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ADVANCED PHOTOVOLTAIC POWER SYSTEM TECHNOLOGY FOR LUNAR BASE APPLICATIONS

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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 into place an adequately supported research and development program that is properly phased to produce the needed technology at the right time. The 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 focused 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 that must be considered. For comparison purposes the cost can be represented by a payload mass multiplication factor that takes into account the total launch mass required to deliver the intended lunar bases 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 92,000 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 (Whr/kg). The advanced power system uses an ultralightweight photovoltaic array and an advanced hydrogen-oxygen regenerative fuel cell (RFC) for storage. The figures of merit for both systems are listed in Table 1. Table 2 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% duty cycle and a 20% 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 suface. 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.

TABLE 1. Figure of merit comparisons for photovoltaic/electrochemical technology options.

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

TABLE 2. Comparison of current and advanced photovoltaic power systems for a manned lunar base.

Power Level (KWe)	Night Duty Cycle	SOA PV/battery Mass (kg)	ADV PV/RFC Mass (kg)	Weight Saved At LEO (kg)	HLV Launches Saved	Additional HLVS Saved with 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	0.2

Figure 1 provides a more graphic comparison between the mass of the SOA phovoltaic/battery system, the advanced PV/RFC 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% 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% 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 RFC system is in the form of gaseous reactants stored in high-pressure tanks, with the result that the RFC can approach 1000 Whr/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 that can be either rigid, such as honeycomb panels, or flexible, such as kapton. The cells, substrate, protective diodes, and wiring harness constitute 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.

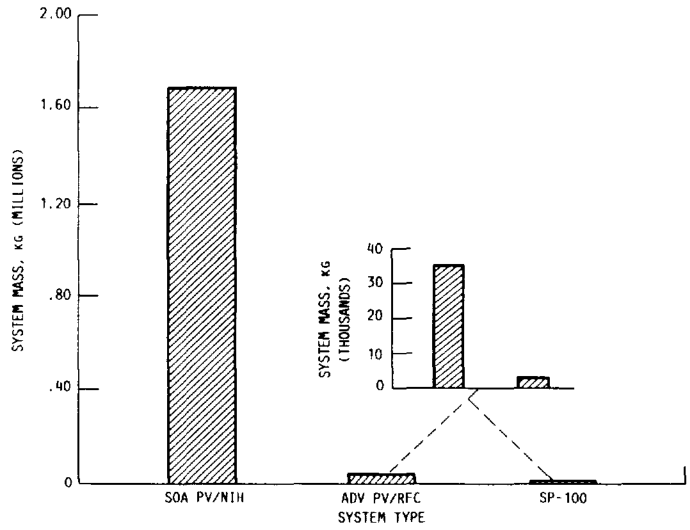

Fig. 1. Power systems mass comparison.

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 AU). 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 (*Scott-Monck and Stella,* 1986). 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 geosynchronous Earth orbit (GEO). 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 3 summarizes the current performance of technologies to be developed for a lunar base power system and their current performance. Gallium-arsenide cells are currently manufactured for space use at an efficiency of about 18%, with research devices achieving 21%. However, the current cell is too thick at 200-250 μm to give the performance needed for lunar base application. Fortunately, because it is a direct-gap semiconductor, GaAs absorbs all photons available for energy conversion within 3-4 μm of the impinging surface. This allows, unlike crystalline silicon, for an ultrathin, high-efficiency cell to be produced. Gallium-arsenide cells 5.5 μm thick have been fabricated using the cleaved lateral epitaxy for film transfer (CLEFT) process (*Fan et al.,* 1984), 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% 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

TABLE 3. Technology status and design projections.

	Lunar Base Design	Current Performance
Photovoltaic Devices		
Gallium Arsenide	25% AMO Eff.	21%
Amorphous Silicon	15% AMO Eff.	9%
Array Structure		
Specific Power	300 W/kg (APSA)	66 W/kg (OAST-1)
Energy Storage		
High-Pressure Gas	1000 Whr/kg	300 Whr/kg (Primary
Regenerative Fuel Cell	60% Eff.	60%Eff. Fuel Cell)

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 APSA design, the structure, blanket box, and deployment mechanism constitute more than 50% of the mass of the entire array. Research and development on the array structure are 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 Fig. 2, along with a detailed cross section of its blanket. Its design specific power of 130 W/kg is met with 13.5% efficient, 63-μm-thick silicon cells. Replacing the silicon cells with GaAs cells of 25% efficiency, assuming the same blanket mass and eliminating the 5% mass contingency built into 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.

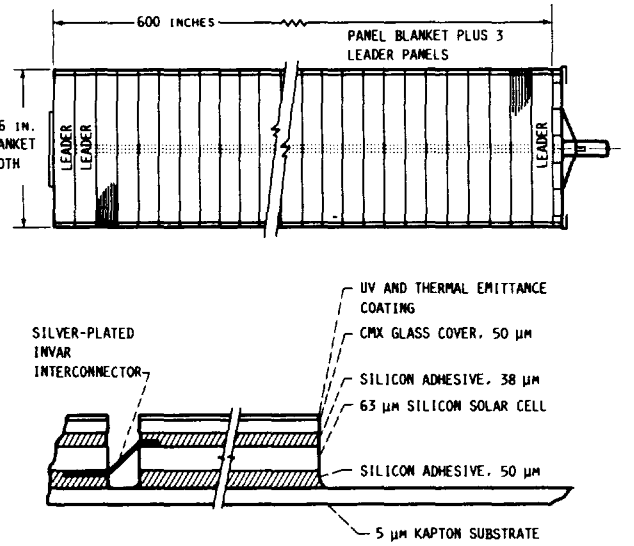

Fig. 2. Advanced photovoltaic solar array (APSA) wing and blanket.

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 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

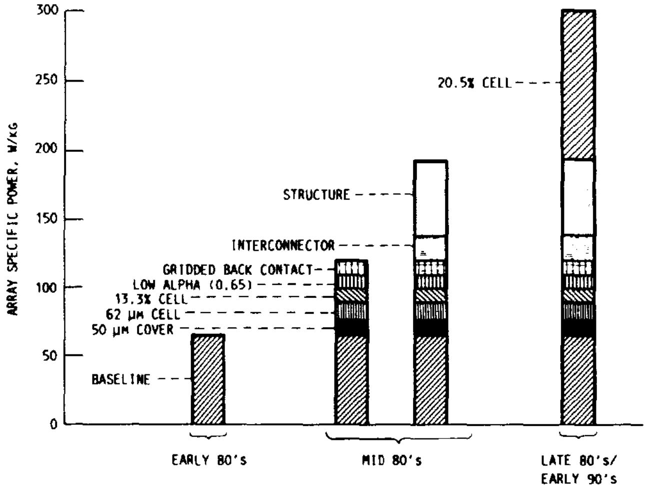

Fig. 3. High-performance solar array research and technology.

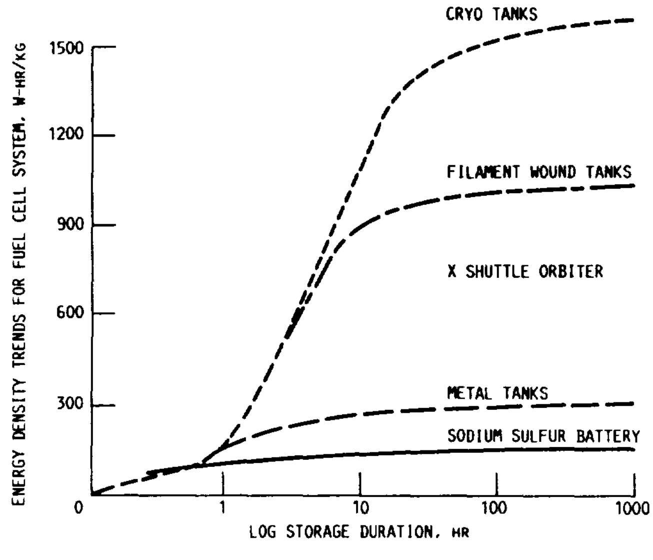

Fig. 4. Approximate energy density characteristic of fuel cell systems as a function of tank type and storage duration.

RFC system energy density for several tank types (L. H. Thaller, personal communication, 1988). 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 Whr/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 that 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 PV/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.

REFERENCES

Fan J. C. C., McClelland R. W., and King B. D. (1984) GaAs cleft solar cells for space applications. In *Proceedings of the 17th Photovoltaic Specialists Conference*, pp. 31-35. IEEE, Piscataway, New Jersey.

Scott-Monck J. and Stella P. (1986) Advanced photovoltaic solar array program—A preliminary assessment. In *21st Intersociety Energy Conversion Engineering Conference, Vol. 3*, pp. 1458-1461. American Chemical Society, Washington, DC.