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NUCLEAR REACTOR SPACE POWER CONVERSION SYSTEMS

by Roger F. Mather
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TECHNICAL PAPER proposed for presentation at Triannual Power Conference sponsored by the U. S. Air Force Office of Scientific Research Chicago, Illinois, April 8-10, 1968

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ABSTRACT

This paper discusses the principal systems now being investigated for converting heat from advanced nuclear reactors to electrical power for manned and unmanned spacecraft. These power conversion systems are the Rankine and Brayton turboalternator, magnetohydrodynamic, and thermionic. The basic operating principles and development status are described for each of these systems. System efficiencies, applicable power levels, development problems and other characteristics are briefly reviewed.

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I. Introduction

Nuclear reactor powerplants present advantages over other power sources for several types of space missions. They are suitable for a range of power outputs from tens of kWe to several MWe. At the higher levels within this range, reactor power appears to be the only attractive type. These systems can be designed for lifetimes of several years of continuous operation. Unlike solar-powered systems, they work equally well at great distances from the sun, and no provision need be made for operating in the earth's shadow or during lunar nighttimes; nor need the spacecraft be oriented with respect to the sun.

The advantages of reactor powerplants derive from the fact that the energy available from nuclear fission is more than a million times that from chemical reactions, on a weight basis. Radioisotope heat sources share this advantage, but must be limited to perhaps 50 kWt by considerations of safety, with availability, cost and weight as additional factors in certain cases. The chief drawback of reactor systems is that heavy shields are required to achieve neutron and gamma attenuation factors of about 10^8 for the crews of manned missions and perhaps 10^6 to protect semiconductor devices in unmanned missions.

This paper outlines the principles, characteristics, and technology development status of the four main systems being investigated for converting reactor heat into space electric power: Rankine and Brayton turboalternator; magnetohydrodynamic; and thermionic.

II. Rankine Turboalternator Systems

Rankine cycle turboalternator space power systems are basically similar to the well-known land-based steam turboalternators. The schematic diagram for SNAP-8 as a representative Rankine space system is shown in figure 1. The reactor is cooled by a liquid metal mixture of sodium and potassium, namely NaK eutectic, which boils the mercury working fluid in a single-pass shell-and-tube boiler. Mercury is used because of its suitable vapor pressure at the operating temperatures. The primary reactor radiation shield is located between the reactor and the boiler, and a secondary shield between the boiler and the rest of the system, because the NaK in the reactor loop becomes radioactive. The pumps in this and the other loops are of the mechanical type. The turbine has four stages, is of axial-flow design, and shares a common shaft with the salient-pole homopolar alternator. The turbine inlet temperature is about 1300° F. The condenser is also of the shell-and tube single-pass type and is cooled by NaK, which in turn is cooled by the radiator. Bearings of the turboalternator and the mercury pump are lubricated by a radiation-resistant organic fluid which also cools electrical components. This fluid, in turn, is cooled by a separate radiator. Net power output of the system is nominally 35 kWe.

SNAP-8 is the only Rankine system under active development, and has an initial goal of 10,000 hours' operation. The program was initiated at the NASA Lewis Research Center in 1960 under contract with Aerojet-General Corporation. Major problems encountered have been (1) corrosion and strength of the stainless steel used in the boiler, (2) small amounts of oil interfering with the mercury wetting the boiler tube, and (3) embrittlement of turbine materials. Recent tests of the boiler and turbine appear encouraging, following changes in design and materials. The following are the maximum endurance times accumulated for individual units to April, 1968:

Boiler	2,500 hours
Alternator	2,500
Turboalternator	2,500
Condenser	5,000
Mercury pump	7,000
NaK pump	8,000
Oil pump	14,000

More advanced Rankine systems than SNAP-8 are in the technology development phase. The advantage of these systems is higher operating temperatures in order to increase the radiator temperature and thus decrease its size. The increase in temperature requires a change in the working fluid to keep the vapor pressure at a reasonable level. Alkali metals are the principal candidates, and potassium is the chief of these. A representative turbine inlet temperature for potassium would be 2100° F, leading to an optimum radiator temperature of about 1200° F. This results in an area per kWt rejected only about 15 percent of that of the SNAP-8 radiator, because the latter operates at an average temperature of 570° F. Projected overall efficiency is about 17 percent.

The Lewis Research Center is developing the technology of the advanced potassium Rankine systems in-house and through contracts. Many data on potassium boiling heat transfer have been accumulated with a 300 kWt superalloy rig and a 100 kWt Cb-1Zr rig. Condensing heat transfer data have been obtained with a 50 kWt stainless steel rig. Representative T-111 tantalum alloy boiler tubes will shortly be fabricated for testing. A two-stage 200-horsepower superalloy turbine having oil bearings and several molybdenum alloy rotor blades has been run for over 5000 hours, with only slight erosion or other deterioration. The vapor contained 3 percent liquid on entering the second stage and 7 percent on leaving that stage. A similar turbine having three stages is now being operated, to increase the liquid in the last stage to 12 percent and thus investigate erosion effects at higher moisture levels. A refractory metal turboalternator for a 300 kWe system is under design. Tests indicate that hydrodynamic pivoted-pad potassium-lubricated bearings will probably be satisfactory as regards wear, conformability, and stability in a zero-gravity environment. The Jet Propulsion Laboratory has built and operated a Cb-1Zr rig comprising an electrically-heated "reactor" loop and potassium loop to explore problems related to startup, control, and stability. No fundamental problems were uncovered. Helical-induction electromagnetic pumps are being considered for the loops of the potassium system. Such pumps have been satisfactorily employed in potassium heat transfer and corrosion loops, and a boiler-feed pump is now being fabricated for endurance tests.

The potassium systems present a number of potential materials problems, and these could prove the greatest obstacle to the successful development of such systems. However, much substantial progress has been made. In addition to the work cited above, characteristics of bearing materials and corrosion of refractory metals by potassium have been studied by General Electric. New tantalum alloys and welding practices for refractory metals have been developed by Westinghouse, who have also investigated the properties of materials for electrical components. Creep and fatigue strengths of refractory metals have been determined by TRW. To summarize this work, materials limitations do not presently appear to be insuperable barriers to the successful development of advanced Rankine systems. Nevertheless substantial problems may be expected to arise in their development.

III. Brayton Turboalternator Systems

Brayton cycle turboalternator space power systems resemble the familiar gas turbine and jet engine, except that closed cycle systems are used to recirculate the working fluid.

The schematic diagram of a representative Brayton space power system is shown in figure 2. In this design, the reactor is cooled by a liquid metal rather than an inert gas; other designs have proposed circulating the gaseous cycle fluid directly through the reactor. The gaseous cycle fluid is then heated by the liquid metal in a heat exchanger before passing into the turbine, which drives the homopolar alternator. From the turbine, the gas goes to a recuperator in order to recover a part of its heat before it is cooled in the heat exchanger of the liquid-metal radiator loop. Next, the gas is compressed by the compressor and heated by the recuperator, before again being heated in the reactor-loop heat exchanger.

The Brayton system is applicable to a wide range of power levels and to radioisotope and solar as well as reactor heat sources. It is highly efficient, of the order of 20 to 30 percent. Use of the inert-gas working fluid eliminates corrosion and erosion effects. Much component technology is already available from other fields. A disadvantage is that large radiator sizes and weights are required because of the low heat-rejection temperature.

The Lewis Research Center and its contractors are engaged in a technology program for developing a Brayton power system capable of providing from 2 to 10 kWe for a period of five years, using either an isotope or a solar energy source. Much of this technology will be applicable to reactor systems of higher power levels. Tests of small compressors and turbines indicate that efficiencies around 80 and 90 percent respectively can be obtained for these components. Alternator efficiencies of 90 percent have been demonstrated. A Brayton turbocompressor has been tested to investigate the performance of gas bearings. Certain problems were encountered, investigation of which is continuing and solutions for which are anticipated.

IV. Magnetohydrodynamic Systems

Electric power can be generated from a flowing conductive fluid by the interaction of electrical and magnetic fields in a magnetohydrodynamic (MHD) generator. This MHD generator could, in principle, replace the turboalternator in either a Rankine cycle, where the conductive fluid may be in the vapor phase, or in a Brayton cycle, where the conducting fluid is a gas. The key problem in such gaseous MHD generators is obtaining the necessary electrical conductivity, at feasible operating temperatures, even though cesium is used for seeding. Adequate conductivity has been achieved and large generators operated using combustion gases, as appropriate for open-cycle systems, but obtaining it at the lower temperatures allowable in reactor systems has so far been infeasible, and more fundamental research is required.

A Rankine cycle can also be used in which the conducting fluid is the liquid phase. Such a cycle, with a liquid-metal MHD generator, is shown schematically in figure 3 with conditions indicated for a 300 kWe system. The system operates as follows: The reactor heats liquid lithium to approximately 1800° F. The hot lithium is then mixed with 1/10 its mass flow rate of cesium, immediately flashing it to vapor. The two-phase mixture of lithium and cesium is then accelerated to about 500 ft/sec in a nozzle. The two phases are partially separated by an abrupt turn. The cesium vapor passes through a recuperator and is then condensed in a radiator prior to injection into the mixer. The liquid lithium has very high electrical conductivity, and interacts with the electric and magnetic fields in the generator to produce electric power. Deceleration in the diffuser produces enough pressure to pump the fluid back through the reactor and to the mixer. As may be surmised, the principal losses are friction in the high-velocity liquid regions of the separator and generator, and electrical and magnetic losses in the generator.

To date, the hydraulic system has been simulated at the Jet Propulsion Laboratory with nitrogen and water and with nitrogen and NaK. Nitrogen and NaK will be run this year through a nozzle, separator, and generator, which under these cold conditions should produce about 50 kWe.

In comparison with the potassium Rankine turbogenerator system, this MHD system has several disadvantages. Because the anticipated overall efficiency is low - perhaps 5 to 6% versus 17% for the turbogenerator system - only one-third as much electric power could be produced using a given reactor, reactor shield, and radiator. However, should the turbogenerator system be infeasible, this MHD system is thus a possible alternate.

V. Thermionic Systems

The thermionic converter, as an element of a nuclear reactor power system, is a heat engine which takes heat from the nuclear fuel at a high temperature, converts a portion of it directly to electrical energy, and rejects the remainder at a lower temperature. Being a heat engine, its performance is limited by the Carnot cycle efficiency. As shown in figure 4, electrons from the heated emitter are transported across a narrow cesium-filled gap to a collector maintained at lower temperature, typically by a liquid-metal coolant. The cesium enhances the emission of electrons and serves to neutralize the space charge caused by the electrons, which would hinder electron transport. Thermionic systems are presently limited to about 1/3 of the Carnot cycle efficiency because of voltage drops in the electrical leads, electrical leakages, thermal radiation and conduction, and plasma losses. At emitter temperatures from 2400 to 3300° F and collector temperatures of 1500 to 1600° F, diode efficiencies of 7 to 20 percent, outputs of 0.3 to 0.9 volts, and power densities of 4 to 20 W/cm^2 of emitter surface can be obtained. These emitter temperatures are sufficiently high that improvements in diode performance continue to be sought, so that they may be reduced. This aspect of performance improvement is deemed more necessary than increasing efficiency and power density at existing temperatures. Because of their strength and stability at high temperatures and their excellent electron-emission characteristics, tungsten and rhenium are considered the prime emitter materials. For collectors, niobium, molybdenum, and nickel are the chief candidate materials. The relatively high collector temperatures may lead to higher radiator temperatures than those of other space power systems, and thus to smaller and lighter radiators. Over-all system efficiencies may be expected to be comparable to - but below rather than above - the reactor turbogenerator systems.

With acceptable efficiencies and power densities already achieved, the primary remaining goal of diode development is the demonstration of increasing operational life. In 1964 only a few electron-beam-heated diodes had operated as long as 3000 hours, whereas by 1966 a number of diodes had operated for as long as 7000 and even 10,000 hours. On the other hand, some diodes continue to fail after relatively few hours. Emitter temperatures were 3150 to 3300° F, power densities 7 to 11 W/cm^2, and efficiencies 11 to 13 percent. Since then, progress has continued toward improved performance and lifetime goals.

Although considerable research and development have been performed on thermionic diodes and many system studies undertaken, no complete system has been assembled and tested to date. More technology investigations must be performed before a system can be designed with confidence. Of the various system configuration concepts being considered, the principal categories are (1) that having the diodes entirely separate from the reactor core, and the heat transported to them; and (2) that having the diodes inside the reactor core, and the waste heat transported to the radiator.

The first type of system, the so-called out-of-core concept, has the advantage that separating the diodes from the core eliminates the close coupling between the reactor and the thermal and electrical aspects of the diode. It also removes the diode electrical insulators from the reactor's fast-neutron flux region, in which they are subject to radiation damage; it eliminates interactions between diode performance and fuel behavior (such as swelling of the clad and fission-gas venting); and it makes the system similar to most other reactor space power systems in that a separate, compact liquid-metal-cooled reactor can be used. The concept suffers from the basic disadvantage, however, that the heat must be transported from the reactor to the diodes at a temperature above the emitter temperature. The emitter temperature is therefore limited by compatibility of the heat-transport fluid with the constructional material, by high-temperature strengths of materials, and by the electrical conductivity and thermal resistivity of the insulators. These factors may limit such emitter temperatures to about 2600° F.

As regards the in-core concept, by having the diode emitters in direct thermal contact with the fuel, insulators are not required at emitter temperatures, but they are exposed to the neutron flux. Furthermore, the temperatures of the insulators and liquid metal are substantially below that of the emitters, and are generally at comfortably low levels as regards electrical properties of ceramics, and strength and corrosion of metals.

Principal fuels investigated for thermionic reactors have been uranium dioxide and its cermets and uranium carbide. The key problems facing the integration of the fuels with the diodes are disposition of gaseous fission products, fuel swelling at high burnups, and radiation damage of insulators and seals. A 1963 survey of in-pile diode tests indicated no fueled-diode surviving beyond a few hundred hours. Reports of recent in-pile diode tests in France have pushed survival times over 1500 hours, while in this country one in-pile diode recently reached 5500 hours and another, 8000 hours.

There has been a serious question as to whether an in-core thermionic reactor would have inherently stable nuclear characteristics. Concern has centered around the possibly slightly positive Doppler coefficient of reactivity of fuels highly enriched in U-235. Analog computer investigation of this problem at the Jet Propulsion Laboratory has indicated the problems may not be critical, although appreciably more work will be required.

VI. Concluding Remarks

From the foregoing account it can be seen that each of the four power conversion systems has its own advantages and disadvantages. And the technology of these systems has not yet progressed to the point that it can be foretold with certainty which of them will prove the most attractive. In the course of time, the potentialities of each will become better known, so that a preference for one or another for a given type of mission will emerge. At some point the development of one or more of the systems will undoubtedly be discontinued due to technical problems and budgetary pressures, particularly as the more promising systems enter the costly development stage. However, at the present time the ultimate capabilities of each system are not defined. Hence no attempt has been made in this paper to predict which systems are most likely to see actual usage.

THE AUTHOR

Mr. Mather graduated with Honors from Cambridge University, majoring in physics, chemistry and mineralogy. He subsequently obtained Masters degrees in metallurgy from Cambridge University and the Massachusetts Institute of Technology. He came to NASA-Lewis Research Center in 1963 after working in development and applications engineering in the steel industry. During World War II he served as Chief Metallurgist of Willys-Overland Motors and, subsequently, of Kaiser-Frazer Corporation. At Lewis Research Center he was initially Chief of Nuclear Power Technology Branch, and is currently Chief of Direct Energy Conversion Systems Branch. He has been a member of some twenty industry and Government technical committees and chairman of several of these, mostly in the field of engineering materials. He has published a number of papers in this area. He has been a member of and served on committees of several professional societies, including IAA, AIME, ASM, ASME, ASTM, and SAE.

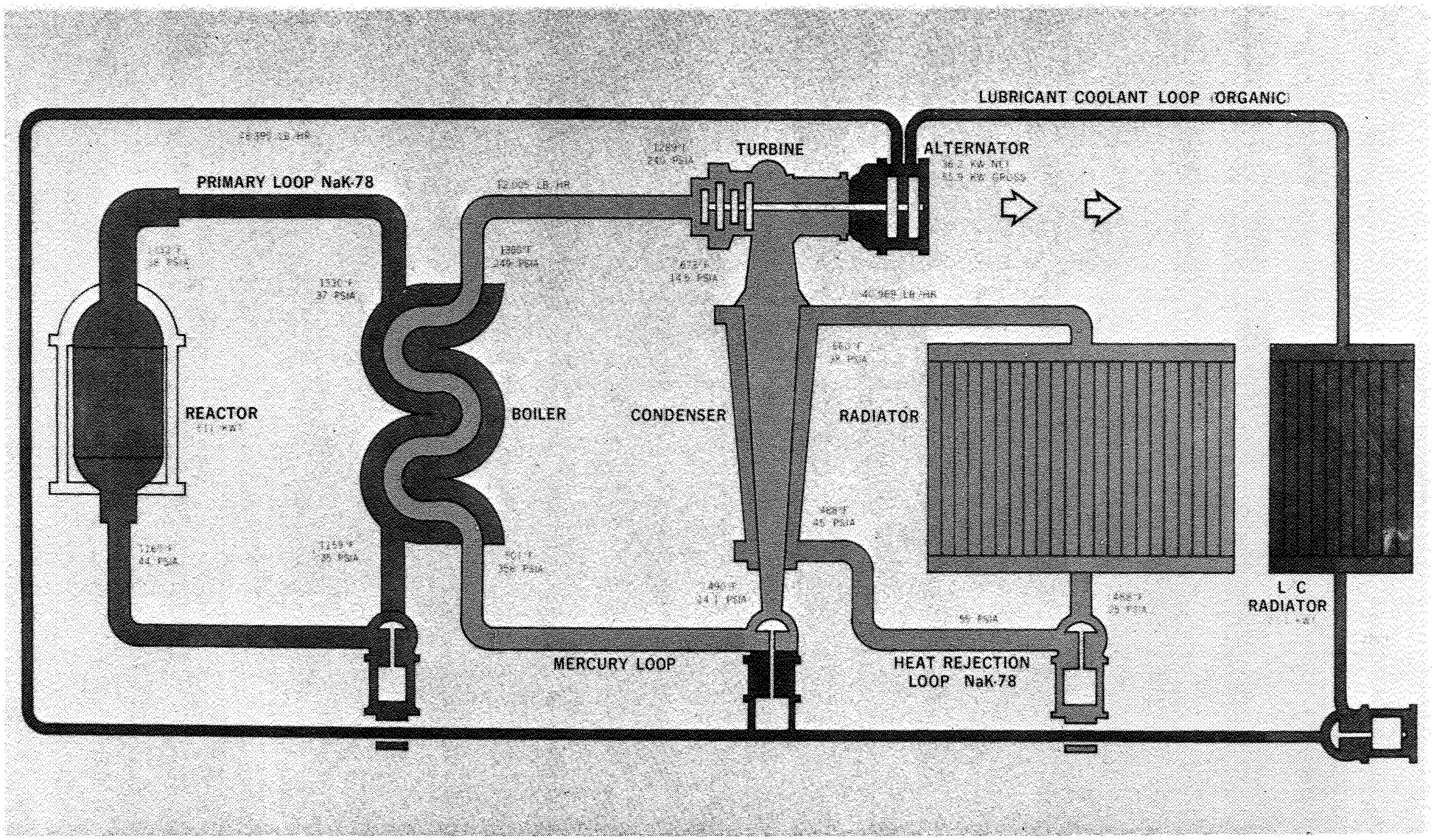

Figure 1. SNAP-8 mercury Rankine turbo-generator system.

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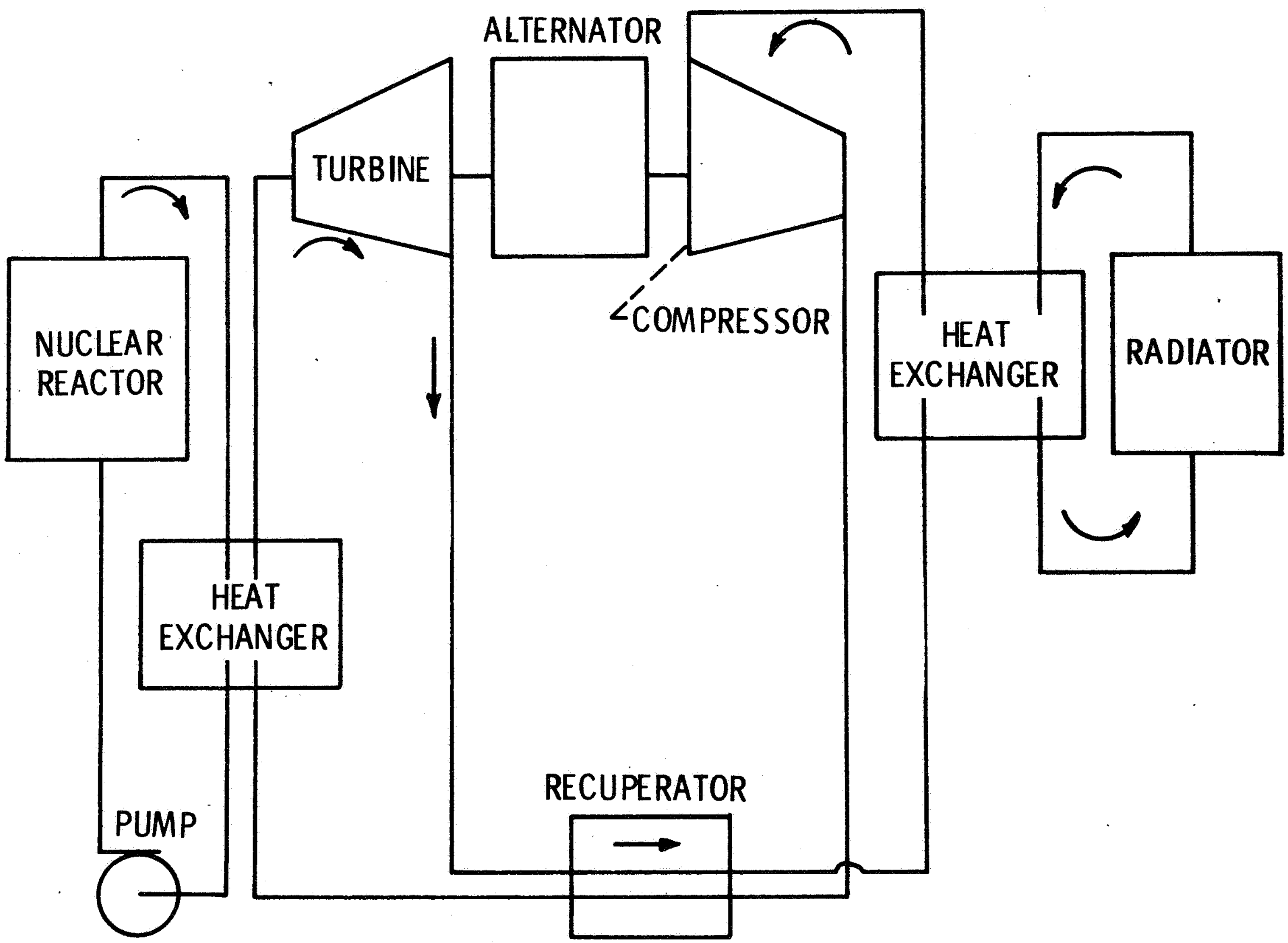

Figure 2. Brayton cycle electric generating system schematic.

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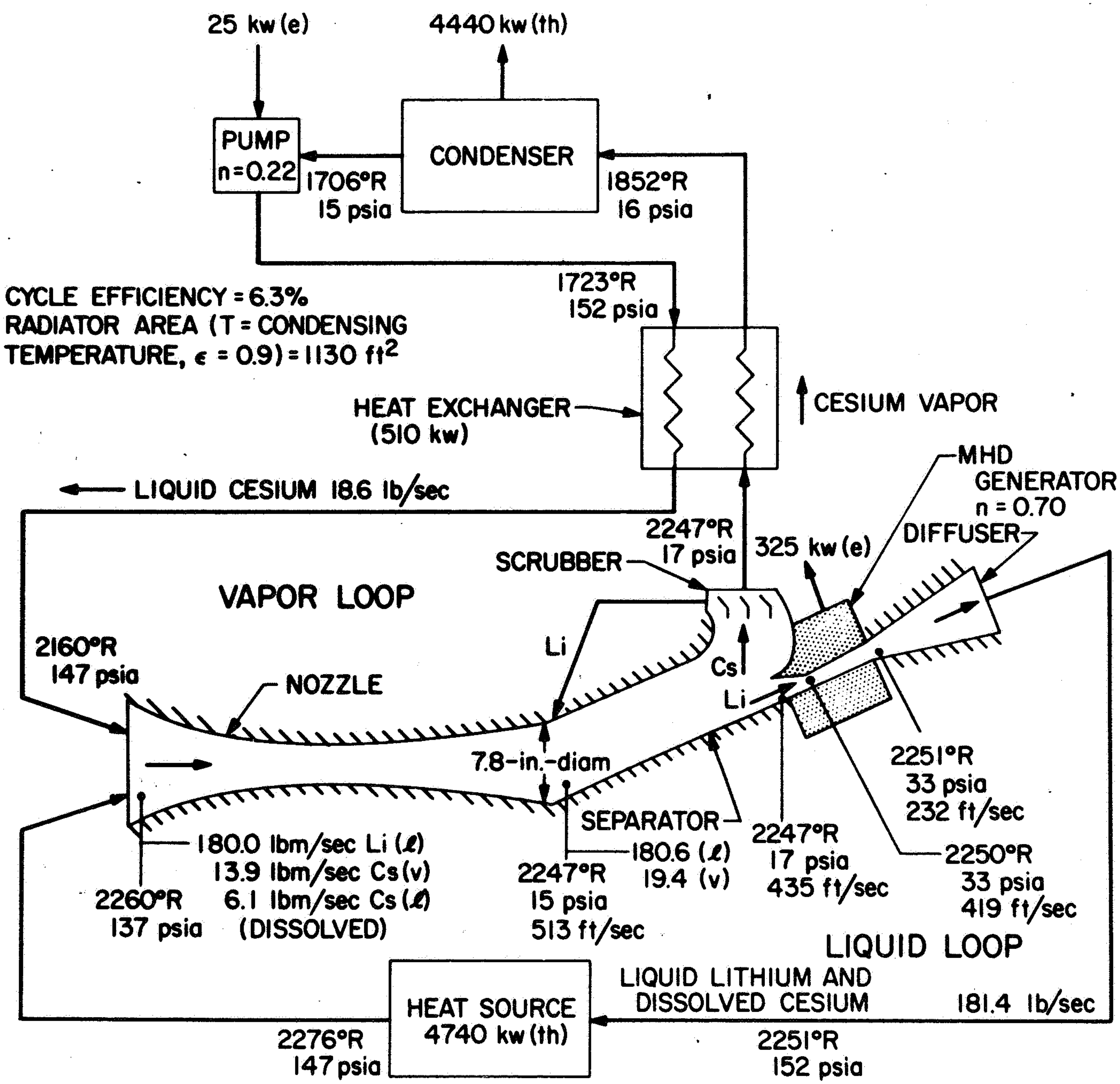

Figure 3. Rankine MHD system.

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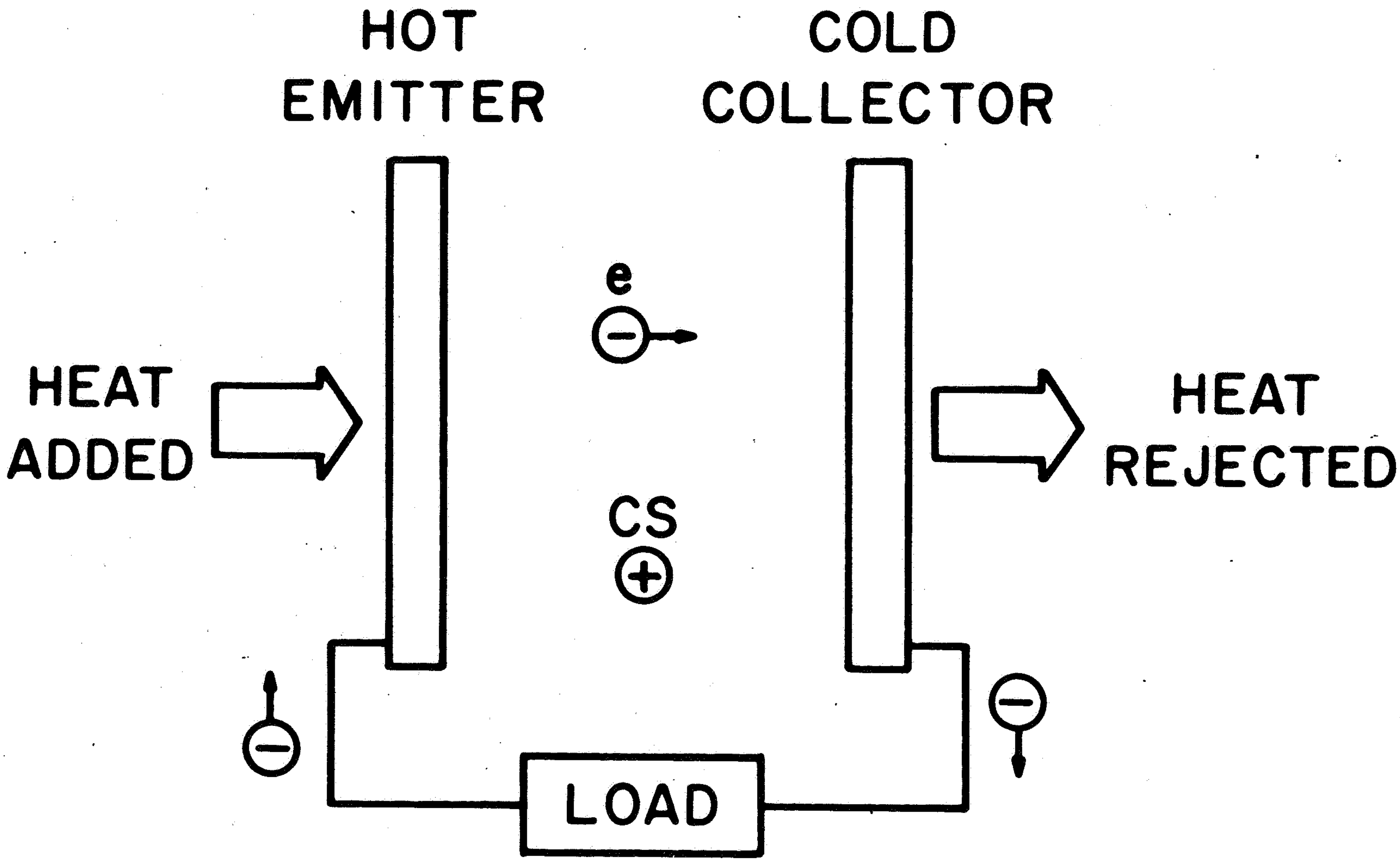

Figure 4. Thermionic converter.