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David Buden

MASTER

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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NUCLEAR REACTORS FOR SPACE ELECTRIC POWER

by

David Buden

ABSTRACT

The Los Alamos Scientific Laboratory is studying reactor power plants for space applications in the late 1980s and 1990s. The study is concentrating on high-temperature, compact, fast reactors that can be coupled with various radiation shielding systems and thermoelectric, dynamic, or thermionic electric power conversion systems, depending on the mission. Lifetimes of 7-10 yr at full power, at converter operating temperatures of 1275-1675 K, are being studied. The systems are being designed such that no single-failure modes exist that will cause a complete loss of power. In fact, to meet the long lifetimes, highly redundant design features are being emphasized.

Questions have been raised about safety since the COSMOS 954 incident. "Fail-safe" means to prevent exposure of the population to radioactive material, meeting the environmental guidelines established by the U.S. Government have been and continue to be a necessary requirement for any space reactor program. The major safety feature to prevent prelaunch and launch radioactive material hazards is not operating the reactor before achieving the prescribed orbit. Design features in the reactor ensure that accidental criticality cannot occur.

High orbits (above 400-500 nautical miles) have sufficient lifetimes to allow radioactive elements to decay to safe levels. The major proposed applications for satellites with reactors in Earth orbit are in geosynchronous orbit (19 400 nautical miles). In missions at geosynchronous orbit, where orbital lifetimes are practically indefinite, the safety considerations are negligible. Orbits below 400-500 nautical miles are the ones where a

safety issue is involved in case of satellite malfunction.

The potential missions, the question of why reactors are being considered as a prime power candidate, reactor features, and safety considerations will be discussed.

I. INTRODUCTION

A vigorous program for use of reactors in space existed from the mid 1950s until the early 1970s. This included the U.S. nuclear powered rocket program, whose prime objective was to provide a propulsion unit for taking men to Mars, and an array of space electric power systems for powering sensors and ion propulsion units. As mission emphasis changed, the various propulsion and space electric power systems being developed no longer were needed to support the revised program plans and by 1973 the development of reactors for space were largely discontinued.

Launch vehicle and payload size limitations to date have resulted in electric power requirements generally being a kilowatt or less except for Skylab, where 16 kW_e was provided. Figure 1, a summary of some 200 NASA spacecraft, shows that less than 100 kW_e of power has been flown, through 1975. This is in contrast with future projections, where a single spacecraft may require 100 kW_e.

The major factor warranting a fresh look at the need for higher power levels, and thus possibly considering nuclear reactors again for space, is the space transportation system (STS) or space shuttle. The space shuttle provides a reusable system that can be considered a true transportation system. As such, it opens a new space era leading to larger satellites and generating new power requirements.

Fig. 1. Space power production experience.
Data source: Historical analysis by
JPL. NASA Hq RP 77-237313. 4-15-77.

II. MISSION REQUIREMENTS

A nuclear power plant should be designed with the intent of meeting a range of potential mission power requirements. Because of development times involved, continually evolving definitions of potential missions, uncertainties during payload integration, and uncertainties with schedules and budgets, it is not desirable to concentrate reactor power plant development on a single mission. Both Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) future missions are being analyzed as a basis for establishing power plant requirements.

A number of potential DoD missions have been identified in communications and electro-optical and radar surveillance requiring electric power in the 10-to 100-kW_e range. A plot of peak projected power requirements (Fig. 2) indicates that electric power requirements would grow continuously from a few

kilowatts currently to $\sim 50 \text{ kW}_e$ in the late 1980s and over 100 kW_e in the early 1990s.

NASA's potential missions for nuclear reactors center on large satellites in geosynchronous Earth orbits (an orbit designed to maintain the satellite at a fixed point above the earth's surface) and planetary exploration. I. Bekey, H. I. Mayer, and M. G. Wolfe¹ did a comprehensive study that categorized various potential space applications as to the function, weight, size, power, orbit, time frame, initial operational cost, and risk. The space shuttle² is estimated to provide about 29 000 kg in low Earth orbit; however, in geosynchronous orbit, the payload estimate capacity is 3180 kg. If the traditional 30% of the payload is devoted to the power supply, the low Earth orbit requirements can usually be handled with a solar-arrays-plus-batteries power supply. However, the weight limitations at geosynchronous orbit imply the need for compact, low-weight power supplies, and thus, this orbit is a potential application for nuclear power sources.

Fig. 2. Maximum single-spacecraft power requirements by year.

Various potential missions in geosynchronous orbit requiring 15-220 kW_e are plotted in Fig. 3. Brief descriptions of the missions follow.

(a) Border surveillance could be used to detect illegal aliens, drug traffickers, and others who are attempting overt or covert crossings of the border. Small, sensitive, seismic sensors are planted along the border and monitored from space. Power level is 20 kW_e .

Fig. 3. Potential NASA applications in geosynchronous orbit. Source: "Advanced Space System Concepts and Their Orbital Support Needs (1980-2000)," Aerospace report AIR-76 (7365)-1.

(b) Police wrist radio communications could provide real-time, secure, anti-jam, high-coverage, wide-area personal communications for policemen. A large-diameter antenna on the order of 60 m could lead to very light transceivers. Power is on the order of 75 kW_e .

(c) Disaster communications could provide command and control to disaster area emergency personnel. Like (b), about 75 kW_e of power are required.

(d) Electronic mail transmission could transmit facsimiles of letters at reduced cost. A satellite could act as a multi-channel repeater for page readers and facsimile equipment at various post offices. Power is 15 kW_e .

(e) An advanced television antenna system could provide improved television coverage especially to mountainous, rural, and remote areas. The 17-m antenna in space would use 150 kW_e of power.

(f) Voting or polling wrist-watch-sized transmitters could be used for convenient, rapid determination of the electorate's stand on candidates and issues. The 46-m antenna would use 90 kW_e of power.

(g) National information services could be established to provide rapid access to information. A 60-m antenna would use 15 kW_e .

(h) Personal communications wrist radio could provide mobile telephone services. A 60-m antenna in orbit would use 21 kW_e and could serve 2.5 million people.

(i) Three-dimensional holographic teleconferencing could reduce the need for travel and thus save appreciable time and money. Laser illuminators and stereo sound could give the impression that all participants were present and active at the meeting. A 17-m antenna with 220 kW_e of power would service 1250 identical conference rooms in 100 urban centers.

(j) Vehicle and package locators could be used to monitor shipments throughout the USA continuously and thus minimize thefts, hijackings, and lost shipments. A transceiver would be

attached to each shipment with a 3200-m antenna in space and 23 kW_e of power for the system.

(k) An energy monitor could be used for fine-tuning electric distribution by monitoring current, voltage, or power readings on the network. A 45-m antenna would be used plus 23 kW_e .

Turning from orbital uses to investigation of the solar system, exploration is being pursued in ever-increasing detail. These missions usually start with reconnaissance probes to bodies in the universe such as our moon, planets, or asteroids; proceed to exploration of these bodies by orbiting sensors and landers; continue by intensive studies using rovers and surface-sample and return techniques; and, finally, establish semi-permanent or permanent bases such as on the moon.

Chemical, solar electric ion propulsion, and nuclear electric ion propulsion can be considered candidates for planetary missions limited to a single shuttle and mission durations of less than 10 yr. Figure 4 depicts expected growth

Fig. 4. Planetary missions. (Based on single shuttle and flight times less than 10 yr).

for planetary missions. The capability expected from various propulsion systems is added in Fig. 5. Chemical power has been the major propulsion source to date, but the limits of its capability are expected to be reached in missions during the 1980s. Solar electric propulsion with ion thrusters may extend the ability to perform planetary missions and meet requirements for the late 1980s and early 1990s, but its limit will be reached in the reconnaissance mission to Uranus and exploration mission to Saturn. Nuclear electric propulsion with ion thrusters extends the capability to investigate the outer planets and to perform solar escape missions as seen in Fig. 5. The nuclear electric propulsion power supply envisioned makes use of a 400-kW_e power plant.

Fig. 5. Planetary missions with propulsion. (Based on single shuttle and flight times less than 10 yr).

III. POWER PLANT REQUIREMENTS

A. Power Output

Nuclear power requirements in geosynchronous orbit cover the range from 10 to 220 kW_e. Above 50 kW_e, nuclear power supplies offer the major option for providing power on an economical basis. DoD and NASA both forecast the need for power in this range. No single, dominant mission has been found as a basis for design. Therefore, any development should be flexible to cover the full range. For planetary missions the requirement is about 400 kW_e.

B. Lifetimes

Lifetimes are established by anticipated developments in other components in the spacecraft. Goals of 7 to 10 yr have been established for spacecraft in geosynchronous orbit and the equivalent of 10-yr full power is required for planetary exploration.

C. Reliability

Power subassembly reliability design goal for geosynchronous orbit is 0.95. For planetary applications it is even greater. Designs that avoid single-point failures and degrade gradually are favored.

D. Mass

A general rule of thumb is that the power subassembly can constitute up to 30% of total spacecraft mass. For a single space shuttle launch using a three-stage rather than a two-stage Interim Upper Stage (IUS) to geosynchronous orbit, this allows a design goal of 955 kg; for a dual-shuttle launched spacecraft, the goal is 1910 kg. For planetary missions the goal is less than 20 kg/kW_e or 8000 kg for a 400-kW_e power plant.

E. Configuration Constraints

The shuttle bay will often be volume, rather than weight, limited. The individual spacecraft will determine the constraints. The 18.3-m overall orbiter bay is reduced 7 m by the three-stage IUS. The shuttle bay diameter limits the power plant to 4.5 m.

F. Radiation

The spacecraft must be able to operate in natural radiation fields. Induced radiation created by nuclear power systems must be reduced by means of shadow or local shields. The maximum acceptable radiation level depends upon each mission's spacecraft components and configuration; for present electronic components it is 10^{13} nvt and 10^7 rad over the mission life.

G. Maneuverability

Maneuverability is mission dependent. No missions requiring special maneuverability have been studied to date.

H. Safety Features

The power subassembly must meet all regulations of the Department of Energy (DOE), NASA, DoD, the Environmental Protection Agency (EPA), etc., plus the National Range Commanders. All payloads using the STS are subject to a uniform set of basic safety and interface verification requirements. The safety requirements are tailored to identify the hazard potential of the payload. The Payload Safety Guidelines Handbook (JSC-11123) provides a basis for selecting design options to eliminate hazards. The STS safety policy requires that the basic payload design ensure the elimination or control of any hazard to the orbiter, crew, or other payloads.

I. Costing

Cost comparisons will include not only the basic cost of the power subassembly but also the subassembly and launch costs for the total system.

Table I provides a summary of power plant requirements to be used as a basis for making various technology decisions.

IV. WHY REACTORS BECOME A PRIME POWER SOURCE?

Projected 1985 power technologies (the technologies that would be used in 1990 missions) indicate that solar arrays with batteries are expected to be heavier than reactors above 10-20

TABLE I
POWER PLANT REQUIREMENTS

	Requirement	
	<u>Geosynchronous</u>	<u>Planetary</u>
Power output (kW _e)	10-200	400
Lifetimes (yr)	7	10
Reliability	0.95	High as possible; no single point failures
Mass		
Single shuttle (kg)	955	8000
Dual shuttle (kg)	1910	
Configuration constraints	Minimize packaging volume in shuttle bay	Minimize packaging in shuttle bay
Radiation attenuation		
Neutrons (nvt)	10 ¹³	10 ¹²
Gamma (rad)	10 ⁷	10 ⁶
Maneuverability	Mission dependent	Ion thrusters
Safety	STS requirements	STS requirements

kW_e (Table II). At 50 kW_e , nuclear system mass is about 60% of the solar system mass, and at 100 kW_e , it is 40%.

Reactors will be less costly than solar power systems. Table II shows a cost comparison including a factor for launch mass differences. At 10 kW_e , the cost of delivery to geosynchronous orbit is estimated to be almost equal, but at 50 kW_e , the reactor cost is one-fourth of the solar cost and at 100 kW_e , it is one-fifth.

The space shuttle is expected to be the main launch vehicle. Considering that the practical limits of most missions around 1990 are two shuttle trips per spacecraft, about 1910 kg would probably be the most that can be devoted to the power supply for geosynchronous orbit missions. This implies that solar arrays will have difficulty in providing 50-kW_e power and will be much too heavy at 100 kW_e . Reactor systems can span the whole range; a 100-kW_e system will weigh between 1600-1900 kg.

Solar arrays have been flight demonstrated in a 16-kW_e system. Because of weight limitations imposed by the shuttle and the mass of a solar array plus battery system, it is doubtful that 50-kW_e power systems can be demonstrated by the mid 1980s. The SNAP 10A is the only flight-demonstrated space reactor, and it operated at 500 W. Today's technology would permit flight testing a fast, compact reactor system in the mid to late 1980s at 100 kW_e .

The SNAP 10A power system successfully started up in orbit on command and operated flawlessly although the mission was terminated prematurely after 952 h by a failure in the spacecraft.³ Moreover, the 1-yr objective was exceeded in 1966 when the ground test of the FS-4 SNAP 10A completed 10 000 h of continuous operation.⁴

Solar arrays have to be oriented sunward. Reactors require no orientation mechanism, power transfer slip rings, array deployment, or mechanism to compensate for tracking disturbances. However, both systems have location limitations.

TABLE II

SOLAR ARRAY VS REACTORS BASED ON PROJECTED TECHNOLOGY, 1985

	10 kW _e		50 kW _e		100 kW _e	
	Solar	Nuclear	Solar	Nuclear	Solar	Nuclear
W/kg	24	14	24	41	22	55
Cost, delivered to geosynchronous orbit (Million \$)	8	7	32	10	63	14
Shuttle Compatible (~ 1910 kg)	Yes	Yes	Difficult	Yes	No	Yes
Space Flight	Demonstrated	Possible	Possible	Possible	Doubtful	Possible

Feature	Solar	Nuclear
Orientation	Sunward	None--No power transfer slip rings, array deployment, tracking disturbances, or battery cycle problem
Location	Shadowed by large antennas	Minimize shielding
Maneuverability	Difficult fold-up arrays	No problem
Radiation		
Natural	Degrades	No effects
Induced	None	Shielding necessary
Reliability	70-90%	95%
Safety and Handling	None	Flight tested on SNAP 10A
Disposal	None	Long-term earth or sun orbit
Maintainability	Large structure interference	Manned shielding

Because of their size and the need to focus on the sun, solar arrays must be arranged to avoid shadowing by large antennas and other spacecraft components. Reactors must be positioned to minimize radiation shielding.

Solar arrays restrict maneuverability. Unless a mechanism for retracting and deploying the arrays is included, the spacecraft will have to be moved slowly to minimize acceleration loads. Reactors are compact, making maneuverability feasible.

Natural radiation affects solar array life but has no effect on nuclear reactors. However, solar arrays do not introduce radiation, which is a major consideration with reactors. Shielding must be provided to attenuate radiation emitted from the reactor. Radiation rates affect component life by both instantaneous intensity (which ionizes sensitive electronic systems) and integral effects (which cause semipermanent lattice defects that create physical and chemical property changes in materials).

An Atomic International study, AI-AEC-130722, showed that 10^6 nvt of fast neutrons and 1.0 rad of gamma rays deteriorate semiconductor components about equally. Figure 6 shows the radiation damage thresholds of typical electronic components that may be used in unmanned space applications. Up to a dose equivalent to 10^{11} nvt and 10^5 rads, "off-the-shelf" components can be used. The allowable dose may be increased to 10^{12} nvt and 10^6 rads by "inspection hardening" (that is, selecting components that, on the basis of existing data, require no irradiation testing). One more step, to 10^{13} nvt and 10^7 rads, is achievable at only 5% cost increase. The technology to design circuitry and parts to survive 10^{14} nvt and 10^8 rads now appears feasible, but accurate cost estimates must be developed.

The amount of radiation shielding depends on the power level, the distance of radiation-sensitive components from the reactor, and component radiation tolerance. Each individual spacecraft's best reactor location must be determined. Figure 7

Fig. 6. Radiation hardness of typical electronic components for unmanned missions.

Fig. 7. Reactor shielding.

shows shielding mass change as a function of distance, half-cone angle from the reactor, and power level. Judicious location will usually permit unmanned shieldings of less than a few hundred kilograms.

Solar arrays create a minimum of safety, handling, and disposal problems. The reactor safety considerations were demonstrated solvable in the SNAP 10A reactor flight test. More concerning reactor safety will be discussed later.

In summary, 5- to 25-kW_e solar array power systems have been demonstrated, but solar arrays with batteries become quite heavy at 50 kW_e. They introduce a minimum of radiation, safety, handling, or disposal problems. Reactor power plants tend to weigh less, have lower unit cost, and are compatible with the shuttle loads at 10 to 100 kW_e. Space reactors are compact and independent of spacecraft orientation. Furthermore, the space reactor power system is unaffected by natural radiation, can be made highly reliable and allows the spacecraft to be maneuverable.

Figure 8 shows the uses for which each technology will be competitive in future missions. The boundaries will move with time, but not appreciably. From 0.5 to 5 kW_e, isotopes and solar arrays offer options for particular missions. From 25 to

Fig. 8. Possible space power sources for DoD missions.

perhaps 50 kW_e, solar arrays and reactors provide the power option. Above 50 kW_e, reactors can provide the primary means of meeting mission power requirements.

V. POWER SYSTEM DESCRIPTIONS

A. Component Description

The power plant includes the reactor, radiation shield, electrical converter, and waste-heat radiator.

1. Reactor. Several reactor configurations are being considered. A typical 1000-kW_t reactor described herein could satisfy the 10- to 220-kW_e power demands for missions in geosynchronous orbit.

The reactor core contains 90 hexagonal fuel elements made of 90% UC and 10% ZrC (Fig. 9). Each element is 27.9 mm across the hexagonal flats and 280 mm long and is contained in a thin-walled

Fig. 9. Reactor core assembly.

molybdenum can. Each fuel element is cooled by a centrally located molybdenum heat pipe, an efficient means of transporting heat from the core. The heat pipe is a self-contained structure that achieves very high thermal conductances by means of two-phase flow with capillary circulation. Heat is transferred within the heat pipe's contained envelope by evaporating a liquid (sodium), transporting the vapor to another part of the container, condensing it, and returning the condensate to the evaporator through a wick of suitable capillary structure. The fuel is segmented to allow for swelling, minimize fabrication problems, prevent bowing, enhance heat transfer, permit variations in uranium loading, and allow for thermal expansion. Fuel elements are clad for storage and for protection against oxidation.

The core is enclosed and is kept compressed by a series of rings. Multifoil insulation minimizes heat transfer from the core to the reflector. The core, with its 90 heat pipes, essentially provides 90 independent loops for removing heat. Loss of one heat pipe causes elevated, but acceptable, temperature increase in the surrounding pipes. The core could sustain several failures with no major degradation of performance.

The core is surrounded by a neutron reflector of beryllium or beryllium oxide on the sides and aft end and beryllium oxide at the forward end. Beryllium oxide is required at the end that the heat pipes penetrate because of higher operating temperatures there. The reactor is controlled by changing the position of neutron-absorbing material within the reflector. Rotating drums were selected for reactivity control because of experience with them in previous space reactor programs. Twelve drums are used in the reflector, each containing a boron-carbide sector that is rotated for power control. The control surfaces are rotated in discrete steps by an actuator placed behind the shield to reduce the incident nuclear and thermal radiation that reaches it. The reactor power will be controlled to maintain a constant outlet voltage from the power conversion units so as to

minimize thermal cycling of the reactor. Redundant instrumentation and control electronics are provided to increase reliability and eliminate single-point failures.

Table III shows typical design parameters for the 1000-kW_t reactor.

2. Shield. Shield design and technology make extensive use of work on space reactor shields for SNAP 2, 8, and 10A, and of ROVER experience. These reactors have certain features in common with current designs, namely, small physical size, unmanned space application with comparable allowance of neutron and gamma doses, and comparable radiation flux levels.

Only shadow shielding is required due to:

- Only unmanned power-plant operation is considered.
- The reactor will be used only in high Earth orbit, where neutron and gamma scattering from air is negligible.
- The reactor can be located at one end of the assembly, followed by the shield, control actuators and radiator, and, finally, the payload.

The shield can be considered as follows: neutron attenuation is provided by lithium hydride (LiH) in the shape of a frustum, and a heavy-metal gamma shield is added at the reactor end of the shield if needed.

To minimize single-point failures, the LiH is to be encapsulated in a number of pancake-shaped cans, so that pressure containment failure from meteoroid penetration or a weld failure, for example, will deplete the hydrogen in only a small part of the shield. The shield is also a structural member that connects to the reactor on one end and by a boom to the payload on the other. The load is carried by the outer conical shield shell.

3. Electric Power Converters.

A number of technologies for electric power converter systems are being developed. The principal near-term ones are

TABLE III
DESIGN PARAMETERS FOR 1000-kWt REACTOR
(1400 K HEAT PIPE TEMPERATURE)

Burn fraction of ^{235}U (%)	2.7	<u>Temperatures (K)</u>	
Fuel swelling (vol%)	8.0	Max fuel delta t	155
		Av delta t across heat pipe wall	17.5
		Av fuel temperature	1 469
		Max fuel temperature	1 581
<u>Reactor Dimensions (m)</u>		<u>Fuel Element Dimensions (mm)</u>	
Core diam	0.28	Width across hex flats	27.9
Core height	0.28	Heat pipe o.d.	15.3
Reactor diam	0.51	Vapor diam	11.9
Reactor height	0.49	Vapor area (mm^2)	110.4
Reflector thickness	0.10		
Pipe length outside reactor	1.00		
Total heat pipe length	1.38		
Overall reactor and heat pipe length	1.49		
<u>Reactor Mass (kg)</u>			
Fuel region	127	(includes 108 kg highly enriched of ^{235}U)	
Reflector	133		
Heat pipes	94		
Control system	33		
Support structure	<u>27</u>		
Total	414		

thermoelectrics and dynamic converters, such as the Brayton cycle, with potential longer term thermionic and Stirling cycle converters.

a. Thermoelectrics. Thermoelectric power conversion by use of high-temperature semiconductor thermoelectric elements (TE) can be used in a space-nuclear power generation system. Thermoelectrics have been used in many space missions as the power conversion element of radioisotope power supplies with demonstrated high reliability.

The heat removed by each reactor heat pipe becomes the heat source of a TE module. The TE operates at about 1275-1375 K.

The cold side of the TE module will be cooled by heat pipes that are an integral part of the heat rejection radiator. The cold-side temperature is a compromise between that required for optimal TE efficiency and that required for optimal radiator size and weight. Other factors involved are materials compatibility, heat pipe working fluid, and radiator size restraints. Preliminary evaluations have shown that it is desirable to operate the radiator about 775 K. This is in the temperature range where potassium-filled heat pipes could be successfully used for waste heat radiator elements.

A number of semiconductor TE materials have been developed. Silicon-germanium alloys have operated above 1275 K and have been studied extensively. This is the material in the multi-hundred watt (MHW) radioisotope generators used in LES 8 and 9, and Mars, Jupiter, Saturn, and Voyager missions. Current Si-Ge has the potential for operating as high as 1400 K with 6.5% efficiency and improved Si-Ge to 9% efficiency.

In the reactor TE system, the heat flux is limited by the semiconductor materials, not the heat source or heat sink capabilities. The reference design is based on a "compression" module that was built and tested several years ago; other designs have also been made with high-performance TE modules.

Figure 10 is a conceptual drawing of the module and shows projected converter efficiencies.

b. Dynamic Converters. The Brayton cycle is used to illustrate dynamic converter systems. Mounted on the end of the reactor heat pipes are heat exchangers to feed redundant Brayton loops. The Brayton loop consists of a rotating group (compressor,

Fig. 10. Thermoelectric design concept and projected converter efficiencies.

turbine, and alternator on a single shaft supported on foil gas bearings) and heat exchangers from the reactor, the recuperator and to the radiator. An inert gas is used as a working fluid in the closed-loop system. The xenon and helium gas working fluid leaving the radiator heat exchanger or cooler at low temperature and pressure enters the compressor and is discharged into the

recuperator at higher pressure. Passing through the recuperator, the working fluid is preheated before it enters the high-temperature heat exchanger, where energy from the reactor heat source is added to the working fluid. When the fluid emerges from the reactor heat exchanger, its temperature is highest and it is expanded in the turbine to drive the compressor and alternator. The working fluid then releases thermal energy in the recuperator and cooler, and the closed cycle resumes. The recuperator, a key component, minimizes waste heat rejection and promotes high cycle efficiency. Efficiencies of 25% are estimated, with provision for full-power operation even after loss of a redundant loop. Typical temperatures and pressures are shown in Fig. 11.

Fig. 11. Brayton cycle power system.

A single-unit Brayton converter has operated over 30 000 h in tests by NASA-Lewis Research Center⁵ at a turbine inlet temperature of 1145 K, although continuous operation was interrupted to make experimental tests. The demonstrated efficiencies were 30-33% at 7-8 kW_e.

4. Radiators

The radiator is being designed for 99% reliability and 7-yr lifetime. Radiator area depends on such factors as the converter efficiency, electric power level, heat rejection temperature, and probability of component failure mainly from meteoroids. The thermoelectric converter radiator is designed to maintain a cold-junction temperature of 775 K. Higher converter efficiencies obtained by designing for a lower temperature would increase system mass and size. The present concept is based on stringer heat pipe arrangement transporting the heat from a thermoelectric cold-junction ring. Circumferential heat pipes surround the stringers to distribute the heat and act as a bumper and as fins. Calculations of meteoroid penetration were based on NASA space shuttle user guidelines for payloads in geosynchronous orbit.^{6,7} To ensure that the heat pipe radiator survives meteoroid penetration throughout the mission, the radiator can be overdesigned and penetration armor can be added. Figure 12 shows how different probabilities of 7-yr stringer survival affect various candidate radiator materials. A low probability means that the surviving stringers must carry more of the load. Higher probabilities imply more armor. The circumferential heat pipes are designed such that if only 78% survive, full power operation will still be maintained. Using them as a bumper for the stringer heat pipes reduces the mass significantly. Beryllium and titanium seem the most promising space radiator materials; others are appreciably heavier.

B. Power plant for 10 to 220 kW_e

Figure 13 shows a thermoelectric system. The core module is for a 1000-kW_t reactor. The core and shield are separated to provide space to bend the core heat pipes around the shield to the thermoelectric converters. The converters are located in a ring of good thermal conductive material. The radiator extracts the heat from the cold junction of the converter ring.

A representative power plant layout for the Brayton cycle is shown in Fig. 14. The Brayton cycle has potential efficiencies

Fig. 12. Radiator mass for various candidate materials.

up to 35%; a 1000-kW_t reactor could deliver 350 kW_e. However, radiator temperatures are low at these high efficiencies, so the radiator becomes quite large. As a compromise between converter efficiency and radiator mass, we use 25% efficiency in analyzing Brayton converter weights. To avoid single-point failures, duplicate loops each capable of full-power operation have been included in the system mass totals. This redundancy achieved at some weight penalty appears feasible within the total weight constraints.

Table IV shows the mass parameters of major components at 10, 50, and 100 kW_e.

Fig. 13. Thermoelectric power plant.

TABLE IV
MASS PARAMETERS FOR NUCLEAR SPACE ELECTRIC POWER
(7-yr lifetime)

	10kW _e		50kW _e		100kW _e	
	<u>TE</u>	<u>Brayton</u>	<u>TE</u>	<u>Brayton</u>	<u>TE^c</u>	<u>Brayton</u>
Reactor power (kW _t)	156	40	781	200	1111	400
Efficiency (%)	6.4	25	6.4	25	9.0	25
Radiator power (kW _t)	146	30	731	150	1011	300
Radiator temp (K)	775	475	775	475	775	475
<u>Mass (kg)</u>						
Core	415	415	415	415	525	415
Shield ^a	165	110	215	130	250	145
Converter	45	250 ^b	235	460 ^b	335	710 ^b
Radiator	35	30	255	200	380	400
Structure	<u>65</u>	<u>80</u>	<u>110</u>	<u>120</u>	<u>150</u>	<u>165</u>
Total	725	885	1230	1325	1640	1835
W/kg	14	11	41	38	61	54

^aAssume 12° cone half-angle at 25 m.

^bDual converter systems.

^cImproved TE material and larger reactor (1500 kW_t).

C. Power plant for 400 kW_e

In addition to the 1000-kW_t design to meet power requirements from 10-220 kW_e, a planetary mission design is being analyzed for 3.05 MW_t and 400 kW_e using thermionic converters.⁸ The mission requirements for compact size and long lifetimes imply the need for a fast-spectrum, highly enriched, densely fueled reactor core, one that will have a large inventory of fuel in a small volume. The reactor is similar in concept to the one described above. Reactor size

Fig. 14. Brayton cycle space electric power supply.

is determined more by the requirements of heat removal and the considerations of fuel swelling than criticality limitations; this permits the use of UO_2 fuels. The UO_2 is contained in a molybdenum matrix to enhance heat removal from the fuel.

A typical fuel element consists of a molybdenum structure, lithium fluid heat pipe bonded along the axis of a hexagonal section, and a molybdenum matrix embedded with small UO_2 pellets. The mechanical and thermal characteristics of the proposed fuel are close to those of molybdenum and it is easily bonded to the heat pipe. A cross-sectional view of the reactor is shown in Fig. 15. The hexagonal section core consists of 90 fuel elements. The core is power flattened radially by varying the fuel loading to obtain a uniform power output from all the converters. Currently, the design shows spring-loaded plungers to hold the core together radially; however, bands may be used.

Fig. 15. Cross section of out-of-core thermionic reactor.

The core is surrounded on all sides, including the ends, by a thermal shield, a thin thermal neutron absorber, and a BeO reflector. The radial reflector contains 18 boron-loaded rotating drums for control of neutron reactivity. Typical parameters are listed in Table V, and operating characteristics in Table VI.

Radiation shielding is provided between the reactor core and thermionic converters to reduce radiation exposure to parts of the power conversion equipment and payload. Neutron attenuation is provided by LiH and gamma attenuation, if needed, by a heavy metal, such as tungsten. The shield is constructed as a honeycomb structure. Heat pipes from the core are routed through the shield in a manner to prevent radiation streaming to the thermionic converters.

TABLE V

REACTOR WEIGHT(kg)

Mo - UO ₂ Fuel, Total		372
	UO ₂ Only	229
	²³⁵ U Only	189
90 Mo Heat Pipes, 207 kg/m (to outer edge of reactor)		110
BeO Reflector		397
Control System		75
Reactor Support Structure (assume 5%)		46
TOTAL		1000

A schematic layout of the baseline system is seen in Fig. 16. Its specific weight is low enough to allow consideration of essentially all planetary missions that have been proposed as well as lunar and Earth orbital applications. Integration of the power system into the spacecraft is shown in Fig. 17. Lifetime of the system is limited by the control margin of the nuclear reactor and not by any identified materials degradation problems. This lifetime is in excess of 10 yr at full power,

TABLE VI

REACTOR OPERATING CHARACTERISTICS

Nominal electrical power output (kW_e)	400
Thermal power level (MW_t)	3.05
Thermionic converter efficiency (%)	15
Lifetime at full power (h)	75 000
Number of fuel elements	90
Average power density in Mo-UO ₂ (MW/m^3 or W/cm^3)	78
Average power density in UO ₂ (MW/m^3 or W/cm^3)	130
Power per heat pipe (kW)	33.9
Heat pipe axial heat flux (MW/m^2)	100
Heat pipe radial heat flux (MW/m^2)	1.2
Heat pipe temperature (K)	1 675
Average fuel temperature (K)	1 788
Maximum fuel ΔT (K) ^a	235
Maximum fuel temperature (K) ^a	1 962
²³⁵ U Burnup (%)	5.8
Fission density in Mo-UO ₂ (10^{20} Fission/ cm^3)	6.3
Fuel volume swelling (%)	10-15
Reactivity change αk due to fuel burnup (%)	3.5
Reactivity change αk due to thermal expansion (%)	1.5

^aAssumes a 1.5 peak-to-average power density ratio.

fulfilling the mission requirement of 15 yr or more duration, where these require some full-power operation and some part-power operation.

VI. SAFETY

Recently, questions have been raised as to whether nuclear reactors can be used safely as electric power plants in Earth orbit.

Safety has been and continues to be a major concern of U.S. scientists involved in using reactors in space. Before

Fig. 16. Schematic layout for nuclear-powered ion propulsion system.

Fig. 17. Nuclear electric propulsion spacecraft with all-heat-pipe thermionic power conversion.

operation, the reactor and its uranium fuel are perfectly safe to handle. There is absolutely no possibility that a nuclear electric power plant can explode.

The key to safe operation before and during launch is to keep the reactor in a nonoperative mode. This is accomplished by adding built-in safety features, such as redundant control elements, where only one element is allowed to be unlocked at a time; brakes on the control element actuating mechanisms to prevent movement without two independent signals; and a reactor designed to remain nonoperative even with environment changes, such as immersion in water.

Analyses and tests are used to show safe launch operation in case of launch pad fires, propellant fires, impact at terminal velocity in case of a launch abort or failure to reach orbit, and water impact. Again, the major requirement for safety is not to operate the reactor until the prescribed orbit is reached.

Most applications considered for nuclear reactors are in high orbits, such as geosynchronous. The higher the orbit, the longer a satellite will remain in orbit. Long orbit times provide time for radioactive elements to decay. An orbit altitude of about 400-500 n mi will provide for over a 1000-yr life and thus could give a margin of conservatism in meeting safety criterion. Doubling the orbit increases the orbital lifetime to about a million years. Satellites in geosynchronous orbit (19 400 nautical miles), the proposed location of most reactor-powered U.S. satellites, will, for all practical purposes, never reenter the earth's atmosphere.

The only U.S. reactor flown in space, SNAP 10A in 1965, was not operated until its 700-n mi orbit was achieved. SNAP 10 A's estimated orbital lifetime is 3800 yr.

VII. PROGRAM STATUS

At the time this report was prepared, screening studies were under way at the Los Alamos Scientific Laboratory to determine the design approach to be followed in developing future electrical power systems. The heat pipe reactors described here

are only one approach under consideration but are heavily favored because of longevity requirements and to avoid single failures that could result in a significant loss in power.

An experimental program is planned to start in FY-1979 to resolve key technical feasibility questions. The experimental program will be performed in areas where sufficient data are not available to make a system selection for a ground demonstration system. This may include experiments on such items as heat transfer characteristics between fuel elements and heat pipes, bending of high-temperature heat pipes, heat pipe coupling methods, lightweight radiator development, heat pipe dynamics, high-density thermoelectric modules, fuel element fabrication procedures, and fuel cladding procedures. The experiments will verify design concepts and provide a measure of the degree of complexity required to develop the ground demonstration system.

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