STATUS OF RANKINE-CYCLE TECHNOLOGY FOR SPACE NUCLEAR POWER APPLICATIONS*

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Abstract

A substantial effort on the development of the liquid metal Rankine cycle space nuclear power system was carried out in programs jointly sponsored by the National Aeronautics and Space Administration (NASA) and the Atomic Energy Commission (AEC) during the period of 1960-1972. Component tests were conducted which have established a considerable technology base for the concept. The development effort and technology status of each component are presented. The key technology issues remaining for development of the system are: refractory metal parts fabrication, turbine blade endurance, turbine bearings and seals, and generator winding seal.

Introduction

Development of liquid metal vapor Rankine cycle power systems began about 1960 in conjunction with the Space Nuclear Auxiliary Power (SNAP) programs, jointly sponsored by NASA and AEC. SNAP systems were designed to produce power in the range of 100-300 KWe. Power conversion components, such as boilers, pumps, turbines and condensers, were designed, fabricated, and tested to support system development. As a result, a considerable technology base on materials and small components was established. The development program was continued until about 1972, but, unfortunately, it was terminated before a complete power system was tested as a whole unit. Consequently, there is variation in the status of the technology among the various components of the system. The development effort on each of the major components is reviewed, and the general status of the technology of each is summarized in this paper. The key technology issues remaining for development of the system are also identified.

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Rankine Cycle Space Power Development Programs

Rankine cycle power conversion development for space power was carried out primarily under two programs: SNAP 50 Space Power Unit Reactor (SNAP50/SPUR) and Medium Power Reactor Experiment (MPRE). Both of these programs were sponsored jointly by NASA and AEC.

SNAP50/SPUR

The SNAP50/SPUR system was designed by Pratt and Whitney Aircraft (P&WA) beginning in 1961. The design finally evolved to a 2.2 MWt lithium-cooled fast reactor coupled to a 300 KWe potassium Rankine power conversion system. Pratt and Whitney conducted development work on the reactor, shield, boiler, and condenser. In conjunction with this program, General Electric Co. (GE) also conducted development work on the boiler, turbine, and condenser.

MPRE

The MPRE system was designed by Oak Ridge National Laboratory (ORNL) beginning in 1959.² The design consisted of a 1 MWt boiling potassium fast reactor connected directly to a 150 KWe turbine-generator. The single-loop system also included a direct condenser-radiator and a turbine-driven liquid feed pump. Development work was carried out on electrically heated boilers designed to simulate a scale model of the reactor, with associated turbine-pumps and condensers.

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Power Conversion Component <u>Development</u>

Boiler

A considerable amount of development work was conducted on once-through potassium boilers by GE. Most of the effort involved single-tube boiler tests in superalloy or refractory metal boiler tubes heated by liquid metal or electric heaters. The boiling tests encompassed a temperature range from 1100 to 1400 K.^{3,4} The tests at the upper end of the temperature range were done in Nb-1 Zr boiler tubes. Boiling heat transfer and pressure drop performance were established for a wide range of mass velocity for exit vapor quality from wet vapor up to over 100 K superheat.

In addition to the heat transfer tests, GE operated other boilers to generate vapor for turbine and other component development testing. Overall, it is estimated that GE accumulated about 35,000 h of potassium boiler operation. The results of their performance tests provide a good basis for the design of once-through boilers for generating saturated or superheated potassium vapor.

An estimated total of about 17,000 h of boiler operation was accumulated at P&WA during the SNAP50 program. A large amount of boiler operation was accumulated at ORNL during the MPRE program, an estimated total of about 75,000 h.² Most of this was in stainless steel tubes or heater rod clusters at temperatures of up to 1100 K. Methods to assure stable boiling were established, and negligible corrosion of stainless steel was observed.

There exists a good technology base for potassium boilers. The development work remaining is to fabricate subscale test boilers of high temperature refractory alloys, such as T111 or Astar 811C, and run confirmatory performance and endurance tests with liquid lithium at 1500-1600 K outside the tubes and boiling potassium at 1400-1500 K inside the tubes.

Liquid Feed Pumps

Two types of liquid feed pumps were tested in operation during these earlier programs: electromagnetic and turbine-driven centrifugal. Most of the experience was on electromagnetic pumps. The estimated accumulated times of operation are 27,000 h at ORNL, 25,000 h at GE, and 5000 h at P&WA.^{1,2} There exists a good technology base for electromagnetic pumps for both the primary liquid lithium loop and for the potassium secondary loop.

The mass of the power conversion system can be reduced by use of a turbine-driven centrifugal feed pump in the potassium secondary loop. A turbine-pump was operated successfully for over 4000 h in the MPRE test loop at ORNL. The pump had potassium lubricated bearings, and no bearing wear or turbine blade erosion was observed at the conclusion of the test run. This experience needs to be extended to larger pumps, higher temperature operation, and longer runs.

Power Turbine

Potassium turbines were designed for the SNAP50/SPUR program, and test turbines consisting of the exhaust stages were fabricated for testing. Testing was focused on the exhaust section because of the concern of the potential erosion problem from liquid droplets in the vapor at the turbine exhaust. The first test turbine was a nominal 150 KWe unit with two stages. This was tested by GE at turbine inlet conditions such that the moisture at the turbine exhaust was about the same level as predicted for the full turbine. The moisture content at the exhaust was about 8%. The turbine inlet temperature was about 1100 K, and the test ran for 5000 h. Negligible erosion wear was observed on the turbine blades. This was followed by a second 5000 h test on a 3-stage turbine. Again, no significant erosion wear was observed.

These results need to be extended to higher temperature operation to determine the allowable limits of moisture in the potassium vapor before serious erosion occurs.

Condenser

The accumulated hours of operation of potassium condensers is virtually the same as boilers for the obvious reason of the need for closing the cycle for continuous operation of a test loop. Much of the condenser operation was gravity-assisted, but in some cases the condenser was oriented horizontal or with a slight upward slope toward the discharge. In the MPRE test program at ORNL, an air-cooled condenser composed of tapered tubes was operated horizontal at a heat load of 300 KWt for over 4000 h with no interruption or maldistribution of vapor or liquid flow.²

The condenser was designed to operate with forced flow of vapor and capillary flow of liquid at the discharge. A liquid-driven jet pump was employed to provide positive liquid flow from the condenser outlet to the inlet of the turbine-driven centrifugal feed pump and to provide suppression head to prevent pump

cavitation. The experience with horizontal condensers demonstrated that potassium condensers can be designed to operate successfully under zero-gravity conditions.

Key Technology Issues

There exists a considerable technology base which indicates a high likelihood that Rankine cycle systems can be successfully developed for operation at high temperature. The development task remaining is to extend the existing technology base of each component to larger size and higher temperature and conduct longer term component and system tests.

There are certain key technology issues in the development of the Rankine cycle power conversion system. These include: refractory metal parts fabrication, turbine blade endurance, turbine bearings and seals, and generator winding seal.

Refractory Metals Parts Fabrication

There is limited experience in the fabrication of parts from high temperature refractory metals such as T-111 and ASTAR-811C. The fabrication experience needs to be extended to more complex and larger parts such as turbine blades, rotors, and casings.

Turbine Blade Endurance

Test turbines were operated in potassium vapor at just over 1100 K with a moisture content of around 8% for about 5000 h with negligible turbine blade wear. The operating experience needs to be extended to high temperatures (1400-1500 K) to determine the allowable limits of turbine blade tip speed and potassium moisture content for long life of the turbine blades.

Turbine Bearings and Seals

The previous experience with turbine bearings and seals needs to be extended to higher temperatures and pressures of the potassium vapor. Liquid potassium lubricated tilting pad journal bearings were successful previously, and it is anticipated that they will perform well at the new conditions. Labyrinth-type shaft seals to protect the bearings from high temperature vapor should also prove successful at the new conditions.

Generator Winding Seals

An enclosure of non-magnetic metal (or alternatively, ceramic) is required to protect the conductor windings in the rotor and stator from potassium vapor (or liquid) which may leak past the shaft seals into the generator. Development of the attachment of the enclosure, by welding or otherwise, to the rotor and stator core is a technology issue.

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