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Reactor Technology for Space Electrical Power (10 to 100 kWe)

David Buden

los alamos
scientific laboratory

of the University of California

LOS ALAMOS, NEW MEXICO 87545

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REACTOR TECHNOLOGY FOR SPACE ELECTRICAL POWER (10 to 100 kWe)

by

David Buden

ABSTRACT

The Los Alamos Scientific Laboratory is studying various reactor power plants for space applications in the range of 10 to 100 kWe to meet space missions in the late 1980's and 1990's. The study is concentrating on a high-temperature, compact, fast reactor that could be coupled with various radiation shielding systems and thermoelectric, thermionic, or dynamic electrical power conversion systems, depending on the mission. Though the study is continuing, this report provides a description of what a typical power plant might contain in the time period and at the power levels of interest.

I. INTRODUCTION

The Los Alamos Scientific Laboratory (LASL) in support of the U.S. Energy Research and Development Administration (ERDA) Nuclear Research and Applications Division program to develop a nuclear space reactor power plant, is conducting studies on mission requirements and power plant technology. The LASL study is to determine the characteristics of various reactor power plants for space applications to select a configuration for future ground demonstration and flight. The study is continuing but this document is intended to meet the need of mission planners for an interim description of what the power plant performance might be.

II. REACTOR TECHNOLOGY

A. Current Status

Nuclear reactors for space power were surveyed by reviewing past concepts and designs.¹ The Los Alamos Scientific Laboratory (LASL) is studying various reactor power plants for space applications to permit selecting a technology and configuration for ground system demonstration and potential flight demonstration. Mission requirements will strongly influence the selection. Various fuels, reactor designs, shields, converters, and radiators are being considered. The study is concentrating on a high-temperature, compact, fast reactor that could

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be coupled with various radiation shielding systems and a thermoelectric, thermionic, or dynamic electrical power conversion system, depending on the mission.

A space electrical reactor power plant has four major subassemblies. The nuclear reactor uses controlled fissioning of uranium atoms to generate thermal energy; the radiation shield protects other parts of the spacecraft from the emitted radiation; the converter produces electricity from the thermal energy generated in the reactor; and the radiator discharges waste heat.

Development of a reactor space power system is within current technological capabilities. Feasible concepts for minimizing possible single-point power plant failures are available. A major technological advance could be use of heat pipes to transfer heat among various parts of the power plant. A review of key components indicates that the material and design technologies have been tested in other programs. No single item required entirely new technology. Though significant, the design problems all appear solvable. A brief assessment of the technology follows.

1. Reactor Core. Zirconium-hydride fueled reactors have actually been flight tested (SNAP-10A). However, 975 K temperature limitations made them bulky and complex. Higher temperature reactors fueled by such materials as uranium carbide, uranium carbide-zirconium carbide, uranium dioxide molybdenum cermet, molybdenum encapsulated uranium dioxide, and uranium nitride would significantly decrease power plant weight and volume. Core exit temperatures of 1675 K and lifetimes of 7-10 yr are possible by the mid-1980's.

Uranium-carbide fuels were developed extensively for the ROVER nuclear rocket program. The work has continued for high-temperature gas reactor (HTGR) and liquid metal fast breeder reactor (LMFBR) fuel elements. The main problems are fuel and cladding compatibility and fabrication to specific dimensions. Experience has shown that control of impurities and atmosphere are important in establishing long-lived fuel elements. Also, the long life characteristics must be demonstrated.

The heat pipe, invented at LASL in 1963, has been used extensively throughout the world and in

space. Heat pipes can be mated with reactor fuel. Good thermal contact between fuel and heat pipes, heat-pipe closure, and impurity control must be demonstrated for long periods.

2. Reflector. Space-type shields have been developed for Rover and Snap. Oak Ridge National Laboratory (ORNL) has run extensive shielding experiments. Shielding technology is considered very mature.

3. Power Converter. ERDA and NASA have funded extensive work on power conversion systems for the radioisotope and heat pipe plus thermionic power programs.

Silicon-germanium thermoelectric technology appears to offer up to 50-kWe power with little risk, and selenides now being developed may extend the useful range of thermoelectrics to nearly 100 kWe. Thermoelectric modules that involve heat pipes and give the desired power density for 7-10 yr must be demonstrated.

Dynamic systems such as the Brayton cycle can be used at higher power levels. Power converter development should be continued by industrial organizations that have already demonstrated high competency in the field. A Brayton converter has been operated over 26 000 h without maintenance and with no wear or failure noted during inspections which would prevent attainment of a 5-yr lifetime.²

Thermionic converters being developed by ERDA and NASA's Jet Propulsion Laboratory (JPL) should be demonstrated at 20% efficiency in the early 1980's.

4. Radiators. Radiator technology is well developed, but the extent of heat-pipe radiator usefulness must be assessed. Higher temperatures planned for radiators with thermoelectric converters will reduce their size and alleviate problems associated with folding or roll-up radiators. Brayton converters require lower temperature radiators to achieve high cycle efficiencies. Therefore, Brayton converter radiators will probably be larger but could use more conventional materials.

5. Controls. Drum actuators extensively developed by Atomics International (AI) could

satisfy the design requirements. Control sensors exist. Control electronics can be surrounded by thermal and radiation shields, so present technology can be used.

B. Power Plant Components.

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

1. **Reactor.** Several reactor configurations are being considered. A typical 1000-kWt reactor described here could satisfy all DoD 10- to 250-kWe power demands, but there would be some mass penalty at the lower power levels, as is discussed later.

The reactor core contains 91 hexagonal 90% UC and 10% ZrC fuel elements (see Fig. 1). Each element is 24.8 mm across the hexagonal flats and 250 mm long and is contained in a thin-walled molybdenum can. Each 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, 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

Fig. 1
Reactor core subassembly.

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 spring-loaded compression plungers. Multifoil insulation minimizes heat transfer from the core to the reflector. The core, with its 91 heat pipes, essentially provides 91 independent loops for removing heat. Loss of one heat pipe causes slightly elevated temperature in the surrounding pipes, but the surrounding elements can easily tolerate the change. The core could thus sustain several failures with no major degradation of performance.

The core is surrounded by a neutron reflector of beryllium 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 reflector is 100 mm thick. The reactor is controlled by changing the position of neutron-absorbing material within the reflector. Both sliding blocks and rotating drums are considered for reactivity control, but rotating drums were selected because of experience with them in previous space reactor development. Six 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 I shows typical design parameters for the 1000-kWt reactor. Table II compares the 1000-kWt with 200- and 600-kWt reactors, and Fig. 2 shows reactor mass vs power level.

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.

- Small physical size

- Unmanned space application with comparable allowable neutron and gamma doses
- Comparable radiation flux levels.

a. Requirements. Most sensitive to radiation in an unmanned spacecraft are electronic circuits and semiconductors.³ A reasonable integrated dose that can be tolerated by carefully selected components is 10^{13} nvt of fast neutrons and 10^7 rads of gamma rays; these doses have been chosen as nominal payload goals. Depending on requirements, shielding can be minimized by increasing the separation of the reactor and payload or by using localized shielding.

b. Design Considerations. Only shadow shielding is required because the operating conditions are as follows.

- 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.
- Generally there will be no material outside the cone of shielding to scatter the radiation toward the payload.

The shield can be considered as follows.

- Neutron attenuation is provided by lithium hydride (LiH).
- A heavy-metal gamma shield is added at the reactor end of the shield if needed.
- The LiH is assumed to be in the shape of a frustum.
- The cone shields the payload and other equipment from all radiation sources, both direct and reflector-scattered.

The shield weight is sensitive to the following variables.

- Attenuation required (a factor of 2 change produces a 10% weight change).
- Cone half-angle (a 1° variation produces about 10% weight change)
- Spacing between reactor and shield (a 7.5-cm variation implies a 10% weight change). This spacing is determined by reactor design requirements.
- Radius at reactor face of the shield (a 1.5-cm variation produces about 10% weight change).

TABLE I
DESIGN PARAMETERS FOR 1000-kWt REACTOR

<u>Temperatures (K)</u>			
Max fuel delta t	142.7		
Ave delta t across heat pipe wall	19.5		
Ave fuel temperature	1467		
Max fuel temperature	1572		
Burn fraction of ^{235}U	0.043		
<u>Reactor Dimensions (m)</u>		<u>Fuel Element Dimensions (mm)</u>	
Core diam	0.25	Width across hex flats	24.8
Core height	0.25	Equiv fuel element diam	26.0
Reactor diam	0.45	Equiv fuel region o.d.	25.4
Reactor height	0.45	Heat pipe o.d.	15.3
Reflector thickness	0.10	Vapor diam	11.8
Pipe length outside reactor	0.75	Vapor area (mm ²)	109.9
Total heat-pipe length	1.10		
Overall reactor and heat-pipe length	1.20		
<u>Reactor Mass (kg)</u>			
Fuel	80 (includes 68 kg of ^{235}U)		
Reflector	114		
Heat pipes	75		
Control system	33		
Support Structure	21		
Total	323		

In the SNAP shields, the LiH is spring-loaded against the cone to improve heat transfer and resist launch loadings. Also, the LiH must be encased to maintain a hydrogen overpressure and prevent gradual hydrogen loss. The LiH must be kept at at least 600 K during operation so that it can reabsorb radiolytically decomposed hydrogen and thereby prevent swelling. Neutron and gamma absorption will generate enough heat to maintain the temperature during operation.⁹

To minimize single-point failures, the LiH can 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 the reactor to the radiator on one end and to the payload on the other. The load can be carried by the outer conical shell, with appropriate end fittings.

c. Lithium Hydride. Lithium hydride is an excellent shielding material for space reactors because it has high hydrogen density (5.9×10^{22} atoms/cm³), low overall density (0.775 g/cm³), and a moderately high melting point (961 K). A great deal of engineering data on LiH is available, and a variety of LiH space nuclear shields have been fabricated and used, as in SNAP 2, 8, and 10A, built in the mid-60's by AI.

TABLE II
REACTOR PARAMETERS

	200 kWt	600 kWt	1000 kWt
Equivalent core diam (mm)	190	220	250
Reactor diam (mm)	392	420	450
Core height/diam ratio	1.0	1.0	1.0
Number of core heat pipes	37	61	91
Width across flats of hexagonal fuel element (mm)	31	27	25
Heat pipe outer diam (mm)	11	14	15

WEIGHTS (kg)

	200 kWt	600 kWt	1000 kWt
Fuel (90 UC - 10 ZrC)	51	64	80
Reflector (Be and BeO)	80	97	115
Heat pipes	14	44	75
Control	33	33	33
Reactor support structure	13	17	21
Total Reactor	191	254	323

Lithium hydride can be used either cold-pressed and sintered or in the cast form. Small LiH bodies are formed most easily by cold pressing and sintering; large bodies are joined by casting. Al can cast very large pieces for reactor shielding.⁴

For long-term missions (~7 yr) at elevated temperatures, LiH must be hermetically sealed to prevent loss of hydrogen by dissociation.⁵ Permeation coefficients of cladding materials will probably govern hydrogen loss. Tight containment of LiH does present a complication in high-neutron-flux fields if natural lithium is used. About 7.5% of natural lithium has a very high thermal-neutron cross section (945 barns at 2200 m/s) for the reaction ${}^6\text{Li}(\eta, \alpha){}^3\text{H}$. The helium this reaction generates would build up significant pressures in the containers during the system lifetime. So it may thus be desirable to eliminate the lithium-⁶ isotope and use only the lithium-⁷ isotope (LiH) in regions of the shield where the thermal-neutron fluence is expected to be high.

Fig. 2.
Reactor mass vs power level.

Lithium hydride has very little strength (~19 MPa ultimate tensile strength at room temperature). It is brittle at room temperature and below but exhibits plastic behavior above ~530 K.⁶ Because of its low strength, it will be reinforced with a metallic-foil web, probably a 300-series stainless steel. The web will prevent the LiH from rattling around in its containers during the shock and vibration of launch and will prevent large cracks from developing.

d. Shield Mass. The shield is shown in Fig. 3. The end of the reflector is rounded to reduce shield weight and the possibility of secondary scattering. The shield may be attached to the reactor as in some Brayton cycle configurations or separated from it to permit bending heat pipes around the shield to the converters as in layouts of thermoelectrics. The shield weight is a function of power level, cone half-angle, and distance between payload and reactor. Lithium hydride neutron attenuation is shown in Fig. 4. Four decades of attenuation require a 570-mm-thick shield.

Figure 5 shows the shield mass for a typical Brayton converter design for 50 kWe (200 kWt) with no separation between reactor and shield. The effect of designing the reactor for 1000 kWt but operating at 200 kWt is shown in Fig. 6. Figure 7 shows the shield for a thermoelectric design. Figure 8 shows variation of shield thickness with separation distances. Figure 9 shows shield weight as a function of power level for 12° cone half-angle in Brayton and thermoelectric converters. The 1000-kWt reactor assumes a single design for all electric power levels,

Fig. 3.
Reactor shielding.

Fig. 4.
Lithium hydride neutron radiation attenuation.

Fig. 5.
Brayton cycle shield mass for 200-kWt design operating at 200 kWt.

Fig. 6
Brayton cycle shield masses for 200- and 1000-kWt designs operating at 200 kWt.

Fig. 7.
Thermoelectric shield mass for 1000-kWt
design operating at 200 kWt.

the customized core design implies a different reactor design for each power level. The mass of any given shield will depend on the mission, and it may vary from a few kilograms to many hundred kilograms.

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

Fig. 8.
Shield thickness vs separation distance.

Fig. 9.
Shield mass based on 25-m separation of core
and payload.

as the power conversion element of RTGs with demonstrated high reliability.

The reactor being considered contains 91 hexagonal fuel elements, each cooled by a centrally located heat pipe. The heat removed by each heat pipe becomes the heat source of a TE module. The hot-side heat source for the TE power conversion module is assumed to be molybdenum heat pipe whose working fluid is sodium. The heat pipe operates at about 1275 K.

The cold side of the TE module will be cooled by heat pipes that are an integral part of the space radiator. The cold-side temperature is a compromise between optimal TE efficiency and space radiator size. Other factors involved are materials compatibility, heat pipe working fluid, and radiator size restraints. The cold junctions may be interconnected to provide redundancy and increased reliability.

Preliminary evaluations have shown that it is desirable to operate the radiator at a high temperature to minimize size and weight. About 775 K TE heat sink temperature seems nearly optimum and is in the range already tested with potassium-filled heat pipes. The reference radiator heat pipe material is beryllium with titanium as an alternate.

A number of semiconductor TE materials have been developed. Three of potential interest are the tellurides (used in several space mission RTGs), silicon-germanium (Si-Ge), and selenides. The tellurides are not considered here because of their low operating temperatures. They have relatively high efficiency (7.5%) and demonstrated reliability, but require low sink temperatures that would lead to very large radiator requirements for high total power outputs.

Silicon-germanium alloys have operated at above 1275 K and have been studied extensively. This is the material in the MHW radioisotope generators used in LES 8 and 9, and MJS missions. Si-Ge is well known and has the potential for operating at as high as 1400 K with 6.5% efficiency.

Minnesota Mining and Manufacturing Co. (3M) is developing selenides for the SIG program. This relatively new material, by simply replacing Si-Ge, could increase output by 50-100%. Extensive testing of a selenide TE ground demonstration system will begin in 1978. Selenide development could significantly increase the output of a space nuclear TE system.

The specific weight and performance of a TE power conversion system matched to the high temperature and high heat flux capability of the heat pipe source and heat pipe sink have been estimated. Simple extrapolation from the RTG technology used in the MHW, LES 8 and 9, or SIG systems is impossible because they were designed for the low heat flux characteristic of the radioisotope heat source. The high power and high heat flux of a heat-pipe

cooled reactor significantly affect optimum TE converter design. 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 Syncal Corp. built and tested several years ago though several other companies have designed high-performance TE modules. Figure 10 is a conceptual drawing of the module.

The TE circuit consists of negative and positive Si-Ge TEs and hot- and cold side electrical connectors placed between hollow metal cylinders. Electrical insulators in the form of cylinder sections isolate the TE circuit from the cylinders. The inner cylinder is the outside wall of a sodium-filled heat pipe. The outer cylinder forms the inner wall of a concentric tube heat pipe. The TE elements are thermally in parallel and electrically in series, with heat flow between the inner and outer heat pipes.

The TE module is made without metallurgical bonds between the components of the compression module. Good thermal and electrical contact among the various parts is ensured by the compression force of the outer cylinder. The complete module is assembled with a shrink-fit outer member. During operation, the thermal gradient from hot inside to cold outside adds further compression. At the expense of weight and complications, compression could be supplied to the cold shoes of the module by spring hardware. Spring compression is the more

Fig. 10.
Thermoelectric design concept.

common approach for lower temperature modules operating at low heat flux.

Projected conversion efficiency of the compression module based on work by Synal Corp. is presented in Fig. 11. The estimated conversion at 1275 K hot side and 775 K cold side is 5.3%. For comparison, a selenide material of twice the output, but limited to 1075 K hot-side temperature, would show no improvement at 775 K sink temperature. At 1175 K, the selenide module efficiency would be about 8% and, at 1275 K it would be > 10%. The selenides thus hold promise for future development.

In summary, the Si-Ge TE conversion system with a hot-side temperature of 1275 K and cold-side temperature of 775 K is projected to have 5% efficiency and weigh 5.5 kg/kWe. Using advanced TE materials, twice the efficiency is possible within the same 5.5-kg/kWe weight.

Fig. 11.

Si-Ge thermoelectric module efficiency.

The electrical power from TE modules depends on operating temperatures, and it scales linearly with the number of modules. The specific mass of the modules is increased from 5.5 to 6.8 kg/kWe to provide for a common TE converter heat sink ring to thermally cross-couple the TE modules with redundant heat rejection paths.

TE thermoelectrics are low-voltage devices that can be combined in a series parallel network. The usual output voltage is 29 Vdc.

b. Dynamic Converters. The Brayton cycle is used here 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, turbine, and alternator on a single shaft supported on foil gas bearings) and heat exchangers from the reactor and recuperator 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 at low temperature and pressure enters the compressor and is discharged into the recuperator at higher temperature and pressure. Passing through the recuperator, the working fluid is preheated before it enters the heat source 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 and pressure are 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 radiator, 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. 12.

A single-unit Brayton converter has operated over 26 000 h in tests by NASA-Lewis Research Center 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 kWe.

Dynamic converter specific mass depends on the number of redundant loops. Representative values are given in Fig. 13. The dimensions of typical components are given in Table III. Key cycle

Fig. 12.
Brayton cycle power system.

parameters, Fig. 14, show that minimum system mass is obtained at about 25% efficiency. The dynamic converters supply most power at 120 Vdc and provide 67-Vac, three-phase, 1733-Hz options. Other voltages and frequencies can be obtained using different power conversion components.

4. Radiators. The radiator is being designed for 99% reliability and 7-yr lifetime. Its area depends on such factors as the converter efficiency, electric power level, heat rejection temperature, and view factor to space. The radiator area required to meet full-power, EOL performance can be computed using

$$Q_{\text{rejected}} (w) = \text{Area} (m^2) \times 5.67 \times 10^{-8} \left(\frac{w}{m^2 K^4} \right)^{(0.9)}$$

$$\left[T_{\text{radiator}}^4 (K) - T_{\text{space}}^4 (K) \right],$$

where

$$Q_{\text{rejection}} (w) = w(c) \left(\frac{1-\eta}{\eta} \right),$$

η being the system efficiency.

The BOL area that accounts for probable component failures depends on the radiator design. The

Fig. 13.

Brayton converter mass vs. power.

thermoelectric converter radiator is designed to maintain a cold-junction temperature of 775 K. Higher efficiencies obtained by designing for a lower temperature would increase mass and size. The present concept is based on stringer heat pipes 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 (Fig. 15). The arrangement is designed to have high redundancy.

Protecting the radiator against meteoroid penetration is considered. Calculations of meteoroid penetration were based on NASA space shuttle user guidelines for payloads in geosynchronous orbit.^{7,8} 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 16 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 for 78% survivability. 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. Beryllium radiator mass as a function of heat rejection is shown in Fig. 17. The area is shown in Fig. 18. Radiator design for a Brayton converter has been estimated from the thermoelectric radiator design.

C. Power Plant Systems

1. System Mass. A general rule-of-thumb in spacecraft design is that the power subassembly will be 30% of the total spacecraft mass. For a single space shuttle IUS launch to geosynchronous orbit, this allows a design goal of 955 kg, and for a dual-launched spacecraft a goal of 1910 kg, for the power system. Within this mass constraint, various converter technologies are being examined, as is the effect of selecting a single reactor to span the entire power range of interest. A single reactor sub-assembly development program should minimize development cost; the shield, converter, and radiator would be sized for a given mission. A heat-pipe cooled reactor is used for a reference system because of the high redundancy that can be built into its design.

Figure 19 shows a thermoelectric system. The core module is for a 1000-kWt 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. Performance parameters for 6° and 12° cone half-angle shadow shields based on a single 1000-kWt design are shown in Table IV.

A representative power plant layout for the Brayton cycle is shown in Fig. 20. The Brayton cycle has potential efficiencies up to 35%, so a 1000-kWt 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, either duplicate loops each capable of full-power operation or three

TABLE III

DIMENSIONS OF BRAYTON CONVERTER COMPONENTS (m)

Component	12.5-kWe	25-kWe	37.5-kWe	50-kWe
Rotating machinery	0.3 x 0.6	0.3 x 0.7	0.3 x 0.7	0.3 x 0.7
Recuperator	0.4 x 0.2 x 0.5	0.5 x 0.1 x 0.5	0.6 x 0.1 x 0.5	0.7 x 0.1 x 0.5
High-temperature heat exchanger length	0.3-0.4	0.3-0.4	0.4-0.5	0.4-0.5
Radiator heat exchanger (gas side)	0.2 x 0.2 x 0.4	0.2 x 0.3 x 0.2	0.2 x 0.3 x 0.3	0.2 x 0.3 x 0.4

parallel Brayton converters each capable of half-power operation have been included in the system mass totals. This redundancy achieved at some weight penalty appears feasible within the total weight constraints. Even if 90% reliability can be provided by a single converter loop, we feel that parallel, independent, redundant loops are needed to significantly minimize single-point failure.

Table V shows the mass parameters of major components at 10, 50, and 100 kWe. Included also are calculations for a thermionic converter with a UO_2 reactor. The mass range is based on a customized reactor vs a single 1000-kWt reactor. In each case, the shield, converter, and radiator are adjusted for the power level. The information in Table IV is plotted in Fig. 21. A single shuttle, allowing 10% for contingencies, could deliver 30 kWe to geosynchronous orbit as a standard 1000-kWt reactor designed using thermoelectric converters. A dual shuttle would deliver about 115 kWe to geosynchronous orbit as a standard 1000-kWt reactor designed using dual Brayton converters.

2. Dimensions. The overall length of the power plant is dominated by the radiator. Assuming that no heat is rejected through the bottom of the radiator because of the payload location or by deliberate design to reduce infrared detection, the lengths of typical power plants are as given in Tables VI and VII. For the thermoelectric systems, the only component located within the radiator is the telescoping boom, so much of the radiator volume is available for storage of other parts of the

payload in the stored configuration. The radiator length can be reduced by increasing the shielding cone half-angle, but only by increasing shield mass. The Brayton converter is located within the radiator. Larger systems may require a deployable radiator because of size constraints imposed by the shuttle bay.

3. Lifetime. Nuclear power plants are being designed for 7-yr lifetimes. The fuel burnup after 7 yr at 1000 kWt is 4.3%. The core lifetime without failures, based on fuel burnup, is 35 yr at 50 kWe and 12 yr at 150 kWe.

4. Reliability. Nuclear power plants have traditionally been designed to very high reliability standards. The overall power plant is being designed for 95% reliability throughout its lifetime. Also, redundancy is incorporated into the designs to avoid any single-point failures.

The power plant is being designed for EOL conditions. Therefore, the design accounts for the fact that a number of heat pipes in the core may fail, the radiator will lose a certain number of heat pipes because of meteorites, etc. The system power is regulated throughout its lifetime by varying the amount of energy generated in the core. Thus, the beginning and final electric power output are programmed to be the same.

To meet the reliability goals, each component will be subjected to rigorous failure-mode analysis. All possible failure mechanisms will be investigated

SYSTEM INCLUDES: 250-kg, 200-kW REACTOR SYSTEM
THREE 25-kW MODULES
TWO OPERATING, ONE ON STANDBY
RADIATOR AT ASSUMED 1.5 kg/m²

Fig. 14.

Brayton cycle performance characteristics at 50 kWe.

methodically as functions of time. This effort involves analysis of each component's behavior with age. Where the material data are inadequate or the component's ability to meet the overall reliability goal is suspect, tests must be performed to determine what action will ensure adequate behavior.

Component failure-mode analysis is an effective engineering design tool that helps reveal potential

Fig. 15.
Radiator layout.

problem areas and design modifications that can minimize or eliminate them. The analysis is a systematic investigation of how a component can fail; it scrutinizes design features and fabrication processes that can lead to failure. The procedure entails preparation of a complete physical description of the component to be analyzed, including drawings or sketches, and identification of significant design features that affect performance. This complete functional description is essentially a summary of specifications of what the component is required to do within specified limits, under specified conditions, for a specified time or number of cycles. Launch and flight environments must be included. The mechanisms of each failure mode must be defined. Intangible factors such as possible contamination or improper assembly must be included. Nonoperational environments such as shipping, storage, and exposure to harmful atmospheric conditions must be taken into account. The failure-mode analysis can lend confidence to the design and provide a basis for development testing.

A systems failure-mode analysis should be performed to define failure modes and their consequences during operation. It will define (1) single-point failures, (2) failures that are automatically compensated for in normal operation, (3) failures that in combination with others may lead to single-point system failures, and (4) failures that directly degrade the output. The objective is to ensure systematic and detailed review of all possible effects of system component failures and to provide a basis for system contingency analysis. The failure mode

Fig. 16.

Radiator mass for various candidate materials.

analysis permits consolidation and traceability of component failure modes and mechanisms to system effects. It will involve identifying the failure modes of each component, the phase of operation applicable to each failure mode, and the failure effect.

Subsystem reliability is calculated as follows: reactor and controls, 98%; converter, radiator, and power regulator, 99% each. The reliability can be obtained as follows.

- By building redundancy into all critical components, including independently redundant converter loops.
- By building redundancy into the reactor core through defense-in-depth design. For example, the fuel elements are designed to maintain their structural integrity. However, they are also encapsulated

Fig. 17.

Radiator mass vs heat rejection.

Fig. 18.

Reject heat vs radiator area.

in canisters to provide backup in the event of cracking. The core is also designed so that if a heat pipe fails, the heat is transferred to other heat pipes to prevent system degradation.

- By keeping the number of frictional moving parts minimal.
- By making the operation a single condition.
- By using only proven materials and technology if possible.
- By designing for slow degradation rather than immediate overall system failure.

Fig. 19.
Thermoelectric power plant.

- By conducting a comprehensive materials and experimental test program including rigorous failure-mode analysis of each component.

5. Effects of Natural Radiation. The reactor components operate within very high radiation levels. At 1000 kWt, the rad levels at the reactor surface are about 10^{10} times higher than those from natural radiation. The space radiation environment will not significantly affect reactor life or performance.

6. Safety

a. Power Plant. Redundancy is the key to providing reliable safe hardware systems. For space systems, however, the number of levels of redundancy must be balanced against resulting increases

in weight and complexity, which themselves reduce the probability of mission completion. Safety features proposed for the nuclear system to prevent a reactor criticality accident are as follows.

- The control drums can be pinned in the shutdown position with captive-key locks for all noncritical Earthbound nuclear operations. It should be possible to unlock and operate one drum at a time for testing. The pins would be removed before launch.
- The AI control-drum actuator has a brake that holds the drum in position until the brake is energized. The motor does not have enough torque to drive the drum with the brake engaged.
- With six control drums, shutdown can be satisfactory when some drums are inoperative.
- A separate shutdown controller will ramp the control drums to their shutdown position if the normal control system fails. This controller should not share

TABLE IV

COMPARISON OF THERMOELECTRICS WITH VARIOUS SHIELD ANGLES
(Based on 1000-kWt core design and 7-yr lifetimes)

	10 kWe		50 kWe		100 kWe	
Reactor power (kW)	125		625		1000	
Efficiency (%)	8		8		10	
Radiator power (kWt)	115		575		900	
Radiator temp (K)	775		775		675	
Shield half-angle (deg)	12	6	12	6	12	6
Mass (kg)						
Core	325		325		325	
Shield	150	100	150	115	210	130
Converter	70		340		680	
Radiator	30		200		555	
Structure	45		85		100	
Total	620	570	1140	1065	1950	1870
Length (m)						
Core	0.5		0.5		0.5	
Separation	0.2		0.2		0.2	
Shield	0.4		0.5		0.5	
Separation	0.1		0.1		0.1	
Converter	0.1		0.2		0.4	
Radiator	2.0	2.7	5.5	8.1	6.8	9.7
Total	3.3	4.0	7.0	9.6	8.5	11.4

electronic components with the normal controller and should have an alternative energy source. It should be able to override any actions of the normal controller after an emergency shutdown is initiated. The system should be capable of being reset for normal operation after an emergency shutdown.

- High redundancy built into the reactor, converter, and radiator provides alternate heat transfer paths with enough parallel heat pipes to guarantee core integrity without an emergency cooldown system.

b. Ground and Launch Operations. Safety during ground and launch operations must be considered; however, safety requirements have been met as demonstrated in the flight test of the SNAP-10A reactor. The safety program will closely parallel that described for isotopes, with tests to show that

Fig. 20.
Brayton cycle layout.

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

	10 kWe			50 kWe			100 kWe		
	TE	Brayton	Thermionics	TE	Brayton	Thermionics	TE	Brayton	Thermionics
Reactor Power (kWt)	125	40	50	625	200	250	1000	400	500
Fuel	UC-ZrC	UC-ZrC	UO ₂ -Mo	UC-ZrC	UC-ZrC	UO ₂ -Mo	UC-ZrC	UC-ZrC	UO ₂ -Mo
Efficiency (%)	8	25	20	8	25	20	10	25	20
Radiator Power (kWt)	115	30	40	575	150	200	900	300	400
Radiator Temp (K)	775	475	900	775	475	900	675	475	900
Mass (kg)^a									
Core	185-325	185-325	305-545	255-325	190-325	320-545	325-325	220-325	400-545
Shield ^b	135-150	90-110	165-190	180-190	105-130	190-210	210-210	125-145	215-235
Converter	70	250 ^c	20	340	460 ^c	110	650	710 ^c	210
Radiator	30	30	10	200	150	55	555	300	110
Structure	45	60	60	85	95	70	180	135	90
Total	465-620	615-775	560-825	1060-1140	1000-1160	745-990	1950-1950	1490-1615	1025-1190
w/kg	21-16	16-13	18-12	47-44	50-43	67-51	51-51	67-62	98-84

^aFirst number is for customized reactor, second for 1000-kWt standard reactor.

^bAssume 12° cone half angle at 25 m.

^cDual converter systems.

Fig. 21.
Nuclear power system mass.

launch pad fires, propellant fires, impact at terminal velocity during a launch abort, and water impact all can be handled safely. The reactor will not be operated before launch, so it will not achieve appreciable radioactivity before flight and can be handled safely. It will not have developed any fission products to cause danger in case of a shuttle malfunction. The uranium fuel poses minimal safety concern.

c. Orbital Operations. Safety during operation is provided by not operating the reactor until a safe orbit is achieved. After the mission, the reactor can be left in orbit or put into a higher orbit. Once the reactor has been operated, there is no plan to return it to Earth.

7. Fluid Freezing. Startup or restart after solidification of the fluids in the heat pipes has been considered and demonstrated many times.

8. Controls and Instrumentation

a. Design Considerations. The current concept is to control the reactor by use of six rotating drums in the reflector. Each drum has an arc segment of neutron-absorbing material on one side. Reactivity

is increased or decreased, respectively, by rotating this material away from or toward the core. Each drum will be rotated by a stepping-motor actuator located on the side of the shield for protection from the high nuclear and thermal radiation. The maximum positive reactivity-rate capability of the control actuators will be very low for safety reasons. On the basis of ROVER experiments, this approach looks very feasible.

For guidance in studying the controls, we assume that the ultimate output would be 28 V from thermoelectrics and 120 Vdc from Brayton converters regulated from full power down to some nominal lower value, possibly zero. Two possible control approaches are as follows.

Control drum operation under closed-loop control to produce a constant output current. The payload voltage would be regulated by dumping unneeded energy into a payload heat radiator, through use of a high-performance series or shunt regulator located in the payload module. A temperature-cutback capability would be provided to prevent overheating high-temperature systems. This approach allows high-temperature systems to operate at essentially constant temperatures. It requires that a radiator be able to radiate the full thermal energy generated by the reactor, but this capability would probably be needed anyway.

Control drum operation as required to provide the correct voltage to the payload with a slow control loop. A shunt regulator would provide rapid regulation of payload voltage. The steady-state power dissipated in the shunt regulator would vary from zero for full payload to several kilowatts at reduced power. As in the above system, a temperature cut-back capability will be necessary. This control approach permits (1) operating the high-temperature systems at lower temperatures, (2) operating the TEs at lower currents, and (3) reducing the payload radiator heat load. However, it produces slow temperature changes in the high-temperature systems.

Information now available is insufficient for proper evaluation of the two approaches. Both will require temperature control based on thermocouples in or near the reactor core for startup. Figure 22 diagrams the control system.

The control and instrumentation electronics will be mostly digital circuits located in the space station. The system probably will be controlled by a

TABLE VI
THERMOELECTRIC SYSTEM DIMENSIONS

	<u>10 kWe</u>		<u>50 kWe</u>		<u>100 kWe</u>	
Efficiency (%)	8		8		10	
Core design Length (m)	<u>Optimized</u>	<u>1000-kWt</u>	<u>Optimized</u>	<u>1000-kWt</u>	<u>Optimized</u>	<u>1000-kWt</u>
Reactor	0.4	0.5	0.4	0.5	0.5	0.5
Separation	0.2	0.2	0.2	0.2	0.2	0.2
Shield ^a	0.4	0.4	0.5	0.5	0.5	0.5
Separation	0.1	0.1	0.1	0.1	0.1	0.1
Converter	0.1	0.1	0.3	0.2	0.4	0.4
Radiator	2.0	2.0	5.5	5.5	6.8	6.8
Total	3.2	3.3	7.0	7.0	8.5	8.5

^a10¹³ nvt at 25 m with 12° cone half-angle.

TABLE VII
BRAYTON SYSTEM DIMENSIONS

Power	<u>10 kWe</u>		<u>50 kWe</u>		<u>100 kWe</u>	
Efficiency (%)	25		25		25	
Core Design Length (m)	<u>Customized</u>	<u>1000-kWt</u>	<u>Customized</u>	<u>1000-kWt</u>	<u>Customized</u>	<u>1000-kWt</u>
Heat exchanger	0.4	0.3	0.4	0.3	0.4	0.4
Reactor	0.4	0.5	0.4	0.5	0.4	0.5
Shield	0.4	0.4	0.4	0.4	0.5	0.5
Piping separation ^a	0.3	0.3	0.3	0.3	0.3	0.3
Radiator (deployed)	3.1	3.1	8.7	8.7	12.9	12.9
Total	4.6	4.6	10.2	10.2	14.5	14.6

^aBrayton components are located inside the radiator.

Fig. 22.

Preliminary block diagram of reactor control system.

microprocessor during normal operation. A shutdown controller will be provided to scram the control drums if emergency shutdown is required.

b. Control Actuators. AI's stepping-motor actuator development for SNAP has established a good technology base for the control actuators. Continued low-level funding has enabled AI to accumulate a lot of test time on their actuator. It is a stepping motor with an output torque of 0.71 N/m (100 oz/in.) and 31.41-mrad (1.8°) step. It requires 12-V, 5.5-A excitation and weighs approximately 3.5 kg (8 lb). It also has an integral brake. Most of the AI high-temperature testing has been at 810 K, but testing at 975 K has produced no failures.

Control-drum actuator design can use the AI actuator in its present form. Heat sinking the actuators to the 775-K converter radiator will probably provide enough cooling. If thermal analysis indicates otherwise, a separate heat-transfer and radiating system will have to be provided for the actuators.

c. Instrumentation. Control information for vehicles in space will be derived from thermocouples on the power plant and from voltage and current measurements. As voltage and current measurements will be made with conventional instrumentation, they are discussed no further.

The primary temperature control parameter is the temperature of the thermoelectric converter package, which should be about 1275 K. Another

important parameter is the core fuel temperature, predicted to be 1390 K. The control temperature will probably be the average of 10-20 measurements to increase its validity and improve long-term reliability. Thermocouple readings that deviate excessively from the average will be rejected from the averaging calculation.

Temperature measurement by means of thermocouples is well within the state of the art. The major problem will be to determine, by information search or by testing, whether long-term stability will require use of refractory-material thermocouples rather than inexpensive medium-temperature devices. The primary transducer candidate is the Chromel-Alumel thermocouple with an Inconel-600 sheath and high-density MgO insulation. Its lowest melting temperatures are 1630 K for Inconel 600 and 1620 K for Chromel. It may be desirable to have a backup refractory-material thermocouple.

Use of the control drums' shaft positions as a control parameter will not be required, but it would be highly desirable to use them for startup and safety purposes. Several transducer approaches are feasible.

The electronics associated with the control and instrumentation systems can be located in the payload module. The payload radiation level is low enough to permit use of conventional electronic components. Redundant electronic subsystems may be used where necessary to avoid single-point failures.

d. Startup and Shutdown. The control system will permit startups and shutdowns both on the ground and in space. The startup scheme for vehicles in space will evolve from analysis of the problem and information from ground tests. Restarting will be complicated by uncertainty about the cold critical control drum position caused by fuel burnup and fission product poisoning. The time allowed for startup will determine the type of system to be developed. One possible scheme is as follows.

- Ramp the control drums relatively quickly from shutdown to a position well below cold critical.
- Ramp the drums through cold critical very slowly.
- When the temperatures at the core end of the heat pipes reach the lowest controllable value, switch to temperature control.
- Raise the control temperature enough to thermally activate the heat pipes by conduction within a reasonable time.
- When differential temperatures along the heat pipes indicate that these are operating, increase the control temperature enough to permit switching to high-power control.

Several good options for nonemergency shutdown are available. Two obvious methods are simply to ramp the control demand to zero or to ramp the control drums to the shutdown position. The ramping would be slow enough to avoid excessive thermally induced stresses.

9. System Performance. Figure 21 showed the performance of UC reactors with thermoelectric and Brayton converters and of UO_2 reactors with thermionic converters. NASA is working to demonstrate a 400-kWe UO_2 reactor with thermionic converters in the late 1980's or early 1990's. Projections are based on the more conservative assumptions about thermoelectrics and Brayton converters. Two curves are shown for each converter. The lower is based on a customized reactor for each power level. However, to minimize development cost, one might be willing to design a single reactor to span the power regime of prime DoD interest. Then the shield, converter, and radiator would be tailored for individual missions. The top curve for each converter is represented by the single reactor design.

The zirconium hydride reactors are added to the data in Fig. 21 in Fig. 23 to show the mass improve-

Fig. 23.
Comparative reactor masses.

ment that is achieved with higher temperature UC reactor systems. What is not obvious is that all single-point failures have been eliminated from the UC and UO_2 reactors, whereas the U-ZrH reactors contain loops that can experience such failures.

III. PROGRAMMATIC ASPECTS

A. Basic Principles

The development plan is based on the following precepts.

- The space reactor power system should meet as many potential space mission requirements as can be determined.
- This program will consider all practicable designs in light of the latest reactor and conversion subsystem technologies.
- Selection of a space reactor power system to develop should be based upon an organized program

of design studies and iterative comparisons with space mission requirements.

- Systems that offer flexibility for a range of missions rather than optimizing for a particular mission will be emphasized. Thus the modular, or building block, approach and future growth will become important in choosing future systems.

B. Major Program Phases

Applications Analysis. This survey of potential users of, and applications for, space reactor power systems will continue at a modest level of activity throughout the program. Periods of increased activity will precede preparation of the three Requirements Reports. These reports will be issued at the end of the Screening Studies and of the evaluation preceding the two major hardware efforts, the ground demonstration system and flight system development phases. The ground demonstration phase is to ensure that the hardware effort is directed to the most promising applications.

Screening Analysis. This analysis is the initial half of the selection process. It calls for a limited conceptual review of a large matrix of possible space reactor power systems derived from the most promising reactor types, conversion systems, and auxiliary technology, that is, heat transfer and reactor control. By a series of iterative screenings, many potential power systems will be reduced to a few (2-4) that seem to have maximum promise.

Design Studies. Design studies are the final half of the selection process. Each potential space reactor system selected as most promising will be the subject of a design study in substantial detail. Where appropriate and necessary, these efforts may include limited experimental programs to study critical design problems. One of the systems so studied will be selected for development into hardware.

Ground Demonstration System. The ground demonstration system phase consists of final design,

construction, and operation of the selected space reactor power system. Reactor power system development is expected to end with ground demonstration. Conversion subsystem development may involve adapting a previously operated system to a new set of operating parameters. If possible, each subsystem should be operated independently before mating, but radiation effects and transfer techniques must be considered. Ground test results and the latest mission requirements will be reviewed, and a DoD requirement letter or equivalent would be in hand before initiation of the final flight hardware effort, for maximum assurance of user acceptance.

Flight System. Flight system development will be based on the ground system performance and mechanical evaluation of the engineering model. A qualification space reactor system, a complete functioning system, will be constructed to the flight configuration design. It will be subjected to qualification level testing and performance mapping and will be placed on life test. If it performs acceptably, the flight system will be constructed to the same design, subjected to flight acceptance level testing, and delivered for flight.

C. Evaluation Activities

The Nuclear Research and Applications Division of ERDA will perform an evaluation following each phase. Results will be compared to the DoD requirements to determine whether to proceed to the next phase or to extend the concluding phase for design refinement.

D. Schedule

Figure 24 is an abbreviated program schedule. Depending on DoD need dates and funding, the schedule can be compressed to provide flight hardware in 1984 if required.

*PSAR = Preliminary safety analysis report.
 **USAR = User safety analysis report.
 ***FSAR = Final safety analysis report.

Fig. 24.
 Program schedule.

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