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Lawrence Radiation Laboratory
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LIVERMORE

A LARGE NUCLEAR-ELECTRIC SPACE POWER PLANT

Carl E. Walter
Oscar C. Kolar
Norman J. Brown
Thomas P. Wilcox, Jr.

May 12, 1967

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A LARGE NUCLEAR-ELECTRIC SPACE POWER PLANT

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ABSTRACT

The characteristics of a large Nuclear-Electric Space Power (NESP) plant are studied. To place the design study in context, a plausible manned mission to Mars is adopted. Mission requirements are such that the specific mass of the power plant must be 7 g/W and it must deliver 5 MW of electric power for about 10 months out of the 15-month duration of the mission. The Rankine cycle is adopted for this application. The nuclear reactor is contained within a primary loop consisting of the reactor, preheater, boiler, and pump. The reactor coolant is lithium and the working fluid is potassium. With only some improvement in current material technology, the NESP system can be designed to meet the mission requirements. The use of a flat heat-pipe radiator results in a relatively efficient, lightweight, and reliable system.

The reactor material system is uranium nitride fuel, tungsten alloy cladding, lithium coolant, and BeO reflector. These materials are thought to be generally compatible with each other. Fuel element design was considered in detail. The selected "hybrid" fuel design provides redundant defense against fission fragment leakage into the coolant stream. Radial power distribution

can be shaped by adjusting the reflector thickness (worth), by spatially varying the enrichment of U^{235} in UN, and by sizing the central coolant return pipe.

NOMENCLATURE

Symbols not defined in this list are defined as they appear in the text.

<u>Symbol</u>	<u>Definition</u>
f	Ratio of Li coolant pipe cross-sectional area to Li coolant flow area in active core.
Δk (OSD)	Reactivity requirement for operational shutdown.
Δk (ER)	Reactivity worth of end reflectors.
Δk (MR)	Reactivity worth of miscellaneous reflection external to reactor.
Δk (FSR)	Reactivity worth of fixed side reflection (e. g., pressure vessel and pressure vessel coolant).
$\theta \Delta k$	Reactivity worth (relative to bare core) of side reflectors in full-out position.
Δk (DTF-calc)	Normalization factor to correct for deficiencies of chosen computational model (the transport code DTF was chosen as a standard for normalization purposes).
Δk (OL)	Reactivity worth due to operational losses (U^{235} and U^{238} burnup, and U^{236} and Pu^{239} production).
Δk (T)	Reactivity worth of temperature effect.

<u>Symbol</u>	<u>Definition</u>
$\Delta k(\text{FS})$	Reactivity worth of fuel swelling.
$\Delta k(\text{R})$	Provision for operational reserve reactivity.
$\text{VF}(\text{Cl})$	Volume fraction of cladding.
$\text{VF}(\text{Co})$	Volume fraction of coolant.
$\text{VF}(\text{F})$	Volume fraction of fuel.
$\text{VF}(\text{Hx})$	Volume fraction of heat transfer fluid.
$\text{VF}(\text{V})$	Volume fraction which is void.
ΔP	Differential radial pressure on cylindrical surface of active core.
ρ	Average core density.
σ	Stress.
t	Cladding thickness.
r	Cladding tube radius.

INTRODUCTION

A large nuclear-electric space power (NESP) plant is desirable for a manned Mars landing mission. The characteristics of such a power plant, particularly those of the nuclear reactor, are the subject of the present discussion. It appears that the appropriate nuclear reactor is technically feasible. It is the authors' opinion that an active development program encompassing all the hardware required for a specified manned Mars mission is a logical sequel to the Apollo program.

Several mission profiles for manned Mars trips utilizing electric propulsion are examined in Ref. 1. For the purpose of establishing power plant requirements, one possible mission taken from that study was adopted. Many others could be considered for the same power plant.

The adopted mission employs a nuclear rocket to provide escape from a low earth orbit. The nuclear rocket and the ion-propelled spacecraft and crew would have previously been boosted for rendezvous and assembly in earth orbit. Mission characteristics are summarized in Table 1.

POWER PLANT ARRANGEMENT

An artist's sketch of the nominal power plant is shown in Fig. 1. The power plant operates on the Rankine cycle and consists of a primary loop heated by the reactor and a secondary loop where power is extracted by a turbine and waste heat is rejected by means of a heat-pipe radiator. The flat radiator is chosen to obviate the need for a large reactor shadow shield or a large separation between reactor and radiator. Mass savings are obtained with the flattened shield cross section permitted by the flat radiator as compared with the circular shield which would be required with a cylindrical radiator. Flat radiators have been suggested previously.¹⁻² The design of the relatively light heat-pipe radiator is treated in more detail below.

The basic NESP system described in the succeeding discussion is chosen to be generally compatible with "potassium Rankine systems technology" being

worked on at the Lewis Research Center.³ That technology is based on a potassium turbine inlet temperature of 1450°K. A schematic diagram of the system is shown in Fig. 2. The information portrayed by this diagram will now be discussed.

Only alkali metal fluids were considered for both the primary and secondary loops. Specifically, there does not appear to be a better reactor coolant than lithium over a wide temperature range. Lithium's importance as a reactor coolant is based on its low vapor pressure (1 bar at about 1600°K), its high heat capacity (4 W-sec/g-°K), and its two greatly different isotopes, Li^6 , a strong absorber, and Li^7 , a weak absorber. In addition to these properties there is a good chemical compatibility⁴ with refractory alloys at 1600°K.

To allow future improvements in high-temperature material technology, a tungsten alloy and uranium nitride fuel are chosen for the reactor. These are apparently compatible with each other in the presence of lithium. This is not the case with uranium oxide or uranium carbide substituted for the fuel, or with tantalum or niobium substituted for tungsten in the cladding and structural material. The material system in the primary loop, then, is lithium, a tungsten alloy, and uranium nitride.

Operating temperature for the reactor is chosen to be generally compatible with the "potassium Rankine systems technology" mentioned above. A reactor exit coolant temperature of 1600°K provides an adequate temperature potential for boiler design. It should be noted that the choice of reactor materials does not limit the reactor to this operating temperature. Indeed, considerably higher reactor coolant temperatures might be attained. The turbine appears to be the temperature-limiting component in the system.

In addition, as the operating temperature is raised the vapor pressure of potassium increases significantly while at the same time the strength of containment vessels and piping decreases greatly. These two effects are comparable in magnitude. Containment vessels (reactor and boiler) may be kept light if they are cooled below the peak system operating pressure. The potassium preheater serves this purpose nicely, with little penalty (small added pump work) in system performance.

A series arrangement of turbines is proposed in which the high temperature stages would operate on a separate shaft at a lower speed consistent with high-temperature material strength. The low temperature turbine could operate at high speed. A potassium turbine operating at 1100°K has, in fact, been successfully demonstrated for several thousand hours³; its maximum temperature capability has not been determined. A parallel arrangement of four turbine pairs was considered to provide the desired 5 MW. On-the-spot cooling systems utilizing the self-contained pumping of heat pipes are suggested as required for cooling of alternators, shields, etc.

HEAT PIPE RADIATOR

The large relative contribution of the radiator mass to the space power system's total mass has in the past strongly influenced the thermodynamic cycle and overall power plant design. Accordingly, careful consideration of

the heat rejection mechanism, the meteoroid environment, and the radiator redundancy is warranted. As a result of this consideration a new radiator concept was evolved.⁵

In this concept the inlet and outlet ducts originally used for vapor delivery and fluid return become, by suitable adjustment, the primary leg of a heat exchanger. Meteoroid protection of this ducting is inexpensive because of its low presented area. One end of each of a large number of heat pipes is inserted into this ducting. The heat pipes operate in parallel, functionally independent one from the other, and form the separate secondary leg of the heat exchanger. Because a large number of independent heat pipes are involved, they can be designed for minimum weight for a specified probability that a certain fraction will remain unpunctured during the mission.⁶ Minimum weight is obtained when 80% of the heat pipes are expected to survive. This arrangement is shown in Fig. 3. The new concept differs from the vapor chamber fin⁷ previously proposed. In the new concept heat transfer to the heat pipe is over an appreciable portion of its length rather than merely at the end as is the case in the vapor chamber fin. A brief list of characteristics of a heat pipe radiator is shown in Table 2 for illustration.

The powerful role of the heat pipe is seen to be that of a heat flux amplifier at nearly isothermal conditions; i. e., an "infinite conductivity" fin. A comparison, for the same thermal performance, of the mass of solid-fin and vapor-fin radiators with the heat-pipe radiator gives relative masses of 1.6 and 1.8, respectively. These values are based on the assumption that the radiators would continue to reject the design heat load with a 99% probability. In Table 2, the mass breakdown of such a heat-pipe radiator is given. The additional mass required for a 0.999 probability of rejecting design heat load in 10,000 hours is seen to be 0.5 g/W.

NEUTRONICS

Neutronic calculations of the core proceed from assumed values of material volume fractions, burnup, and length-to-diameter ratio. The core dimensions, enrichment, and control requirements can then be calculated. Vernier control of the reactor would be accomplished by varying side reflector effectiveness. Means of accomplishing this variation were not studied in detail. However, the thickness of side reflector required to supply the necessary control requirement reactivity is presented. This procedure provides a point of departure for design of the control system and, further, exposes the magnitude of the variables involved.

Burnup is defined by

$$BU = \frac{\text{uranium atoms fissioned}}{\text{total uranium atoms initially present}} \quad (1)$$

Note that the numerator is uniquely determined by the reactor thermal power and power-on time. These quantities are respectively 25 MW and 10^4 hours.* Given the accrued value of BU at end-of-life, the initial uranium mass can be determined.

Table 3 lists maximum, minimum, and nominal values of the above-mentioned parameters. In the definition of L/D, the diameter D is the inside

*A power-on time of 10^4 hours is actually approximately 40% greater than is required by the mission.

diameter of the pressure vessel. Any parameter in Table 3 can be associated with any other parameter. The fuel volume fraction VF(F) is a dependent variable given by

$$VF(F) = 1 - VF(Co) - VF(Hx) - VF(Cl) - VF(V). \quad (2)$$

Assuming a reactor core geometry as shown in Fig. 4, the dimensions may be derived as follows:

$$R_0 = \left[\frac{0.2303 \times 10^4}{2\pi(L/D)} \frac{1 + f VF(Co)}{(BU) VF(F)} \right]^{1/3}, \quad (3)$$

$$R_1 = \left[\frac{f VF(Co)}{1 + f VF(Co)} \right]^{1/2} R_0, \quad (4)$$

$$L = 2R_0(L/D). \quad (5)$$

The pressure vessel thickness T_P is determined from allowable material strength. Finally, when the control requirements have been established, the reflector thickness T_R can be calculated.

The bare-core effective multiplication factor, $k_B(\text{calc})$, is:

$$k_B(\text{calc}) = 1 - \Delta k(\text{OSD}) - \Delta k(\text{ER}) - \Delta k(\text{MR}) - \Delta k(\text{FSR}) - \theta \Delta k - \Delta k(\text{DTF-calc}). \quad (6)$$

Two computational techniques were used. For rapid survey purposes, one-group calculations were performed as described in Appendix I. For more accurate calculations the ZOOM multigroup diffusion-theory code⁹ was used. Table 4 lists the assumptions made for the values of the worths appearing on the right-hand side of Eq. (6). Diffusion theory appears to provide satisfactory results when normalized to transport theory calculations, and considerable saving in calculation time results.

The one-group equations of Appendix I correspond to a cylindrical core with side and end reflectors. The end reflectors are of equal thickness but not necessarily equal to the side reflector thickness. The geometry is two-region, two-dimensional. The central coolant pipe as depicted in Fig. 4, however, cannot be accommodated. The fraction f , and hence the radius R_1 , used in Eqs. (3) and (4) are zero in this formulation, so that the results obtained are useful for survey purposes only.

Reactivity effects of fuel depletion are estimated by solving the differential equations for fuel atom concentrations as a function of time. A new value of effective multiplication factor can thus be calculated at end-of-life.

The two other dominant effects upon reactivity are the reactivity loss due to thermal expansion of the core, and the displacement of lithium from the core by fuel swelling due to burnup.

The first of these effects is evaluated simply by calculating the effect on reactivity due to thermal expansion between room temperature and the assumed operating temperature of 1600°K. The overall core expansion is determined by the thermal expansion coefficient of the tungsten alloy structure. The UN fuel also expands, but its effect is merely to displace lithium from the core. Finally, the lithium itself expands, resulting in a change in lithium density.

The additional effect of fuel swelling due to burnup is taken into account by assuming a net loss of lithium in the amount of 1.6% of the active core volume per % of burnup. The required side reflector worth, $\Delta k(\text{SR})$, is then given by

$$\Delta k(\text{SR}) = 1.47 [\Delta k(\text{OL}) + \Delta k(\text{T}) + \Delta k(\text{FS}) + \Delta k(\text{OSD}) + \Delta k(\text{R})] . \quad (7)$$

The factor 1.47 is based on the assumption that the control system consists of six hinged side-reflector segments. (This model was chosen merely as a point of departure.) This factor approximately accounts for a redundancy factor to allow for failure in the open position of one reflector vane out of six, vane interaction, and vane worth in open position.

Figure 5 displays the required enrichment of the bare core, using the method of "offset carpet plots." In this method the only function of the axis of abscissae is to provide an interpolation grid. The results are given in Fig. 5 only for the case of 0.8% burnup and $L/D = 1.4$.

Figure 6 presents, in the same fashion, the required reflector thicknesses. These results are presented for 1.2% burnup and $L/D = 1.4$. Again, it is to be borne in mind that the results given in Figs. 5 and 6 are exploratory only, since the reactor geometry is not accurately represented.

In the multigroup calculations, it was assumed that the frontal area of the coolant return pipe is equal to that of the coolant in the fueled core. Actually, since the hydraulic impedance of the large pipe is less than that of the multitude of small coolant channels, the pipe could be made smaller. It appears, however, that it would be desirable to have a larger central pipe to further enhance the side reflector worth, flatten the radial power profile, and provide for additional reactivity control. This could be done by having the outer portion of the central pipe contain a separate lithium circuit or void. The lithium isotopic composition has a strong effect on reactivity.

Determination of fuel enrichment proceeds as already described. A summary of the calculations is given in Table 5, and curves of k_{eff} vs enrichment are presented in Fig. 7. Note that a higher enrichment relative to that for the solid core reactor is required. This is to be expected, since

fuel has been moved outward from the core center, which is neutronically the most important region of the reactor.'

The determination of the reflector thickness proceeds as before. Moving the fuel outward increases the outer surface area of the fueled core, and thus the neutron leakage of the bare core is increased. Addition of a reflector to a core with a central coolant return then has a very marked effect on reactivity. Spectral changes also contribute to the enhancement of the side reflector worth.

A summary of calculations involved in determining the control requirements and side reflector thickness is presented in Table 6. Curves of reflector worth vs thickness for each burnup condition are presented in Fig. 8. A slight increase in control requirements is offset by the greatly enhanced reflector worth.

REACTOR CONFIGURATION

The NESP reactor is shown, rather idealized, in Fig. 1. The active core is a cylindrical bundle of hexagonally close-packed cylindrical fuel pins and coolant tubes terminating on either end in thin tube sheets. The active core is supported on the downstream end by a structure made up of tungsten alloy links loaded primarily in compression. This design was selected because (1) a crack in a compressively loaded structure is less likely to produce failure than in a tension member, and (2) a compressively loaded

structure is generally more rigid than structures of the same mass loaded in bending. The volume of this structure is useful for attenuation of radiation from the core. Axial and radial expansions of the core are accommodated at the upstream face by a spline attachment to the pressure vessel.

Cladding serves to maintain fuel location, prevent cooling channel blockage, and isolate the fuel from the primary coolant stream. Low structural reliability of the cladding is overcome by the structurally redundant close-packing arrangement maintained over most of the core length by a radially inward hydrostatic pressure transmitted through a tungsten alloy membrane. The necessary differential pressure ΔP for a side load of $n g$'s is

$$\Delta P = n \rho R_0$$

where ρ is the average core density and R_0 its radius as before. Side loads during reactor operation are anticipated to be low. Launch accelerations can be accommodated by the greater strength of "cold" material and by an auxiliary structure of expanded solid coolant which melts during start-up in orbit.

Three types of fuel element configurations (shown in Fig. 9) were considered: spaced pins, hexagonal tubes, and a hybrid arrangement of fuel pins and coolant tubes. Fuel element dimensions were selected on the basis of an elastic thermal stress criterion of 5000 psi. (There is not a strong justification for this, but start-up and shutdown procedures would be simplified.) To prevent gross core dimensional changes, a swelling allowance is provided for each fuel element. In the case of fuel pins and hybrid elements, this space is initially filled with stagnant lithium. The high conductivity of liquid lithium reduces the fuel temperature 80°K below that which would exist if helium were used in this space or 350°K below that for the case of either nitrogen or lithium vapor.

Hexagonal fuel tubes must be located by means of multiple spacers to allow for swelling and to transmit the required radial pressure. Fuel volume fractions range from 45% for the hybrid configuration to 65% for the pin configuration and 75% for the tube configuration.

The hybrid configuration was selected for this application with a fuel cladding thickness-to-radius ratio of 0.1. This yields an average fuel power density of 340 W/cc, a fuel radius of 0.28 cm, and an average peak fuel temperature 50°K above the local coolant temperature. The coolant tube wall thickness was set 20% greater than the fuel cladding to insure against collapse, yielding an average heat flux of 92 W/cm², and a total core pressure drop of 0.3 bar at a fluid velocity of 590 cm/sec. A map of the average temperature distributions and the "hot dimensions at the beginning of life" is shown in Fig. 10.

The clad stress due to the radial preload is given approximately by the relation

$$\frac{\sigma}{\Delta P} \left(\frac{t}{r} \right)^2 = 0.62.$$

Fuel is pelletized and a radial preload of less than 0.01 bar is sufficient to restrain cladding-induced bowing over 90% of the core length.

A central coolant return channel whose cross section is 30% of the active core primary coolant cross section yields a pressure drop 10% of that of the core. This region would be surrounded by an annulus composed of individually encapsulated fluid control elements, which provide gross lifetime reactivity changes as previously discussed. Increasing this central volume actually reduces the combined size of the reactor and reflector until a minimum is reached when the central volume is about 20% of that of the active core.

The external reflector interferes with the radiation cooling of the pressure vessel which in turn degrades the effectiveness of the reflector. The pressure vessel is cooled as indicated in Fig. 2 by a coolant bypass flow through the preheater. An optimization can be made trading off the weight saved with a cooler pressure vessel and smaller reflector against the weight penalty of preheater, pump, and insulation. This optimization occurs at a vessel temperature of about 1300°K. Thus the pressure vessel may be of tantalum alloy (T-111) 0.3 to 0.4 cm thick. The nuclear heat load in the pressure vessel is less than 1 MW.

SHIELDING

In designing the shield for this NESP system, it was assumed that the effective residual dose¹⁰ (ERD) to a man would never exceed 100 Rem during a 10,000-hour mission. This value is chosen somewhat arbitrarily and may have to be reduced as more is learned about the risks of radiation exposure versus the other hazards of space flight. There are five specific sources that contribute to this dose; three of these can be readily estimated or arbitrarily assumed:

1. A rapid passage through the earth's trapped radiation belts, 5 Rem (ERD).
2. The galactic radiation of space, 4 Rem (ERD).
3. Maintenance of the power plant, 25 Rem (ERD).

The remaining two sources, solar flares and the reactor itself, then may account for the remaining 66 Rem (ERD). In order to determine what amount may be allocated to each of these two causes, a simple optimization problem was solved to minimize the weight of the reactor's shadow shield and a "storm cellar" shielding seven men from solar flares.

The results of this work indicate that the reactor should contribute only 2.6 Rem (ERD). This low figure occurs since it takes much less weight to reduce the reactor-caused dose rate than to reduce the solar flare contribution. In a typical case, it requires 700 pounds of shadow shield and 18,000 pounds of solar flare shield to alter their respective doses by a factor of 10. In reality, the optimization cannot be correctly performed until both the power plant and the space capsule have been roughly designed. The general trend, however, should remain the same.

The ERD of 2.6 Rem attributable to the reactor is equivalent to a real dose rate of 32 mRem/day or a total integrated dose of 13.3 Rem.

A conventional shadow shield is considered. The main shield, considered to be made of lithium hydride, has the shape of a frustum of a right circular cone. It completely shadows a 5-meter-diameter payload 100 meters behind the core from a fictitious reactor whose diameter is assumed to be greater by 20 cm. This allows for scattering from side reflectors, control actuators, etc. To this shadow shield are added wings (see Fig. 1) which shield the flat radiator and prevent it from scattering radiation. The mass of the wings is taken to be the same as that of the main shadow shield.

Two additional components of the shield are considered part of the design. The first of these is the hot shield, a region of tungsten and liquid lithium immediately behind the core. This region absorbs some radiation energy and

enables the main shield to be moved closer to the core without the danger of its front surface exceeding a safe working temperature.

On the payload side of the main shield a region composed of the equivalent structure of pumps, radiator, etc., as well as possible material added to the main shield, is considered. This region is effective in the absorption of secondary gammas.

Theoretical calculations of the shield were performed by simple point kernel methods. Though these methods would not be used for a final design, they were adopted to enable fast machine calculations to be performed in a system optimization code. Neutron dose rates are obtained by numerical integration of a removal theory kernel. The Albert-Welton kernel is used for hydrogen and a flat power distribution is assumed throughout the core. A similar method is used to obtain the gamma dose rate using six energy groups and the appropriate build-up factors. Secondary gamma production is estimated from the number of neutrons removed within each component and this information is then used to obtain the secondary gamma dose rate.

The gamma and neutron heating rates on the front surface of the main shield are calculated and assumed to be the maximum that occurs within the shield. (This would not necessarily be true for a multilayer shield.) Assuming no axial heat condition, this result is then used to find the maximum temperature of the shield.

For any given system design, the thickness of the main shield is varied until the required dose rate is obtained. The shield position is adjusted to satisfy the maximum allowable temperature. Typical results for this system are shown in Fig. 11.

NESP SYSTEM CHARACTERISTICS

Based on the foregoing considerations, the characteristics of the complete NESP systems were determined. A summary of these characteristics is given in Table 7. Weight and performance values are based on detailed analysis in the case of the radiator, reactor, and shield. Weight and performance values for other components included in the analysis are based on general estimates. The low system weight which results is encouraging.

APPENDIX I

ONE-GROUP DIFFUSION CALCULATION PROCEDURE

To obtain quick estimates of reactivity effects, and to produce a rapid but fairly accurate calculation for a computer-programmed survey code, one-group neutron diffusion theory was used. This calculation was formulated as follows:

$$k_{\text{eff}} = \frac{k_{\infty}}{1 + M^2 B_g^2}, \quad (\text{I-1})$$

$$k_{\infty} = \nu \Sigma_f / \Sigma_a,$$

$$M^2 = (3 \Sigma_{\text{tr}} \Sigma_a)^{-1}.$$

In these definitions, ν is the average number of neutrons per fission, and Σ_f , Σ_a , and Σ_{tr} are the one-group macroscopic cross sections for fission, absorption, and transport, respectively. M^2 is the migration area and B_g^2 is the geometric buckling. For a fully reflected (i. e., side-reflected and end-reflected) cylindrical core, the geometrical buckling B_g^2 is given by

$$B_g^2 = \left(\frac{\pi}{L + 2\delta + 2\text{ERS}} \right)^2 + \left(\frac{2.405}{R + \delta + \text{SRS}} \right)^2. \quad (\text{I-2})$$

In this definition L is the physical core length, δ is the core extrapolation distance ($\delta = 0.71/\Sigma_{\text{tr}}$), ERS is the end reflector savings, and SRS is the side reflector savings.

ERS is taken to be the reflector savings calculated for an infinite slab (of appropriate core and reflector composition). ERS is defined as

$$\text{ERS} = \frac{1}{2} (L_0 - L_c),$$

where L_0 is the bare critical thickness and L_c is the reflected critical thickness. A simple one-group calculation yields

$$\tan B_m (\text{ERS} + \delta) = \frac{B_m D_c}{K D_r} \tanh KT, \quad (\text{I-3})$$

where

$$B_m^2 = 3\Sigma_{tr} (\nu\Sigma_f - \Sigma_a)$$

$$D_c = (3\Sigma_{tr})^{-1},$$

$$D_r = (3\Sigma_{tr,r})^{-1},$$

$$K^2 = 3\Sigma_{tr,r} \Sigma_{a,r},$$

and T is the reflector physical thickness plus the reflector extrapolation distance ($0.71/\Sigma_{tr,r}$). In these definitions, the subscript r refers to the reflector. The preceding transcendental equation can be solved for $(\text{ERS} + \delta)$, which is then used in calculation of B_g^2 .

SRS is taken to be the reflector savings calculated for an infinite cylinder (of appropriate core and reflector composition). SRS is defined as

$$\text{SRS} = r_0 - r_c$$

where r_0 is the bare critical radius and r_c is the reflected critical radius. In this case, r_c is calculated separately and $(SRS + \delta)$ is obtained by subtraction of r_c from $(r_0 + \delta)$, where

$$r_0 + \delta = \frac{2.405}{B_m} ;$$

r_c is obtained as the solution of the equation

$$\frac{J_0(B_m r_c)}{J_1(B_m r_c)} = \frac{B_m D_c}{K D_r} \cdot \frac{K_0(Kr_c) - \alpha I_0(Kr_c)}{K_1(Kr_c) - \alpha I_1(Kr_c)} , \quad (I-4)$$

where

$$\alpha = \frac{K_0(Kr_c + KT)}{I_0(Kr_c + KT)} .$$

One-group cross sections were generated from pointwise data compiled at LRL.¹¹ A weighting spectrum was obtained from a DTf¹² representation of a typical fast reactor. The cross sections so obtained are displayed in Table I-1.

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Table 1. Nominal mission profile (taken from Ref. 1).

Mission	Manned Mars lander
Mission time, days	450 ± 30
Power-on time, days	300
Wait time at Mars, days	40 ± 10
Earth escape	Nuclear, high thrust
Earth return	Atmospheric braking
Number in crew	7
Electric power required for propulsion, MW	5
Powerplant specific mass required, g/W	7
Thruster efficiency	0.78
Thruster specific impulse, sec	6400
Mass breakdown, 10 ³ kg:	
Initial earth-orbit assembly:	270
Nuclear stage	110
Electric stage:	160
Power plant	35
Propellant	40
Payload	77
Thruster	3
Miscellaneous	5

Table 2. Heat pipe radiator configuration.

Heat rejected	20 MW
Rejection temperature	1000°K
Radiant heat flux	4.67 W/cm ²
Convective heat flux (turbine working fluid to heat pipe)	50 W/cm ²
Heat pipe diameter	1.5 cm
Heat pipe wall thickness	0.04 cm
Length of heat pipe in primary side fluid	6.25 cm
Length of heat pipe which radiates	106 cm
Energy rejected per heat pipe (50% of attainable heat transport) ⁸	1.55 kW
Number of heat pipes required (end of life)	12,800
Number of heat pipes provided	16,000
Probability of no damage to barrier	0.99
Radiator plan form	14 m × 22 m
Radiator specific mass	1.7 g/W
Radiator mass:	8500 kg
Heat pipe	4900 kg
Heat pipe fluid	530 kg
Primary side fluid	330 kg
Manifolds	40 kg
Feed line	260 kg
Return lines	20 kg
Barrier ^a	2420 kg

^aProbability of no excessive damage can be raised to 0.999 by increasing the barrier mass by 0.5 g/W.

Table 3. Range of parameters for NESP reactor survey.

	Minimum	Nominal	Maximum
Volume fraction of flowing Li, VF(Co)	0.15	0.2	0.25
Volume fraction of stagnant Li, VF(Hx)	0.05	0.1	0.15
Volume fraction of W structure, VF(Cl)	0.1	0.2	0.3
Volume fraction of void, VF(V)	0	0.1	0.2
Core length-to-diameter ratio, L/D	1.2	1.4	1.6
Burnup, BU	0.004	0.008	0.012

Table 4. Assumed worths for specification of calculated bare-core effective multiplication factor, $k_B(\text{calc})$.

	$\Delta k(\text{OSD})$	$\Delta k(\text{ER})^a$	$\Delta k(\text{MR})$	$\Delta k(\text{FSR})$	$\theta \Delta k^b$	$\Delta k(\text{DTF-calc})$
One-group calculations	0.02	0	0.01	0 ^c	0	0 ^d
ZOOM calculations	0.02	0.03	0.01	0 ^e	0	calculated

^aEnd reflection can be explicitly included in the one-group calculation; end reflectors of 50 vol % W and 50 vol % Li were assumed to be 2.54 cm thick. ZOOM, however, is strictly a one-dimensional code. Thus, an estimate of $\Delta k(\text{ER})$ must be included in the ZOOM specification of k_B .

^b $\theta \Delta k$ was neglected in these early survey calculations to avoid iterating. Typically $\theta \Delta k$ will be less than 0.01, but in more precise calculations it should be obtained by an iterative procedure.

^cIn the one-group calculations, fixed side reflection is represented by 0.5-cm-thick BeO. This is because the one-group calculation is a two-region calculation and therefore the pressure vessel, etc., must be mocked up by side reflector material.

^dThe one-group calculations agree with multigroup transport calculations well enough to permit $\Delta k(\text{DTF-calc})$ to be neglected for survey purposes.

^eZOOM is a multiregion calculation and therefore permits exact representation of the fixed side reflection. That is, the ZOOM radial representation includes everything inside the side reflector.

Table 5. Determination of fuel enrichment.

	BU = 0.004	BU = 0.008	BU = 0.012
$\Delta k(\text{OSD})$	0.0200	0.0200	0.0200
$\Delta k(\text{ER})$	0.0300	0.0300	0.0300
$\Delta k(\text{MR})$	0.0100	0.0100	0.0100
$\Delta k(\text{DTF-calc})$	0.0185	0.0299	0.0396
$k_B(\text{calc})$	0.92	0.91	0.90
Enrichment	0.365	0.49	0.59

Table 6. Summary of control requirements and side reflector thicknesses.

Effect	Δk		
	BU = 0.004	BU = 0.008	BU = 0.012
U^{235} depletion	-0.0058	-0.0091	-0.0115
U^{236} generation	+0.0001	+0.0003	+0.0005
U^{238} depletion	-0.0001	-0.0002	-0.0002
Pu^{239} generation	+0.0015	+0.0014	+0.0009
Temperature	-0.0167	-0.0204	-0.0222
Fuel swelling	-0.0005	-0.0012	-0.0021
Operational shutdown	-0.0200	-0.0200	-0.0200
Operational reserve	-0.0100	-0.0100	-0.0100
Total adjustable reactivity required	0.0515	0.0592	0.0646
Reflector efficiency factor	1.47	1.47	1.47
Reflector worth required	0.0757	0.0870	0.0950
Worth of 10-cm reflector	0.1176	0.1724	0.2063
Required reflector thickness (cm)	3.4	2.5	2.2

Table 7. NESP system characteristics.

Power, MWe	5
Life, hours	10,000
System efficiency	0.20
Overall turbine efficiency	0.76
Alternator efficiency	0.93
Reactor outlet temperature, °K	1600
Turbine inlet temperature, °K	1450
Turbine temperature ratio	0.69
High-temperature turbine speed, rpm	12,000
Low-temperature turbine speed, rpm	18,000
Reactor coolant	Lithium
Working fluid	Potassium
Radiator (heat pipe) fluid	Potassium
Reactor coolant pressure, bars	6
Working fluid pressure, bars	15.6
Radiator fluid pressure, bars	0.6
Specific mass estimate, g/W:	
Radiator (0.999 assurance)	2.2
Alternator and cooling system	0.8
Shield	0.8
Structure	0.6
Turbines	0.4
Reactor	0.3
Power conditioning distribution, and controls	0.2
Boiler, preheater, and pumps	0.2
Miscellaneous	0.1
Contingency (25% of above items)	1.4
Total NESP specific mass	7.0

Table I-1. One-group cross sections for fast reactors.

Material	ν	σ_p , barns	σ_c^a , barns	σ_s , barns	$\bar{\mu}^b$	σ_{tr} , barns
Li ⁶	—	—	0.7157	1.829	0.1447	2.281
Li ⁷	—	—	0.0149	1.688	.0885	1.522
Be	—	—	0.0169	3.770	.1408	3.212
C	—	—	1.96×10^{-3}	3.162	.0844	2.897
N	—	—	0.0610	2.633	.0755	2.495
O	—	—	3.66×10^{-3}	3.585	.0897	3.267
Na	—	—	7.55×10^{-4}	3.814	.1284	3.325
Al	—	—	5.65×10^{-3}	3.892	.1725	3.227
Si	—	—	9.80×10^{-3}	3.338	.1643	2.814
P	—	—	0.0209	3.146	.2130	2.497
K	—	—	0.0339	2.625	.2146	2.095
Fe	—	—	5.96×10^{-3}	3.832	.1332	3.328
Ga	—	—	0.0239	4.877	.0762	4.529
Nb	—	—	0.0506	6.913	.1860	5.677
Mo	—	—	0.0214	7.096	.1854	5.801
Ta	—	—	0.3636	7.021	.1974	5.996
W	—	—	0.1235	7.518	.1662	6.387
Pb	—	—	5.38×10^{-4}	6.933	.1708	5.746
U ²³³	2.576	2.194	0.1731	6.096	.2578	6.887
U ²³⁴	2.689	0.7536	0.2156	7.556	.2689	6.659
U ²³⁵	2.529	1.421	0.2778	7.086	.2506	7.002
U ²³⁶	2.760	0.2901	0.1346	8.107	.2306	6.656
U ²³⁸	2.816	0.1316	0.1616	8.511	.2335	6.807
Pu ²³⁹	2.984	1.824	0.2355	6.912	.2562	7.197
Pu ²⁴⁰	3.059	0.7647	0.7731	6.835	.2447	6.697
Pu ²⁴¹	2.896	2.088	0.2627	6.950	0.2538	7.531

^aIncludes radiative capture only. The contribution from the (n,2n) reaction is omitted.

^bAverage cosine of the elastic scattering angle.

FIGURE CAPTIONS

- Fig. 1. Artist's sketch of NESP system showing principal components.
- Fig. 2. Schematic diagram of NESP system.
- Fig. 3. Heat pipe radiator for 5-MWe NESP system.
- Fig. 4. Radial section of reactor geometry assumed for neutronic calculations.
- Fig. 5. Fuel enrichment for various core volume fractions. In all cases shown, $BU = 0.012$, and $L/D = 1.4$.
- Fig. 6. Required thickness of BeO side reflector for control for various core volume fractions. In all cases shown, $BU = 0.008$ and $L/D = 1.4$.
- Fig. 7. Plot of k_{eff} vs enrichment for bare core with nominal volume fractions and $L/D = 1.4$.
- Fig. 8. Side reflector worth vs side reflector thickness with nominal volume fractions and $L/D = 1.4$.
- Fig. 9. Geometrical relations for several fuel-element geometries.
- Fig. 10. Temperature distribution in fuel above bulk coolant temperature.
- Fig. 11. Shielding mass as a function of hot shield and back shield thickness.

Walter - Fig. 1

Walter - Fig. 2

Walter - Fig. 3

Walter - Fig. 4

Walter - Fig. 5

Walter - Fig. 6

Walter - Fig. 7

Walter - Fig. 8

A = Cell area, F_F = fuel volume fraction, F_{Cl} = clad volume fraction, F_S = swelling allowance fraction, F_{SC} = stagnant coolant fraction, F_C = primary coolant fraction, D_H = hydraulic diameter, α = linear swelling allowance.

Pin-type A	Pin-type B	Hybrid	Tube
$\Gamma = t/r_1$	$\Gamma = t/r_1$	$\beta = t_1/r_1$	$\beta = r_0/r_1$
$\beta = r_2/r_1$	$\beta = r_2/r_1$	$\Gamma = t_2/r_1$	$\Gamma = t/r_0$
$A = \frac{\sqrt{3}}{8} r_1^2 (1 + \beta)^2$	$A = \frac{r_1^2 (1 + \beta)^2}{2\sqrt{3}}$	$A = \frac{\sqrt{3}}{2} r_1^2$	$A = \frac{r_1}{2\sqrt{3}}$
$F_F = \frac{2\pi}{3\sqrt{3}} \left(\frac{1 - \Gamma}{1 + \beta} \right)^2 / (1 + \alpha)^3$	$F_F = \frac{\pi\sqrt{3}}{6} \left(\frac{1 - \Gamma}{1 + \beta} \right)^2 / (1 + \alpha)^3$	$F_F = \frac{\pi}{3\sqrt{3}} (1 - \beta)^2 / (1 + \alpha)^3$	$F_F = \left(1 - \frac{\pi\sqrt{3}}{6} \beta^2 \right) / (1 + \alpha)^2$
$F_{Cl} = \frac{4\pi}{3\sqrt{3}} \left[\frac{\Gamma + 2\beta\Gamma - 3\Gamma^2/2}{(1 + \beta)^2} \right]$	$F_{Cl} = \frac{\pi\sqrt{3}}{2} \left[\frac{2\Gamma/3 - \Gamma^2 + \beta^2}{(1 + \beta)^2} \right]$	$F_{Cl} = \frac{\pi}{3\sqrt{3}} (\Gamma - \Gamma^2/2 + 2\beta - \beta^2)$	$F_{Cl} = \frac{\pi}{2\sqrt{3}} \beta^2 (2\Gamma - \Gamma^2)$
$F_S = [(1 + \alpha)^3 - 1] F_F$	$F_S = [(1 + \alpha)^3 - 1] F_F$	$F_S = [(1 + \alpha)^3 - 1] F_F$	$F_S = [(1 + \alpha)^3 - 1] F_F$
$F_C = 1 - F_F - F_{Cl} - F_S$	$F_C = (1 - F_F - F_{Cl} - F_S)$	$F_{SC} = 1 - \frac{\pi}{2\sqrt{3}}$	$F_C = 1 - F_F - F_{Cl}$
$D_H = \frac{12F_C A}{\pi r_1} / \left(\frac{1}{2} + 2\beta - \Gamma \right)$	$D_H = \frac{8F_C A}{\pi r_1} / \left(\frac{1}{3} + \beta \right)$	$F_C = 1 - F_F - F_{Cl} - F_S - F_{SC}$	$D_H = 2r_0 (1 - \Gamma)$
		$D_H = 2r_1 (1 - \Gamma)$

Walter - Fig. 10

Hot Shield	Main Shield	Back Shield
---------------	----------------	----------------

Walter - Fig. 11

- o Hot shield is inherent in reactor plenum, structure, boiler, preheater. It is assumed to be 70% Li, 30% W by vol.
- o Main shield is lithium hydride.
- o Back shield is tungsten.

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