NASA Technical Memorandum 102019

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(NASA-TM-102019) PHOTOVOLTAIC POWER SYSTEM CONSIDERATIONS FOR FUTURE LUNAR BASES (NASA. Lewis Research Center) 8 p CSCL 10B N89-23517
Unclas
G3/20 0209826

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Prepared for the
International PVSEC-4
cosponsored by The Institution of Radio and Electronics Engineers of Australia
and The University of New South Wales
Sydney, Australia, February 14–17, 1989

NASA

PHOTOVOLTAIC POWER SYSTEM CONSIDERATIONS FOR FUTURE LUNAR BASES

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SUMMARY

Recent advanced planning activities within the National Aeronautics and Space Administration have been focused on the possibility of establishing a permanent manned presence on the moon. It is recognized that such a goal represents a severe challenge, not the least part of which will be to provide an adequate source of power. It is expected that a lunar base will undergo an evolutionary growth in size, capability, and complexity, with a concomitant growth in power requirements from an initial tens of kilowatts to an ultimate level in the megawatt range. Although 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 also generally held that the initial base will require a photovoltaic power system that is modular, lightweight, and easily deployed. An important issue facing future lunar base mission planners is that of energy management, particularly when confronted by the need to provide power during the 336 hr lunar night. There will also be issues associated with the loads themselves; e.g., whether there will be multiple loads in parallel fed from a common power source, or whether certain loads will have a dedicated power source (e.g., "housekeeping" power) while the so-called functional loads are powered from a common source. A third possibility includes a combination of a number of dedicated sources and one common source with multiple loads, and in a fourth scenario all loads would have a dedicated source. The paper will discuss results of an investigation to determine an optimum load management strategy for a lunar surface array, and will discuss the impact such optimization has on total system mass. The paper will also describe the attributes a photovoltaic power system must possess to be considered for this unique application, which will use space photovoltaic technology in a terrestrial-like system, but in a nonterrestrial environment.

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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.

While the definition of a complete set of time-dependent requirements is an unfinished task, an understanding of key issues has emerged to help guide technology development for such a mission scenario. Technologies intended for

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application on the lunar surface will be driven by mass considerations, primarily because of the high cost of payload delivery to the moon. The implication of so strong a driver is that there can now be a trade-off in solar array efficiency if the result is a decrease in mass. 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. 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. Using them allows a quantitative comparison of power system alternatives in terms of an operational impact - the number of launch vehicles required to deliver the system elements to LEO for subsequent transport to the lunar surface.

POWER SYSTEM MASS CONSIDERATIONS

The key figure of merit for a photovoltaic array is the power per unit mass in watts per kilogram, or 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 Wh/kg. Table I compares the system masses for a state-of-the-art photovoltaic generation/battery storage power system, sized to deliver 100 kW to a lunar base, to that projected for an advanced version of such a system. The SOA system is similar to that intended for deployment on the space station. The advanced system uses an ultralightweight photovoltaic array and a regenerative H-O fuel cell for storage. The figures of merit for both systems are listed in table II. 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 table provides compelling evidence that there is substantial payoff to be had in developing the advanced PV/RFC (regenerative fuel cell) technology, particularly when placed in the "operational" context of the weight saved at LEO. A third case also exists in which the astronauts' stay would be limited to the 336 hr lunar day, with a night duty cycle of zero. Whatever storage would be required would be supplied by the lander's energy storage system. In this case, only a solar array would have to be delivered to the lunar surface. The potential five fold mass reduction between the SOA array and an advanced array offers a very significant advantage under such a restricted mass budget.

SOLAR CELL AND ARRAY TECHNOLOGY

Improvement in the specific power of a solar array can be achieved through two different, although often coupled, approaches; increasing the conversion efficiency of the solar cell, and reducing the cell/blanket mass and/or array structure mass. The program objective in the Surface Power Program of NASA's Project Pathfinder is an array specific power of 300 W/kg at air mass zero (AMO) insolation. At present, lightweight photovoltaic array technology has been demonstrated on a space shuttle experiment at 66 W/kg. A recent design, under development at the Jet Propulsion Laboratory for NASA, was established at 130 W/kg (ref. 1). This design, the advanced photovoltaic solar array

(APSA), is based on 2 mil thick silicon cells. However, both of the above array designs are intended for the zero gravity conditions of LEO and GEO (geosynchronous Earth orbit). For lunar base applications, a new or modified array structure must be developed that will withstand the 1/6 g of the lunar surface and still meet the 300 W/kg goal.

Two solar cell technologies have been identified for further development to achieve the 300 W/kg specific power goal. These candidate cell types are ultrathin gallium arsenide (GaAs) and amorphous silicon (α-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 350 μm to meet the mass requirements 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 light irradiated 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, a technique in which a single crystal thin GaAs layer is grown on a masked GaAs substrate and mechanically removed (ref. 2). Other processes, such as chemical thinning of the substrate, have also been successfully demonstrated to be capable of producing high quality, ultrathin layers and cells (ref. 3). 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 (ref. 4). The electronic structure of the disordered, amorphous material allows for a total cell thickness of less than 1 μm and the use of flexible substrates. This is compatible with very high blanket specific power and low volume storage requirements. Although an extensive manufacturing base already exists for α-Si terrestrial solar cells, several major hurdles must be overcome before it can be considered to be 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. 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. For the advanced photovoltaic solar array (APSA) design, the structure, blanket box, and deployment mechanism constitute more than 50 percent of the mass of the entire array. The 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 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 a 0-g APSA structure. The latter might be possible since manual deployment is an option for a manned lunar base and could eliminate the deployment motor and mast.

ENERGY MANAGEMENT CONSIDERATIONS

The lunar base scenario, with its evolution from a temporary outpost that will be revisited and expanded over time into a full lunar base, requires that a reevaluation of space power system design philosophy be made. Space power systems have thus far been designed to accommodate a known set of loads, with no changes (and certainly no growth) in energy requirements expected throughout the life of the mission. As a result, it is common to operate the array as a constant current source, often with very large margins on voltage regulation. Accommodating growth in output power, which would be required by virtue of an increase in the number of loads, means the system should function as a utility rather than as a dedicated power supply. The latter implies that operation more nearly like a constant voltage power source may be required.

The choice between solar array operation as a constant current power source or as a constant voltage power source can have an effect on the mass of the array. As shown in the analysis by Appelbaum presented in this volume (ref. 5), the "energy utilization," defined as the ratio of the energy actually supplied to the loads to the total energy that could be produced by the array, can be different for various configurations of loads and power sources. The key feature is whether or not the loads have a common power source, or are connected to separate power sources. Any one configuration which results in a lower energy utilization than another will increase the mass of the system by comparison, since more array area will be needed to properly supply all the loads with their rated power. Figure 1 (ibid.) illustrates the situation for the simple case of resistive loads only. The region in the figure on the left side of the maximum power point corresponds to use of an array as a constant current source. The region on the right of the maximum power point corresponds to operation as a constant voltage source. The figure shows (for the simple cases discussed in ref. 5), that if the array is used in the constant voltage mode (i.e., to the right of the maximum power point), the energy utilization will be higher if the array is used as a common source for the loads. Separating some of the loads from the rest and providing them with a dedicated power source will result in a lower energy utilization, and subsequently in an increase in the mass of the system.

The figure also illustrates the point that it may be necessary to examine the issue of common versus separate sources even when the array is used as a constant current source. Mass optimization will depend on a detailed analysis of all of the load characteristics. Other mission requirements, such as redundancy and safety, may overrule the outcome, but the mass penalties for doing so can now be understood. Detailed numerical calculations of the energy utilization associated with a given configuration would be required to predict the actual mass impact on the system design.

CONCLUSION

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 array blanket, using either ultrathin GaAs or amorphous silicon solar cells, would be integrated with a structure designed for the 1/6 g of the moon. The extreme need for minimum mass will require careful attention to proper energy management for a lunar power system to assure that the highest possible array energy utilization factor can be achieved.

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

Power level, kWe	Night duty cycle, percent	SOA PV/BATT, mass, kg	Advanced PV/RFC mass, kg	Weight saved at LEO, kg	HLV launches saved
100	100	1 680 000	34 500	7 910 000	87
100	20	336 420	7 133	1 580 000	17

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

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

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 Wh/kg	300 Wh/kg (primary fuel cell)
Regenerative fuel cell	60 percent efficiency	60 percent efficiency

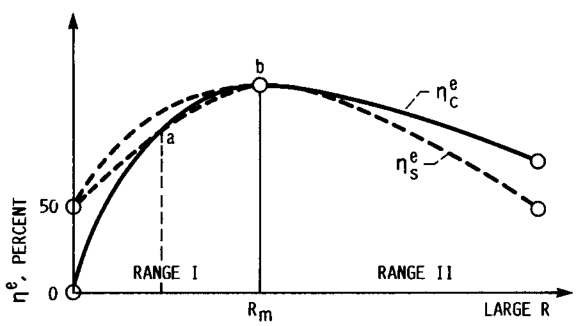

FIGURE 1. - ENERGY UTILIZATION OF SEPARATE AND COMMON SOURCE SYSTEM IN THREE EXTREME CASES $R_1 = R_2 = R_m$; $R_1 = 0$ AND R_m; R_m AND LARGE R_2.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102019		

4. Title and Subtitle	5. Report Date
Photovoltaic Power System Considerations for Future Lunar Bases	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Dennis J. Flood and Joseph Appelbaum	E-4744
	10. Work Unit No.
	506-41-11
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the International PVSEC-4 cosponsored by The Institution of Radio and Electronics Engineers of Australia and The University of New South Wales, Sydney, Australia, February 14-17, 1989. Joseph Appelbaum, National Research Council–NASA Research Associate.

16. Abstract

The cost of transportation to the lunar surface places a premium on developing ultralightweight power system technology to support the eventual establishment of a lunar base. This paper will describe the photovoltaic technology issues to be addressed by the Surface Power program element of NASA's Project Pathfinder.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Photovoltaics Space power Solar arrays Thin film solar cells	Unclassified – Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

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