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Comparison of Solar Photovoltaic and Nuclear Reactor Power Systems for a Human-Tended Lunar Observatory

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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.

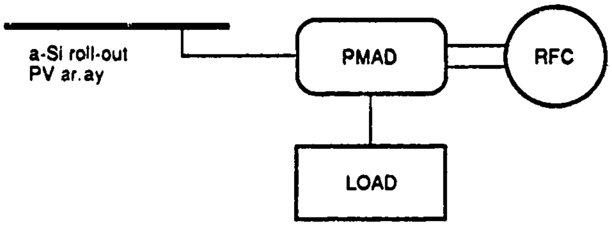

Fig. 1. a-Si PV power system schematic.

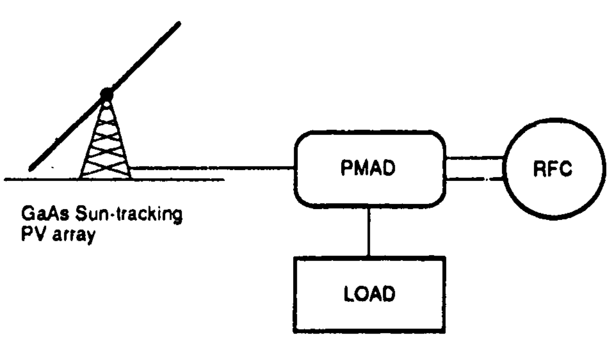

Fig. 2. GaAs PV power system schematic.

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.

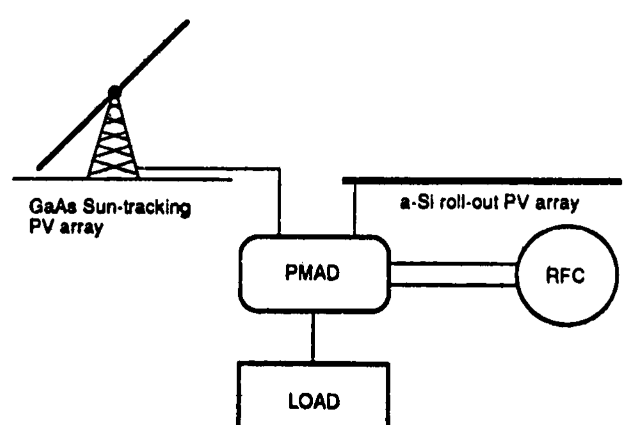

Fig. 3. Hybrid a-Si/GaAs PV power system schematic.

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.

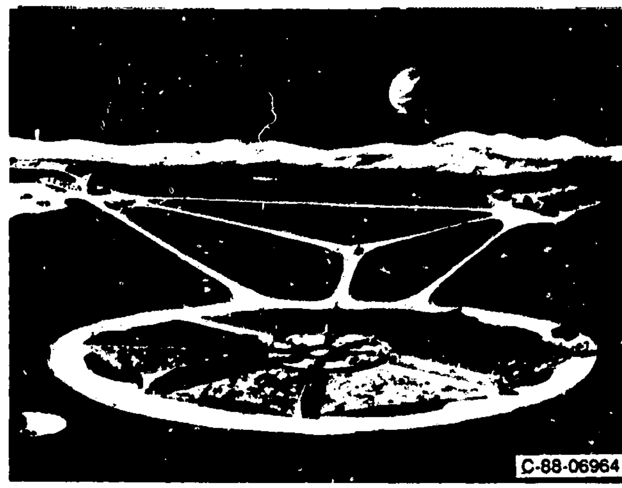

Fig. 5. Lunar base power system with SP-100 reactor and stirling cycle dynamic energy conversion.

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.

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Fig. 6. Lunar observatory power system with SP-100 thermoelectric energy conversion.

Fig. 7 System masses for PV arrays with gaseous reactant RFC storage.

After landing at the surface site, radiators are automatically deployed from their stowed configuration, and power cables from the SP-100 thermoelectric power conversion system are manually routed down a landing strut terminating in a DC bus. A power system shunt load dissipator and an observatory interface module are manually positioned in a small excavation (on the order of 1 ft^3) created in the lunar surface, which provides an in-situ radiation shield. The main and secondary power busses are then manually deployed onto the lunar surface to the observatory site. A shaped 4π radiation shield is integrated into the lander/reactor system and is man-rated at a distance of 1-km (i.e., 2.5 rem dose in 14 days) from the lander. Astronauts and scientists would therefore be able to visit the observatory during the baselined 14-day observatory maintenance missions. No maintenance is possible or required on the nuclear power system after system operation is initiated, and it is recommended that the reactor power system and lander remain at its original site at the end of its life of 7 years.

RESULTS

Figure 7 compares power system mass for the three PV systems employing gaseous reactant RFC energy storage as a function of power level. The power system masses consist of the PV array mass and the mass of the RFC storage stacks, gaseous reactant tanks, radiators, and power management and distribution equipment. Although the three systems have similar mass estimates, there may be slight gains to be made by selecting the hybrid a-Si/GaAs PV system.

Since the hybrid PV system is composed of both the GaAs and the a-Si PV systems, it would seem reasonable that the value of its mass would lay between those for the other two systems. This would be true if it were not for the roll-out a-Si arrays' inability to track the Sun. As previously mentioned, a-Si arrays at an equatorial latitude have to be oversized by 60 percent to compensate for the obliquity of the solar insolation for daylight times other than lunar noon. There is also a period of time in the lunar morning and evening when the angle of insolation is so great (as measured from the normal to the surface) that the power generated is less than that required by the observatory load.

For 26 hr and 41 min from lunar dawn and for an equal amount of time before lunar sunset, an a-Si array sized to supply 30 kW_e continuously (day and night), would be unable to provide power at that 30-kW_e level. (At lunar noon, the array would provide 128 kW_e, with 98 kW_e distributed to the RFC's.) Thus, for 15 percent of the lunar daylight, the arrays cannot supply rated power. During these lunar morning and evening periods, RFC's would be required to provide additional power. The a-Si array area would be scaled to supply this additional energy for storage. The RFC radiator and tankage mass would each increase by 7.5 percent for this case. Since most of the mass of a PV power system is attributable to the energy storage, an increase of 7.5 percent in the RFC mass for the 30 kW_e case amounts to an increase of 1.3 metric tons, enough to cause the total a-Si system mass to be greater than both the GaAs PV system and the hybrid PV system masses.

The GaAs PV system and the hybrid PV system are both Sun-tracking, and, therefore, do not have the problem of having auxiliary power supplied from RFC energy storage during daylight hours. The hybrid PV system is less massive than the pure GaAs PV system through its use of the very lightweight a-Si arrays to recharge the RFC's. This results in a mass savings of 2.6 to 5.9 percent, compared with the GaAs PV system over the 30- to 100-kW_e range.

The hybrid PV system shows advantage over the GaAs system in relation to providing early construction power, and it has a clear mass advantage over a-Si at every power level above 30 kW_e for observatory operational power. This system was therefore selected as the regenerative PV power system to compare with the nuclear systems and the cryogenic reactant PV power system.

Figure 8 compares system mass against power level for the two nuclear systems, the hybrid PV system, and the cryogenic reactant RFC energy storage PV system. Clearly, the hybrid PV system does not compete with the other systems because of the massive RFC system necessary to power the observatory at night. The cryogenic storage GaAs PV power system shows the lowest mass at the 20- to 40-kW$_e$ range, a reasonable span of power levels for the observatory. There would, however, need to be a moderate-to-large infrastructure present to assemble and emplace the cryogenic reactant tanks and refrigeration plant. No prior infrastructure would be necessary for the nuclear lander.

Because of the major active development activities currently in progress, the nuclear power system options discussed here are at a greater level of technology readiness than the gaseous reactant RFC energy storage and the cryogenic RFC energy storage subsystems. Although the technology readiness levels of the two nuclear power systems examined are comparable, the dynamic conversion option will require a solar PV/energy storage power system for construction. However, the SP-100 lander concept, with only a few minor variations, is similar to the current SP-100 design for space applications. Also, it requires negligible construction power, has a very low mass, and should exhibit the fastest and least labor intensive setup and construction of all the concepts examined.

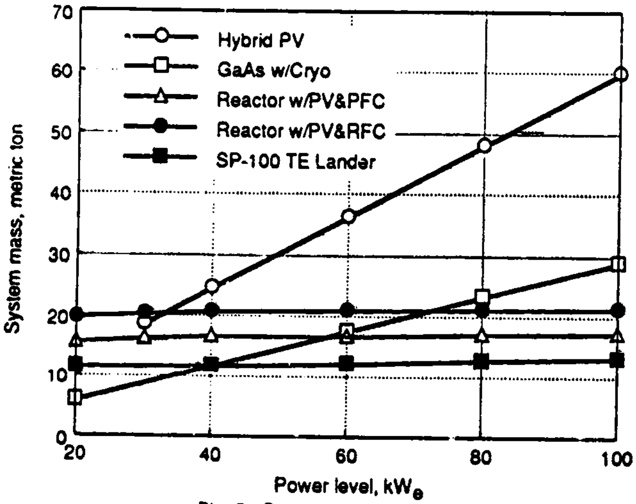

Fig. 8. System mass comparison.

CONCLUSION

A variety of solar and nuclear power system options were investigated for a lunar observatory application across a 20- to 100-kW$_e$ power level range. The photovoltaic power system options using gaseous regenerative fuel cell energy storage were shown to be noncompetitive due to their storage component masses. The gallium arsenide photovoltaic power system using cryogenic RFC storage weighed much less than the other PV systems, and at low power was competitive with the nuclear systems. The SP-100 thermoelectric lander had the lower mass of the two nuclear system options and was the least massive of all the systems considered at medium to high power levels.

Final selection of a lunar observatory power system is beyond the scope of this study. This comparison has shown (1) that the initial rapid deployment of low-mass a-Si PV blankets is highly desirable and that this technology should be developed for all lunar surface missions; (2) that cryogenic RFC energy storage technology has significant mass benefits for low-power lunar applications and that increased development efforts are justified; and (3) that consideration of the evolution and growth to higher power levels leads to the need for nuclear power systems for lunar surface missions.

Multiple SP-100 landers could be used in a modular fashion. If more power is required, another lander could be emplaced and connected to the power grid. The nuclear lander system could also serve as a precursor to a much larger installed, dynamic conversion reactor power system [4]. An SP-100 TE lander system could provide sufficient power for construction and would act as an auxiliary and backup power supply to the larger system. A single nuclear lander and one large nuclear dynamic conversion system could provide power in the 1-MW range considered necessary for lunar materials processing.

The SP-100 thermoelectric lander may also, with modification, be applicable to Mars and/or Phobos missions. A generic, multipurpose space power system will be required as manned exploration advances; the SP-100 system will likely be the workhorse of those future power systems. The nuclear lander appears to be well suited to become the standard power system for surface applications. Studies of SP-100 lander suitability for the Martian system will be performed for the NASA Office of Exploration in 1989 as part of a broad power systems study for Mars and Phobos.

REFERENCES

[1] The Presidential Directive on National Space Policy, January 5, 1988.

[2] Exploration Studies Technical Report, Vol. I: Technical Summary, FY 1988 Status, NASA TM-4075, Dec. 1988, p. 1.

[3] Scenario Requirements Document, ver. 1.0, Doc. No. Z-MAS-SRD-001, June 2, 1988.

[4] "Lunar Observatory Staytime Extension Study," Exploration Studies Technical Report, Vol. II: Study Approach and Results, FY 1988 Status, NASA TM-4075, Dec. 1988, p. 4-50.

[5] Kohout, L.L., Cryogenic Reactant Storage for Lunar Base Regenerative Fuel Cells, NASA Lewis Research Center, Proc. IAF Intern. Conf. Space Power, June 5-7, 1989, Cleveland, Ohio.

[6] Mason, L.S., Bloomfield, H.S., and Hainley, D.C., SP-100 Power System Conceptual Design for Lunar Base Applications, Proc. 6th Symposium on Space Nuclear Power Systems, Jan. 9-12, 1989, Albuquerque, New Mexico.

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