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STUDY OF A 300-KILOWATT RANKINE-CYCLE ADVANCED NUCLEAR-ELECTRIC SPACE-POWER SYSTEM

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16. Abstract

A system analysis is presented for a nominal 300-kW-electric potassium system employing a lithium-cooled fast reactor and with 2100° F (1420 K) turbine inlet temperature. Trends in performance and weight are discussed for variations in design parameters. Performance and design of major components are reviewed, including material considerations. A typical conceptual system layout is shown.

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SUMMARY

A study was made of a nominal 300-kilowatt-electric (kWe) advanced Rankine-cycle space-power system. Thermal energy is supplied to the system by a 2-megawatt-thermal lithium-cooled fast-spectrum nuclear reactor. The potassium working fluid enters the turbine as a superheated vapor at 2100° F (1420 K) and exits at 1220° F (930 K). A multistage axial-flow turbine with interspool and interstage condensate removal devices is used to directly drive a 10-pole homopolar electrical generator. Regenerative boiler-feed heating is employed to improve cycle efficiency. Waste heat from the cycle is rejected to space by segmented radiators using pumped liquid sodium-potassium (NaK). Two liquid-potassium loops are used for auxiliary cooling and bearing lubrication. Electromagnetic pumps are employed in all of the liquid-metal loops. The temperature-sensitive electronic equipment required for engine power conditioning and controls is cooled with a pumped organic fluid.

Tradeoff studies of system parameters including reactor temperature rise, ΔT, and cycle condensing temperature are discussed. Major emphasis in selecting components and system design was placed on achieving high overall system reliability and still maintaining a system with reasonable specific weights.

System output is estimated to be 375 kilowatts, and net system efficiency is calculated to be 19 percent. System weights for an unmanned, shadow-shielded application were calculated to be approximately 22 000 pounds (10 000 kg), giving a system specific weight of approximately 59 pounds per kWe (27 kg). The major system components are described and the status of component and refractory-metal technology programs is presented.

INTRODUCTION

As part of the NASA Lewis Research Center's responsibility for the advancement of space-power technology, a research and technology program is being conducted with industry participation on liquid-metal Rankine systems. The specific system discussed in this report is based on the use of a 2-megawatt-thermal fast nuclear reactor to produce a nominal 300 kWe. A simplified schematic of the three basic liquid-metal loops of the system is shown in figure 1. The primary loop employs lithium to transfer heat from the reactor to the boiler. The power conversion loop employs potassium vapor from the boiler to produce electrical power in the turobalternator. Waste heat is rejected in the radiators by circulating liquid NaK in the third loop.

The performance of this system is discussed for several operating conditions, and the current status of major component technology and refractory alloy material programs is outlined. The advanced 2100° F (1420 K) system represents the current reference engine that has been evolved during the course of the continuing alkali-metal Rankine-cycle technology program. This system is not under development but assists in establishing specifications and goals for the NASA's component and subsystem research efforts. The reference system is subject to continuous modification and upgrading as additional analyses and data become available. It is anticipated that the component performance levels attained and the problem areas solved at this reference system power level would apply to a wide range of power output and other missions.

The selection of a lithium-cooled fast reactor and a 2100° F (1420 K) turbine inlet temperature was predicated on the viable and continuing refractory-metal alloy technology program. System design parameters that were varied for this performance study included turbine exhaust pressure, modes of moisture extraction, and reactor coolant temperature rise. Mission-dependent variables such as radiator survival probability and mission duration were varied to determine their effects on reference system size and weight.

The performance values of the turbine and alternator components that were used in the system analysis were based on the NASA-sponsored performance investigations of two- and three-stage potassium turbines and preliminary design studies of flight prototype turboalternators. A conceptual scale layout of the reference engine was prepared for an unmanned application. Component weights were computed and trends in the reference system's specific weight were determined for the range of design variables investigated.

It is also recognized that limited-scope system studies of this type usually overestimate performance and underestimate total weights so that the computed efficiency and the estimated specific weight are probably optimistic. For this reason the system described herein, which has a 375-kWe estimated output, is referred to as a "nominal 300-kWe system."

This report is based on systems components work conducted at the Lewis Research Center. The technical contributors to the work were M. U. Gutstein boilers and condensers; J. P. Couch, electromagnetic pumps and radiators: J. P. Joyce and E. E. Kempke, Jr., turboalternators: G. M. Kaplan, shielding: and R. L. Davies, materials.

ENGINE DESIGN PARAMETERS

To provide a meaningful base upon which to conduct studies of the three-loop liquid-metal systems, powerplants in the form of conceptual scale layouts were prepared and refined during the course of the studies. The system and its major components as configured for an unmanned spacecraft are shown in figure 2. The installation and location of the components follow conventional practice of placing the reactor at the cone apex with a shadow shield at its base. For the system to be applicable to manned installations, the primary loop components must also be shielded from the personnel-occupied areas. A method of accomplishing this protection is to place the primary loop boiler and pump in a gallery between a primary and secondary shield. Where shadow shielding only is required, the size and weight of the secondary shield are very sensitive to the volume in the gallery that is necessary to contain the boiler and pump. Therefore, to widen the number of system applications, the boiler and pump have been designed for minimum gallery size.

The operation of the system is briefly traced through its major components and a more detailed discussion is presented in the next section.

Liquid lithium in the primary loop is circulated through the reactor by an electromagnetic pump. Lithium at 2200° F (1475 K) boils potassium in a tube-and-shell boiler and supplies 2100° F (1420 K) superheated potassium vapor to the multistage turbine. The turbine drives an alternator in which 1600-hertz electric power is generated. The spent turbine exhaust vapor is condensed and subcooled in four parallel tube-and-shell condensers. The liquid is pumped back to the boiler inlet by an electromagnetic boiler feed pump. Each condenser has a separate NaK loop and radiator to reject the waste heat to space.

Lithium was selected as the reactor coolant because its excellent thermal properties result in low pumping power and for its good compatibility with the refractory-metal loop materials. Electromagnetic pumps have been selected for use throughout the engine (except for an organic coolant loop) for their high reliability potential. Further, the pumps may be used redundantly in series with low pressure drop penalty in the inactive pumps. Only fixed cylindrical-conical shaped radiators were considered in this study for simplicity.

However, reduction of the size and weight of the non-man-rated conical shield can be made with other radiator shapes. One radiator that has been proposed has the shape of a flat plate. Prior to operation, stowed radiator panels would be extended to the required planar area. The shape of the shadow shield would be correspondingly reduced to match the relatively thin radiator panels.

RANKINE-CYCLE POWER SYSTEM

Studies of the system tradeoffs for the nominal 300-kWe advanced Rankine system have been in progress at Lewis over the past several years. While high system efficiency and low specific weight have been important considerations, major emphasis has been placed on reliability. The tradeoff studies made, therefore, have been strongly mindful of component limitations and sound engineering approaches.

The present nominal 300-kWe system schematic is shown in figure 3. Potassium liquid is used to cool and lubricate the turbine and alternator bearings, the alternator rotor and stator, and the electromagnetic (EM) pump stators. An organic fluid cools the electronic equipment. The turbine bearings are lubricated and cooled separately from the alternator and the pump stators for the following reasons: First, it increases the isolation of the refractory metals used in the turbine from the nonrefractory metals used elsewhere in alternator and pump stator coolant passages, thus reducing the potential for mass transfer. It also permits an independent choice of temperature level for the turbine bearing lubricant and coolant and for the rest of the cooling functions. In particular, the turbine coolant flow can be operated at a higher temperature level (>900° F (>755 K)), reducing radiator area and weight and, more importantly, reducing the temperature gradients in the turbine bearing compartments, especially at the hot end of the turbine.

A temperature level of 700° F (645 K) instead of 900° F (755 K) is used for cooling the alternator rotor because of strength limits imposed by H-11 rotor magnetic material at the higher temperature. The 700° F (645 K) temperature level used for the alternator stator coolant temperature reduces heat transferred to the alternator rotor and thereby further improves its mechanical integrity. The lower coolant temperature used in the EM pump stators improves their reliability and ease of development. The lower radiator temperature level results in a larger radiator area than would normally be required if a higher temperature level were maintained in the loop. However, the assumption of a two-stage Saturn V configuration permits the use of the larger area. The additional weight accompanying the use of the reduced temperature level coolant is offset to some degree by permitting the use of stainless-steel-clad aluminum fins.

In the nominal 300-kWe system, responsibility has been assumed for power conditioning the power required for internal system use, including the EM pump power. The boiler feed and primary EM pump designs optimize at approximately 60 and 25 hertz, respectively, as compared with the 1600 hertz generated by the alternator. It was found to be beneficial to the system to select pump designs at optimum frequencies and then convert power for the pumps from the high-frequency alternator output. It has been assumed that solid-state devices are used for the bulk of the power conditioning because of their high efficiency (~90 percent) and reliability. Hence, the temperature level for this loop is in the 140° to 150° F (333 to 339 K) maximum range, and an organic coolant is used.

Another feature of the system is that, as the instantaneous mission load varies, the excess power generated by the system is passively rejected to space through the use of a high-temperature parasitic load resistor (PLR). Long-term variation in power requirements will be handled by modulating the reactor power.

Additional features of the power conversion loop not previously described include the moisture separators and the regenerative boiler feed heater. If no moisture removal devices were used, the turbine exit quality would approach 80 percent. With this low quality, the erosion damage problem in the turbine latter stages would probably be untenable. Therefore, two moisture separators are incorporated in the turbine, an interspool moisture separator at the exit of the fifth turbine stage and an interstage separator at the exit of the ninth stage. In the interspool separator, the entire turbine flow passes through the separator, condensate being removed from the flow and also with it some of the vapor. At the ninth-stage interstage separator, condensate is centrifuged off the shrouds of the ninth-stage rotor blades to a slot in the turbine casing, where it is removed. There is some vapor loss associated with the condensate removal here also. By using these moisture removal devices, the moisture levels at critical areas in the turbine are reduced and, hence, the potential for erosion damage is lessened to a safe degree. The analyses presently available indicate that no erosion problems should be expected. Experimental studies further investigating the erosion phenomenon include condensate removal performance and endurance testing in a three-stage potassium turbine at General Electric. A study of the flow in a multistage steam turbine is planned.

Once the need for moisture removal devices was established, tradeoff studies indicated the advantage of using the liquid and vapor removed from the turbine to preheat the boiler feed flow, following steam turbine practice. The boiler feed flow temperature is increased by over 200° F (367 K) thus reducing the size of the boiler and improving system efficiency. These gains more than offset the weight of the additional component, the boiler feed heater.

Table I shows the power output at various stages of generation for the present nominal 300-kWe Rankine system. The 2 megawatts of net reactor thermal input is converted to 375 kWe of net electrical power at 1600 hertz as supplied to the user, using turbine and alternator efficiencies of 81.3 and 94.5 percent, respectively. This yields a net system efficiency of nearly 19 percent. About 12.4 percent (53 kWe) of the gross alternator output of 428 kWe is used for internal engine power requirements.

A digital computer program was used to assist in making parametric analyses of the system variables. The program calculates fluid properties; performs heat balances for all the loops; and allows variation of the loop pressure levels, temperature levels and differences, component efficiencies, modes of moisture removal and regenerative feed heating, and various auxiliary cooling loop configurations. Investigations of the effects on system performance of the numerous system variables were made. The values chosen for the nominal 300-kWe Rankine system, as reflected in the system schematic, were selected on the basis of these studies tempered with a knowledge of the component problems and limitations, and with an objective of developing a reliable as well as efficient and low specific weight system. Two examples which illustrate the philosophy used are discussed in the following paragraphs:

The first example is the selection of the reactor ΔT. Early in the studies, an analytical investigation was made which indicated that the system output power varied less than 3 percent as the reactor temperature rise was varied over the range from 50° to 150° F (283 to 339 K), with an optimum power output occurring with the reactor ΔT in the range 75° to 100° F (297 to 311 K). Reactor studies being conducted at the time indicated that a value of 100° F (311 K) allowed a reasonably small core with low pressure drop, and also kept reactor thermal stresses to low values. The reactor temperature rise was therefore fixed at a value of 100° F (311 K) and maintained throughout the rest of the study. As the nominal system was evolved and other state points in the system were changed, subsequent checks showed that 100° F (311 K) is still a near optimum value.

Second, one of the most significant variable selections is the choice of the turbine exhaust pressure. As the exhaust pressure (and, hence, condensing pressure and temperature) is reduced, the system efficiency increases but at the expense of a larger and heavier radiator, assuming we are reducing the temperature such that the cycle temperature ratio is below 0.75. The resultant effect on system specific weight is shown in figure 4, in which the relative specific weight is shown as a function of condensing temperature. Corresponding values of condensing pressure are given. The specific weights have been normalized with a value of 1 assumed for the reference nominal 300-kWe Rankine system shielded for an unmanned application. The three curves assume different fixed values for the reactor and shield weight and other system weights which are not a strong function of condensing temperature. In other words, the figure shows the effect of radiator weight on system specific weight as condensing temperature is varied. The main radiator configuration assumed was a conical structure with stainless-steel tubes and stainless-steel-clad copper fins armored so that there is a 0.99 probability that three of the four radiator units will survive a mission lifetime of 3 years.

Several things can be noted from figure 4. First, for all the curves, the specific weight is still decreasing even down to a condensing temperature as low as 1100° F (865 K) (a cycle temperature ratio of 1560/2490 = 0.627). Thus, the fixed weights of the system predominate over the radiator weight, and increasing the system efficiency reduces the overall system specific weight faster than the radiator component specific weight increases, over the condensing temperature range covered. Secondly, as the fixed weights of the system are increased as would be the case for man-rated shadow shield or sculptured 4π man-rated shield, the advantages of operating at as low a condensing temperature as practicable are even greater. Of course, if the radiator criteria are made more stringent, such as requiring 0.999 probability that three of the four units survive and the mission time is increased, the advantages of lower condensing temperature would be diminished, and at some point the radiator weight would eventually dominate.

Figure 4 also shows that if the condensing temperature were selected on the basis of the analytical study alone, a condensing temperature less than the 1220° F (930 K) level selected for the nominal system would have been chosen. There were several reasons for not choosing a condensing temperature below 1220° F (930 K). Among these are the following: Without excessive subcooling, as the condensing temperature is reduced the net positive suction head (NPSH) available for the EM pump is reduced. It was felt that, with the present knowledge about the boiler feed EM pump and the pressure losses in the condenser and piping to the EM pump, 1220° F (930 K) was the limit of condensing temperature which could safely provide margin for the NPSH requirements of the EM pump and, hence, prevent pump cavitation problems. Also, as the turbine temperature ratio (and, hence, pressure ratio) is increased, more turbine stages are required to maintain an efficient turbine design. Associated with a high number of turbine stages are rotor dynamics problems in the turbomachinery and reduced reliability of design. Finally, as the condensing temperature is reduced, the turbine operates deeper in the moisture region of the Mollier diagram. It was felt that at the 1220° F (930 K) condensing temperature level erosion-free operation of the turbine could be maintained, assuming that the moisture removal devices perform as predicted by analysis.

However, in the event that planned experimental work on moisture removal techniques should show that this is not the case, a brief investigation of a reheat cycle was made. Several schemes were investigated; a schematic of the method tentatively selected is shown in figure 5. The schematic diagram is essentially the same as that of the reference nominal 300-kWe system with the exception that the potassium vapor from the boiler exit is split, part going to the first spool of the turbine and part going to the reheater. After expanding through the first turbine spool, the flow is reheated and then goes through the second turbine spool. The potassium flow used for reheating is then used for regenerative boiler feed heating and is mixed with the main flow at the condenser exit. About 13 percent of the boiler exit flow is used for reheating. The split spool turbine concept used in the nominal 300-kWe system lends itself readily to the reheat system. The boiler now under development for the 300-kWe system could be used in the reheat system. Figure 6 shows the wetness levels of the reference turbine designed for the nominal 300-kWe system and a reheat turbine designed to give equal equilibrium moisture levels at the exit of the first turbine spool and at the turbine exit. A maximum reheat temperature of approximately 2000° F (1365 K) is anticipated as a reasonable temperature limit for the turbine design. Figure 6 shows that the maximum wetness level of the reheat turbine is approximately 8 percent, while for the nonreheat design operation higher wetness levels exist in portions of the turbine. Using results of some preliminary turbine efficiency calculations for the reheat turbine supplied by AiResearch Manufacturing Company, it was found that the reheat system efficiency was not significantly lower than the nominal 300-kWe system efficiency. Therefore, reheat may be resorted to without serious performance penalties to provide low turbine moisture levels if other methods prove ineffectual.

REFRACTORY MATERIALS

Component performance levels and system temperature levels were based on the current government sponsored refractory-metal alloy technology programs. It is only with such an adequate and thorough materials program that serious consideration can be given to the development of usable liquid-metal space-power systems. The high temperatures and long operating life that are required to provide competitive and reliable power systems require a thorough evaluation of the materials. Briefly discussed here are several of the major refractory-metal technology programs to provide information on corrosion resistance, long-time creep, compatibility, and fabrication techniques. The metallurgical details of these and related programs can be obtained from quarterly and final reports on the programs cited.

Corrosion Resistance

The selection of containment materials for the advanced Rankine system is based to a great extent upon their inertness to lithium and potassium at operating temperatures exceeding 2000° F (1365 K). The corrosion resistance of tantalum, molybdenum, columbium, and tungsten is excellent, based strictly on the very low solubility of the pure elements in these alkali metals. However, corrosive attack is drastically accelerated when oxygen is present, requiring the addition of zirconium or hafnium as a getter to form stable and insoluble oxides. A sample of tantalum alloy T-111 (Ta-8W-2Hf), selected for use as the prime high-temperature containment material for the system, has been exposed to potassium at 2400° F (1590 K) for 2000 hours with negligible corrosion. By way of comparison, an ungettered tantalum alloy. Ta-10W, suffered catastrophic attack at 1800° F (1255 K) after only 128 hours. The tantalum oxides, in the latter case, were preferentially attacked and removed by the potassium, leaving voids in the parent alloy (ref. 1).

The gettering element can, however, become saturated with oxygen. It has been established that oxygen pickup during all phases of processing must be closely controlled, including limiting of oxygen content in the alkali metals and welding atmospheres to less than 10 ppm. In general, refractory alloys containing hafnium or zirconium display negligible corrosion in contact with the alkali metals for times up to 10 000 hours and at temperatures of up to 2200° F (1475 K) when established procedures of limiting oxygen content are followed. Sufficient confidence in the acceptable corrosion-resistance characteristics has been obtained in refluxing capsule tests to permit selection of candidate containment materials.

A test loop fabricated from the columbium alloy Cb-1Zr showed negligible attack after 5000 hours of exposure to flowing potassium that boiled at 1850° F (1280 K), superheated to 2000° F (1365 K), and condensed at 1425° F (1045 K). Currently, under NASA contract (NAS3-6474), a 10 000-hour corrosion test to simulate system operation conditions is underway. The pumped two-loop test facility is fabricated primarily of T-111 and employs lithium at 2250° F (1505 K) as the heat source for the two-phase potassium loop. The potassium test conditions are generally similar to the reference system cycle state points. At this writing, 3000 hours of satisfactory test operation have been accumulated.

Long-Time Creep

Assurance of adequate creep strength at elevated temperatures and life requirements in excess of 3 years is a prime requisite for reasonable component sizes and weights. Good creep strength is particularly required in the multistage turbine, where high efficiency requires close wheel-tip clearances and relatively thin rotor hubs to reduce rotor dynamics problems. The 1 percent creep strength of the selected containment material T-111, along with that of other refractory materials under investigation, is shown in figure 7 (ref. 2).

Stress values shown for the T-111 alloy in figure 7 are the minimum values of the data obtained in a wide range of tests. On the basis of the superior creep properties exhibited by one sample of ASTAR 811C sheet after 20 000 hours exposure at 2600° F (1700 K), additional samples of ASTAR 811C of various heats have been committed to the creep program (NAS3-9439).

Where welding is not a requirement, such as in the turbine rotor disks, a higher strength, creep resistant refractory-metal alloy TZM (Mo-0.6Ti-0.1Zr-0.035C) is employed. Also shown in figure 7 is a summary of creep data on representative TZM samples plotted as stress against temperature for 1 percent creep. A similar curve for Cb-1Zr is included for comparison.

NUCLEAR REACTOR

In order to heat the flowing lithium from 2100° to 2200° F (1420 to 1475 K), a fast-spectrum nuclear reactor was selected as the 2-megawatt-thermal power source. A drawing of one type of high-temperature lithium-cooled nuclear reactor is shown in figure 8. The core consists of a large number of fuel elements containing uranium-235 nitride fuel. The fuel is wrapped in tungsten barrier foil and then encased in a T-111 tube. The elements are not vented, and therefore the cladding must withstand fission gas pressure buildup during the lifetime of the core. A discussion of the characteristics of nuclear reactors with and without venting of the gaseous fission products is presented in reference 3.

In this reactor concept, the core is reflected at the top, bottom, and partially around the sides with TZM. Reactor control is achieved by rotating six cylindrical drums that surround the basic core (ref. 4). The drums contain fuel in a 120° sector on one side and a tantalum alloy poison on the opposite 120° sector. The remainder of the drum is a molybdenum alloy. Control of reactor thermal power is affected by rotating the drums to change the net geometry of the core.

The reactor pressure vessel construction is predicted on the use of T-111. The overall dimensions of the pressure vessel would be about 23-inch (58-cm) outside diameter and 32-inch (81-cm) length. The design lifetime for this reactor is 50 000 hours based on a fuel burnup of 3.8 atom percent. Such a reactor is very compact and would permit low shield weight.

SHIELDING

One of the major considerations in a system study of a nuclear-powered space-electric-power system is the shielding requirements imposed on the system. These requirements may range from a simple non-man-rated shadow-shield case to the extreme of requiring uniform man-rated 4π shielding. The shielding weight is determined by the specific application of the power system. The shield design and resulting weight is characterized by specifying acceptable dose rates at some distance from the reactor and then defining the geometry of the area to be protected at the specified distance. In the simplified case of a non-man-rated shadow shield considered here, these dimensions determine a solid cone whose base must be protected by the shield. An example of the effect of shield cone angle on relative shield weight is shown in figure 9. A half-cone angle of

10^{o} was selected for this system study and is shown in the figure as having a relative value of 1.0; the minimum half-cone angle for a number of Saturn V configurations investigated is 8^{o}. Use of the 10^{o} half-cone angle results in a non-man-rated shadow-shield weight of 6000 pounds (2700 kg). When biological shielding requirements are added to the simple non-man-rated shadow-shield system, the resulting shield weights exceed the weight of the power conversion system. Figure 10 shows the variation in these shield weights with gallery length for the reference 10^{o} half-cone angle configuration. Shield weights are shown for two assumptions of gaseous-fission-product release into the primary lithium loop, 1 percent and 0.1 percent. Thus, the minimum 4-foot- (1.22-m-) long gallery required by the boiler and pump of this system results in approximately and 18 000-pound (8000-kg) shadow shield for an assumed 0.1 percent fission-product release. This shield weight exceeds the power conversion system weight by about 2000 pounds (900 kg). This shield weight may be reduced somewhat by adding an intermediate lithium loop between the primary reactor coolant and power conversion loops. This tends to reduce the gallery length (and, hence, weight) by substituting a compact liquid-to-liquid heat exchanger for the boiler in the gallery, but with the penalty of the additional pumping power and system complexity.

When uniform man-rated 4π shielding is required, the shield weight may increase by a factor of as much as 10 over the man-rated shadow-shield case. Results of simplified calculations made on the weights of such a 4π shield system indicated that a weight of 142 000 pounds (64 000 kg) is required to uniformly limit the dose rate to 2 millirem per hour at a distance of 50 feet (15.2 m). The reactor and gallery components employed in the computations were similar in overall size to those of the reference system.

The foregoing shield weights were computed on the basis of the simplified assumption that the shields would be radiatively cooled, and no allowance was made for piping and structural voids. Cooling systems must be provided for man-rated 4π shields, particularly for the lithium hydride component which melts at 1260^{o} F (955 K).

POTASSIUM BOILER

The boiler for the advanced Rankine-cycle system must produce relatively dry, superheated potassium vapor at a temperature of 2100^{o} F (1420 K). The boiler must perform stably during system startup and at system operating conditions. In addition, the boiler must be structurally resilient to withstand system and environmental stresses over the tens of thousands of hours of powerplant life. Because the boiler may be situated within a gallery, compactness is still another major requirement. Preliminary studies have identified a boiler design which might achieve the above stringent requirements. This boiler design prepared by General Electric is shown in figure 11. The boiler would consist of approximately 31 tubes, each 90 inches (230 cm) long, contained within a 6-inch- (15.2-cm-) diameter shell. The diameter of the tubes is in the range of 0.5 to 0.75 inch (1.27 to 1.9 cm) with 0.030 inch (0.076 cm) wall thickness. Potassium flows in a single pass (once through) inside the tubes, and the lithium heating fluid flows in the space between the tubes and the shell in a direction countercurrent to the potassium. The material used in the construction throughout the boiler is the refractory-metal alloy T-111.

As shown in figure 11, the boiler is formed into an arc of a circle to be compatible with the minimum length design of a gallery. This shape likewise permits differential thermal expansion between the tubes and the shell and thus minimizes stresses. Each tube of the boiler contains a swirl-generating insert, such as a helical vane or wire coil. The insert augments the heat-transfer processes in the boiling fluid and renders the boiler's operation insensitive to gravitational effects.

The temperature of the lithium and potassium fluids as a function of length along the boiler is shown in figure 12. In addition, the heat-transfer regions generally encountered in potassium boilers are shown crosshatched in this figure. Figure 13 presents the distribution of heat flux and heat-transfer coefficients expected within the boiler. Again, the various heat-transfer regions of the boiler are identified in this figure. The heat-transfer and fluid flow characteristics of once-through potassium boilers are discussed in detail in references 5 and 6. A procedure for the thermal design of potassium boilers is described in reference 7.

POTASSIUM CONDENSER

The advanced Rankine-cycle system will employ segmented all-liquid radiators. In consequence, the vapor exiting the turbine will be liquefied and subcooled inside convectively cooled condensers. These condensers will consist of tubes contained inside a shell. The potassium vapor will flow within the tubes and the radiator fluid, liquid eutectic NaK, will flow in the shell space countercurrent to the potassium. Previous experimental investigations conducted with potassium condensing inside single tubes have resulted in correlations of condensing heat-transfer coefficients and pressure differences in the temperature range of 1100° to 1400° F (865 to 1030 K) (ref. 8). These correlations make possible the steady-state thermal design of potassium condensers. However, zero-gravity operation, condensate management within the tubes, and flow stability are areas of uncertainty for condenser design. For example, techniques such as tapering the tube to enhance condensate flow to the tube outlet and swirl-generating inserts for minimizing gravitational effects have been suggested and are being investigated. Orifices at the outlet end of the tubes are believed to be required to prevent tube-to-tube instabilities. The pressure drop across these flow control devices constitutes the major pressure loss across the condenser. Improved understanding of this mode of instability might permit a reduction in the orifice pressure drop. Such a reduction would allow the condensation process to take place at a lower saturation pressure, thereby further increasing turbine output.

TURBOALTERNATOR

In concert with in-house studies of this reference system, the NASA has sponsored preliminary design studies of the potassium turboalternator (KTA) (refs. 9 and 10), which is the key component of the power conversion loop. The KTA design employing a straddle-mounted, split turbine spool (ref. 9) was selected for purposes of this system study and is shown in figure 14. The 11-stage KTA design of reference 10 is similar but with the high-pressure turbine overhung.

The KTA assembly in figure 14 consists of a 10-stage axial-flow turbine flexibly coupled to a 10-pole homopolar alternator. The turbine and alternator rotors are each supported on a pair of potassium-lubricated pivoted-pad journal bearings. A double-acting potassium pivoted-pad thrust bearing in each component supports forward and reverse loads.

The KTA rotates at a design speed of 19 200 rpm and produces a net electrical power of 428 kWe at the alternator terminals at the design cycle state points. The KTA is approximately 6 feet (1.83 m) long and 2 feet (0.61 m) in diameter at the alternator, and weighs approximately 1300 pounds (~590 kg).

The turbine aerodynamic design has been optimized to achieve an efficiency of 0.813 within the prescribed design cycle state points. However, in the direct expansion of the two-phase potassium vapor to 5.44-psia (3.75-N/cm^2) exhaust pressure at this efficiency, the moisture level at the turbine exit is an excessive 20 percent. Unless steps are taken to reduce this moisture fraction and the corresponding blade-tip velocities, catastropic blade damage may occur from moisture impact erosion. This source of damage has been anticipated, of course, from similar problems encountered in steam turbines.

Adopting initially the moisture extraction methods employed in steam turbine design, the KTA design includes both an external (or between spool) separator and a moisture removal slot aft of the next to the last rotor of the second spool. These devices have presently been designed to reduce the moisture fraction entering the tenth rotor to 6 percent or less. Further, the tenth-stage rotor blade-tip speed has been limited to 981 feet (300 m) per second. The foregoing criteria to limit blade erosion to a tolerable level are engineering judgements based on the impact erosion work of W. D. Pouchot and T. C. Varljen of Westinghouse and R. Spies of Rocketdyne (refs. 11 and 12, respectively) under NASA contract.

Analytical work to accurately predict quantitative damage to turbine blades by moisture impact is continuing under NASA sponsorship. The erosion problem is being further investigated experimentally for the NASA by General Electric in a three-stage potassium turbine (refs. 13 to 15). The program includes provisions to evaluate the performance of both external (between spool) (fig. 15) and interstage moisture removal devices (fig. 16).

The General Electric interspool moisture separator shown in figure 15 is designed to swirl the entire turbine flow exiting the first spool by the upper set of vanes, thereby centrifuging the liquid to the wall. A slot in the wall scavenges the liquid and some vapor and returns the combined condensate to the boiler feed heater. The lower set of vanes straightens the vortex flow prior to its entry into the second turbine spool. Figure 16 shows two types of interstage moisture removal devices. One type, shown at the exits of stages 2 and 3, consists of a slot in the casing, located just aft of the rotor shroud, which entrains liquid centrifuged from the shrouded rotor blade. The second type, shown on the third-stage stator, consists of slotting the trailing edge of the stator and applying low condenser pressure to extract the moisture. Thus, until data are available from tests at General Electric, the KTA design and its predicted performance are based on the approach that the turbine blading must be kept relatively dry.

The mechanical design of the turbine is characterized by the use of Curvic couplings to join both the rotor disks and the nozzle diaphragms. A central prestressed tie-bolt clamps the rotor disks and interstage seals making up the turbine shaft. The nozzle diaphragms are stacked inside a one-piece cylindrical housing to minimize distortion at the elevated temperatures. All of the blading, the rotor disks, and the tie-bolt are fabricated from TZM. T-111 is used for the high-temperature static parts while Cb-1Zr alloy is employed for the lower-temperature parts. Turbine stages 6 to 9 use shrouded blades, inserted in the rotor disks, to improve overall efficiency and also to act as slingers where moisture removal is required.

The KTA alternator is a potassium-cooled, brushless, homopolar inductor generator designed by Westinghouse. Its design rating is 450 kWe at a power factor of 0.75 lagging, 480/832 volts, three phase, 1600 hertz. The alternator has a calculated electrical efficiency of 0.945, including rotor windage.

The 10-pole alternator rotor is a one-piece H-11 forging to provide adequate strength and magnetic properties. The potassium coolant temperature was selected to be 700° F (645 K) to provide adequate rotor strength and permit the use of a simple central coolant hole in the rotor.

An ultralow pressure of 0.002 psia (0.00275 N/cm^2) is maintained in the alternator cavity to reduce windage losses to a low level, and in turn, enable the rotor pole temperature to be kept below 850° F (725 K). The low pressure is attained by using a viscoseal to establish a potassium liquid-vapor interface inboard of the bearings, and by the use of several stages of molecular screw-type pumps which provide the final required pressure in the rotor cavity. The combination of low pressure and elevated temperature in the cavity precludes condensation of any potassium leakage. However, the presence of the potassium vapor in the closed rotor cavity presents a special sealing problem. While the H-11 rotor will resist attack by the potassium vapor, the exposed high-temperature insulation in the stator must be protected from attack. A ceramic bore seal, shown in figure 17, is proposed to perform this function.

A ceramic is employed to seal the stator housing because any metallic materials interposed in the magnetic path will create unwarranted eddy current losses. These losses would result in heating the pole tips and a loss in generator efficiency.

The bore seal design provides for differential thermal expansion in both the axial and radial directions while maintaining close alinement with the rotor. The ceramic-to-metal end closures are designed to protect the ceramic seal from shock and vibration.

The stator consists of two magnetic lamination assemblies having a toroidal field core in between. The 0.004-in. (0.01-cm) thick laminations are made of Hiperco 27. The stator and field coils are mounted in a solid magnetic frame made of a Hiperco 27 forging. The alternating-current windings, made of Anadur-S insulated Inconel-clad silver, are continuous except for joints at the bus rings, terminals, and crossovers. Slot liners made of 99.9 percent alumina are used. A circumferential manifold on the stator frame and a manifold around the field coil comprise the 700° F (645 K) potassium cooling configuration, which is designed to limit the hot-spot temperature to 1000° F (180 K).

PRIMARY AND BOILER FEED ELECTROMAGNETIC PUMPS

Electromagnetic (EM) pumps were selected for all of the liquid-metal loops in the system because of their inherent simplicity. Both the primary and boiler feed pumps are of the three-phase helical induction type. Design analyses of the pumps and their requirements performed by General Electric have shown that the helical induction pump is the best compromise design (ref. 16). A sketch of the boiler feed helical induction pump is shown in figure 18.

The liquid metal enters the pump at the right into an annular passage. The pump is analogous to an induction motor except that the rotor has been replaced by a liquid-metal-filled annular passage. The rotating magnetic field imparts a force on the liquid, causing it to rotate circumferentially in the annulus. Since the fluid is constrained to flow within the helical channel in the annulus, the fluid is forced to move from one end of the pump to the other. At the same time, the fluid static pressure increases along the helical channel. The high-pressure fluid makes a 180° turn at the end of the annulus and exits the pump at the right through the center pipe. With both fluid connections at the same end of the pump, the stator and cooling passages can be removed, if necessary, without disturbing the sealed liquid-metal loop (ref. 17).

Figure 19 shows a cross section of the primary loop pump. As can be seen, it is quite similar to the boiler feed pump, and has an added central coolant passage because of its elevated-temperature requirements. The helical design has a relatively simple stator and is a good pressure vessel because of its cylindrical shape.

The design specifications of both pumps are presented in tables II and III. These design values were established from earlier system studies and are conservative with respect to the requirements of this reference system. The pumps were initially designed to employ NaK at 800° to 850° F (700 to 725 K) as the liquid-metal coolant. Due to the current arrangement of the auxiliary coolant loops, described in the next section, the pumps will be cooled with potassium supplied at 700° F (645 K). The lower coolant supply temperature provides an additional margin in maintaining acceptable temperatures within the pumps. The calculated efficiencies of the boiler feed and primary loop pumps are 19 and 16 percent, respectively, at the initial design specification points. Table IV identifies the various materials employed in the design of both pumps.

Currently, the boiler feed pump and the pump test loop fabrication is complete. Testing of the pump has been initiated. A preliminary design of the primary loop EM pump has been completed.

RADIATORS

The reference Rankine system has four radiators, the main radiator (or radiators), two auxiliary cooling radiators, and an electronics coolant radiator. The main radiator is comprised of four panel groups (one being redundant) with a probability of 0.99 that three of these groups will survive for 3 years. The main radiators are made of stainless-steel tubes with conducting bumper fins made of stainless-steel clad copper (fig. 20). The fins are coated with iron titanate with an emittance ϵ_t of 0.90. The main radiators reject heat from the condenser through a eutectic NaK coolant.

There are two auxiliary radiators, and both employ liquid potassium as the coolant. One rejects heat from the pumps and alternator coolant loop, and the other rejects heat from the turbine bearing lubricant loop. The 700° F (645 K) alternator and auxiliary coolant loop radiator is composed of stainless-steel tubes with stainless-steel clad aluminum bumper fins. The 900° F (755 K) turbine bearing lubricant loop radiator is composed of stainless-steel tubes with stainless-steel clad copper bumper fins. Iron titanate coating is used for both auxiliary radiators.

The fourth radiator is for the low-temperature electronics coolant loop. This is an all-aluminum bumper fin radiator using Z-93 coating with an emittance ϵ_t of 0.88 and an absorptivity α_s of 0.19. The coolant fluid is Dow Corning 200 (0.65 cS).

The three lower-temperature radiators all assume a no-puncture probability of 0.99 for 3 years. Table V presents a summary of the major characteristics of the four radiators.

All four radiators are arranged on a cone in a manner shown in figure 21. The reactor shield and power system weight is attached to the radiators at ring A-A. The launch vehicle is assumed to have a two-stage Saturn V configuration. Sink temperatures were calculated by assuming a 300-nautical-mile (555-km) equatorial orbit with the sun at its zenith. This is a rather conservative assumption. Only the low-temperature radiator is sensitive to sink temperature.

Contracted programs under NASA sponsorship have explored structural requirements of radiators (ref. 18). They also have compared conical and flatplate radiators (ref. 19), showing that conical radiators gave minimum system weight. In a comparison of direct-condensing and indirect-condensing radiators (ref. 20), the direct-condensing radiator gave tighter system weight but had serious startup and operating problems.

A current contract program (NAS3-12976) is underway which will compare a conventional conducting bumper fin radiator with a vapor chamber fin (heat pipe) radiator.

ESTIMATED WEIGHTS

System specific weights were derived from component weight estimates and the reference conceptual engine layout. Table VI presents a summary of the estimated weights of the major system elements. The weights of all of the components, except for the electrical equipment and structure, were computed from specific component designs or computer programs. The weights of the electrical equipment were derived by scale factors applied to similar low-power-level equipment. The weight of the undefined support structure was assumed to be 10 percent of the system total weight.

CONCLUDING REMARKS

The study shows that for the nominal 300-kWe advanced Rankine system investigated component limitations and uncertainties were of major importance in the selection of the system state points and configuration. The system has an efficiency of 19 percent and a specific weight of 59 pounds (27 kg) per kWe for unmanned applications. A broad-based research and technology program is in progress investigating components and materials for high-temperature advanced nuclear Rankine space-power systems. This research and technology program will continue to provide information applicable to advanced Rankine systems over a wide range of power levels to meet the anticipated future space-power requirements.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 19, 1969,
120-27.

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TABLE I. - POWER DISTRIBUTION FOR

ADVANCED RANKINE POWER SYSTEM

Net thermal power input, MW	2.0
Net shaft power, kW	453
Alternator output power, kWe	428
Internal engine requirements, kWe	53
Net unconditioned power to user, kWe	375
Net system efficiency	0.187

TABLE II. - DESIGN SPECIFICATIONS FOR BOILER

FEED ELECTROMAGNETIC PUMP

	Design	Off-design range
Fluid	Potassium	
Fluid inlet temperature, ^{o}F (K)	1000 (811)	900 to 1400 (755 to 1033)
Flow rate, lb/sec (kg/sec)	3.25 (1.47)	0.75 to 4.25 (0.34 to 1.93)
Developed pressure rise, psi (N/cm^2)	240 (166)	350 (242) maximum
Net positive suction head, psi (N/cm^2)	7 (4.8)	2 to 35 (1.4 to 24)
NaK coolant inlet temperature, ^{o}F (K)	850 (730)	800 to 900 (700 to 755)
Coolant temperature rise, ^{o}F (K)	50 (280)	50 to 100 (280 to 310)

TABLE III. - DESIGN SPECIFICATIONS FOR PRIMARY

LOOP ELECTROMAGNETIC PUMP

	Design	Off-design range
Fluid	Lithium	
Fluid inlet temperature, ^{o}F (K)	2100 (1425)	1900 to 2200 (1310 to 1480)
Flow rate, lb/sec (kg/sec)	30 (13.6)	10 to 35 (4.5 to 15.8)
Developed pressure rise, psi (N/cm^2)	20 (14)	10 to 40 (7 to 28)
Inlet pressure, psia (N/cm^2)	20 (14)	20 to 30 (14 to 21)
NaK coolant inlet temperature, ^{o}F (K)	800 (700)	700 to 900 (645 to 755)
Coolant temperature rise, ^{o}F (K)	100 (310)	50 to 100 (280 to 310)

TABLE IV. - MATERIALS USED IN PRIMARY LOOP

AND BOILER FEED ELECTROMAGNETIC PUMPS

Component	Material
Duct	T-111 alloy
Stator magnetic laminations	Hiperco 27
Core magnetic laminations	Hiperco 27
Interlaminar insulation	Plasma-sprayed alumina
Slot (ground) insulation	99.5 Percent alumina
Phase-to-phase insulation	99.5 Percent alumina
End-turn insulation	S-glass tape
Conductors	Nickel-clad silver (20 area percent Ni)
Stator environment	Argon

TABLE V. - RADIATOR CHARACTERISTICS

[Radiator type, armored tube and fin; meteroroid protection, 0.99 probability of no puncture in 3 yr.]

Characteristic	Main radiator	Auxiliary radiators		Electronics cooling loop radiator
		Alternator	Turbine	
Number	4	1	1	1
Fluid	NaK	K	K	DC-200
Maximum temperature, $^{\circ}F$ (K)	1200 (922)	739 (666)	920 (767)	150 (339)
Temperature drop, $^{\circ}F$ (K)	220 (378)	39 (277)	20 (267)	10 (261)
Tube and armor material	Stainless steel	Stainless steel	Stainless steel	Al
Survivability	3 out of 4	(a)	(a)	(a)
Coatings	Iron titanate	Iron titanate	Iron titanate	Z-93
Coating emittance, ϵ_t	0.90	0.92	0.90	0.88
Coating absorptivity, α_s	0.75	0.75	0.75	0.19
Total heat-transfer area, ft^2 (m^2)	760 (70.6)	126 (11.7)	19 (1.77)	325 (30)

[a]Not applicable.

TABLE VI. - NOMINAL 300-kWe ADVANCED RANKINE-CYCLE SPACE-POWER SYSTEM WEIGHT ESTIMATES

	Weight			Weight	
	lb	kg		lb	kg
Reactor (2 MW thermal, 3.8 at. % fuel burnup,	4000	1810	Alternator coolant loop (K):		
50 000-hr life) and reactor controls, drive, and			Radiator panel	320	145
structure			Pump	130	59
			Expansion tank	50	23
Primary loop (Li):			Piping	80	36
Boiler	300	136	Potassium inventory	(a)	(a)
Pump	700	317	Total weight	580	263
Pipe and insulation	320	145			
Expansion tank	180	82	Turbine coolant loop (K):		
Lithium inventory (6.5 cu ft (0.18 m^3) = 160 lb (72.5 kg))	(a)	(a)	Radiator	75	34
Total weight	1500	680	Pump	50	23
			Expansion tank	50	23
Power conversion loop (K):			Piping	35	16
Turboalternator	1300	590	Potassium inventory	(a)	(a)
Condensers (4)	240	110	Total weight	210	96
Boiler feed pump	300	136			
Condensate heat exchangers (2)	100	46	Electronics cooling loop (DC-200):		
Separator	50	23	Radiator	275	124
Potassium inventory control	100	46	Pump	25	11
Potassium injection tank	250	114	Expansion tank	25	11
Potassium inventory	150	68	Piping	105	48
Vapor piping	250	114	Inventory	100	46
Liquid piping	50	23	Total weight	530	240
Total weight	2800	1270			
			Electrical equipment:		
Main heat-rejection loop (NaK):			Speed control	100	46
Radiator panels (4)	2170	982	Voltage regulator-exciter	200	92
Pumps (4)	480	217	Internal power conditioning	200	92
Expansion tanks (4)	400	181	Parasitic load resistor	600	270
Piping	430	195	Interconnecting cable	50	23
NaK inventory	(a)	(a)	Controls and instrumentation	50	23
Total weight	3480	1575	Total weight	1200	546
Shadow shield (for unmanned spacecraft, 10° half-cone angle, 150 ft (~46 m) to payload	6000	2700	Structure (assumed to be 10 percent of engine weight)	1962	890
Total estimated weight				22 262	10 070

[a]Included in above weights.

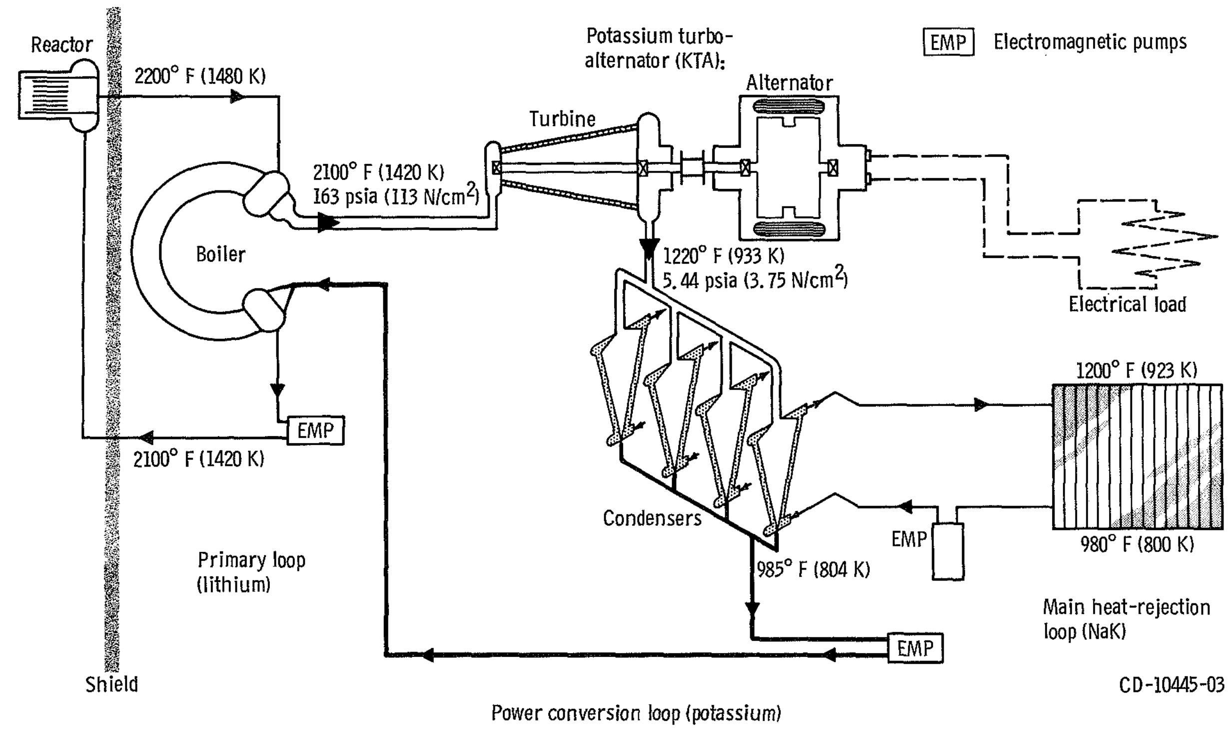

Figure 1. - Schematic of advanced Rankine power system.

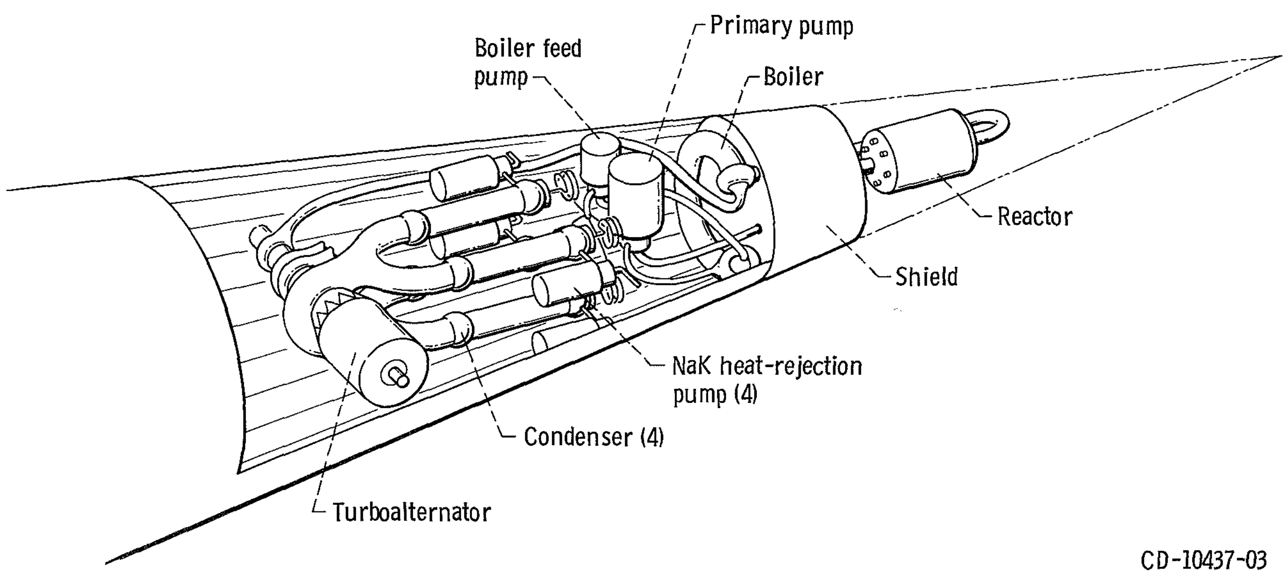

Figure 2. - Advanced Rankine engine concept.

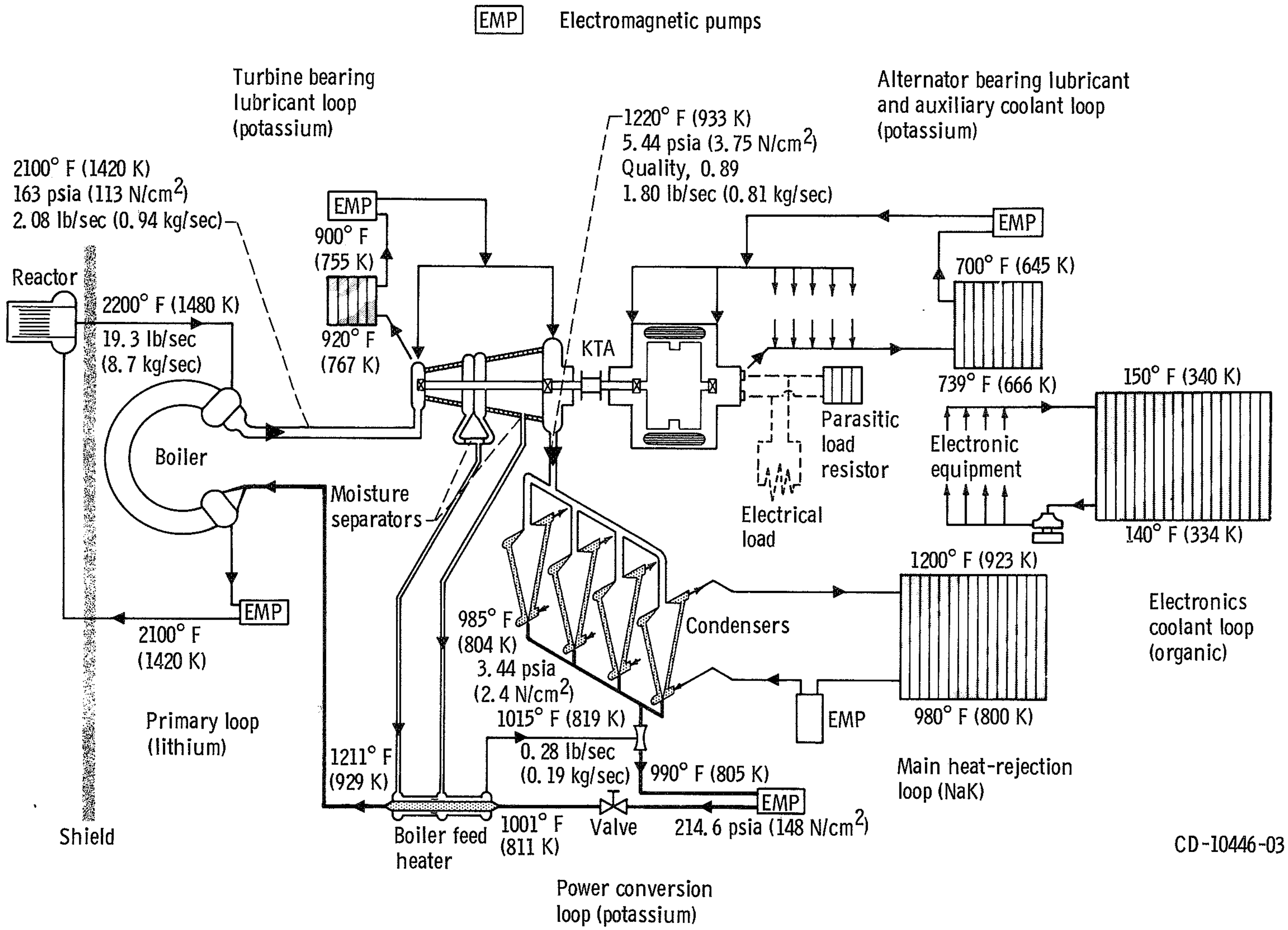

Figure 3. - Advanced Rankine power system (nominal 300 kWe).

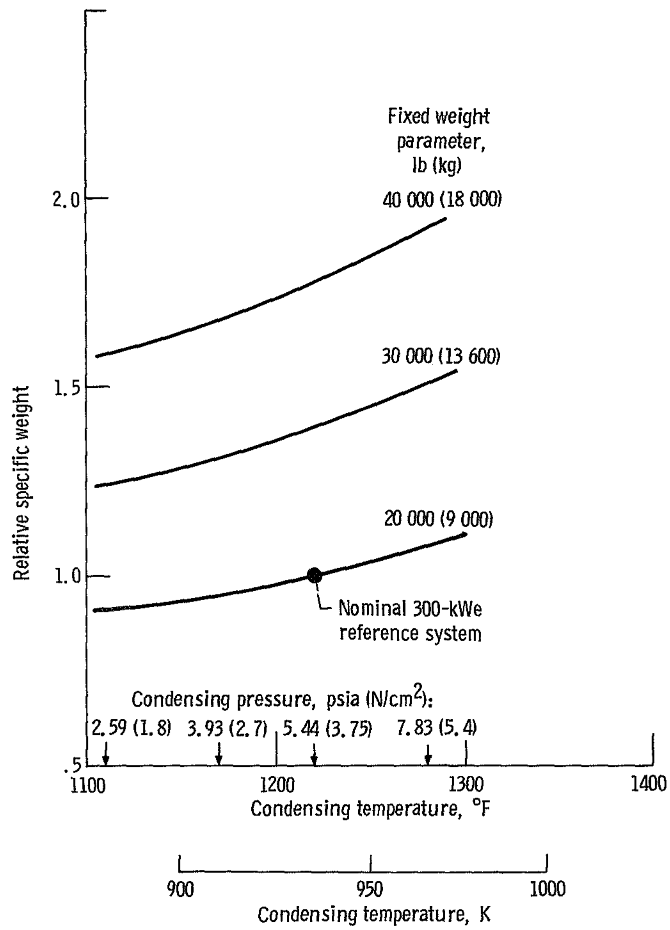

Figure 4. - Relative specific weight as function of condensing temperature.

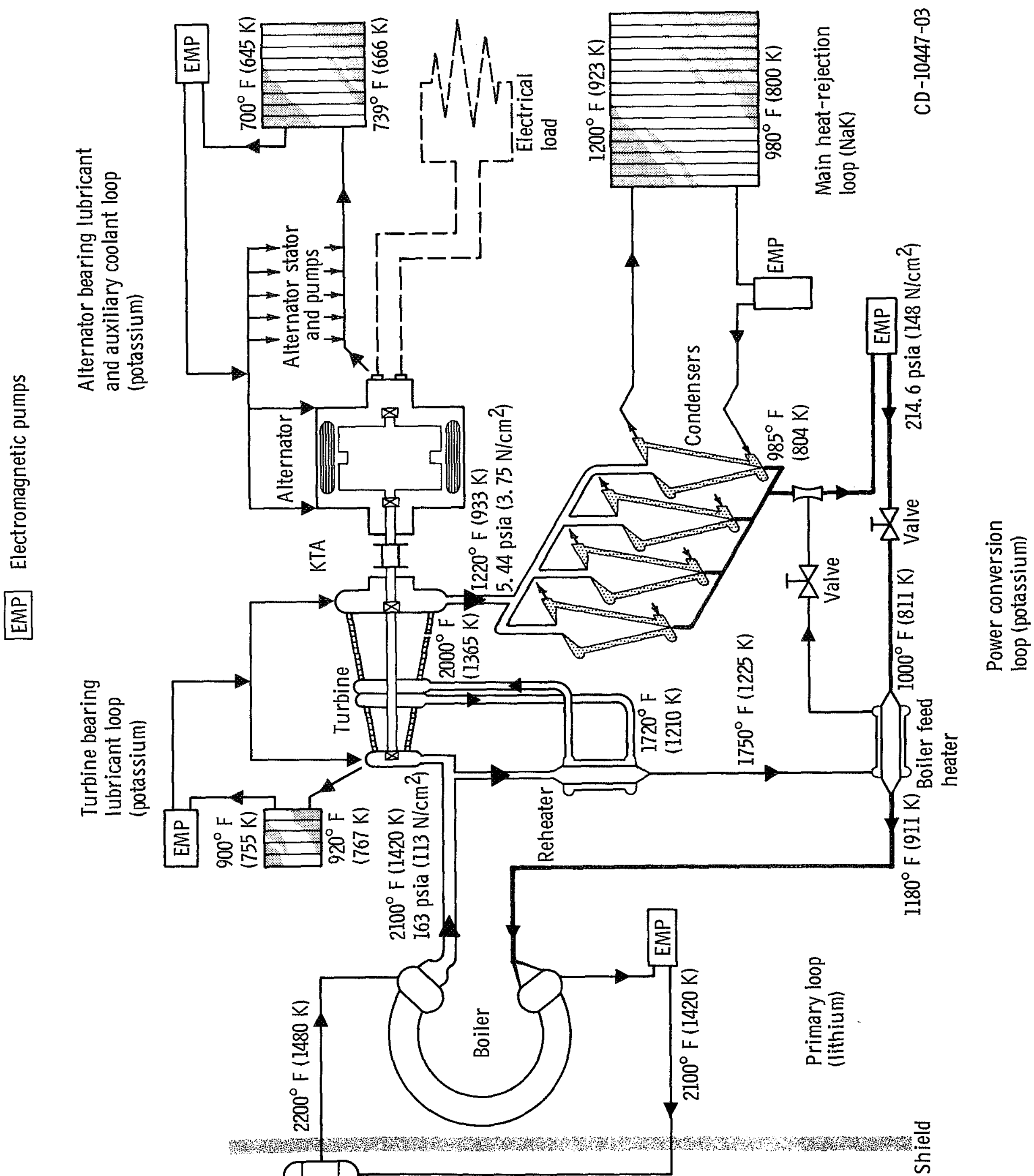

Figure 5. - Reheat-boiler exit potassium used as reheat fluid.

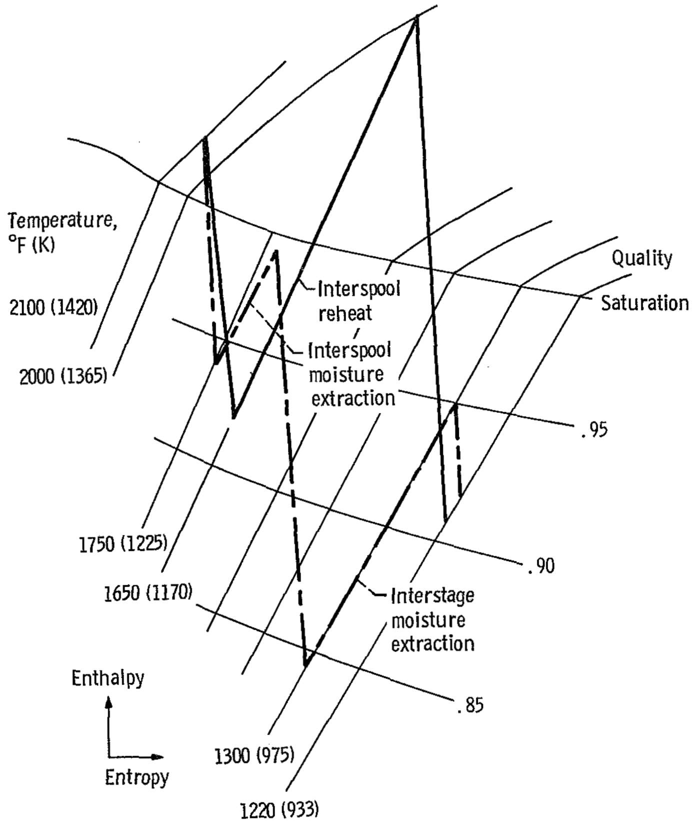

Figure 6. - Diagram of potassium enthalpy as function of entropy for turbine expansions with reheat compared with moisture extraction.

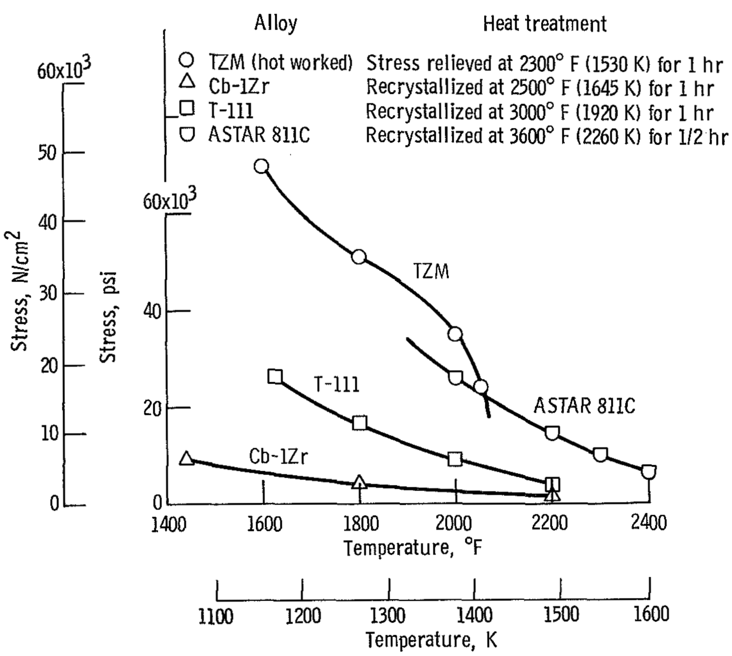

Figure 7. - Refractory-metal alloy creep properties. Stress for 1 percent creep in 10 000 hours. From reference 2.

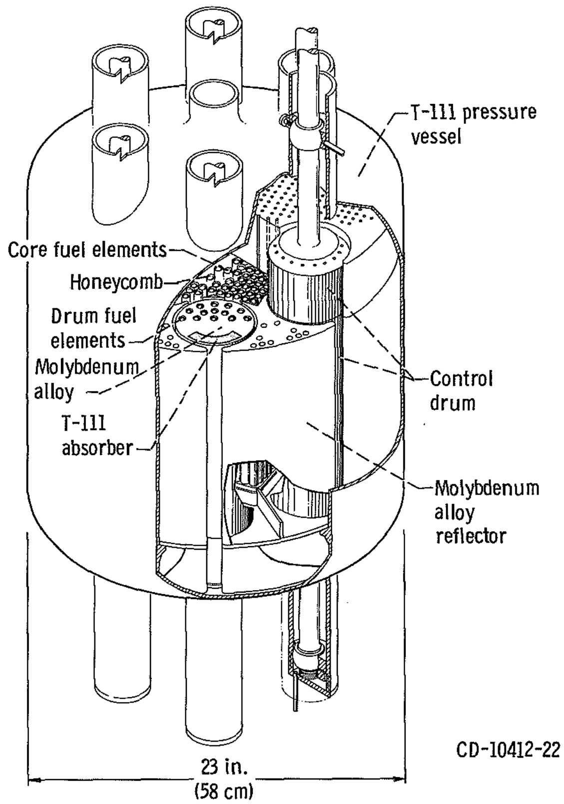

Figure 8. - Lithium-cooled fast reactor.

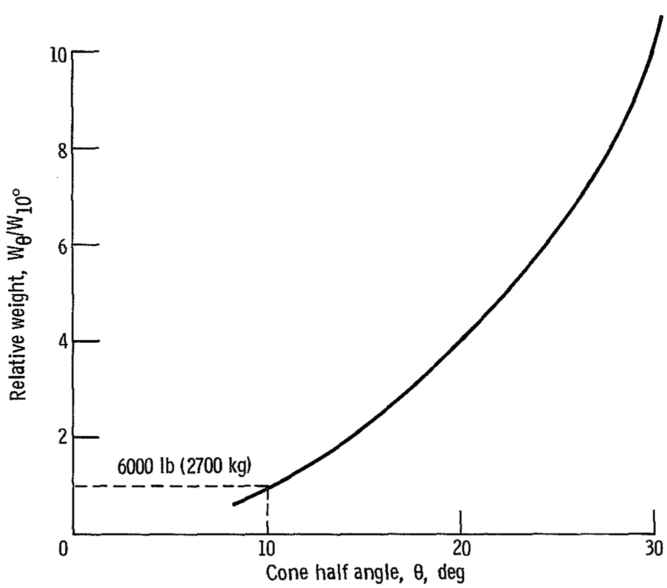

Figure 9. - Relative non-man-rated shadow-shield weight as function of cone angle. Shield composition, 4.4 inches (11 cm) of tungsten and 36.6 inches (93 cm) of lithium hydride.

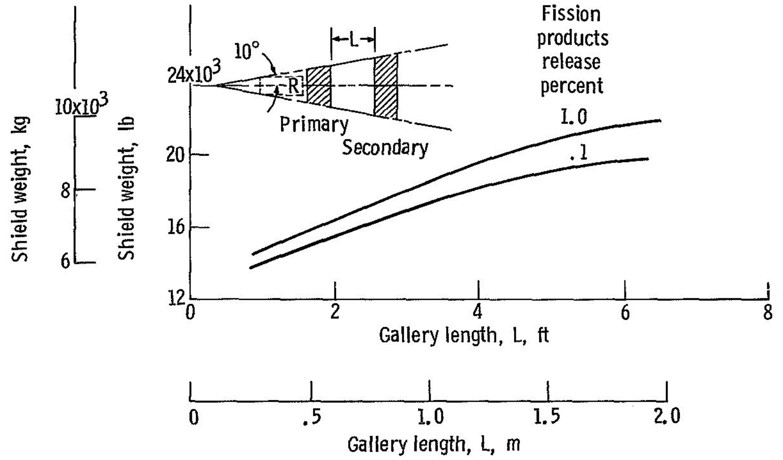

Figure 10. - Man-rated shield weight as function of gallery length.

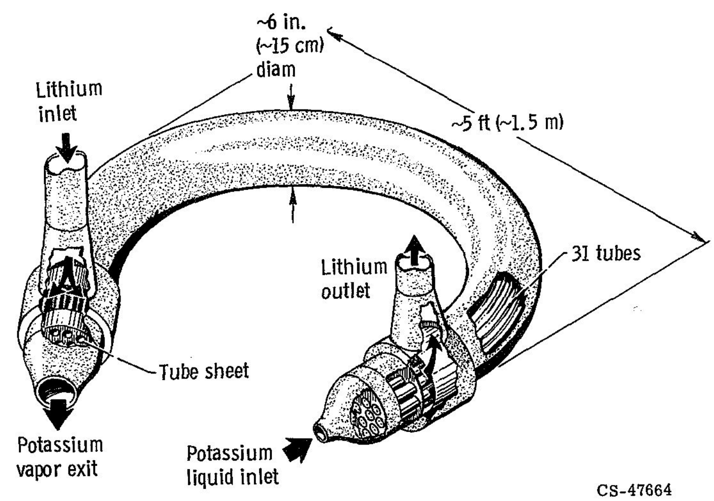

Figure 11. - Once-through 2-megawatt-thermal potassium boiler, advanced Rankine space-power system.

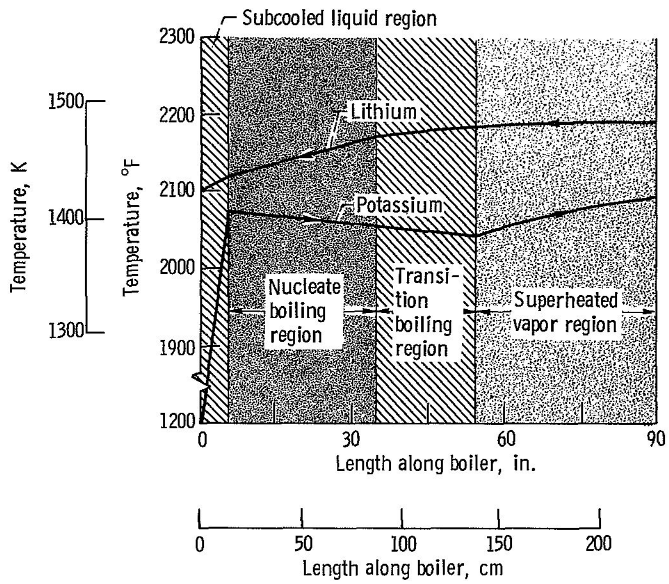

Figure 12. - Temperature distribution in boiler.

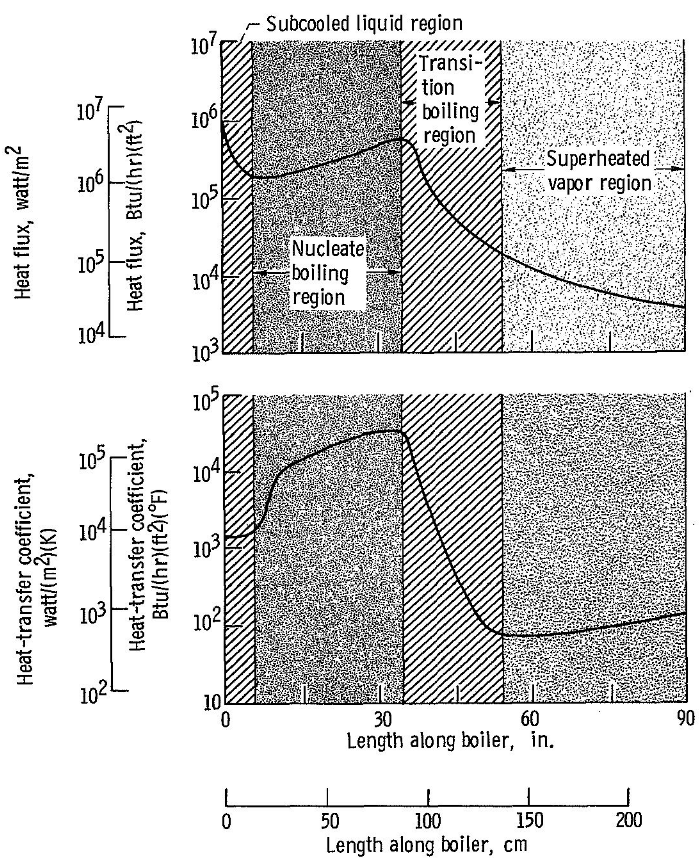

Figure 13. - Distribution of heat flux and heat-transfer coefficient in boiler.

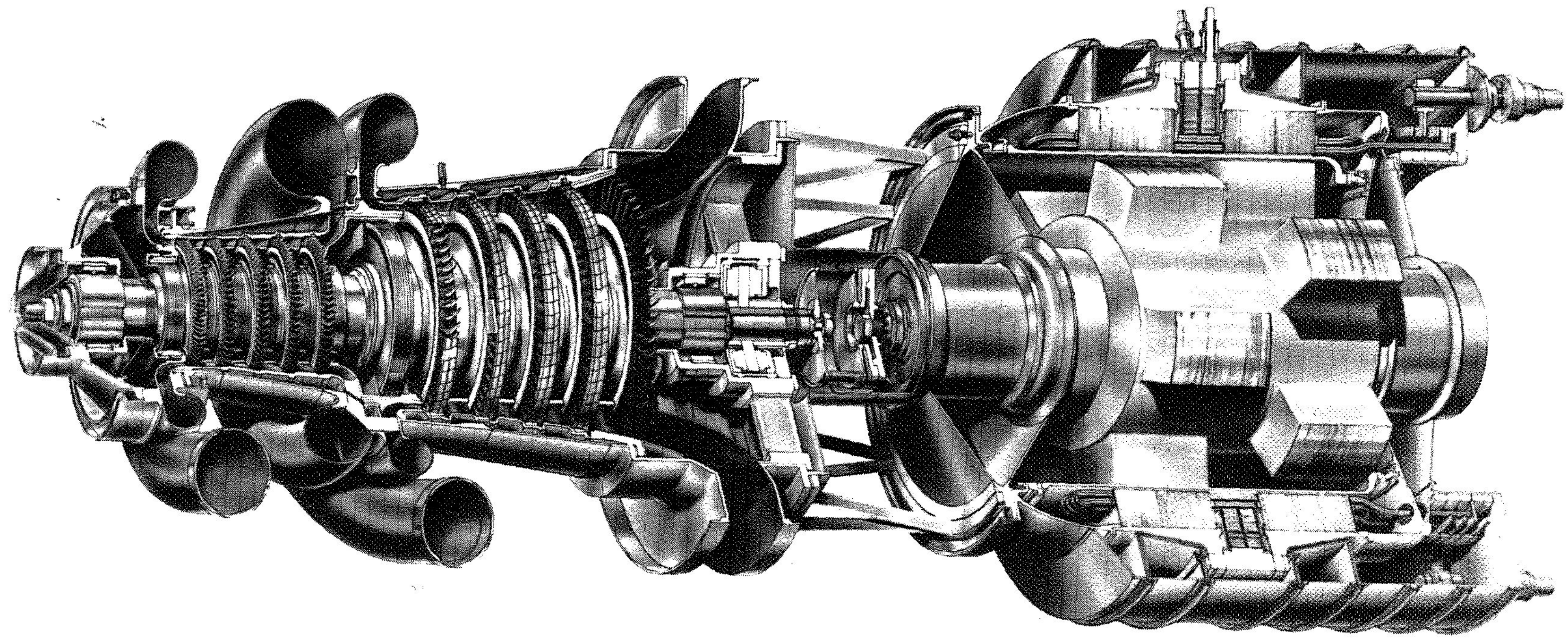

Figure 14. - Potassium turboalternator (KTA), preliminary design. CS-50707

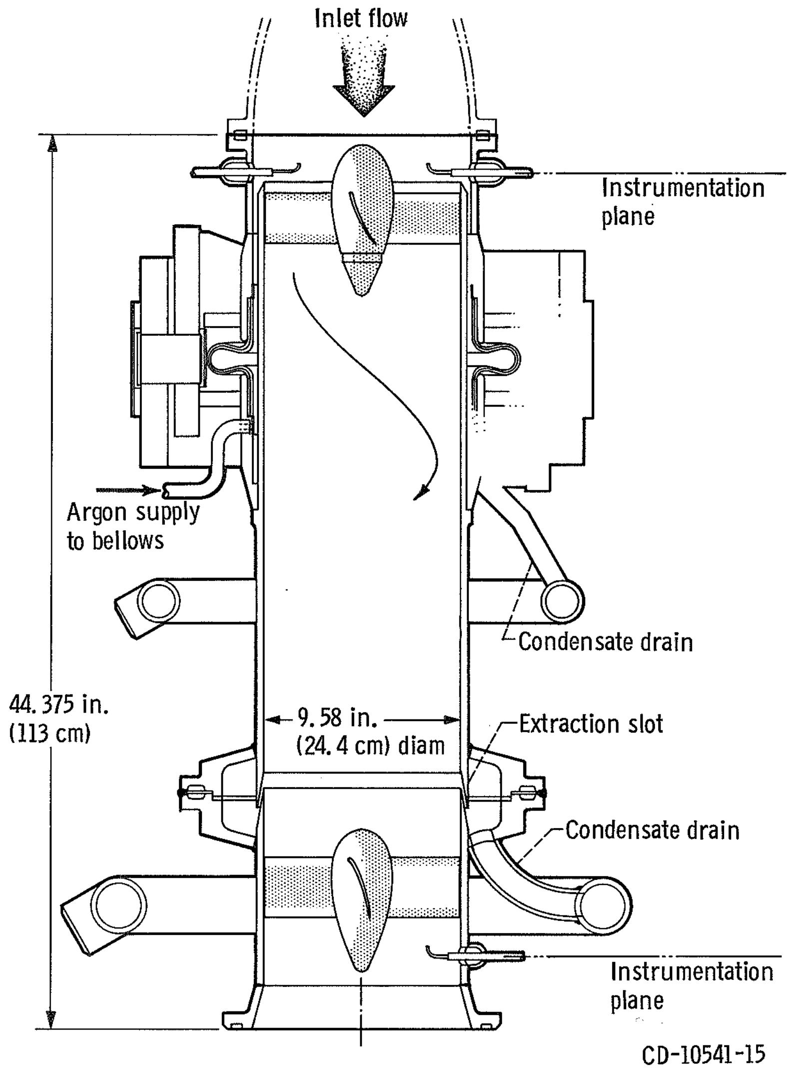

Figure 15. - Interspool vortex separator test configuration.

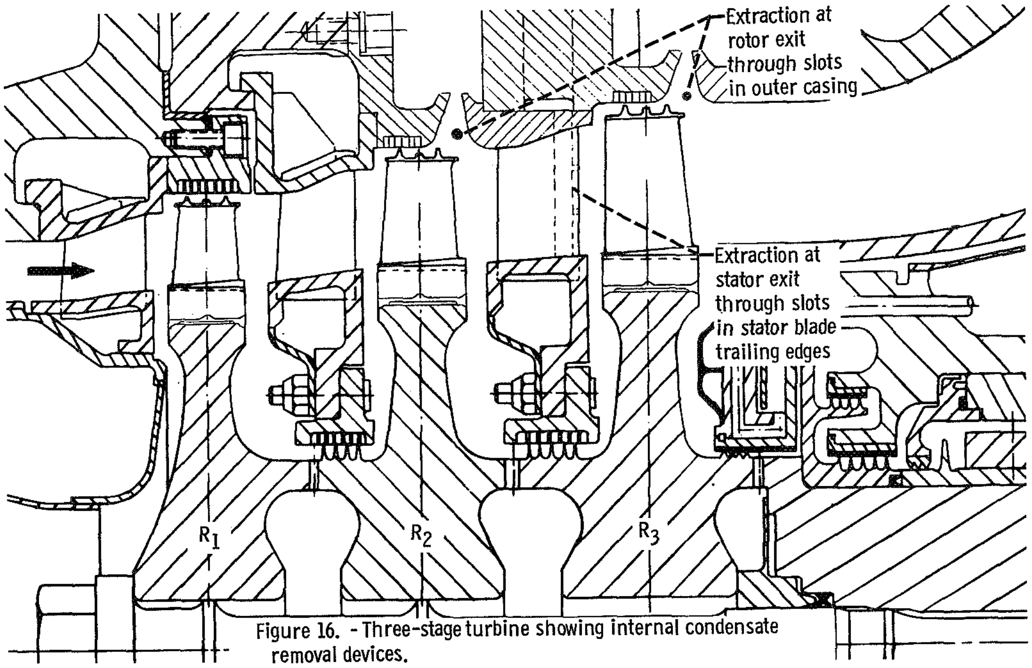

Figure 16. - Three-stage turbine showing internal condensate removal devices.

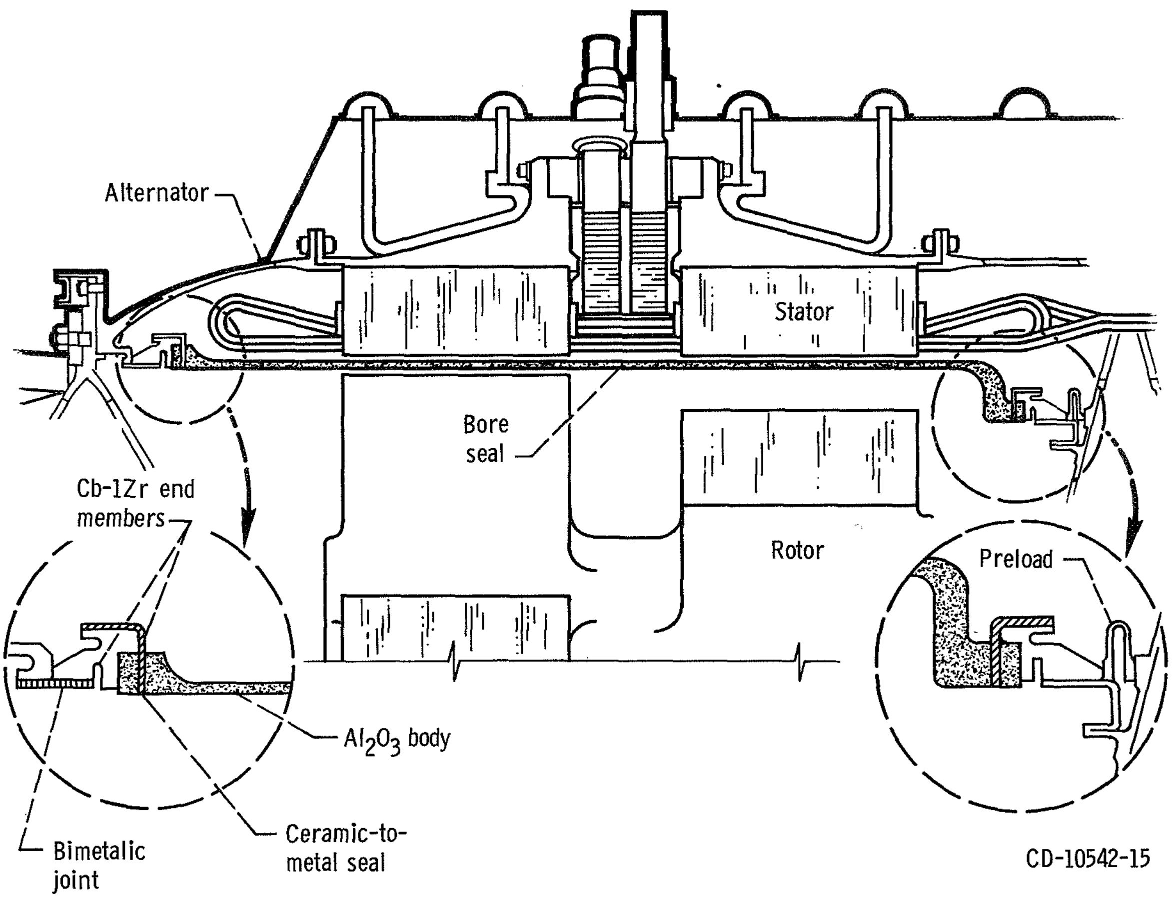

Figure 17. -Bore seal mechanical design.

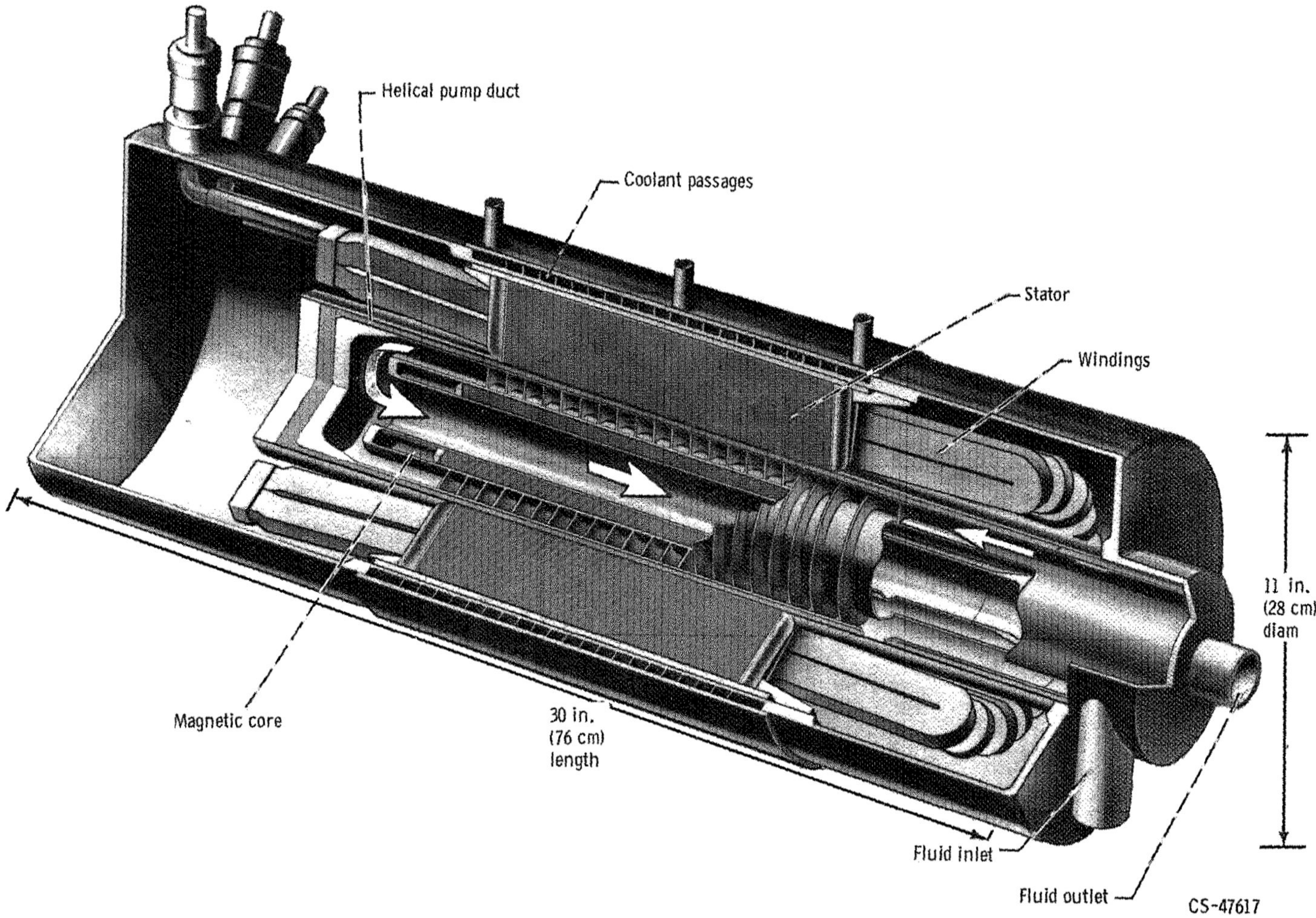

Figure 18. - Electromagnetic helical induction pump - boiler feed.

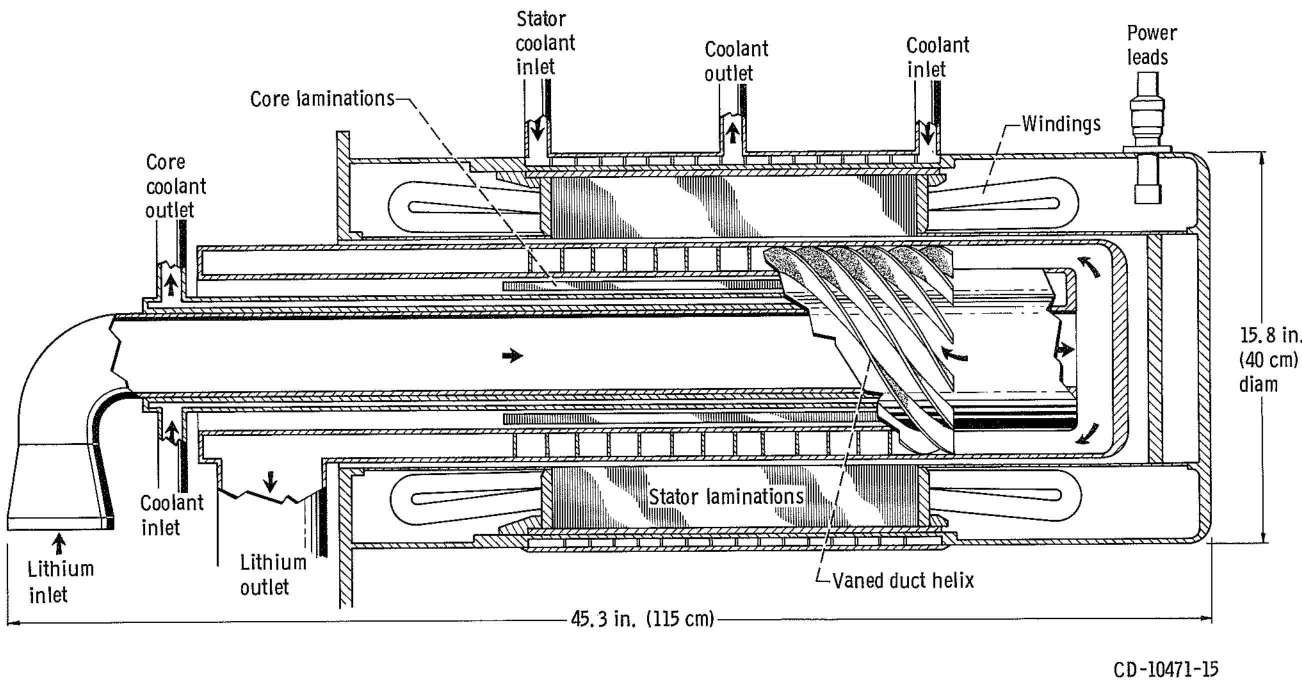

Figure 19. - Electromagnetic helical induction pump - lithium reactor coolant.

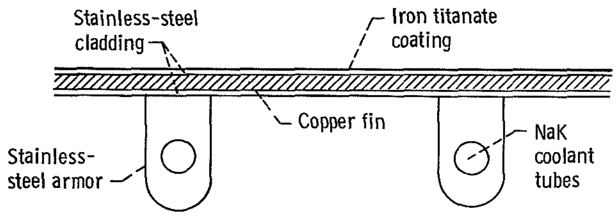

Figure 20. - Schematic of conducting bumper fin-and-tube radiator.

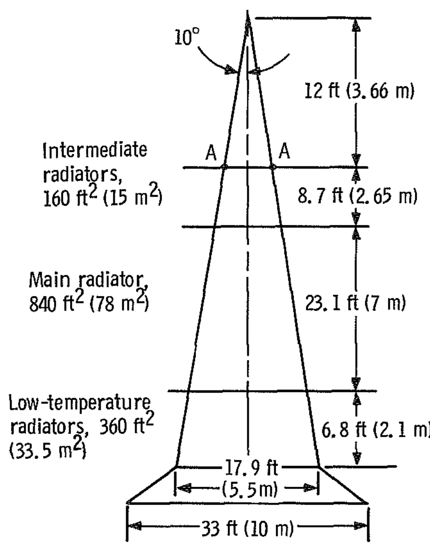

Figure 21. - Radiator arrangement. System weight is applied at A-A ring. No shroud on radiators. Each radiator area is oversized by 10 percent to allow for structure.

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