solar collector size of $\sim 1\text{m}^2$ for the solar double focus line collectors to be used for the evaporants, and $\sim 1.5\text{m}^2$ for the regolith melting line focus collector. These solar collectors would yield enough thermal energy for the evaporation and melting of required materials, with the rates for silicon evaporation defined in Table 8. The silicon film thickness at the substrate listed in Table 8 is defined by the flux spreading from the source times the nominal 1 cm/min motion of the fabrication system over the surface of the Moon.

Table 8. Temperatures, vapor pressures, evaporation rates, and film thickness for Silicon under solar thermal heating.

Silicon Temp ($^{\circ}\text{C}$)	Vapor Pressure (Torr)	Evaporation Rate at Source ($\mu\text{m}/\text{min}$)	Film Thickness at Substrate (μm)
1520	1×10^{-3}	13	80
1580	5×10^{-3}	65	35
1640	1×10^{-2}	130	8

In addition, a determination has been made of the amount of raw materials required by the vapor deposition system to fabricate thin film cells on the surface of the Moon for a period of one Earth year (Table 9).

Table 9. Materials and Thermal Energy Requirements for deposition of silicon PV cells

	Thickness	Mass (g/m^2)	Evaporation Temperature ($^{\circ}\text{C}$)	Heat required (kWh/m^2)
Fused regolith	1mm	2700	1200 $^{\circ}\text{C}$	0.9
Conducting layer (metallic iron)	1 μm	7	1800 $^{\circ}\text{C}$.003
Silicon	20 μm	48	2000 $^{\circ}\text{C}$.026
Conducting grid (15% coverage)	1 μm	1	1800 $^{\circ}\text{C}$.0005
Antireflectance coating (SiO_2 or TiO_2)	1 μm	3	2200 $^{\circ}\text{C}$.002
Dopants	---	$<10^{-6}$		

3. Lunar Silicon Solar Cell Fabrication Crawler

The fabrication of the lunar silicon solar cells will be accomplished by as movable crawler traversing the surface of the Moon and depositing the solar cells on the regolith. As noted the regolith will be melted for a 'glassy' substrate for the cells, and the solar cell layers will be sequentially evaporated onto the regolith substrate. The crawler will support double focused parabolic trough solar collectors to give line focused solar energy to a linear evaporator or a liner stripe of lunar regolith. The crawler will initially be used in equatorial regions of the Moon,

with an East-West motion to minimize the need for complicated tracking of the sun by the parabolic trough collectors – only one degree of rotational freedom will be needed to track the sun. The crawler will support a plow in front to smooth the regolith and move larger (non-easily meltable) rocks. It will also have a solar panel to support the communication, command and control and motive functions of the crawler. A sketch of the crawler is shown in Figure 8.

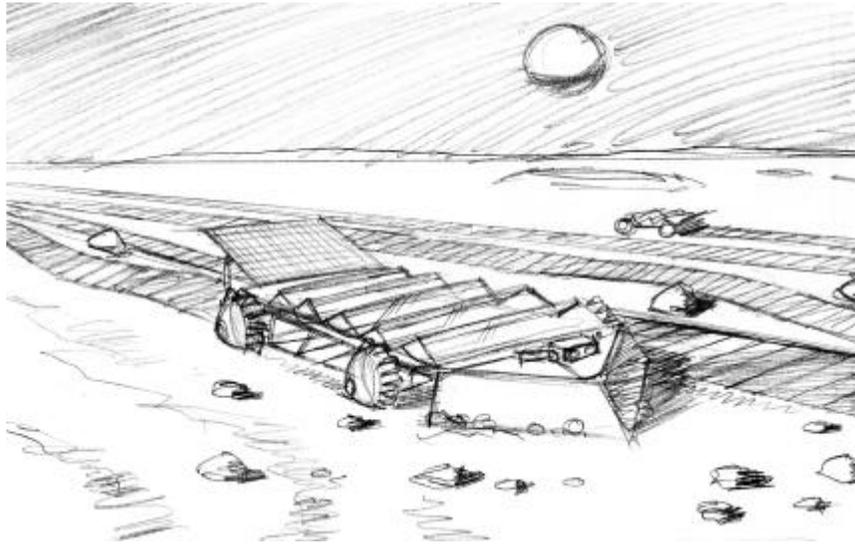


Figure 8. Sketch of the Lunar Crawler to be used for fabrication of lunar solar cells on the surface of the Moon.

4. Preliminary Investigation of Lunar Solar Cell Substrates

A key element toward the deployment/fabrication of solar cells on the moon is the development of a substrate that could support the thin film solar cell structure. In terrestrial thin film cells (fabricated on glass) the substrate thickness is in the mm range and hence represent over 95% of the solar cell weight : the thickness of the Si active region is about few micrometer . Typical requirements for a suitable substrate are listed below:

1. Be mechanically robust and chemically stable
2. Have a specular surface and a roughness $<1 \mu\text{m}$.
3. Be electrically compatible with the Si
 - i. Do not form a junction of reverse polarity (e.g. Schottky contact)
 - ii. Have a stable electrical behavior (insulator substrates are preferable)
4. Not contaminate Si solar cell material (minimal cross diffusion of element into the substrate).
5. Have thermal expansion coefficients that are close to that of Si, in order to prevent cracking of Si films.

Preliminary Investigation.- regolith melting

The investigation consisted in the melting of JSC1 ore and its evaporation. The melting process was performed under high vacuum conditions (10^{-6} Torr) using an electron beam gun. The resulting surface exhibited relatively specular /glossy morphology. At a microscopic scale surface irregularities were visible (Fig. 9)

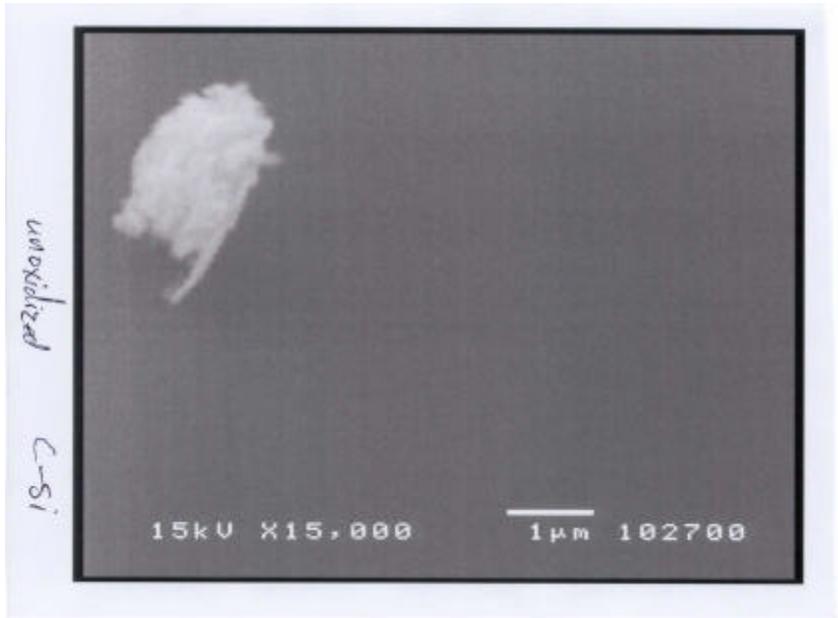


Figure 10. Optical micrograph (x50) of the surface of melted JSC 1

Figure 2 shows the surface morphology under higher magnification obtained by SEM. Surface defect size ranges from 1-20 microns. The areas with specular morphology contains Si, Ca, Al and Fe and O. A local X-ray analysis of the compositional chemistry of the surface defects indicates that they are essentially made of Si with possible traces of Fe (Fig 3).



Figure 11. Plan view scanning electron micrograph of melted JSC1 surface

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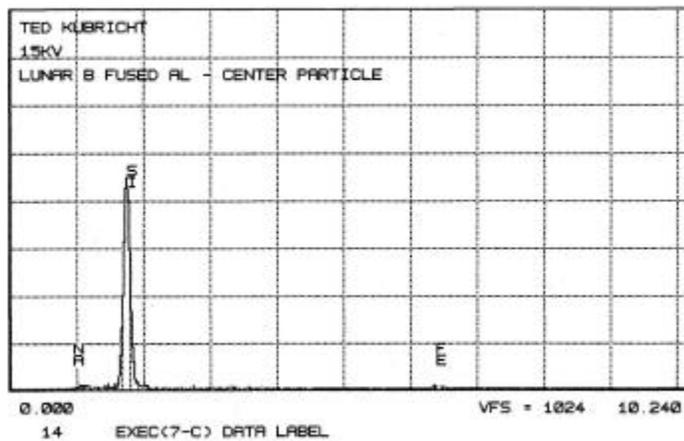


Figure 12. Chemical signature of surface defects.

Electrical measurements have yielded a resistance of $> 40M\Omega$ for the melted regolith indicating excellent electrical properties as a substrate for silicon solar cell deposition.

The above regolith melting data confirms and adequately smooth surface, good electrical properties such that melted regolith should support as a substrate the direct deposition of silicon solar cells.

Task 4. Performance Modeling for Assessing Cost/Benefit Ratio for the Power System Concept

A cost Model has been developed for the installation of electrical power on the Moon utilizing in-situ production of silicon solar arrays. The model incorporates power requirements, installation rate, machinery mass, machinery lifetime, transportation costs, development costs, and operations costs. A comparative is also made with the costs of power delivered from the Earth and is shown in Table 9.

Table 9. Model for installation of electrical power on the Moon utilizing in-situ production of silicon photo-voltaic arrays

Power from Solar Cells Fabricated on the Moon	10MW System	1,000 MW System
Total Power Requirement (MW)	10	1000
Installation Period (yr)	10	10
Annual Installation Rate (MW/yr)	1	100
Installation capacity (MW/machine/yr)	1	1
No. operational machines required	1	100
Expected machine lifetime (yr)	1	5
Replacement rate (machines/year)	1	0.2
No. replacement machines/yr	1	20
Total no. machines transported to Moon	10	280
Mass of machine (kg)	250	250
Materials utilization (kg/machine/yr)	50	50
Annual materials utilization (kg/yr)	50	5000
Total materials utilization over 10 yrs. (kg)	500	50000
Transportation cost (,000\$/kg)	500	500
Machine transport cost over 10 yrs. (\$)	1,250,000,000.00	35,000,000,000.00
Materials transport cost over 10 yrs. (\$)	250,000,000.00	25,000,000,000.00
Operations cost (Earth) M\$/yr	10	100
Total operations cost over 10 years (M\$)	100	1000
Development cost (M\$)	1000	1000
Total cost over 10 years (\$)	2,600,000,000.00	62,000,000,000.00
Productive period for array on lunar surface (yr)	20	20
Total amount of energy produced (kWh)	1,600,000,000.00	160,000,000,000.00
Cost of energy produced (\$/kWh)	1.625	0.3875
Comparative cost of power delivered from Earth		
Efficiency of Earth-derived solar power system	0.35	
Specific mass of Solar Power System (kg/kW)	30	30
Mass transported to Moon over 10 years (kg)	300,000.00	30,000,000.00
Transportation cost (\$)	1.5E+11	1.5E+13
Cost of energy (\$/kWh)	93.75	93.75

It is evident from Table 9 that the cost of electrical energy at the Moon as supplied by lunar solar cells fabricated on the surface of the Moon can be more than 100 x lower than the cost of delivering the solar power system from Earth.

Competing solar cell technologies on the Moon have also been evaluated to identify the cost/benefit ratio for thin film evaporation of silicon solar cells on the surface of the Moon. Seven different silicon solar cell technologies (including thin film evaporation) have been evaluated under a new set of metrics developed specifically for space application of solar cell technology. The metrics represent the cost of launch (weight and volume) and the need for electrical energy to fabricate/assemble components. The metrics are:

- 1.) Power generated/mass transported: $\frac{W_{gen}}{kg_{trnas}}$
- 2.) Power generated/energy used to mfg: $\frac{W_{gen}}{kJ_{used}}$
- 3.) Power generated/volume used: $\frac{W_{gen}}{V_{used}}$

Within these metrics the fabrication of thin film solar cells by evaporation exceeds all other methods of solar cell production by factors of from 50 to 1000.

Task 5. Definition of Potential Applications to Mars

PV deposition on Mars using the vacuum evaporation technique will require a somewhat different approach than on the Moon. Melting the surface material may not be as successful as on the Moon, in part because of the volatile content. Viking data indicated that there is 1-2% water of crystallization in the regolith, which is released at temperatures around 500°C. Rapid heating to 1200°C is likely to produce a frothy glass, which may also be more viscous than that of melted lunar regolith. Also, in all of the places that spacecraft have landed, the surface is rocky except where drifts have formed. The drifts also change shape with time, which may be a problem. As a result, a directed crawler concept for fabrication would not be as effective as on the Moon.

The atmosphere is also too dense to allow for vapor deposition without evacuation. This may significantly reduce the rate at which a mobile robot could traverse the surface, lowering the effectiveness of the process.

Because of the atmosphere, metallic calcium and maybe even metallic iron may not work as an electrical conductor on Mars.

All of these things suggest to me that a different approach should be taken, in which solar cell arrays are manufactured on a suitable substrate and emplaced, rather than deposited on, the surface. This system would use primarily electrical energy rather than direct solar energy. The PV cell production facility would be fixed and the emplacement facility mobile. A separate substrate step would produce glass plates perhaps a millimeter in thickness from natural regolith material. If we assume that we will emplace 3500 m² of cells in a year (1m²/hr), we would require 3.5m³ of glass (about 2 mt) and a glass production rate of about .6 kg/hr. This could be a very small electrical furnace a few kilograms in mass. The hot glass would probably have to be rolled out into plates, because it may be fairly viscous. The plates (say .25m²) would roll off of the glass production furnace onto a mobile platform. A conceptually simple but operationally too complex approach would be to make the mobile platform the base of a bell jar assembly that would contain one of the vaporization steps. The platform would position itself under the bell jar, the jar would be lowered onto the base, the air pumped out, and the material vapor deposited. Perhaps the same bell jar could be used with a changeable source of materials to vaporize, perhaps the process would have to be repeated for each stage of the evaporation process. When

evaporation is complete, the mobile platform moves to the location where the device is to be installed. The facility would have mechanical arms that are capable of lifting a PV cell from the mobile platform, laying it next to the previous cell, and making the appropriate connections.

This approach sounds complex, but might have some advantages over the mobile robot deposition crawler. Production of the glass is the time consuming step, and all the steps of the process are done with electrical energy. As a result, an initial bank of solar cells would have to be transported to Mars and after the initial earth-produced power system is installed, bootstrapping can occur and quite soon all of the energy needs on Mars could be provided from the in-situ resource utilization system. The crawler could have a regenerable fuel cell that returns to the main power supply to be regenerated.

With respect to silicon production on Mars, it is known that the regolith has significant silicon, most likely in the form of pyroxenes and feldspars and their weathering products (clay minerals). There is plenty of carbon in the atmosphere, from which CO can be extracted by CO₂ electrolysis. There would probably be no need to recycle carbon. The products of the reactor would probably also have to go through a refining step, which could be similar to the distillation/vacuum evaporation process proposed for the lunar case, except that a simple thin walled 'vacuum' chamber would need to be utilized.

Task 6. Identification of Key Tasks and Customers for Phase II of the Program

The goals and objectives of the Phase II study are:

1. Develop a complete architecture for the silicon PV production system, including operations subsystems.
2. Conduct preliminary design of the principal subsystems, will allow the mass, power and other key parameters of the complete system to be defined.
3. Design a conceptual experiment in the 20-40 kg range, suitable for carrying to the Moon by a robotic mission that will demonstrate the

The key Tasks for future development are as follows:

1. Produce a complete system architecture, identifying performance requirements for each subsystem and the required interfaces between the subsystems.
2. Produce a complete operational scenario for PV cell production, taking into consideration the lunar surface operations that will be supported by the PV power system.
3. Using the requirements generated in tasks (1) and (2) to conduct a preliminary design of each subsystem element that is required, including at a minimum the following subsystems:
 - i. Materials production
 - ii. PV emplacement crawler

- iii. Power management and distribution system installation
- iv. Surface utility vehicle
- v. Operational command and control system

The designs will minimize the amount of mass that must be transported from Earth, with the design goal being to be able to emplace all needed systems for $1\text{m}^2/\text{hr}$ production level in two packages, neither of which is >200 kg in mass.

4. Analyze the preliminary designs for each subsystem to determine the critical element(s) of the subsystems that must be verified by demonstration on the lunar surface. Design an experiment that has a mass of ~ 20 kg, suitable for deploying on the Moon with a robotic spacecraft, that can demonstrate the needed technologies.

Conclusions

This NIAC Phase I study had clearly pointed to the feasibility of the development of an electric power system on the Moon through the direct fabrication of silicon solar cells on the surface of the Moon using in situ lunar resources. The thin film evaporation process to produce the cells is physically possible, technically workable and economically viable for the emplacement of a power system. The processing of the regolith can yield useful raw materials for the solar cell fabrication process although probably with the addition of a vacuum distillation step, and such processing can occur after the first set of solar cell array have been fabricated by the facility using raw materials brought from earth.

The requirement for further definition of the physical parameters and chemical processes required to produce good quality silicon and metallic components for solar cell fabrication is clear and will be supported by the NASA Cross-Enterprise Technology Development Program.

The need to define a more detailed architecture for the complete silicon solar cell production system and its accompanying subsystems including preliminary design of the crawler and the power management and distribution system is paramount under a NIAC Phase II. Such a design plan can directly lead to a energy-rich technology that will critically enhance future NASA missions into the solar system.