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COMPUTER OPTIMIZATION OF REACTOR-THERMOELECTRIC SPACE POWER SYSTEMS

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16. Abstract

This report describes a computer simulation and optimization code that has been developed for nuclear space power systems. The results of using this code to analyze two reactor-thermoelectric systems are presented.

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SUMMARY

The selection of a particular nuclear space power system is a result of a trade-off study of the system performance with some predetermined figure-of-merit such as weight, size, cost, or reliability. This report describes a computer simulation and optimization code that has been developed for nuclear space power systems. The code computes the steady-state operating conditions and the component design characteristics that correspond to the optimum system as defined by the figure-of-merit.

The code was used to analyze two reactor-thermoelectric space power systems for net electrical power requirements between 5 and 40 kilowatts. One system used the SNAP zirconium hydride reactor coupled to lead telluride thermoelectric converters, while the other was a higher temperature system using a uranium nitride fueled reactor coupled to silicon-germanium thermoelectric converters. The program generated the minimum-weight-against-power curve for each system.

INTRODUCTION

Electric power requirements for future space missions have been estimated to range from a few kilowatts to more than 100 kilowatts. The lower power requirements (<5 kWe) will be supplied by solar cells which have proved to be a dependable, lightweight power source. For the higher powers and for conditions of inadequate sunlight, the use of nuclear energy as a heat source for various energy conversion devices appears to be most promising.

The power converters include thermoelectric, thermionic, Rankine, and Brayton. To obtain acceptable conversion efficiency, these devices must be coupled to a high-temperature, liquid-metal-cooled nuclear reactor. The waste heat is rejected to space by radiation.

The selection of a particular power system is a result of a tradeoff study of the system performance with some predetermined figure-of-merit such as weight, size, cost, or reliability. The figure-of-merit for a system is totally dependent on the figures-of-merit for each of the components in the system. An optimum system, therefore, can only be determined by considering the relation of each component to the total system.

This report describes a computer simulation of a reactor-thermoelectric space power system and a technique for determining the optimum system when the figure-of-merit is minimum weight.

METHOD OF ANALYSIS

Powerplant

The reactor-thermoelectric powerplant is represented schematically in figure 1. It is designed to produce electrical power for unmanned space applications (ref. 1) which require high reliability for as long as 5 years of continuous operation. The system consists of a nuclear reactor heat source coupled to the hot side of thermoelectric converter modules. The cold side of each module is coupled to a radiator that rejects the waste heat to space. The heat is transferred by means of two circulating liquid-metal loops which are pumped by dual-throat electromagnetic pumps powered by separate thermoelectric modules. An expansion compensator in each loop accommodates the thermal expansion of the liquid metal and maintains a void-free loop for zero-gravity operation. The reactor is separated from the power conversion equipment and the payload by a shadow shield that attenuates the gamma and neutron radiation to acceptable levels. For this analysis the radiation dose at the payload mating plane was assumed to be 10^6 roentgens and 10^{12} nvt in 5 years.

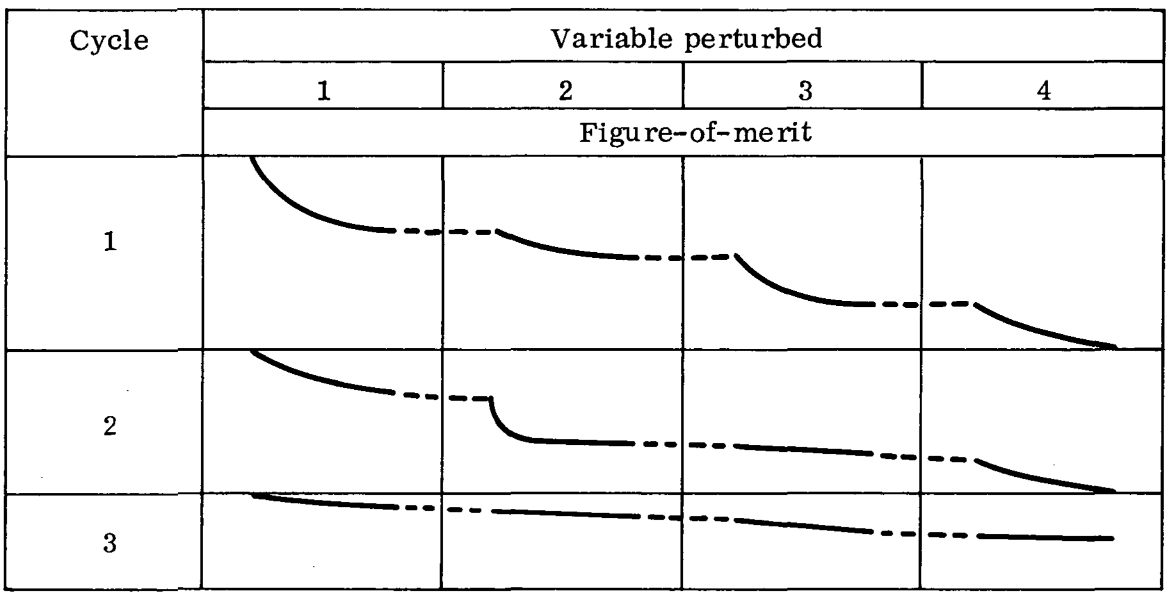
A typical arrangement of system components is shown in figure 2. This figure represents the flight configuration of the 5-kilowatt-electric space power system consisting of a zirconium hydride (ZrH) reactor and lead telluride (PbTe) thermoelectric converters.

Optimization Procedure

A simplified flow chart for the computer program is shown in figure 3. Starting with the input data, which consist of the required electrical load and an initial estimate of the operating conditions, the program performs a cycle analysis that establishes the loop flow rates and a consistent set of state-point conditions. The cycle analysis is a heat and material balance for the system which includes the pumping power required to circulate the coolants, the efficiency of the pumps, the conversion efficiency of the thermoelectric modules and power conditioner, and all heat losses from the system.

Each component is then designed for the operating conditions established by the cycle analysis. The figure-of-merit for the total system is then determined by summing the figures-of-merit for each component. The optimization routine compares this value with a previously calculated value and decides whether it represents the optimum (e.g., the minimum system weight or the minimum cost). If not, the program returns to the input step and perturbs one of any number of predetermined variables (e.g., radiator outlet temperature). Then with this new set of operating conditions the calculations are repeated and a new system figure-of-merit is determined. The program continues to perturb each variable in a consistent manner until the figure-of-merit for the system reaches the optimum.

This procedure is depicted graphically by the following illustration:



Four variables were chosen to be perturbed to illustrate the principle of operation of the optimization program. Starting with variable 1 the initial value is perturbed in the direction (higher or lower) that improves the figure-of-merit, and this continues until the figure-of-merit does not show improvement. Then starting with the optimum operating conditions from variable 1, the second variable is perturbed, and so on through variable 4. The program then returns to variable 1, and the calculation cycle is repeated until no further improvement in the figure-of-merit is realized. It then prints the final set of state-point operating conditions and component design characteristics.

Components

Each powerplant component is represented by a subroutine in the program, the purpose of which is to design the component for the state-point conditions determined by the cycle analysis. The result of each design calculation is some figure-of-merit that describes the component along with any other design details (e.g., heat-exchanger surface area) that might be pertinent to the investigator.

Reactor. - Two nuclear reactor types, representing different temperature limits, were considered for this study. The lower temperature reactor was the SNAP design using uranium/zirconium hydride fuel contained within a metal cladding tube lined with a thin glass barrier to retain the hydrogen moderator. The fuel elements are in a triangular pitch array with spiral fins used to maintain positive spacing. Sodium potassium-78 (NaK-78) is the liquid-metal coolant. Fuel swelling limits the coolant outlet temperature to 922 K. The core is surrounded by movable beryllium segments which reflect neutrons and control the reactor.

The high-temperature reactor is modeled after the SNAP reactors but uses uranium-235 nitride (^{235}UN) fuel clad in T-111 refractory-metal tubing. The pressure vessel and internal supports are also T-111 with lithium-7 as the liquid-metal coolant. Fuel swelling limits the coolant outlet temperature to 1477 K. The fuel pins are arranged in a triangular array with spiral fins providing positive spacing. The core is surrounded by a sliding beryllium oxide reflector for control.

The relation between reactor thermal power and dry weight for a 5-year life is shown in figure 4. The ZrH reactor designs are based on fuel elements which are 40.6 to 45.7 centimeters long with the lattice pitch varying between 1.7 and 2.6 centimeters. The linear heat flux does not exceed 3.28 kilowatts per meter. With these restrictions the maximum thermal power is about 500 kilowatts. For the high-temperature reactor a standard fuel pin 2.38 centimeters in diameter (2.43 cm pitch) and 40.6 centimeters long was used. A minimum core size of 55 fuel pins was used for reactor powers to 375 kilowatts. For powers between 375 and 750 kilowatts the core size increased to maintain a limiting heat flux of 30 watts per square centimeter. For powers greater than 750 kilowatts a new reactor design should be determined.

Pressure drop correlations for both reactor types were based on the method presented in reference 2 and were verified with prototype test data.

Thermoelectric converters. - Electrical power is produced by the direct conversion of heat to electricity in thermoelectric converter modules. A high-temperature and a low-temperature converter were considered for this study. The low-temperature (922 K max) converter utilizes PbTe as the thermoelectric material. Each converter module shown in figure 5 consists of an assembly of PbTe washers fabricated from 2P-doped (sodium) and 2N-doped (iodine) material arranged alternately along a central tube and separated by mica washers which act as insulators. Conductor rings span adjacent washers on both the inside diameter and outside diameter to provide a serpentine electrical path through the module. The conductor rings are electrically isolated from the center refractory tube and the outer stainless-steel cladding by thin sleeves of boron nitride, which also provide good thermal contact between clad and rings. This complete assembly with appropriate end closures containing electrical feedthroughs is compacted by an autoclave process into a rugged, void-free, sealed module. The module is enclosed within a larger tube that provides an annular passage for the cold-side NaK flow. The hot-side NaK flows through the center refractory tube; the resulting temperature difference across the PbTe washers creates the driving force for current flow.

The high-temperature (1273 K max) thermoelectric converter utilizes N- and P-type silicon-germanium (SiGe) alloys. This module is based on the "compression module" design described in reference 3. It is similar to the low-temperature module, where an inner and outer cylinder form the hot and cold surfaces between which the heat flows radially. However, the SiGe thermoelectric material is arranged in radial, pieshaped segments with insulators and conductors positioned to form an electrical series connection but in a serpentine, circular path.

A standard-load power module producing about 325 watts at 4 volts dc was used to characterize each thermoelectric converter. The description includes dry weight, liquid weight, and size for the modules and associated piping. The total heat load per module was determined from experimental and analytical data as a function of the temperature difference between hot and cold clad junctions. However, the conversion efficiency was determined as a function of the average hot and average cold clad temperatures. The efficiency curves are shown in figure 6. With this information the total number of standard-load power modules can be determined for a given system defined by power and voltage.

A standard-pump power module was also specified for each converter. This differed from the load module because of the high-current, low-voltage requirements for the liquid-metal electromagnetic pumps.

Pressure drop correlations for the complex flow passages within the modules were determined from experimental data and analysis (ref. 4).

Electromagnetic pumps. - The pumps used for both hot and cold liquid-metal loops are dual-throat dc-conduction electromagnetic (EM) pumps powered by separate thermoelectric converters that are designed to supply high-current, low-voltage power. The principal advantage of EM pumps is high reliability, which is inherent because they have no moving parts. The pump design is based on steady-state operation at end-of-life conditions. During startup and shutdown, auxiliary power is supplied to maintain loop circulation.

Radiator. - The waste heat from the converters is rejected to space by radiation. The radiator considered here has a conical-cylindrical shape with only one side radiating. The liquid metal (NaK) is contained in stainless-steel tubes and headers, while the armor and fins of the radiating surface are fabricated from either aluminum or copper, depending on whether the maximum fluid temperature is less than or greater than 672 K, respectively. Radiator size and weight are determined by a method similar to that used by J. P. Couch of Lewis for the assumptions that the radiator is in a 720-kilometer equatorial orbit with its axis perpendicular to the orbital plane and that the no-puncture probability is 0.99 for 50 000 hours.

Piping. - Connecting the major components in each loop are two sections of pipe, each operating at different liquid-metal temperatures. A pipe section consists of straight-run tubing, welded fittings (elbows, bends, and tees), and insulation. Pipe material is either 316 stainless steel (used for NaK at temperatures less than 922 K) or Cb-1Zr (used for lithium at temperatures less than 1273 K) as limited by the SiGe thermoelectrics. The piping subroutine will size the pipe according to the friction pressure drop specified by the cycle analysis and the length of pipe section assumed for the particular powerplant. Knowing the pipe size permits calculation of pipe weight, insulation weight, and fluid weight.

When lithium is used in the high-temperature loop, a weight penalty must be applied to melt the lithium and then heat it and the piping to a reasonable pumping temperature for startup. The heat required for this is calculated, and the weight of a battery to supply electrical heating is added to the insulation weight for this pipe section.

Expansion compensator. - An expandable reservoir is required in each loop to accommodate the thermal expansion of the liquid metal in going from room temperature to operating temperature and also to maintain the system at a positive pressure sufficient to prevent pump cavitation or local boiling in the reactor. Each compensator consists of a tandem bellows enclosed in a housing with a positive stop to prevent bellows compression beyond a stacked height. The first bellows provides volume for the expanding fluid. The volume between the bellows is filled with static fluid for redundancy. An inert gas surrounds the second bellows to serve as the pressure source.

The SNAP programs have provided sufficient information about expansion compensator design to determine an empirical relation between the required expansion volume and component weight and size.

Shield. - For unmanned applications a shadow shield is sufficient to attenuate the gamma and neutron radiation to acceptable levels. The attenuation covers a shadow area corresponding to the space vehicle diameter at some specified distance from the reactor where the payload is located. The shield is multilayered: tungsten and uranium are used for gamma attenuation, and lithium hydride cast in a stainless-steel container is used for neutron attenuation. Shield weight was determined for each reactor type as a function of the reactor power and for a constant cone half-angle of 8°. These correlations are shown in figure 7. The increase in weight with power for the ZrH reactor is continuous because the reactor size is constantly increasing, which requires that both the shield thickness and diameter increase accordingly. For the high-temperature UN reactor, the reactor size is constant below 375 kilowatts and then increases with power. The first section of the shield curve therefore reflects only a change in shield thickness, while the second section includes both diameter and thickness changes. The slopes of these two sections indicate the strong influence of reactor size on shield weight.

Power conditioner. - The power conditioner converts the low-voltage power from the thermoelectric modules to a voltage acceptable for the payload. For this study the 4000-volt power conditioner of reference 5 was assumed to be applicable. Reference 5 reports conditioner specific weight and conversion efficiency as a function of input power and voltage. The component weight was modified to include the additional radiator weight required to dissipate the heat generated in the power conditioner.

Physical properties. - A separate subroutine is provided to store the physical properties of the various materials used throughout the program. This makes it possible to interchange materials quite easily and thereby investigate their effect on the system.

RESULTS AND DISCUSSION

A computer simulation program similar to this one has been initiated for various nuclear reactors coupled to thermoelectric, thermionic, and Brayton electrical power generation systems. The goal of this work was the development of a management tool that would select the optimum space power system for specific power requirements and figures-of-merit. The results presented herein represent an initial effort to identify the optimum reactor-thermoelectric space power system for requirements ranging between 5 and 40 kilowatts of electrical power conditioned to 4000 volts. The figure-of-merit used to define optimum is total system weight.

Figure 8 shows the optimum system weights for the low-temperature ZrH/PbTe and the high-temperature UN/SiGe systems as a function of net electrical power. The optimization parameters (i.e., the operating variables that were perturbed) for this study were the cold-side temperatures into and out of the radiator and the pressure drop in each of the four piping sections. The reactor inlet and outlet temperatures were fixed to adhere to component design criteria. For the ZrH reactor the 866 K inlet and 922 K outlet temperatures were determined by the maximum allowable fuel temperature of the ZrH-uranium alloy. For the UN reactor a maximum allowable temperature of the SiGe thermoelectric material set the reactor outlet temperature at 1273 K. The UN reactor inlet temperature was set at 1216 K to correspond to a reasonable temperature drop across the reactor core. Both curves represent the optimum weights for each system. The fact that both systems weigh the same at the minimum power point is coincidental.

The comparisons shown in figures 9 to 11 point out the distinct advantage of the high-temperature system throughout the power range investigated. The principal reason for this advantage is the smaller radiator area required to reject the waste heat. The radiator for the high-temperature system operates at average temperatures between 589 and 616 K, compared to 491 to 505 K for the low-temperature system. This selection of optimum radiating temperature for each system is a trade-off between radiator weight and conversion efficiency. As radiator temperature increases the radiator becomes smaller and lighter but the conversion efficiency decreases, causing the whole system to become larger and heavier. This trade-off results in the high-temperature system operating at an optimum conversion efficiency of 5 percent, while the low-temperature-system efficiency is 6 percent. It is interesting to note that both of these optimum efficiencies are well below the maximum efficiencies obtainable for the PbTe and SiGe thermoelectric materials, as shown in figure 6.

Figure 10 shows that the specific weight for both systems reaches a minimum at some power level and then increases with power. This happens because the radiator area is increasing and to maintain the same meteoroid puncture protection for the exposed area, the armor thickness must increase.

The comparisons show that the ZrH/PbTe system is not operable beyond 26 kilowatts electric. This represents a reactor thermal power of 500 kilowatts, which is the limit for the reactor design subroutine used in the program. It also represents a practical limit in terms of available volume in the cargo bay of the proposed space shuttle.

Figure 11 shows the contribution of component type to the total system specific weight. The major contributor for both power systems is the heat-rejection fraction, which includes radiator, cold-loop piping, pump, liquid metal, and expander. This fraction increases continuously with net electrical power. The power generation fraction, which includes the reactor, thermoelectric converters, hot-loop piping, pump, liquid metal, expander, and insulation, remains fairly constant with increasing power. The shield represents a small fraction of the system, and its contribution decreases with increasing electrical power.

The computer code can also be used to determine the sensitivity of the different variables to changes. Sensitivity analysis is a technique used to evaluate system performance by varying one or more of the input parameters, with the remainder held constant, and determining the change that results. This technique provides insight into what would happen if some key variables deviated from their expected values, and it identifies those variables that most strongly affect system performance. An example would be the effect of thermoelectric converter efficiency on system specific weight, as shown in figure 12. This emphasized the importance of knowing the degradation rate of the thermoelectric so that the system can be designed for the proper end-of-life conditions.

SUMMARY OF RESULTS

A computer simulation and optimization code has been developed for nuclear space power systems. The code consists of a cycle analysis for the closed-loop system, a series of subroutines that describe each component, and an optimization technique that manipulates the operating variables to arrive at an optimum system as defined by some figure-of-merit.

The code was used to analyze two reactor-thermoelectric space power systems for net electrical power requirements between 5 and 40 kilowatts. The figure-of-merit used to define optimum was minimum system weight. A low-temperature system using a zirconium hydride reactor coupled to lead telluride thermoelectric converters and a high-temperature system using a uranium nitride reactor coupled to silicon-germanium thermoelectric converters were investigated. The results show that the high-temperature system was smaller and lighter for the power range investigated, even though the converter efficiency was about 1 percentage point lower. The radiating temperature at which the waste heat was rejected to space was the dominant factor.

The code also enables the user to perform system analyses to determine the effects of various real or proposed changes, and it serves as an accessible storage bank for all pertinent information about a system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 18, 1973,
503-25.

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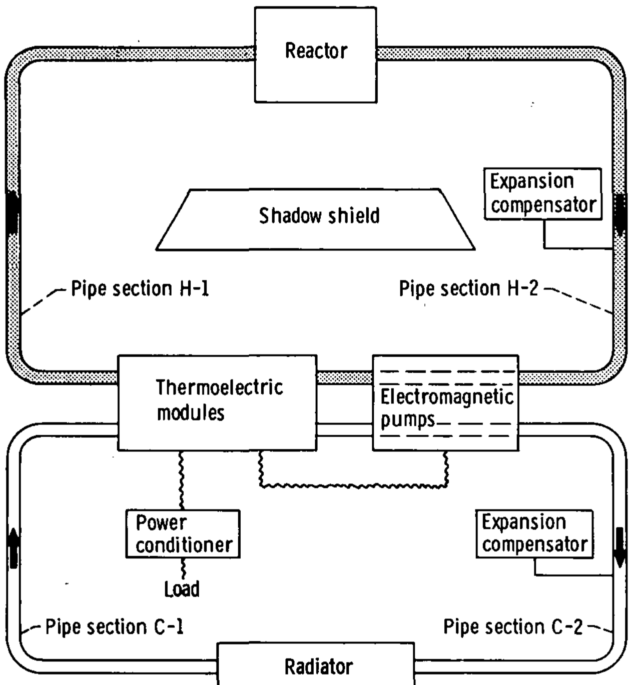


Figure 1. - Reactor-thermoelectric powerplant.

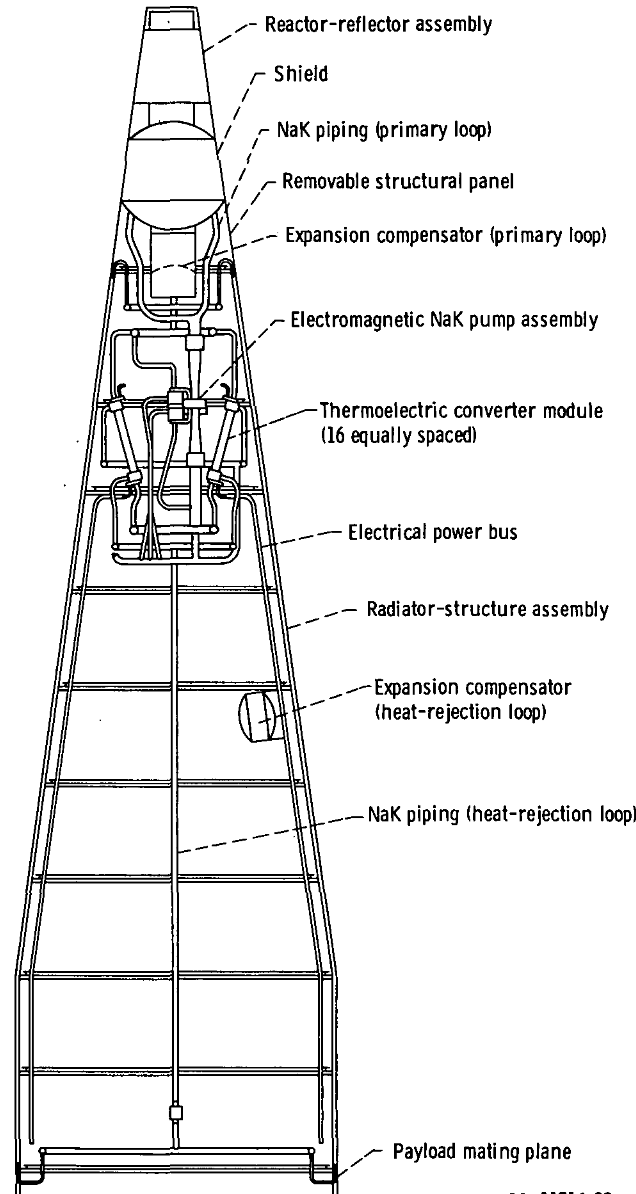


Figure 2. - 5-Kilowatt-electric reactor-thermoelectric power system.

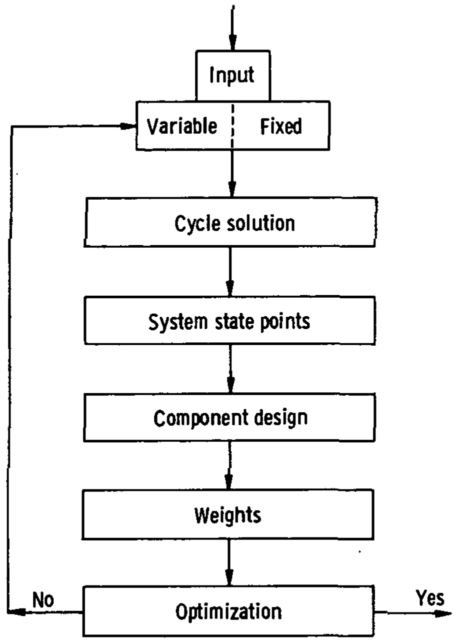


Figure 3. - Program flow chart.

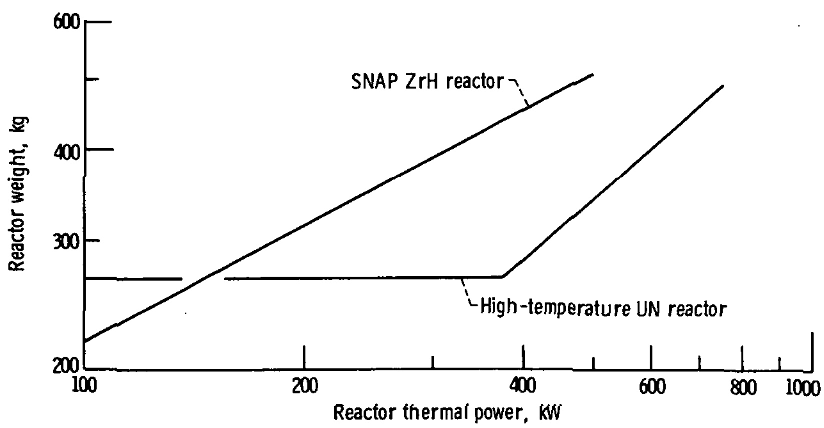


Figure 4. - Relation of reactor weight to power.

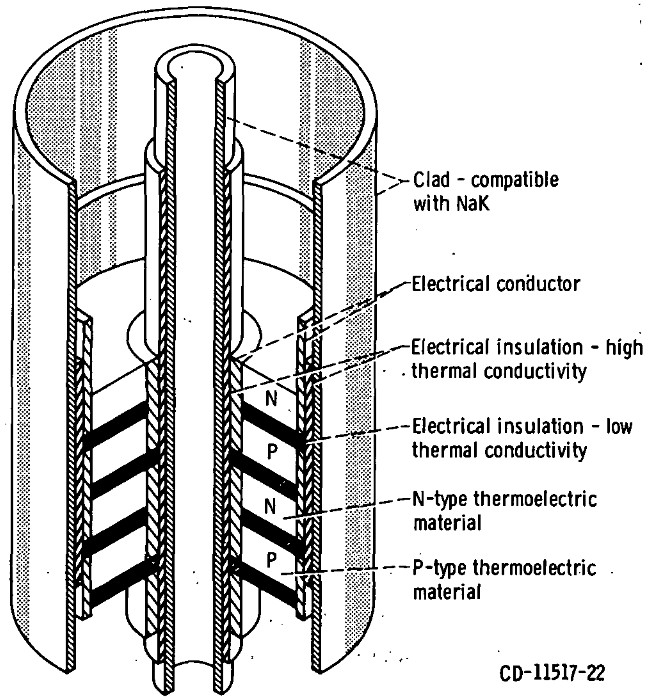


Figure 5. - Compact, tubular lead telluride thermoelectric module.

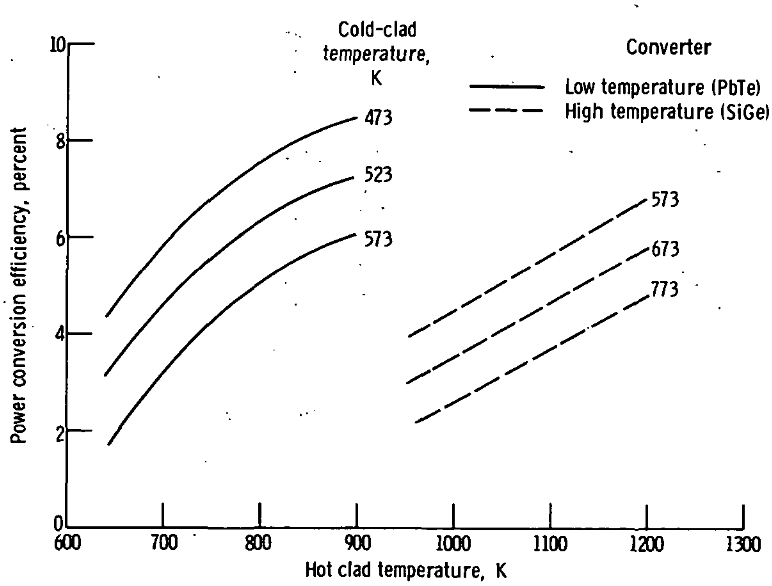


Figure 6. - Thermoelectric efficiency.

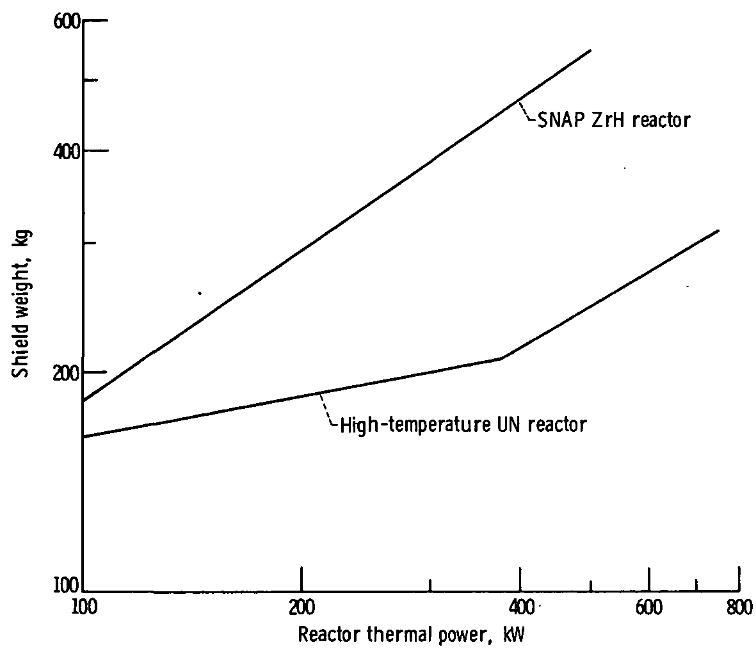


Figure 7. - Relation of shield weight to reactor power.

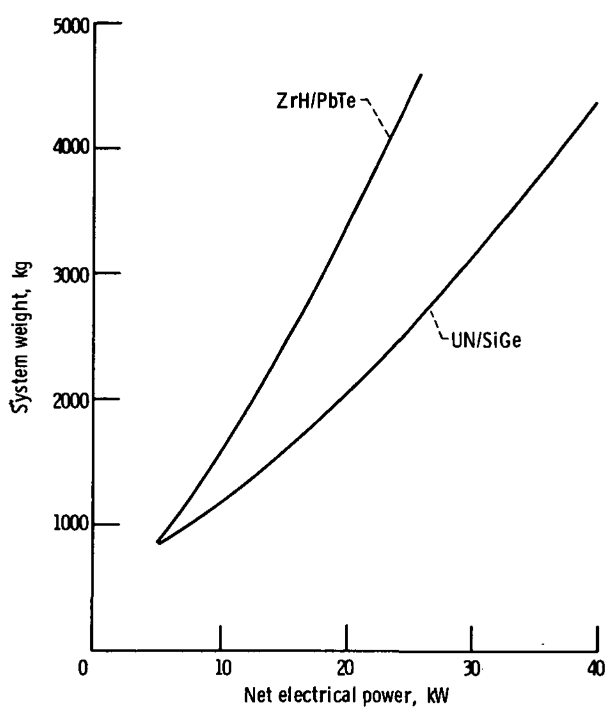


Figure 8. - System weight comparison.

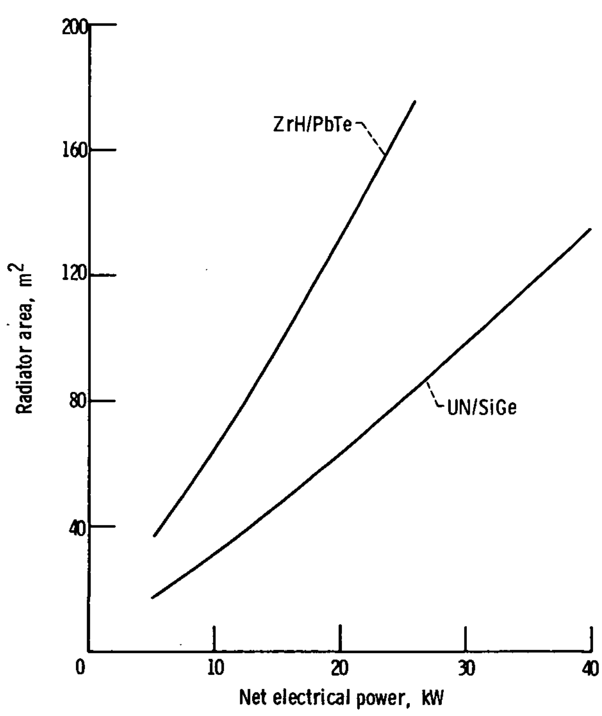


Figure 9. - Radiator area comparison.

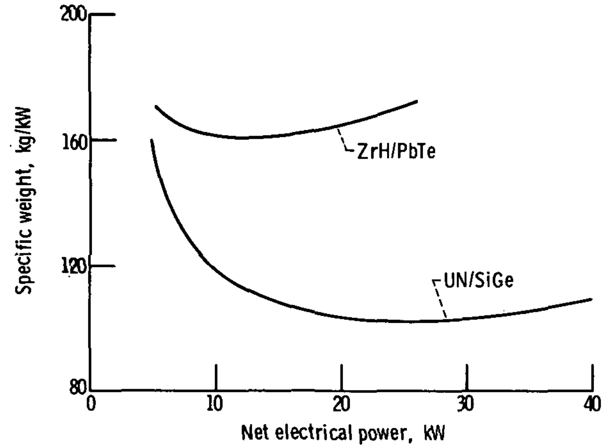
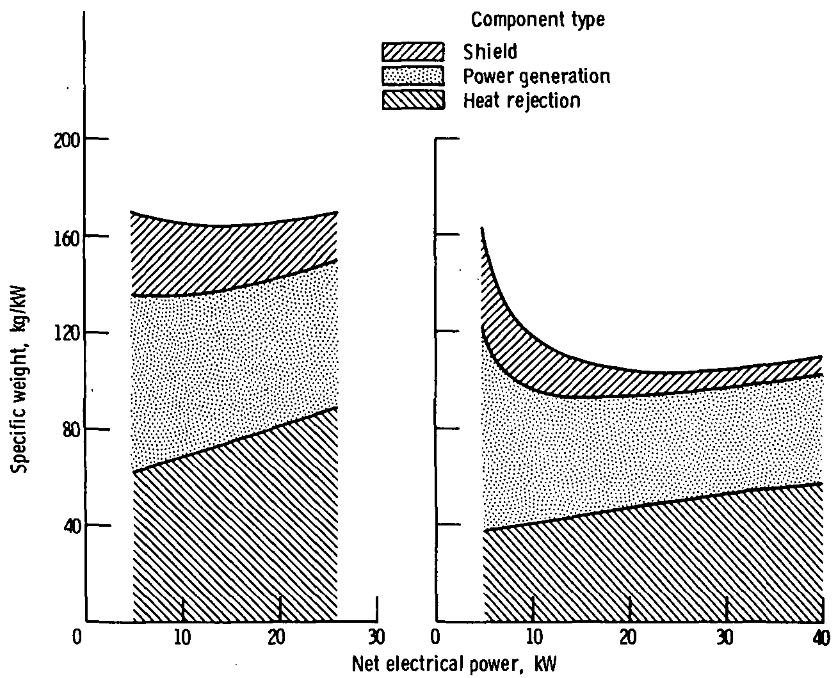


Figure 10. - System specific-weight comparison.



(a) ZrH/PbTe system.

(b) UN/SiGe system.

Figure 11. - Component specific-weight comparison.

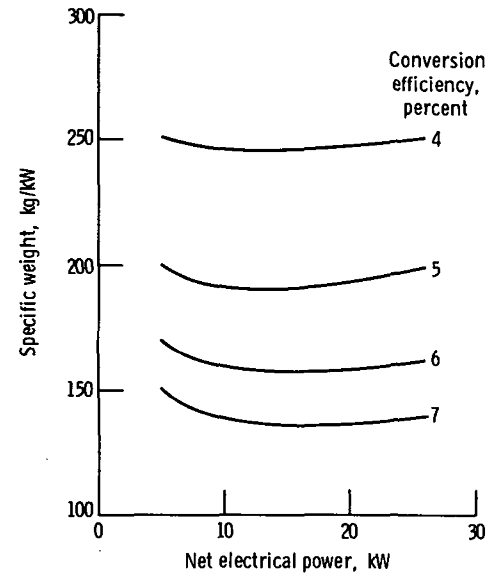


Figure 12. - Effect of thermoelectric efficiency for ZrH/PbTe system.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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