1990 25TH Intersociety Energy Conversion Engineering Conference

Vol. 6

IECEC-90
August 12-17, 1990
Reno, Nevada

PROCEEDINGS OF THE 25th INTERSOCIETY ENERGY CONVERSION ENGINEERING CONFERENCE

VOLUME 6

Post-deadline Papers
Unpublished Papers from IECEC-89
Subject Index for 1989 and 1990
Author Index for 1989 and 1990

Participating Societies

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American Institute of Chemical Engineers
345 East 47th Street, New York, NY 10017

ISBN 0-8169-0490-1

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USAF SPACE POWER REQUIREMENTS

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ABSTRACT

This paper discusses recent studies conducted by the Space Nuclear Power Systems branch of the Weapons Laboratory. These studies addressed the issues of qualification testing and integration of a reactor power system for Air Force missions. These studies generated a number of technical and programmatic requirements for reactor development programs. Chief among these requirements are specific power of 7 to 12 w/kg, on-orbit restart capability, no credible mission-ending single point failures, and demonstrable life cycle costs at least equal to those of a comparable solar power system.

INTRODUCTION

The Weapons Laboratory (WL) of the Air Force Space Technology Center has performed a number of studies aimed at defining the Air Force's requirements for space nuclear power. The most important of these studies were those defining qualification and acceptance testing procedures and those investigating the integration of space nuclear power systems with planned Air Force satellites. From these studies, WL derived preliminary performance, survivability, testing, reliability, and cost requirements. This paper will not discuss survivability because of classification issues.

QUALIFICATION STUDIES

Several qualification studies have been performed by the Energy Technology Engineering Center (ETEC) for WL [1, 2]. In these studies, ETEC defined a test regimen to meet most of the requirements of Mil-Std-1540B.

The purpose of ground testing space vehicles is to ensure successful operation in space. Various studies [3] have shown the degree of test thoroughness and the number of on-orbit failures are related. The tests specified in Mil-Std-1540B are labelled development, qualification, acceptance, pre-launch validation, or other tests.

Qualification tests are formal demonstrations that the design, manufacture, and assembly of hardware meets the specification requirements and that adequate operating margins exist in the design. To accomplish these goals, the qualification test environments exceed the range of predicted environments expected from manufacture through mission completion. The qualification testing process also serves to validate the planned acceptance test procedures.

Acceptance tests demonstrate the flight readiness of each deliverable item. They are the required formal tests conducted to demonstrate performance to specification requirements and to act as quality control screens to detect deficiencies of materials or workmanship. Acceptance tests are performed to the predicted flight environments.

Tests in Mil-Std-1540B are categorized as functional or environmental and verify the operational capability of the space system in the space environment. Functional tests verify the mechanical and electrical performance of the space vehicle. Environmental tests verify the flight system's ability to withstand and function in the worst case environments it will be exposed to during operation. Environmental tests include electromagnetic compatibility, acoustic, vibration, shock, pressure, thermal vacuum, thermal balance, thermal cycling, and possibly some form of weather testing.

Due to variations in satellite design and operation, the user tailors Mil-Std-1540B to optimize his test program. Tailoring the standard for testing a nuclear reactor power system poses several difficulties. First, proper simulation of the combined vacuum, thermal, and radiation environment is difficult, even at the component level. Second, environmental testing of the reactor core is potentially hazardous. Third, most designs use liquid metal coolants, which presents problems from a freeze/thaw standpoint, particularly for acceptance testing. Fourth, checking temperature coefficients (i. e. operating at higher than zero power) may be difficult (launching a reactor with fission products in the core is not current US policy and a discussion of the merits of doing so is beyond the scope of this paper).

The ETEC work focused on qualification and acceptance testing problems for a space nuclear power system. ETEC defined three options for testing a reactor power system. The options covered the range of cost and risk of failure, with failure defined as not finding a critical (life, reliability, or performance limiting) problem during qualification or acceptance testing. The options defined were: 1) a full system nuclear test unit, 2) a full system non-nuclear test unit with a separate nuclear subsystem test, and 3) subsystem level test units, including a nuclear subsystem test unit.

The study determined that the cost and risk of failure for options 1 and 2 were nearly identical. The main difference between the two options was the increased schedule risk of option 1; a major failure requiring repairs would take more time to correct for option 1, due to the need to let the unit cool down enough for repair work to begin. Option 3 was lower cost, but the risk of failure was too high, due to the lack of a full system test. Since the qualification test program incorporates the acceptance test program, the lack of a full system test means that many welds would not contact hot liquid metal until the system operated on orbit, a situation which is currently unacceptable to the Air Force. Based on this work, WL concluded that testing the reactor core separate from the rest of the power system does not appreciably increase the risk of failure and is more economical than full nuclear system testing. In addition, a full system test at temperature is necessary to verify weld integrity.

Each of the three options includes substantial component testing prior to any subsystem or system testing. Since failure recovery is cheaper at the component level, the most stressing environments should be applied at that level. This approach reduces schedule risk and failure risk.

INTEGRATION STUDIES

Two integration studies were performed by WL. These studies sought to identify mission enhancements provided by a nuclear power system, understand the satellite designers' decision process and its impact on space nuclear power development, and determine the performance goals that should be established for space reactor technology.

Both studies identified potential mission enhancements provided by space nuclear power. The first study was performed with an Electro-Optical Surveillance (EOS) satellite. The enhancements identified in this study all resulted from more power for the main sensor. The second study was performed on a Spaced Based Radar (SBR) satellite. In this study, the enhancements all resulted from increases in orbital duty factor and in available base power.

Both studies provided a better understanding of the designers' thought process. A major finding of the studies was that cost, not performance, is more important to the satellite developers. The mission enhancements discussed above were mostly of interest only when they reduced the life cycle cost of the constellation.

Several major design issues were identified by the satellite designers. First, the reactor's specific power (mass) must at least equal a comparable solar array/battery system, with targets of 7 w/kg at 10 kWe and 15 w/kg at 30 kWe. Second, the heat rejection subsystem must not produce a thermal loading greater than one sun (1.4 kW/m^2) on the payload. Third, the reactor/boom combination must pose less of a problem to the spacecraft's attitude control system than a comparable solar array/battery system. Fourth, the reactor system must be able to demonstrate reliability by design, analysis, and testing of greater than 0.95 for 10 years of full power operation. This design issue includes a requirement for no credible, mission-ending, single point failures. The best definition of credible at this time is less than 0.01 percent chance of occurrence per year. Fifth, the power system must be capable of multiple restarts on orbit. These restarts could be planned (periodic testing) or unplanned (inadvertent scram).

Some secondary design issues were identified by the satellite designers. First, the power system must minimize the jitter it causes to the payload. Second, the deployed power system must not limit spacecraft acceleration. Third, the radiation from the reactor must not reduce the lifetime of the spacecraft electronics. Fourth, the power system/spacecraft must fit into the launch vehicle without employing mechanisms that reduce reliability below .95 for 10 years.

PROGRAMMATIC ISSUES

The Weapons Lab has identified or inferred a number of programmatic issues from these studies. These issues can be summarized by three questions:

1) Can you build it?
2) Can you fly it?
3) Can you afford it?

The first question, "Can you build it?", covers all of the technical feasibility issues associated with a given concept. It also addresses the issues of fabricability, including factory requirements, strategic materials, and Nth of a kind lead time. A reactor development program must answer these questions before a user will appear.

The second question, "Can you fly it?", addresses issues of testability and safety. A reactor development program must establish the qualification and acceptance testability of the system. Further, the program must ensure that the system is demonstrably safe, in all mission phases, for all credible accidents.

The third question, "Can you afford it?", addresses the issues associated with the life cycle cost of a particular reactor concept mated to a particular satellite. The answer to this question is perhaps the most important one of all, since it usually determines which technology gets used for an application. Particular aspects of this question that a reactor development program must identify include development costs, qualification and acceptance testing costs, safety testing costs, time or schedule cost (if the reactor takes longer to build and test than the satellite), operating costs, and disposal costs. The goal of a reactor development program must be to make the life cycle cost for a reactor powered constellation of satellites at least competitive with a comparable solar powered constellation.

SUMMARY

A number of studies executed by and for the Weapons Lab have identified an initial set of technical and programmatic reactor power system requirements. These requirements may be used to guide a development program, but final design requirements will be specific to the satellite and mission.

References

[1] Jeanmougin, N. M., et al., SP-100 Flight Qualification Test Assessment, Energy Technology Engineering Center, Canoga Park, CA, September 1987.

[2] Schmidt, G. L., et al., SP-100 Test Program Options, Energy Technology Engineering Center, Canoga Park, CA, May 1989.

[3] Hamberg, O., et al., Space Division Acquisition Logistics and Test Space Vehicle Training Course, Vol I and II, The Aerospace Corporation, El Segundo, CA, March 1986.

LUNAR ORBITING MICROWAVE BEAM POWER SYSTEM

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ABSTRACT

A microwave beam power system using lunar orbiting solar powered satellite(s) and surface rectenna(s) was investigated as a possible energy source for the moon's surface. The concept has the potential of reduced system mass by placing the power source in orbit. This can greatly reduce and/or eliminate the 14 day energy storage requirement of a lunar surface solar system. Also propellants required to de-orbit to the surface are greatly reduced.

To determine the practicality of the concept and the most important factors, a "zero-th order" feasibility analysis was performed. Three different operational scenarios employing state of the art technology and forecasts for two different sets of advanced technologies were investigated. To reduce the complexity of the problem, satellite(s) were assumed in circular equatorial orbits around the moon, supplying continuous power to a single equatorial base through a fixed horizontal rectenna on the surface.

State of the art technology yielded specific masses greater than 2500 kg/kw, well above projections for surface systems. Using advanced technologies the specific masses are on the order of 100 kg/kw which is within the range of projections for surface nuclear (20 kg/kw) and solar systems (500 kg/kw). Further studies examining optimization of the scenarios, other technologies such as lasers transmitters and nuclear sources, and operational issues such as logistics, maintenance and support are being carried out to support the Space Exploration Initiative (SEI) to the moon and Mars.

INTRODUCTION

Operations on the surface of the moon will depend on a reliable electrical energy source. Providing low cost electrical power on the surface presents a significant challenge. Energy storage requirements for the 14 day eclipse period make surface solar power systems heavy. Proposed nuclear power sources have masses highly dependent on power level and may have political and safety concerns. An alternative is to place the the power source in orbit and beam the energy to the surface. The concept has the potential of lowered system mass by greatly reducing and/or eliminating energy storage and also reducing propellents required to de-orbit to the surface.

Specific masses for surface power plants are projected to range from a low of approximately 20 kg/kw for high powered nuclear up to approximately 500 kg/kw for continuous solar power [1]. The objective of this study was to determine, with reasonable technology projections, if a beam power system was competitive with surface power sources.

Multiple approaches including systems using nuclear sources and/or laser beaming can be conceived and will be addressed in future work. For this study, a simple system where energy is beamed at microwave frequencies from a solar powered satellite(s) to a fixed non-tracking rectenna (an antenna that receives and converts the RF energy to useful dc electrical energy) is investigated. To further reduce the complexity, a single equatorial base and satellite(s) in circular equatorial orbit were assumed.

It is recognized that more optimum designs are possible and will be explored in future work. Likewise, operational issues such as logistics, installation, maintenance, etc. must be addressed. (See Future Work and Conclusions Section). This first assessment with limited scenarios and technology is thus presented as an initial scoping document.

APPROACH

Three different scenarios of beaming power from orbit to the lunar surface were investigated. Figure 1 shows the block diagrams for each scenario.

The first scenario, Case 1, consists of a single satellite in orbit that transmits power to the surface when in the field of view of the receiver (rectenna). Energy storage is needed on the satellite as well as the ground. Batteries on the satellite provide power for transmission when the satellite is in the eclipse while within the beaming field of view (see figure 2) The energy storage on the surface provides power to the user while the satellite is out of view.

Case 2 is a constellation of satellites providing continuous coverage of the rectenna (see figure 2). Energy storage on the surface is therefore not necessary. Batteries are provided on each satellite as the energy source for transmission to the surface when that satellite is in the eclipse.

Case 3 is also a constellation of satellites providing continuous coverage, but with the energy storage located only on the surface to provide power to the user when the satellites are in the eclipse.

Figure 1. System Block Diagrams

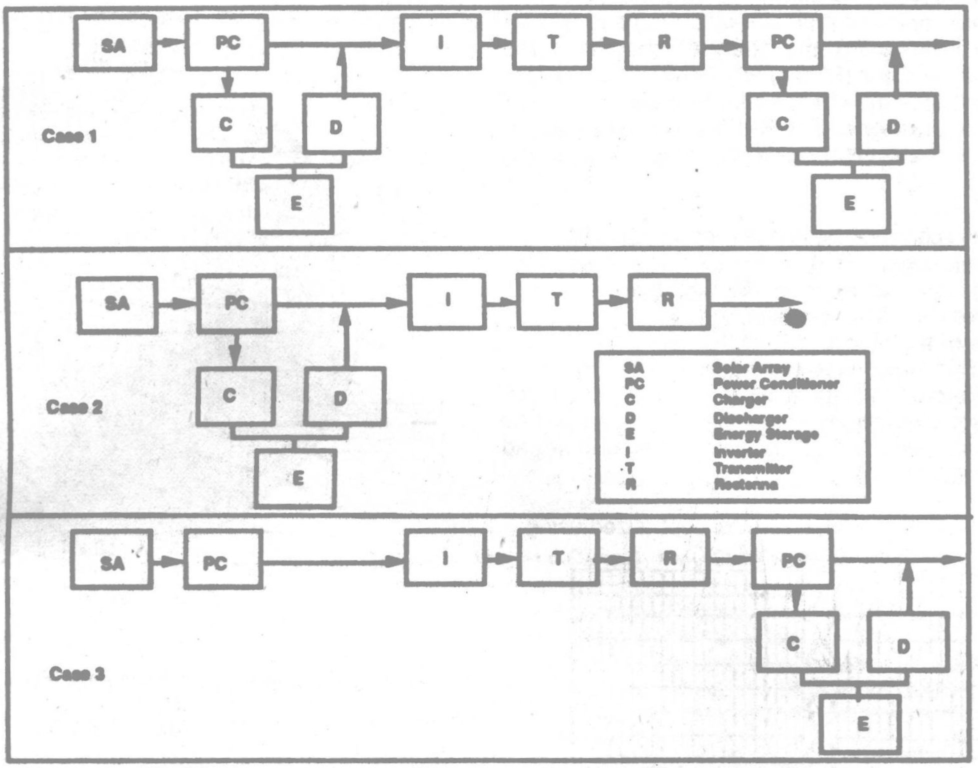


Figure 2. Lunar Orbiting Satellites

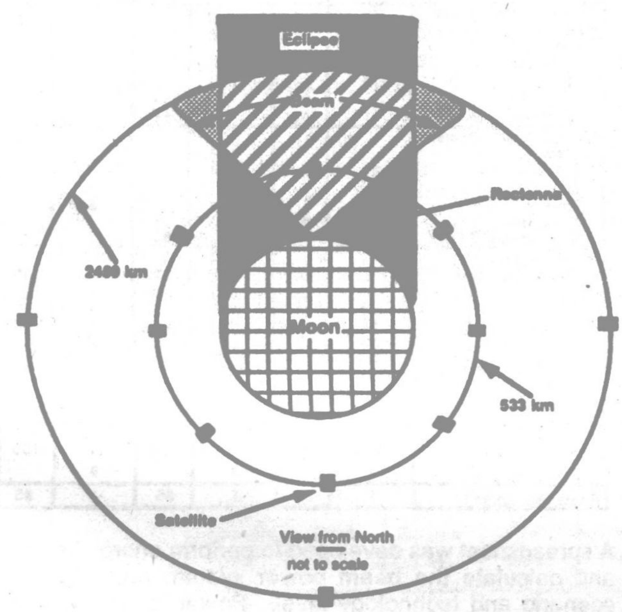


Table 1 indicates the specific masses and efficiencies assumptions for the technologies used in this study. Three levels of technologies were considered:

1. State of Art (SOA) : This design is similar to the Solar Power Satellite (SPS) studied considerably in the 1970's, but uses SOA components available in the 1990's (see figure 3). The structure uses Space Station Freedom (SSF) trusses. (An "average" specific mass is shown in Table 1, but structure mass is not a linear function of area). The solar array employs single crystal silicon cells, and nickel hydrogen batteries are chosen for energy storage (SSF designs). The nickel hydrogen batteries are sized assuming a depth of discharge (DOD) of 50%. Power Management and Distribution (PMAD) uses components developed for SSF. The thermal management radiators' specific masses assume a rejection temperature of 25^{O} C. Six percent of the masses for solar array drives, batteries, transmitter, and PMAD is added to account for integration masses.

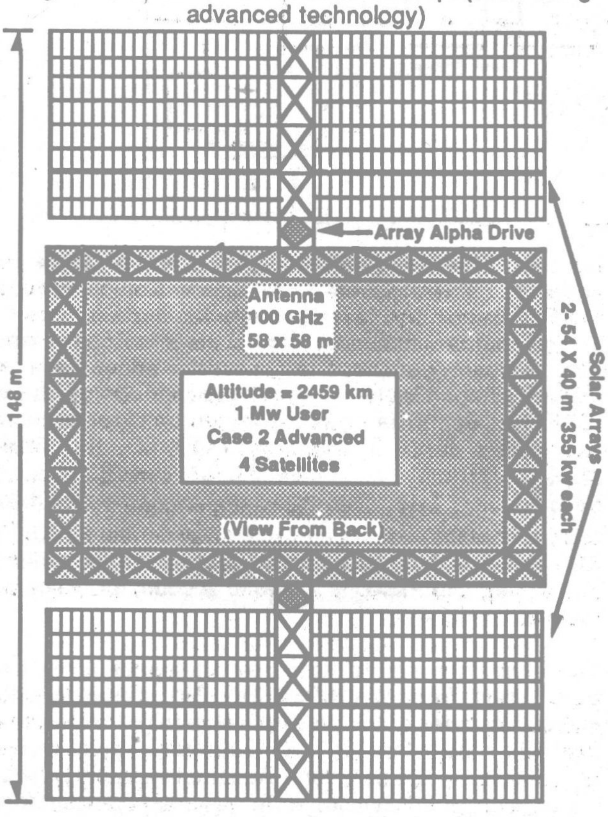
The aluminum slotted waveguide antenna array uses parameters from the SPS [2]. No space qualified microwave tubes of the power level required were known, therefore parameters for 35 GHz terrestrial gyrotron were assumed for the transmitter. (As for all technology levels, the transmitter efficiencies were assumed constant for all frequencies. Efficiency is expected to decrease with higher frequency, and this effect will need to be factored in later analyses, but it is expected that the efficiency at higher frequency will be more a function of time and technology evolution than basic physics.)

2. Advanced: Advanced technology represents the evolution of state of the art technologies to levels believed to be possible by the year 2000. Advanced lightweight solar cells and batteries are used for the power source. Satellite batteries in this case are sodium sulfur operating at

a temperature of 350^{o} C which leads to a correspondingly lower specific mass for the radiators. The sodium sulfur batteries are sized assuming 50% DOD. PMAD components are improved and their operating temperature is also raised, lowering the thermal specific mass. Regenerative Fuel Cells (RFC's) were chosen for surface energy storage since the charge and discharge cycles are of relatively long durations. The RFC's are sized assuming an 80% DOD. The transmitter is an improved efficiency tube.

Figure 3 shows schematically a beam power satellite using advanced technology. Four of these Case 2 satellites beaming power at a frequency of 100 GHz from an altitude of 2459 km provide 1 Mw of continuous power to a user(s) on the surface of the moon. It is of the same general size as SSF. The SSF transverse boom length is 145 m and its solar array "tip-to-tip" length is 72 m. The beam power satellite's overall dimensions are 148 x 58 m. As will be discussed later, lower power levels or altitudes would reduce each satellite's size.

Figure 3. Beam Power Satellite Concept (sized using advanced technology)



3. Thin Film: Thin film solar cells and solid state MMIC (Microwave Monolithic Integrated Circuit) devices are presently available for terrestrial applications and projections were made if space versions of these products could be developed around 2000. This technology assumes an inflatable structure to support an integrated solar array and antenna , see figure 4 [4]. Amorphous silicon solar cells and RFC's are chosen for power components. The transmitters are solid state MMIC devices in a phased array. This technology level is used only for Case 3 since no thin film storage technology was known to exist for the satellites.

Figure 4. Thin Film Technology Beam Power Satellite Concept [4]

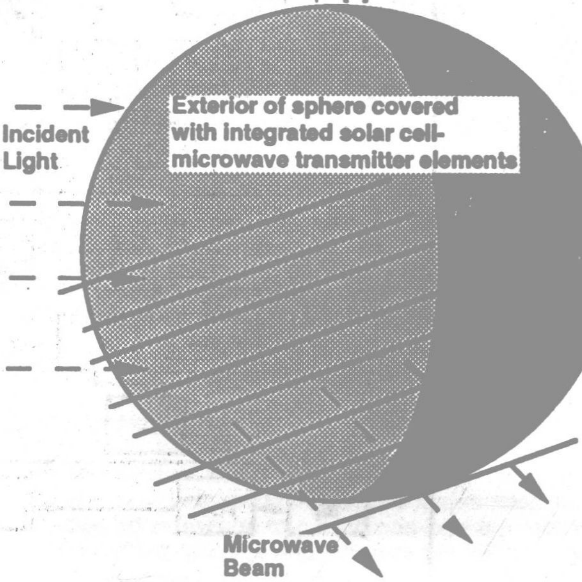


Table 1. Technology Performance Parameters [1,2,3,4]

	SOA		Advanced		Thin Film	
System	(kg/kw) -or- (kg/kwh)	%	(kg/kw) -or- (kg/kwh)	%	(kg/kw) -or- (kg/kwh)	%
Solar Array System						
Solar Array	20	14	3	25	.7	5
Drives	1		1		0	
Structure	3		3		0	
Energy Store System (Satellite)						
Cells	21		10			
Packaging	6		3			
Thermal	70		15			
Charge Eff.		95		95		
Discharge Eff. @ DOD		84		84		
Energy Store System (Surface)						
Cells	21		.5		.5	
Packaging	6		.5		.5	
Thermal	70		5		5	
Charge Eff.		95		80		80
Discharge Eff. @ DOD		84		80		80
PMAD System						
Power Conditioner	5	97	3	97	1	98
Inverter	10	95	2	98	1	98
Charger	14	95	7	95	1	95
Discharger	14	96	7	96	1	96
Thermal	70		15		5	
Integration	6 %		6 %		6 %	
Transmitter System						
Transmitter	3	40	3	80	.1	50
Thermal	5		5		5	
Antenna System						
Antenna (kg/m^2)	4.6	100	4.6	100	.1	100
Structure (kg/m^2)	3		3		0	
Rectenna (kg/m^2)	1	85	1	85	1	85

A spreadsheet was developed to perform energy balances and calculate the beam power system mass for each scenario and technology level. Power components are sized as a function of user power. End-to-end system masses are calculated including all support such as thermal management and structural subsystems. By using three different technology levels under three scenarios, the sensitivity of system specific mass to various subsystem and component performances was obtained. Also, the