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2

HEAT PIPE SPACE NUCLEAR REACTOR DESIGN ASSESSMENT

Volume I of II

Design Status of the SP-100 Heat Pipe Space Nuclear Reactor System

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This document reviews the design status, as of October 1982, of the SP-100, heat pipe space nuclear reactor system. It also identifies those systems and components requiring additional research to support continued SP-100 system development.

The heat pipe reactor was designed by Los Alamos National Laboratory (LANL) to produce 100 KWe of continuous power in a space environment. The design constraints include an expected system operation time of 7 years and a maximum weight of 3000 kg. The reactor, employing an unclad, highly enriched uranium dioxide core, operates as a fast reactor, and is cooled by high temperature molybdenum -- 13 percent rhenium, heat pipes with lithium working fluid. Electric power is generated by thermoelectric converters, with the bulk of the thermal energy rejected to space by a radiator panel system.

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PREFACE

This report, the first of two volumes of the final technical report to be issued under Contract No. F29601-82-K-0055 with AFWL, has a twofold purpose: 1) to review the design status, as of October 1982, of the SP-100 heat pipe space nuclear reactor system (Refs. 2 and 14), and 2) to identify technical areas, components, and systems requiring additional research needed to support continued SP-100 system development.

The second volume summarizes the results of an investigation into the feasibility of upgrading the SP-100 system design to achieve higher power (1 to 10 MWe). Those areas for research emphasis which are most likely to expedite the upgrade to higher power will also be identified.

Note: This document reviews the heat pipe reactor, which was the SP-100 reactor design as of October 1982. Since current SP-100 designs include other concepts, "SP-100" whenever it appears in this report should be interpreted as "heat pipe reactor."

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I. INTRODUCTION

1. SPACE POWER SYSTEMS

The recent success of the Space Transportation System (Space Shuttle) puts the United States in a position to more effectively use the frontier of space. It is now possible to launch higher power satellites and other space exploratory vehicles more easily and economically. This better use of space can best be accomplished by the development of space systems of higher powers (100 kWe to several MWe). Such high power systems have both civilian and military uses. Civilian uses include disaster communications networks, holographic conferences, meteorological surveillance, zero-g manufacturing, as well as planetary and lunar exploration and resource utilization. Military uses include space-based radars with increased coverage, communications and surveillance with better survivability, longer range and with onboard processing, jammers, orbital transfer and maneuver vehicles, as well as particle beam and laser weapons.

High power systems in space should have the following characteristics:

(1) High specific power (power per unit mass) because of the high launch costs per unit mass;

(2) Small size, because of the constraint of the Space Shuttle's bay volume;

(3) High reliability, to insure the completion of the mission and to eliminate or reduce the need for system maintenance; and,

(4) Safety to the Space Shuttle crew and to the general populace.

Nuclear reactors are potentially the best source of high power levels (in excess of 100 kWe) for space. Other possible sources are chemical combustion, radioisotope thermoelectric generators (RTGs), and solar. Figure 1 shows the ranges of power generation and of use duration for these four power sources in space (Ref. 1). Chemical combustion is capable of producing high power levels but only for short periods of time because of the large masses of fuel required per unit of power produced. RTGs can provide low power for long durations (20-30 yr) because of the long half-life, $T_{1/2}$ of the radioisotopes used. Usually, because of the large $T_{1/2}$ of the radioisotope, the power level is fairly constant. However, to build high power RTGs, a relatively large mass of a long-lived radioisotope (usually a heavy element) is needed. The result significantly reduces specific

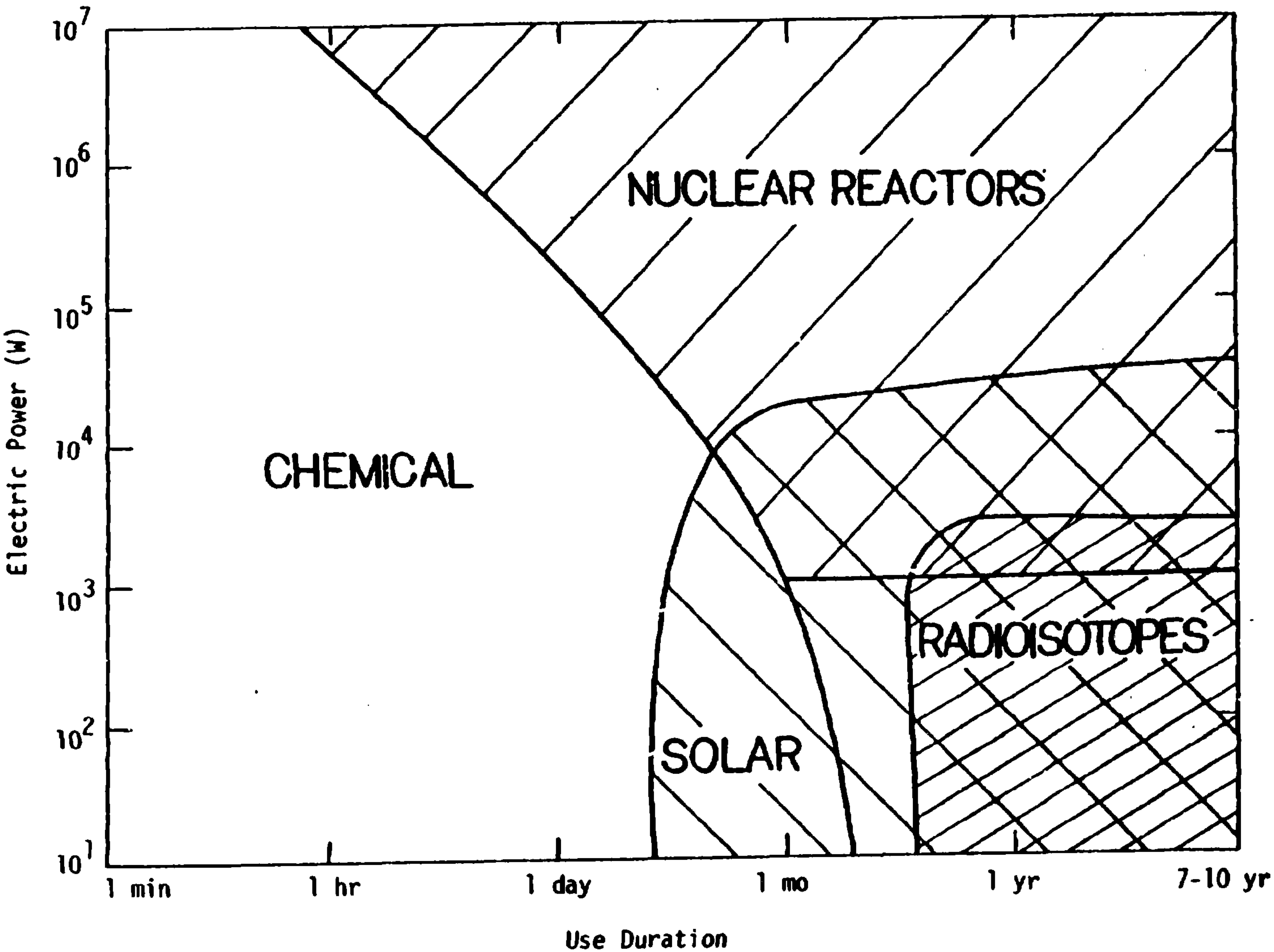

Figure 1. Possible power sources for space missions

power and increases weight and system size. For missions longer than a few months, only solar arrays and nuclear reactors can be configured as a compact power source of greater than 10 kWe. Table 1 compares solar to nuclear power at three power levels (Ref. 1). The mass of 1910 kg under "Shuttle Compatibility" refers to the mass allowed for the power system. Nuclear systems become superior at about the 50 to 100 kWe levels. Requirements of various features are compared in the second part of the table. The main disadvantages of solar power are the lower power density, the large size of solar collector panels, and the requirement of deployment and sunward orientation. The latter feature could obstruct the view available to payload antennas and the maneuverability of the system. The main disadvantage of nuclear power is the need for shielding of the payload from radiation. However, even considering the additional weight of shielding, nuclear reactor systems still provide much higher power density than solar arrays.[1]

Unlike chemical combustion, RTGs, and solar power systems, nuclear reactors can operate in both steady state and pulsed modes of operation. While steady power would suffice for many of the expected uses of power in space, a number of applications would require a pulsed source. The peripheral pulse-forming networks and energy storage systems required for non-nuclear systems would be bulky and heavy. The nuclear reactor system, on the other hand, could be designed with both intrinsic steady and pulsed modes of routine operation, thus avoiding the extra complexity and mass penalty required of the other systems. Power consumed by a space platform could range from low power station keeping and communicating to high power orbital maneuvering and operating defense systems.

2. SPACE NUCLEAR POWER

a. Background--The idea of using nuclear reactors as a prime source of power in space is not new. In 1944, only 2 yr after the world's first controlled nuclear fission experiment, the use of nuclear energy to launch space vehicles was considered. Germany's development of V-2 rockets led to secret feasibility studies of nuclear rockets by North American Aviation and

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[1] Specific power of current solar space power systems is 10-14 W/kg and of advanced solar space power systems is 15-25 W/kg, while nuclear power systems can provide a specific power of 40-55 W/kg (Ref. 2).

TABLE 1. COMPARISON BETWEEN SOLAR AND NUCLEAR REACTOR SPACE POWER (Based on projected technology) (Ref. 1)

	10 kWe		50 kWe		100 kWe	
	Solar	Nuclear	Solar	Nuclear	Solar	Nuclear
W/kg	24	14	24	41	22	55
Relative Cost	8	7	32	10	63	14
Shuttle Compatible (<3000 Kg)	yes	yes	difficult	yes	no	yes
Space Flight	demonstrated	possible	possible	possible	doubtful	possible

Limitations

Feature	Solar	Nuclear
Orientation	Sunward	No requirements
Location	So that it will not be shadowed by large antennas	So that shielding is minimized
Maneuverability	Fold-up arrays	No problem
Natural radiation	Degrades collectors	No effects
Induced radiation	None	Shielding of some components necessary
Reliability	70-90%	95%
Safety	No problem	Some precautions necessary
Disposal	No problem	Long-term earth or sun orbit
Maintainability	Large structure interference	Manned shielding required

Douglas Aircraft Company in 1946. However, the unavailability of materials that could withstand high temperatures discouraged further development until 1955 when the Nuclear Propulsion Division of Los Alamos Scientific Laboratory was formed to undertake the Project Rover rocket development program. In 1959-60, three Kiwi-A reactor rocket engines using uranium impregnated graphite fuel rods and hydrogen propellent were tested. In 1958, the National Aeronautics and Space Administration (NASA) was created in response to the Soviet technological threat manifested by the successful launchings of the Sputnik satellites (Ref. 3). From 1964 to 1969 a series of redesigns and tests under the Nuclear Engine for Rocket Vehicle Application (NERVA) program demonstrated that graphite core rocket engines could be employed over a range of both starting and operating conditions. In the late 1960s two gas core nuclear rockets were designed, the Coaxial-Flow Reactor and the Nuclear Light Bulb Reactor; each heated the hydrogen propellant radiantly. Preliminary tests of concepts gave encouraging results (Refs. 4 and 5).

b. SNAP Program--The Systems for Nuclear Auxiliary Power (SNAP) program concentrated on the development of nuclear reactors for space electrical power generation (Refs. 6 and 7). The SNAP 2, 8, 10, and 50 reactor programs and designs are summarized in Table 2.

The first three SNAP reactors, developed by Atomics International, were thermal reactors, the fuel was approximately 10 percent by weight (wt%), 93 percent enriched uranium (U), alloyed with hydrided zirconium (Zr), and was in the form of clad rods 25 mm in diameter and less than 0.5 m long. The primary core coolant used was NaK (sodium potassium alloy), and reactivity control of the core was provided by rotating Be control drums located in the outer beryllium (Be) reflector. Testing and development of SNAP 2 were successful but the flight testing scheduled for 1963 was cancelled due to governmental budget cuts. SNAP 10A was actually launched and operated in orbit in 1965 for 43 days until it shut down automatically because of the failure of an electronic subsystem. In 1969, testing of the larger, higher-powered, SNAP 8 developmental reactor was prematurely terminated due to ruptured cladding on approximately one-third of the fuel elements, caused by excessive fuel swelling.

The SNAP 50 design, unlike the preceding SNAP reactors, includes a fast-spectrum reactor with UN (uranium nitride) or UC (uranium carbide)

TABLE 2. OVERVIEW OF SNAP PROGRAMS (Ref. 7)

Reactor Development Program	SNAP 2	SNAP 8	SNAP 10A	SNAP 50
Years program in effect	1959-62	1963-69	1958-65	1962-65
Fuel	Hydrided Zr 10 wt%, 93% enriched U	Same	Same	UN or UC
Number of fuel elements	61	211	37	--
Neutron spectrum	Thermal	Thermal	Thermal	Fast
Cladding	Hastelloy B, N (with H diffusion barrier coating)	Hastelloy N (with coating)	Same	Columbium alloys
Reflector	Be	Be	Be	BeO
Reactivity control	Be reflector drums	Same	Same	BeO reflector drums
Primary coolant	NaK	NaK	NaK	Lithium
Power conversion	Hg-Rankine	--	Thermoelectric converters	K-Rankine
Power output	3-5 kWe	400-600 kWt	500 We	350-550 kWe (proposed)
Prime contractor	Atomics Intl.	Atomics Intl.	Atomics Intl.	Pratt and Whitney
Reason for termination of program	U.S. government budget cuts	Cladding rupture	U.S. government budget cuts	Funding cut since no specific application

fuel, lithium coolant and a beryllium oxide (BeO) reflector-control system. Component testing and system development were completed by Pratt and Whitney in 1965. However, a total reactor system was not built, and the funding was terminated because of the lack of a specific need for such a reactor at that time.

In the early 1970s, the use of in-core thermionic conversion for space power was tested. The Gulf General Atomic design of a 40 kWe thermionic power system for a manned space laboratory (Ref. 8) was one such effort. It was designed to be launched by the Space Shuttle in two loads because of its large mass (12,100 kg), most of which was the shielding necessary for the manned space station. In a second design, the power system was designed to be tethered 2 mi away from the space station. This reduction in the required shielding allowed the system mass to be reduced by one-half.

c. Soviet Space Nuclear Reactors--"Romashka" and "TOPAZ", two nuclear reactors, have been developed by the Soviet Union over the last 20-25 yr for use in space (Ref. 9). Romashka is a 500-800 We (40 kWt) fast fission reactor with a maximum temperature of -2000 K and no active cooling system. Thermal-to-electrical energy conversion is performed using silicon-germanium (Si-Ge) thermocouples with a conversion efficiency of 2 percent. The core carries 50 kg of uranium and the overall reactor system weighs over 500 kg. This system's specific power in the range of 1.0-1.6 W/kg is much smaller than most space solar systems. TOPAZ, which is currently being used by the Soviet Nuclear Powered Radar Ocean Reconnaissance satellite (RORSAT) program, employs the thermionic principle for direct conversion of thermal energy to electricity with a conversion efficiency of 12 percent. The TOPAZ reactor weighs 105 kg (Ref. 9) with an estimated thermal rating of 85 kW and electrical rating of between 5-10 kW. This means that specific power of the TOPAZ system is between 47-95 W/kg which is about 5-10 times higher than current space solar power systems.

d. SP-100 Program--In the late 1970s the Space Power Advanced Reactor (SPAR) project was created at Los Alamos Scientific Laboratory. The goal was to provide a technology base and initial design studies for a higher power, unmanned nuclear reactor space power source with a long design lifetime (7 yr). A 100 kWe, high temperature, uranium dioxide (UO_2) fueled, heat pipe[2] cooled, fast reactor with a thermoelectric conversion system was adopted as the reference design. This selection was based upon the redundancy in heat removal from the core that heat pipes can provide, thus avoiding single failure points (Ref. 1).

The SP-100 (Space Power Reactor, 100 kWe) Program, begun in October 1981 at Los Alamos, is a continuation of the SPAR project. The basic requirements in the selection of the nuclear power subsystem in the SP-100 design are (Ref. 11):

(1) Power output of 1400-1600 kW(t) (100 kWe)
(2) Operational lifetime of 7 yr
(3) Maximum UO_2 fuel swelling of 10 percent by volume (vol%)
(4) High reliability, no single failure points
(5) Heat pipe evaporator temperature of 1500 K
(6) Optimized mass-to-power ratio to 20-30 kg/kWe
(7) Radiation attenuated at payload to 10^{12} neutron fluence and 10^6 rd of γ radiation.

Figure 2 shows the overall system configuration (Refs. 11 and 12). The following is a brief description of the power subsystem components. Figure 3 is a schematic of the SP-100 reactor core (Ref. 11). The core consists of 120 heat pipe fuel modules arranged in five concentric rings around a central plug region. As shown in Figure 4, the fuel module consists of a central molybdenum/rhenium[3] (Mo/Re) alloy heat pipe with integral fins (Ref. 11). The individual fuel modules are held tightly at both ends of the molybdenum core container. Fuel wafers of 93.1 percent enriched UO_2 are

[2]A heat pipe is a closed structure containing a working fluid which will be near its saturation point at the operational design temperature of the pipe. During operation, the fluid evaporates at the hot end of the pipe (the evaporator) and travels as vapor to the cooler end of the pipe (the condenser), where it condenses giving up heat to the electrical conversion system. Capillary forces pump the condensate back to the evaporator region of the heat pipe through a screen wick along the tube wall. The smaller the mesh size of the screen, the higher is the capillary force which circulates the working fluid in the heat pipe (Ref. 10).

[3]This alloy of 13 percent rhenium with molybdenum was chosen for the fins and heat pipes rather than pure molybdenum, which has better neutronic properties, mostly because of the lower ductile-brittle transition temperature of the alloy. Thus there is more likelihood that the alloy fins and heat pipes can withstand launch vibrations without cracking.

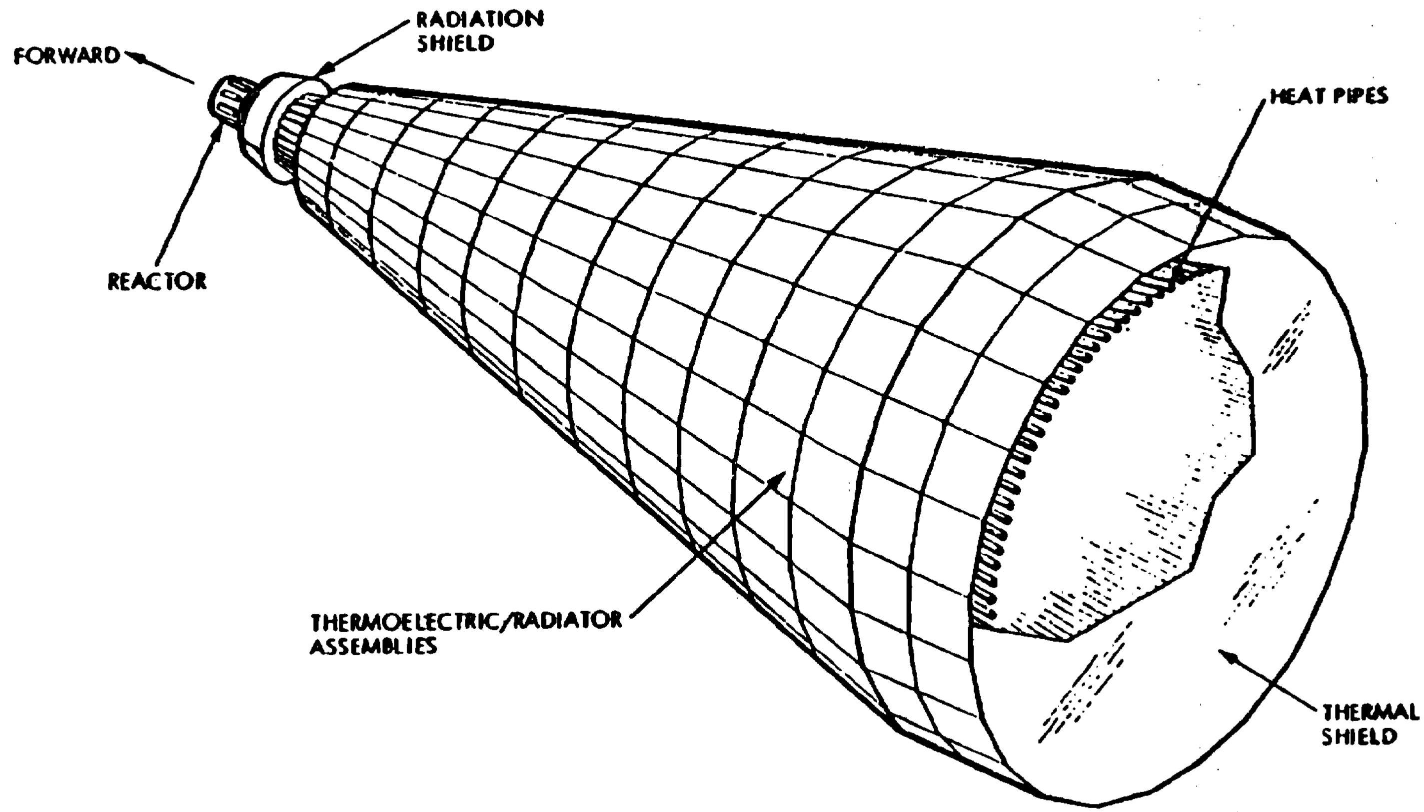

Figure 2. Conceptual configuration for the SP-100 power system.

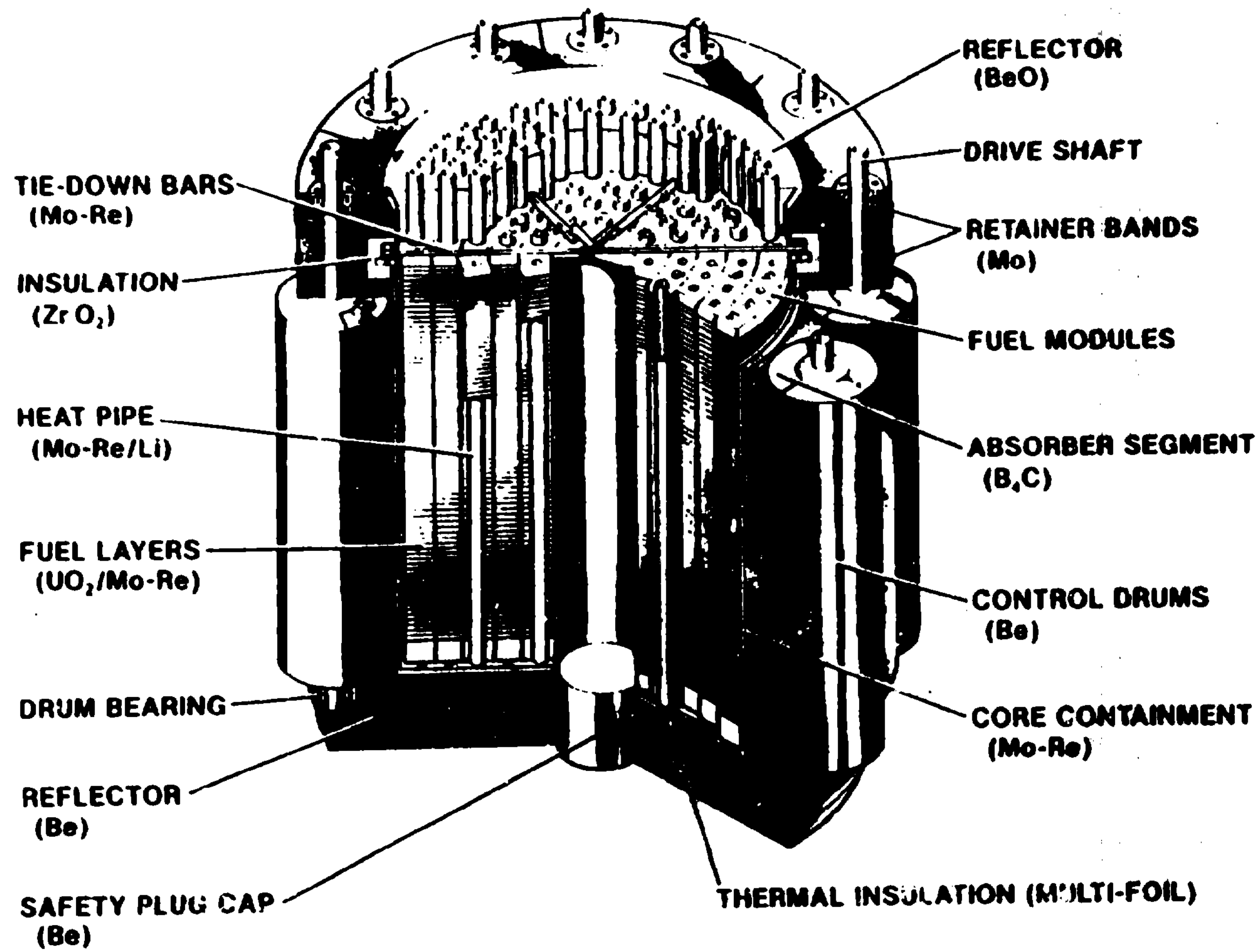

Figure 3. Cutaway drawing of the SP-100 reactor core.

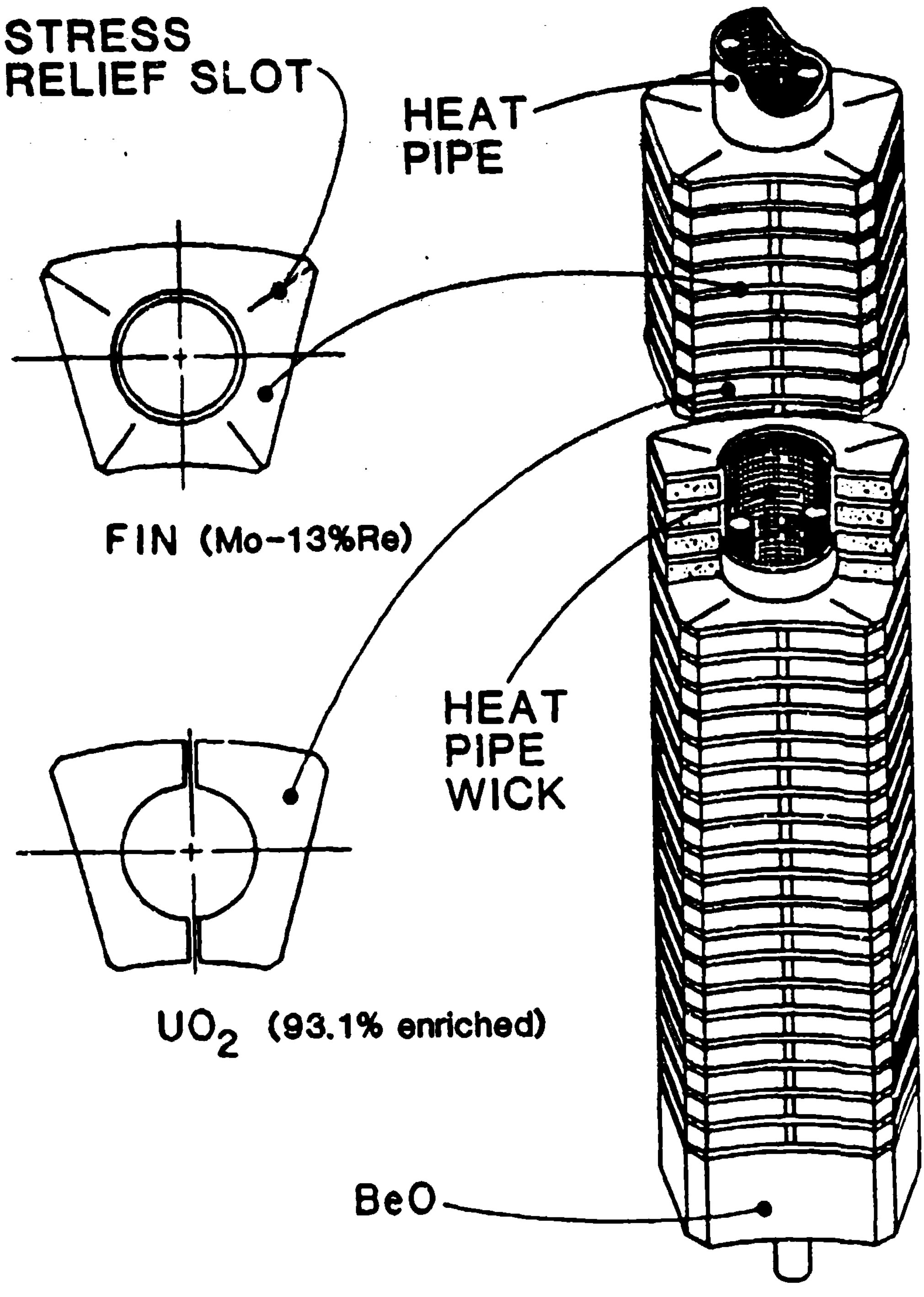

Figure 4. Drawing of the typical SP-100 fuel module.

placed between the fins. The molybdenum alloy can is surrounded radially by a beryllium reflector region containing twelve evenly-spaced, rotating control drums. One-third of each control drum cylinder is boron carbide (B_4C). The boron in the B_4C is 90 percent enriched with boron-10 (B^{10}), a neutron absorber which provides criticality control. The remaining two-thirds of each control drum, except for the drive shaft, is beryllium.

Another beryllium reflector is at one end of the core. At the other end is a reflector of BeO around the heat pipes outside the core. BeO was used, rather than beryllium, because of the high temperatures expected in this region where the heat pipes will be exiting the core. Multifoil (containing zirconium dioxide (ZrO_2)) thermal insulator surrounds the containment can and the heat pipes along their adiabatic section, the section between the exit from the top of the fuel-fin region and the entrance into the radiator-conversion region.

The central safety plug consists of boron or B_4C, enriched in B^{10} and is approximately 72 mm in diameter. This plug will assure subcriticality of the core in case of a water immersion accident until the Space Shuttle has attained orbit. Once a successful orbit is achieved and just before the power system is deployed, the central plug is replaced with a BeO reflector plug.

The advantages of the individual fuel module concept in the current SP-100 core design include the relative simplicity of core assembly and the ease with which a damaged heat pipe can be removed or replaced. The cylindrical core, without reflectors, is 33.1 cm high by 33.1 cm in diameter.

After the heat pipes leave the core, they bend around the radiation shadow shield on their way to the conversion-radiation system as shown in Figure 5 (Ref. 11). The shield, based on SNAP shield designs, is composed of three materials. Lithium hydride (LiH) and tungsten (W) attenuate the neutron and gamma radiation, respectively, emitted from the reactor in the direction of the payload. The mechanical strength of the shield is provided by a stainless steel honeycomb structure.

Beyond the radiation shield, the heat pipes enter the power conversion-radiator section. There, the heat acquired in the core is transferred radiatively from the heat pipes to the thermoelectric (TE) converters located in the thermoelectric radiator panels. Because of the temperature gradient

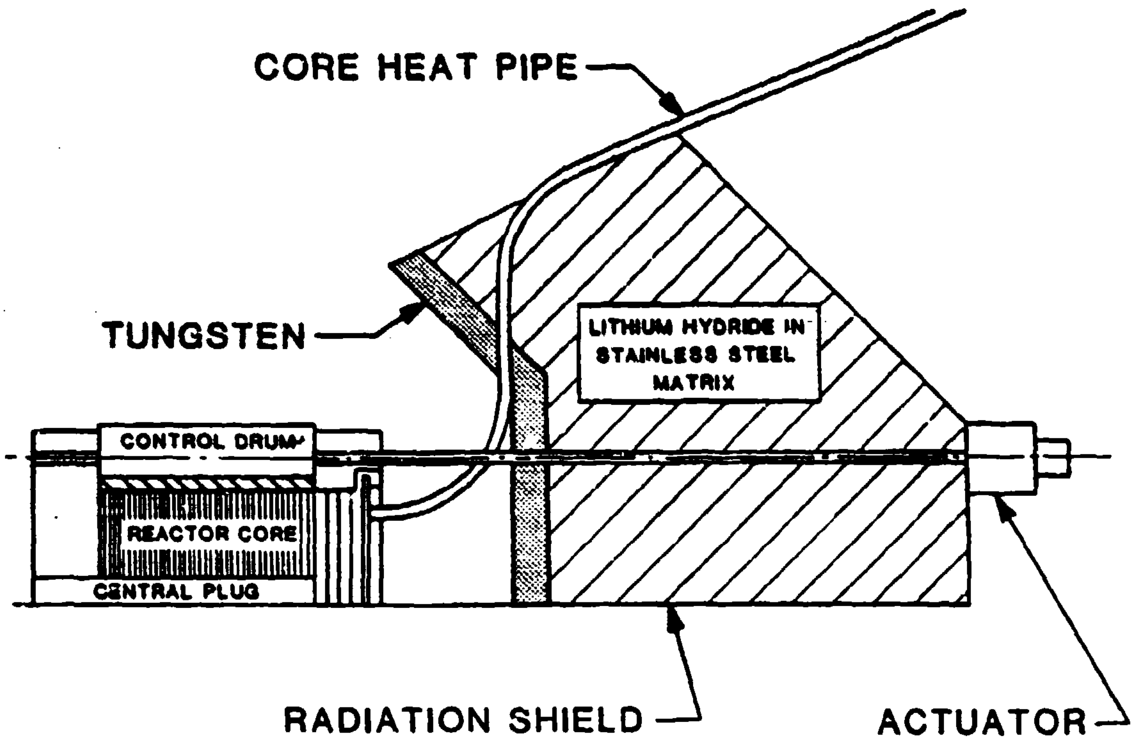

Figure 5. Axial cross-sectional diagram through the SP-100 reactor core and radiation shield.

across the semiconductor material of the TE converters, a voltage drop is created, and, with a complete circuit, the thermal energy is partially (~6.8 percent) converted into electricity. The rest of the heat (~93.2 percent) must be radiated into space from the cold side (outer surface) of the radiator panels. Specific details of the various design features of the SP-100 will be given in the remainder of this report and can also be found elsewhere (Refs. 11-13).

II. SP-100 DESIGN LIMITATIONS

This section reviews the status of the SP-100 design as of October 1982. The components of the design (the nuclear reactor core, the radiation shield, the energy conversion system including the heat pipes, radiative coupling, and radiator, as well as miscellaneous systems) are discussed. This section emphasizes current design limitations and concludes with a discussion of the technical developments remaining to be [illegible] before fielding the present design.

1. NUCLEAR REACTOR CORE

As mentioned earlier, the core of the current SP-100 design is a cylinder 33.1 cm in diameter by 33.1 cm high (not including the reflectors) and consists of 120 heat pipe fuel modules (see Fig. 4). The fuel, 93.1 percent enriched UO_2, is in the form of annular wafers (126 wafers per heat pipe) sandwiched between Mo-13 percent Re fins integral to the heat pipe walls. The fuel-fin region is 80 percent by volume of UO_2, and 20 percent by volume of Mo-13 percent Re (Ref. 13).

a. Fuel Material--Four types of fuel materials were considered for the SP-100 reactor core: uranium carbide (UC-10 a/o ZrC), uranium dioxide (UO_2), uranium nitrate (UN), and a uranium dioxide molybdenum cermet (UO_2-40 percent by volume of Mo). Table 3 summarizes various characteristics of these fuel materials.

Uranium carbide was dropped from consideration for the following reasons:

(1) It chemically reacts with molybdenum (the primary component of the heat pipe wall material) at the core operating temperature of 1500 K. The production of molybdenum carbide (Mo_2C) (Ref. 1) may cause significant changes in the thermophysical properties of the heat pipe wall.

(2) Because UC is a chemically active agent, handling and manufacturing processes of the fuel must be conducted under vacuum in a glove box.

(3) Cladding is therefore required for UC fuel; this would increase the weight of the system in three ways. First, the clad itself

TABLE 3. CURRENT SP-100 DESIGN FUEL CHOICES

Fuel System	Chemical Reaction in Core	Fuel Swelling	Contain Under Pressure	Handling	Cladding	Conductivity
UC	yes	highest	no	in vacuum	yes	high
UO_2	no	moderate	no	no problem	no	low
UN	no	low	yes	no problem	yes	moderate
UO_2-Mo cermet	no	low	no	no problem	no	high

adds extra weight. Second, more fuel is required for a critical system to make up for neutron losses due to absorption in the cladding and decreased fuel density. Third, the shield will need to be wider to protect the same cone angle and so will probably be heavier.

(4) UC fuel has the highest swelling among the fuels considered (Ref. 15), followed by UN, UO_2, and the cermet (see Fig. 6).

Uranium carbide, however, has a higher thermal conductivity and higher uranium metal density than either UN or UO_2; consequently, UC allows higher operating power densities and fuel burnup.

In spite of its low swelling, UN was also rejected as the fuel choice because of the requirement for a pressurized system to prevent the loss of nitrogen from the fuel matrix. This would add weight and seriously complicate the design of the reactor. Also, the technology for manufacturing UN is not well established. Although the UO_2-40 percent Mo cermet offers an improvement in thermal conductivity over pure UO_2, it was rejected as the fuel choice because of the extra weight of the molybdenum in the fuel matrix.

The remaining fuel candidate is UO_2, which has the lowest thermal conductivity among the fuels considered. Since UO_2 experiences only moderate swelling and is chemically inert, cladding is not required. Also, the technology of fabrication processes for UO_2 is available through commercial industries. In addition, most irradiation and operation properties of UO_2 are well known from longtime experience with light water reactors (LWRs). Because of these factors, UO_2 was judged to be the overall best choice for the SP-100 core design. However, the emphasis on the development of a carbide fuel continues by the Carbide Fuel Development program at the Los Alamos National Laboratory (LANL) (Ref. 16).

b. Fuel Swelling--The total amount of fuel (93.1% enriched UO_2) in the core would provide 1600 kW(t) power from fission (assuming 190 MeV/fission) for 7 yr. This results in an average burnup of 3.6 atom percent (~3.6 MWd/kg), and an average fission density of 8×10^{20} fissions/cm^3 over the 7 yr of continuous operation (Ref. 11).

The current design is limited to the 1600 kWt power level by the expected fuel burnup. The accompanying fuel swelling for the fuel

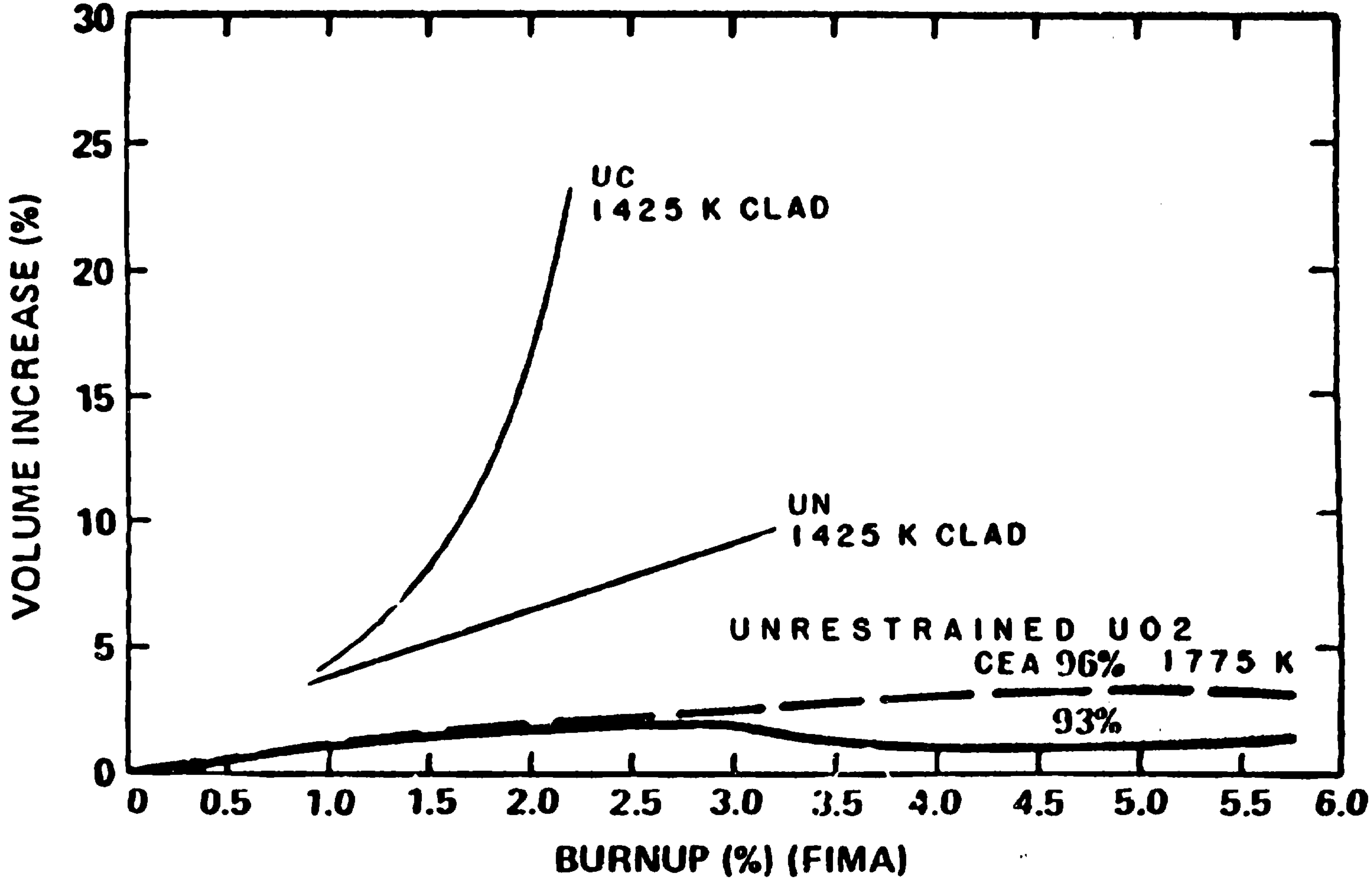

Figure 6. Fuel swelling versus burnup for UC, UN, and UO_2.

temperature range of 1510 to 1730 K (determined by requiring the inner wall of the heat pipe evaporator to be at 1500 K) would vary from 6 to 14 percent. These results are predicted based on integrating experimental measurements performed by Zimmerman and Grando (Ref. 17). Thus, fuel wafers and modules are designed with gaps to accommodate this estimated swelling. Figure 7 shows the swelling predictions used by the LANL group in their computer modeling of the core (Ref. 17). One prediction of the effects of fuel swelling can be seen in Figure 8 (Ref. 18). In that figure the computed beginning-of-life (BOL) and end-of-life (EOL) longitudinal cross sections through heat pipe modules are compared.

In the reference SP-100 design, the heat load is radiatively transmitted from the entire condenser length of the heat pipes to passive thermoelectric converters. Without changing the size or number of fuel modules in the core, an increase in core power will necessarily mean an increase of the heat pipe temperature and, therefore, an increase of the fuel temperature and burnup. Since fuel swelling increases with both temperature and burnup, increasing the core power in this manner will increase fuel swelling. As can be seen in Figure 8, such swelling can produce stresses in the heat pipe wall. These stresses could eventually lead to a heat pipe failure, either by cracking the containing tube wall, allowing the escape of the lithium working fluid, or by destroying the contact between wick and inner heat pipe wall. The predicted fuel swelling and the effectiveness of the gaps to accommodate it could be verified in in-pile testing of a heat pipe fuel module which was planned in the Experimental Breeder Reactor (EBR-II) at Argonne National Laboratory in Idaho Falls, Idaho.

c. Criticality Safety--The current safety guidelines require that the SP-100 reactor be subcritical in the event of a launch abort that leads to the reactor's being completely immersed in and all voids filled with water. To satisfy this requirement, the current design includes a central plug of neutron absorber (B^{10} or $B_4{}^{10}C$, 7-cm diameter) which will be removed and replaced by a BeO reflector plug once the Space Shuttle has attained orbit. Recent calculations by LANL indicate that with the boron-10 plug inserted and the reactor totally immersed in water, the reactor is 86 cents

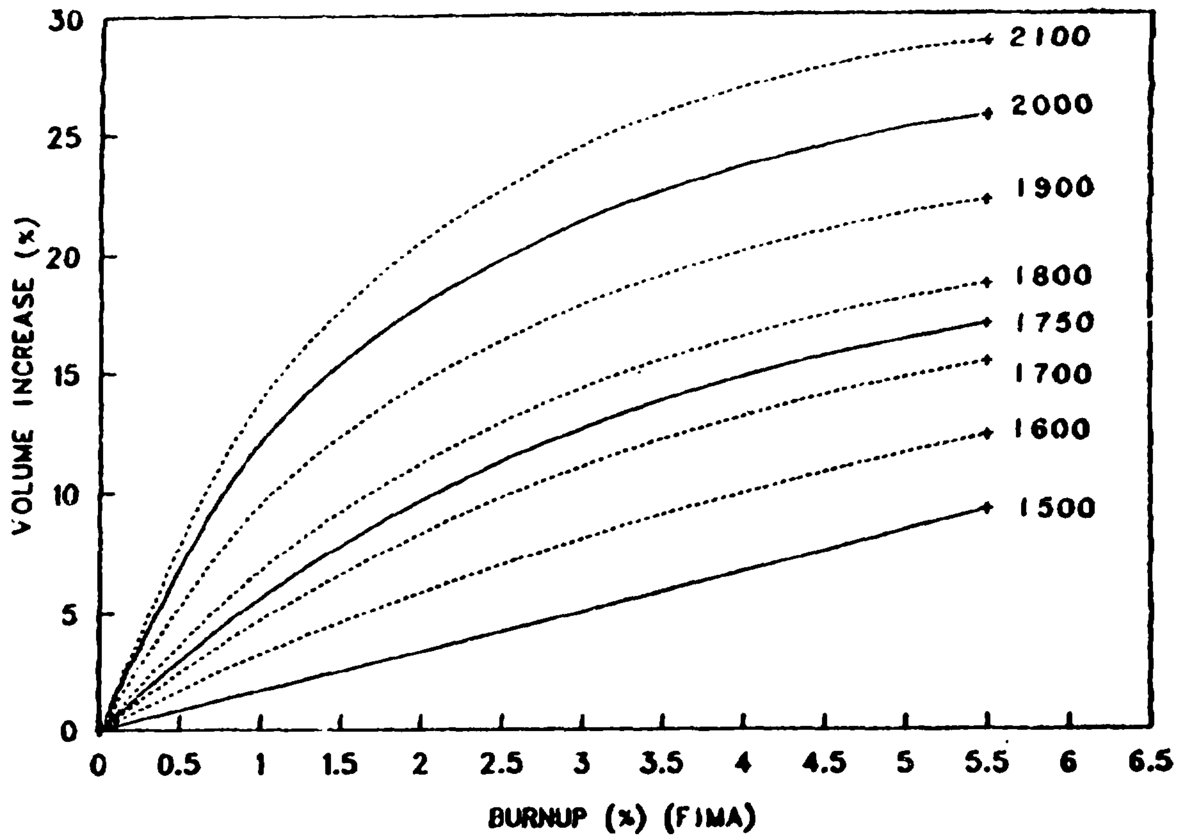

Figure 7. UO_2 fuel swelling as a function of temperature and fuel burnup.

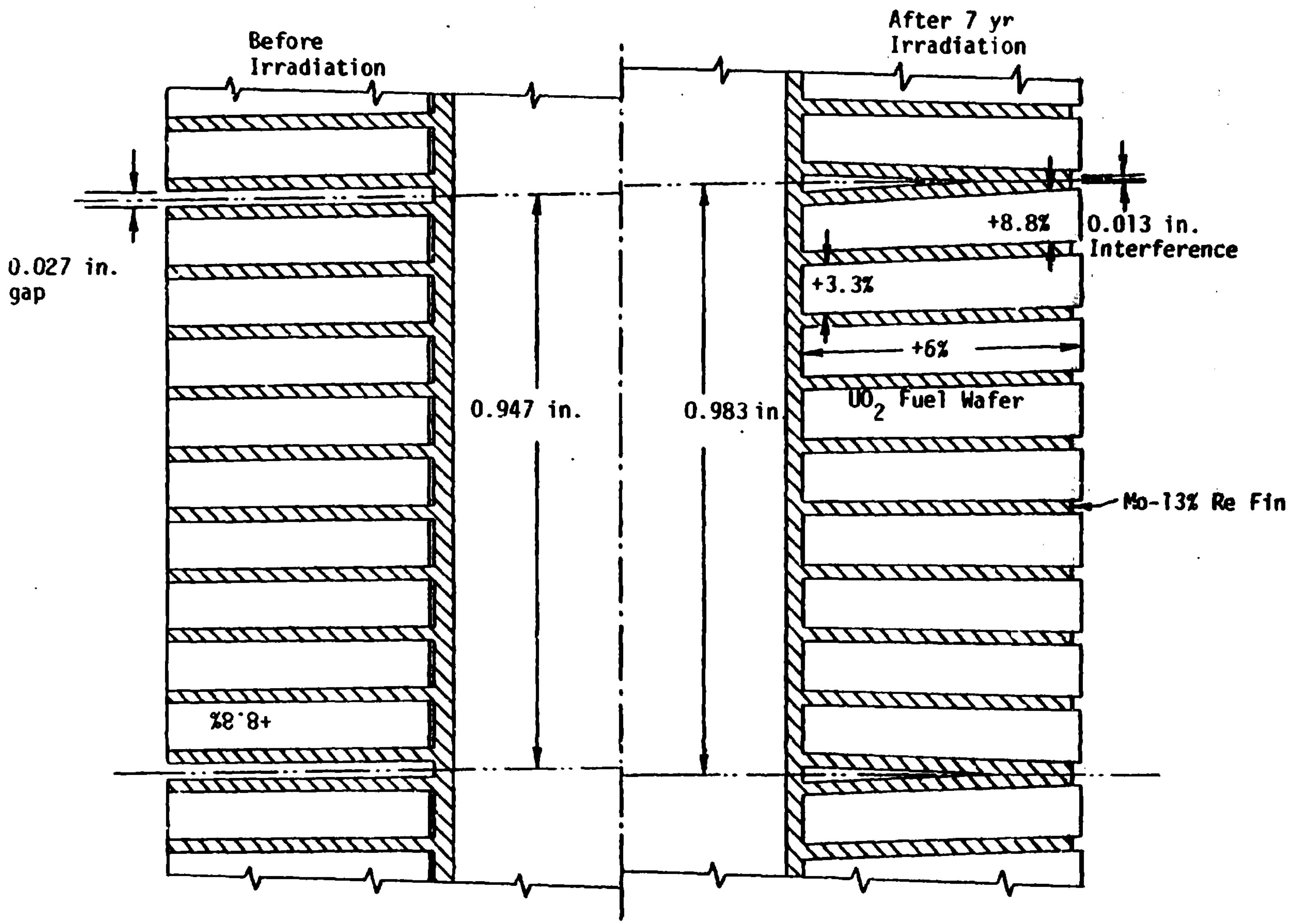

Figure 8. Predicted effect of axial fuel swelling on finned heat pipe.

subcritical[4] (Ref. 19). The calculation assumes that the reflector is in place, that the control drums are locked into their control-in (safe) positions, and that water surrounds the reactor and is in all core voids, including inside the heat pipes. In a hypothetical accident, other combinations of events, such as removal (mechanical damage) of the reflector, incomplete filling of the heat pipes with water, or the presence of absorbers in the water (i.e., salt water), would increase the safety of the system with respect to unplanned criticality. The calculations of k-effective were performed with a Monte Carlo (MCNP) code, which is accurate to within three standard deviations (Ref. 20).

To better fulfill more stringent guidelines which may apply in the future, the possibility of designing a reactor whose reflector will come off either at launch abort or at reentry is still under consideration. In the case of a water immersion accident, the boron-10 plug would provide a negative reactivity to a bare core of almost $3[5], which is a very safe configuration.

2. RADIATION SHIELD

The shield design is based on the LiH-stainless steel shield designs developed in previous SNAP and ROVER programs (Ref. 13). The location of the shield is shown in Figures 2 and 5. A reference shield was designed to atte[illegible] the 7 yr neutron fluence to 10^{12} n/cm^2 and the 7 yr gamma dose to 10^6 rd at an unmanned payload location 25 m from the center of the core (Ref. 12). The area protected by such a shield is 150 m^2 of circular area perpendicular to the line of sight to the reactor. This requires a shield cone-angle of 30 deg. Neutron attenuation is provided by the LiH, while gamma attenuation is provided by the tungsten (W) plus the stainless steel honeycomb structure in the LiH shield.

The mass of the reference shield, 790 kg, is 28.5 percent of the total system mass of SP-100. Unlike design constraints imposed on the core and

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[4]This is based on a value for β, the delayed neutron fraction for U_{235} fast fission, of 0.0165 (Ref. 21).

[5]A dollar worth of reactivity is the amount of reactivity equal to the effective delayed neutron fraction, β.

heat pipes by fuel swelling and wicking limit power, respectively, the shield mass is not firmly limited to this 790 kg. Because of the high launch cost per unit mass, minimal mass is a prime consideration for space power systems. Since the shielding requirements are highly mission dependent, ways to reduce shield mass can be investigated, once the specific use of the SP-100 system is determined. Examples of ways to reduce the required shield mass are as follows:

(1) Move the payload farther away from the reactor.
(2) Configure the payload so that it subtends a smaller solid angle.
(3) More accurately determine the radiation limits of payload components to see if perhaps larger dose rates could be tolerated.
(4) Individually shield the most highly radiation-sensitive parts of the payload.
(5) Better determine the attenuated spectrum and any spectral dependence of radiation damage to the payload so that perhaps only spectrum specific shielding would need to be provided.
(6) Determine more exactly the lifetime, power levels and power utililization factor required by the particular mission, so that the shielding mass can be reduced accordingly.
(7) Develop new shielding materials (alloys or metallic composites) which are light in weight.

3. ENERGY CONVERSION SYSTEM

The energy conversion system consists of the core heat pipes, the thermoelectric converter modules, and the radiator panels. This section reviews the design features of those system components with comments on the design limitations of each.

a. Heat Pipes--The current SP-100 core design uses 120 heat pipes made of an alloy of molybdenum and rhenium (Mo-13 percent Re) with lithium as the working fluid. The design power of each heat pipe is 15 kWt. However, there is some variation in the amount of power that can be carried by each pipe (1600 kWt/120 heat pipes = 13.3 kWt/pipe average) (Ref. 13). Thus, some allowance for possible heat pipe failure exists. If 13 heat pipes were to fail and if the 1600 kWt were evenly distributed among the remaining heat pipes (107 in total), they would still be operating slightly below their design power of 15 kWt.

To determine the actual heat pipe design (diameter, type, and dimensions of wick, screen pore size, etc.), a factor-of-safety of 1.5 is applied to the design power of the heat pipe (Ref. 22). Thus, the design chosen has a theoretical maximum power of 22.5 kWt, which is the wicking limit at 1500 K. If all heat pipes in the SP-100 core were operating at their wicking limit, they could carry 2400 kWt of power out of the core.

Besides the amount of power to be transported, other considerations affect the choice of heat pipe wall thickness and number. Reliability and quality assurance, with a factor-of-safety of 2 applied, required a wall thickness of 0.75 mm. Although the mass is minimized with about 45 heat pipes, such a low number of heat pipes would cause the consequences of a single heat pipe failure to be more severe. Because fewer heat pipes also necessitate larger diameter fuel wafers, such a design would force higher fuel temperatures, thereby substantially increasing fuel swelling. Taking all of these considerations into account, a reference design of 120 heat pipes was chosen (Ref. 22).

b. Radiative Coupling--The previous SPAR and subsequent SP-100 design called for thermoelectric converters to be in physical contact with the condenser ends of the heat pipe. Such conductive coupling has been replaced in the current SP-100 design with radiative coupling between the heat pipes and thermoelectric converters in order to add redundancy in the heat flow path.

With conductive coupling, for example, failure of a heat pipe causes the string of TE converters in contact with it to cease producing electricity. With radiative coupling, on the other hand, each thermoelectric converter receives radiant heat from a large number of heat pipes. If a heat pipe fails, the remaining heat pipes could still carry all the power from the core and radiate it to all of the TE converters. Therefore, with radiative coupling, all TE converters would still be operable with one or more heat pipes inoperable.

Additional advantages of radiative over conductive coupling are the following:

(1) Radiative coupling allows design of the radiator-energy conversion subsystem to proceed relatively independently of the design of the reactor-heat pipe subsystem. Thus, the work on the

radiator-conversion subsystem is not so dependent upon the design status of the core and heat pipe subsystem.[6]

(2) The conductive coupling system requires an additional set of heat pipes to transport waste heat to the radiator. Use of radiative coupling avoids this completely.

(3) Power flattening in the core is less critical since single heat pipe failure does not lead to loss of that fraction of the core power output.

(4) No electrical insulator is needed between the hot shoe of the thermoelectric converter and the heat pipes, as it was in the conductive coupling design.

(5) The waste-heat radiator is not as vulnerable to meteorite damage as the heat pipe radiator of the conductively-coupled system, which contains thin-walled radiator heat pipes. Meteorite damage to the heat pipe radiator could lead to loss of the heat pipe working fluid, and a subsequent failure of a section of radiator panel. Meteorite puncture of the radiatively-coupled radiator panels does not significantly alter their operational characteristics.

(6) In the conductively-coupled design, overheating of the electrical insulator between heat pipes and TE converters could cause significant alteration of the thermal conductivity of the material. This problem does not exist in the radiative coupling design.

Disadvantages of radiative coupling (Ref. 11) as compared to conductive coupling are:

(1) Higher fuel and heat pipe temperatures are required to radiate the same amount of heat. These higher temperatures lead to greater

[6] It should be noted that there are certain pitfalls associated with the independent design of two or more subsystems. A specific example of the kind of problem designers of independent subsystems may encounter can be given for the SP-100 design (Ref. 23). The total SP-100 system weight for various configurations (Ref. 12) was obtained by adding the LANL-derived minimized reactor/shield mass to the Jet Propulsion Laboratory-derived minimized radiator/converter mass. The procedures for minimizing mass of a subsystem include optimizing the number of heat pipes used. Thus, for the power systems whose specific masses are given in Ref. 12, the number of heat pipes leaving the reactor core for a minimized reactor/shield mass may not be equal to the number entering the radiator region for a minimized radiator/converter mass.

mechanical stresses to the heat pipes and structure in the reactor core (caused by increased fuel swelling, increased creep rates, etc.).

(2) High-emissivity (ϵ = 0.85) surfaces on the heat pipes and hot shoes are necessary, requiring further technology development.

(3) Longer heat pipes (~8 m) are required to provide the area for radiating the design power at an emissivity of 0.85. Longer heat pipes are likely to be more difficult to fabricate and to start up thermally. In addition, it is not known if the extra length of the heat pipes will affect their reliability and lifetime.

(4) Increased fuel temperature increases the possibility of fuel-migration, a further limit on the core lifetime.

c. Thermoelectric Converters--The primary development problem for the thermoelectric converters relates to obtaining higher energy conversion efficiencies. For a given electric power output, small improvements in efficiency can lead to dramatic weight savings in the radiator system. The development of new thermoelectric converter materials with high performance is complicated by the requirement for long lifetime operation in the radiation environment expected for the SP-100. The thermal and vacuum environments couple to require a durable coating in order to minimize TE material sublimation over the expected operating history of the system.

d. Conversion Efficiency--The conversion efficiency, η, of a thermoelectric converter material (Ref. 1), is approximately defined by

$$\eta = \frac{1}{4} Z \, \Delta T \qquad (1)$$

where ΔT is the temperature drop across the converter, and Z is the figure-of-merit for the converter material.[7] The figure-of-merit, Z, is defined by

$$Z = \left[\frac{\alpha_p - \alpha_n}{\sqrt{\rho_p k_p} + \sqrt{\rho_n k_n}} \right]^2 \qquad (2)$$

[7]A more accurate empirical formula for η, which included temperature dependence, was used by JPL for the converter design calculations (Ref. 23).

where α, ρ, and k are the Seebeck coefficient, electrical resistivity, and thermal conductivity of the semiconductor material, respectively. The subscripts n and p refer to n-type and p-type material. Since the material properties α, ρ, and k are all strongly temperature dependent (Ref. 1), the conversion efficiency of a given thermoelectric material is highly temperature dependent. Figure 9 displays the theoretically derived variation of Z with temperature for various thermoelectric materials (Ref. 1).

The efficiency value of 6.8 percent assumed for the SP-100 design assumes the use of a converter material with a z value of $1.0 \times 10^{-3}\ K^{-1}$ at 1350 K. Such a material is not yet available (Ref. 12), although the SiGe + (Gallium phosphite) GaP is within 20-30 percent of that value. It is noteworthy that in the present design a space is available between hot and cold shoes for larger TE converters, as can be seen in Figure 10. Thus a 100 kWe system could be designed without any extrapolation of known thermoelectric converter technology. Such a design would, however, require a somewhat larger core thermal power and higher radiator area. Upon optimizing these parameters to obtain the 100 kWe output desired, the currently available TE material would lead to a 20 percent increase in the mass to power ratio of the SP-100 (Ref 12).[8]

e. <u>Converter Sublimation</u>--Another design limit of the present SP-100 system is the expected durability of the sublimination coating required by the TE converter. Without such a coating, a significant amount of the TE material would sublimate at the hot junction temperature of 1350 K during the 7 yr operating lifetime. However, a vapor suppression coating which is known to work under these conditions is not yet available for the SP-100[9] (Fig. 11).

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[8]The curves in Figure 9.1 of Ref. 12 are somewhat deceptive because they do not match the design value of specific weight quoted earlier in that text. Those curves should be adjusted downward to match that value of 27.7 kg/kW(e) as should others which follow in the text.

[9]Recent testing of SiO_2 as an anti-sublimation coating is described in Ref. 24. This yields an improvement over the material previously used for that purpose, Si_3N_4. Figure 11 shows the data obtained for the SiO_2 coating at a temperature of 1323 K for 2500 h. The researchers interpreted the sudden increase in sublimation near the end of the experiment as an effect of contamination of the coating by volatiles (possibly the TE material itself). It is hoped that vacuum firing of the coating for future tests will eliminate this problem (Ref. 24).

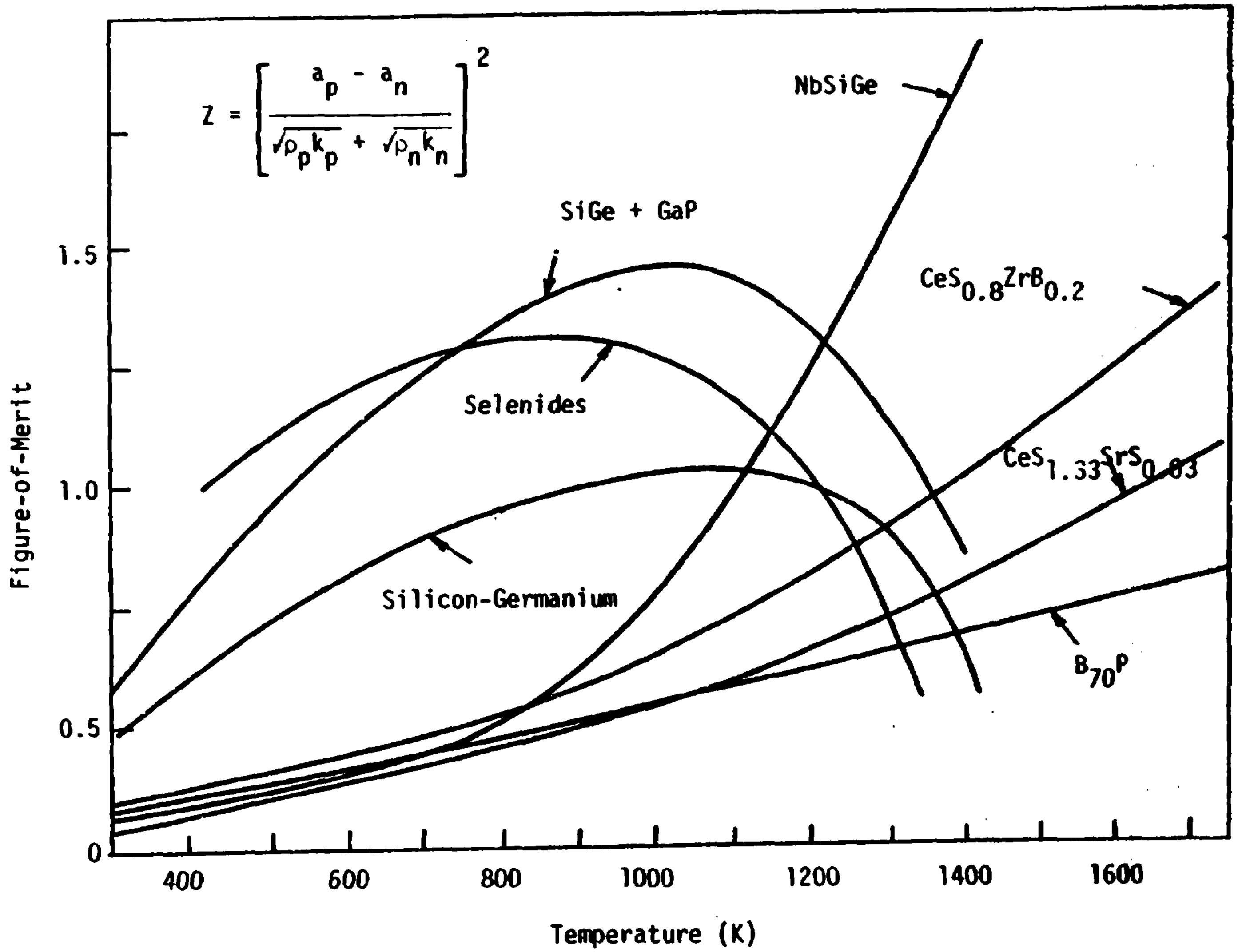

Figure 9. Figure-of-merit for thermoelectric materials.

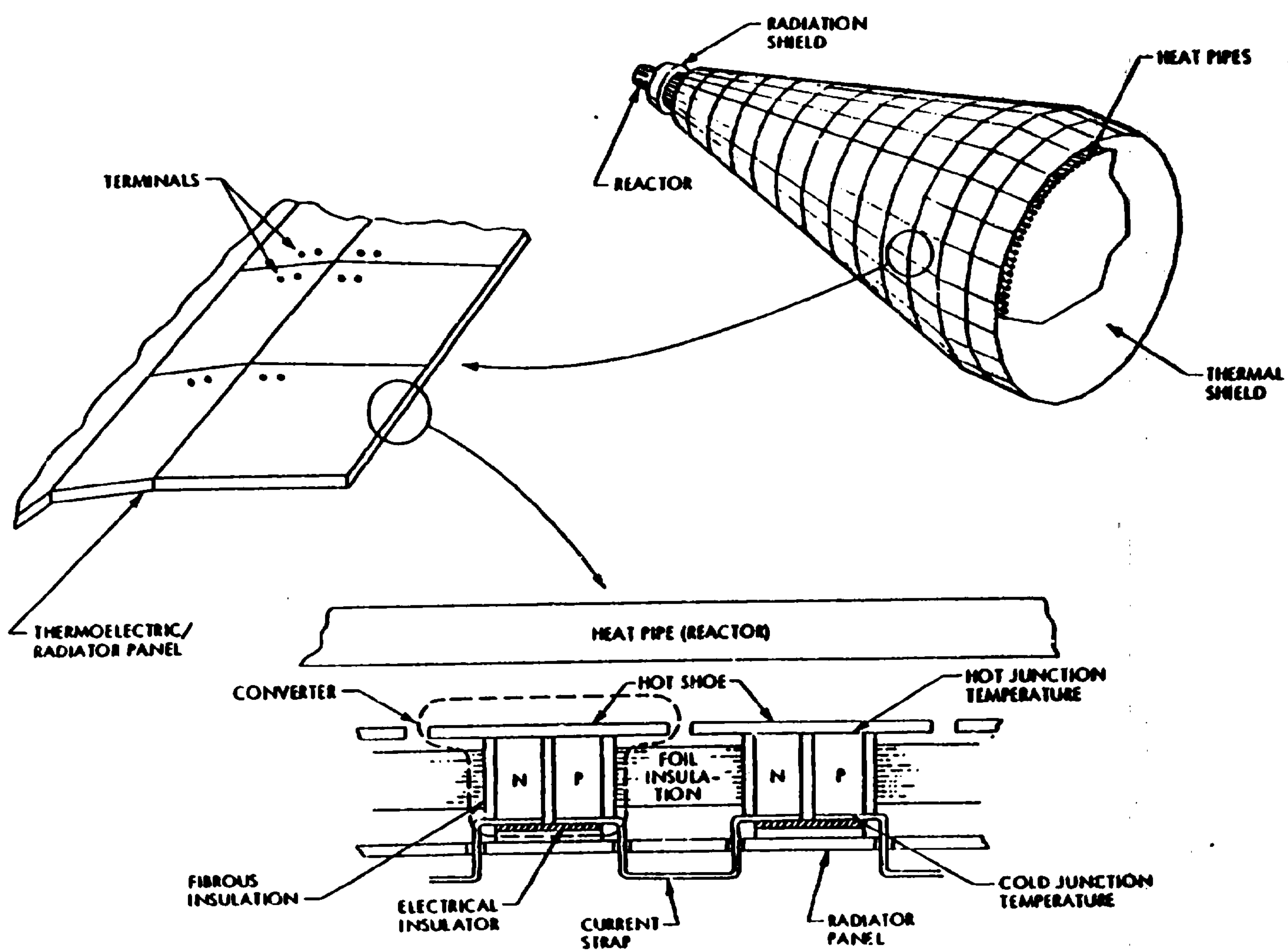

Figure 10. SP-100 power conversion matrix.

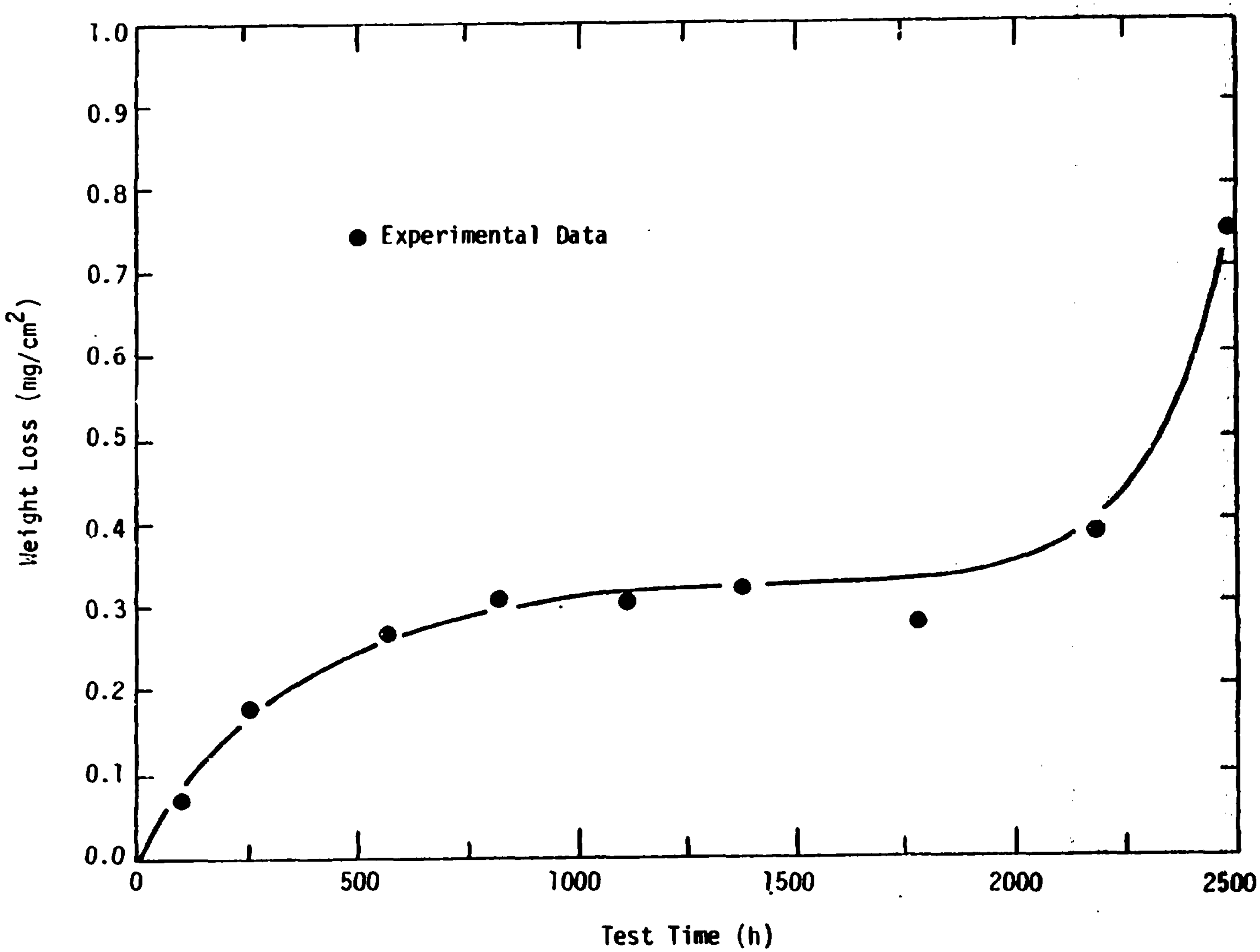

Figure 11. Isothermal weight loss test of n-type SiGe + GaP coated with SiO_2 at 1050°C.

The conversion efficiency of a TE material is directly proportional to the temperature drop across the junction. Assuming emissivities of 0.85, the temperature drop achieved across the converter depends on the thickness, surface area, and thermal conductivities of the hot and cold shoes and of the TE material. The JPL code for optimization of the TE energy conversion includes the ability to vary the area and thickness of the converter to minimize system mass (Ref. 23). The minimal mass requirement along with the assumed material properties at the operating temperatures of the radiator/converter limit the overall thermal-to-electric conversion efficiency of the subsystem to the 6.8 percent previously noted.

f. Radiator--The waste-heat radiator design uses a carbon/carbon composite (theoretical emissivity, $\varepsilon = 0.85$), which has an area of 70 m^2. With its average operating temperature of 800 K, it would radiate 93.2 percent of the heat that reaches the radiator-conversion system to outer space. This assumes that the view factor to outer space at a temperature of 0 K is 1, which certainly is not always the case, since possibly the earth, the moon, and the sun subtend part of the solid angle seen by the radiator. Correcting for this effect slightly lowers the amount of heat which can be radiated.

In outer space, waste heat cannot be rejected by conduction or convection, as on earth. Instead it is removed by radiant heat transfer. The quantity of heat that can be exchanged radiatively between two objects in space depends on their tempeatures, surface areas, and the solid angles subtended by each surface at the other surface (shape factors).

In space, the heat sink would be the empty space and nearby objects, such as the sun and the earth. The waste heat radiator of a satellite in the vicinity of the earth would receive about 1400 W/m^2 of direct solar radiation, about 420 W/m^2 of solar radiation reflected from the earth, and about 243 W/m^2 of earth-emitted radiation, as worst case estimates (Ref. 1). If the radiator's absorptivity to solar radiation is 0.21 and its absorptivity to earth-emitted radiation is 0.85, radiation from the sun and earth providing additional heat load to the radiator of $(1400 + 420) \times 0.21 + 243 \times 0.85 \approx 590$ W/m^2. Because the radiator is conical, less than half of its surface "sees" the sun or the earth, a better worst-case estimate is half of this amount (590 W/m^2) or approximately 300 W/m^2. Since the SP-100 radiator area is 70 m^2 (Ref. 12), this represents a total heat input of 21 kWt. Thus, the radiator's heat rejection capacity must be the 1370 kWt of waste heat from the power conversion process plus the 21 kWt of absorbed radiation from the sun and the earth. This extra 21 kWt represents a radiator temperature increase of approximately 3 K.

4. CONTROL DRUM ACTUATORS AND REFLECTOR

An important subsystem of the SP-100 is the actuator control system. The actuator controls the startup, scram, and power level changes of the reactor by rotation of the 12 control drums. For high reliability, the actuator should be simple to operate and should be able to function properly even if several drums are inoperable.

The detailed design of the actuator control system for the SP-100 has not yet been done. It is to be based on those designed for the SNAP program (Ref. 11). The controls will be on the payload side of the radiation shield (see Fig. 5) and must be able to withstand the same radiation doses experienced by the TE converter.

The design of the Be reflector is limited by the requirement that its temperature be kept below approximately 900 K. At temperatures higher than this, significant swelling of the Be occurs (Ref. 11). Gaps left between the Be reflector and the control drums must be large enough so that after the expected swelling of the Be and of the B_4C of the control drums, the control drums are free to turn when actuated. It is desirable, however, that these gaps be as small as possible to minimize neutron leakage, thereby minimizing the reactor fuel mass.

It is expected that the reflector will be cooled by radiation to outer space. To prevent overheating of the reflector by conduction from the core, thin, lightweight multifoil thermal insulation[10] will be used between the core containment can and the reflector. Most heating of the reflector is expected to be from neutron and gamma radiation (Ref. 11). The second largest heating source is expected to be from conduction through the core mounts at the top of the core. Ceramic blocks (ZrO_2) are to be used there as thermal insulation. A preliminary thermal analysis by the LANL design

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[10]Of the type made by ThermoElectron Corporation, Waltham, Massachusetts.

team indicates that such insulation should be sufficient to keep the Be temperature below 900 K (Ref. 11). A more rigorous analysis, which includes the decrease in thermal conductivity of the beryllium with neutron irradiation and the possibility of a failed heat pipe near the core mount, should be done to insure that swelling of the beryllium will not lead to inoperable control drums.

III. ADDITIONAL RESEARCH AND DEVELOPMENT

Although the SP-100 is in an advanced state of concept development, there are a number of important aspects of that design which require additional research and development. The purpose of this section is to identify those areas of research which might lead to substantial design revisions. In the area of nuclear core design, fission gas and its volatile release and fuel migration have been identified as possible causes of core can pressurization and subsequent mechanical failure, and are worthy of additional study. With respect to heat pipe development, there is the problem of propagation of single heat pipe failure through transient thermal stresses and/or lithium and fission product contamination to be considered. In addition, the heat pipe development area still suffers from (1) lack of fabrication technology for long pipes, (2) little understanding of the effects of the radiation environment on heat pipe operation, and (3) lack of long-life, high-emissivity coating technology. The present design of the radiation shield has poorly understood thermal characteristics and requires further design. Other areas of concern are the assurance of criticality safety, the technology of producing thermoelectric converters that can withstand the severe radiation and vacuum environment, the effects in the control drums of self-welding, and the need for the reflector and mechanical actuators to be functional in the SP-100 environment.

1. NUCLEAR REACTOR CORE

Fuel Swelling--The nuclear reactor core is designed to accommodate 6-14 percent fuel swelling (Ref. 25). Swelling beyond this limit could lead to a heat pipe failure. As the wafer swells axially, it causes the pipe to deform (see Fig. 8 for details of the geometry). Depending on the elastic behavior of the Mo-13 percent Re alloy under stress, cracking can occur. This alloy's ductility, however, may be modified by the irradiation history and the thermal cycling which it would experience.

The predicted amount of fuel swelling depends on the interpretation of available data and the application of the data to the SP-100 fuel design (Refs. 15 and 25). No tests have been done on unconstrained fuel wafers of the size and shape of those of the SP-100, in a fast neutron flux and at the expected SP-100 fuel temperature. The amount of fission gas release depends on the fuel temperature and fuel burnup and to a lesser extent on the grain size, and on the geometry and methods of preparation of the fuel wafer (Ref. 26). One mechanism of swelling is the presence of gas molecules within the fuel and the formation of interstitial gas bubbles. This includes both volatile and gaseous fission products and helium produced by (n,α) reactions. It should be easier for these gases to be released at low pressure and a high surface-to-volume ratio, presumably resulting in reduced fuel swelling. Such a result for the SP-100 operational parameters needs to be verified by experiment.

Although the 1.3 yr in-pile testing of a fuel module in EBR-II will not exactly simulate SP-100 operating conditions (Ref. 11), it should provide useful data to verify the amount of swelling expected. In addition,the EBR-II testing should give some indications of correct void placement to accommodate fuel swelling and may also suggest modification of subsequent in-pile testing.

a. Vented Gas Gap--Another area for further investigation is the modeling and design of the vented gas gap between fuel modules and the subsequent venting into outer space (Ref. 27). The current design calls for a 0.8 mm spacing between the fuel modules. The purposes of the gap are:

(1) To make assembly easier,

(2) To allow room for fuel swelling,

(3) To ensure that the core will easily break apart, burn, and disperse upon atmospheric reentry (Ref. 28), and

(4) To allow for fission product (gases and volatiles) release and venting into space.

The Mo-13 percent Re core containment can (see Fig. 4) was not designed as a pressure vessel. It has been described as sufficiently leaky so that fission product gases released into the gaps will be vented into space and so that the approximate pressure in the gaps is zero (Ref. 29). The SP-100 design team also expects that some fuel may be lost over the 7 yr reactor lifetime to space via the gaps by sublimation (Ref. 29). Although designers suggested that the vents be placed at the exits of the heat pipes from the core, there are a number of design flaws associated with this treatment of fission gas and volatile release in the SP-100 design.

As the heat pipes exit the core, they will be insulated from the surrounding BeO reflector by multifoil. The presence of this multifoil will interfere to some extent with the release of gases to space via this route. Some build up of fission gas pressure within the core is necessary in order to provide the gradient which drives the fission gas flow to the exhaust vents. After the beginning of reactor operation, this state of gas production and flow will produce a varying internal pressure. The magnitude of this internal pressure will be determined by:

(1) the rate of release of fission gas and volatiles, as well as the fuel vapor, from the fuel surfaces, and

(2) the rate of gas discharge, which is in turn dependent on

  (a) cross-sectional flow area at the exits,

  (b) fuel gap and structure temperatures,

  (c) frictional resistance offered by the flow path, as well as

  (d) kinematic viscosity of the gas mixture.

It is yet to be determined that this pressure will be low enough not to cause structural damage to the core, in particular to the structurally weak multifoil insulation (which is to reduce thermal losses from the core and from the heat pipes along their adiabatic section to less than 9 percent).[11] An engineered venting system may be needed in order to maintain the internal pressure required by the mechanical structure and prevent potential plugging of the system.

Beyond modeling the steady-state internal pressure in the core, two other analyses related to venting fission gases should be considered. One is to investigate the effect on core pressure of closing of the gas gaps with time because of fuel swelling. The other is an analysis of the possibility of plugging of the vents due to the freezing and redeposition of fission volatiles on the vent walls. Since the temperature of the vents to space is significantly lower than the temperature of the core, the exit temperature is likely to be below the condensation temperature of most of the fission volatiles. The continuous deposition of fission products on the vent wall will restrict the exits and cause an increase of core internal pressure with time.

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[11]The power produced in the core is 1600 kWt. The power entering the converter radiator region is 1470 kWt (Ref. 11). Thus, the thermal loss factor is 0.081.

Larger gaps and vents could be added to the SP-100 design, in order to assure adequate venting of the fission gases. However, enlarging the gaps and vents would increase neutron leakage and so may necessitate additional fuel, which would increase the system's weight. An alternative is to model the complicated dependence of internal core pressure on the characteristics of gap and gases, including the effects of deposition. This design problem should be examined in greater detail.

Another area of concern which has received little treatment in the SP-100 design is the effect of the fission gas cloud released from the reactor. The fission gases and volatiles vented from the reactor would expand outward in the vacuum surrounding the system. Most such fission products would escape the local environment of the reactor system and produce no further effects. However, that fraction of those volatiles with trajectories back toward the radiator and payload could condense onto available surfaces. The additional radiation burden of these volatiles could cause damage over time. Although the low exhaust temperature would likely prevent it, some of these fission volatiles could possibly become charged. If this occurs, those charged volatiles and gases would not depart from the reactor system and could form an electrostatic cloud remaining with the system. Such possible effects should be seriously considered in the application of a vented reactor, such as the heat pipe reactor, to a manned space station.

b. Heat Pipe Failure--A heat pipe failure may impact the core in at least two ways. There is an immediate increase in the fuel temperature in the vicinity of the failed heat pipe, leading to increased fuel swelling and sublimation. In addition, there is possible contamination of the fuel and structure by the lithium which leaks from a damaged heat pipe, leading to material property modification. Each of these effects can increase the likelihood of subsequent heat pipe failure.

c. Failure Propagation--The temperature rise near a recently failed heat pipe depends on the extent of the coupling between the fuel wafers and the fins of the failed heat pipe and also between that fuel module and the neighboring fuel modules. A combination of fuel swelling and UO_2 deposition on the fins could alter the thermal characteristics of the failed module and its ability to keep the temperature rise small.[12] Although only a small temperature rise is a possibility under such conditions, it is expected that there will be a substantial temperature rise. Higher fuel temperatures of the failed module and surrounding modules will lead to increased fuel swelling and increase the likelihood of failure of the surrounding heat pipes. There has been considerable work by the SP-100 design team on this problem, and the team has concluded that failure propagation would be at an acceptable level for the lifetime desired for the system. Nevertheless, further work should emphasize the importance of this problem. The temperature rises that occur when a heat pipe fails must not lead to a propagation of that failure to other heat pipes.

d. Lithium Contamination--Because lithium is chemically active, it will combine with oxygen from UO_2 in the core, thereby reducing the UO_2 to uranium metal. Because the melting point of the uranium metal (1405 K) is lower than the fuel operating temperature (>1500 K), regional melting of the fuel will occur if uranium metal is present. Such melting and possible fuel reconfiguration may change the power profile and disturb the operation of the core. In a zero gravity vacuum environment, melted fuel would tend to densify and clump, possibly leading to a reactivity excursion. Fuel melting could lead to closing of the vent gaps and reduced fission gas release. In turn, such pressurization could lead to enhanced fuel swelling and possible mechanical failure of the core containment. Further work needs to be done to determine the effects of a lithium leak in the core, and either to mitigate such effects, or assure that the likelihood of a leak is very small.

2. HEAT PIPE DEVELOPMENT

The heat pipes for the SP-100 reactor design are in the most advanced state of development of any system component, other than the reactor core. The outstanding issues presently receiving the bulk of the development

[12] The BOL emissivity of the fins is only 0.3, but fuel deposition can increase that to a value as high as 0.8. That increased emissivity would lead to better radiant transfer with surrounding fuel modules. Similarly, fuel swelling could lead to better thermal conduction between fuel modules.

effort are the fabrication of long heat pipes and the manufacturing of durable, high emissivity coatings. In addition to reviewing the status in those areas, this section discusses the research needed in relation to heat pipe transient behavior and the effects of radiation on heat pipe operation.

Fabrication--The current SP-100 design calls for an 8-m-long heat pipe, approximately 16 mm in diameter, made of Mo-13 percent Re. However, such a heat pipe has not yet been constructed. The Mo-13 percent Re alloy chosen for the heat pipe has only recently been acquired. Its physical properties at high temperature have not yet been measured and have only been inferred from an interpolation between the properties of molybdenum and a Mo-40 percent Re alloy. The design of an 8-m heat pipe in which the entire condenser length (greater than 6.5 m) is certain to be active and which can be reliably started up in space is yet to be done.

Once the 8-m-long heat pipe is designed, the fabrication, fill, and testing processes remain. Molybdenum alloy tubing of consistent high quality is needed (Ref. 11). Although a number of such heat pipes have been manufactured and tested, fabrication procedures for 2-m-long heat pipes are yet to be perfected. Problems with bonding the distribution wick to the heat pipe wall still must be solved. Drawing the tubing down onto the wick has caused wick buckling and subsequent cracking. Expansion of the wick to contact the wall has resulted in incomplete wick-wall contact. Each of these effects results in a degradation of heat pipe performance. Fill procedures which prevent too high an impurity level have been accomplished for 2-m-long heat pipes, but these must be modified for 8-m pipes. Testing facilities for 8-m pipes must be built, and it must also be ascertained that bending the heat pipes will not significantly damage the wicking structure. Reliability testing must also be done on a large number of such manufactured heat pipes, prior to their use in a space environment.

b. Radiation Effects--The effects of neutron and gamma irradiation on heatpipe performance are not well understood. Neutron irradiation of the lithium working fluid can produce helium gas through an (n,α) reaction. The seriousness of this effect depends on the fraction of Li^6 remaining in the Li^7-enriched lithium used as the working fluid. Such helium gas may plug the wick, restricting the circulation of the working fluid, consequently causing local dryout of the wick and failure of the heat pipe. The irradiation of the working fluid may either enhance or suppress the formation of local vapor bubbles, but it is difficult to predict what will occur without experimental data in the operational parameter regime. Irradiation damage to the heat pipe and wick material could lead to swelling and to a significant change in heat conduction and mechanical properties. Increased brittleness could increase the probability of material failure from stress. Impurities (e.g., He gas) inside the heat pipe would degrade heat pipe performance. Chemical interactions of fission products (such as Cs and I) with heat pipe material could also modify the thermophysical properties of the heat pipes and shorten their operational lifetime. Thus, there are a number of areas of concern related to modified material behavior in the heat pipes. The planned EBR-II in-pile tests should give indications of the magnitudes of these effects, but further analysis and modeling is also recommended.

c. High Emissivity Coatings--A high emissivity coating for the condenser section of the heat pipes has not yet been achieved. The emissivity of molybdenum is 0.3, and the Mo-13 percent Re alloy of the heat pipes is expected to be similar. The current SP-100 design assumes a heat pipe condenser emissivity of 0.85, requiring a dramatic improvement in emissivity over the material of the heat pipe wall. It is crucial that the high emissivity coating which is developed remain bonded to the heat pipe wall and maintain its high emissivity over the lifetime of the system. With SP-100 design parameters, this requires seven years of operation at 1500 K in a severe radiation and vacuum environment. The technological task of designing and testing such a coating is receiving further study by the SP-100 design team.

3. RADIATION SHIELD

The design operating range of the LiH-stainless steel shield is 600-680 K, a narrow range. The lower limit assures the reabsorption of radiolytically decomposed hydrogen. The upper limit avoids excessive thermal dissassociation and subsequent hydrogen loss if the casing is punctured by meteoroids (Ref. 12). However, no significant thermal analysis of the shield has been completed (Ref. 30). It is not known that the shield will remain within the design temperature range. The shield will be heated by gamma and neutron radiation and cooled by radiating its heat to space. The heat pipes bending around the shield (thermally insulated by multifoil) will cut down on the radiation view factor. Heat balance calculations should be performed to ascertain the operational temperature distribution in the shield. If the temperature range is not that required for shield integrity, then a cooling system must be designed and implemented for the SP-100 shield.

4. CRITICALITY SAFETY

According to design team computations, the SP-100 reactor is very safe, from a criticality accident point of view, when the reflector is not attached. For the most extreme water immersion or impact accident, a subcritical configuration seems assured without the reflector in place. Although not a requirement of the current design, the design modification of a separate reflector that could be easily attached seems desirable. The Shuttle crew could perform such a procedure while they are removing the central safety plug.

Final safety guidelines prior to launch of a reactor of the SP-100 type will require quantitative assurance of criticality safety in the event of high velocity impact or explosion type accidents. Such a requirement assures safety in the event of an explosion of the space shuttle's external tank. Although scoping studies in this area have been made (Ref. 20), a rigorous analysis remains to be done. The SP-100 design team at Los Alamos National Laboratory includes criticality safety with its mandate. Additonal computations in the area of an explosive compression of the core are underway there. The assurance of the nuclear safety of a reactor to be deployed in space has an overriding importance to all involved in the project.

5. THERMOELECTRIC CONVERTERS

The primary development problems remaining for thermoelectric converters are the achievement of the performance goals included in the SP-100 design. TE materials need to be developed with higher figure-of-merit which can withstand high radiation environments without substantial degradation. Antisublimation coatings which also survive in such environments must be developed. This is a primary research and development area of the JPL design group.

6. CONTROL DRUM ACTUATORS AND REFLECTOR

These are examples of aspects of the SP-100 design that have received little attention because the details are perceived to be straightforward engineering tasks. Examples of areas worthy of further study are: (1) a thermal analysis for the reflector and actuators in order to ascertain that thermal expansion will not lead to binding of the control elements (rotating drums); (2) a study of the self-welding phenomenon and its effect on the performance of the control drums; and (3) a complete design of a control system which is operable in the high radiation environment of the SP-100.

IV. CONCLUSIONS

This report reviews the status of the SP-100 heat pipe space nuclear system design as of October 1982. The following components of the design are discussed: the nuclear reactor core, the radiation shield, the energy conversion system including the heat pipes, radiative coupling and radiator, and miscellaneous systems. Current design limitations have been emphasized and those technical developments which remain to be achieved prior to the fielding of the present design have been reviewed.

Although the SP-100 is in an advanced state of concept development, a number of important aspects of that design require additional research and development. This report identifies research areas which might lead to substantial design revisions. In the area of nuclear core design, fission gas and its volatile release and fuel migration have been identified as possible causes of core can pressurization and subsequent mechanical failure as worthy of additional study. Also identified, with respect to heat pipe development was the problem of propagation of single heat pipe failure through transient thermal stresses and/or lithium and fission product contamination. In addition, the heat pipe development area still suffers from lack of fabrication technology for long pipes, from little understanding of the effects of the radiation environment on heat pipe operation, and from lack of long-life, high emissivity coating technology. The present design of the radiation shield has poorly understood thermal characteristics and requires further design. Other areas of concern are the assurance of criticality safety, the technology of thermoelectric converters to withstand the severe radiation and vacuum environment, and the need for the reflector and mechanical actuators to be functional in that environment.

In summary, the SP-100 design is the most advanced of any nuclear reactor for space power applications presently being considered. However, a number of design features will continue to require substantial technology development before the system can be considered for deployment. Areas presently receiving programmatic emphasis include:

(1) Heat pipe design, fabrication, and testing;

(2) High emissivity, long-lived coating development;

(3) Nuclear fuel module design and testing;

(4) Criticality safety; and,

(5) Thermoelectric converter development.

Areas deserving additional research effort in order to support continued SP-100 development include:

(1) Modeling and testing of heat pipe transient behavior and performance in a radiation environment;

(2) Modeling of fission product release and fuel vapor movement in the SP-100 reactor core;

(3) Design of a system that allows adequate venting of the gaseous and volatile fission products from the reactor core;

(4) Analysis of the effects of material modifications caused by the chemical interactions of fission products with fuel, heat pipes, and structural materials;

(5) Analysis of the effects on heat pipe performance of fission-produced impurities;

(6) Thermal and structural analyses of the radiation shield of the SP-100;

(7) Additional analyses of the effects on control drum operation of material swelling and self-welding;

(8) Continued improvement of the conversion efficiency of the thermoelectic converters;

(9) Continued development of high-emissivity surfaces for the heat pipes and radiators which will be stable in radiation and vacuum environments;

(10) Additional analyses of the consequences of heat pipe failure, including the effect of lithium contamination on the system behavior; and

(11) Continued development of alternative radiator concepts for enhanced system efficiency.

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