9 I. REFRACTORY-ALLOY REQUIREMENTS FOR SPACE POWER SYSTEMS

T. A. Moss,* R. L. Davies,* and G. J. Barna*

SUMMARY

Various types of large nuclear space power systems are being investigated in support of missions projected for the post-1980 period. Among the approaches being considered to meet projected needs are the potassium Rankine cycle, Brayton cycle, and thermionic systems operating at relatively high temperatures in order to achieve high performance. All these systems require refractory alloys for structural purposes and employ alkali metals as process fluids. Heat for driving the systems would be supplied by a liquid-metal-cooled fast reactor. In the potassium Rankine engine, liquid potassium is vaporized in a boiler and used to power a vapor turbine similar to a central station steam-electric powerplant. Inert gas is compressed, heated, and expanded through a turbine in the Brayton cycle similar to air in the jet engine. Thermionic systems are dependent upon boiling electrons off a hot nuclearly heated surface and collecting them on a colder adjacent surface. The Rankine engine is characterized by a moderate system efficiency and small radiator; the Brayton cycle usually exhibits a high efficiency with a relatively large radiator but a relatively low system efficiency. The system specific weights for the Rankine and Brayton engines are approximately the same, while that of the thermionic system would be higher. Technology programs have been conducted in support of all three types of systems and, in particular, considerable effort has been placed on characterizing the refractory alloys which would be required for the construction of the systems. Papers presented in this report are the result of these refractory-alloy technology programs.

INTRODUCTION

Since the beginning of the space age with the launching of the first Sputnik, electric power used on spacecraft of all types has continued to increase from tens

*NASA Lewis Research Center, Cleveland, Ohio.

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of watts to the low-kilowatt level. This growth of auxiliary electric power for space applications is compared to the growth of power requirements for aircraft in figure I-1. Power requirements started out at relatively low levels for airplanes like the Ford Trimotor and gradually increased over the years as the size of the aircraft and mission requirements increased. Larger power requirements for cabin air-conditioning, communication, navigation aids, weapon systems, and countermeasures gradually increased the amount of electric power needed to sustain normal operation. Although in recent years the rate of growth of demand by aircraft for electric power has diminished, the required powers have increased to several hundred kilowatts.

Not unlike aircraft, the power requirements for spacecraft started at a relatively low level (fraction of a kilowatt) and, as the sophistication of the missions increased, the demand for power increased over the years. The power requirements for nearly all the unmanned satellites have been met by utilizing a combination of solar cells and batteries, while the manned spacecraft have utilized both fuel cells and batteries. Unmanned spacecraft like Nimbus and OAO typically require between 400 and 800 watts of electrical power, which is easily met by solar cells and batteries. Solar-cell systems as large as 3 kilowatts have been flown in a few unmanned satellites, and it is likely that solar-cell systems in the tens of kilowatts will be flown in the 1970's. However, because of the low efficiency of the solar cell and the low power density of solar flux, the relatively large areas and orientation toward the Sun which solar panels require limit their usefulness for these large powers.

Manned spacecraft have used hydrogen-oxygen fuel cells coupled with batteries to meet their present needs. An inherent characteristic of the fuel cell is that it requires a continual supply of reactants in order to produce power; therefore, for long missions the weight of the power supply is directly proportional to the length of the mission. For missions longer than 1 or 2 months, more advanced systems using nuclear energy as the power source appear more promising because of their lower specific weights. Earth-orbiting space laboratories are presently estimated to require a few hundred kilowatts of electric power during the early 1980's.

Several types of power systems could potentially satisfy these demands for electric power for future Earth-orbit space missions. The general area in which each type of power system has the lowest weight is shown in figure I-2. For missions longer than 10 weeks and requiring powers of 100 kilowatts or more, nuclear reactor systems offer advantages over the solar-cell and fuel-cell systems used on space missions to date. These future reactor systems which will produce high power for long times are discussed in this paper.

In order for these reactor power systems to be both compact and of low weight,

they must have the following general characteristics. The nuclear reactor must be small in size, for reactor size has a marked effect on shield weight, which is substantial for manned missions. The alkali liquid metals permit high heat-transfer rates and thus help reduce reactor size if they are used as the reactor coolant. Attainment of high efficiency in the conversion of heat into electric power also helps decrease weight per electric kilowatt for the reactor and shield, simply because a larger amount of electric power can be produced from a given reactor and shield if the conversion efficiency is high. For thermionic systems, the great sensitivity of this conversion efficiency to operating temperatures makes desirable the use of the highest practical temperatures. Radiator size is another factor affecting both the size and weight of these power systems, and high operating temperatures drastically reduce radiator size. Therefore, for all these reactor power systems, alkali liquid metals and the highest practical operating temperatures (perhaps 2000° F or higher) are both desirable.

Operating at temperatures of 2000° F or above presents a number of materials problems, but especially alloy strength and compatibility with the process fluids. Figure I-3 shows the typical strength of superalloys and tantalum alloys. Because these nuclear power systems are required to operate for several years, the data shown are for 1 percent creep in 3 years. The superalloys have little strength at temperatures above 1600° F; for higher temperatures, refractory alloys must be considered. Shown specifically are data for the relatively fabricable tantalum-base alloys, which have strength over the temperature range 1800° to 2600° F superior to that of most other alloys. It is, in part, for this reason that the tantalum alloy T-111 (Ta-8W-2Hf) has been selected as the reference alloy for most high-temperature space power systems.

The use of refractory alloys and the 2000° F temperature limits the substances that can be employed for process fluids to the inert gases and alkali metals. Inert gases can be used with confidence over the temperature range of interest and present no compatibility problem with refractory alloys if they are maintained free of oxygen and other contaminants. Alkali metals must also be kept free of contaminants if compatibility with the refractory metals is to be maintained. In addition, extreme care must be exercised to prevent contamination of the refractory alloy with oxygen during processing, fabrication, and terrestrial testing.

As shown in figure I-4, the alloy Ta-10W is severely attacked by potassium at 1800° F, the potassium penetrating the whole wall thickness of the refluxing capsule within 128 hours. On the other hand, exposure of the T-111 (Ta-8W-2Hf) alloy in figure I-5 to potassium at 2400° F for 2000 hours resulted in essentially no attack. These alloys are nearly identical in composition except for the addition of the 2 weight percent hafnium to the T-111 alloy. In the case of the Ta-10W, oxygen

picked up during processing and testing is dissolved in the tantalum base matrix and produces a high oxygen concentration at the grain boundaries. The alloy is then susceptible to preferential attack by the alkali metal in these regions of high oxygen content, oxygen and base metal being removed by the alkali metal to form voids along the grain boundaries. This type of intergranular attack is clearly visible in the Ta-10W alloy.

Hafnium in the T-111 alloy getters oxygen picked up during processing or testing, combining with it to form the very stable hafnium oxide (HfO_2). This oxide is relatively unaffected by the alkali metal, as are the pure elements columbium, tantalum, tungsten, molybdenum, and rhenium. If, however, the hafnium in the alloy becomes totally oxidized, the Ta-10W and T-111 alloys behave similarly, both being attacked. The control of the oxygen level and the gettering of any oxygen in the containment alloy are thus the most important items in successfully containing alkali metals. In general, alloys containing hafnium display negligible corrosion in contact with the alkali metal for periods of up to 10 000 hours at temperatures up to at least 2200°F when the proper procedures are followed.

Since alkali metals are desired as process fluids for these high-temperature nuclear systems, most of the alloys being considered for these systems contain a gettering element such as hafnium. In addition, stringent controls are exercised throughout the programs conducted in support of these systems in order to limit the amount of oxygen present in the alloy, in the alkali metal, or added during either welding or testing.

A number of different schemes can be employed to convert the thermal energy from a nuclear reactor into electricity. Three basic types of systems which are presently being actively developed by NASA for large nuclear power requirements are the potassium Rankine cycle, the Brayton cycle, and thermionic systems. In the potassium Rankine system, potassium vapor is used to drive a turbine similar to steam in a central powerplant. For the Brayton-cycle system, inert gas is compressed, heated, and then expanded through a turbine as is done in the jet engine; and the thermionic systems depend upon boiling electrons off the hot surface of an electron emitter and collecting them on a cooler surface, thereby generating a voltage between the hot and cold electrodes. Each of these approaches has its own inherent advantages and disadvantages, which are covered later in this paper, and they must operate at temperatures of the order of 2000°F or above in order to achieve low specific weights. It will be shown that each system utilizes refractory alloys for structural purposes and requires alkali metal loops to transport heat about the system.

POTASSIUM RANKINE CYCLE

The potassium Rankine system is shown schematically in figure I-6. The engine consists of four separate fluid loops: an all-liquid reactor loop, a two-phase power-conversion loop, an all-liquid waste-heat-rejection loop, and an all-liquid cooling loop. In the reactor primary loop, lithium at 2100°F is pumped through the nuclear reactor, where it is heated to 2200°F . The lithium then flows through a tube-and-shell counterflow heat exchanger, where heat from the lithium is used to boil potassium; from this heat exchanger, the lithium is returned to the primary pump.

In the boiling-and-condensing power conversion loop, 1000°F potassium is discharged from the pump through the boiler, where it is converted from liquid to superheated vapor at 2100°F . The high-pressure potassium vapor is expanded through a turbine which is used to turn an alternator and generate electricity. From the turbine the mixture of vapor and liquid at 1220°F is exhausted into the condenser, where the remaining vapor is condensed. The tube-and-shell condenser is cooled by 980°F sodium-potassium eutectic (NaK), which is circulated to a space radiator by a pump; waste heat from the cycle is rejected by radiation from this radiator to space. The low-temperature-potassium cooling loop is an appendage of the power-conversion loop and is used to provide 700°F potassium lubricant to the turboalternator bearings and cooling to electrical windings.

Lithium is used in the primary loop to cool the reactor because of its relatively low vapor pressure at 2200°F and its high specific heat, which results in low pumping power. Potassium is selected for the two-phase working fluid because of its appropriate vapor pressure for this application. NaK is utilized in the radiator because its relatively low melting temperature prevents freezing of the fluid during initial startup of the engine. Fluid in each of the loops could be circulated by electromagnetic pumps, although centrifugal pumps would improve system efficiency. All of the piping and major components in the lithium primary and two-phase potassium loops are of refractory metal; transition from refractory alloys to superalloys is made between the condenser and the radiator.

An artist's sketch of the system and its major components as configured for an unmanned spacecraft is shown in figure I-7. The nuclear reactor is placed at the cone apex or nose of the payload with a shadow nuclear shield of tungsten and lithium hydride immediately below it. The remaining power conversion components and the rest of the spacecraft are hidden behind the shadow shield, where the radiation dose rate is of an acceptable level, usually 5×10^{12} nvt for unmanned applications. Shaping of the various components and lines is used to obtain efficient compact packaging of the engine within its radiator. Typically, conical or cylindrical radiators are

used for these engines. One of the biggest advantages of the Rankine engine is that its relatively high main radiator temperature results in a relatively low specific radiator area (approx. $3 \text{ ft}^2/\text{kWe}$),¹ which can easily be fitted on available launch vehicles. The net system efficiency for a nominal-300-kilowatt-electric Rankine system is approximately 19 percent at the temperatures shown in figure I-6.

A conceptual 2-megawatt-thermal fast-spectrum nuclear reactor which could be used in conjunction with the Rankine and other power conversion systems is shown in figure I-8. The once-through lithium-cooled reactor consists of approximately 250 fuel elements containing uranium-235 nitride fuel clad in T-111 tantalum alloy. Uranium nitride was selected as the fuel form because of its relative compatibility with the lithium coolant as compared to the oxide or carbide. However, a 5-mil tungsten barrier must be interposed between the nitride fuel and the 60-mil T-111 cladding in order to prevent reaction between the fuel and hafnium in the cladding. The fuel elements are not vented and, therefore, the cladding must withstand fission-gas pressure buildup during the lifetime of the reactor. Each fuel element will be approximately 3/4 inch in diameter and be contained in a honeycomb matrix of T-111 tubes.

Control of the reactor is achieved by rotating six control drums containing fuel in half the drum and tantalum (T-111) neutron absorber on the opposite half with electric stepping motors external to the pressure vessel. As fuel is turned toward the center of the core and tantalum neutron absorber moves away from the core, reactor reactivity can be increased in order to compensate for fuel burnup. Conversely, rotating the fuel out and tantalum in reverses the process. Each control drum assembly is supported on lithium-lubricated bearings.

The pressure vessel would be fabricated from T-111 alloy, as would be the whole primary loop. The approximate overall dimensions of the pressure vessel would be an outside diameter of 23 inches and a length of 32 inches. Estimated fuel burnup of such a reactor would be approximately 3.8 atomic percent in 50 000 hours.

The potassium boiler (fig. I-9) is a counterflow tube-and-shell heat exchanger in which the hot lithium is used to vaporize and superheat the potassium to 2100°F and 163 psia. For a 2-megawatt-thermal boiler, approximately 31 tubes of 0.5-inch diameter, 0.035-inch wall, and 80-inch length are required to provide the necessary heat-transfer area. Special twisted-tape or wire-coil inserts are used in each tube to enhance heat transfer and avoid possible zero-gravity effects on the boiling process. The T-111 alloy is used throughout, and the boiler is designed in

¹All specific radiator areas are based on total radiator area, i.e., sum of the main radiator, intermediate temperature radiator, and electronic coolant radiator areas necessary for controls and pump power conditioning.

a C-shaped configuration to accommodate differential thermal expansion between the relatively hot shell and cooler tubes.

One potassium turboalternator being considered for the Rankine engine consists of a 10-stage axial-flow turbine straddle mounted on potassium-lubricated bearings and flexibly coupled to the alternator, which also has its own set of potassium-lubricated bearings. Potassium vapor entering the turbine at 2100°F is expanded through the first five stages and is then ducted from the turbine to an external moisture separator or reheater. The dry or nearly dry vapor then passes through the last five stages and exits at approximately 1220°F and 5.4 psia to the condensers. Interstage moisture extraction might be employed prior to the last-stage rotor in order to maintain the potassium quality at a high enough level. Turbine tests presently under way will help determine the vapor quality required in order to keep erosion damage to the blades at an acceptable level.

Scroll and casing for the first five stages would be T-111 alloy for temperature resistance, while the intermediate and exit scrolls and the aft casing would be Cb-1Zr alloy for reduced weight, as shown by figure I-10. TZM (Mo-0.5Ti-0.08Zr) has been selected for the turbine rotor and blades because of its superior strength-to-density ratio at the design conditions. The turboalternator would be approximately 6 feet long and 2 feet in diameter at the alternator and would weigh approximately 1300 pounds.

BRAYTON CYCLE

Another high-temperature dynamic system of interest for high power levels is the Brayton-cycle engine shown in figure I-11. A reactor similar to that used for the Rankine engine would supply heat to, say, four parallel power conversion systems, one of which is shown. Lithium, exiting the reactor at 2200°F , would heat in a compact heat exchanger a compressed mixture of He-Xe gases, with an average molecular weight of approximately 40. This molecular weight is the same as that of argon; however, the mixture is used because it has relatively high thermal conductivity owing to the helium, while the average molecular weight of argon favors the performance of the compressor in the system.

In the power conversion loop, the inert gas is compressed by the compressor, preheated to 1443°F in the recuperator, heated to 2100°F in the heat-source exchanger, and then expanded through the turbine to produce mechanical energy. The turbine exhaust energy is then used in the recuperator to preheat the compressor discharge and so increase the overall cycle efficiency. One of the main advantages of this cycle is its high overall efficiency of approximately 25 percent.

The turbine exhaust, after leaving the recuperator, is ducted to the waste heat exchanger and then back to the compressor to complete the closed cycle. Waste heat from the cycle is transported from the waste heat exchanger to the radiator by means of a liquid coolant loop of highly refined mineral oil. A separate organic loop is used to cool bearings and electrical equipment. Since the radiators for this engine operate at such relatively low temperatures (556° to 211° F), the specific radiator area for the engine is approximately 15 square feet per kilowatt electric, or roughly five times as large as for the Rankine engine. Refractory metals need be used only in the reactor primary loop, heat-source heat exchanger, turbine, and turbine scroll of this engine.

A compact heat-exchanger core similar to that required for the heat-source heat exchanger of the Brayton engine is shown in figure I-12. It consists of a liquid manifold feeding 21 tubes of 1/8-inch diameter, each tube having 30 extended-surface fins per inch along its length. In the design shown, the liquid makes eight passes as it loops up and down across the gas duct. Such a heat exchanger for the high-temperature Brayton engine would be constructed primarily from T-111 but would possibly have Cb-1Zr fins brazed to the tubes.

Figure I-13 is an isometric drawing of a possible configuration for a high-temperature Brayton rotating unit with the turbine, alternator, and compressor all on the same shaft. A single-stage radial-flow turbine is employed instead of a multistage axial turbine as was used for the Rankine engine. A single-stage radial-flow compressor is also used. Hydrodynamic gas bearings are shown supporting the shaft; however, oil-lubricated bearings are also being considered. The high-temperature Brayton rotating unit will probably operate above 24 000 rpm, and windage loss caused by the drag of gases in the alternator rotor cavity is of serious concern in the design of the machine. For this reason, the alternator will have a smooth rotor.

NUCLEAR THERMIONIC SYSTEMS

Thermionic static conversion systems are also being considered for large space electric power systems. As mentioned earlier, the basic phenomenon of the thermionic system depends upon boiling electrons off a hot emitter surface of a diode and collecting them on the nearby cold collector surface; useful work is done in an external load as the electrons are returned to the emitter. Typically, a very high temperature is required in order to maintain the thermionic process, a factor which limits the materials used in these devices to the refractory metals. Nuclear systems using the thermionic principle may contain the diodes within the reactor

core or may use a liquid-metal-cooled reactor similar to the one previously described and place the diodes external to the core within a liquid-to-liquid heat exchanger.

A schematic of the in-core thermionic system in figure I-14 shows the system to consist of three major components: reactor, radiator, and electromagnetic pump. An alkali metal is used to transport the waste heat of the system from the diode collector within the core to the radiator. Also, figure I-14 shows a cross section of a typical flashlight diode array. Uranium dioxide or carbide fuel is encapsulated by vapor-deposited tungsten, which acts as the diode emitter. Tungsten with preferential crystal orientation is used for the emitter in order to increase the performance of the diode. Compatibility of the fuel with the cladding and fuel swelling during operation at 3000° F are major problem areas of the system.

The hot emitter is separated from the columbium collector by 10 mils. The separation distance between the emitter and collector has a large effect on the performance of the diode and must be maintained within acceptable levels. The gap between the collector and emitter usually contains cesium at a low (perhaps 1 torr) pressure in order to increase diode performance and stability. Each diode emitter is separated from another by alumina insulation. Alumina is also used to insulate the collectors from each other and from the coolant channel. Degradation of the insulators by neutron damage may be one of the major problems of the concept.

The power density of the diode depicted in figure I-14 might be 11 watts per square centimeter at 0.7 volt. Within each flashlight string, the diodes are connected in a series. Individual strings within the reactor would then be connected in a series-parallel array in order to achieve the desired voltage output from the system. Net system efficiency of approximately 12 percent may be achieved with a specific radiator area of about 5 square feet per kilowatt electric, which is somewhat higher than for the Rankine engine. Reactor size would also be increased by the volume occupied by the diodes.

Figure I-15 shows the schematic for the thermionic system in which the diodes are contained in a heat exchanger external to the reactor core. Lithium, circulated by an electromagnetic pump, is heated in the reactor to 2800° F and used to heat the diode emitters in the heat exchanger. The heat exchanger is made up of a large number of diode strings similar to that shown in the cross section (fig. I-14). Hot lithium flows down the center T-111 tube, which is surrounded by the individual diodes. The oriented-tungsten emitter, the lithium-containment tube, and the alumina insulator separating them form a monolithic bonded structure which is referred to as a trilayer. A metallurgical bond must be maintained between the individual layers of the trilayer if adequate thermal conductivity is to be maintained between the emitter surface and the hot lithium.

A second trilayer is required between the collector and the NaK coolant of the radiator loop. As before, diodes in a string are connected in series. The power density of these converters would be approximately 6 to 8 watts per square centimeter at 0.5 volt, and system efficiency would be about 10 percent. Since the radiator temperature is lower than for the in-core system and efficiency is also lower, the specific radiator area is higher by about 8 square feet per kilowatt. The transition between refractory alloys and superalloys would be made between the diode heat exchanger and the radiator.

PROGRAM APPROACH

The program approach which has been used to develop space electric power systems for future space missions has included the following procedures: conceptual engines were defined to satisfy general mission application, power ranges, and lifetimes, after which the engines were analyzed for potential problem areas where technology programs had to be undertaken to support their development. As an example, extensive technology programs were conducted in the areas of turbine erosion, boiling heat transfer, alkali-metal compatibility, and refractory-alloy strength. Work on gas bearings was done in support of the Brayton cycle engine, while for the thermionic system primary emphasis has been on the diodes. After the supporting technology is well in hand and understood, a more definitized or nominal engine is evolved, and development of major engine components is undertaken. Following component demonstration, proven components will be integrated into a complete nuclear system, which will be tested in the Space Power Facility at Plum Brook.

The refractory-metal technology which is covered in the remaining papers was performed in support of the various systems that have been described. At the present time, most of the technology necessary to support development of major components has been completed, and some components such as the boiler-feed pump for the Rankine engine are built and ready for testing. During the next 2 or 3 years, the emphasis of the program will continue to shift from supporting technology to component development in which new problems associated with building hardware will be encountered.

Figure I-1. - Growth of aeronautical and space power systems.

Figure I-2. - Electric power systems for Earth orbit.

Figure I-3. - Strength capability of tubing alloys.

Figure I-4. - Corrosion of tantalum-10 tungsten alloy by potassium. Ungettered alloy.

Figure I-5. - Corrosion of T-111 alloy by potassium. Gettered alloy.

Figure I-6. - Potassium Rankine system.

Figure I-7. - Typical flight configuration.

Figure I-8. - Nuclear powerplant reactor.

Figure I-9. - T-111 potassium boiler. Nominal power, 2000 kilowatts thermal; heating fluid, lithium; potassium outlet temperature, 2100° F.

Figure I-10. - Potassium turbine-alternator.

Figure I-11. - High-temperature reactor Brayton cycle.

Figure I-12. - Typical compact heat exchanger core.

Figure I-13. - Brayton turbine-alternator-compressor.

Figure I-14. - In-core thermionic system.

Figure I-15. - Out-of-core thermionic system.