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FABRICATION AND TESTING OF TUNGSTEN HEAT PIPES FOR HEAT PIPE COOLED REACTORS

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ABSTRACT

Efficient heat extraction from nuclear reactors at elevated temperatures has been one of the weak links in application of thermionics as well as other high temperature conversion systems. The lithium filled heat pipe can be shown theoretically to excel in this area.

The heat pipes described herein were designed and fabricated with the following criteria in mind, operation at 1850 K in contact with nuclear fuel, axial heat flux greater than 7 kW/cm^2, and a configuration allowing direct coupling to a cross flow heat pipe heat exchanger. Chemically vapor deposited tungsten was used as the outer shell and lithium as the working fluid.

In the study both annular and channeled wicks were investigated along with methods of wick fabrication using tungsten and tungsten rhenium. Calorimetric heat throughput measurements at various operating temperatures are presented.

INTRODUCTION

Many advanced space power systems advocate the use of heat pipes in order to achieve a compact high performance reactor. One such concept as proposed by Breitwieser and Lantz[1] further advocates a completely modular system from fuel elements to a heat pipe cooled radiator. Though not restricted to thermionics the modular approach was suggested for use with out of core thermionic converters. The term "modular" implies that each subsystem is made up of many identical, independent components. The modularity of the primary coolant system is obtained by the use of a network of many tungsten reactor heat pipes coupled to the secondary heat pipe network through a cross flow heat exchanger as shown in Figure 1. The modular cross flow feature greatly reduces the hazards of propagating failures in or out of the reactor core. Thermal contact between the mating flat surfaces of the primary and secondary components is necessary for efficient heat transfer between systems. The reactor pipes, as proposed, would be circular in cross section in the core where they are in contact with uranium carbide (UC) fuel pins yet rectangular in cross section in the heat exchanger. Each pipe is designed to transfer between 2 and 3 kW at 1850 K for periods in excess of 10,000 hours. This paper describes the fabrication of such a tungsten reactor pipe and its heat transfer characteristics up to 1900 K.

PIPE CONSTRUCTION

Previously, tungsten has not been advocated strongly for heat pipe applications due primarily to fabrication difficulties. Here the choice of chemically vapor deposited (CVD) tungsten as the heat pipe shell is based primarily on three factors: first, the conclusions of Busse, et al.[2] that tungsten and tungsten-base alloys present the least oxygen corrosion problems of all refractory metals tested; second, demonstrated chemical compatibility of tungsten with UC fuel; and third, the flexibility of shape and inherent purity of material achievable by the CVD process.

Thus far, two types of pipes have been built and operated; one a smooth wall pipe utilizing autoclaved tungsten screen wicks in both the evaporator and condenser (Figure 2) and one with channels in the condenser wall and a swaged tungsten screen wick in the evaporator (Figure 3). Some important dimensions for both pipes are listed in Table I.

Table I

Reactor Heat Pipe Dimensions

	Smooth Wall Heat Pipe	Channled Wall Heat Pipe
Evaporator O.D.	1.0 cm	0.955 cm
Evaporator Wall	.1 cm	.1 cm
Evaporator Length	18. cm	13.0 cm
Evaporator Area	56. cm^2	39.4 cm^2
Condenser Cross Section	1.3x2.0 cm	0.955x1.91 cm
Condenser Length	12. cm	10. cm
Wick I.D.	0.72 cm	0.63 cm
Adiabatic Throat Area	0.41 cm^2	0.264 cm^2
Adiabatic Length	2.2 cm	2.2 cm
Wick Thickness	.015 cm	.021 cm

The pipes, as deposited, are open only at the rectangular end to keep welds outside of the evaporator region and to allow easy installation of wicks. Tungsten is deposited on a molybdenum mandrel and ground to 0.040" wall thickness before the mandrel is removed by chemical etching. In the case of the channeled condenser wall the mandrel is grooved prior to deposition. Both the smooth wall and channeled condenser pipe designs require a wick transition piece which provides liquid communication between the rectangular

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section and the circular wick. Accumulators are provided in the condenser section to allow the entire pipe to operate at essentially constant temperature even with an excess of lithium. A tungsten wire spring is used to hold the evaporator wick and the wick transition in place. After the wick assembly, spring, and accumulators are inserted into the tube, a W-26% Re end plate with a fill hole in its center is tungsten inert gas (T.I.G.) welded onto the condenser end.

This assembly is then heated in vacuo to 1600 C, cooled, and backfilled with argon. From this point to completion, the pipe never experiences any environment but argon or vacuum. Solid rods of high purity lithium are inserted through the fill hole in the end plate in an argon environment. A circular W-26% Re plug is then inserted in the fill hole, the assembly is evacuated, and the fill plug is electron beam (E.B.) welded to the end plate.

WICK CONSTRUCTION

In fabricating both autoclaved and swaged wicks, five layers of 120 mesh W-3% Re screen with .002" diameter wire were compressed between a molybdenum mandrel and a molybdenum sheet.

Autoclaved wicks were compressed at 10,000 psi for one hour at 1500 C. These conditions resulted in a rigid wick structure with good bonding between layers of wires, but the structures were somewhat brittle and required careful handling.

Swaging, which was done at room temperature, compacted the screen layers into a flexible wick structure by entanglement of the wires rather than by bonding. Relative pore size was compared by using the equation $\Delta P = \frac{2\sigma}{r}$ where ΔP represents air pressure necessary to produce the first bubble through a wick submerged in water, σ is the water surface tension, and r is the pore radius. This comparison showed that pore sizes of autoclaved wicks are 60 to 70 percent that of swaged wicks. However, swaged wicks are faster and more economical to produce and, further, the pore size obtainable by swaging (approximately 0.006" dia.) was considered more than adequate to provide the required pumping in these short pipes.

HEAT PIPE OPERATION

The smooth wall heat pipe, shown in Fig. 2, was first operated a number of times using R.F. heating. Poor coupling between the pipe and the R.F. coil arrangement used prevented heating above 1200 K in these tests. The pipe was subsequently heated to 1900 K using electron bombardment (E.B.) heating. During operation a lithium leak was observed in the transition section. Examination of the transition section showed that an opening occurred at a grown-in imperfection in the CVD tungsten transition fillet. This problem was corrected in subsequent pipes by enlarging the fillet radius from .06" to 0.15". The larger radius allows the CVD coating to deposit evenly over the entire length of the pipe yielding uniform wall thickness and continuous properties at the transition.

The pipe with the channeled condenser wall was also started several times using both R.F. and E.B. heating techniques. In the R.F. tests of this pipe better matching of the pipe to the coil allowed operation up to 1900 K as shown in Figure 4. At these conditions the bare condenser was rejecting about 1400 watts. In order to increase the heat rejection capability of the condenser to the design level it was necessary to extend the radiative area of the condenser by the use of solid fins as seen bolted to the pipe in Figure 5. These three tantalum fins are capable of rejecting about 3 kW if the fin base (in contact with the condenser wall) is at 1800 K. Startup under large thermal loads such as these fins presents a problem similar to that observed by other investigators[3] and will be discussed in the next section.

A diagram of the life test station now being used on the channeled pipe is shown in Figure 6. A cylindrical electron gun is used for heat input and the water cooled enclosure, starting at the transition, is used as the calorimeter. Figure 7 shows heat throughput with three fins attached as a function of pipe temperature. At 1850 K condenser temperature the fins are rejecting 2135 watts, corresponding to an axial heat flux of 8090 w/cm^2 in the adiabatic region. A 200 C temperature drop between the pipe and the fin base, due to poor thermal contact, resulted in lower heat rejection than anticipated. The pipe has operated continuously at temperatures in excess of 1800 K for 500 hours up to the writing of this paper and is still operating.

STARTUP WITH FINS ATTACHED

Problems associated with startup of a pipe with an auxiliary heat sink are discussed in detail in reference 3 and will be summarized here from my observations. With three fins attached to the condenser, the evaporator temperature could be raised to approximately 950 C at which time the temperature front moved quickly through the transition to a point just past the front of the first fin and stopped. With the heat input held constant, the front would not advance. Increasing the heat input raised the temperature of the evaporator but simultaneously caused a hot spot, or wick dryout, in the evaporator with again no advance of the front. The pipe could not be started.

From our observations and the explanations given in reference 3 it is apparent that this starting limit is directly associated with a sonic limit.

Startup was achieved by the following

method. Heat input to the evaporator was set at a level sufficient to maintain the evaporator at 900 C. At this condition the temperature of the condenser near the first fin was approximately 800 C. An auxiliary electron beam heater was then used to inject 400 to 500 watts into the condenser end for periods of 5 to 20 minutes. Shutting down the auxiliary condenser heater after 5 or 10 minutes resulted in the condenser temperature dropping steadily until the initial no start temperature profile was reached. Employing the auxiliary heater for a period in excess of 15 minutes resulted in the condenser temperature dropping to 750 C and stabilizing. Further increases in heat input to the evaporator, with no additional use of the auxiliary heater, resulted in flattening of the temperature profile across the entire pipe and normal pipe operation.

The role of the auxiliary heater is to supply heat sufficient; first, to overcome the heat capacity of the auxiliary load (the fins) and second, to increase the vapor pressure in the colder end of the pipe to the point where the limiting heat transfer rate is higher than the heat rejection rate.

Startup of the reactor pipes in a system such as proposed in reference 1 will not be as difficult since each set of heat pipes (3 sets in all) are thermally decoupled at startup and one set of pipes cannot begin to conduct until the previous set is started.

SUMMARY

A tungsten heat pipe was designed for use as a primary coolant system with a compact high temperature reactor. To date, two such pipes have been constructed and operated up to at least the design temperatures of 1850 K. Startup problems on a thermally loaded pipe were circumvented by using auxiliary heating on the condenser during startup. One CVD pipe with liquid return channels in the condenser walls has been operated continuously at axial heat fluxes above 7300 watts/cm^2 for 500 hours and is still operating.

References

1. R. Breitwieser and E. Lantz, Fifth Intersociety Energy Conversion Engineering Conference, Sept. 1970, Las Vegas.

2. C. A. Busse, F. Geiger, and D. Quataert, 1970 Thermionic Specialists Conference, IEEE, Miami.

3. J. Deverall, J. Kemme, and L. Florschuetz, "Sonic Limitations and Startup Problems of Heat Pipes," LA-4518.

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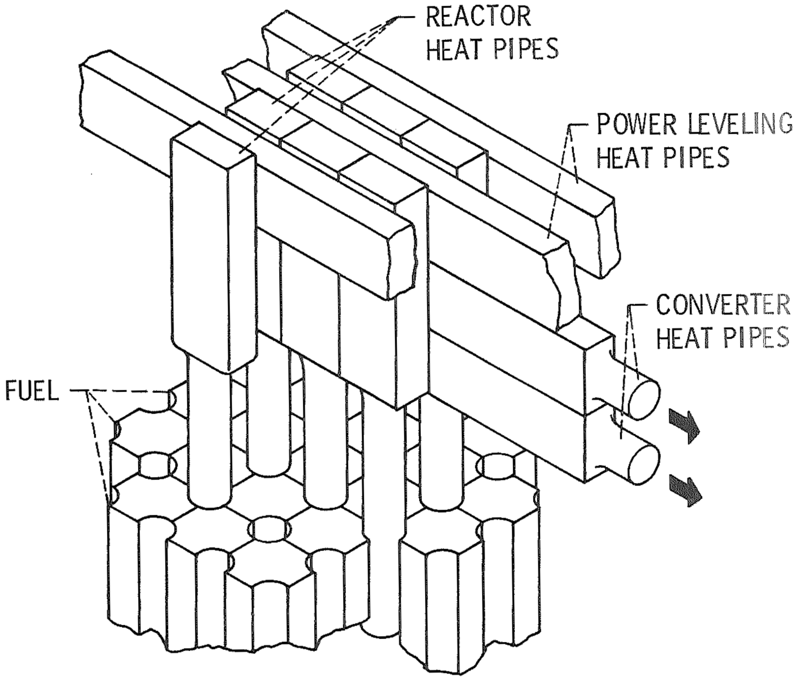

Figure 1. - Cross flow heat exchanger.

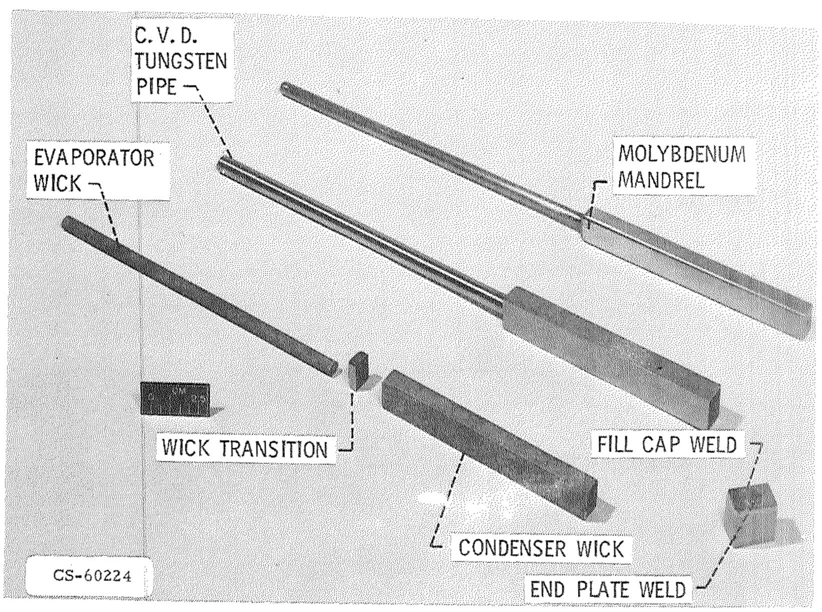

Figure 2. - Smooth wall C.V.D. tungsten heat pipe.

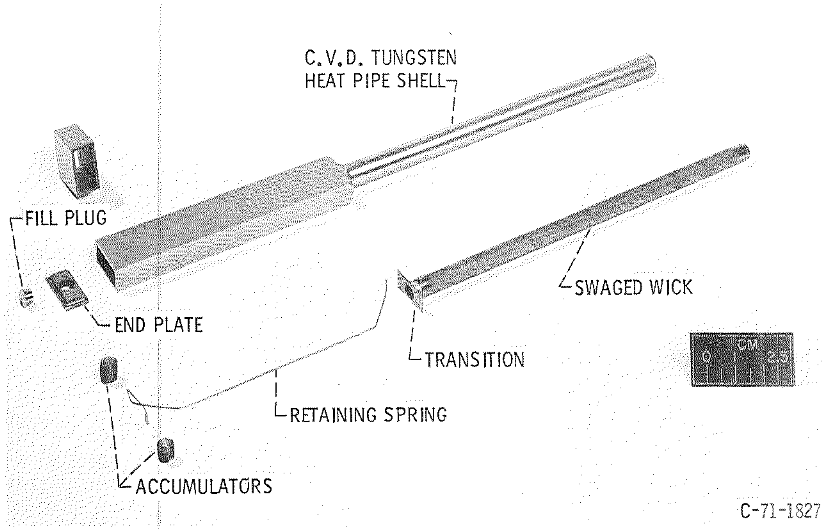

Figure 3. - Channel wall tungsten heat pipe.

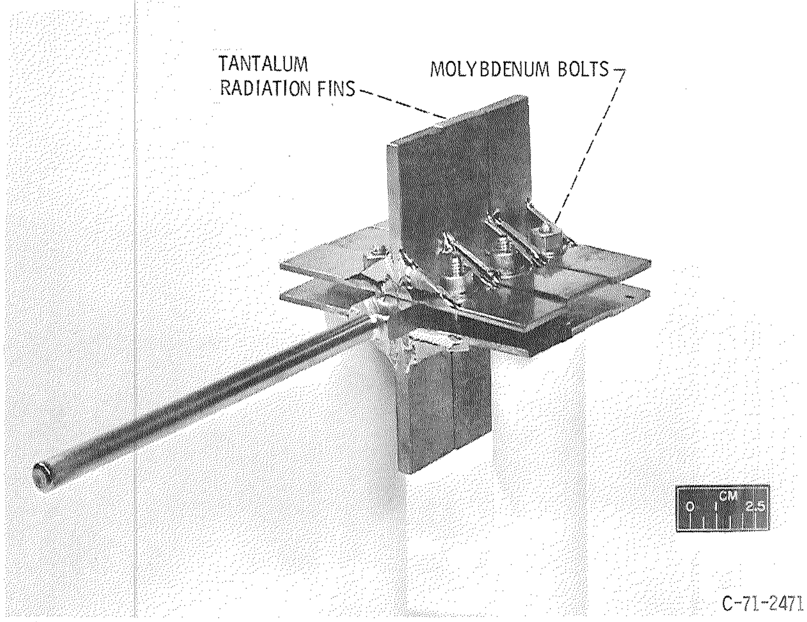

Figure 4. - Tungsten heat pipe with fins.

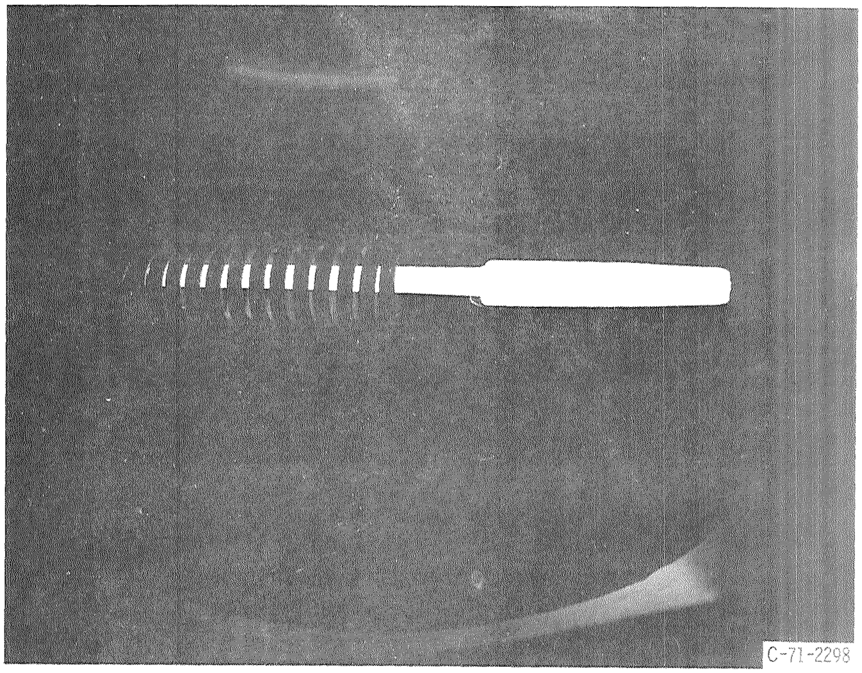

Figure 5. - Channeled heat pipe operating bare at 1900° K.

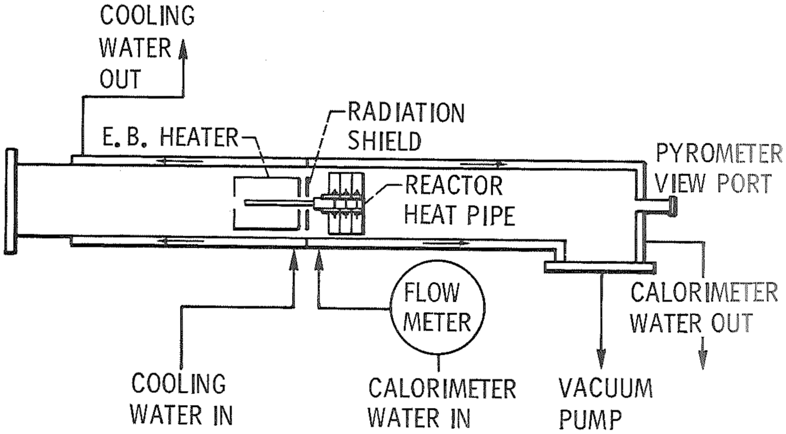

Figure 6. - Reactor heat pipe life test station.

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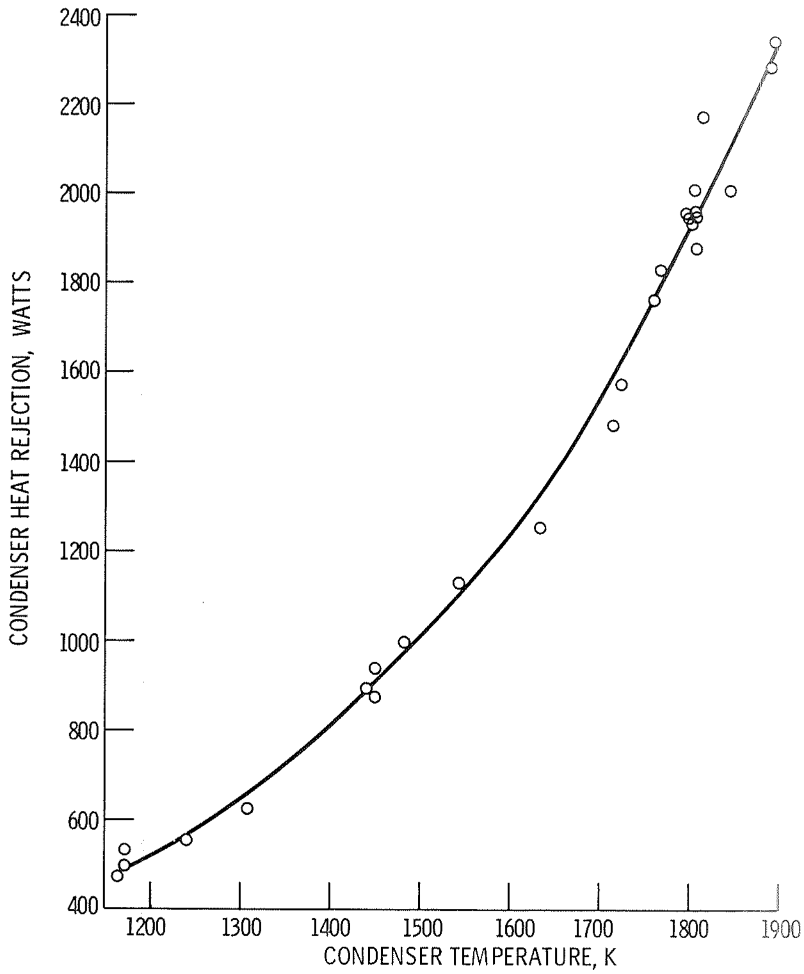

Figure 7. - Heat throughput tungsten reactor heat pipe with three fins.