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VOLUME 1 Missions and Systems
Integration and Requirements
Space Thermal Management
Computer Simulation for Aerospace Power Systems
Space Power Autonomy
Space Station Freedom
Space Environmental Effects
Superconductivity
Advanced Space Power Concepts
Power Conditioning

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PREFACE

The scope of the Intersociety Energy Conversion Engineering Conference (IECEC) series has grown from a straightforward treatment of energy conversion engineering to a broad involvement in all aspects of energy systems, including primary resource processing, utilization and environmental issues in addition to conversion and storage. The other notable trend has been toward increased international participation and, as the papers in this volume attest, IECEC-89 can truly claim to be an international forum on energy engineering with a significant proportion of the papers being presented being from beyond the confines of the United States. It is a particular pleasure to include, for the first time, a sizeable contribution from the USSR.

These developments are indeed appropriate for energy conversion engineering has to be undertaken within the broader context of energy systems and energy issues which are not constrained by national boundaries. The increasing and proper concern for the impact of energy systems not only locally but also globally is particularly reflected in the nearly 500 papers appearing in a Proceedings which has now grown to six volumes. In these, the reader will find a comprehensive coverage of recent work on energy systems and technologies relevant to the expected conditions of the 1990's and beyond. The international character of IECEC-89 shows not just through participation from many countries but the large measure of common ground evident in the contributions made by the many national and international organizations involved in the energy engineering field.

The organization of this large amount of interrelated material poses considerable challenges which have been met in the first instance by dividing the Conference and, by extension, the Proceedings, into a number of major topical areas. From a narrow applications viewpoint, it is tempting to view aerospace and terrestrial energy system issues separately since they generally involve meeting different criteria. This has not been done in the present Conference in large measure because an IECEC objective is to find and emphasize points of commonality. Accordingly, a blend of interests will be found throughout, as for example, in Volume 2 devoted to energy conversion technologies where space and terrestrial photovoltaics are grouped together.

To facilitate use of the volumes, the Table of Contents is repeated in each Volume and an author Index appears in Volume 6. In addition, the now well-established feature of IECEC, the SAE cumulative index for the past four years is also included in Volume 6. This may be used to locate recent related work reported at the IECEC and, in due course, it will be updated to include the current Conference.

The task of preparing these Proceedings has only been possible through the unstinting efforts of the Program Committee, Session Organizers and the IECEC-89 staff whose many contributions are gratefully acknowledged by the Editors. In fairness to other technologies in which the Institute of Electrical and Electronics Engineers is prominently involved, the critical role of computers, FAX machines and other aspects of modern communications technology in permitting the assembly of this body of material also deserves recognition.

William D. Jackson, *Editor*
Dorothy A. Hull, *Associate Editor*

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COMPARISON OF SOLAR PHOTOVOLTAIC AND NUCLEAR REACTOR POWER SYSTEMS FOR A HUMAN-TENDED LUNAR OBSERVATORY

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ABSTRACT

In a study for the NASA Office of Exploration, photovoltaic and nuclear surface power systems were examined at the 20 to 100 kW_e power level range for use at a human-tended lunar astronomical observatory, and estimates of the power system masses were made. One system, consisting of an SP-100 thermoelectric nuclear power supply integrated with a lunar lander, is recommended for further study due to its low system mass, potential for modular growth, and applicability to other surface power missions, particularly in the Martian system.

INTRODUCTION

The emplacement of a human-tended astronomical observatory on the far side of the Moon is a viable, low-risk NASA mission option. Such a mission would require far fewer resources than a mission to Mars or a permanently manned lunar base, yet it would provide valuable scientific information while continuing to establish and promote an increased manned presence beyond Earth orbit.[1]

NASA is currently defining power requirements and configurations for missions such as the lunar observatory. An important figure of merit useful in selecting appropriate power system options is the system mass, although the least massive power system may not necessarily be appropriate for a particular application. Not only is it more expensive to launch more massive systems, they may not be feasible with near-term or projected transportation capability.

This study, originally performed for NASA's Office of Exploration (OEXP), compares the mass estimates of photovoltaic (PV) power systems with those of nuclear power systems for the establishment and operation of a far-side lunar observatory. The power required to operate the lunar observatory was not precisely defined by OEXP but was baselined in the many tens of kilowatts range. For that reason mass estimates were calculated for various power systems for the operation of the observatory in the 20- to 100-kW_e power level range. Power for the construction of the observatory was assumed to be 20 kW_e, the minimum power value of the operational observatory. Incorporation of the construction power system into the observatory power system was considered for each case.

Three PV systems employing gaseous reactant (hydrogen/oxygen (H_2/O_2)), regenerative fuel cell (RFC) energy storage were examined. Also studied was an advanced, low mass PV concept using cryogenic H_2/O_2 RFC storage. Two nuclear reactor power system concepts based on SP-100 reactor technology were considered: one with free-piston Stirling cycle dynamic energy conversion and the other using SP-100 technology thermoelectric static energy conversion.

BACKGROUND

The NASA Office of Exploration is responsible for providing "recommendations and viable alternatives for an early 1990's national decision on a focused program of human exploration of the solar system" [2]. The OEXP is also responsible for making recommendations to the agency regarding exploration policy and technical development that will affect the options available in the early 1990's. To develop these alternatives and options, cycles of case studies are being performed to distill the most logical and representative set of exploration scenarios. In the 1988 cycle of case studies, a scenario was studied wherein a moderately sophisticated complement of scientific observational instrumentation would be emplaced and operated on the far side of the Moon. The ground rules for this case study were that the setup of the observatory be accomplished over a 2-year period beginning in the year 2000 and that one cargo and crew mission per year be sent [3]. Crew stay times for construction and maintenance were base lined at 14 days per trip or less. Since the lunar observatory would be operating unattended for long periods, the power system selected must show high reliability and autonomy.

It was determined that two 14-day stays may not be sufficient to construct both the power system and the observatory. Therefore, it was decided that all power systems considered in this study would be capable of providing continuous construction power through the lunar night. This is beneficial in several ways. First, the lunar observatory requires continuous day/night operational power. By integrating the construction power system into the operational power system when the construction phase is complete and upgrading if necessary, this requirement for the operational power system is satisfied. Second, additional, albeit reduced, construction activity would be possible during the lunar night, bringing the number of useful construction days through the lunar day/night/day cycle (i.e., one and one-half lunar synodic periods) to just over 43 days. Finally, by allowing a single crew to stay through this period, at least one launch would be saved. The benefits of extending the crew stay-time through the lunar night would seem to outweigh the penalties of increased mass and other mission requirements [4].

CANDIDATE SYSTEMS

PV Systems with Gaseous Reactant RFC Storage

In this study, three PV solar cell array technologies with gaseous reactant RFC energy storage systems were considered for the operational observatory power system: amorphous silicon (a-Si), gallium arsenide (GaAs), and a hybrid a-Si/GaAs PV system.

The a-Si PV system consists of a-Si solar cells on a flexible array. These arrays are rolled flat onto the lunar surface and connected to a power management and distribution bus to provide either AC or DC power, as required (Fig. 1). These planar arrays would require no additional structure and could be deployed in a relatively short time. Additional time would be required to set up the RFC's that will supply power to the observatory through the 354-hr lunar night. Because these arrays lie flat on the surface and do not have a mechanism to follow the Sun, incident insolation will fall obliquely on the cells except at lunar noon. This will reduce the power density of the incoming sunlight, requiring the arrays to be oversized (60 percent additional array area) to supply the required energy for both the daytime power needs and night time energy storage. It is assumed that the observatory will be located on the lunar equator. Other latitudes would require even greater array area because of the increased incident solar insolation angles.

The second type of array considered uses gallium arsenide (GaAs) solar cells on a rigid array structure (Fig. 2). This array would track the Sun as it traverses the lunar sky. The GaAs PV Sun-tracking arrays were considered because the efficiency of the GaAs solar cells is more than double that of the a-Si cells (22.5 percent efficiency for GaAs versus 9.2 percent efficiency for a-Si cells) and because Sun-tracking arrays do not have the inefficiencies of flat arrays caused by the decreased energy density of oblique insolation. However, the GaAs arrays, which require a Sun-tracking support frame, pivots, and tracking mount, have a higher specific mass and would probably require a longer construction time than for the a-Si system.

While assembling the power system that will supply the observatory, it may be necessary to generate power for the construction vehicles and equipment. For PV systems this is not a problem because PV array panels are modular. As soon as one panel is installed it could generate power to support the erection of subsequent panels. Because the a-Si PV arrays studied here are more easily deployed than the GaAs PV arrays requiring the Sun-tracking structure, the construction crew could roll out an area of a-Si PV blanket sufficient to supply the construction power requirements, whereas the GaAs PV power system may require some initial auxiliary power such as primary fuel cells to power the construction equipment necessary for erecting the first GaAs PV array panels.

To avoid the use of relatively heavy primary fuel cells for the initial construction power for the GaAs PV power system, a hybrid a-Si/GaAs PV system consisting of the two types of arrays working simultaneously and independently (Fig. 3) was considered. An a-Si planar array is initially rolled out with sufficient area to provide 20 kW_e for both the lunar day and night (via a gaseous reactant RFC energy storage system). The a-Si arrays could be rapidly assembled such that the GaAs arrays and fuel cells may be setup before lunar nightfall, as well as a portion of the observatory. Once the GaAs arrays have been assembled, the a-Si arrays will be dedicated to recharging the RFC's. The rigid Sun-tracking GaAs arrays will provide the daytime power requirement for the observatory. A disadvantage of this strategy is that two different cell technologies would have to be developed simultaneously.

It is possible to reduce the total power system mass (including the array and RFC masses) by using a-Si arrays to supplement the GaAs arrays for daytime power requirements. However, optimizing the ratio of a-Si cells to GaAs cells to minimize the hybrid system mass makes little difference in the overall system mass, especially when compared with the systems considered below. The value of 20 kW_e day/night continuous power from the a-Si arrays was selected based on the assumption that 20 kW_e would be sufficient for construction power.

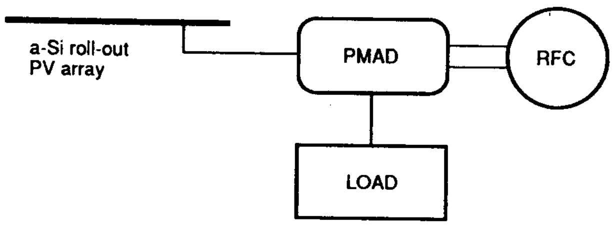

Fig. 1. a-Si PV power system schematic.

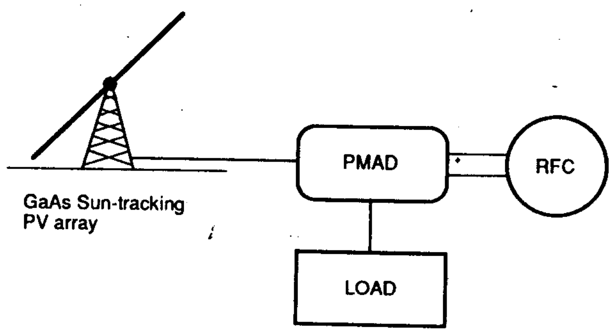

Fig. 2. GaAs PV power system schematic.

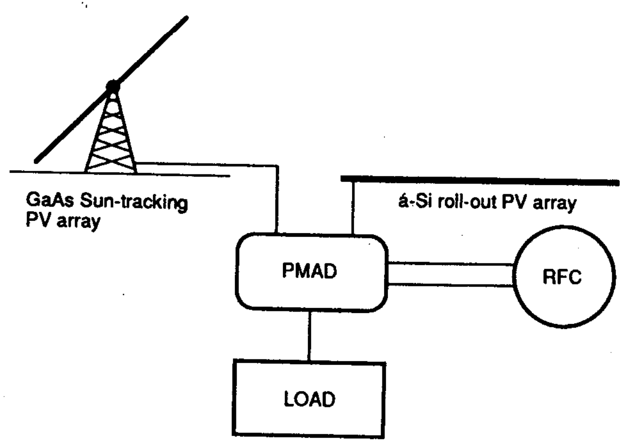

Fig. 3. Hybrid a-Si/GaAs PV power system schematic.

Gallium Arsenide PV Power System with Cryogenic Reactant RFC Energy Storage

A major disadvantage of the three solar power systems described above is the mass of the storage system required to supply power through the 354-hr lunar night. The RFC energy storage for these systems accounted for 92 to 95 percent of the total system mass. Cryogenic reactant storage, however, should result in much lower tank weights compared with gaseous reactant storage. A study was performed at NASA Lewis to determine the effect of cryogenic reactant storage on the mass of an alkaline RFC power system for a lunar application [5]. The study showed that storing cryogenic reactants results in a significantly lower overall system mass than conventional pressurized gas storage, despite the additional mass of a required refrigeration plant and the associated solar array area necessary to provide power for cryogenic reactant refrigeration and storage.

A GaAs Sun-tracking PV system was selected for this study because of its high efficiency and Sun-tracking capabilities. The masses of the array, GaAs support frame, pivots, tracking mount, wiring harness, power management and distribution, and RFC's were included in the system mass. The mass of the refrigeration plant is also included. Figure 4 depicts a conceptual layout of a lunar observatory powered by a GaAs PV/cryogenic storage RFC energy system.

Nuclear Power System with Stirling Cycle Energy Conversion

The dynamic conversion nuclear reactor power system considered was derived from a NASA Lewis study entitled, "SP-100 Power System Conceptual Design for Lunar Base Applications" [6]. This design uses the SP-100 reactor thermal power source, located in a surface excavation, thereby employing lunar soil for radiation shielding (Fig. 5). Thermal energy is converted to electricity via Stirling cycle energy conversion. In the original study eight Stirling engines, each with a dedicated heat pipe radiator assembly, are arranged radially outward from the reactor to produce 825 kW_e. In this study the power system was scaled to the assumed 20 to 100 kW_e operational power range. The power level can be varied up or down by varying the engine size and/or the number of operating engines and spares. System reliability is optimized by providing at least two spare Stirling power conversion subsystems. In addition, the design provides the capability to maintain the nonnuclear components, including the Stirling engines and radiator panels. A disadvantage of this system option is that the construction of the power system and the observatory would probably take more than the baselined 14-day stay time unless sufficient workers and construction vehicles are provided.

Unlike the PV power systems, which can supply both initial construction and operational power by erecting additional modules, the nuclear power system cannot provide any power toward its construction. A separate power system must be assembled to provide the necessary power to construct the nuclear power system, which will eventually supply the observatory power requirements. Because of the ease of deployment, an a-Si PV roll-out array power system was assumed as the construction power system, providing 20 kW_e continuous day and night power. Both gaseous RFC storage and primary fuel cell (PFC) energy storage were considered. Although the a-Si PV power system with PFC energy storage is about 30 percent lighter, it can only provide power for one lunar night, and the mass advantage was not deemed sufficient to justify its selection. The a-Si PV power system with RFC energy storage can provide multiple night power should construction problems arise, and it can serve as a backup power system for future activities.

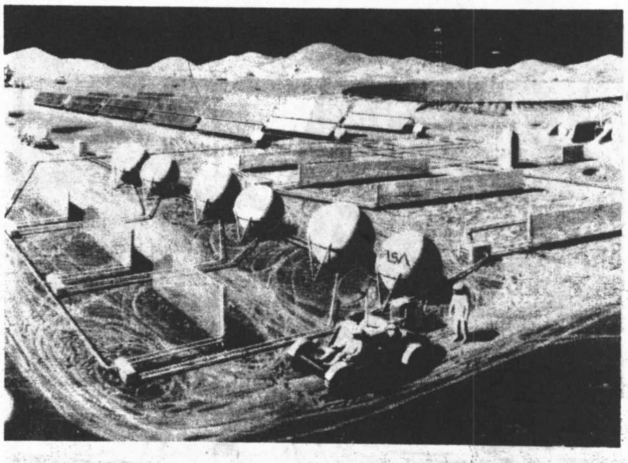

Fig. 4. Lunar observatory with GaAs solar PV tracking arrays and cryogenic regenerative fuel cell storage system.

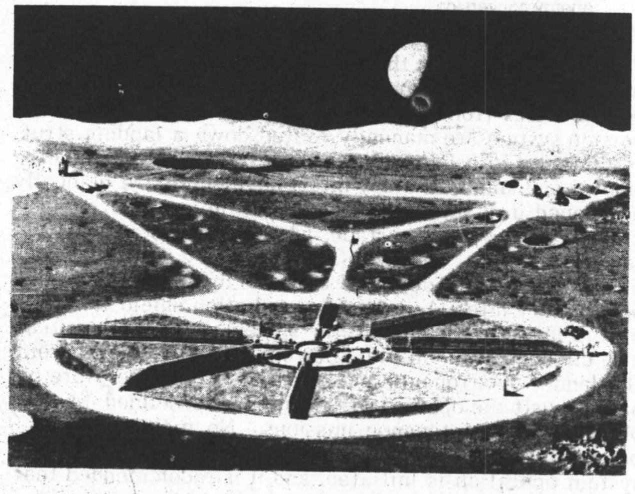

Fig. 5. Lunar base power system with SP-100 reactor and stirling cycle dynamic energy conversion.

Nuclear Power System with Thermoelectric Energy Conversion

To ameliorate the possible problem of long construction times for the nuclear Stirling power system, an alternative nuclear power system was considered (Fig. 6). In this concept a completely assembled SP-100 nuclear reactor power system using thermoelectric energy conversion is integrated with a dedicated lunar lander (i.e., descent capability only). Only a few hours are required to connect power busses to the lander. An additional 24-hr startup period would be needed to thaw out frozen coolant lines before power would become available. A small part of the construction time would be required for the setup of the power system, enabling the crew to spend most of its surface stay constructing the observatory.