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Lawrence Radiation Laboratory
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**CONCEPTUAL DESIGN OF A 10-MW_e
NUCLEAR RANKINE SYSTEM
FOR SPACE POWER**

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CONCEPTUAL DESIGN OF A 10-MW_e NUCLEAR RANKINE SYSTEM FOR SPACE POWER

ABSTRACT

The conceptual design of a 10-MW_e Rankine system for nuclear-electric space power is described. The system includes a compact nuclear reactor operating at 1650°K. The reactor design is based on uranium mononitride as the fuel, lithium as the coolant, and tungsten-25% rhenium as the structural material. An efficient heat-pipe radiator rejects waste heat at 1100°K. Overall system efficiency is 17.5%.

INTRODUCTION

Lawrence Radiation Laboratory at Livermore is engaged in a program to develop the technology necessary for building advanced, high-temperature reactors for nuclear-electric space power systems. This program is directed toward systems operating over an electrical output power range from tens of kilowatts to megawatts. Reactor concepts are being examined for use with liquid-metal Rankine cycle, out-of-pile thermionic, and other conversion systems that would operate in the years beyond 1980.

Such a technology development can best be placed in proper perspective by examining specific overall power system

designs. These designs provide a framework for reactor operating conditions, serve to identify specific problem areas, and show the relative importance of the many parameters, physical laws, and system configurations involved.

This report presents results from one of these design studies—a conceptual design of a 10-MW_e, Rankine-cycle, nuclear-electric space power system. This design, designated as SPR-6, has been partially optimized to obtain a low power-plant specific mass with a high system reliability.

The primary application of the SPR-6 system is to provide propulsion energy for long-duration manned interplanetary

missions. For example, nuclear electric propulsion offers substantial savings of initial mass in earth orbit for the execution of manned Mars landing missions ^{1*} Although the SPR-6 design constraints were chosen to correspond to such a manned Mars landing expedition, the reactor technology developed in this study is applicable in general to high-performance,

*Numbers refer to references which appear in a list at the end of the report

long-lifetime space nuclear power plants. The reactor performance and design should be considered as a general case capable of being adjusted for use in any future manned or unmanned exploration of the solar system and outer space. Many design considerations of the SPR-6 system have been reported previously in regular quarterly progress reports.²⁻⁷ Details of these considerations have not, in general, been repeated here.

GENERAL SYSTEM DESCRIPTION

Principal design constraints of the SPR-6 power plant are listed in Table 1 and an artist's sketch is shown in Fig. 1. The power plant would be launched in a partially assembled condition and some manual work would be required in low earth orbit to ready the system for operation.

A schematic diagram of the system with a reactor coolant outlet temperature

Table 1 SPR-6 design constraints.

Electrical output power	10 MW
Design lifetime	10,000 hr
Power conversion method	Rankine cycle
Application	Electric propulsion
Design power on-off cycles	6
Payload	
Type	Manned
Diameter	10 m
Distance (from reactor)	50 m

of 1650°K is shown in Fig. 2. The cycle thermal economy is given in the flow chart of Fig. 3. High-purity liquid lithium is heated in the reactor and then forced through a heat exchanger where its heat is transferred to a boiling potassium working fluid. Four turbine-alternator units extract 2.5 MW_e each of useful power from the working fluid, and waste heat is rejected from a highly efficient heat pipe radiator. Overall system efficiency is 17.5%

The design of the reactor is based on uranium mononitride (UN) as the fuel, lithium as the coolant, an alloy of 75 at. % tungsten and 25 at. % rhenium as the structure. Compatibility of these materials at operating temperatures is substantiated by experimental data. The active core consists of 8000 UN fuel pins and half as many coolant channels. These form an approximate right circular cylinder. A central duct returns the coolant to the core. Reactivity of the reactor is regulated with a

dual-control system consisting of a thin, axially translating molybdenum side reflector and centrally located liquid control circuits that are filled with the isotope Li^6 . Incorporation of these features results in a very compact reactor design.

Major components of the SPR-6 system are shown to scale in Fig. 4. The reactor is separated from all the other components by the main lithium hydride (LiH) shadow shield, which effectively blocks any direct line of sight between materials on the reactor side and the components on the other side. This reduces radiation damage and

undesired nuclear heating caused by the high radiation fields present around the reactor. It also eliminates activation and scattering problems that would cause a lethal radiation dose for a manned payload. Additional gamma ray shielding necessary for the payload has been added in the form of a 30% tungsten, 70% lithium hot shield and a heavy 100% dense tungsten back shield. The piping passes through the main shield at an angle to reduce secondary scattering from the reactor to the payload.

To keep the reactor subcritical prior to startup, the reactor loop in the fueled core

Fig. 1. Artist's sketch of SPR-6 system.

Fig. 2. SPR-6 system schematic.

region is initially filled with lithium enriched 28% with the strong neutron-absorbing isotope, Li^6 . The remainder of the reactor loop is filled with the weak neutron-absorbing isotope, Li^7 . Initial

separation of these isotopes is possible since lithium is solid below 450°K. The multiplication factor, k_{eff} , of the reactor in this state is about 0.88. During startup, the two isotopes are mixed together in the

reactor loop to give a nearly neutral, homogeneous mixture of 97% Li^7 and 3% Li^6 .

Control required for operational shut-down, temperature effects, and lifetime effects ($\Delta k = 0.048$ total) may be obtained from either in-core liquid control circuits or by axial translation of the side reflector. Each system is capable of independently controlling the reactor once a nearly

neutral coolant mixture has been obtained in the reactor loop. This dual control system considerably increases system reliability.

The liquid control circuits consist of a number of tubes placed inside the fueled core in an annular region surrounding the central coolant return duct. The tubes are filled with liquid Li^6 and helium gas. A capillary structure inside the tubes is

Actual system efficiency = 17.5%

Fig. 3. SPR-6 thermal economy.

used to evenly distribute the lithium. The mass of lithium present can be varied, depending on the amount of reactivity desired, by adjusting the pressure level inside the tubes.

Individual segments of the side reflector are axially translated with fluid drive mechanisms and fluidic actuators. The reflector-actuating systems contain no electrical components near the reactor because of the sensitivity of electrical insulating materials to radiation damage.

The reactor vessel is made of a tantalum alloy material and cooled by a separate liquid-lithium auxiliary coolant loop connected to the boiler-preheater. The fueled core is separated from the reactor vessel by the auxiliary cooling loop channel and a W-25% Re membrane. Tantalum is not permitted to be in contact with either the nuclear fuel or the reactor coolant since it is chemically incompatible with either UN or N₂.

Heat is transferred from the reactor-loop liquid lithium coolant by a 70-cm-diam, countercurrent-flow, shell-and-tube-type potassium boiler. The potassium working fluid boils inside some 2900 tantalum tubes, each 1 cm in diameter, 154 cm long, and containing a helical insert that assures boiling stability. The tubes are arranged in a triangular pattern with a center-to-center spacing of 1.3 cm and are clad with tungsten on their outside surface. Liquid lithium coolant circulates around the tubes. Pressure in the reactor loop is adjusted to minimize the pressure difference across the boiler tube walls. The boiler pressure vessel and the auxiliary lithium coolant for the reactor vessel are cooled by liquid potassium returning from the main radiator in an

annular preheater which is incorporated into the boiler. The boiler is positioned on the payload side of the shield in order to reduce the activation of the natural potassium working fluid to acceptable levels for manned missions.

Useful energy is extracted from the potassium working fluid in four identical turbine-alternator units. The units are operated in a counterrotating fashion with each other in order to decrease undesirable torque problems during starting and shutdown. Windings on each alternator are cooled by an 800°K auxiliary heat-pipe radiator cooling system.

Waste heat from the potassium working fluid is rejected in a large, but extremely light, flat rectangular heat pipe radiator. Utilization of heat pipes reduces the mass of the radiator to about one-half that of a conventional fin-and-tube type. The heat pipes operate in parallel, and thus offer the advantage of redundancy.

Reactor loop piping is constructed of W-25% Re material. Flanged connections with the tantalum alloy reactor and boiler pressure vessels are proposed to withstand existing stresses. Separate sealing mechanisms made of thin sheet material would be necessary. Tantalum alloy piping is used in the power conversion loop and pressure vessel cooling loop, except for niobium alloy piping in the main radiator. Flow rate is varied in each loop by adjusting the power to the three mechanical pumps used in the system. There are no valves. Additional redundant pumps can be introduced with only a small mass penalty. A liquid metal storage-expansion tank is required in each loop to maintain the desired system pressures.

Fig. 4. SPR-6 system layout. Dimensions are in centimeters.

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Operating characteristics of the SPR-6 system are given in Table 2, and a specific mass breakdown is given in Table 3. The low specific mass of 7 g/W is made possible by postulating a high fuel burnup capability, high strength alloys, a compact radiation shield, and highly efficient heat pipe radiators. The smallest reasonable

reactor is utilized since reactor size affects not only the weight of the reactor but also that of the shields. This low specific mass is a desirable attribute regardless of application but is particularly important to difficult electric propulsion missions. A discussion of mission applications for nuclear-electric space power systems is given by MacKay et al.¹

Table 2. Operating characteristics of the SPR-6 system.

<u>Reactor Loop</u>									
Reactor power level, MW	.	.	.	.	.	.	.	.	57
Reactor inlet temperature, °K	.	.	.	.	.	.	.	.	1577
Reactor outlet temperature, °K	.	.	.	.	.	.	.	.	1650
Reactor inlet pressure, bars	.	.	.	.	.	.	.	.	26.2
Reactor outlet pressure, bars	.	.	.	.	.	.	.	.	25.3
Lithium coolant fluid flow rate, kg/sec	.	.	.	.	.	.	.	.	191
Reactor-loop piping inside diameter, cm	.	.	.	.	.	.	.	.	19
Detailed reactor characteristics	.	.	.	.	.	.	.	.	Table 4
<u>Shields</u>									
Main shield maximum temperature, °K	.	.	.	.	.	.	.	.	800
Main shield thickness, cm of LiH	.	.	.	.	.	.	.	.	140
Back shield thickness, cm of W	.	.	.	.	.	.	.	.	12
<u>Power Conversion Loop</u>									
Power-conversion-loop pump inlet pressure, bars	.	.	.	.	.	.	.	.	1.6
Power-conversion-loop pump outlet pressure, bars	.	.	.	.	.	.	.	.	25.4
Potassium working fluid flow rate, kg/sec	.	.	.	.	.	.	.	.	29
Turbine inlet temperature, °K	.	.	.	.	.	.	.	.	1560
Alternator net output power, MW	.	.	.	.	.	.	.	.	10
Auxiliary radiator total heat rejection, MW	.	.	.	.	.	.	.	.	1.2
Auxiliary radiator rejection temperature, °K	.	.	.	.	.	.	.	.	800
Auxiliary radiator total projected area, m ²	.	.	.	.	.	.	.	.	40
Main radiator heat rejection, MW	.	.	.	.	.	.	.	.	45.4
Main radiator inlet temperature, °K	.	.	.	.	.	.	.	.	1110
Main radiator projected area, m ²	.	.	.	.	.	.	.	.	400
Radiator characteristics	.	.	.	.	.	.	.	.	Table 10
Turbine-alternator characteristics	.	.	.	.	.	.	.	.	Table 11
Boiler-preheater characteristics	.	.	.	.	.	.	.	.	Table 12
Pump characteristics	.	.	.	.	.	.	.	.	Table 13

Table 3. SPR-6 system masses.

	Mass, kg	Specific mass, g/W	Relative mass
Shields	33,000	3.30	0.472
Main radiator	13,400	1.34	0.191
Alternators (including auxiliary cooling radiators)	7,200	0.72	0.102
Reactor	4,200	0.42	0.061
Boiler-preheater	1,800	0.18	0.026
Structure	1,500	0.15	0.021
Turbines	1,400	0.14	0.020
Reactor loop piping	1,000	0.10	0.014
Lithium coolant pump	1,000	0.10	0.014
Potassium working fluid pump	600	0.06	0.009
Lithium fluid	600	0.06	0.009
Power conversion loop piping	500	0.05	0.007
Potassium fluid	400	0.04	0.006
Controls	300	0.03	0.004
Pressure vessel cooling loop pump	100	0.01	0.001
Miscellaneous	<u>3,000</u>	<u>0.30</u>	<u>0.042</u>
TOTAL	70,000	7.0	1.000

Interactions between the reactor and other parts of the system were examined by combining performance characteristics of each component into a single system model and varying the important thermodynamic parameters one by one. Minimum system mass was selected as an optimization parameter. Because of the changing nature of the system model and other assumptions made during the optimization studies, the SPR-6 system described is only partially optimized. A perturbation study could reveal slight changes in the stated conditions.

It was determined that a near-optimum reactor outlet temperature existed at

1650°K. For lower reactor outlet temperatures, a larger radiator was required to reject waste heat; although the lower vapor pressures permitted lighter piping and containment vessel masses, these savings were more than offset by the heavier radiator, resulting in a higher specific mass for the system. At higher reactor outlet temperatures the piping and containment vessel masses increased and the turbine blades became overstressed.

A turbine temperature ratio* of 0.7 was found to give a minimum specific mass for

*Turbine temperature ratio is defined as turbine outlet temperature divided by turbine inlet temperature.

the system. This value is close to Pitkin's predicted value of 0.75 for a system dominated entirely by the radiator mass.⁸ An optimum turbine

temperature ratio slightly lower than 0.75 is expected since the radiator mass is not entirely dominant in the SPR-6 system.

THE REACTOR

GENERAL DESCRIPTION

The core of the reactor is composed of a close-packed bundle of fuel elements supported on the downstream end by a 30-cm-thick tungsten support structure and on the upstream end by a spline attachment providing for axial and radial growth. The downstream support structure also acts as a radiation shield. Figure 5 is an artist's sketch of the SPR-6 reactor. General characteristics are given in Table 4.

In cross section, the active core is an annular region surrounding a central coolant-return passage and a liquid control region. The outer boundary of the core is a dodecagon (12 sides) to accommodate the hexagonal packing pattern of the fuel elements. The fueled core is enclosed by thin polygonal W-25% Re membranes at the inner and outer radii.

A slight radially inward net pressure is produced on the outer membrane by venting the stagnant lithium fluid present between the core and the pressure vessel to the upstream pressure. A slight radially outward net pressure exists across the inner membrane because of the core pressure drop. Thus the core acts as a rigid column between the upstream and downstream supports, dynamically restrained by the

side membranes and the radial pressure gradients. This concept of a dynamically restrained core prevents changes in position of the fuel elements and keeps the flow passages aligned.

Surrounding the core is a 1.2-cm-thick cooled tantalum pressure vessel and a segmented 2-cm-thick molybdenum side reflector as shown in Fig. 5. The reactor pressure vessel is clad on the inner surface with tungsten material so that the reactor coolant is exposed only to the UN fuel and tungsten base materials. Chemical compatibility between the UN fuel, W-25% Re cladding, and lithium is discussed later in the section on Reactor Materials Selection.

A separate cooling loop maintains the reactor pressure vessel, as well as the boiler-preheater pressure vessel, at temperatures below 1400°K. Although this cooling loop adds some complexity to the system, it makes possible a minimum reactor-vessel thickness which enhances the side-reflector control worth, reduces the overall system mass, and makes fabrication of the pressure vessel simpler. The cooling loop extracts heat from the reactor and boiler-preheater pressure vessels by conduction and transfers it to potassium liquid in the preheater.

Table 4. Characteristics of the SPR-6 reactor.

Nuclear Parameters

Power level, MW _t	57
Lifetime, hr	10,000
Average fuel burnup, at %	2.1
Maximum fuel burnup, at %	3.3
Fuel density, fraction of theoretical	0.97
Average fuel enrichment, atom fraction of U ²³⁵	0.70
Maximum fuel enrichment, atom fraction of U ²³⁵	1.0
Average fuel power density, W/cm ³	575
Radial peak-to-average power density	1.12
Axial peak-to-average power density	1.40
Overall peak-to-average power density ^a	1.57
Median neutron energy causing fission, MeV ^b	0.30-0.33
Maximum neutron flux in core above 1 MeV, n/cm ² -sec	2.6×10^{14}
Average neutron energy, MeV	0.25
Prompt neutron lifetime, ℓ^* , sec	8.1×10^{-8}
Delayed neutron fraction, β_{eff}	0.0068
Worth of 1% increase in U ²³⁵ enrichment, Δk	0.008
Worth of 1-cm increase in radius of fueled core, Δk	0.023
Worth of 1-cm increase in length of fueled core, Δk	0.001
Assumed worth of end reflection, Δk	0.0065

General Dimensions

Fueled core length, cm	87.0
Fueled-core mean outer diameter, cm	62.1
Liquid-lithium-control-zone outer diameter, cm	22.7
Reactor-coolant-return-duct diameter, cm	15.3
Pressure-vessel inside diameter, cm	65.0
Side-reflector inside diameter, cm	67.4
Side-reflector outside diameter, cm	71.4

Hybrid Fuel Element Dimensions

Fuel radius, cm	0.216
Fuel-element-cladding inside radius, cm	0.225
Fuel-element-cladding outside radius, cm	0.250
Coolant-tube inside radius, cm	0.220
Coolant-tube outside radius, cm	0.250
Number of fuel tubes	8064
Number of coolant tubes	4032

Table 4. (Continued)

Fueled-Core Volume Fractions

Fuel volume fraction	0.433
Cladding, plus coolant-tube volume fraction	0.183
Primary-coolant volume fraction	0.234
Interstitial-fluid volume fraction	0.093
Swelling-allowance volume fraction	0.057
Total fueled-core volume, m ³	0.228

Masses

Mass of uranium required, kg	1242
Mass of U ²³⁵ required, kg	865

Control Worth

Ground safety, initial separation of Li coolant isotopes, Δk	0.100
Operational shutdown, Δk	0.022
Operational losses due to fuel burnup etc., Δk	0.018
Temperature effects, 293-1650°K, Δk^c	<u>0.008</u>
Total control-reactivity required, Δk	0.048
Total worth of reflector, Δk^b	0.050-0.054
Total worth of liquid control circuits, Δk^b	0.047-0.050
K_{eff} prior to reactor startup	0.878
K_{eff} after mixing Li coolant isotopes, 600°K	0.977

Thermal-Hydraulic Parameters

Reactor-coolant flow rate, kg/sec	191
Reactor-coolant outlet temperature, °K	1650
Reactor-coolant temperature rise, °K	73
Reactor-coolant inlet pressure, bars	26.2
Reactor pressure drop, bars	0.9
Core Reynolds number	5.9×10^4
Reactor coolant velocity inside core, cm/sec	740
Average heat flux at coolant channel surface, watts/cm ²	117
Average centerline fuel temperature, °K above local coolant temp.	46

^aProduct of axial and radial peak-to-average power densities.

^bValues given vary between the limits shown depending upon the amount of Li⁶ in control circuits and amount of side reflector utilized.

^cThis maximum value occurs with no side reflector and 30% Li⁶ in the liquid control circuits (see Fig. 10).

Fig. 5. Artist's sketch of the SPR-6 reactor.

A liquid-lithium, high-temperature primary radiation shield is created by an enlarged exit plenum. A W-25% Re structure, also present in the plenum, acts as the axial support for the core. A neutron flux attenuation of 10^{-2} in this region reduces the problems of overheating in the main LiH radiation shield located outside the pressure vessel.

The reactor coolant is returned to the reactor by a 15.3-cm-diam central duct. An annular region 3.7 cm thick surrounding the central duct contains liquid-lithium

control circuits. Pressure drop in the reactor coolant return duct is about 10% that in the core. The optimum cross-sectional area of the reactor coolant return duct plus the annular control region is about 15% of the fueled core area.

The radial power profile is flattened by varying the U^{235} enrichment in four annular zones. Radial peak-to-average power density ratio is 1.12. Axial U^{235} enrichment is uniform and yields the natural cosine-like power density with a peak-to-average value of 1.4 (see Fig. 6).

Fig. 6a. Radial power density profile of SPR-6 reactor.

Fig. 6b Axial power density profile of SPR-6 reactor.

DESIGN

Preliminary reactor studies were carried out with a one-group, diffusion-theory computer program which permitted rapid surveys of the characteristic reactor behavior.² Further refinement of the reactor design, including the variation of parameters, was done with the one-dimensional, multigroup, multiregion diffusion code, ZOOM, specifically adapted to fast reactor calculations.⁹ Final numerical specifications of the reactor, however, were determined with a modified version of the one-dimensional neutron transport code DTF,¹⁰ with an S_4 approximation. This DTF code was coupled to a thermodynamic program which permitted use of a variety of thermomechanical constraints. Two-dimensional calculations with transport codes or with Monte Carlo codes were considered to be unwarranted for the purposes of this conceptual design study.

The theoretical basis underlying the adaptation of the ZOOM diffusion code to

Table 5. SPR-6 cross-section energy grouping.

Group	Energy range, MeV	Group	Energy range, eV ^a
1	10-3	9	550-100
2	3-1.4	10	100-30
3	1.4-0.9	11	30-10
4	0.9-0.4	12	10-3
5	0.4-0.1	13	3-1
6	0.1-0.017	14	1-0.4
7	0.017-0.003	15	0.4-0.1
8	0.003-0.00055	16	0.1-10 ⁻⁶

^aNote change in units to eV in this column, as compared to MeV in column to left.

small fast cores was reported by Doyas and Koponen.¹¹ Their improved neutron-leakage correction was included in the ZOOM code, and the agreement with DTF results was excellent. ZOOM calculations of multiplication factor, k_{eff} , for an SPR-6 bare core and a core reflected with 2 cm of molybdenum were within 0.6% and 0.8% respectively of the DTF calculations.

Neutron cross sections for all calculations were derived from the Howerton evaluated cross section library.¹² The cross section data was collapsed into the 16-group structure shown in Table 5.¹³ Neutron flux weighting was based on a neutron energy spectrum typical of the fueled core region in a fast reactor.

Neutronic design philosophy was based on nuclear safety and reliability of reactor operation. The integration of these aspects, plus realistic mechanical considerations, into the early neutronic design provided a sound basis for reactor optimization. The neutronic model of the reactor is described in Fig 7 and Table 6

1. Hybrid Fuel Elements

The core contains hybrid-type fuel elements in an arrangement of close-packed, equal-diameter metal tubes (see Fig 8). Every third tube is unfueled and serves as a reactor coolant passage. Interstices between the tubes are filled with stagnant liquid lithium. Allowance for fuel swelling due to burnup is provided by a small gap between the fuel pellets and the cladding.

This hybrid fuel element has several advantages. Cladding redundancy exists since the flowing lithium coolant is separated from the fuel by a double wall. Fuel

Fig. 7. SPR-6 model and region designations employed in neutronic calculations (see Table 6)

swelling is permitted without dimensional changes in the fuel tube cladding. This adds structural stability to the core and decreases temperature effects on reactivity. The element is assembled simply and has a high apparent reliability. Its pressure drop characteristics are intermediate between those of the pin-type and tube-type fuel elements reported in Ref. 6. Although a low fuel volume fraction results from the use of hybrid fuel elements, reactor criticality is easily achieved.

The fuel pellets are centered inside the cladding to reduce angular temperature differences. Linear swelling is assumed to be equal to twice the burnup fraction. Establishment of an average 2% burnup limit appeared reasonable in light of avail-

able material data. There is little difficulty accommodating fuel swelling up to twice that assumed.

The swelling allowance gap is initially filled with liquid lithium bonding fluid. Fission gases are removed continually from the fuel rather than being allowed to collect. This implies a nominal circulation of the lithium bonding fluid and continuous separation of fission products. By comparison, if helium instead of lithium were used as a bonding agent, there would be a 130°K temperature drop across the swelling allowance gap.

The temperature distribution of the hybrid elements, shown in Fig. 8, does not vary significantly from that of a uniformly cooled rod. This is due to the high and

Table 6. Atomic densities of materials in SPR-6 reactor, and description of the various reactor regions (see Fig. 7) in terms of the volume fractions of material they contain.

Material	UN	Li	W-25% Re	Ta	Mo	Li ⁶
Atomic density, ^a 10 ²⁴ atoms/cm ³	0.0321	0.0364	0.0640	0.0553	0.0640	0.0364
Volume fractions of material by reactor region:						
A	—	1.0	—	—	—	—
B	—	—	1.0	—	—	—
C	—	0.1	0.3	—	—	0.6
D	—	—	1.0	—	—	—
E	0.433	0.384	0.183	—	—	—
F	—	—	1.0	—	—	—
G	—	1.0	—	—	—	—
H	—	—	—	1.0	—	—
I	—	1.0	—	—	—	—
J	—	—	—	1.0	—	—
K	—	—	—	—	1.0	—
L	—	1.0	—	—	—	—
M	—	0.7	0.3	—	—	—
N	—	1.0	—	—	—	—

^aAtomic density at design temperature and pressure.

nearly equal value of the thermal conductivities of lithium and tungsten.

Heat transfer for these elements is based on a slug-flow model. If the coolant is assumed to flow with uniform velocity through the passage and if there is assumed to be temperature continuity at the coolant-cladding interface, the problem reduces to a source-sink conduction problem. With this assumption a constant Nusselt number of 8 is applicable for heat transfer in circular tubes.¹⁴

Fuel element dimensions are selected on the basis of fuel thermal stress. Thermal stress is considered to be important during startup and shutdown of the reactor. The degree of fuel cracking that could be tolerated, however, is not known. Data on

UN indicates a modulus of rupture strength of 700 bars at 1650°K. An allowable stress of half this value was applied in sizing the fuel elements.

Stresses in the cladding and coolant tubes due to bundling pressure are quite low. Distortion of the coolant tubes is avoided by making their wall thickness 20% greater than the fuel cladding thickness.

2. Reactor Control

Nuclear ground safety prior to reactor operation is provided by initially filling the fueled core with lithium having 28% enrichment in the isotope Li⁶, and by filling the remaining volume of the reactor coolant loop with Li⁷. The increased concentration of Li⁶ in the fueled core during

(a) Fuel element configuration

- Uranium mononitride fuel
- Tungsten-25% rhenium cladding
- Lithium coolant
- Stagnant lithium

(b) 30° segment of hybrid fuel element

(c) Hybrid fuel element temperature rise above mean coolant temperature

Fig. 8. SPR-6 hybrid fuel element.

ground handling renders the reactor sub-critical by 10% Δk . This isotope separation is easily maintained since lithium is solid below 450°K.

At the beginning of life, all the lithium mixes together in the reactor coolant loop. This, in effect, removes Li^6 from the fueled core and renders the reactor near critical. The advantage of this ground safety concept lies in the absence of mechanical devices in the reactor.

Reactivity coefficients due to thermal effects are all negative as shown in Table 7. These coefficients were calculated through perturbations at the design point. In each case, a detailed description of the reactor was prepared and fed into the neutronic DTF computer code.

Temperature-dependent properties of materials were used throughout, and volume fractions, material densities, component dimensions, etc., were recomputed as required for each perturbation.

The reasons for isolating the temperature coefficients require some explanation. The core was divided into three components: the fuel, cladding, and primary coolant. This was necessary for control stability analysis because the rather large

fraction composed of cladding and stagnant lithium tends to decouple the fuel from other core components. For example, a step change in power, from zero to full power, results in an initial rate of fuel temperature rise of 300°K per second. In such a case, the fueled core is thermally isolated from both the pressure vessel and the coolant return; and to some extent the fuel, cladding, and primary coolant are thermally isolated from each other. During a rapid power oscillation, the individual effects in fuel, cladding, and primary coolant differ both in magnitude and phase. Without proper analysis to recognize these differences, a design based solely on uniform reactor temperature can lead to a conditionally unstable reactor.

The effect of temperature on reactivity is reduced by a fuel element geometry in which the fuel pellets are free to expand both radially and axially within a stagnant lithium bonding fluid (see Fig. 8). Operational losses are also decreased because fuel swelling does not alter the overall size of the fueled core.

The selection of a final reactor coolant mixture containing 3% Li^6 and 97% Li^7 is based on three constraints: First, operational safety considerations require that

Table 7. Thermal effects on multiplication factor, k_{eff} , for SPR-6 reactor. All calculations performed with the reactor kept near design conditons.

	Beginning of life	Midlife	End of life
Δk_{eff} due to lifetime effects	0	-8.99×10^{-3}	-1.78×10^{-2}
$\Delta k_{\text{eff}}/^{\circ}\text{K}$ fuel temperature rise	-3.43×10^{-7}	-3.54×10^{-7}	-3.80×10^{-7}
$\Delta k_{\text{eff}}/^{\circ}\text{K}$ cladding temperature rise	-6.47×10^{-6}	-6.18×10^{-6}	-5.99×10^{-6}
$\Delta k_{\text{eff}}/^{\circ}\text{K}$ reactor coolant temperature rise	-7.45×10^{-7}	-6.65×10^{-7}	-6.54×10^{-7}
$\Delta k_{\text{eff}}/^{\circ}\text{K}$ inlet temperature rise (bias)	-4.56×10^{-6}	-4.23×10^{-6}	-4.12×10^{-6}

the reactor should become subcritical in case of rupture of the reactor coolant loop and subsequent loss of fluid. To attain this for the SPR-6 system, the final mixed reactor-loop coolant must contain more than 95% Li^7 .

Second, it is necessary to select the final mixed Li^6 concentration in the reactor loop so that any positive reactivity changes can be controlled during the early stages of melting and mixing in the coolant. During these early stages it is conceivable that nearly pure Li^7 coolant would enter, and temporarily occupy, the entire fueled core. The resulting reactivity surge must be less than the 2.2% Δk operational shutdown reserves available in the reflector and liquid control circuits (see Fig. 9).

Third, a significant change in reactivity should be realized between the initial separation and subsequent mixing of the lithium isotopes. A plausible value of 10% Δk was selected.

It should be noted that all the lithium in the fueled core, with the exception of the liquid control circuits, has the same isotope composition in order to prevent reactivity changes in case of accidental coolant transfer. This pertains to the bonding fluid between fuel pellets and cladding, the interstitial coolant between fuel pins and coolant tubes, and the coolant in the main reactor loop itself.

Redundancy in reactor control is assured through two independent control systems. This dual control system exhibits several advantages over a single control scheme. The required adjustable reactivity range of each control system can be held relatively small since reactivity reserves and provisions for failure of individual segments of each system are accounted for by the

backup controls. Each mechanism, by itself, is capable of carrying the mission to completion.

A 2-cm-thick molybdenum side reflector is utilized for the mechanical control system. Variations in reactivity are made by axially translating segments of the reflector.⁶ The segmentation plus individual controls for each segment provide a high degree of redundancy.

Molybdenum was chosen as the side reflector material over the slightly more effective BeO since it offered a simple construction of solid metal reflector segments. Beryllium oxide would require a metal container.

Lithium control tubes positioned in a 3.7-cm-thick annulus between the central duct and the fueled core are used for the liquid control system. These tubes can be filled with or voided of Li^6 , which acts as the neutron-absorbing medium. Heat removal from the control region is accomplished through the interstitial coolant of the core which is circulated between adjacent control tubes. Control tubes are double walled as an added precaution to prevent accidental transfer of Li^6 into the main coolant stream. The control tubes contain metal screens in the form of capillary wicks, similar to those in heat pipes. This allows uniform distribution of the liquid lithium under zero-gravity conditions.

The quantity of lithium in the control tubes is varied with a control element loop.⁷ Lithium vapor leaves the capillary screens continuously by evaporation and passes out of the control tubes through a duct. The vapor is condensed and the resulting liquid is pumped back into the control tubes to

Fig. 9. Multiplication factor as a function of Li^6 and Li^7 isotope concentration in reactor coolant.

complete the cycle. The rate of evaporation is determined by the rate of heat generation in the control tubes. If liquid is pumped into the control tubes faster than it is evaporated, the proportion of liquid will increase.

The advantages of this liquid control system are the absence of moving parts in or near the high temperature core, the simplicity of heat removal from the control elements, the capability of remote control by hydraulic means with valves and pumps located in relatively low temperature regions behind the radiation shield, and the

ease of providing redundancy through independently adjustable control circuits. Simultaneous loss of lithium from all the liquid control circuits is improbable since each has a separate actuator.

Since the mechanical and the liquid control systems act respectively on the periphery and inner boundary of the fueled core, there is little interdependence between the systems. This is brought out clearly by Fig 10 which shows the control range of the dual control system.

With this dual control system, one can approach a particular reactivity state

Fig 10 Range of SPR-6 dual control system for adjustments of reactivity

through numerous possible control states of the individual controls as long as their combined effect matches that of the desired reactivity requirement. This is illustrated in Fig. 10 by the shaded area for achievement of criticality at the beginning of life and 600°K. The solid arrow indicates a possible path.

The design point for the dual control system was chosen with 75% Li⁶ in the control system and an equivalent 0.7-cm-thick side reflector. This renders the reactor critical at the beginning of life and at the design temperature of 1650°K.

Many combinations of reactivity states in the two independent control systems can now be used to compensate for operational losses. The dotted arrow shows a possible path. Completion of the 10,000-hr mission at design power can be achieved with partial or total loss of either control system.

The SPR-6 reactor is reasonably safe from nuclear excursions due to accidental

immersion in water. The prevailing neutron energy spectrum is softened by the presence of water, and a high fraction of neutrons are then captured in the tantalum pressure vessel, and in the W-25% Re structural material present in the central control region and throughout the core. The greatest gain in reactivity occurs with a simple reflection by water outside the core and is only +1% Δk . This small amount of excess reactivity is readily compensated for by either one of the two control systems. As water progressively displaces lithium in the central return duct and then in the core, the reactivity decreases monotonically. The additional inclusion of EuN barriers against epithermal and thermal neutrons for the prevention of nuclear excursions in water is not necessary for the SPR-6 design (because of the Ta and W-25% Re neutron capture already mentioned). This is in contrast with other reactors reported by Hampel *et al.*¹⁵

SHIELD

The shielding was designed to give protection to a manned spacecraft. The total integrated crew dose of 13.3 Rem from the power plant was set by utilizing a maximum of 100 Rem for Baum's "effective residual dose."¹⁶ Passage through the trapped radiation belt, galactic radiation, and power plant maintenance were assumed to account for 33 Rem of this permitted amount. The remaining dose was divided between the reactor and the solar flares by assuming typical reactor shielding and

solar flare shielding considerations and attempting to achieve a minimum weight for a typical spacecraft. The resulting division is shown in Table 8. With a constant dose rate, 3 Rem of effective residual dose is given by a real dose rate of 1.33 mRem/hr.

Shield calculations were performed with GEISHA computer code using point kernel methods.¹⁷ Removal theory, with the Albert-Welton¹⁸ fit to experimental data for hydrogenous materials, was em-

Table 8. Contributions to the payload effective residual dose, Rem.

	Effective residual dose, Rem
Trapped radiation (Van Allen belt)	5
Galactic radiation	3
Power plant maintenance	25
Reactor operation	3
Solar flares	64
Total	100

ployed for neutrons. Six energy groups and appropriate buildup factors were used for gamma rays. Secondary gamma ray production was accounted for by assuming that all the fast neutrons "removed" within a component are absorbed within that same component.

The three-part shield configuration used in the calculations is shown in Fig. 11. The first component, labeled "hot shield," is a region 30 cm long located within the reactor vessel. This region includes the reactor downstream support structure and is considered to have a volumetric composition of 70% lithium and 30% tungsten. Reactor-loop lithium coolant flows through this region, and heat deposited here is easily removed.

The main shield, formed of lithium hydride, was positioned so that its maximum temperature was equal to or less than 800°K. For an integrated dose of 13.3 Rem at the payload center, the thickness of this region was determined to be 113 cm. To account for the effects of the necessary shield penetrations, however, this thickness was increased to 140 cm.

The back shield, a 12-cm-thick slab of tungsten, serves three purposes: it shields

the payload (1) from secondary gammas produced in the hot and main shields, (2) from scattered gammas, and (3) from bremsstrahlung gammas produced in the piping and boiler. This third source results from the activation of the Li^7 in the coolant

The resulting beta particles produce gamma rays with energies from zero to 13 MeV by the bremsstrahlung process.

Additional attenuation of radiation available from the presence of the pumps, turbine-alternators, radiators, and piping is not considered in the calculation. From this standpoint, the results obtained are conservative.

When a shadow shield is employed, attention must be given to insure that radiation is not scattered around the shield to the position of the payload. A simplified approach was used to determine the effect of scattering centers on the dose at the payload. Results showed that an unshielded five-cent piece placed within 20 m of the side of the reactor produced a payload dose rate due to neutron scattering in excess of the total allowed dose rate. From this it was concluded that all components must be placed in the shadow of the shield. In order to meet this condition for the radiator and its associated piping, wings were added to the main lithium hydride shield. These wings are an extension of the main shield and are designed to cast a shadow over the components on the payload side of the shield. An isometric view of the main shield showing these wings is

*The Be^8 isotope has a half-life of 3×10^{-16} sec.

Fig. 11. SPR-6 shielding calculational model.

given in Fig. 12. Approximate scattering calculations indicate that a wing thickness equal to the central portion of the main shield provides more than the required attenuation for neutrons.

The tungsten back shield is extended around the boiler and along the wings to similarly reduce the dose from scattered gammas.

Figure 13 displays a carpet plot of the results of a parameter study varying the hot and back shield thickness. The total relative mass of the hot, main, and back shields is indicated. A broad minimum is seen to exist at about 30 cm of hot shield and 12 cm of back shield. While the total weight varies little over this range, the shielding geometry varies considerably.

Fig. 12. Isometric view of the SPR-6 main LiH shield.

Fig. 13. The effect of hot shield and back shield thickness on total shield mass for a given integrated payload dose of 13.3 Rem and a maximum main shield temperature of 800°K.

Table 9 shows the effects on the design of varying the hot shield thickness by only 10 cm from the accepted design point. It is to be noted that the minimum permissible distance between the hot and main shields varies from zero to 102 cm.

Shutdown activity produced by fission product decay gammas and gammas from

system components activated during operation by the core neutrons was found to be negligible for any point within the shadow of the shields. However, dose rates ranging from 10,000 R/hr near the reactor to several hundred R/hr near the payload are expected for points exposed to a direct line of sight with the reactor 24 hr after shutdown.

Table 9. Effects of varying hot shield thickness 10 cm either way from design point of 30 cm, keeping back shield thickness constant at 12 cm and integrated dose at payload constant at 13.3 Rem.

	Hot shield thickness, cm		
	20	30	40
Main shield thickness, cm	163	113	75
Main shield thickness with primary pipe penetration, cm	190	140	102
Minimum distance between hot and main shields, cm	102	39	0
Components of integrated dose at payload, Rem:			
Neutrons	0.001	0.1	3.4
Core gammas	0.23	0.08	0.02
Secondary gammas	12.1	12.1	8.9
Bremsstrahlung	1.0	1.0	1.0
Totals	13.3	13.3	13.3

POWER CONVERSION

HEAT PIPE RADIATORS

Lightweight power plants require a method of rejecting waste heat which is reliable and at the same time has low specific mass. The radiator studies conducted at LRL started with the classical

fin-and-tube approach.¹⁹ Then, after optimum fin-and-tube radiators were found to be extremely heavy due to the required meteoroid protection, a change was made to a heat pipe radiator. The heat pipe approach, at SPR-6 power levels, proved to be a good choice, with a near-optimum design specific mass of 1.34 g/W_e.

The heat pipe radiator differs in design principle from a vapor fin radiator,²⁰ which also employs heat pipes. In the heat pipe radiator, direct contact between the heat pipe and the fluid to be cooled (see Fig. 14) considerably increases heat transfer effectiveness over that of a vapor fin radiator. Another advantage of the heat pipe radiator is that the designer can freely select the relative proportions of heat pipe area used for absorption and for dissipation of heat.

The main heat pipe radiator is constructed of a series of manifolds, positioned in a rectangular array, whose walls are penetrated by a large number of heat pipes. The manifolds and other ducting carry the same amount of meteoroid protection as required in other radiator designs. However, because of their low presented area,

they make a small contribution to the total radiator mass.

The heat pipes transfer heat at substantially isothermal conditions and operate in parallel, functionally independent of each other. Minimum radiator mass occurs when the heat pipes are designed so that some will fail during lifetime due to meteoroid penetration. An excess of heat pipes is installed at the beginning of life and the pipe wall thickness is determined so that 10% of the heat pipes fail from meteoroid penetration during their lifetime. The effect of the puncture of a heat pipe is only that it will cool at its outer end and not contribute significantly as a heat exchange member.

The main radiator was designed with a computer program. Some of the results obtained are shown in Table 10. The results are based on heat pipes that utilize

Fig 14. Main radiator heat pipe layout

Table 10. Heat pipe radiator characteristics.

	Main radiator	Auxiliary radiators
Total heat rejection required, kW	45.4	0.3 per radiator
Total projected area (including piping and manifolds), m ²	400	10 per radiator
Total radiator mass, kg	13,400	300 per radiator
Number of heat pipes	24,000	100 per radiator
Number of radiators	1	4
Heat pipe fluid	Potassium	Sodium
Heat pipe rejection temperature, °K	1080	800
Heat pipe radial input flux, W/cm ²	50	50
Heat pipe inside diameter, cm	1.5	2.4 to 3.0 (in radiator) 1.7 (in alternator area)
Radiator survival probability	0.99	0.99

potassium as a working fluid. Niobium is used for a structural material with beryllium for a meteoroid barrier where required. A radiator survival probability of 0.99 was used to determine the thickness of the meteoroid barrier material.

The effects of various parameters on the SPR-6 main radiator mass were investigated. While the parameter variation was not exhaustive, enough was done to specify a near-optimum main radiator design. The radiator survival probability was found to be the major parameter effecting the radiator mass. Figure 15 shows the mass penalty necessary for probabilities higher than 0.99.

Auxiliary heat pipe radiators necessary to cool the alternator windings were similar in design to the main radiator except that the heat pipes were inserted directly into the area around the windings. Heat from the windings is removed by conduction to heat pipes that utilize sodium as a working fluid. The auxiliary radiator

rejection temperature is 800°K as shown in Table 10.

TURBINE-ALTERNATORS

Although the turbine-alternators account for only one-sixth the total system mass, their performance, namely efficiency, has a direct influence on the size of most other components and therefore on the system mass. Consequently, a brief investigation was conducted to determine the general effects on performance of specified parameters such as working fluid, number of units, and rotational speed. Important characteristics of the turbine-alternator selected are tabulated in Table 11.

The turbines selected are the full-admission axial flow type with 20-40% reaction per stage. To simplify the analysis, moisture removal and interstage drainage—which might be necessary because of turbine erosion problems—are

Fig. 15. Effect of meteoroid penetration survival probability on the main radiator mass.

not included. Instead a performance penalty of 1/2% efficiency for each 1% of exit moisture was assumed throughout the turbine analysis.

The selection of potassium as the working fluid in the power conversion loop was based on turbine efficiency and size, overall system mass, and available data on operating liquid metal turbines. Primarily sodium, potassium, and cesium were considered. Sodium turbines tend to be larger in size and contain more stages than potassium turbines operating at the same conditions. On the other hand, cesium results in a more desirable turbine configuration and efficiency than potassium, but cesium's high vapor pressure is detrimental to the mass of other components and results in a higher overall system mass.

The selection of four turbine-alternator units to generate a combined 10-MW_e output was based on reliability

considerations. A smaller number of units would result in an excessive reduction of total output power should one of the units malfunction. On the other hand, more units would add additional complexity to the system.

Rotational speed is limited by the maximum allowable stress in the turbine blades and alternator rotors. A high rotational speed of 12,000 rpm was selected since it was compatible with standard alternator frequencies and since turbine-alternator mass varies inversely with rotational speed. Several typical high-temperature turbine blading materials were considered, among them the molybdenum alloys of TZM and TZC as well as the tungsten alloy designated "Sylvania A". Allowable blading stress was set at the value resulting in one percent creep in 10,000 hr. The material selected as representative for the SPR-6 turbines is TZC. Allowable stress values were based on the use of molybdenum

alloys for the turbine structural members and H-11 steel with a nickel alloy core for the alternator rotors.

The SPR-6 alternator is a radial-gap homopolar machine with a single field coil. This type of unit features a solid forged steel rotor with a nickel alloy core that requires no rotating windings, slip rings, or rectifiers. The field coil is located on the stator.

Both stator and field coil windings are cooled by sodium heat pipes imbedded in the outer edge of the stator. These pipes extend in a planar array to form radiators that operate at 800°K. Energy is transmitted from the stator teeth and electrical conductors to the heat pipes by thermal

conduction. Thermal conduction out of the field coil region is facilitated by copper sheets imbedded in the windings.

Dynamic seals are provided at each end of the rotor to keep the generator cavity pressure at about 0.1 torr. This pressure level was selected because it permits thermal coupling between various components of the alternator and also minimizes fluid friction losses by assuring vaporization of any potassium in the cavity. The alternators each utilize two potassium-lubricated bearings and are directly coupled to the turbines.

The electromagnetic analysis used for design of the alternators was based on a method of Jain.²¹ This method was used

Table 11. Turbine-alternator characteristics.

<u>General Characteristics</u>										
Number of units	.	.	.	.	.	.	.	.	.	4
Rotational speed, rpm	.	.	.	.	.	.	.	.	.	12,000
<u>Turbine Characteristics</u>										
Potassium mass flow rate, kg/sec per unit	.	.	.	.	.	.	.	.	.	7.25
Turbine efficiency	.	.	.	.	.	.	.	.	.	0.78
Inlet temperature, °K	.	.	.	.	.	.	.	.	.	1560
Exit temperature, °K	.	.	.	.	.	.	.	.	.	1110
Exit quality	.	.	.	.	.	.	.	.	.	0.83
Inlet pressure, bars	.	.	.	.	.	.	.	.	.	24.8
Exit pressure, bars	.	.	.	.	.	.	.	.	.	2.0
Number of stages	.	.	.	.	.	.	.	.	.	7
<u>Alternator Characteristics</u>										
Output power, MW _e per unit	.	.	.	.	.	.	.	.	.	2.6
Power factor	.	.	.	.	.	.	.	.	.	0.8
Voltage, V	.	.	.	.	.	.	.	.	.	2400, 3-phase
Frequency, Hz	.	.	.	.	.	.	.	.	.	2400
Stator current density, A/cm ²	.	.	.	.	.	.	.	.	.	1000
Current loading, A/cm	.	.	.	.	.	.	.	.	.	1000
Pole pitch, cm	.	.	.	.	.	.	.	.	.	7
Number of poles	.	.	.	.	.	.	.	.	.	24
Auxiliary radiator rejection temperature, °K	.	.	.	.	.	.	.	.	.	800

to establish optimum values of stator current density, current loading, and pole pitch. These optimum values were used in a new set of calculations to determine the best choice of frequency. A value of 2400 Hz was found to give a minimum alternator specific mass. The high selected voltage of 2400 V was judged to be reasonable from a standpoint of insulation break-

down in the alternator and will also aid in reducing thruster power-conditioning mass.

BOILER-PREHEATER

The boiler-preheater is constructed in the counterflow, shell-and-tube arrangement shown in Fig. 16. Subcooled

Fig. 16. Boiler-preheater schematic.

potassium from the radiator first enters a preheater section consisting of an annular region that surrounds the main boiler tube array. Heat transferred from the cooling-loop liquid lithium to the subcooled potassium in this preheater section permits both the reactor and boiler vessels to be cooled below 1400°K. The still-subcooled potassium next enters the approximately 2900 boiler tubes—each 1 cm in diameter and 154 cm long—from which it leaves as saturated vapor. A helical flow swirler is positioned inside each boiler tube to

keep the liquid portion of the potassium next to the tube wall and prevent boiling instability. The boiler tubes are separated slightly from each other to permit adequate flow of the reactor loop coolant around the outside surfaces of the tubes. General characteristics of the boiler-preheater are tabulated in Table 12.

Reactor-loop liquid lithium coolant enters the boiler at 1650°K, flows around the boiler tubes in a single-pass, cross-counterflow arrangement, and exits at a temperature of 1577°K. Fluid in the

Table 12. Boiler-preheater characteristics.

<u>General Dimensions</u>									
Overall length, cm	.	.	.	.	.	.	.	.	187
Pressure vessel outside diameter, cm	.	.	.	.	.	.	.	.	81.0
Pressure vessel inside diameter, cm	.	.	.	.	.	.	.	.	78.5
Preheater outer diameter, cm	.	.	.	.	.	.	.	.	78.0
Boiler outer diameter, cm	.	.	.	.	.	.	.	.	75.0
<u>Boiler Tube Dimensions</u>									
Total length, cm	.	.	.	.	.	.	.	.	154.3
Length with subcooled potassium, cm	.	.	.	.	.	.	.	.	2.5
Length with boiling potassium, cm	.	.	.	.	.	.	.	.	151.0
Length with superheated potassium, cm	.	.	.	.	.	.	.	.	0.8
Outside diameter, cm	.	.	.	.	.	.	.	.	1.0
Inside diameter, cm	.	.	.	.	.	.	.	.	0.95
Number of tubes	.	.	.	.	.	.	.	.	2917
<u>Thermal and Hydraulic Characteristics</u>									
Reactor-loop lithium flow rate, kg/sec	.	.	.	.	.	.	.	.	191
Reactor-loop lithium inlet pressure, bars	.	.	.	.	.	.	.	.	26.2
Reactor-loop lithium exit pressure, bars	.	.	.	.	.	.	.	.	24.5
Reactor-loop lithium inlet temperature, °K	.	.	.	.	.	.	.	.	1650
Reactor-loop lithium exit temperature, °K	.	.	.	.	.	.	.	.	1577
Power-conversion-loop potassium flow rate, kg/sec	.	.	.	.	.	.	.	.	29
Power-conversion-loop potassium inlet pressure, bars	.	.	.	.	.	.	.	.	25.4
Power-conversion-loop potassium exit pressure, bars	.	.	.	.	.	.	.	.	24.8
Power-conversion-loop potassium inlet temp, °K	.	.	.	.	.	.	.	.	1080
Power-conversion-loop potassium exit temp, °K	.	.	.	.	.	.	.	.	1560

pressure vessel cooling loop flows in the annular preheater area in a single-pass counterflow direction. The tantalum-alloy boiler vessel wall is cooled by the cooling loop fluid which in turn is cooled by the power conversion loop potassium.

The boiler tubes are constructed of a tantalum alloy and clad with tungsten on the outside surface. A tube wall thickness of 0.025 cm was selected as being practical from a manufacturing standpoint. Problems of structural integrity and leak tightness are minimized by maintaining the fluids on both sides of the boiler tubes at approximately 25 bars (the saturation pressure for potassium at 1560°K). The liner separating the boiler and preheater sections is also clad with tungsten on the inside so that only tungsten metal is in contact with the reactor loop coolant.

Heat transfer in the boiler is dominated by the potassium heat transfer coefficient in the large two-phase region inside the tubes. On the basis of experimental data,^{22, 23} a conservative value of 0.85 W/cm²-°K was selected for an average boiling heat transfer coefficient. In actuality, the boiling heat transfer coefficient is a function of a number of parameters and varies along the length of the tubes. Taking it to be a constant simplifies calculations and may be as accurate as more

complicated schemes where data is not available near the operating conditions picked for the boiler.

PUMPS

Mechanical pumps were chosen for the SPR-6 system because they have higher efficiency and lower mass than electromagnetic pumps. Operating characteristics, shown in Table 13, were estimated

Table 13. Assumed mechanical pump operating characteristics.

Pump efficiency	0.50
Motor efficiency	0.75
Cycloconverter efficiency	0.90
Transformer efficiency	0.98
Power factor	0.85

from other pumps used in the nuclear industry.²⁴ The power conversion loop pump is actually a combination jet-mechanical type. The jet portion raises the inlet pressure to the mechanical portion sufficiently so that cavitation is prevented. Pump design is not crucial since differences in performance of various types of pumps caused a relatively minor effect on the overall system operating characteristics or mass

REACTOR MATERIALS SELECTION

The selection of materials for the reactor was based on both neutronic and chemical considerations of the three essential components of the

core: fuel, coolant, and cladding. The materials selected were uranium mononitride, lithium, and W-25% Re respectively.

FUEL

The choice of UN as the fuel was made not on the basis of one superior quality, but rather because it combines several favorable characteristics. UN has the advantages of high uranium density, good thermal conductivity, a high melting point, and satisfactory nuclear properties, and it is comparatively easy to fabricate and handle. It is believed to have a relatively low tendency to swell with burnup. Nitrogen has low affinity both for lithium and for W-Re alloys.

Of the several uranium compounds that were considered as possible fuels, the nitride was chosen over the sulfide because more information was available and because nitrides are potential strengthening additions to the tungsten alloys being considered. The oxide was rejected because it would react strongly with the lithium coolant should the cladding fail. The carbide is reactive unless the stoichiometry (U/C ratio) is precisely controlled, which is difficult.

A potential danger exists in the use of UN because at high temperatures there is a tendency to lose nitrogen, which can lead to chemical activity due to the freed uranium. It may be necessary to operate the reactor with an overpressure of N_2 to suppress this tendency, so that the fuel elements operate within the one-phase region shown in Fig. 17. A nitrogen overpressure of 10^{-4} torr was chosen for the SPR-6 design temperature of 1650°K. At temperatures below about 1570°K the nitrogen overpressure is probably not necessary. Transients into the two-phase region are permissible for short times

since no appreciable change of phase will result.

COOLANT

Lithium was chosen as the reactor loop coolant in preference to other liquid metals because of its low corrosive effect on refractory metals, low activation cross section, low vapor pressure, and good heat transfer properties. The nuclear properties of Li^6 and Li^7 are particularly advantageous since the amount of the strong neutron absorber, Li^6 , mixed in the reactor coolant can be utilized for adjustments of the reactivity and control of the reactor.

The relatively low vapor pressure of lithium minimizes the possibility of boiling inside the reactor, and gives lower stress in the reactor piping.

CLADDING

The cladding must resist dissolution by the hot flowing coolant and must not react adversely while in intimate contact with the fuel. The structure, in addition, should provide maximum resistance to deformation at high temperatures.

Of all the metals, tungsten offers the greatest potential performance for the cladding and structure. Semitheoretical considerations predict that it has a creep rate far lower than Ta or Mo at SPR-6 temperatures, and that its solubility in molten lithium is extremely low. It is chemically compatible with the fuel because of the thermodynamic instability of

Fig. 17. Uranium-nitrogen phase diagram.

tungsten nitride. Clearly, tungsten is the outstanding candidate for the ultimate reactor.

Unfortunately, pure tungsten is also difficult to fabricate. It cannot be

fabricated into the shapes required for the reactor, and further, the pure material is prohibitively brittle at room temperature. For this reason, W-25% Re was selected for the reactor cladding and

structure. This alloy has appreciable room temperature ductility, and can be fabricated by relatively conventional techniques.

Tungsten alloy development for applications above 1500°K has been directed mainly toward single-phase solid solutions,

such as W-25% Re, because of fabrication difficulties. Unfortunately, these alloys do not have exceptionally good creep resistance under the conditions of time, temperature, and stress that are required in the reactor. It is believed, however, that incorporation of a second dispersed phase will help strengthen these alloys.

CONCLUSIONS

The feasibility of advanced, high-temperature nuclear space power systems is evident from this study of a 10-MW_e Rankine cycle conceptual design. The reactor design utilizes uranium mononitride as a fuel, lithium as a coolant, and W-25% Re as a structural material.

Hybrid fuel elements are selected for the reactor because they are easy to assemble and because they separate the fuel from the coolant with a double wall, thus increasing reliability. Fuel swelling is permitted without dimensional changes in the fuel tube cladding. Fission gases are vented, so high-strength cladding material is not essential.

The radial power distribution in the reactor is improved by incorporating a

central lithium coolant return duct and radially variable U²³⁵ enrichment. A dual control system, composed of a movable 2-cm-thick molybdenum side reflector and a number of central liquid-lithium control circuits, offers desirable redundancy. Each control system is capable, by itself, of carrying the mission to completion.

Heat pipe radiators are utilized to reject waste heat from the system. The use of heat pipes reduces the mass of the radiators to about one-half that of conventional fin-and-tube radiators. The planar radiator results in a winged conical shield which provides adequate radiation protection to a manned payload.

A total system specific mass of 7 g/W_e is calculated.

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