NASA Technical Memorandum 102127

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(NASA-TM-102127) SOLAR POWER FOR THE LUNAR NIGHT (NASA. Lewis Research Center) 19 p
CSCL 03B
N89-26799
Unclas
G3/91 0222717

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

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

# SOLAR POWER FOR THE LUNAR NIGHT

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

## *Abstract*

Providing power over the 354 hour lunar night provides a considerable challenge to solar power concepts for a moonbase. The paper reviews concepts for providing night power for a solar powered moonbase. The categories of solutions considered are electrical storage, physical storage, transmitted power, and "innovative concepts". Electrical storage is the most well-developed option. Less developed electrical storage options are capacitors and superconducting inductors. Physical storage options include storage of potential energy and storage of energy in flywheels. Thermal storage has potentially high energy/weight, but problems of conduction and radiation losses during the night need to be addressed. Transmitted power considers use of microwave or laser beams to transmit power either from orbit or directly from the Earth. Finally, innovative concepts proposed include reflecting light from orbital mirrors, locating the moonbase at a lunar pole, converting reflected Earthlight, or moving the moonbase to follow the sun.

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**National Research Council—NASA Research Associate.*

## *1. Introduction*

The possible options for the power source are solar (either photovoltaic or dynamic), or nuclear. There is interest in making a lunar base solar powered, due to the considerable political and technical barriers, real and perceived, to the use of nuclear power. A permanent lunar base is a considerable challenge for solar power technology, due to the necessity of providing fourteen days of power during the darkness of the lunar night. While some base systems can be shut down or run at reduced power during the night, other systems, such as running greenhouse lights, providing air recycling, *etc.*, may even have increased power consumption during the night.

For a typical moonbase design, the storage required for lunar night operation will be the major mass component of the electrical system. For conventional Ni-H batteries with 32 W-hr/kg (current technology), a 100kW daytime power requirement and 50% night power, one estimate puts the mass of the batteries alone at over a million kilograms [1,2]. In contrast, the photovoltaic panels themselves would be quite light: 500 kg for an APSA technology array with thin GaAs cells [1], and potentially even less for advanced thin-film technologies [3,4]. Clearly, then, higher performance concepts for power during the lunar night would be desirable.

Due to the high cost of delivering mass to the moon, the important engineering figure of merit for an energy storage system is the energy to weight ratio, or specific power, measured in watt-hours per kilogram (W-hr/kg). A similar consideration is applicable to beamed power and innovative power systems, where the effective stored energy is equal to the power times 354 hours. Other important figures are the ratio of charging energy to energy output during discharge, or energy efficiency, and the lifetime, both of which must be high; and the required maintenance, which should be low. Of considerably less importance is the capital cost, since the transportation cost is likely to dominate the total cost.

Finally, for long-range use it is important that the system can be manufactured from materials which can be mined and refined from available lunar resources, since the long-term evolution of the lunar base is likely to be by a “bootstrap” process. It is widely accepted that solar cells can be manufactured on the moon, however, for a self-sufficient lunar base, it is important that the energy storage (or transmission) capability also have the possibility of being locally manufactured.

This paper briefly surveys and discusses the possible options for night power. The paper is intended as a brief and perhaps superficial survey of the concepts proposed, and should not be taken for a comprehensive critical review, which has not to date been written.

The concepts discussed can be divided into storage technologies and continuous power concepts. Storage includes electrical storage methods and physical storage methods, while continuous power concepts can be roughly categorized as transmitted power systems or “innovative concepts”.

## 2. Electrical Storage

### *Electrochemical Storage*

The existing state of the art in electrical storage for spacecraft is the nickel-hydrogen (Ni-H) cell. The specific energy for the best cells currently on spacecraft is 32 W-hr/kg (Intelsat-VI) [5], with 45 W-hr/kg in the prototype stage [5], and up to 75 W-hr/kg projected [6]. Lithium and sodium-sulfur batteries, neither of which are currently in use, have the potential similar specific energy, up to a maximum of about 100-150 W-hrs/kg [7].

A potentially lower mass technology is the hydrogen/oxygen regenerative fuel cell. "Regenerative" indicates that water produced during the discharge is electrolyzed by the solar panels during the charging cycle. The technology is not fully developed. The highest mass element is the pressure tank required to store the reactant gasses. Current technology uses steel pressure tanks, with a specific power on the order of 50 W-hr/kg. Next-generation technology will use composite (Kevlar) filament-wound tanks, with specific power on the order of 500 W-hr/kg. Even with composites, the tanks still comprise nearly 60% of the system mass. Future technology may use cryogenic reactant storage, with up to 1500 W-hr/kg [8]. The technology will require a cryogenic refrigeration plant to liquefy the reactant gasses and store them at cryogenic temperatures.

### *Capacitive and Inductive Storage*

An alternative to electrochemical storage is energy storage in capacitors or inductors. In a capacitor, energy is stored as electrical charge on layers of metal separated by thin insulator film. Capacitors have lower specific energy than electrochemical storage, typically under 1 W-hr/kg, although capacitors of up to 10 W-hr/kg are possible, and 20 W-hr/kg is seen as a reasonable goal in the timeframe 2000+ [7]. An attractive possibility for the long term could be capacitors manufactured using aluminum as the metal and $SiO_2$ or $Al_2O_3$ as the insulator, both refined from locally available materials.

The amount of capacitance required would be very large. For example, at a storage voltage of 10 kV, 100 kW of storage for 354 hours would require over two thousand farads of capacitance, a very large figure by conventional electronic standards.

In inductive storage the energy is stored as a magnetic field associated with a continuous current flow. To avoid resistive losses, an inductive storage system would necessarily have to be made using high critical field superconductors, and such storage is often referred to as "Superconducting Magnetic Energy Storage System", or SMES. Recent advances in high temperature superconductors (HTS) make inductive storage more reasonable [7], since the inductors could possibly be shielded from sunlight and Earthlight and need no refrigeration. The recently discovered class of high-temperature superconductors are composed of materials that, except for oxygen, are not generally found on the moon. However, HTS technology needs to be significantly advanced in terms of critical field, current densities, mechanical strength and stability, and the ability to make the materials in the form of wires.

Typical inductive storage projects using conventional ($Nb_3Sn$) superconducting technology have specific energy of about 0.5 W-hr/kg. For example, a recent design for a 14 kW-hr demonstration superconducting inductive energy storage ring had a coil mass of 26 tons [9]. However, a design study for a 5 GW-hr storage ring estimated a mass of 50,000 to 270,000 tons (depending on the design) [10], for a specific energy of 18-100 W-hr/kg. This mass is for the $Nb_3Sn$ superconducting coil alone; additional elements such as mechanical supports are likely to reduce this value to only a small fraction of the coil-alone value.

The ultimate limit to the specific energy of an inductor is set by the strength of materials, which must withstand the magnetic forces on the system. The upper limit is about 300 W-hrs/kg at structural failure, assuming that composite materials are used for the strengthening elements. Current storage systems do not approach this limit.

## 3. Physical Storage

*Potential Energy Storage*

On Earth, the most common energy storage medium used by electrical utilities is Earth's gravitational field, where the storage method is to hold water behind a dam, running it through turbines when power is desired. Due to the absence of water on the moon, this is not a usable solution. A variation of this concept suitable for the moon would be to store and release energy by lifting and lowering lunar rocks, *e.g.*, on cables suspended from a tower, raised and lowered by an electric winch. The advantage is that the storage medium, rocks, are easily available and need no processing. The problem is that it is difficult to store much energy this way--the moon's gravity is just too feeble. The storage capacity is about 1 kW-hr for each 150 ton boulder lifted 30 meters.

Energy storage in the form of compressed air has also been studied as a method of load-levelling for electrical utilities on Earth. These applications typically use an auxiliary combustion stage to heat the gas during the discharge phase [11]. Storage is typically in natural caverns or mines. Energy storage without auxiliary combustion is not competitive on Earth [12]. This is unlikely to be a useful storage system on the moon, since auxiliary combustion is not possible, the gas itself would have to be brought from the Earth, at least for the early use (for expansion, lunar generated oxygen may be an option), and leakproof natural lunar caverns are unlikely to be available at the moonbase site.

### *Thermal Energy Storage*

Thermal storage is being considered for the solar-dynamic power systems planned for use on the phase two version of space station "Freedom" [13]. In this storage option, energy is stored in the form of heat, typically in a phase-change material. The heat storage itself is expected to have specific energy of ~250 W-hr/kg [14], although only a fraction of this will be accessible as electric power. Thermal storage is a much more likely option for space station applications, where the storage required is only 30 minutes, than for the moon, where the material must remain hot for fourteen days. This is a viable option if the primary power system for the lunar base is solar dynamic. Since the energy losses are likely to be dominated by radiation loss, a low-temperature system is more amenable to long period storage than a high-temperature system.

An alternative version of thermal storage is to use lunar rock as the storage medium. This drastically decreases the amount of material which has to be brought from Earth. In a low-temperature thermal system, an insulated pit containing lunar rocks would be heated to a storage temperature of ~300° C by embedded heat pipes carrying solar energy during the lunar day, and this energy would be used to run a heat engine during the night [15]. In a high temperature system, the regolith could be heated to 1700°K [16] and thermal radiation from the hot rock used to illuminate a photovoltaic array optimized for IR conversion. Radiation not usable by the solar cells could be reflected back to the source. Eder [16] estimates that, neglecting losses, a volume of regolith 4-5 m in each dimension should suffice to provide 100 kW of night power.

The difficulty of this system is insulating the rock bed against heat loss to the surrounding lunar soil. Higher temperature systems have considerably greater difficulties with both radiation and conduction losses, although the higher energy densities allow more compact storage and thus reduced surface area. This problem has not to date been analyzed in depth. Solar furnace designs for melting regolith are discussed by Lewis [17], who estimates that a 21 ton mass of regolith glass will cool from 1700°K to 1200°K in roughly 1.5 days [18]. However, if this could be done without a large amount of required mass, the system weight could be considerably lower than that of other storage methods.

Losses in thermal systems decrease as surface to volume ratio decreases and thus are less important as the system size increases. The cooling time of larger mass systems scales proportionately to the cube root of the mass. Thermal storage thus becomes increasingly attractive for larger base sizes.

Since a manufacturing facility is likely to use many high-temperature processes such as magma electrolysis or glass manufacturing, the waste heat of the processing could also be used for the electrical power [17,19].

If thermal storage is to be considered, issues of conduction and radiation losses during the night must be examined in detail. Because of the long storage times, thermal storage is unlikely to be competitive using present day materials, but may be possible with improved materials.

### *Flywheel Storage*

A final possibility is storage as kinetic energy by use of a flywheel. The best current technology flywheels have specific energy of about 20 W-hrs/kg. A composite flywheel with specific energy of 120 W-hr/kg at failure has been demonstrated [20] (not counting support systems, bearings, motor/generator, *etc.*) Counting a factor of three for safety margin and 50% additional mass for support systems, this comes to about 36 W-hrs/kg. These values are considerably below the theoretical limits of advanced composite materials [21], about 300 W-hrs/kg at failure.

A problem with flywheels for terrestrial storage is the requirement for vacuum. This is not a problem on the moon, where the vacuum is available. A second problem is that a flywheel must have a containment system, to prevent high-velocity fragments from causing injury in case of a catastrophic failure. On the moonbase, the flywheel can easily be placed below ground level, where this is also not a problem.

It is likely glass fiber for a composite flywheel could be manufactured from available materials [19], albeit with ultimate strength less than that of advanced composite fibers such as Kevlar or graphite. Materials for the polymer matrix, however, is not likely to be available. If a metal matrix, such as titanium or aluminum, could be used, then flywheel storage is an attractive option for future storage based on locally manufactured, all-lunar material technology.

Flywheels have losses due to residual friction, eddy currents, *etc.*, which in some cases can be quite large. These losses would have to be reduced to below about 0.2% per hour for flywheels to be useful for the entire lunar night.

## *4. Transmitted Power*

Power could be beamed to the moonbase in the form of an electromagnetic wave. Beamed power has been investigated in some detail for other applications, including satellite solar power systems (SSPS) [22]. The main options for the beam are microwave or laser.

### *Electromagnetic Beams*

The fundamental limit to the transmitter and receiver aperture sizes is set by the diffraction limit,

$$r_r r_t = 0.61\, d\, \lambda \qquad (1)$$

where $r_r$ is the aperture radius of the receiver, $r_t$ the aperture radius of the transmitter, d the source to receiver distance, and $\lambda$ the wavelength.

For a microwave beam, aperture size is the antenna radius; for a laser, it is the radius of the lens or reflector used to focus the beam. (The receiver radius is here defined as the first zero in the diffraction pattern; this contains 84% of the beam energy. If a larger fraction of the transmitted energy is to be captured, the receiver aperture must be larger than this value.) The minimum total area is when the transmitter and receiver are of equal size, and the area is proportional to the square of the wavelength used. Thus, it is important to use the shortest practical wavelength (*i.e.*, the highest practical frequency).

The power efficiency of a microwave beamed system is projected to be very good, both as the transmitter and at the receiver; typically over 85% can be expected, with efficiencies above 90% not unreasonable. Unlike laser systems, an additional receiving rectenna is required on the surface. A difficulty of microwave systems is that to form narrow beams the antennas need to be large due to diffraction effects. However, a microwave antenna can in principle be made from a very light metal mesh. Microwave transmission at 2.5 GHz ($\lambda$ =10 cm) has been demonstrated. 30 GHz ($\lambda$ = 1 cm) has been identified as a target frequency for transmission. Shorter wavelengths yet would be desirable.

Laser transmission is an attractive option because optical wavelengths are considerably shorter than microwave wavelengths, which reduces diffraction effects and allows narrower beam spread and consequently much smaller apertures. If the laser wavelength is selected properly, the receiver can be the same solar array used to provide daytime power. Laser power transmission is discussed by de Young *et al.*, [23]. A difficulty is that the power efficiency of conventional lasers is typically not very high, *e.g.*, about 10% for a Kr-F excimer laser. Free-electron lasers have potentially efficiencies as high as 65% [24] as well as high power and a wavelength range down to $\leq 0.2\mu$, but are extremely massive, too massive to be used except for a surface-based system. De Young *et al.* recommended development of large arrays of diode lasers for power transmission. Since the maximum power of each individual diode laser is typically about one watt, an array consisting of a very large number of individual lasers would have to be used. Arrays of diode lasers have recently demonstrated power densities as high as 50 W/cm$^2$ with total energy efficiency of 40% [25].

An attractive alternative is the possibility of a laser directly powered by solar energy, which increases the effective efficiency by eliminating the intermediate step of conversion of solar energy into electricity [26]..

The efficiency of conversion at the receiver is also not nearly as high as microwave conversion. The best solar cells can be expected to convert about 50% of the incident light into electricity at the optimum wavelength (energy just higher than the bandgap). For photovoltaic receivers the efficiency drops to zero for wavelengths much longer than the optimum. For wavelengths shorter than the optimum, the expected efficiency E is roughly

$$E = \eta_{\text{(optimum)}} ( \lambda_{\text{laser}} / \lambda_{\text{cutoff}}) \qquad (2)$$

where $\eta_{\text{(optimum)}}$ is about 50% for the best cells, and $\lambda_{\text{cutoff}}$ is determined by the bandgap of the solar cell material,

$$\lambda_{\text{cutoff}}(\mu) = 2.24/E_g \qquad (3)$$

Thus, as long as all of the transmitted power falls on the receiving array, the solar cell material is preferably tailored to the laser wavelength, or vice versa. However, if the spot size is larger than the receiving array, it is optimal to decrease the wavelength to put more of the power on the array. This can be from seen comparing equation (1) and equation (2). The beam area is proportional to $r_s^2$, and so the fraction of the beam which is intercepted by the array increases as $\lambda^2$, while the efficiency only decreases proportionately to $\lambda$.

### *Transmitted Power from Space*

A question of considerable importance to beamed power systems is the best location for the primary (transmitter) station.

Placing the primary power station in low lunar orbit (LLO) minimizes transmission distance. Low-lunar orbits tend to be unstable for periods of more than about 100 days; this means that the orbit will have to be actively maintained.

If a single primary power satellite is used, it will be in line-of-sight to the base for no more than half of the orbit. A LLO satellite will also be in the lunar shadow for a considerable fraction of its orbit. For a 1000 km orbital altitude, the orbital period is roughly four hours. Thus, several hours of energy storage will still be required at the base. Since providing several hours of storage when the satellite is on the other side of the moon is considerably easier than providing 354 hours of storage for the entire lunar night, this is still a major improvement.

Alternatively, at least three primary power satellites are required if one is to be in line of sight of the base at any given time.

Placing the primary power satellite at libration point L-1 (between Earth and Moon) requires transmission of power over a longer distance. The advantage is that only one satellite is needed, since L-1 is always in sight from near side of moon. The orbit is unstable for periods greater than about 50 days, but the corrections needed are small if the location is not allowed to drift very far from the equilibrium point. Occasional eclipses by the moon and the Earth will interrupt power for brief periods.

Placing the primary power station on the lunar surface, at a location on the far side of the moon preferably exactly 180° away from the base, requires the use of one or more relay satellites to transmit the power. This allows a single photovoltaic array to be used, fixed on the surface. The requirement for relay satellites means that this arrangement is unlikely to be more efficient than producing the power directly at the satellites.

An alternative to beaming power would be to transmit the power across the surface of the moon on a physical link from the second solar array on far side of moon. This would require roughly 5500 km of power lines; about distance from NY to San Francisco. While the link could be a conventional high-voltage lines, possibly made from locally-available aluminum or calcium, resistance losses would be high unless extremely high voltages were used or very large diameter wire was used. (For example, at 0.1 $cm^2$ cross section and 100 kV, the resistance losses for a 100 kW system are about 20%, and the mass of wire required is about 600,000 kg). If two ground power stations were used, each located 90° in longitude from the base, the transmission distance would be halved and the wire mass proportionately decreased. The required transmission line length could be greatly reduced if the base is not located at the equator. For example, if the base is located at 60°N and the transmission lines run across the north pole, the total length can be reduced by a factor of three.

This has an additional advantage that the lines could probably be "tapped" at points along the length to run remote experiments, as well as to serve as charging stations for electrically powered exploration vehicles.

Use of superconductors for the lines would eliminate the resistance losses and allow lower wire cross section. These will need to be kept cool; this could be done by shielding them from the ground and from direct sunlight (also possibly from reflected light from the Earth).

Alternatively, the link could be fiber-optic light-guides (made from locally available silica) which direct a laser beam.

In any case, this option is likely only for an advanced moonbase.

### *Beamed Power from Earth*

Finally, power could be beamed directly from stations on the Earth. The advantage of this is that electric power is cheap on Earth (~5¢/kW-hr), and there is no need to loft a large solar array or power beaming equipment into cislunar space. For the following example I will assume power transmission by laser.

Consider a baseline system with a wavelength $\lambda = 1\mu = 1.10^{-6}$ m. This is the approximate wavelength range for a Nd:YAG laser (1.06 $\mu$), or a GaAs laser diode array, and is near the optimum wavelength for conversion for a Si solar cell. d(Earth-Moon) is $3.8 \cdot 10^{8}$ m, and the lens diameter is 2 meters. A two meter diameter lens (or mirror) is very large by telescope standards (for example, the Hubble Space Telescope is a 2.4 meter diameter mirror). However, the lens need not be telescope quality. The lens could be a fresnel lens, or, since it need only function at a single wavelength, a holographic optical element.

For diffraction limited beam spread, the spot size is 230 meters; the illuminated area 170,000 $m^2$. For the array specified at 100 kw and a solar conversion efficiency of 18.5% efficiency, the array area is 400 $m^2$, and so the array intercepts only 0.25% of the beamed power. The required beam power would be 85 MW.

This can be reduced by decreasing the laser wavelength to 0.5$\mu$ and increasing the solar cell bandgap from 1.1eV (Si), to 2.0 eV (GaAlAs alloy). This is about the widest bandgap that will still give good solar conversion efficiency for daytime power (also, wavelengths below about 0.3$\mu$ begin to be significantly absorbed in the atmosphere.) The array is then oversized by a factor of two over the size required for daytime power, and stationary reflectors are used to intercept an additional factor of 4. Since the Earth is nearly stationary in the Lunar sky, these reflectors do not require tracking, and need be no more than thin reflective sheets of plastic. The array will now intercept 8% of the beam. If 50% power at night is now assumed, the required beam power is 2.2 MW. Further reductions in power could be achieved by the use of a larger area of thin reflectors, as discussed in the next section.

Note that the total system requires twice as many lasers as are actually in use, since at any given time half will be on the wrong side of the Earth. Such a system would utilize many lasers from different sites--presumably desert areas and mountaintops--so that laser failure will not interrupt power. The required 4.4 MW could be provided, for example, by 56 eighty-kw lasers (twenty-eight of which are running at any given time). Such power levels are high compared to those achieved by current technology CW visible light lasers, but in the range likely to be reasonably achievable for future high-power lasers. It is many orders of magnitude higher power than currently achieved by diode lasers. Problems of tracking, reliability, and atmospheric turbulence remain to be addressed. The intensity of the beam at the site is considerably less than solar intensity, and thus would not present a hazard to base personnel unless they look directly into the beam. This hazard could be removed if the solar array is located in an area which is kept off limits to astronauts during the night, or if the suit visors and the windows of the base are designed to incorporate a rejection filter at the proper wavelength.

## 5. *Innovative Concepts*

### *Solettas*

One proposal has been to use "Solettas", or orbital mirrors, to reflect sunlight to the surface solar panels [27]. The fundamental limit to soletta illumination is the minimum spot size $d_s$ at the receiving array. This is fixed by the angular diameter of the sun and the orbital altitude:

$$d_s = h\alpha + d_m \tag{4}$$

where h is the slant range between the orbiting mirror and the ground spot, $\alpha$ is the angular diameter of the sun (about .01 radian), and $d_m$ is the mirror diameter. The spot size can be decreased by lowering the orbital altitude, but this means that the fraction of time that any particular mirror can view the receiving array also decreases, thus increasing the required number of mirrors in orbit. When the mirror size $d_m$ is less than $h\alpha$, the illuminated spot size is constant and the illumination intensity decreases with mirror area. Except for very large systems, the spot size is much larger than the solar array, and thus the array intercepts only a small fraction of the energy reflected by the mirror. The mirror size needed is thus independent of the array size. Consequently, the concept is most suited for very large power requirements.

An initial design discussed by Criswell [27], as shown in figure 1, is calculated for 800 kW of night power. Four mirrors are assumed, each 40 km$^2$ in area. The illumination level is 11% of the daytime illumination. The mirrors were assumed to be fabricated from light-weight solar-sail technology, with a total mass of 1 million kilograms.

Finally, it should be noted that the soletta concept requires exceptionally good mirror surface accuracy and pointing accuracy at comparatively high slew rates. A quarter degree of pointing error will result in the illuminated spot missing the surface array; a similar amount of ripple in the surface will defocus the spot. These surface and pointing tolerances are considerably higher than those needed for solar sail technologies.

### *Conversion of Earthlight*

The Earth is nearly fixed in the lunar sky. This raises the intriguing possibility of utilizing the solar array to convert sunlight reflected from the Earth [28].

The albedo of the Earth is 0.36 (±.06, depending on cloud cover). Even when full, the Earth is 10,000 times less bright than the sun. At half phase, which is the worst case for a base located at the center of the near side of the moon, the Earth is 20,000 times less bright than the sun. Therefore, to produce full power at sunset and sunrise, a solar array would have to be 20,000 times larger than the one required for daytime power. If 30% power is acceptable as the nighttime average, the array need be only 4,000 times larger than the daytime array.

This could conceivably be done using mirror concentrators. A minimum mirror need be no more than a flat sheet of very thin reflective plastic. One micron thick aluminized Kapton has a mass of 1.4 $gr/m^2$, 600 times lighter per unit area than the 300 W/kg solar array assumed. Thus, a minimum mass 4000x concentrator could weigh as little as about 7 times the mass of the solar array itself. This is still a considerable problem: the system would require 4,000 sheets of Kapton, each one carefully aligned, for each panel of the array. The mass does not include the additional area required for cosine theta loss and reflectance losses, and additional mass for the structure to support it. Also, the array will likely also require tracking: the Earth doesn't move much, but it does move some. In short, this solution is unlikely to be practical.

### *Lunar Polar Base*

It is possible that locating a lunar facility at one of the poles of the moon could alleviate the problem of the lunar night, since the axis tilt of the moon is so low that placing the arrays on a relatively short tower (or conveniently placed mountain) could allow them to be constantly illuminated [29,30]. This is shown in schematic in figure 2.

A problem with the polar location for a lunar base is that, like the Earth, the polar regions of the moon are subject to six months of darkness during the hemisphere's "winter". This could make exploration and work outside very difficult. Even during the "summer," the sun angle remains very low (within 1.5° of the horizon). This means that inky black shadows will cover almost all of the surface, making exploration (and even walking around!) very tricky.

### *Sun-following Moonbase*

In the sun-following moonbase concept, the lunar base constantly moves around the moon to stay continually in sun [31]. The rotational velocity at the lunar equator is 16.6 km/hr (10 MPH). If the moonbase is sited 60° N, where the local sun angle is a comfortable 30° off horizon, the required average velocity is only 8.3 km/hr (5 MPH); and even less if the path chosen is across the pole. Actual moonbase speed will be 10 MPH during 12-hr "drive" shift and 0 MPH during 12-hr "work" shift. Figure 3 shows a version of such a mobile moonbase using design concepts familiar from other space habitat structures.

Conceptually this is an extreme solution to a simple problem, but as well as providing continual solar power, it does have other advantages: it eliminates the 354-hr dark period when outside exploration is difficult or impossible, thus effectively doubling the working hours of the staff; and the base is not "stuck" in one spot, but continually samples new territory.

The path should be maintained near the sunrise terminator, to give as close to 14 day of "slack" as possible for repairs. Since the moonbase would consist of many independently mobile modules, no single failure would be critical. Any one unit could be evacuated if necessary and repaired on the next cycle.

An alternative version would be to have two separate lunar bases on opposite sides of the moon, with the crew transferred from one to the other on a two-week cycle. This has the disadvantage that the entire moonbase must be doubled.

## 6. Conclusions

A constant supply of electrical power is important to human occupancy on the moon, and one such supply is solar energy. The major difficulty in a solar-powered moonbase consists in providing steady power over the long and dark lunar night. At the moment, the promising solution for a near-term moonbase appears to be the use of regenerative fuel-cells with cryogenic storage, a technology which is not yet fully developed but is unlikely to have any fundamental technical difficulties in development. Nevertheless, a wide variety of other concepts for solar night power have been proposed, which are summarized in table 1. Not all have been examined in depth. All have some apparent drawbacks; many will only be useful for a large, "evolved" moonbase.

There is certainly room yet for clever new ideas.

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**Table 1**
Approaches to solar power for the lunar night

### Storage Options

| *method* | *Specific Power (W-hr/kg)* present | *Specific Power (W-hr/kg)* anticipated |
|---|---|---|
| ***Electrical Storage*** | | |
| Batteries | 32 | 150 |
| Fuel Cells | 50 | 1500 |
| Capacitors | 10 | 20 |
| Inductors | 0.5 | 100 |
| ***Physical Storage*** | | |
| Compressed Gas | | *(impractical)* |
| Thermal storage | - | 250* |
| Lunar thermal storage | | 10000† |
| Flywheel Storage | 20 | 35 |
| Gravity Storage | - | <1 |

**heat*
*†heat. Will depend on insulation requirement*

### Continuous Power Concepts

| *method* | *comments* |
|---|---|
| ***Transmitted Power*** | |
| Microwave beam | *Primary station in LLO or at L-1* |
| Laser beam | *Primary station in LLO or at L-1* |
| Transmission lines | *Primary station on Lunar farside* |
| Ground-based laser | *Primary station on Earth* |
| ***Innovative Concepts*** | |
| Soletta | *Orbital mirrors; practical only for large systems* |
| Earthlight Conversion | *Requires very large collectors* |
| Lunar Polar Base | *Low sun angle at base* |
| Sun-Following Moonbase | *Not at fixed location* |

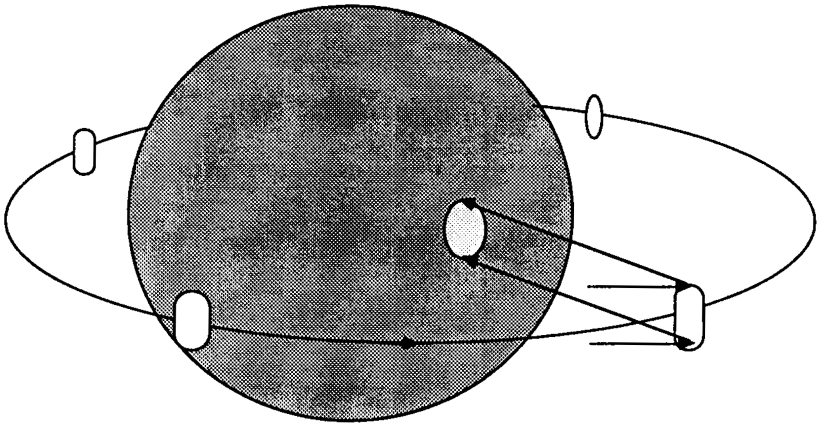

**Figure 1: the "Soletta" solution:**
Four mirrors in high-inclination, low altitude orbit
provide 10% of one sun illumination to solar arrays
orbital altitude = 500 km periapsis, 1050 km apoapsis
8.7 km diameter mirrors at 6 grams/sq. m
240 tons each; 1000 tons total
minimum spot size 34 km
illuminated area 1000 square kilometers

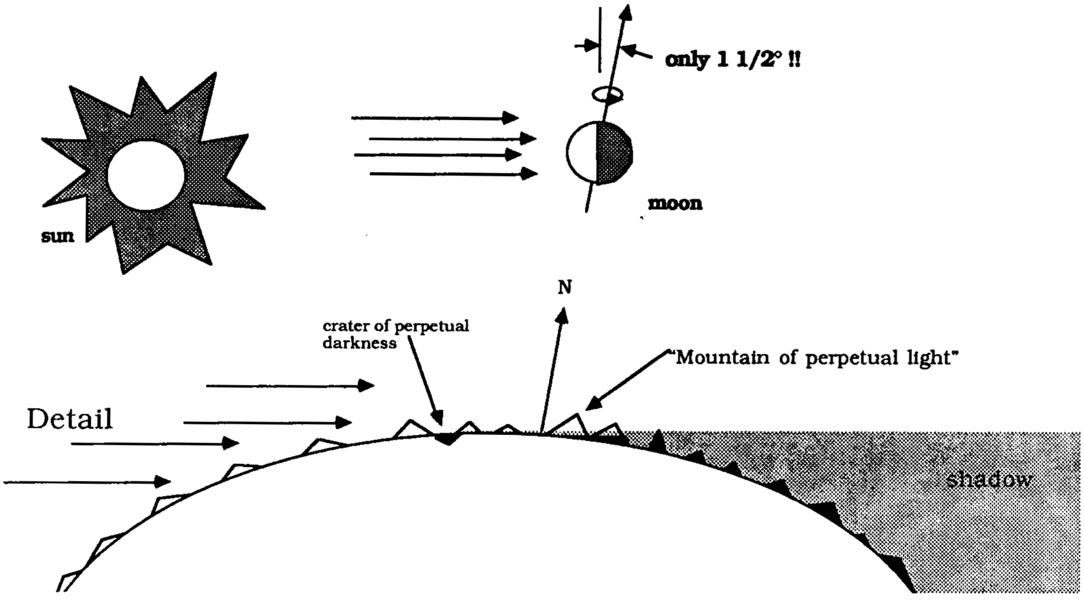

**Figure 2. Lunar Polar Base (Schematic)**
by placing the solar array atop a high enough mountaintop close to the lunar pole, it will always be in sunlight!

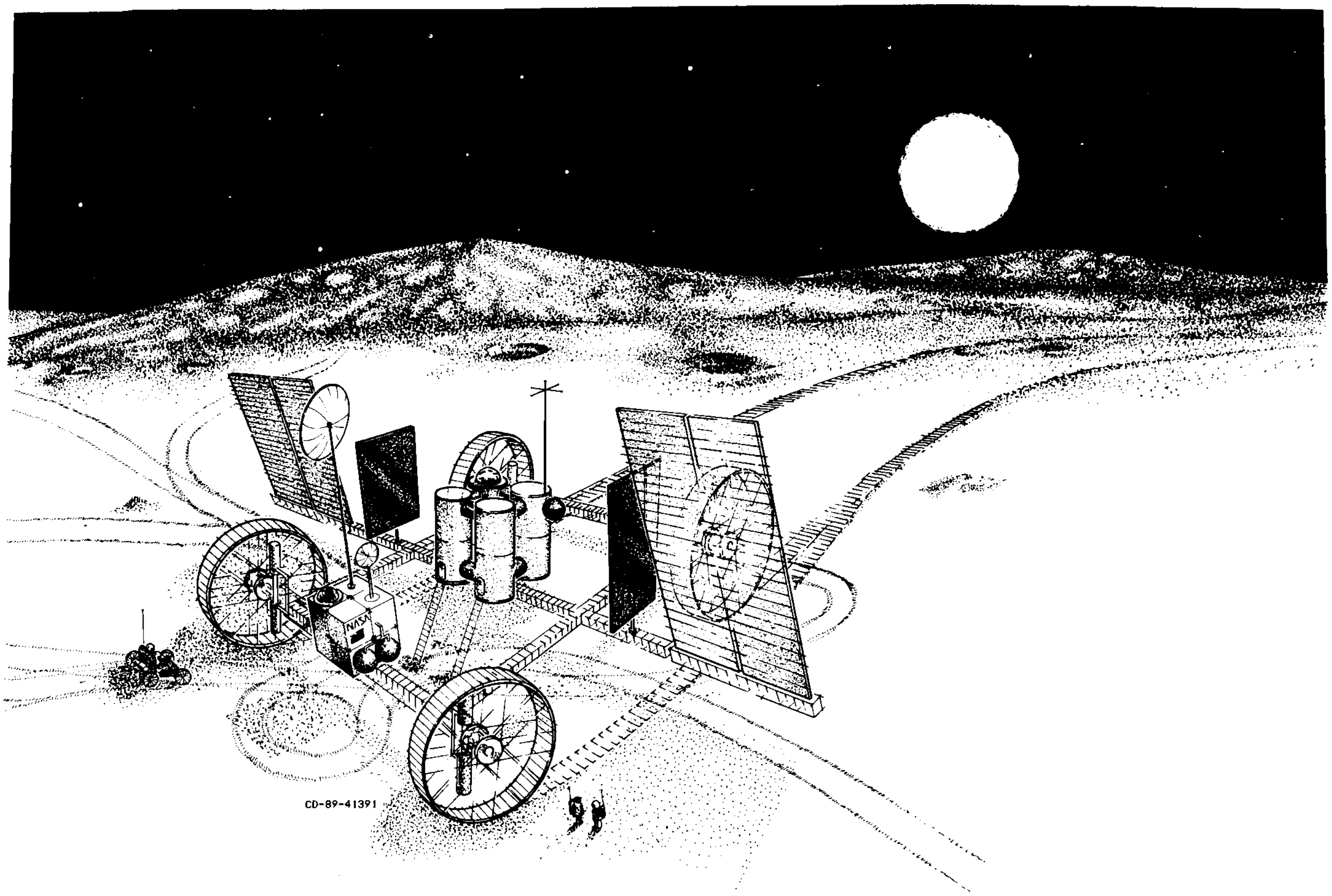

**Figure 3: Sun-following moonbase**
moonbase moves continuously around the moon to stay in sunlight
moonbase speed:
10 MPH during 12-hr "drive" shift
0 MPH during 12-hr "work" shift

National Aeronautics and
Space Administration

# Report Documentation Page

| | | |
|---|---|---|
| 1. Report No.<br>NASA TM-102127 | 2. Government Accession No. | 3. Recipient's Catalog No. |

4. Title and Subtitle
Solar Power for the Lunar Night

5. Report Date

6. Performing Organization Code

7. Author(s)
Geoffrey A. Landis

8. Performing Organization Report No.
E-4913

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. Geoffrey A. Landis, National Research Council—NASA Research Associate.

16. Abstract

Providing power over the 354 hour lunar night provides a considerable challenge to solar power concepts for a moonbase. The paper reviews concepts for providing night power for a solar powered moonbase. The categories of solutions considered are electrical storage, physical storage, transmitted power, and ''innovative concepts''. Electrical storage is the most well-developed option. Less developed electrical storage options are capacitors and superconducting inductors. Physical storage options include storage of potential energy and storage of energy in flywheels. Thermal storage has potentially high energy/weight, but problems of conduction and radiation losses during the night need to be addressed. Transmitted power considers use of microwave or laser beams to transmit power either from orbit or directly from the Earth. Finally, innovative concepts proposed include reflecting light from orbital mirrors, locating the moonbase at a lunar pole, converting reflected Earthlight, or moving the moonbase to follow the sun.

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|---|---|
| 17. Key Words (Suggested by Author(s))<br>Moon Base; Photovoltaics;<br>Energy storage; Solar cells;<br>Solar power | 18. Distribution Statement<br>Unclassified—Unlimited<br>Subject Category 91 |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No of pages<br>18 | 22. Price*<br>A03 |

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161