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Advanced Photovoltaic Power System Technology for Lunar Base Applications

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ADVANCED PHOTOVOLTAIC POWER SYSTEM TECHNOLOGY FOR LUNAR BASE APPLICATIONS

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SUMMARY

Establishment of a permanent manned presence on the moon will be a severe challenge, not the least part of which will be to provide a source of power. Since a lunar base may well experience evolutionary development in size, capability, and complexity, power requirements will also exhibit an evolutionary growth from an initial tens of kilowatts level to an ultimate level in the megawatt range. It is commonly held that the latter will require a nuclear reactor power source to minimize the weight that must be launched to the lunar surface. It is quite likely, however, that the initial base will require an easily deployed system for start-up and early operations. It is also reasonable to assume that the first phases of growth will depend on modular expansion of the initial power system until the SP-100 nuclear system can be incorporated into the base. Since the SP-100 is designed to supply 100 kWe, system changeover would not be expected to occur until that level of power becomes a modular unit. This paper will discuss and compare advanced photovoltaic/electrochemical (batteries or regenerative fuel cells for storage) power system options for a lunar base, and will compare estimated system masses with those projected for the SP-100 nuclear system. The results of the comparison will be quantified in terms of the mass saved in a scenario which assembles the initial base elements in LEO and launches from there to the lunar surface. A brief summary will be given of advances in photovoltaic/electrochemical power system technologies currently under development in the NASA/OAST program. A description of the planned focussed technology program for surface power in the new Pathfinder initiative will also be provided.

E-4258

INTRODUCTION

The establishment of a permanently manned presence on the lunar surface represents a formidable challenge to a broad spectrum of space technologies. While all the technologies that will be required to sustain the evolution of a lunar base, from its initial establishment as an outpost to its final manifestation as a permanent, life-sustaining and productive habitat are essential, the pacing technology for it all is the production of power. A new aspect of such an endeavor is that the "mission" requirements are no longer fixed, but will evolve over time. It is now necessary to examine and develop a time-dependent set of requirements for the power system, and to put in place an adequately supported research and development program that is properly phased to produce the needed technology at the right time. The NASA Lewis Research Center, as the lead center for space power for the Office of Aeronautics and Space Technology (OAST) has taken the first steps in that direction with the implementation of a program in High Capacity Power, and the impending implementation of programs in Surface Power and Rover Power. All the preceding initiatives are the outgrowth of planning activities that have been conducted by OAST over the past few years, and which have culminated in the establishment of the Civil Space Technology Initiative (CSTI), and the Pathfinder Program. The High Capacity Power program is an element of CSTI, and the Surface Power and Rover Power programs are elements of Pathfinder.

POWER SYSTEMS MASS COMPARISON

While the definition of a complete set of time-dependent requirements is an unfinished task, an understanding of key issues has been developed to help guide the focussed technology programs mentioned above. Technologies intended for application on the lunar surface will be driven by mass considerations, primarily because of the high cost of payload delivery to the Moon. Even if the assumption is made that low operational cost cargo vessels will be available for transit from low earth orbit (LEO) to the Moon, there will still be a high cost for delivery to LEO which must be considered. For comparison purposes the cost can be represented by a payload mass multiplication factor which takes into account the total launch mass required to deliver the intended lunar base elements to LEO. Although a universally agreed-on value for such a multiplier does not exist, primarily because the exact nature of future heavy-lift launch capabilities is not known, a value of 5 has been assumed for this discussion, along with an assumed heavy lift vehicle (HLV) payload capability of 91 000 kg (200 000 lb) to LEO. Such assumptions are not unreasonable with respect to future launch systems. No further justification for using them will be provided except to point out that doing so allows a quantitative comparison of power system alternatives in terms of "operational" impact - the number of launch vehicles required to deliver the system elements to LEO for subsequent transport to the lunar surface.

The key figure of merit for a photovoltaic array is the power per unit mass in watts per kilogram, W/kg. For a storage system the appropriate figure of merit is the amount of available energy per unit mass in watt-hours per kilogram, or W-hr/kg. The advanced power system uses an ultralightweight photovoltaic array and an advanced hydrogen-oxygen regenerative fuel cell (RFC) for storage. The figure of merit for both systems are listed in table I. Table II compares the system masses for a state-of-the-art photovoltaic generation/battery storage system sized to deliver 100 kW to a lunar base to that performance projected for an advanced version of such a system. Two cases are considered for the 336 hr lunar night: a 100 percent duty cycle and a 20 percent duty cycle. Also shown is the mass saved in delivering the advanced system to LEO, along with the resulting number of HLV launches saved, under the assumptions given above. The final column of the table shows the additional number of HLV launches that would be saved by using the SP-100 nuclear power system currently under development, and intended to have a specific power of 33 W/kg. The table provides compelling evidence that there is a substantial payoff to be had in developing the advanced PV/RFC technology, particularly when placed in the "operational" context of the weight saved at LEO. A third case also exists, that in which the astronauts' stay would be limited to the 336 hr lunar day with a night duty cycle of zero, or close enough to zero so that lander energy storage would be sufficient. In this scenario, only a photovoltaic array would have to be delivered to the lunar surface. A state-of-the-art PV array to supply 100 kWe has a mass of 1515 kg, while an advanced array would weigh only 333 kg, a significant savings under a restricted mass budget.

Figure 1 provides a more graphic comparison between the mass of a SOA photovoltaic/battery system, the advanced photovoltaic/regenerative fuel cell system, and the SP-100 nuclear power system. As can be clearly seen, the advanced PV/RFC technology has the potential to reduce the mass of a 100 kWe lunar surface power system using state-of-the-art technology by more than a factor of 45, to a value less than 2.5 percent of the mass of the latter. (The SP-100 system, even though projected to be lighter than the advanced PV/RFC system by a factor of 10, will only save a little more than another 2 percent of the SOA system mass.) The long lunar night is clearly the major issue in determining the mass of the lunar base photovoltaic-electrochemical storage system. The key feature that allows such a large mass reduction is that the stored energy in an advanced regenerative fuel cell system is in the form of gaseous reactants stored in high pressure tanks, with the result that the RFC can approach 1000 W-hr/kg, a factor of 4 or 5 better than that projected for advanced batteries, and a factor of more than 60 better than SOA batteries (NiH, for example). The remainder of this paper contains a more detailed description of the technology that will be pursued in the Surface Power program to achieve these gains.

PHOTOVOLTAIC ARRAY TECHNOLOGY

The key figure of merit for a photovoltaic array is the power per unit mass, also referred to as the specific power. A photovoltaic array consists of a number of solar cells interconnected to provide the required voltage and current levels to the electrical load, usually through a power management and distribution system. The cells are mounted on a substrate which can be either rigid, such as honeycomb panels, or flexible, such as Kapton. The cells, substrate, protective diodes and wiring harness comprise the blanket. The remaining portion of the photovoltaic array is the mechanical structure, which includes the stowage container, the deployment mechanism and the struts to maintain the blanket in a planar configuration pointed at the sun. Improvement in the specific power can be achieved through two different, although often coupled, approaches; increasing the conversion efficiency of the solar cell and reduction of the cell/blanket mass and/or array structure mass. Improvements in cell efficiency not only increase the array specific power but also decrease array area, if a fixed power level is required. For a system such as that envisioned for a rover vehicle, reduction in array area can be critical.

The program objective in the Surface Power program of Pathfinder is an array specific power of 300 W/kg at Air Mass Zero (AMO) insolation (solar insolation at 1 A.U.). At present, lightweight photovoltaic arrays have been demonstrated on a Space Shuttle experiment (OAST-1) at 66 W/kg. A recent design, under development at the Jet Propulsion Laboratory for OAST, was established at 130 W/kg (ref. 1). This design, the Advanced Photovoltaic Solar Array (APSA), is based on 2 mil thick silicon cells. These two array designs are intended for the zero gravity conditions of LEO and GEO (Geosynchronous Earth Orbit). For lunar base applications, the array structure must be rugged enough to withstand the 1/6 g of the lunar surface.

To achieve the 300 W/kg specific power goal, two solar cell technologies have been identified for further development. These candidate cell types are ultrathin gallium arsenide (GaAs) and amorphous silicon (a-Si). Table III summarizes the technologies to be developed for a lunar base power system and their current performance. GaAs cells are currently manufactured for space use at an efficiency of about 18 percent, with research devices achieving 21 percent. However, the current cell is too thick at 200 to 250 μm to give the performance needed for lunar base applications. Fortunately, because it is a direct gap semiconductor, GaAs absorbs all photons available for energy conversion within 3 to 4 μm of the impinging surface. This allows, unlike crystalline silicon, for an ultrathin, high efficiency cell to be produced. 5.5-μm thick GaAs cells have been fabricated utilizing the CLEFT (Cleaved Lateral Epitaxy for Film Transfer) process (ref. 2), a technique in which a single crystal thin GaAs layer is grown on a masked GaAs substrate and mechanically removed. Other processes, such as chemical thinning of the substrate, have also been successfully demonstrated as capable of producing high quality, ultrathin layers and cells. Basic research and development in cell interconnectors and cell incorporation into a space compatible blanket will be critical because of the brittleness of the ultrathin GaAs cells.

Amorphous silicon is primarily a terrestrial photovoltaic material, however 9 percent space performance has been measured. The electronic structure of the disordered, amorphous material allows for total cell thickness of less than 1 μm and the use of flexible substrates. This is compatible with a very high blanket specific power and low volume storage requirements. An extensive manufacturing base already exists for a-Si terrestrial solar cells, however, several major hurdles must be overcome before it can be considered as a viable space cell candidate. Among these are low conversion efficiency and cell performance degradation under constant illumination. Although terrestrial arrays are manufactured on flexible, rugged substrates, few of the materials used are compatible with space requirements, necessitating basic studies in blanket materials and design.

Additional improvement in the photovoltaic array specific power can be achieved by minimizing the mass of the array structure. For the Advanced Photovoltaic Solar Array design, the structure, blanket box and deployment mechanism constitute more than fifty percent of the mass of the entire array. Research and development on the array structure is also warranted by the need, for the first time, for a space solar array to operate in a continuous gravity field. An APSA wing is pictured in figure 2 along with the a detailed cross-section of its blanket. Its design specific power of 130 W/kg is met with 13.5 percent efficient, 63 μm thick silicon cells. Replacing the silicon cells with GaAs cells of 25 percent efficiency, assuming the same blanket mass and eliminating the 5 percent mass contingency built in to the design yields a specific power of 260 W/kg, quickly approaching the lunar base goal. This also assumes that a reduced gravity structure will weigh no more than the zero-g APSA structure; which is possible since manual deployment or erection is an option for a manned lunar base and could eliminate the deployment motor and mast. Figure 3 shows the approach taken by NASA toward a 300 W/kg zero-g array. Improvements in the structure and cell interconnector wiring, coupled with a high efficiency cell, will enable attainment of this performance level. These improvements, as well as the overall design experience gained with zero-g arrays, will be incorporated into the lunar base array structure.

REGENERATIVE FUEL CELL TECHNOLOGY

At present only primary fuel cells exist and regenerative cells, which do not limit mission time or power availability by the amount of hydrogen and oxygen that can be carried along, have not yet been designed. The primary focus of RFC research for a lunar base power system will be on fuel cell stack configurations including oxygen electrode catalysts, thermal and gas management and lightweight, high pressure, robust tank technologies. The principal effect of the 336 hr duration of the lunar night is the requirement for a very large fuel cell reactant mass. Therefore, significant mass gains can be made by reduction of the storage tank mass. Figure 4 illustrates the effect of storage duration on RFC system energy density for several tank types (personal communication with L.H. Thaller of NASA Lewis). For the high pressure gas storage system chosen for the lunar base, the use of filament wound tanks enables the storage system energy density to approach 1000 W-hr/kg. This is exceeded only by cryogenic reactant storage which at present has application for primary fuel cells only and is not viable for the lunar base mission.

SUMMARY

The development of an advanced photovoltaic power system which would have application for a manned lunar base is currently planned under the Surface Power element of Pathfinder. Significant mass savings over state-of-the-art photovoltaic/battery systems are possible with the use of advanced lightweight solar arrays coupled with regenerative fuel cell storage. The solar blanket, using either ultrathin GaAs or amorphous silicon solar cells, would be integrated with a reduced-g structure. Regenerative fuel cells with high pressure gas storage in filament wound tanks are planned for energy storage.

In conclusion, an advanced photovoltaic/RFC power system is a leading candidate for a manned lunar base as it offers a tremendous weight advantage over state-of-the-art photovoltaic/battery systems and is comparable in mass to other advanced power generation technologies.

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2. Fan, J.C.C.; McClelland, R.W.; and King, B.D.: GaAs Cleft Solar Cells for Space Applications. Proceedings of the 17th Photovoltaic Specialists Conference, IEEE, Piscataway, NJ, 1984, pp 31-35.

TABLE I. - FIGURE OF MERIT COMPARISONS FOR PHOTOVOLTAIC/ ELECTROCHEMICAL TECHNOLOGY OPTIONS

	State-of-the-art	Advanced
Array Storage	66 W/kg, OAST-1 14 W-hr/kg, NiH battery	300 W/kg, ultralightweight 1000 W-hr/kg, H-O RFC

TABLE II. - COMPARISON OF CURRENT AND ADVANCED PHOTOVOLTAIC POWER SYSTEMS FOR A MANNED LUNAR BASE

[Instrument shielding only for SP-100.]

Power level, kWe	Night duty cycle, percent	SOA PV/battery mass, kg	Advanced PV/RFC mass, kg	Weight saved at LEO, kg	HLV launches saved	Additional HLV's saved W/SP-100
100	100	1 680 000	34 350	7 910 000	87	1.6
100	20	336 420	7 133	1 580 000	17.4	.2

TABLE III. - TECHNOLOGY STATUS AND DESIGN PROJECTIONS

	Lunar base design	Current performance
Photovoltaic devices		
Gallium arsenide	25 percent AMO efficiency	21 percent
Amorphous silicon	15 percent AMO efficiency	9 percent
Array structure		
Specific power	300 W/kg (APSA)	66 W/kg (OAST-1)
Energy storage		
High pressure gas	1000 W-hr/kg	300 W-hr/kg (primary fuel cell)
Regenerative fuel cell	60 percent efficiency	60 percent efficiency

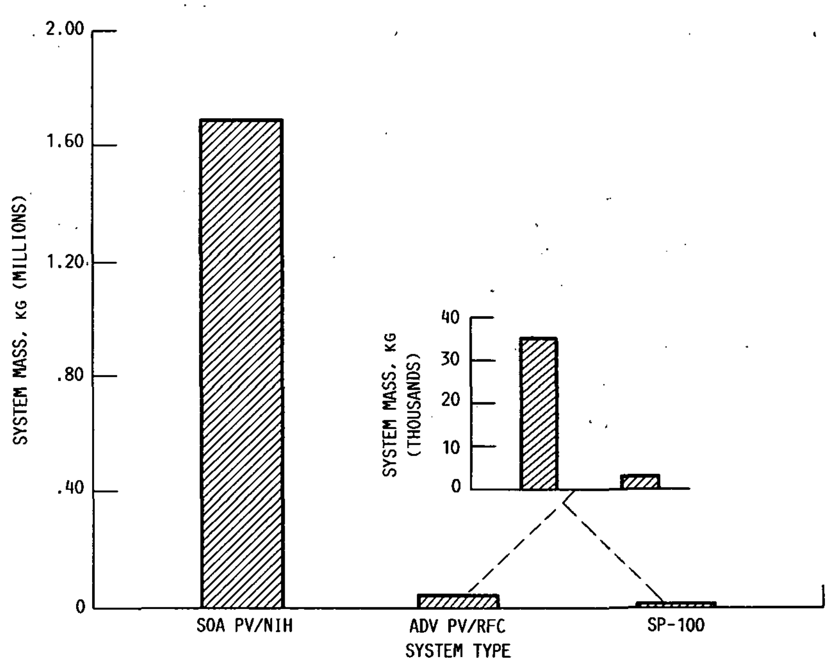

FIGURE 1. - POWER SYSTEMS MASS COMPARISON; 100 kWe LUNAR BASE, 2 WEEK STORAGE.

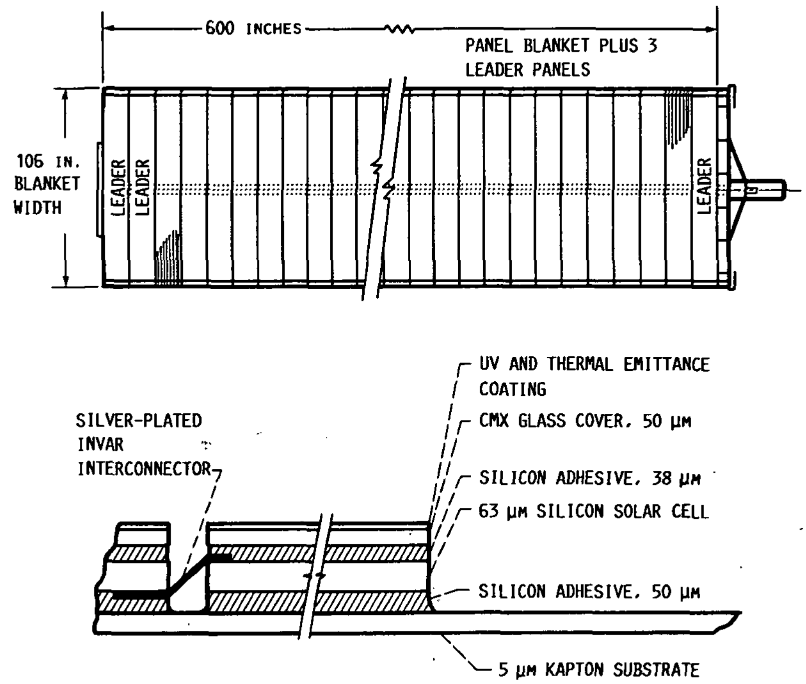

FIGURE 2. - ADVANCED PHOTOVOLTAIC SOLAR ARRAY (APSA) WING AND BLANKET.

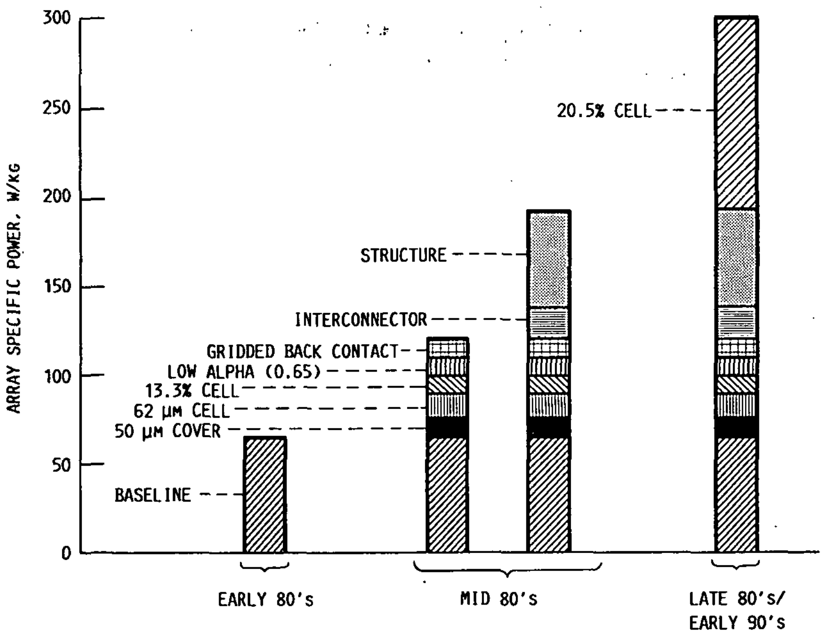

FIGURE 3. - HIGH PERFORMANCE SOLAR ARRAY RESEARCH AND TECHNOLOGY.

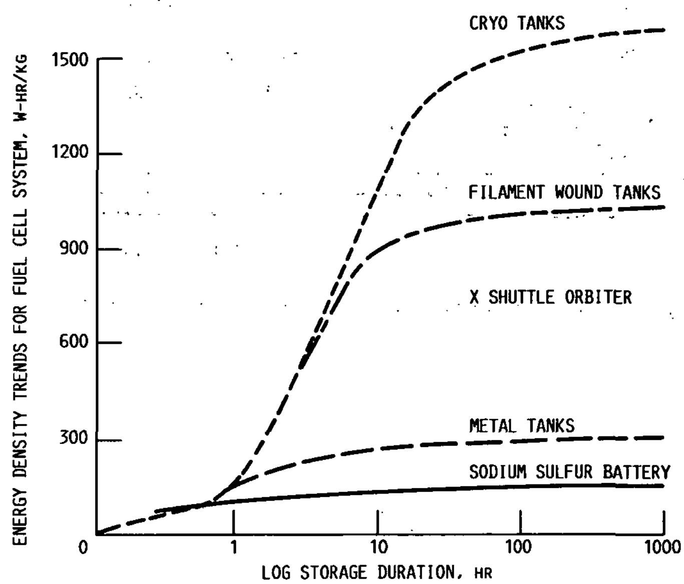

FIGURE 4. - APPROXIMATE ENERGY DENSITY CHARACTERISTIC OF FUEL CELL SYSTEMS AS A FUNCTION OF TANK TYPE AND STORAGE DURATION.

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16. Abstract
Establishment of a permanent manned presence on the moon will be a severe challenge, not the least part of which will be to provide a source of power. Since a lunar base may well experience evolutionary development in size, capability, and complexity, power requirements will also exhibit an evolutionary growth from an initial tens of kilowatts level to an ultimate level in the megawatt range. It is commonly held that the latter will require a nuclear reactor power source to minimize the weight that must be launched to the lunar surface. It is quite likely, however, that the initial base will require an easily deployed system for start-up and early operations. It is also reasonable to assume that the first phases of growth will depend on modular expansion of the initial power system until the SP-100 nuclear system can be incorporated into the base. Since the SP-100 is designed to supply 100 kWe, system changeover would not be expected to occur until that level of power becomes a modular unit. This paper will discuss and compare advanced photovoltaic/electrochemical (batteries or regenerative fuel cells for storage) power system options for a lunar base, and will compare estimated system masses with those projected for the SP-100 nuclear system. The results of the comparison will be quantified in terms of the mass saved in a scenario which assembles the initial base elements in LEO and launches from there to the lunar surface. A brief summary will be given of advances in photovoltaic/electrochemical power system technologies currently under development in the NASA/OAST program. A description of the planned focussed technology program for surface power in the new Pathfinder initiative will also be provided.

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