Conceptual Design of a 2-Mw$_t$ (375 kw$_e$) Nuclear-Electric Space Power System

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The power system described includes a unique nuclear reactor-boiler unit operating at 1500°K that utilizes heatpipes in lieu of a conventionally pumped primary loop. An efficient heatpipe radiator rejects waste heat at 1035°K. Over-all system efficiency is 18.8% yielding a net electrical output of 375 kw$_e$. The system specific mass is 10 kg/kw$_e$ including a generous shadow shield for unmanned payloads.

Introduction

THE subject 2-Mw$_t$ Rankine cycle, nuclear-electric space power system (Figs. 1 and 2), uses sodium heatpipes† to transport energy from the reactor heat source to a boiler (Fig. 3) employing natural potassium as the working fluid. The heatpipes replace the primary loop of a conventional reactor system and eliminate the need for a primary pump. In contrast, a 10 Mw$_e$ system reported by Pitts and Walter[1] used flowing liquid lithium in a conventional primary loop to transfer the heat from the reactor to the boiler. By emphasizing work on the reactor-boiler and nuclear shield, and by utilizing existing designs for other components, it was possible to partially optimize the SPR-4 system with respect to obtaining a low specific mass (Table 1) with high reliability. This system could be applied to electric-propulsion systems for unmanned space missions, to auxiliary electric-power systems, to lunar bases, and to Earth-orbiting power stations. Its characteristics could be adjusted to suit a variety of uses, including auxiliary power for manned missions.

The system comprises an integral reactor-boiler (Fig. 3 and Table 2) operating at 1500°K, a nuclear shadow-shield composed of two layers of lithium hydride separated by a layer of tungsten, a turbine-alternator unit, two heatpipe radiators (one operating at 1035°K and the other at 770°K), and a single electromagnetic pump for the circulation of the potassium working fluid in the power conversion loop. An over-all length of ~10 m allows the system to be launched as an integral unit. Criticality would occur after it was placed in a stable Earth-orbit or positioned on the moon or other interplanetary body. System efficiency is 18.8%, and system design life is 20,000 hr.

The reactor uses uranium nitride (UN) as the fuel, an alloy of 75% tungsten and 25% rhenium (W-25% Re) as the structural material, and sodium as an interstitial thermal bonding agent and heatpipe fluid (Fig. 3). The U^{235} enrichment is varied in two radial zones. The UN fuel has high density, good thermal conductivity, a high melting point, and excellent physical properties. Each of the 378 hexagonal fuel elements has a central hole through which a heatpipe, partially filled with sodium, is inserted.[2] Two potassium boilers are integrated with the reactor, one on each end of the cylindrical core (Fig. 3). The potassium working fluid is boiled on the outside surfaces of the heatpipe tubes protruding into the boilers. Thus, heat is transferred under nearly isothermal conditions from the fueled core to the boilers. The potassium flow rate is adjusted to ensure that the fluid leaves the boilers as saturated vapor.

Reactivity is regulated with a dual control system consisting of a 2-cm thick, axially translating, Mo reflector, and centrally located, in-core, liquid Li^6 control circuits. Each system could control the reactor independently throughout its entire lifetime.

The reactor-boiler is separated from all other components by a nuclear shadow-shield, which reduces the dose rate at the payload and electronic equipment to acceptable levels. Excess heat is removed from the alternator windings through the use of an auxiliary heatpipe radiator operating at 770°K.

Net electrical power	- 375 kW
Total power plant mass	- 3750 kg
Overall length	- 10 m
Maximum width	- 5.3 m
Lifetime	- 20,000 hr

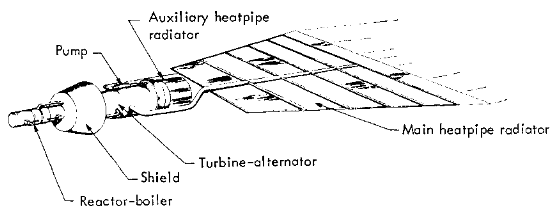

Fig. 1 SPR-4 space nuclear-electric power plant.

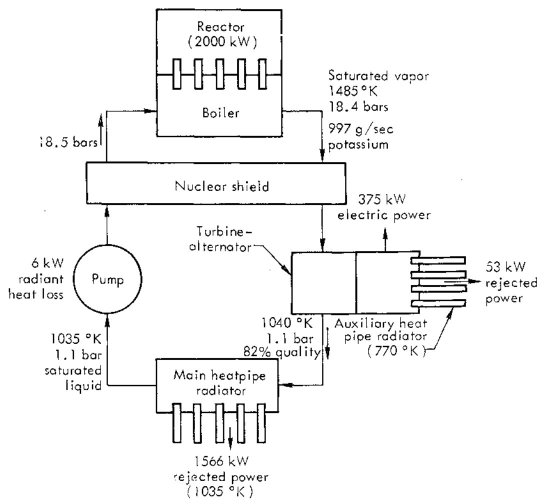

Fig. 2 System schematic.

Received March 3, 1970; revision received June 4, 1970. A paper such as this results from the work of many people. Although the Nuclear Space Power program at Lawrence Radiation Laboratory is now complete, we extend our thanks to the entire program staff for their support and contributions. This work was performed under the auspices of the U. S. Atomic Energy Commission.

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† Heatpipes are self-contained, thermal conductance devices having high thermal efficiencies.

Table 1 System masses for 375 kw_e output

	Mass, kg	Relative mass, %
Shield	1400	37
Reactor-boiler	900	24
Turbine-alternator	400	11
Main radiator	400	11
Pump	200	5
Miscellaneous	450	12
	3750	100

The vapor leaving the turbine is subsequently condensed in a large, low-mass, flat radiator containing 2200 heatpipes.[3] The mass of this radiator is ~0.5 that of a conventional fin-and-tube radiator. The heatpipes operate independently and in parallel, thereby providing unprecedented redundancy.

The system does not require high-temperature pumps. The most critical pump operates in the power conversion loop at 1035°K. An electromagnetic pump was chosen for this use because of its reliability. The slight differences in electromagnetic pump performance have a negligible effect on system power output or on system specific mass, which is 10 kg/kw_e (see Table 1). The smallest practical reactor was selected because reactor size affects not only the mass of the reactor but, more importantly, the mass of the nuclear shield.

Interactions between individual components were examined using a flexible, simple mathematical representation of the system,[4] but the system has been only partially optimized, since detailed performance characteristics and masses were determined only for the reactor. The turbine temperature ratio of 0.7 is slightly lower than the classic turbine temperature ratio[5] of 0.75 because the radiator mass is not predominant in the SPR-4 system.

Reactor-Boiler

This unit is a double-ended, heatpipe-cooled reactor from which the heatpipes extend to form an integral boiler (see Table 2). The sodium heatpipes, made with a composite groove and mesh wick structure, penetrate the core from each end and extend to the core mid-plane (Fig. 3). They are held in a hexagonal array by core end plates and five additional 2-mm-thick transverse plates equally spaced along the core axis. A dodecagon was selected as most suitable core cross section consistent with the hexagonal fuel array. Because of the nearly isothermal characteristics of heatpipes and the good thermal conductivities of UN, liquid sodium, and W-25% Re, the total difference between the peak fuel temperature and that of the potassium leaving the boiler is only 48°K.

Table 2 Characteristics of the reactor-boiler (see also Figs. 3 and 4)

Fuel atom burnup, %: average, maximum	0.68, 1.08
Fuel enrichment (fraction of U^{235}): avg., max.	0.93, 0.99
Average fuel power density, w/cm^3	100
Radial peak-to-average power density ratio (at most severe transverse cross section)	1.18
Over-all peak-to-average power density ratio	1.59
Average neutron energy, Mev	0.39
Prompt neutron lifetime, l^*, sec	2.4×10^{-8}
Fueled core: length; mean o.d., cm	41.9, 33.9
Mean Li^6 control zone o.d., cm	12.8
Potassium vapor return duct i.d., cm	6.3
Pressure vessel i.d., cm	36.2
Side reflector: i.d.; o.d., cm	37.2, 41.2
Numbers of fuel elements; heatpipes	378; 756
Volume fractions: fuel; heatpipe metal	0.616; 0.062
Intermediate tube spacer volume fraction	0.016
Heatpipe fluid volume fractions: heatpipe liquid vapor	0.117; 0.150
Swelling allowance volume fraction	0.039
Total fueled core volume, liter	32.4
Total heatpipe fluid flow rate, kg/sec	0.566
Heatpipe fluid saturation temperature, °K	1500
Heatpipe fluid saturation pressure, bar	11.0
Heatpipe inward radial heat flux: avg.; max., w/cm^2	46.4; 85.8
Maximum heatpipe axial heat flux based on vapor volume, kw/cm^2	7.0
Nominal peak fuel temperature, °K	1533

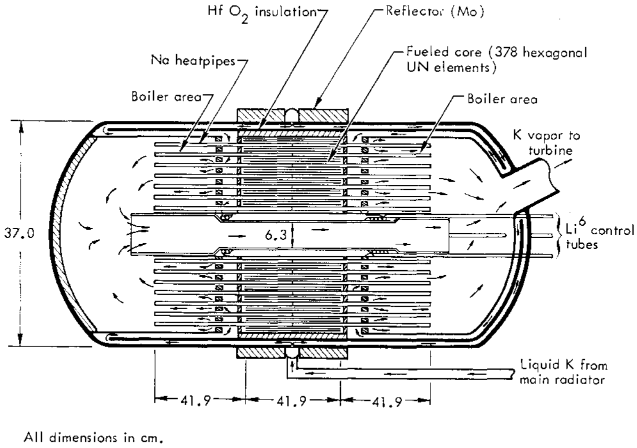

Fig. 3 Schematic diagram of integral reactor-boiler.

The double-ended boiler with a central vapor return duct was chosen for two reasons: 1) the reactor radius is smaller than it would be for a single-ended configuration without a return duct (because of limitations in heat transfer from the core faces) and 2) this configuration facilitates fabrication, testing, and assembly of heatpipes into the reactor. Each of the two heatpipe assemblies can be pretested independently before surrounding them with fuel. The two reactor-boiler halves would be joined by a single girth weld. Only a small net force acts on the core due to vapor flow in the central duct.

The reactor heatpipes extend from the nuclear core to provide twice the heat-transfer area of the core for boiling the potassium in the power conversion loop. Boiling data for

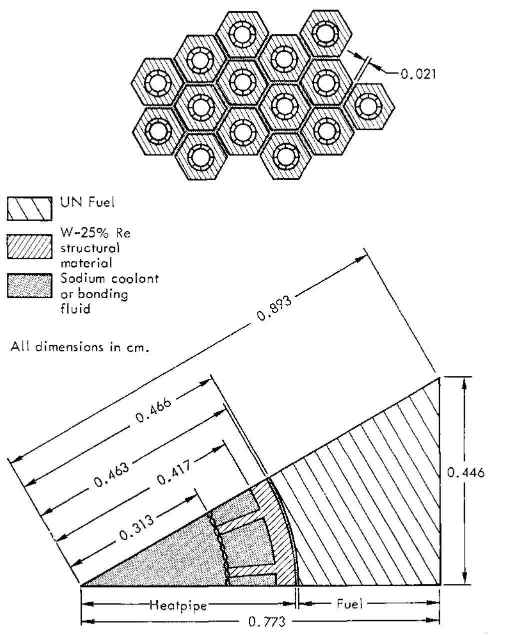

Fig. 4 30° segment of hexagonal heatpipe—fuel pellet assembly.

flow inside tubes[6] indicate that high-quality vapor is obtained with average heat flux rates of 25 to 50 w/cm^2. Thus, the limiting heat flux is governed by boiling of potassium on the outer surface of the heatpipes.

In Fig. 3, liquid K [$K_{(l)}$] at 1035°K is admitted to the reactor at the core midplane. The flow divides and continues axially in a 2-pass arrangement along the pressure vessel toward the end faces of the reactor-boiler. This flow arrangement, together with HfO_2 tile insulation, maintains the maximum reactor vessel temperature below 1250°K. After reaching the core end faces, the flow is distributed radially and then continues axially through the boiler. The K leaves the boiler as a saturated vapor. Fluid vaporized in the outboard boiler is returned through a 6-cm-diam central return duct. Total pressure drop in the potassium, as it flows through the reactor-boiler, is only 0.1 bar.

With the heatpipe-fuel pellet geometry shown in Fig. 4, heat is removed along the center of the fuel pellets and the temperature at the periphery of the fuel is higher. Based on thermodynamic arguments, fission gas bubbles would tend to move away from the heatpipe and be released at the outer free surface of the fuel pellets. Provisions must be made to remove fission gas which would be generated during the life of the reactor. At the peak fuel operating temperature of 1533°K, nitrogen overpressure for the UN fuel may not be required, but it can be easily provided.[1] The choice of Na (at 1500°K) as the heatpipe working fluid results in higher heatpipe performance and hence in a smaller core size compared to those necessary when Li or K is used. A disadvantage of using Na is the adverse pressure gradient of approximately 7 bars on the heatpipes in the boiler region, but preliminary calculations indicate that the pressure differential with Na and K will be tolerable from the standpoint of creep buckling in the heatpipes.

Natural K was chosen as the power-conversion-loop fluid because: 1) information on K turbines was readily available, and 2) its use produces considerably fewer neutron activation problems than use of Na. Natural K contains only 7% radioactive K^{41}, which is acceptable for the dose criterion chosen for SPR-4. This concentration can be reduced economically to less than 0.1% if necessary.[7] A manned payload application requiring a reduced dose rate could be accommodated only if the stable K^{39} isotope were used.

The tungsten heatpipes are externally clad with tantalum where they extend into the boilers to avoid dissimilar metal difficulties in the K loop. The core is contained in a sealed can made from 0.15-cm-thick, W-25% Re sheet. This can is also externally clad with tantalum.

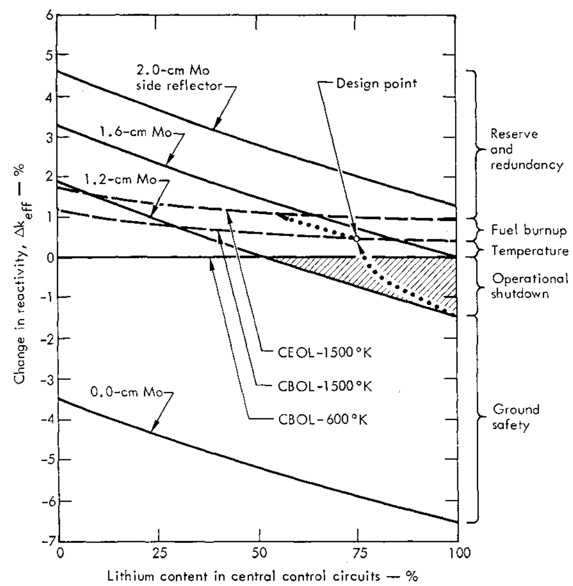

Fig. 5 Range of the dual control system for SPR-4 reactor. CEOL designates critical at end of life; CBOL indicates critical at beginning of life.

The outside reflector radius for the double-ended heatpipe reactor is 20.6 cm, compared with 17.2 cm for a conventionally cooled reactor. The increased radius and additional length of the integrated reactor-boiler requires a larger shield. Whether or not the heatpipe reactor is justified depends on factors such as reliability and development potential of the heatpipe and conventional systems. However, an additional advantage to heatpipe cooling is that it prevents overheating of the reactor after shutdown, because heat from decay products is more easily removed from the reactor.

Design Methods

The reactor was designed using a composite computer code,‡ which considers, in a single pass, nuclear performance, structural component sizes, expansion due to fuel swelling and thermal effects, plus production of daughter fissile species. The code permits small perturbations to be made with a high degree of numerical consistency, and allows complex interactions to be studied in detail. Thus, unanticipated interactions can frequently be uncovered. Inputs include the boundary conditions of thermal power, lifetime, operating temperature, core aspect ratio, materials, limits on thermal stress, fuel-wall temperature difference and fuel-surface heat flux. From this information, temperature- and time-dependent material properties can be determined. For small, criticality-limited cores such as that of the SPR-4 the maximum allowed fuel enrichment is specified and fuel burnup is an independent design variable. A minimum porosity core is designed within the assumed constraints.

Once the core is designed, the code adds thermal insulators, the pressure vessel, and the external side reflector. Whenever desired, boundaries of the fuel element rows can be examined to determine optimum power-flattening zones. The dimensions and volume fractions of this trial mechanical design are translated into a dimensional and an atom density array, which is then fed automatically into the neutronic subroutine which calculates the multiplication factor. Core dimensions are then reduced to room-temperature dimensions and the atom density array is manipulated to appraise reactivity effects in water. This amount of detail is necessary to evaluate reactivity under all conditions because of the strong interactions between heat transfer, thermal expansion, fuel swelling, and nuclear effects.

Performance Characteristics

Axial heat flux in the reactor-boiler heatpipes was based on the mean core power and the factors listed in Table 3 (assumed deviations from the mean core power). The resulting combined factor is 3.4, which is applied as a multiplier to the total power expected for an average heatpipe.

The controls[9] of the SPR-4 reactor provide for adjustments to the neutron leakage external to the core and the neutron capture inside the core. Mechanical reactivity adjustments are made by separating the two halves of the axially translating Mo side reflector. Liquid reactivity adjustments are made through the use of in-core control circuits, with Li^6, the neutron absorbing isotope, as the liquid control agent. Each of the control systems is capable of carrying the mission to completion without using the other system (see Fig. 5). Reactivity effects of the two systems are decoupled because they act on the periphery and inner boundary of the fueled core, respectively. With a dual control system, a particular

‡This code is similar to that described by Brown and McCauley[8] except that certain features such as noncriticality when immersed in water and choice of other uranium isotopes were not included.

Table 3 Factors applied to the mean core power

Radial peak-to-average power density ratio	1.1
Heatpipe working fluid property uncertainty	1.2
Increased load in the event of a failure of an adjacent heatpipe	1.17
Core power fluctuations	1.1
Safety margin	2.0

Table 4 Nuclear shield sandwich dimensions

Layer	Thickness, cm	Mass fraction	Maximum diameter, cm
LiH	11.8	0.10	111.1
W	1.2	0.19	111.7
LiH	62.4	0.71	142.9
	75.4	1.00	

reactivity state can be approached by combining the possible control states of the individual controls, as long as the combined effect matches that of the desired reactivity requirement. This is illustrated in Fig. 5 by the shaded area for achieving criticality at the beginning of life and at 600°K. The dotted arrows indicate a suggested path.

Ground safety is achieved by opening the side reflector to the least reflective position and completely filling the liquid control circuits with Li^6. Once the reactor is launched into space, the reflector halves are partially closed and the Li^6 is removed to reach criticality. Because the reflector halves are fairly close together throughout most of the core lifetime, a long-time, large-motion actuator is not needed.

Molybdenum was chosen for the side reflectors in preference to MgO, Al_2O_3, Ni, or BeO (even though these materials are somewhat more effective) because it permits simple construction and is compatible with high-temperature operating conditions in the radiation environment. The oxides would require a metal supporting structure.

The reactor's self-regulating temperature characteristics arise from negative void coefficients for the Na in the core. Total loss of Na from the fueled core results in a change in multiplication factor, Δk, of -0.62%. Its self-regulating characteristics for power result from changing effective thickness of the $K_{(l)}$ in the boilers adjacent to each end of the core. Here, the $K_{(l)}$ affects the end leakage of neutrons and renders a maximum effect of $\Delta k = 0.23\%$. As reactor power increases, the effective $K_{(l)}$ thickness decreases, causing a small loss of reactivity which effectively reduces power.

Neutron-streaming out of the core end-faces through the voids in the heatpipes and through the central vapor duct was estimated using the 05R Monte Carlo code.[10] A nominal Δk loss of 0.5% is attributed to neutron-streaming along heatpipes and an additional loss of 1.8% is attributed to streaming in the central duct.

Radial power flattening was computed automatically by the reactor design code by changing fuel enrichment in two radial zones. The axial power profile assumes a natural cosine-like shape with a peak-to-average power-density ratio of 1.35.

Nuclear Shield

For the unmanned mission, payload dose levels of 10^{13} nvt for neutrons and 10^6 R for γ rays at a plane 10 m from the nearest reactor face represent a reasonable compromise between the cost of hardening electronic components and the mass savings in the nuclear shield. If care is used in selecting electrical components, designing redundant circuits, and providing local shielding, these values may be increased to 10^{14} nvt and 10^7 R. Attenuation of radiation at the payload due to components other than the shield is neglected. The LiH-W sandwich structure (Table 4) yields minimum mass. The LiH attenuates neutrons and tungsten attenuates γ rays. A slight H_2 overpressure (≤ 50 torr) may be required to prevent dissociation of the LiH. The shield is contained inside a stainless steel vessel that prevents H_2 leakage. This vessel is protected against meteoroids by 1 cm of beryllium. The internal heating rate in the shield is high enough to cause excessive LiH temperatures if internal cooling is not used. Total heat generation inside the shield is expected to be about 5 kw. This heat may be dissipated by adding heatpipes to conduct heat from the center to the surface where it can be radiated.

The shield was designed using point-kernel techniques with a method developed by Wilcox.[11] The removal theory kernel was used for neutrons, the Albert-Welton kernel for hydrogen, and an effective reactor point source was obtained from a DOT[12] problem. Seven energy groups of γ rays were used with the appropriate build-up factors. The production of inelastic γ rays was related to the removal of fast neutrons, while the capture rate of thermal neutrons was given by solving the diffusion equation in one-dimensional slab geometry with a source given by the fast removal kernel. The thickness of the laminated regions of the shield were varied to obtain minimum shield mass using a steepest-descent method. As far as the shield is concerned, the reactor is simulated by an equivalent point source emitting 0.73 neutron/fission and 1.41 Mev of γ-ray energy/fission.

Calculations indicated that 4.6×10^{13} n/sec were absorbed in the potassium coolant. Part of these neutrons are absorbed in K^{41}, which then becomes activated and produces delayed γ-ray radiation. Because potassium circulates throughout the system and behind the shield, this activation produces a fixed dose rate at the payload. Assuming that 1) K^{41} has the same fast neutron absorption cross section as natural potassium, 2) the radiator can be considered as a flat trapezoidal source of uniform strength per unit area, 3) half the potassium is behind the shield, and 4) the attenuation of the radiator is neglected; it was found that the use of natural potassium (6.91% K^{41}) caused an integrated γ dose at the payload of 2100 R. This value is negligible when compared to the γ-ray dose criterion of 10^6 R.

Power Conversion

In the main radiator (Fig. 1), the advantages of redundancy and low mass are achieved through the use of about 2200 highly efficient, independent, potassium heatpipes. The radiator has a total projected area of 19.2 m^2 and a specific mass of 0.25 kg/kw of rejected power. It is constructed as a series of manifolds, positioned in a rectangular array, with a large number of heatpipes penetrating the manifolds, following the design of Werner and Carlson.[3] The manifolds and other ducting are protected against meteoroids in the same way as other radiator designs. Because of their low presented area, however, they contribute only slightly to the total radiator mass. An excess number of heatpipes is installed at the beginning of life, and pipe-wall thickness is determined so that approximately 10% of the heatpipes fail from meteoroid penetration during their lifetimes. The actual number of heatpipe failures is predicted using a normal distribution. The composite radiator survival probability is the major parameter affecting the radiator mass, but heatpipe diameter also has a significant influence, with the smaller diameters producing smaller masses. Inside diameter selection of 0.75 cm was based upon fabricability. The mass penalty incurred for radiator survival probabilities higher than the chosen value of 0.99 is 20% for 0.999 and 60% for 0.9999.

Design of the auxiliary heatpipe radiator for the alternator windings is similar to that for the main radiator except that the heatpipes are inserted directly into the area around the windings and sodium is used as the working fluid, with a rejection temperature of 770°K.

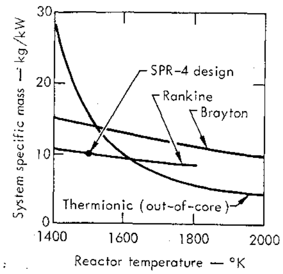

Fig. 6 System specific mass comparison.

The turbine-alternator characteristics were based on a General Electric Co. 400-kw, K turbine-alternator unit.[13] The turbine portion is a six-stage counterflow unit using the potassium of the power conversion loop as a fluid. Interstage moisture extraction was considered unnecessary as long as adequate consideration was given to turbine bucket erosion through appropriate aerodynamic design. The alternator is a radial-gap, homopolar-inductor type. Both the stator and field-coil windings are cooled with heatpipes. The evaporator region of each heatpipe is embedded in the outer region of the stator casing. The condenser region extends outward from the end of the alternator to form a cylindrical ring which operates as an auxiliary heatpipe radiator surface.

A helical-induction electromagnetic pump, based on the design of Diedrich and Gehan,[14] was selected as the condensate pump in the power conversion loop. Other miscellaneous low-temperature pumps which are necessary for the reactor-liquid control circuits are not considered to be a major design problem.

Comparison to Other Systems

The SPR-4 system can also be compared to other types of conversion systems[15] as shown in Fig. 6. The greatest potential for improvement in this rough comparison is shown by the Li heatpipe, out-of-core thermionic diode system.

The Rankine cycle system with K as a working fluid and a sodium heatpipe reactor could achieve a minimum specific mass of 9 kg/kw_e by reducing the shield angle by one-half and increasing the reactor temperature to 1650°K. Turbines tend to become overstressed when the reactor temperature exceeds 1800°K.

Conclusions

Analysis of an integral heatpipe reactor-boiler confirms its attractiveness as a space nuclear heat source. Computer codes incorporating simultaneous neutron-transport, structural, and fluid dynamic analysis now exist for the detailed design of such reactors. The fast spectrum heatpipe reactor-boiler and the heatpipe radiator provide considerable system redundancy and permit pump operation at temperatures no higher than is required for heat rejection. High reliability is predicted. A dual reactivity control system with centrally located Li^6 control circuits and an axially translating molybdenum side reflector provides an efficient method of achieving a redundant reactivity reserve. Mass of the nuclear shield is minimized through the use of alternate layers of lithium hydride and tungsten; even so, 37% of the specific mass of 10 kg/kw_e is contributed by the shield.

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