JUL 1 1968

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UCRL - 70863
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CONF-680802--6

MINI-100

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RANKINE CYCLE SYSTEMS STUDIES FOR NUCLEAR SPACE POWER

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May 31, 1968

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This manuscript was prepared for submittal in the
Proceedings of the Intersociety Energy Conversion Conference,
August 1968, Boulder, Colorado.

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RANKINE CYCLE SYSTEMS STUDIES FOR NUCLEAR SPACE POWER*

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ABSTRACT

Two different types of Rankine cycle systems studies are described which can be used to advantage in conjunction with each other. A simple, flexible conceptual design representation gives consistent, general trend results and yet requires minimum expenditure of effort to incorporate changes. After initial design phases are complete, a detailed system representation that includes extensive neutronic and shielding information is used to give final design characteristics of the complete system and components of interest. Some recommendations for future effort are made.

INTRODUCTION

The Lawrence Radiation Laboratory at Livermore has participated in a program to develop the technology necessary for building advanced, high-temperature reactors for nuclear space power systems. Reactor concepts were examined for use with liquid metal Rankine cycle, out-of-pile thermionics, and other conversion systems that could be operable in 10 to 20 years.¹⁻⁴

This paper presents methods and results of liquid metal Rankine cycle systems studies conducted during the course of this program. The complete system was represented mathematically so that interactions between individual components could be examined. Results permitted specification of appropriate operating conditions for each

component, pointed out areas where changes were necessary, and assured that all components could be successfully integrated.

During the studies, the final system evolved from initial conception through a large number of changes. These changes resulted from improvements in component operating characteristics and in the general system layout. A number of the improvements were a direct result of the system studies themselves. A current system representation was found to be essential since most of the components are interrelated and a change in one portion of the system many times had a significant effect on other portions of the system. Interactions between the reactor and the nuclear shield (see Figure 1) were particularly pronounced. For the system studied, shield mass varied in proportion to reactor size. Since over half of the total system mass was contributed by the shield, a small change in reactor size made a relatively large effect on total system mass.

During initial conceptual design stages, when major changes are frequent, use of a flexible, simple system representation that gives consistent, general trend results offers considerable savings in manpower and computer time, since it permits simple incorporation of changes and allows the representation to be kept current with a minimum of effort. Such a representation utilizes an ideal thermodynamic cycle performance adjusted for anticipated inefficiencies. Influence coefficients obtained from individual equipment perturbation studies are used to represent major system components.

After the frequency of changes has diminished, detailed design parameters can be better determined with a more complicated representation that includes extensive neutronic and shielding information. In such a representation, detailed digital computer models of the major components are integrated into a single system computer representation. This type of system representation has the advantage of producing detailed and more accurate optimized parameters. It is not feasible to utilize such a representation for conceptual studies because of the large effort required to incorporate modifications, and to develop and integrate the individual component models. Final design characteristics are the end result of this type of system representation.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

¹C. E. Walter, O. C. Kolar, N. J. Brown, and T. P. Wilcox, Jr., "A Large Nuclear-Electric Space Power Plant," *Advances in Energy Conversion Engineering* - papers presented at 1967 International Energy Conversion Engineering Conference, Miami Beach, Florida, pp. 739-747, August 13-17, 1967.

²J. H. Pitts and C. E. Walter, "Conceptual Design of a 10 MW_e Nuclear Rankine System for Space Power," Lawrence Radiation Laboratory, Livermore, Calif., UCRL-50382, January 1968.

³C. S. Barnett, "An Out-of-Pile Heat Pipe Thermionic Space Power Concept," *Trans. Am. Nucl. Soc.*, 9, p. 338, 1966.

⁴W. E. Loewe, "Out-of-Core Thermionic Space Power," Lawrence Radiation Laboratory, Livermore, Calif., UCRL-70816, 1968.

Overall system performance was evaluated frequently and was used for optimization considerations. A choice was made to optimize the system by minimizing system specific mass in grams per watt of net electrical power output. It is realized that minimum specific mass may not be the best or only criterion for optimization, however it is one logical choice and can be simply calculated. Other criteria, such as reliability, for example, require arbitrary specification of a minimum acceptable value that can be varied at will by changing redundancy of components. Wilde and Beightler⁵ have pointed out that optimization is only the last of three steps needed to reach a rational decision. The first two, a description of the system and adoption of a measure of effectiveness, are absolutely prerequisite for the third.

The main justification for attempting to optimize an engineering design is that it motivates good modeling and places all designs on a common basis for comparison purposes. The actual optimization criterion utilized is not as important as the process of optimization itself.

The results obtained from any study are dependent upon the assumptions used to specify the model and establish boundary conditions. Too often, systems developed from different assumptions are compared directly without taking into account the effects of these various assumptions. For example, different selections of strength values for structural materials or the nuclear dose allowed at the payload can easily change the system specific mass by 30%.

Fortunately, the system description is generally transferable, should the variables chosen for optimization or the assumptions underlying the model be modified. Values of some of the system specifications used at this Laboratory are shown in Table 1. An artists' sketch of a typical system layout is shown in Figure 1.

Table 1. Some typical specifications used in LRL system studies.

Item	Typical values
System thermal power	2 - 60 MW
System lifetime	10,000 - 20,000 hours
Reactor fuel temperature	1400 - 1700°K
Non-penetration probability of components by meteoroids	0.99
Payload nuclear dose (unmanned)	10 ⁶ rad (gamma), 10 ¹³ nvt (neutron)
Shielding half-angle	3 - 14°
Payload distance	10 - 50 meters
Radiator temperature	1000 - 1200°K
Reactor average fuel burnup fraction	0.0068 - 0.021

⁵D. J. Wilde and C. S. Beightler, "Foundations of Optimization," Prentice-Hall, Inc., pp. 464-465, 1967.

CONCEPTUAL DESIGN SYSTEMS REPRESENTATION

The conceptual design system representation permits approximate general trends to be obtained with a minimum output of manpower. The representation is kept simple and flexible so that improvements in the various system components can be incorporated easily. The simplicity of this type of analysis allows calculations to be performed without the use of a computer, if desired.

Basically, the calculations are performed in two parts. First, approximate component masses and efficiencies are found by either individual component studies or through interpolation (or extrapolation) of available data in the literature. The use of influence coefficients or a graph showing the variation of component mass and efficiency with important parameters is helpful since exact component operating conditions are not known initially.

Second, the complete cycle thermodynamic performance is predicted for an ideal system and then adjusted for the component inefficiencies found from the individual component studies. Miscellaneous heat losses can be neglected if they are small with respect to the heat rejected in the radiator. Putting this in mathematical terms,

$$\eta_S = \eta_T \eta_{AL} \eta_{IR} = \eta_T \eta_{AL} \left[\frac{Q_A - Q_R}{Q_A} \right] \quad (1)$$

where

$$\eta_S, \eta_T, \eta_{AL}, \text{ and } \eta_{IR}$$

are thermal efficiencies of the system, turbine, alternator and ideal Rankine cycle. Q_A and Q_R represent the heat added and heat rejected in the ideal Rankine cycle.

The resulting system specific mass can be calculated by taking the reactor power to be constant, calculating the net electrical output power from the cycle thermodynamic analysis, and totaling the masses of each individual component. Should it be desired to hold the net electrical output power constant, the cycle thermodynamic analysis would be utilized to determine the necessary operating capacity of each component.

Optimization of the system is accomplished by varying the system operating parameters one by one and comparing system specific masses. Constraints such as maximum reactor temperature, maximum turbine blading stress, etc. are imposed where required.

Utilization of a calculational method can many times be explained more clearly by studying a specific example. Take, for example, the system diagrammed in Figure 2.

The source is considered to be a sodium heat-pipe-cooled reactor⁶ where heat pipes act as small

⁶C. E. Walter, N. J. Brown, V. E. Hampel, T. P. Wilcox, and E. W. McCauley, "An Advanced 2000 kW Nuclear Heat Source," Lawrence Radiation Laboratory, Livermore, Calif., UCRL-70978, March 1968.

primary coolant loops transferring heat from the reactor to a boiling potassium working fluid (see Figure 3). Relatively cool liquid potassium from the radiator flows inside the reactor-boiler pressure vessel and then boils as it passes around the outside of the heat pipes in the boiler area. Stability characteristics of such a boiler under zero gravity conditions have not been examined in detail, however, it is expected that some type of flow swirler would be needed to keep the liquid potassium in contact with the outside of the heat pipe wall. For example, the addition of twisted tapes located centrally in the space between the heat pipes could be used.

A central duct is used to return potassium vapor from the far side of the reactor-boiler since the duct helps to flatten the radial power distribution in the reactor and enhances the worth of the reactor side reflectors. The pressure vessel is insulated with hafnium-oxide (Hf O_2) to keep the wall relatively cool.

This type of integrated heat source eliminates the need for a pump in the primary loop. Since the heat pipes are essentially isothermal devices, the reactor temperature is only slightly higher than the boiler potassium outlet temperature. For purposes of these system studies, this temperature difference is taken as a constant.

Detailed reactor design calculations, although very important in determining the reactor operating characteristics, are really only necessary to determine reactor size from a conceptual system studies standpoint. Reactor diameter, length and mass were approximated using the values of Ref. 6, based on the design method of Ref. 7. The reactor usually operates at its maximum allowable temperature and the mass of the reactor-boiler is nearly constant for the various system operating conditions.

Preliminary nuclear shielding calculations are performed with removal length theory [Eq. (2)] used to determine the required thickness of both a lithium-hydride shield and a tungsten gamma shield

$$A = e^{-T/L} \quad (2)$$

where

A = shield attenuation
 T = shield thickness, cm
 L = removal length, cm

Although accurate removal lengths can only be determined from detailed calculations, estimates are available in the literature.^{8,9} The calculated shielding thickness is held constant since neither the reactor power or allowable payload dose are varied.

⁷N. J. Brown and E. W. McCauley, "Lawrence Radiation Laboratory Fast Reactor Design-Analysis Codes," Lawrence Radiation Laboratory, Livermore, Calif., UCRL-50429, 1968.

⁸E. P. Blizard and L. S. Abbott, editors, "Reactor Handbook," Interscience Publishers, Second Edition, 1962.

⁹H. M. Dieckamp, "Nuclear Space Power Systems," Atomic International Memo #7585, Rev. 2, September 1964.

The shield mass then can be calculated easily once the reactor-boiler size, payload distance, and shielding angle are established.

Although the turbine-alternator accounts for only a small portion of the system mass, its performance (efficiency), has a direct influence on the size of most other components and therefore on system mass. Influence coefficients were obtained from Figures 4 and 5 and used in conjunction with the system thermodynamic analysis to predict system performance and specific mass. These curves of turbine efficiency and specific mass were generated by a computer code based on the work of Glassman^{10,11} and Stewart.¹² The turbines utilized were full-admission axial flow type with 20 - 40% reaction per stage. Rotational speed was held constant at 24,000 rpm. To simplify the analysis, moisture removal and interstage drainage, which might be necessary because of turbine erosion problems, were not included. Instead, a performance penalty of one-half percent efficiency per percent of exit moisture was assumed throughout the analysis.

The turbine specific mass increases as the temperature ratio increases because the amount of energy which can be extracted decreases monotonically. Since total turbine mass and efficiency are weak functions of temperature ratio, this decrease in the amount of energy extracted dominates the specific mass curve.

Alternator characteristics of Figure 5 were calculated for a radial gap homopolar design based on a method proposed by Jain.¹³ The advantage of a homopolar design is that there are no rotating windings, slip rings, or rectifiers. The field coil is located on the stator. This enhances reliability, and permits higher operating temperatures and rotational speeds. Efficiency was determined to be nearly constant over the range of rotational speeds examined. Although lower alternator specific mass is obtained by increasing rotational speed, turbine stress limitations prevent operation above 24,000 rpm.

The heat pipe radiator curve of Figure 6 was obtained utilizing an analysis and computer code developed by Werner and Carlson.¹⁴ In the heat

¹⁰A. J. Glassman and S. M. Futrol, "Analytical Study of Turbine-Geometry Characteristics for Alkali-Metal Turboelectric Space Power System," NASA-TN-D-1710, 1963.

¹¹A. J. Glassman, "Alkali-Metal Turbine Geometry as Affected by Blade-Speed Limitations," NASA-TN-D-2777, April 1965.

¹²W. L. Stewart, "A Study of Axial-Flow Turbine Efficiency Characteristics in Terms of Velocity Diagram Parameters," ASME Paper 61-WA-37, 1961.

¹³Turbine temperature ratio is defined as the turbine outlet temperature (or radiator inlet temperature) divided by the turbine inlet temperature.

¹⁴G. C. Jain, "Design Aspects of a Homopolar Inductor-Alternator," IEEE Trans. Power Apparatus and Systems, 83, pp. 1009-1015, 1964.

¹⁴R. W. Werner and G. A. Carlson, "Heat Pipe Radiator for Space Power Plants," Lawrence Radiation Laboratory, Livermore, Calif., UCRL-70777 (also a publication of this Conference), 1968.

pipe radiator the inlet and outlet ducts, originally used just for vapor delivery and fluid return in other types of radiators, become the primary leg of a heat exchanger. One end of each of a large number of heat pipes is inserted into this ducting to a depth suitable for convective heat transfer. The other end of each heat pipe radiates to space. These heat pipes operate in parallel, functionally independent one from the other, and form the separate, secondary leg of the heat exchanger. Since a large number of independent heat pipes are involved, they can be designed for a minimum weight with a specified probability that a certain fraction will remain unpunctured during the mission. The number of heat pipes surviving at the end of the mission must be sufficient to reject the required heat, and is determined by approximating a binomial distribution of heat pipe failures with a normal distribution.

$$N_x P = N_s + Z \sqrt{N_x P (1-P)} \quad (3)$$

Z = value of standard normal variable for a given value of radiator survival probability.

N_s = surviving number of heat pipes

N_x = starting number of heat pipes

P = probability of survival of individual heat pipe

This formulation can represent accurately radiators with widely ranging numbers of heat pipes. The effect of the puncture of a heat pipe is only that it will cool and not contribute significantly as a heat exchange member. The ducting must have the desired degree of meteoroid protection to assure that no punctures occur.

Since the thin-walled heat pipes are inserted directly into the meteoroid shielded duct, the large temperature drop caused by conduction loss present in other types of radiators is eliminated. Additionally the area available for condensing heat transfer may now be set at whatever value is optimum.

The mass of a heat pipe radiator is typically less than one-half that of a conventional fin and tube radiator. Mass varies directly with the amount of heat rejected and approximately inversely with rejection temperature to the 4th power. For a radiator inlet temperature of 1040°K, mass is about 2.5 g/cm² of radiator planform area.

The mass of the heat pipe radiator depends on the equation used for meteoroid protection. Werner and Carlson¹⁴ used a meteoroid flux distribution based on Clough and Lieblein¹⁵ (revised) to obtain Eq (4) for calculation of barrier thickness

$$t = 6.15 \frac{1}{E^{1/3} \rho^{1/6} \bar{H}^{1/4}} \left(\frac{\tau}{10,000} \right)^{1/4} A^{1/4} \quad (4)$$

where

t = barrier thickness - ft

E = modulus of elasticity - lb/ft²

¹⁵N. Clough and S. Lieblein, "Significance of Photographic Meteor Data in the Design of Meteoroid Protection for Large Space Vehicles," NASA-TN-D-2958, August 1965.

ρ = barrier material density - lb/ft³

τ = lifetime - hours

A = vulnerable area - ft²

$\bar{H}$ = average number of penetrations in area A in time τ

Pump design is not as crucial as other components from a systems design standpoint since differences in performance cause relatively minor effects on the overall system mass. It is important, however, that reliable pumps be available that can function under all system operating conditions.

Efficiencies and specific mass of pumps can be obtained from the literature.¹⁶ An efficiency and specific mass of ~20% and 4 g/w* respectively for an electromagnetic pump were assumed.

Following the calculations of individual component masses and efficiencies, the ideal Rankine cycle efficiency is determined. Figure 7 shows the ideal cycle efficiency for a potassium power conversion loop where 100% efficient components, and constant heat addition and heat rejection temperatures were assumed.

The actual net cycle output power is calculated by multiplying the ideal cycle output power by the turbine and alternator efficiencies, and then subtracting the required pumping power. Component operating power levels can be obtained in a similar fashion. Both the fluid energy increase due to the pump operation and miscellaneous heat losses are generally small enough to neglect.

Some typical results from an optimization study of the system described are shown in Figures 8 and 9 where the relative system specific mass is compared for various radiator and turbine inlet temperatures. These graphs point out that a turbine temperature ratio should be about 0.7 in order to obtain a minimum system specific mass. This value is close to Pitkin's¹⁷ predicted value of 0.75 for a system dominated entirely by the radiator mass. A 5-10% lower optimum turbine temperature ratio than 0.75 is expected since the radiator mass is not dominant.

Figure 9 also shows that a minimum specific mass occurs when the turbine inlet temperature is as high as possible, consistent with the constraints of the system. Values above 1500°K are not permitted in this example since the reactor maximum allowable temperature is exceeded. Table 2 shows a breakdown of the system component masses.

These general trends serve the important function of specifying the appropriate operating conditions for each component, and along with the mass tabulation show the relative importance of each component on the optimizing parameter.

¹⁶J. P. Verkamp and R. G. Rhudy, "Electromagnetic Alkali Metal Pump Research Program," NASA-CR-54019, Volumes 1, 2, and 3, 1967.

*Based on electrical input power to the pump.

¹⁷E. T. Pitkin, "Optimum Radiator Temperature for Space Power Systems," Am. Rocket Soc. J., 29, August 1959, pp. 596-598.

Table 2 Typical system component masses

Component	Mass (kg)	Relative Mass	Specific Mass (g/We)
Shield	1930	0 560	5 51
Radiator	480	0 139	1 37
Reactor	370	0 107	1.06
Boiler	200	0 058	0 57
Alternator	180	0 052	0 51
Turbine	70	0 020	0 20
Pump	80	0 023	0 23
Miscellaneous Items	140	0 041	0 40
TOTAL	3450	1 000	9 85

System net electrical output power - 350 kW

DETAILED DESIGN SYSTEMS REPRESENTATION

Following an initial conceptual design systems study, further refinement in the systems calculations is desirable. This can be accomplished with the aid of a system representation that combines individual component design computer codes into a single integrated systems code. The detailed representation includes the same major components as the conceptual representation, however, miscellaneous items such as controls, piping, power distribution, and power conditioning are included in more detail.

The individual component computer codes are incorporated as subroutines and may be as detailed as desired as long as computer memory storage is not exceeded. This is in contrast to the conceptual design procedure where the individual components were analyzed separately to obtain either influence coefficients or parameter variation curves. Although not necessary, it is logical to use the same basic individual component analysis codes used for conceptual design, expanded to give detailed design dimensions and mass distribution.

The system mass and performance calculations begin with knowledge of the required output or payload power. Neither system efficiency, turbine efficiency, or alternator efficiency are known initially, hence, reactor power is unknown. Values of the reactor-boiler temperature, turbine inlet temperature, and turbine temperature ratio are input. A guess is made at the required turbine input power. Miscellaneous heat losses can be reduced through appropriate use of insulation, and are assumed negligible.

With this information, the enthalpy drop through the turbine, the working fluid flowrate, and the turbine exit quality can be calculated. Radiator power is then determined with the radiator subroutine¹⁴ utilizing the fact that the working fluid exits from the radiator as saturated liquid. Boiler power can then be calculated from the flowrate, radiator exit temperature and turbine inlet temperature. Reactor power is assumed equal to that of the boiler.

The required alternator output power is found

by adding pumping power requirements to the payload power. Utilizing a calculated alternator efficiency, the turbine output power is determined. A new value of turbine input power, to compare with the initial guess, is then found with the use of a turbine subroutine. The calculation is repeated until the desired convergence is obtained.

Generally, a single study emphasizes one or two components only, with other components represented in a minimum of detail. Such was the case here where emphasis was placed on the reactor and the nuclear shielding, with perhaps sufficient if not final detailed consideration of the balance of the system. The reactor design method⁷ integrated both mechanical and neutronic calculations. Neutronic analysis was based on the 16-group, one-dimensional transport theory described in Refs. 2 and 7. Such integrated calculations have considerable merit since structural considerations, which require placement of materials at discrete locations in and around the nuclear core, can have significant effect on the neutronic design.

For example, the thickness of the pressure vessel that surrounds the core has an important effect on a reactor utilizing movable side reflectors. If the vessel wall is too thick, a large percentage of leakage neutrons are reflected by the wall itself, thereby making the side reflectors ineffective. In order to obtain adequate neutronic control characteristics, it was necessary to cool the vessel wall with power conversion loop potassium. This, coupled with the hafnium-oxide thermal insulation, permitted the reduction of wall thickness to an acceptable value.

Materials used in reactors must not only have good high-temperature strength properties but also have nuclear and chemical compatibility. The choice of materials can easily make a 10% change in reactor over-all dimensions. It is important that all aspects of a particular materials choice be excessive reactor sizes and to provide adequate reliability.

One acceptable reactor materials combination uses a tungsten-rhenium alloy, W-25% Re, as the structural material and uranium-mononitride, UN, as the fuel. W-25% Re has good creep strength at high temperatures and is compatible with UN, lithium, sodium, and potassium. In addition, there is evidence that tungsten has increased strength at high temperatures and high radiation levels.¹⁸ The use of other creep-resistant materials such as tantalum is still permissible if surfaces have tungsten vapor deposited upon them. UN has a high density, melting point, and thermal conductivity, also it is comparatively easy to fabricate and handle.

¹⁸R. C. Rau, J. Moteff, and R. L. Ladd, "Comparison of Microstructure with Mechanical Properties of Irradiated Tungsten," J. Nucl. Materials, Vol. 24, No. 2, p. 172, November 1967.

One problem which exists in the design of reactors is the accuracy to which nuclear cross sections are known. Smith¹⁹ states that it is desirable to obtain fission cross sections to about 1/2% over a wide energy range. Yet, some precision cross-section measurements differ by over 10%. For reactors such as the type described by Walter,¹ a 1% change in U²³⁵ fission cross section results in nearly a 1% change in reactivity. The importance of improving cross-section data can readily be seen.

Detailed nuclear shielding calculations were determined necessary for a final design since shielding accounted for approximately one-half of the system mass. Nuclear shielding has been an area where development of design methods has not kept pace with theory. Over-conservative design has been necessary to compensate for uncertainties in results. Solutions for fast reactor neutron attenuation have differed by several orders of magnitude, depending on the method being used and who is using it.²⁰ Although shielding uncertainties can be reduced by using Monte Carlo techniques, calculational time is prohibitive at the present. The detailed shielding calculational method used at this Laboratory is felt to be conservative. Further refinement of the method should be pursued with the objective of reducing computational time while increasing the accuracy.

Present shielding calculations were performed with the GEISHA²¹ computer code, using point kernel methods. Removal theory, with the Albert-Welton²² fit to experimental data for homogeneous materials, was employed 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 final shield was composed of a lithium-hydride neutron shield plus a tungsten gamma shield similar to the conceptual design but of different thicknesses.

Accurate reactor and shielding analyses are important first to assure that each is of minimum size and mass, and second to determine radiation dose levels present at other components and the payload. Other than the reactor and the shield, component design codes used in the detailed system representation were similar to those used in the conceptual design representation.

¹⁹R. D. Smith, "Nuclear Data Requirements for Fast Reactor Design and Operation," Conference Proceedings, Nuclear Data for Reactors, Vol. 1, pp. 27-38, October 1966.

²⁰R. L. Ashley and W. E. Kreger, "Neutron Attenuation in Optically Thick Shields," ANS-SD-1, April 23, 1964.

²¹T. Wilcox, "Geisha-II, A CDC 6600 Code for Use in Parametric Shielding Surveys," Lawrence Radiation Laboratory, Livermore, Calif., UCIR-151, September 1966.

²²R. D. Albert and T. A. Welton, "A Simplified Theory of Neutron Attenuation and its Application to Reactor Shield Design," WAPD-15 (Del.), November 1950.

Results from the detailed design systems representation include parameter variation curves similar to those obtained through conceptual design studies plus detailed dimensions and mass distributions of components of interest. Results can be used to make general system layouts and to compare various optimized systems for their relative merit.

Following the determination of the reactor size and shielding thickness, the interrelation of the reactor-shield on the total system mass can be found by varying the shielding half-angle. Two opposing effects are present. As the half-angle is decreased, the shield diameter and therefore shield mass decrease. On the other hand, radiator mass increases because larger structural members are required to maintain stiffness in the resulting long-narrow radiator planform area. The change in radiator mass is approximately proportional to the cube of the radiator length as indicated in Eq. (5)

$$M - M_n = m_n \left[\left(\frac{L}{L_n} \right)^3 - 1 \right]^* \quad (5)$$

where

M $\equiv$ Total radiator mass
 M_n, m_n $\equiv$ Total radiator mass and radiator structural mass respectively for nominal radiator geometry.
 L, L_n $\equiv$ Radiator length and radiator length for nominal radiator geometry, respectively.

Results shown in Figure 10 indicate a minimum system mass exists at a shield half-angle of about 6 degrees. The actual value chosen for the nominal case reported here was larger so that the possibility of docking maneuvers can be considered.

In comparing various systems, care must be exercised to make sure that the system input parameters and constraints are similar. Figure 11 shows the effect on system specific mass of two different containment material strength criteria. If two systems using such different strength criteria are not properly compared, the relative merit of one system over the other may be obscured. The two materials compared in Figure 11 were both tungsten, however, the expected future material was considered to be the strongest achievable and would not be available in the immediate future. Specific strength criterion numbers used can be found in Ref. 23.

The detailed system representation was used for a number of studies such as that shown in Figure 12. These results show that potassium is preferable to cesium as a working fluid for this space power system and that an optimum reactor temperature exists. This optimum temperature results from an interchange between the mass of

*Assumptions used to justify this equation along with a derivation are shown in Appendix A.

²³"Advanced Space Nuclear Power Program, Progress Report No. 3, April through June 1966," Lawrence Radiation Laboratory, Livermore, Calif., UCRL-50004-66-2, pp. 13-14.

the various containment vessels and the radiator. At higher temperatures the radiator is lighter due to the increase in radiating power per unit area. However, higher temperatures result in lower material strength limits and heavier containment vessels. Above a particular optimum temperature, the containment vessel masses dominate and the system specific mass increases with temperature. Below this optimum temperature, the radiator mass dominates and system specific mass varies inversely with temperature.

Utilization of a systems representation through both conceptual and detailed design phases helps to assure that all components will operate in an efficient manner when integrated into a single system and that a near maximum system electrical power output is obtained

CONCLUSIONS

Use of a simple conceptual design system representation followed by a more detailed representation permits benefit of a systems study to be obtained with a minimum of manpower and computer time. The conceptual design representation can be kept current during initial studies since improvements in individual components can be incorporated easily. General trend results, obtained from a conceptual design representation, assure near optimum conditions are being attained and that all components can be integrated into an efficient system.

A detailed design representation is utilized after the frequency of changes has diminished to specify correct operating conditions for each component and obtain detailed component dimensions, masses, and operating characteristics. The use of system representations permits optimization studies which are necessary for comparison purposes and points out areas in the system where changes are necessary. Detailed reactor and nuclear shielding analyses are necessary to assure minimum component size and mass, and that radiation dose levels are acceptable. The reactor and shield combined account for more than half of the total system mass.

An integrated mechanical-neutronic design of reactors for space power is considered essential for a final design calculation since structural considerations, which require placement of materials at discrete locations in and around the nuclear core, can have significant effect on the neutronic design. Some reactors studied as separate mechanical and nuclear entities have been found to be subcritical or unstable. Iterations necessary to achieve a realistic reactor design are reduced considerably with the integrated design method.

Further effort is desirable in improving nuclear cross-section accuracy since available measurements, which differ in some cases by more than 10%, cause uncertainties in reactor criticality and stability that are unacceptable for final design purposes. Also, further work in the development of nuclear shielding analysis methods is desirable in order to reduce required computer time and improve accuracy. Additional information is required on the changes in strength of materials at high tem-

peratures and at high radiation levels in a fast reactor energy spectrum.

The results of a system study depend upon the model, the assumptions, and the boundary conditions. Comparisons between systems must be made with these features defined and understood.

ACKNOWLEDGMENT

In addition to those people at LRL whose references are cited, the technical assistance of A. Iantuono is gratefully acknowledged.

APPENDIX A

An approximate relationship between radiator mass and length for a constant planform area, flat heat pipe radiator.

In the type of heat pipe radiator described, the major contributing member to structural stiffness is a circular vapor inlet pipe which extends nearly the total length of the radiator. If it is assumed that the vapor inlet pipe has a constant thin annular cross section and that other members do not contribute appreciably to the radiator stiffness then the radiator structural mass, m , and moment of inertia, I , are

$$(A) \quad m = \rho \pi r t L$$

$$(B) \quad I = \pi r^3 t$$

Vapor inlet pipe cross section

where ρ is material density and L is radiator length. Taking the mean radius of the vapor pipe to be constant and assuming a constant density, a ratio of structural masses, can be formed

$$(C) \quad \frac{m}{m_n} = \frac{tL}{t_n L_n} = \frac{IL}{I_n L_n}$$

The subscript n denotes a radiator of nominal geometry along with which structural mass is known.

If the radiator is required to support a constant buckling load, P , regardless of shape then

$$(D) \quad P = \frac{N \pi E I}{L^2} = \text{constant} \quad \text{where } N \text{ is an integer depending on end conditions of the column.}$$

From which

$$(E) \quad I = C L^2 \quad \text{where } C \text{ is constant equal to } \frac{P}{N \pi E}$$

Substituting in equation (C)

$$(F) \quad \frac{m}{m_n} = \left(\frac{L}{L_n} \right)^3$$

If, on the other hand the overall deflection angle, θ , is required to be constant, for a given side force, F ,

$$(G) \quad Y_{\max} = \theta L = \frac{F L^3}{3 E I} \quad \text{where } Y_{\max} \text{ is the deflection of the end of the column where } F \text{ is applied.}$$

$$(H) \quad \theta = \frac{FL^2}{3EI} = \text{constant}$$

From which

$$(I) \quad I = K L^2 \quad K = \frac{3EI\theta}{F}$$

Substituting in equation (C) the same criterion of equation (F) is again satisfied.

Since the change in total radiator mass, $M - M_n$, nearly equals the change in radiator structural mass, $m - m_n$, it follows that:

$$(J) \quad M - M_n \approx m - m_n = m_n \left[\left(\frac{L}{L_n} \right)^3 - 1 \right]$$

FIGURE CAPTIONS

- Figure 1.. Typical reactor system layout.
- Figure 2. Rankine cycle system schematic.
- Figure 3. Integrated heat pipe reactor-boiler.
- Figure 4. Turbine specific mass variation.
- Figure 5. Homopolar alternator specific mass variation.
- Figure 6. Heat pipe radiator mass variation.
- Figure 7. Ideal Rankine cycle efficiency.
- Figure 8. Effect of radiator inlet temperature on system specific mass.
- Figure 9. Effect of Turbine inlet temperature on system specific mass..
- Figure 10. Change in system specific mass for various shield angles.
- Figure 11. Effect of material strength criteria on system specific mass.
- Figure 12. System specific mass variation.

NET ELECTRICAL OUTPUT - 350 kW
TOTAL MASS - 3450 kg
OVERALL LENGTH - 10 m
MAXIMUM WIDTH - 5.3 m

Pitts - Fig. 1

Pitts - Fig. 2

Pitts - Fig. 3

Pitts - Fig. 4

Pitts - Fig. 5

Pitts - Fig. 6

Pitts - Fig. 7

Pitts - Fig. 8

Pitts - Fig. 9

Pitts - Fig. 10

Pitts - Fig. 11

Pitts - Fig. 12

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