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POTASSIUM RANKINE CYCLE POWER CONVERSION SYSTEMS FOR LUNAR-MARS SURFACE POWER*

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ABSTRACT

The potassium Rankine cycle has good potential for application to nuclear power systems for surface power on the moon and Mars. A substantial effort on the development of the power conversion system was carried out in the 1960's which demonstrated successful operation of components made of stainless steel at moderate temperatures. This technology could be applied in the near term to produce a 360 kW(e) power system by coupling a stainless steel power conversion system to the SP-100 reactor.

Improved performance could be realized in later systems by utilizing niobium or tantalum refractory metal alloys in the reactor and power conversion system. The design characteristics and estimated mass of power systems for each of three technology levels are presented in the paper.

INTRODUCTION

The concept of employing an alkali metal, especially potassium, in a Rankine cycle power conversion system to produce electrical power for space applications has been recognized for over 30 years to offer several technical advantages. In this concept heat generated in a liquid metal-cooled nuclear reactor is transferred from the reactor coolant in an external boiler to generate potassium vapor. The vapor is expanded through a turbine, which drives a generator, then the vapor is condensed in a condenser-radiator which dissipates the waste heat by thermal radiation to space. Liquid from the condenser is returned by a pump, either electromagnetic or turbine driven, to the boiler to complete the cycle.

The advantages offered by the cycle, compared to other cycles, are relatively high thermodynamic cycle efficiency, small radiator area, and low specific mass. The high cycle efficiency is a result of the favorable thermodynamic properties of potassium for use in a Rankine cycle. A small radiator area is made possible by the high temperature at which heat may be rejected from the cycle. The low specific mass stems from the combined effects of the small radiator area and high power density achievable in both reactor and the turbine-generator.

Development work on the potassium Rankine cycle was carried out from about 1959 until 1972 under the SNAP 50 Space Power Unit Reactor program and the Medium Power Reactor Experiment (MPRE), both of which were jointly sponsored by NASA and AEC.

Pratt and Whitney Aircraft Co. designed the SNAP 50/SPUR system and conducted development work on the reactor, shield, boiler and condenser.¹ Another major contractor was General Electric Co. who carried out development work on the boiler, turbine, and condenser.

The MPRE system was designed by Oak Ridge National Laboratory (ORNL).² This system consisted of a boiling potassium fast reactor connected directly to a turbine generator, and included a turbine-driven liquid feed pump and a direct condenser-radiator. Development work was conducted on electrically-heated boilers designed to simulate a scale model of the reactor, with associated turbine-pumps and condensers. A potassium vapor temperature of about 1110 K was chosen so that stainless steel could be used as the major construction material. A condensing temperature of 833 K was selected, which yielded the minimum weight for the system for a turbine inlet temperature of 1110 K.

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The overall results of the development work demonstrated cycle components (boilers, turbines, condensers, and pumps) fabricated from stainless steel would operate successfully, with negligible corrosion or turbine blade erosion, at temperatures of the order of 1100 K for up to several thousand hours.² The most noteworthy results were achieved in successful tests of 5000 h each of two 150 kW potassium turbines operating at 1100 K by General Electric Co.³

Boiling and materials tests in refractory metal alloy tubes (Nb-1Zr and T-111) demonstrated successful operation with potassium for temperatures of up to 1450 K.^{4,5} These results indicate that there is a high probability that turbines fabricated from tantalum alloys would also operate successfully at temperatures up to 1450-1500 K.

The potassium Rankine cycle, coupled to a liquid metal-cooled nuclear reactor, has very great potential as a lightweight power plant for applications on the surface of the moon or Mars.

The object of this paper is to investigate the conceptual design of Rankine cycle systems utilizing the SP-100 nuclear reactor as a heat source.⁶ System designs are considered at three levels of cycle peak temperature, corresponding to three different types of material for construction of the power conversion system or reactor.

SP-100 REACTOR RANKINE CYCLE POWER SYSTEMS

The past development effort on the Rankine cycle demonstrated the chemical compatibility of potassium with stainless steel and successful operation of key components at temperatures up to 1100 K. Further, boiling and materials tests demonstrated good chemical compatibility of potassium with refractory metal alloys at temperatures up to 1450 K. These results suggest that one interesting approach to the application of Rankine cycle power conversion might be a phased approach wherein the first system would be built of stainless steel and operate at a peak temperature of 1100 K and thus capitalize on the technology previously demonstrated. Follow-on systems would employ refractory metals and operate at higher temperatures. The stainless steel system, while yielding lower performance, offers the advantages of reduced time and cost for testing since it could be fabricated more easily and could be tested exposed to the atmosphere, avoiding the need for a vacuum chamber, which would be required for systems made of refractory metal alloys.

The Rankine cycle system is ideally suited for use with the SP-100 reactor currently being developed. Heat from the primary lithium coolant would be transferred in a compact boiler to generate potassium vapor for driving the turbine in the power conversion loop. A conceptual design of an SP-100 reactor-Rankine cycle power plant for use on the surface of the moon or Mars was examined for each of three technology levels:

1. SP-100 reactor with a coolant outlet temperature of 1190 K with a power conversion system made of stainless steel with a peak potassium temperature of 1100 K.
2. SP-100 reactor with a coolant outlet temperature of 1350 K with a power conversion system made of refractory metal alloy with a peak potassium temperature of 1260 K.
3. An advanced SP-100-derivative reactor with high temperature refractory metal fuel cladding and a coolant outlet temperature of 1590 K with a power conversion system made of high temperature refractory metal alloy with a peak potassium temperature of 1500 K.

The flow schematic diagram is shown in Fig. 1. The arrangement of the system envisioned is the same for each design. It is assumed that the reactor would be placed in a hole excavated and backfilled and that the balance of the plant would be located at the surface. The radiators would be deployed in two directions 180° apart.

STAINLESS STEEL SYSTEM — Employing stainless steel as the material of construction in the power conversion system restricts the potassium vapor temperature at the boiler outlet to about 1100 K to avoid material compatibility problems. The optimum condensing temperature for near minimum system mass, is about 850 K which yields a cycle efficiency of 15%. The SP-100 reactor is designed for refractory metal alloy fuel cladding and structure to produce a heat output of about 2.4 MW(t) at a lithium coolant outlet temperature of 1350 K. In this concept, the coolant outlet temperature would be reduced to 1190 K, but the heat output retained at 2.40 MW(t). This would yield an electric power output of 360 kW(e), which would be of considerable value for the early stages of manned lunar or Mars bases.

The power conversion system characteristics were computed by means of the ALKASYS computer code for Rankine cycle space nuclear power systems.⁷ The key results for performance and size are given in Table 1. The design employs 2 operating and 1 standby turbine-generator. Each turbine consists of 5 axial stages, with an overall outer casing diameter of 44 cm at the discharge end and an overall length of 64 cm.

The computed mass for each subsystem is shown in Table 2. The power conversion subsystem, consisting of 3 turbine-generators and associated pumps, feed heaters and piping, has a mass of 821 kg. The condenser-radiator is the heaviest subsystem, 3398 kg. The relatively large radiator area results from the lower condensing temperature in this concept. The mass of the power conditioning subsystem was assumed on the basis of 5 kg/kW(e). The overall system has a mass of 7770 kg, yielding a specific mass of 21.6 kg/kW(e), which is attractive

Fig. 1. Rankine cycle flow schematic diagram.

Table 1. System design characteristics

System	Stainless Steel	Refractory Metal	Advanced Reactor
Net power output, kW(e)	360	480	550
Net cycle Efficient, %	15	20	22.3
Reactor Outlet Temperature, K	1,190	1,350	1,590
Turbine Inlet Temperature, K	1,100	1,260	1,500
Turbine Inlet Pressure, kPa	186	579	1,965
Turbine Exhaust Temperature, K	850	900	1,025
Main Radiator Temperature, K	806	856	981
No. Turbine Stages	5	6	6
Turbine Exhaust OD, cm	44	35	25
Turbine Length, cm	64	63	56
Turbine speed, RPM	18,000	26,000	47,000
No. T-G, Operating/Standby	2/1	2/1	2/1
Main Radiator Planform Area, m ²	127	90	52
Auxiliary Radiator Planform Area, m ²	9	10	11

Table 2. Mass summary

	Stainless steel	Refractory metal	Advanced reactor
<i>mass (kg)</i>			
Reactor	740	740	740
Shield	975	975	975
Boiler	36	39	125
Power Conversion	821	578	493
Condenser-Radiator	3,398	2,500	1,588
Power Conditioning	1,800	2,400	2,750
Total	7,770	7,232	6,671
Specific Mass kg/kW(e)	21.6	15	12.1

compared to the specific mass for an SP-100 reactor-Stirling engine system, which has been estimated to be about 30 kg/kW(e).⁸

REFRACTORY METAL SYSTEM — An SP-100 reactor-Rankine cycle power system which employs a power conversion system fabricated from refractory metal alloys of niobium (Nb1-Zr or PWC-11), as well as the primary system, offers improved performance over the stainless steel system. Operating at a reactor heat output of 2.4 MW(t) and an outlet coolant temperature of 1350 K, the power conversion system could run at 1260 K turbine inlet temperature, which for a condensing temperature of 900 K would yield a cycle efficiency of 20% and an electric power output of 480 kW(e).

As noted in Table 1, each turbine consists of 6 axial stages, with a casing OD of 35 cm at the exhaust and an overall length of 63 cm. As seen in Table 2, the computed mass of the power conversion subsystem is 578 kg. The mass of the radiator is 2500 kg and the total system mass is 7232 kg, yielding a specific mass of 15 kg/kW(e). This improved performance over the stainless steel power conversion system, yielding both a higher power output and a lower mass, provides an attractive incentive to develop the refractory metal system.

ADVANCED REFRACTORY METAL SYSTEM — In the advanced concept, in order to further enhance the performance, higher temperature refractory alloys of tantalum (T-111 or ASTAR 811C) would be employed in both the reactor and power conversion system. Operating an advanced SP-100-type reactor at 2.5 MW(t) and a lithium outlet temperature of 1590 K would permit a turbine inlet temperature of 1500 K, which with a condensing temperature of 1025 K would yield a cycle efficiency of 22.3% and an electric power output of 550 kW(e).

The major improvement obtained from the higher performance is reduction in the area of the main radiator, from 90 m² to 52 m². This in turn yields a lower mass of the radiators, down from 2500 kg to 1588 kg. The overall system mass is computed to be 6,671 kg, resulting in a specific mass of 12.1 kg/kW(e).

The mass of the systems can be reduced further with the use of lightweight radiators and high temperature electronics for power conditioning. The mass of the radiators in the designs presented are based on metallic heat pipes. The successful development of carbon-carbon or ceramic fiber heat pipes with metal liners compatible with potassium will yield a significant reduction in mass. Power conditioning components which can operate at higher temperature (500-600 K) will also yield important mass reductions.

SUMMARY

A potassium Rankine cycle power conversion system coupled to an SP-100 reactor has good potential as a lightweight power plant for applications on the lunar or Mars surface. The technology developed in previous years could be applied in the near term by employing a power conversion system fabricated of stainless steel designed to operate at 1100 K with a power output of 360 kW(e). Improved performance could be obtained with the development of refractory metal systems for operation at higher temperatures. A niobium alloy system designed for 1260 K and 480 kW(e) is estimated to yield a specific mass of about 15 kg/kW(e). Employing tantalum alloys in both the reactor and power conversion system would permit operation at 1500 K and 550 kW(e), which would result in a specific mass of about 12 kg/kW(e).

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