

POTASSIUM RANKINE CYCLE NUCLEAR POWER SYSTEMS FOR SPACECRAFT AND LUNAR-MARS SURFACE POWER*

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ABSTRACT

The potassium Rankine cycle has high potential for application to nuclear power systems for spacecraft and surface power on the moon and Mars. A substantial effort on the development of Rankine cycle space power systems was carried out in the 1960's. That effort is summarized and the status of the technology today is presented. Space power systems coupling Rankine cycle power conversion to both the SP-100 reactor and thermionic reactors as a combined power cycle are described in the paper.

INTRODUCTION

The concept of employing potassium, or other of the alkali metals, in a Rankine cycle power conversion system coupled to a liquid metal-cooled nuclear reactor to produce electrical power for applications in space has been recognized to offer several technical advantages since about 1959. In this concept, heat generated by the nuclear fuel is removed by circulating liquid metal coolant and transferred in an external boiler to generate potassium vapor. The vapor is expanded through a turbine, which drives a generator, and the vapor is then 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.

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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.

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. 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 system has very good potential for nuclear space power applications for spacecraft and lunar or Mars surface power. It is ideally suited for use with liquid metal-cooled nuclear reactors currently being developed: the SP-100 reactor⁶ and the thermionic reactor with in-core fuel element-converters.⁷ The potassium Rankine cycle has potential for enhancement to even higher performance levels through the development of high temperature (1500-1600 K) refractory metal reactors and power conversion systems.

In this paper, the conceptual designs of Rankine cycle systems coupled to either the SP-100 reactor or a thermionic reactor are investigated. 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 spacecraft or 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. In spacecraft applications, a conical-cylindrical radiator geometry would be employed. The arrangement of the system envisioned for surface power 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 spacecraft applications and 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.⁸ The key results for performance and size are given in Table I. 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.

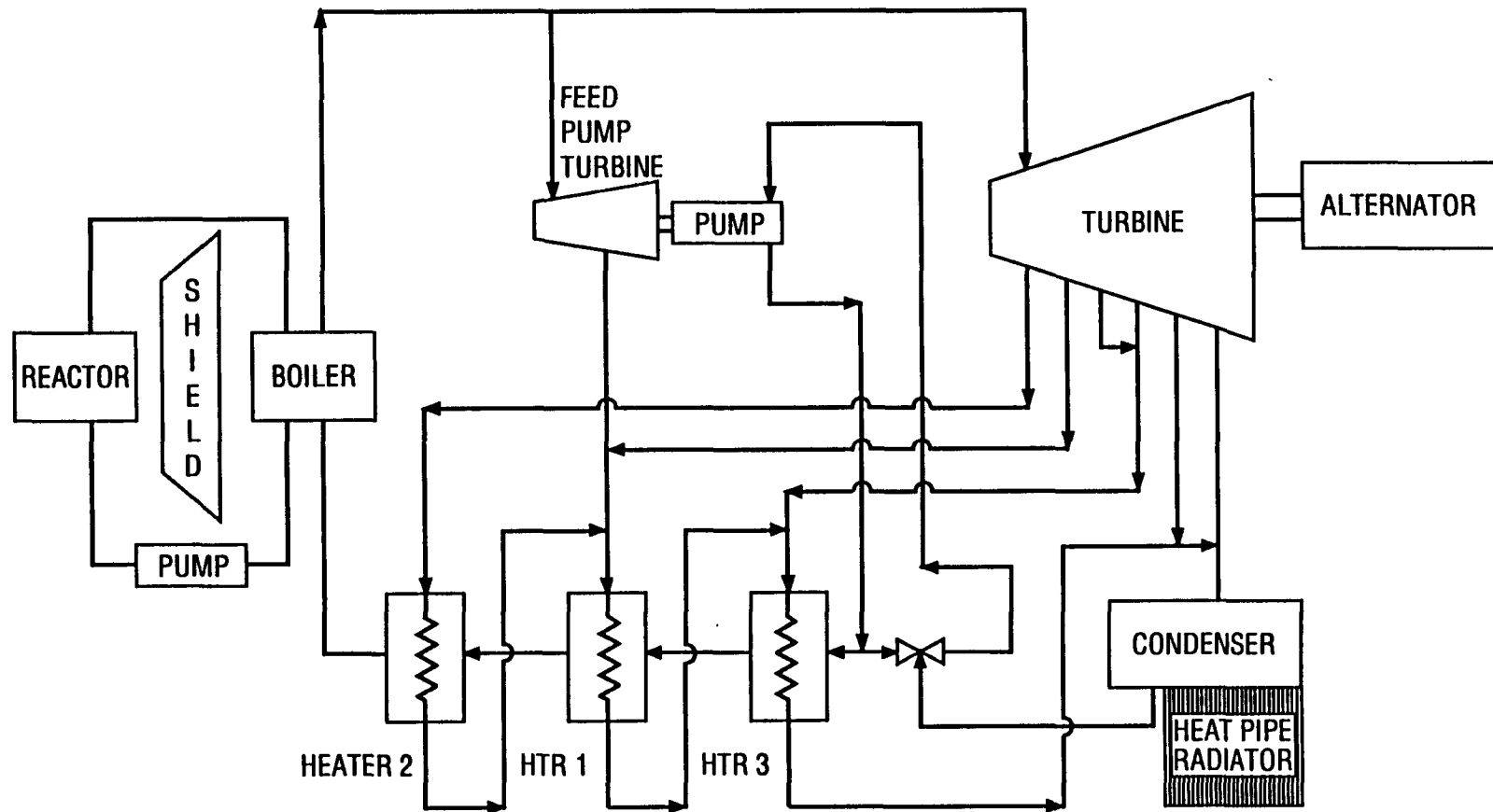


Fig. 1. Rankine cycle flow schematic diagram.

Table I. System design characteristics

System	Stainless Steel	Refractory Metal	Advanced Reactor
Net power output, kW(e)	360	480	550
Net cycle Efficiency, %	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

The computed mass for each subsystem is shown in Table II. 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 compared to the specific mass for an SP-100 reactor-Stirling engine system, which has been estimated to be about 30 kg/kW(e).⁹

Table II. 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

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 I, 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 II, 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.

Larger advanced potassium Rankine cycle systems, with power outputs of 5-10 MW(e), offer the potential of sufficiently low specific mass, on the order of 4-5 kg/kW(e), to be very attractive candidates for powering nuclear electric propulsion vehicles, for both cargo and manned missions.

THERMIONIC-RANKINE COMBINED CYCLE SYSTEMS

A promising potential application of the Rankine cycle system is employing it in a combined cycle with a thermionic reactor where the reactor coolant transfers the reject heat from the thermionic converters to a potassium boiler which generates vapor to drive a turbine generator. Thermionic converters operating at emitter temperatures of 1800-1900 K would have a conversion efficiency of about 8% for a collector temperature of 1200 K. This temperature would be sufficient to drive a potassium Rankine cycle at a turbine inlet temperature of 1100 K. The resulting overall efficiency of the combined cycle would be about 22%. A combined cycle of this type offers the advantage of excellent performance, high efficiency and low specific mass, while permitting the use of stainless steel (or other conventional superalloys) in the potassium system with a lower attendant development cost. The power output from a thermionic reactor could be almost tripled by the addition of the Rankine cycle power conversion as a bottoming cycle. For example, the power output from a 500 kW(t) reactor could be increased from about 40 kW(e) to 110 kW(e). A 2.5 MW(t) reactor would produce 550 kW(e) employing the combined cycle. The characteristics of a 550 kW(e) combined system are shown in Table III. The mass of each subsystem is given in Table IV. The specific mass of this system is estimated to be 17.9 kg/kW(e).

Even greater output could be attained from an advanced thermionic reactor with an emitter temperature of 2100 K coupled to an advanced Rankine cycle employing refractory metal alloys and a turbine inlet temperature of about 1300 K. This combination would yield an overall efficiency of about 28%, so that a 500 kW(t) reactor would produce a power output of about 140 kW(e). Larger systems employing the high temperatures would provide attractive candidates for lunar-Mars surface power applications. For example, a 2 MW(t) reactor would produce a power output of about 560 kW(e). The system characteristics are given in Table III, and the mass summary in Table IV. The specific mass is estimated to be 13 kg/kW(e), significantly lower than the specific mass of the thermionic—stainless steel Rankine cycle system.

Table III. Thermionic-Rankine system characteristics

System	Stainless Steel	Refractory Metal
Thermionic power output, kW(e)	200	200
Total power output, kW(e)	550	560
Combined cycle efficiency, %	22	28
Reactor outlet temperature, K	1,190	1,390
Turbine inlet temperature, K	1,100	1,300
Turbine inlet pressure, kPa	186	731
Turbine exhaust temperature, K	850	900
Main radiator temperature, K	806	856
No. turbine stages	5	6
Turbine exhaust OD, cm	44	31
Turbine length, cm	64	58
Turbine speed, RPM	18,600	31,400
No. T-G, operating/standby	2/1	2/1
Main radiator planform area, m ²	123	61
Auxiliary radiator planform area, m ²	9	7

Table IV. Thermionic-Rankine system mass summary

	Stainless steel	Refractory metal
<i>mass (kg)</i>		
Reactor	1,760	1,410
Shield	1,190	950
Boiler	36	28
Power Conversion	797	417
Condenser-Radiator	3,304	1,712
Power Conditioning	2,750	2,800
Total	9,837	7,317
Specific mass, kg/kW(e)	17.9	13

SUMMARY

The potassium Rankine cycle power conversion system is ideally suited for use with both the SP-100 reactor and thermionic reactors for spacecraft and extra-terrestrial surface power applications. A near-term system fabricated of stainless steel, or other conventional materials, would produce 360 kW(e) coupled to the SP-100 reactor, or 550 kW(e) employed in a combined cycle coupled to a 2.5 MW(t) thermionic reactor. An advanced system fabricated of niobium alloy would produce 480 kW(e) with the SP-100 reactor for a specific mass of 15 kg/kW(e), or 560 kW(e) combined output with a 2 MW(t) thermionic reactor for a specific mass of 13 kg/kW(e).

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