DESIGN CONSIDERATIONS FOR LUNAR BASE PHOTOVOLTAIC POWER SYSTEMS

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ABSTRACT

A survey was made of factors that may affect the design of photovoltaic arrays for a lunar base. These factors, which include the lunar environment and system design criteria, are examined. A photovoltaic power system design with a triangular array geometry is discussed and compared to a nuclear reactor power system and a power system utilizing both nuclear and solar power sources.

INTRODUCTION

As part of the Space Exploration Initiative, NASA is investigating photovoltaic power systems for the lunar surface. Power systems considered are for short duration stays without storage (14 days) and prolonged periods with energy storage so that power can be supplied during the lunar night. The purpose of this paper is to discuss the various issues and constraints which affect the design of photovoltaic power systems on the moon.

LUNAR BASE POWER REQUIREMENTS

The power requirements for a lunar base are determined by the crew size, evolutionary stage, and mission objectives of the base (1). It is widely accepted that a lunar base will grow in capacity and function, and thereby in power requirements, over time. To support this growth, additional crew members will be required. A minimum power level of approximately 3 kilowatts of electrical power (kW_e) is required to support each crew member (2). As the mission objectives evolve over time, additional power generation units may be necessary.

The baseline power source options are photovoltaic (PV) arrays or a nuclear system. Photovoltaic arrays have the advantage of being modular, lightweight, and reliable, but the disadvantage of requiring an energy storage system if nighttime power is required. PV arrays have a long record of reliable power production in space and on the moon, which reduces the technical risk. Nuclear power systems have the advantage of providing continuous power and of lower mass at high power. However, nuclear power systems present a potential radiation hazard to base personnel and equipment. Adequately safeguarding the base is a major design concern. In general, the use of nuclear power in space is a highly sensitive political issue.

To make use of the strengths of each power system technology, a lunar base may use photovoltaic power for the initial set-up, and then augment this with a nuclear reactor as power requirements increase. However the base power system is configured, crew surface time for deployment and set-up will be severely limited. It is important that power system components (e.g., arrays) be designed such that little or no assembly or intervention by base personnel is required.

If 100 kW_e or more is required within the first few flights of the development of the base, mission planners may forgo photovoltaic arrays entirely, except as a deployable emergency power generation system. For high power levels, the mass of the energy storage system required to supply power over the 354-hour lunar night is high. A system being considered by NASA for early high power generation is a modified SP-100 nuclear reactor with thermoelectric energy conversion. Such a nuclear power "module" could be emplaced within the first few flights providing 100 kW_e early in the base development. Additional thermoelectric modules could be emplaced to build up base power. Alternatively, dynamic conversion engines could be used in place of the thermo-electrics to yield 500-1000 kW_e. Power levels in this range will be necessary for in-situ resource utilization (ISRU), i.e., lunar mining and processing.

Photovoltaic arrays with regenerative fuel cell energy storage (PV/RFC) is a power system candidate in a lunar base development plan that does not require high power levels early. Option A of the Reference Architecture of the NASA Lunar/Mars 90-Day Study Period manifests a PV/RFC system module followed by two additional modules on the second and third flights to the moon, respectively (3). Each module would provide 25 kW_e during the lunar day and 12.5 kW_e at night to support a four-person crew. This same study option then manifests a 100 kW_e nuclear power module on flight seven, about three and one-half years into the base development. Option E of this same study includes PV arrays for the lunar base only as an emergency backup to nuclear reactor power.

For low power outposts (i.e., less than 50 kW_e), away from the main base, such as an astronomy science outpost on the moon's far side, PV/RFC units are mass competitive with all other power systems. Should outpost power be required only during daylight hours a photovoltaic power system (without RFC energy storage) would be the system of choice on a mass basis, especially in the region of 10-100 kW_e.

LUNAR ENVIRONMENT

Array Temperature

A solar array on the moon will operate at significantly higher temperatures than arrays in near-earth space. Operating temperatures are determined by the energy balance, where the incident energy minus the energy converted into useful power is radiated thermally according to the fourth power of temperature. The lunar soil is a good thermal insulator, and thus the solar array will be able to radiate to space only from one side. The operating temperature on the moon can thus be estimated from operating temperatures in high orbit by assuming that the solid angle available for radiation is cut in two. The maximum operating temperature on the moon is therefore increased by about 19%. Since typical operating temperatures for geosynchronous orbit arrays are ~305K, this yields a maximum operating temperature of 90°C (decreasing slightly if the cell efficiency increases). This is very close to the temperatures reached by the lunar surface at local noon (4). Average daytime temperature will be somewhat lower.

These numbers are roughly consistent with those measured by instrument packages left on the moon during Apollo. For example, the Apollo 11 PSEP reached a maximum temperature of 88°C at lunar noon (5). Similarly, the Apollo 12 Surface Magnetometer reached a maximum external temperature of about 78°C (6).

The large areas required for the solar array make it unlikely that cooling techniques will be usable. Since solar cell performance decreases with increasing temperature, the solar cell material selected should not be highly sensitive to temperature. The temperature dependence is primarily a function of the bandgap of the material with lower temperature sensitivity for wide-bandgap materials, such as GaAs or amorphous silicon. If the bandgap can be increased, as by going to a ternary III-V compound such as AlGaAs, the temperature sensitivity is decreased yet further, although at some cost in decreased efficiency at standard temperature. Cascade (or "tandem") cells also have high temperature sensitivity, typically equal to the sum of the sensitivities of the individual component cells, and are thus less desirable for lunar use, although of higher baseline performance at standard temperature.

The temperature variation of power ($1/P\ \partial P/\partial T$) for gallium arsenide cells is about 0.25%/°C (7,8). For cell operation at 90°C, the power would be derated by about 17% due to temperature. Amorphous silicon would be comparable or slightly better. For silicon, the temperature variation is about 0.33%/°C, leading to about 23% loss, with $CuInSe_2$ expected to be about the same.

For the single crystal solar cell technologies, GaAs and Si, the temperature extremes are not expected to present lifetime problems if adequate design safeguards against thermal cycling are taken. For thin-film technologies, long-term operation at high temperatures and vacuum thermal cycling stability have not yet been demonstrated, and reliability will have to be verified before such arrays can be used on the moon.

Radiation Environment

The moon has no permanent general magnetic fields; hence, there are no trapped radiation belts. The major source of natural particle radiation for an array on the lunar surface is solar flares which consist mainly of protons. Protons damage cells by displacing atoms within the lattice causing defects. These defects change the electronic properties of the material shortening cell life. Unlike the continuous Van Allen belt radiation, solar flares occur sporadically with varying magnitudes. The effect of solar flare protons is usually handled statistically with an equivalent 1-MeV electron annual fluence of 1.1×10^{14} e/cm^2 for silicon cells with a 3 mil (75 micron) coverglass (9). Data for other coverglass thickness are shown in fig. 1. During the lunar night, when the moon is between the sun and the arrays, the arrays will be protected from solar flare protons. Thus the flux shown in fig. 1 will effectively be reduced by a factor of two.

Lunar Dust

Dust on the array surface will reduce light incident to the array and increase the array operating temperature. Likewise, dust on radiator surfaces--fuel cell radiators, for example--will reduce the radiator effectiveness. Dust can be transported to the array and radiator surfaces by astronauts or rovers kicking up dust during EVA, by dust blown onto the array by the landing rocket, and possibly by other mechanisms involving electrostatic transport. To a large extent, this problem can be ameliorated by locating the solar arrays away from high-traffic areas of the base, and not allowing astronaut activity in the array vicinity. Since small dust particles will likely be electrically charged, any dust on the array will adhere to the surface by electrostatic attraction. If it is not possible to eliminate dust from the surface, the adhesion could be reduced by a transparent conductive surface layer to ground the electrostatic charge.

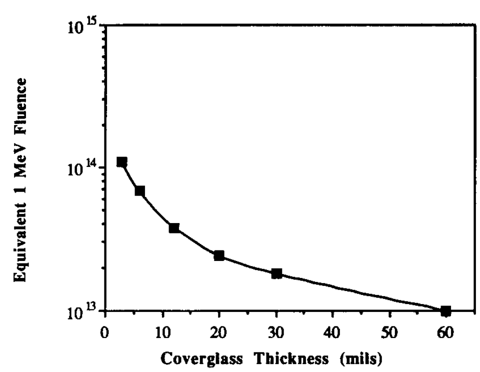

Fig. 1 Annual Equivalent 1 MeV Electron Fluence Due to Solar Flares

PHOTOVOLTAIC SYSTEM DESIGN

Cell Technology

Current technology spacecraft solar cells are made from silicon (Si) and gallium arsenide (GaAs) (10,11). The best present flight technology uses thin (62 micron) silicon cells. Efficiencies of 19% AM0 (Air Mass Zero) have been demonstrated; however, production cells are more typically around 15% efficient. GaAs cells with an 18% AM0 efficiency are in production, and production readiness has been demonstrated for 20% efficient GaAs cells. Recent GaAs cells have been manufactured on germanium substrates to improve its handling characteristics (12). The germanium can then be etched down to a 50 micron thickness to reduce the weight. An alternate method of producing such ultra lightweight GaAs cells is to use a technique which separates the cells from a reusable substrate, such as the CLEFT process (13). An array of such thin GaAs cells using existing array structures could have a specific power of about 300 W/kg.

Cascade solar cells make more efficient use of the solar spectrum by stacking subcells of different materials designed to absorb a different wavelength range. This technology has produced the highest efficiency solar cells to date, with demonstrated efficiencies under space (AM0) sunlight of over 30%. However, the technology is still in the research stage and is unlikely to be production ready for near-term use.

Thin-film technologies include CdTe, $CuInSe_2$, ternary compounds, and amorphous silicon, plus cascade cells made from these materials. Current technology for these materials is comparatively low efficiency (5-9% AM0), but the cells can be made extremely thin (1 to 2 microns) and thus potentially have specific powers of well over 1000 W/kg (14). Cascade thin-film solar cells, such as CdZnTe on $CuInSe_2$, have potential for both high efficiency and low weight. To date only amorphous silicon has been produced on thin, lightweight polymer substrates, which have efficiencies less than those achieved on rigid substrates. Polymer substrates have not been extensively studied as most thin-film research has been directed toward terrestrial applications.

Storage

The energy storage requirements for nighttime power supply dominate the power system mass. Currently used power storage systems, such as NiH_2 batteries, are inadequate for the large power requirements for a lunar base. The baseline reference for energy storage at the lunar base calls for hydrogen/oxygen regenerative fuel cells (RFC). These H/O RFC's are expected to provide 500 Whr/kg by the year 2000, using gaseous reactants. By cryogenically cooling the H/O reactants, specific energies of 1000-1500 Whr/kg are anticipated (15). Other energy storage systems such as superconducting energy storage coils, massive flywheels, and thermal salts are either insufficiently advanced to be available for the lunar base or impracticable for application on the moon (16). Even advanced cryogenic RFC's, however, can constitute 80-90% of the mass of a PV/RFC power system (fig. 2). Therefore, even tremendous advances in cell technology will not significantly affect the total mass of a solar power system. Consideration must be given to other figures-of-merit, such as cost, technology readiness, lifetime, reliability, maintainability, and safety.

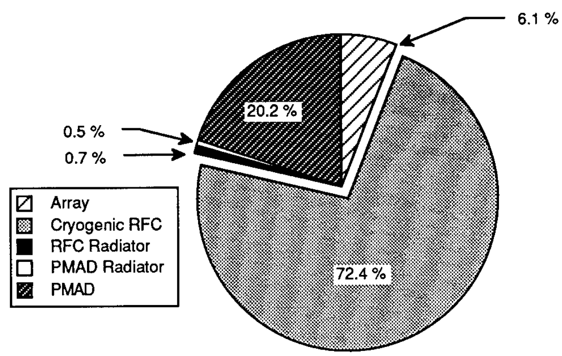

Fig. 2 Mass Breakdown of Lunar PV Array Tent with RFC Energy Storage

To minimize storage requirements, the power used during the night should be minimized. Some applications such as resource utilization (for example, recovery of oxygen or hydrogen from lunar soil for use as rocket propellant) could be scheduled to require power primarily during the daytime. Other usage, however, such as lighting and life support, will require continuous power. One option for reducing the nighttime life support requirements is to store the waste gasses at night for processing during the daytime, rather than to reprocess during the night. This has the potential for reducing the minimum required night power to below the 3 kW per person baseline. To account for the fact that night power requirements may be different from day requirements, we define the power fraction f as the ratio of the required night power to the required day power. (This value is also sometimes referred to as the energy storage duty cycle.)

Array Orientation

One major design feature of the lunar PV array is its orientation to the sun. Both planar and concentrating arrays are possible. A concentrator array requires constant tracking to within about a degree of arc which in turn requires additional structure and mechanisms. For the purpose of this study, the complexity of a tracking concentrator array eliminates it from consideration. A planar array in a horizontal configuration will have times during the lunar day where little or no energy is being generated due to poor sun angles.

An array geometry which lessens this problem is a triangular or "tent" configuration (fig. 3). This arrangement of two panels sloping upwards toward each other is more efficient near lunar dawn and dusk than a horizontal configuration. By setting a requirement that the arrays must provide 100% of the daytime load power from sunrise to sunset, the mass of the storage system that would otherwise be required to supply energy during the lunar morning and evening is obviated. The angle of array tilt required to provide this power profile is discussed in the next section. Fig. 3 shows an artist's conception of how a power system for a moon base might appear shortly after landing.

Triangular Array Tilt Angle. Consider an array consisting of two identical panels, each tilted an angle α from the horizontal, respectively toward sunrise and sunset. If the rated array power at normal incidence of the panels

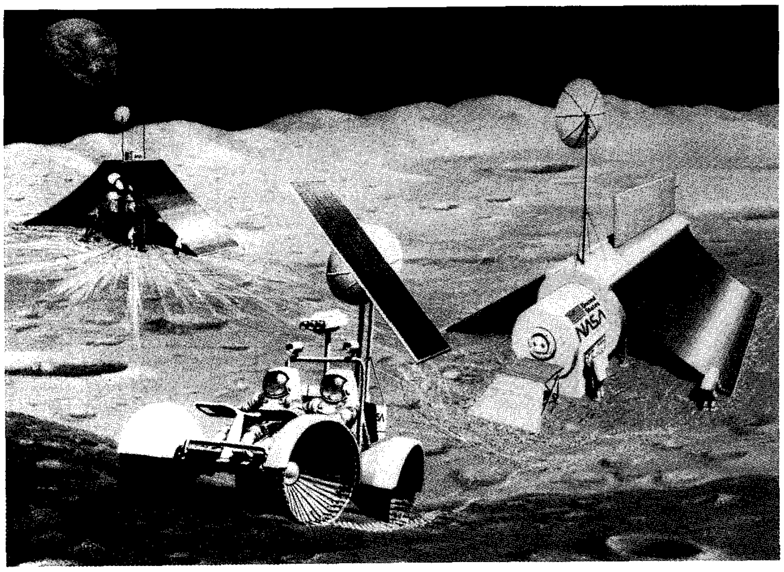

Fig. 3 Artist's Conception of Photovoltaic Power Systems Employed on a Lunar Base, Showing the East/West "Tent" Array Orientation

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Triangular Array Tilt Angle. Consider an array consisting of two identical panels, each tilted an angle α from the horizontal, respectively toward sunrise and sunset. If the rated array power at normal incidence of the panels combined is A, and θ is the sun angle with $\theta=0$ defined as solar noon, the power for the tilted array is:

(1a) $P = A\cos\alpha\cos\theta$, for $|\theta|<\pi/2-\alpha$,

(1b) $P = A(\cos\alpha\cos\theta-\sin\alpha\sin\theta)/2$, for $-\pi/2 \leq \theta \leq -\pi/2+\alpha$,

(1c) $P = A(\cos\alpha\cos\theta+\sin\alpha\sin\theta)/2$, for $\pi/2-\alpha \leq \theta \leq \pi/2$, and

(1d) $P = 0$, for $|\theta|>\pi/2$.

Thus, the average power over the daytime is:

(2) $P_{ave} = A[\cos\alpha + 1]/\pi$

which, as should be expected, has a maximum value of $2/\pi$ for $\alpha = 0$, a horizontal array. (For comparison, a tracking array has $P_{ave}/A = 1$.) The power at sunrise equals the power at sunset,

(3) $P_{sunrise} = (\sin\alpha)/2$.

Consider energy storage with an efficiency η (energy out/energy in) and power fraction f. Then the average power generated during the day, P_{gen}, must be larger than the daytime load by a factor k:

(4) $P_{gen} = (1 + f/\eta)P_{day} \equiv kP_{day}$,

where we have defined $k = (1 + f/\eta)$. To minimize the storage, we require that the array power at sunrise equal the daytime load P_{day}, i.e., immediately at sunrise no power is drawn from the storage system. This then gives us an equation for the array tilt angle α:

(5) $\sin\alpha = 2(\cos\alpha + 1)/(\pi k)$.

The solution to this equation is:

(6) $\alpha = \cos^{-1} [(k^2 - 4/\pi^2) / (k^2 + 4/\pi^2)]$.

As an example, suppose night and day power requirements are equal, and the energy storage efficiency is 100%. Then the sunrise power must be exactly half the average daytime power, and the angle α is:

(7) $\alpha = \cos^{-1} [(\pi^2-1)/(\pi^2+1)] = 35.3°$.

From equation 2, the array considered provides 58% of the power per unit area of a tracking array. For a more realistic example, suppose the required night power is half the daytime power and the round-trip storage efficiency is 60%. Then $f/\eta = 0.833$, and the array angle $\alpha = 38.4°$. This is 57% of the power per unit area of a tracking array.

As can be seen, the required angle increases as f/η decreases.

This method yields the array tilt angle such that the average power integrated over the lunar day is sufficient for daytime load and nighttime storage requirements. Care must be taken, however, in cases where the nighttime power requirement is a low percentage of the daytime power (low f). In these cases, the tilt of the arrays from the horizontal is so large that the power variation during the day may drop below the load requirement, requiring use of energy storage during the daytime. This would require additional array area and fuel cell radiators designed to work at the higher daytime temperatures. A triangular array with a round trip storage efficiency of 60% (η=0.60) and a power fraction of only 5% yields a tilt angle of 60.9° (fig. 4). Tent angles above 60° allows the generated power to dip below the load power level. The tilt angle α will equal 60° when $k = 2\sqrt{3}/\pi$.

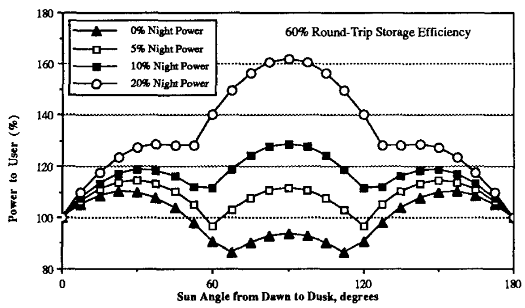

Fig. 4 Effect of Low Nighttime Power Fraction on Power Profile

Different constraints apply if no storage is required, as for a base occupied during the daytime only. In this case, it is desirable to make the power profile as close to uniform as possible. This is accomplished with a tilt angle of 60°. An array with α=60°, called an equilateral tent array, will have four power generation minimums (at θ=0°, 60°, 120°, and 180°, i.e., lunar dawn, 118 hours, 236 hours, and sunset, respectively). The minimum is equal to the load requirement.

For high power fractions (>50%), the power generated at lunar noon is several times the load level requirement (fig. 5). The larger the peak power, the more massive the power management system becomes. It would be advantageous to keep peak power close to the load level without dropping below it. This is especially true for a PV power system designed to provide power only during the lunar day. This is also best accomplished at a tent angle of 60° (fig. 6).

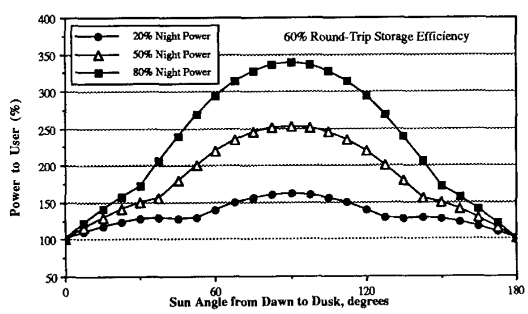

Fig. 5 Effect of High Nighttime Power Fraction on Power Profile

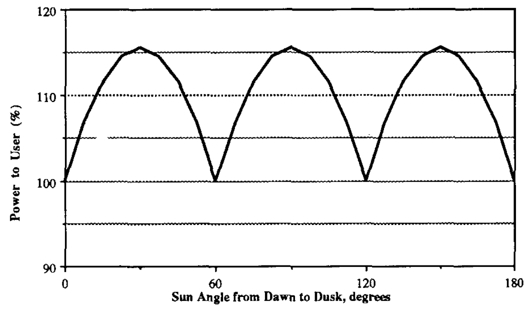

Fig. 6 Power Profile for 60 Degree Tent Angle

Power Management and Distribution

The power management and distribution (PMAD) system for the lunar base will be required to supply power to crew habitats, science stations, ISRU facilities, and launching and landing facilities. Each of these activity zones must be several kilometers distant from each other and from the PV arrays; the activity from one zone must not interfere with the activity or operation of another. The science laboratories within the habitation unit or in special attached lab modules will require a standard operating voltage and amperage. Much like in the Space Station Freedom and with terrestrial utilities, the power conditioning must be able to service many users with different power requirements.

The long transmission distances (on the order of one kilometer from the central habitation zone to any of the other zones) and the accommodation of users will drive up the mass of the PMAD system. Transmission distances from nuclear reactors would most likely be on the order of a kilometer or more to reduce radiation effects. This would require the formation of a "zone of exclusion" around the reactor wherein human activity would be severely restricted.

Specific masses of PMAD systems range from the Space Station Freedom PMAD system at several hundred kg/kW_e to 1 kg/kW_e or less for advanced systems with dedicated loads. It was assumed in this study that the lunar base PMAD specific mass would be about 20 kg/kW_e. This is based on the assumption of a more advanced PMAD system than for the Space Station with consideration of user requirements and transmission distances.

COMPARISON OF PHOTOVOLTAIC TO NUCLEAR REACTOR AND MULTIPLE SOURCE POWER SYSTEMS

When comparing masses of potential lunar base power systems, photovoltaic power systems are generally found to be heavier than nuclear power systems at high power levels (17). This occurs because the energy storage subsystem required by PV power systems to provide power over the 354-hour lunar night is extremely massive, constituting up to 80-90% of the PV power system mass.

In fig. 7, a nuclear reactor power system is compared with two versions of the "array tent" PV power system, one using cryogenic reactant RFC storage (1500 Whr/kg), the other using gaseous reactant RFC storage (500 Whr/k-g). Each PV system uses multi-junction solar cells on a 3 mil silicon substrate. A fourth power system, shown in the figure employs multiple power generation sources.

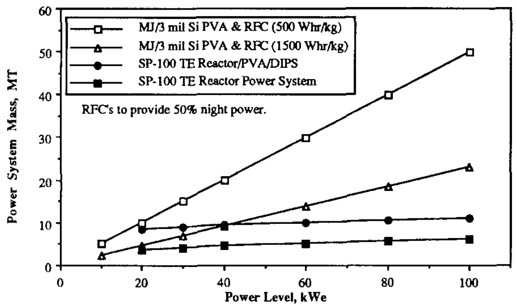

Fig. 7 Comparison of Systems for Continuous Power Generation

During NASA's 90-Day Study process, concerns were raised that a single source power system would be vulnerable to systemic power system failure. For example, if dust is a problem for habitat arrays, then it will be a problem for arrays on rovers and on remote scientific instruments. If thermal cycling reduces the lifetime of the refractory metals in one nuclear power module, then other similarly designed modules may have the same problem.

One solution may be to design the lunar power system using multiple sources. Autonomous sources could generate power, independently feeding into a power grid as with terrestrial power plants. Alternatively, a single source could serve as the primary source with other sources available for emergency backup power. The multiple source power system used for comparison in figures 7 and 8 is of the latter type. This system uses a SP-100 thermoelectric reactor power module as the primary source. In the event of power loss--whether permanently through reactor failure or coolant loss, or temporarily through a transmission line break near the habitat--a deployable PV array would be used for daytime power and a dynamic isotope power system (DIPS) would be used at night to supply continuous survival power for base personnel for an extended period, say until a new reactor module can be emplaced or repairs affected. The emergency PV array is a horizontal GaAs on 3 mil Ge array sized to provide 25 kW_e. The DIPS is comprised of five 2.5 kW_e DIPS units. Both the DIPS and the PV array would have independent lines and conditioning units.

Fig. 7 shows that this multiple source system is lighter than the PV/RFC systems above 40 kW_e. This is due primarily to the massive RFC systems which in this instance are only providing 50% night power. Fig. 8 shows that if storage is not necessary, PV power systems are less massive than nuclear systems. Note, however, that nuclear systems can provide power through the lunar night, whereas PV systems without storage can only provide power during the lunar day.

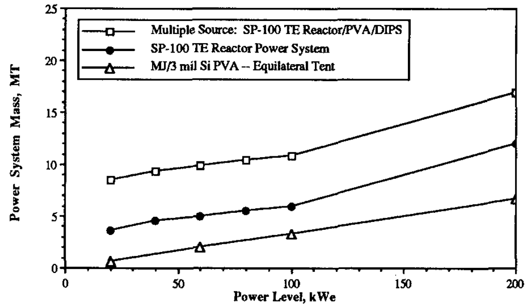

Fig. 8 Comparison of Systems for Daytime Power Generation

Standby PV Arrays. Photovoltaic arrays used as an emergency power source would need to be designed with certain characteristics. Since they are used during a power emergency, they would need to be deployed quickly and without requiring power (at least from the primary source). When the emergency is over, they will need to be retracted to mimize the potential damage of solar flares, dust, and other environmental hazards. Both of these operations should be achievable with a minimum of human assistance. The deployable PV array should have minimal weight, a low storage volume, and a long shelf life. These characteristics would be satisfied by a lightweight, thin-film roll-out blanket, for example.

SUMMARY

Several features and constraints of photovoltaic power systems for the lunar surface have been discussed. The main findings are:

1) The solar array is a small percentage of the overall PV power system mass.

2) Energy storage for the lunar night is the main mass driver. Minimizing nighttime power usage will significantly lower mass.

3) A "tent" array configured in an east/west orientation has advantages over a fixed tilt or horizontal array due to power generation at dawn and dusk.

Future studies of lunar surface PV systems should include a detailed analysis of the power management and distribution system (PMAD); a detailed thermal analysis of the PV array; long term effects of lunar environmental factors such as dust and the cycling to very low temperatures due to the 354-hour dark period; development of low mass energy storage systems; and further development of low mass, deployable PV arrays.

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