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ABSTRACT

A prototypic heat pipe system for an out-of-core thermionic reactor has been built and tested. The emitter of the concentric thermionic converter consists of the condenser of a tungsten heat pipe utilizing a lithium working fluid. The evaporator section of the emitter heat pipe is radiation heated to simulate the thermal input from the nuclear reactor. The emitter heat pipe thermal transport is matched to the thermionic converter input requirement. The collector heat pipe of niobium, 1%-zirconium alloy uses potassium as the working fluid. The thermionic collector is coupled to the heat pipe by a tapered conical joint designed to minimize the temperature drop. The area ratio of the evaporator to condenser is 16:1, which increases the radiation area. The composite wick structure consists of seven arteries and cylindrical wraps. The collector heat flux matches the design requirements of the thermionic converter.

CYLINDRICAL THERMIONIC CONVERTERS with heat pipe-heated, heat pipe-cooled electrodes are the best representation of state-of-the-art technology in space power systems. Such converters can be used for a wide range of space power applications, including nuclear electric propulsion, space solar thermionics, and space isotopic power systems. Heat pipe thermionics results in a light-weight, mechanically simple power system: there are no moving parts; relatively small radiators are required because of high heat rejection temperatures; and, because thermionic power systems are modular in construction, single-point failures are automatically eliminated. Furthermore, development costs are reduced because power systems can easily be tested by building scaled models. Such a scaled, three-converter module has been designed, fabricated, and tested. Each heat pipe converter in the module consists of three major components: the emitter/emitter heat pipe assembly, the collector assembly, and the collector heat pipe. Figure 1 shows a cutaway view of the completed cylindrical converter.

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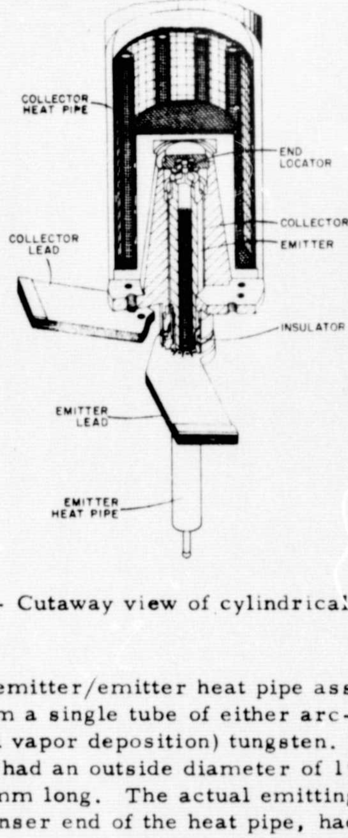

Fig. 1 - Cutaway view of cylindrical converter

The emitter/emitter heat pipe assembly was made from a single tube of either arc-cast or CVD (chemical vapor deposition) tungsten. The emitter heat pipe had an outside diameter of 19 mm and was 222 mm long. The actual emitting surface, the condenser end of the heat pipe, had an area of 35 cm^2. A tungsten wire mesh was used for a wick, and the working fluid was lithium. The collector was constructed from a niobium, 1%-zirconium alloy. The active collector surface consisted of a vapor-deposited layer of tungsten oxide. The collector heat pipe was also made from niobium, 1%-zirconium. This heat pipe had an outside diameter of 70 mm and was 515 mm long. A multiple screen wick artery system was used for the liquid return using potassium as the working fluid. The collector heat pipe was bonded onto the collector assembly with a tapered conical joint.

Three heat pipe converters were then assembled into a completed module. This paper gives the details of the design, construction, and testing of the emitter and collector heat pipes. The construction and testing of the converter and module have been described previously. (1)*

EMITTER HEAT PIPE

FABRICATION-The emitter of the thermionic converter is heated by radiation using a heat pipe that is integral with the emitter. The heat pipe allows the heat source to be remote from the emitter surface. The design requirements specified a tungsten emitter surface; thus, the whole emitter-heat pipe assembly was fabricated from a single tungsten tube. The crystal structure of the tungsten was closely controlled, thus allowing the welding of the end caps. The desirable elongated crystal structure can be obtained by extruding an arc-vacuum-cast tungsten billet, and making the tube from the extrusion by electrical discharge machining. Alternatively, the tube can be formed by CVD on a mandrel that is later dissolved. Heat pipes were fabricated by both methods.

Two end caps are attached to the tungsten tube by electron beam welding. One end cap has a projection used to center the emitter in the collector assembly; the other end cap is equipped with a thin-walled tungsten tube, as shown in Figure 2.

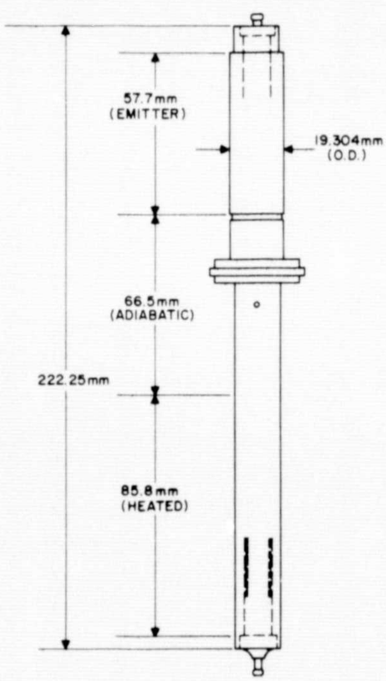

Fig. 2 - Emitter heat pipe

*Numbers in parentheses designate References at the end of the paper.

A tungsten wick and wick retainer are inserted prior to welding the second end cap. The moly-rhenium emitter sleeve assembly is welded on at this time. A photograph of a completed emitter heat pipe is shown in Figure 3.

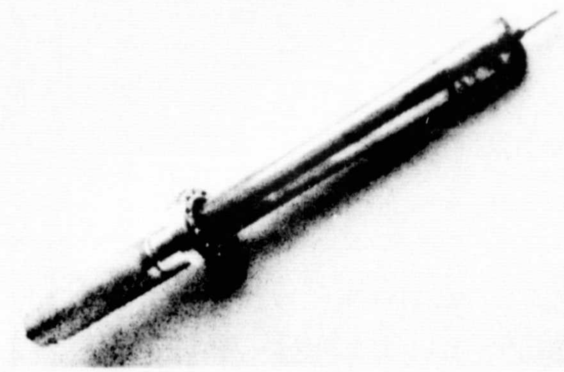

Fig. 3 - Photograph of completed emitter heat pipe

The distillation of the lithium is performed in a vacuum system. The lithium distillation container is terminated in a thin, hollow tungsten needle, which is inserted into the tungsten tube of the heat pipe. The slip fit of these two tubes permits the heat pipe to be outgassed prior to the distillation of the lithium. The lithium can contains a U trap so that only the lithium can enter the heat pipe, and the impurities (mainly oxides) remain in the can. Heaters are provided on the lithium can, the heat pipe, the heat pipe filling neck, and the tungsten fill tubes. The temperatures in the system are suitably varied so that the lithium can be distilled through the can into the heat pipe, or alternately from the heat pipe back into the can. At any point during the distillation process, the heat pipe can be checked to determine if it has been charged with the proper amount of lithium. This is accomplished by operating the heat pipe in the usual mode and checking for uniform temperature along its length.

The final closure of the heat pipe is accomplished once proper heat pipe operation has been observed. A current ($\approx$700 A) is passed through the concentric fill tubes causing them to melt and form a leaktight tungsten bead at the end of the tube. The completed heat pipe, under test, is shown in Figure 4.

TESTING-The emitter heat pipes are heated by a radiation source enclosed in a MULTI-FOIL insulated furnace, 152.4 mm in diameter and 152.4 mm high, consisting of 30 layers of tungsten foil and 30 layers of molybdenum foil. The foil spacing is achieved by zirconia particles.

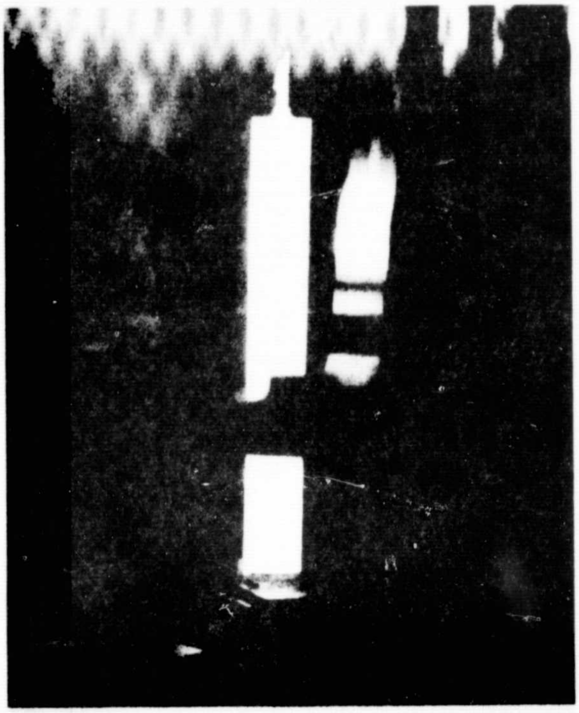

Fig. 4 - Photograph of emitter heat pipe during test

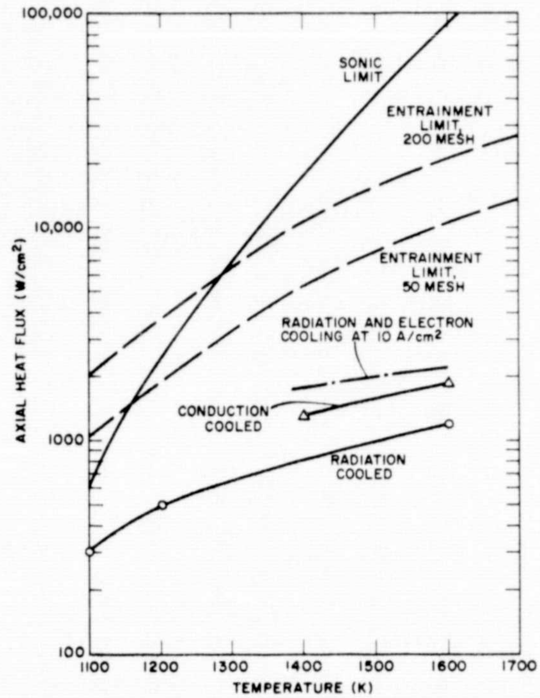

Fig. 5 - Heat flux in emitter heat pipe

The characteristics of the furnace were measured with a water-cooled calorimeter that was installed in the furnace. The furnace temperature was determined by an optical pyrometer sighting on a blackbody hole in a molybdenum target at the bottom of the furnace. The power output of the furnace to the water-cooled load was determined by measuring the water flow rate using a graduated cylinder and a stopwatch. The water inlet and outlet temperatures were determined by test thermometers graduated at 0.1 K intervals. The furnace losses, mainly conduction losses through the tungsten filaments, were determined by subtracting the output from the input. The heat input to the heat pipe was determined, and the axial heat flux calculated, as shown in Figure 5. The heat loss from the heat pipe, which is mainly by radiation, was calculated from the measured surface temperature of the condenser of the heat pipe. For a lithium heat pipe that was conduction cooled, a higher heat flux was reached. (2)

The heat flux expected to be imposed during thermionic converter operation is also shown in Figure 5. The principal heat losses in a thermionic converter are radiation and electron cooling. (3) Thus, if the electron cooling (measured at 10 A/cm^2) is added to the observed radiation loss, an estimate of the total thermal load on the heat pipe during converter operation is obtained. It is seen that the required performance is far below the sonic and entrainment limits.

The theoretical heat flux limits for a lithium heat pipe are also shown in Figure 5. The sonic axial heat flux limit, Q/A, for the lithium heat pipe was calculated from the following expressions: (4, 5)

$$Q_s/A = \rho_v L V_s \qquad (1)$$

$$V_s = (\gamma R_o T/M)^{1/2} \qquad (2)$$

where ρ_v is the vapor density, L is the latent heat of vaporization, V_s is the sonic velocity, γ is the ratio of specific heats, R_o is the gas constant, T is the temperature, and M is the molecular weight. It is seen that, at a low operating temperature and at startup, the sonic limitation is the most severe restriction in the operation of the heat pipe.

The entrainment axial heat flux limit for the heat pipe was also calculated. This limit occurs when the vapor exiting from the evaporator prevents the return of the liquid from the condenser by removing the droplets from the pores of the screen. This limit, Q_E/A, is given as follows:

$$Q_E/A = L(\rho_v \gamma/Z)^{1/2} \qquad (3)$$

where Z is the characteristic distance of the pores for a screen wick, generally taken as the distance between the wires. The entrainment limit for the lithium heat pipe also is shown for two screens, 200 mesh and 50 mesh. It is seen from Figure 5 that the axial heat flux is not limited by either of these parameters of the desired heat pipe operating range.

COLLECTOR HEAT PIPE

FABRICATION-The collector and the collector heat pipe are made from niobium, 1%-zirconium alloy. They are joined by a tapered seat. The working fluid is potassium. Due to the unavailability of proper size tubing, the heat pipes were fabricated by rolling and electron beam welding sheets into the desired tubes. After the first rolling operation, the edges of the sheet were trimmed so that, upon welding and rerolling, the desired tube size was obtained without further machining. A drawing of the collector heat pipe is shown in Figure 6. Microgrooves were machined on the heat pipe surface to increase its apparent emissivity. The tube was then cleaned and annealed. The collector heat pipe transfers heat from the collector of the thermionic converter, a concentric cylinder about 70 mm high, to the outside cylinder, the radiator of which is 515 mm high. The liquid from the radiator is returned to the collector through a series of wick arteries that bridge the angular gap between the collector and the radiator at the bottom portion of the heat pipe, as shown in Figure 7. The wicks and arteries were inserted, the end caps were welded on, and the charging and evacuation tubes were attached. The heat pipe was outgassed using electrical resistance heaters. Then the potassium capsule was cracked and the potassium distilled into the heat pipe. Electron beam pinch-offs on the niobium, 1%-zirconium tubes were made. As an additional precaution, pinch-off protector caps were electron beam welded over the pinch-offs.

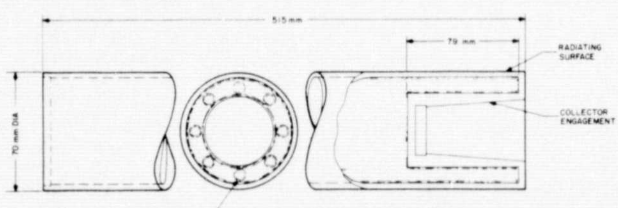

Fig. 6 - Collector heat pipe

TESTING-Upon fabrication, each heat pipe was instrumented with thermocouples and mounted in a water-cooled copper heat receiver. An electron bombardment filament was inserted in the collector cavity of the heat pipe to simulate the collector heat load, as shown in Figure 8. Each heat pipe was tested up to an 850 K radiator temperature. The heat radiated to the water-cooled shield was measured by noting the temperature rise and flow rate of the cooling water. The results are shown

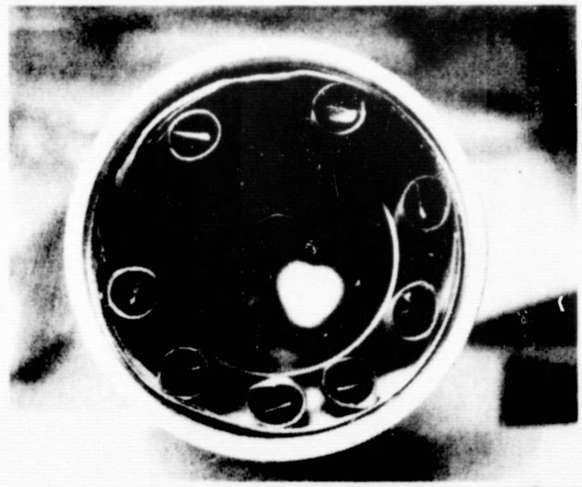

Fig. 7 - Photograph of collector heat pipe arteries

in Figure 9. If it is assumed that all the heat, Q_R, radiated to the copper-cooled shield was transferred by radiation, then the effective emissivity, ϵ, can be calculated from the known radiator temperature, T_R, and sink temperature, T_S, from the following equation:

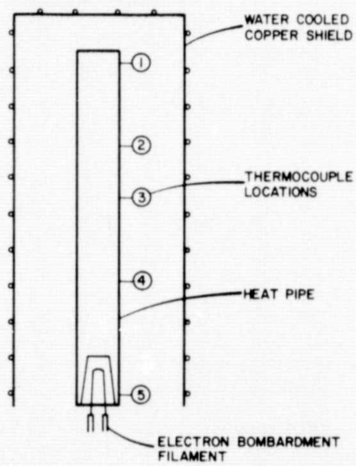

Fig. 8 - Collector heat pipe test arrangement

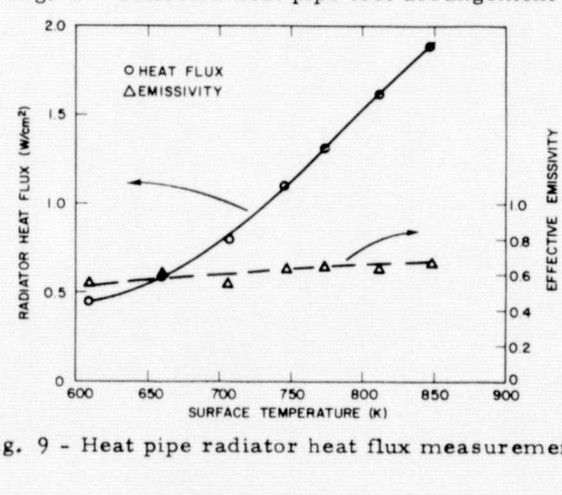

Fig. 9 - Heat pipe radiator heat flux measurements

$$Q_R = \epsilon\sigma\,(T_R^{\ 4} - T_S^{\ 4}) \qquad (4)$$

where σ is the Stefan-Boltzmann constant. Also shown in this figure is the apparent emissivity of the surface, based on measured radiator surface temperature. The temperature profiles along the heat pipe for several operating conditions are shown in Figure 10. The locations of the thermocouples are shown in Figure 8.

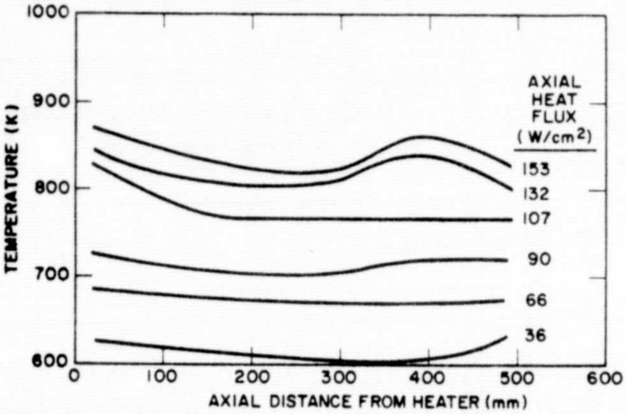

Fig. 10 - Temperature profiles in collector heat pipe

It is seen from Figure 11 that, at the highest temperature tested (≈ 850 K), the heat pipe flux is limited by the ability of the radiator to reject heat to the environment, not by the thermal performance of the heat pipe. When the heat pipe is

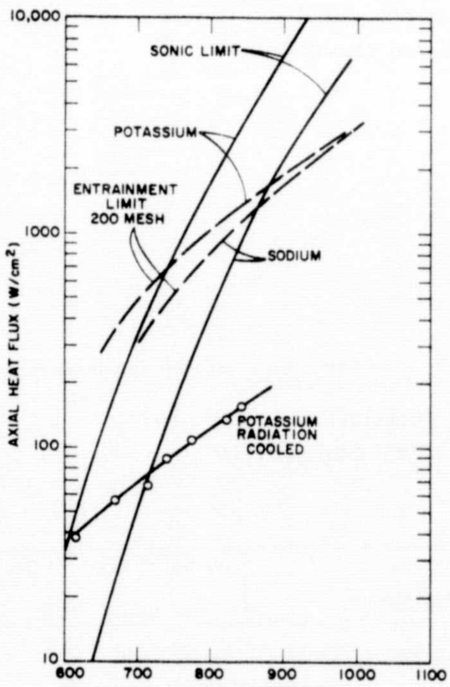

Fig. 11 - Axial heat flux for collector heat pipe

operated at the lowest temperature tested (≈600 K) the operation is near the sonic limit. It is seen that a heat pipe operating with sodium as the working fluid could not operate below ≈700 K. In order to extend the range of operation of the thermionic device to lower temperatures, potassium was chosen rather than sodium.

CONCLUSIONS

The heat pipes for operating radiation-heated and radiation-cooled thermionic converters were shown to be within the theoretically calculated performance limits for such heat pipes. It was shown that experimentally observed performance of these heat pipes fulfilled the design requirements imposed by the thermionic converters.

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