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GRAVITY-ASSIST HEAT PIPES FOR THERMAL CONTROL SYSTEMS

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ABSTRACT

Sodium heat pipes, operating in the gravity-assist mode, have been incorporated into irradiation capsules to provide a means for establishing and controlling a desired specimen temperature. Investigations were made of new wick structures for potassium heat pipes to operate at lower temperatures and higher heat transfer rates, and a helical trough wick structure was developed with an improved heat transfer capability in the temperature range of interest. Test results of these heat pipes led to the study of a new heat pipe limit which had not previously been considered.

I. INTRODUCTION

In the development of the fast breeder reactor as a future source of energy, one important consideration is the irradiation testing of reactor structural and fuel materials.¹ All materials used in reactor construction must be subjected to irradiation for evaluation of radiation damage and effects before they can be incorporated into a final reactor design. One major problem in conducting irradiation tests is establishing a desired, uniform temperature of the specimens which will remain constant over the duration of the test period. In most cases, it is not possible to instrument the test capsules so that specimen temperatures are not known during the test, and the radiation input is neither accurately known nor constant with time. In irradiation testing, the specimens are placed in a capsule, which is inserted into a reactor core, and heated by the reactor radiation. The desired radiation flux exposure can be obtained to some degree by locating the capsule in a selected row of the core assembly for a certain period of time. The test temperature is established by the heat

rejection rate from the capsule to the reactor sodium coolant stream.

The general method used in an attempt to establish a desired test temperature is to place the specimens in a dewar which provides a gas-gap between the specimen chamber and the reactor coolant stream. The dewar is designed so that the gap-width and type of gas in the gap will provide a thermal conductivity for the necessary heat rejection rate to maintain the desired specimen temperature at the expected radiation input flux. However, this system does not provide a satisfactory temperature control with any appreciable changes from the design radiation input flux. Further, it does not produce isothermal conditions over the height of the specimen section and the desired temperature is not well established. During an extended test, the specimen temperature may vary several hundred degrees kelvin because of variations in reactor flux and changes made in fuel elements or other experiments adjacent to the capsule. In some cases, temperature monitors, in the form of melt wires or silicon carbides, are placed in the test capsules; however, these monitors indicate only the maximum

temperature attained and do not provide any temperature history of the experiment. Post-irradiation analysis of the monitors is difficult and the results are uncertain. In any event, no means is provided for control of the temperature of these capsules even if the temperatures were continuously monitored. Both the establishment and control of a desired test temperature can be obtained by incorporating a heat pipe into the capsule as a thermal control device.

II. THE HEAT PIPE

The heat pipe is a self-contained heat transfer device which has no moving parts, can transfer heat isothermally, and has a thermal conductance higher than any known material.² A heat pipe is a sealed container in which a fluid is continuously evaporating and condensing thereby establishing an essentially constant temperature throughout the length of the container. The heat is transferred by mass flow of the fluid, utilizing the inherently high thermal characteristics of heat of vaporization, resulting in a heat transfer rate several orders of magnitude higher than that of thermal conduction. Heat addition to the evaporator section of the heat pipe is distributed throughout the condenser by flow and condensation of vapor. The cycle is completed with the return of the condensate to the evaporator by capillary action through a wick structure lining the container wall.³ The driving force for the vapor is created by a slightly higher vapor pressure in the heat input zone (see Fig. 1).

In a two-phase system, the vapor pressure is a function of temperature. If a heat pipe is operated at a pressure that corresponds to a section of the vapor pressure curve having a steep slope, the pressure difference necessary for the vapor driving force produces a very small temperature drop along the length of the pipe (see Fig. 2). Therefore, except for extremely high input heat fluxes, pipe operation is essentially isothermal.

Heat pipes can be built to operate from cryogenic temperatures to 2270 K by choosing fluids with suitable vapor pressures for the desired temperature ranges, as shown in Table I.

Liquid metal heat pipes have been operated with axial heat fluxes up to 15.5 kW/cm^2 of vapor passage area.⁴ Life tests of high temperature heat pipes,

Fig. 1. The heat pipe.

Fig. 2. Vapor pressure curve.

TABLE I
HEAT PIPE FLUIDS

Fluid	Approximate Temperature Range °K
Liquid Nitrogen	70 - 300
Freon	
Alcohols	
Water	300 - 470
Phenyl Ether	370 - 570
Mercury	520 - 820
Cesium	650 - 970
Rubidium	650 - 970
Potassium	720 - 1070
Sodium	820 - 1170
Lithium	1170 - 1770
Lead	1570 - 1970
Silver	1870 - 2270

TABLE II
DEMONSTRATED HEAT PIPE LIFETIME CAPABILITIES

Fluid	Container	Temp °K	Hours of Operation	Remarks
Li	W-26Re	1870	10 000	No failure
Li	TZM	1770	10 526	Weld failure
Li	TZM	1770	9 800	Weld failure
Li	Nb-1%Zr	1770	9 000	Continuing
Na	Nb-1%Zr	1120	16 000	Continuing
Na	Ni	1070	13 755	No failure
Na	304 SS	1000	11 500	No failure
Na	Haynes 25	1000	12 000	No failure
Na	Hastelloy-X	990	33 000	No failure
K	Ni	870	6 000	No failure
K	Ni	870	41 000	No failure

shown in Table II, indicate that successful operation for several thousand hours has been achieved.⁵

III. GAS-CONTROLLED HEAT PIPES

A heat pipe can operate isothermally over its entire length if there are no noncondensable gases in the pipe. If a noncondensable gas is present, it will be pumped to the condenser end of the pipe, forming a gas pocket, which results in a large temperature drop over this section. For a given amount of gas, the length of this section will depend upon the operating temperature of the pipe. As shown in Fig. 3, this mode of operation can be utilized to create a thermal control system. The operating temperature T_0 can be established for a given Q_0 by loading the proper amount of an inert gas into the pipe. The gas pressure will be equal to the vapor pressure at T_0 and this fixes the length of the heat rejection area Q_{R0} . If the heat input is increased to Q_1 , the temperature will increase to T_1 , compressing the gas, and the heat rejection zone will increase to Q_{R1} . Conversely, if Q_0 is decreased to Q_2 , T_0 will decrease to T_2 ; the gas will expand decreasing the heat rejection zone to Q_{R2} . This produces a variable heat rejection zone and if the pipe is operating at the steep slope section of the vapor pressure curve, a small temperature change produces large pressure changes. Therefore, for a

Fig. 3. Gas-controlled heat pipe.

relatively large variation of heat input, the heat rejection zone has a large variation, and the temperature change is small. This method of temperature control has been used by incorporating heat pipes into irradiation capsules at Los Alamos Scientific Laboratory (LASL) for evaluating radiation damage of materials for thermionic diodes. Test results indicate that this means of thermal control can be extended to irradiation testing of a variety of reactor structural and fuel materials over a broad temperature and radiation flux range.

IV. THERMAL CONTROL IRRADIATION CAPSULES

A. Vacuum-Gap Dewar Capsule

A typical vacuum dewar capsule used by LASL for irradiating thermionic diode materials is shown in Fig. 4. In this capsule the specimens are mounted in good thermal contact with a gas-controlled heat pipe operating in the gravity-assist mode. The

Fig. 4. Vacuum dewar irradiation capsule.

container is an evacuated dewar to prevent radial heat rejection and the heat pipe not only provides the temperature control but is the sole means of heat rejection from the capsule to the reactor sodium coolant. As the heat pipe operation is essentially isothermal, the temperature is constant over the height of the specimen section. Several successful irradiation experiments have been made with this type of capsule.

1. Ceramic Insulator Irradiation Capsule.

Thermionic insulator materials placed in a vacuum-dewar capsule were subjected to irradiation in the LASL, Omega West Reactor (OWR) at 1013 K for a period of 3700 h.⁶ The capsule was temperature controlled by a sodium heat pipe containing neon as the control gas. A thermocouple was attached to the heat pipe at the center of the specimen section, and the temperature was recorded during the entire test to monitor the control capability of the heat pipe. During the test period, the desired temperature was maintained with a variation of only ± 5 K.

2. Irradiation Capsule for Sheathed Insulator Voltage Test. To determine the combined effects of temperature, electrical stress, and neutron irradiation on the resistivities of thermionic insulators, specimens were placed in a vacuum-dewar capsule and irradiated in the OWR for a period of 2179 h. The specimens were temperature controlled by a sodium heat pipe with neon as the control gas. A thermocouple at the center of the specimen section indicated that the desired temperature of 1023 K was maintained within ± 20 K during the test.⁷

3. Irradiation of Thermionic Tri-Layer Materials. A vacuum-dewar capsule, containing test specimens of thermionic tri-layer materials, was irradiated in the EBR-II Fast Reactor (Experiment X-171) for a period of one year. This unit was designed to operate at 1000 K in the outer row of the reactor core with an input flux of 500 W. The heat pipe was 2.8-cm o.d. with sodium as the working fluid and neon as the control gas. Preliminary tests of the heat pipe indicated that it would operate at the desired temperature with a maximum control temperature change of 20 K when the power input varied from 500 to 1000 W. Further work was done to develop a heat pipe for this type of capsule to operate in the center of the reactor core with a heat transfer capability of 5 kW. A prototype of

this heat pipe was tested up to 6 kW, and the temperature control obtained is shown in Fig. 5. This curve shows that for the design heat-rejection rate of 5 kW at 1000 K, a temperature control of ± 15 K could be maintained for a power input variation of ± 1 kW. Over the entire test range from 2 to 6 kW, a temperature rise of only 56 K occurred when the power input was increased by a factor of three. Due to the cancellation of the thermionics program, this heat pipe was never operated in an irradiation capsule.

B. Gas-Gap Dewar Capsule

The EBR-II reactor is the main experimental fast-flux facility for virtually all materials irradiation involved in fast breeder reactor development. The size of the test holes in the EBR-II reactor core for irradiation capsules is uniform and fixed so when capsules are placed in high flux

Fig. 5. Heat pipe thermal control.

regions at the center of the core, the heat rejection rates become very high. At any given temperature there is a maximum heat transfer limit for a heat pipe. However, by combining radial heat rejection through the capsule wall with the variable axial heat rejection of the heat pipe, large heat fluxes can be accommodated. If the reactor coolant and the capsule wall temperatures are relatively constant, the radial heat rejection is constant. Changes in the input heat flux to the system would then be controlled by the variable heat rejection rate of the heat pipe. The ratio of the heat rejection through the capsule wall to that of the heat pipe can be adjusted according to the magnitude of the total heat rejection required and the desired temperature control.

A typical irradiation capsule with a gas-gap dewar for radial heat rejection and a gas-controlled heat pipe, to establish a predetermined operating temperature and a variable heat rejection zone for temperature control, is shown in Fig. 6. The radiation capsule consists of a double-walled dewar which provides a gas-gap for conduction of a portion of the heat to be rejected radially to the reactor coolant stream. This portion of the heat rejection is predetermined by the gas-gap spacing and the thermal conductivity of the gas used. The capsule also contains a liquid metal heat pipe which extends through the top of the capsule into the reactor coolant stream for axial heat rejection. The inert-gas control zone at the top of the pipe provides the variable heat rejection area for temperature control. A liquid-sodium pool covers the test specimens to provide good thermal contact with the heat pipe and the inner capsule wall. An inert buffer gas above this sodium pool provides an insulation zone to prevent axial heat loss except for heat removal by the heat pipe as required for temperature control. All capsules for irradiation in the EBR-II reactor are restricted to a maximum module diameter so the number, size, and shape of the test specimens are determined by the gas-gap spacing of the dewar and the diameter and number of heat pipes required to reject the necessary heat absorbed to maintain the desired operating temperature.

1. Irradiation of Fast Breeder Structural Materials. A temperature controlled, gas-gap capsule has been developed for the Naval Research Laboratory

Fig. 6. Gas-gap dewar irradiation capsule.

(NRL) to irradiate structural materials for the fast breeder reactor development program.⁸ This capsule contains approximately 2200 g of structural specimens and is temperature controlled by a gas-controlled sodium heat pipe 2.22-cm o.d. by 55.2 cm long. Two of these capsules are now being irradiated in the EBR-II reactor in row 7 of the core and will be exposed to an irradiation of 25 000 megawatt days at a temperature of approximately 910 K. In row 7, the average radiation flux is 3 W/g so with the total weight of the capsule and specimens, the required heat rejection to the reactor sodium coolant is 7.5 kW. The capsules were constructed with a 0.0254-cm gas gap in the dewar wall containing neon gas for the radial heat conduction. At operating temperature, the calculated value of radial heat rejection is 5.25 kW and the axial heat rejection of the heat pipe, determined experimentally, is

Fig. 7. Thermal control of gas-gap capsule.

2.25 kW with a total heat rejection capability of 7.5 kW. The combined heat rejection rate of the heat pipe and gas gap vs temperature is shown in Fig. 7. As indicated by the composite curve, a variation of radiation input flux of ± 2.5 kW ($\pm 33\%$) would result in a temperature variation of approximately ± 22 K.

The construction of two more of these capsules is now in progress. These capsules contain the same type of specimens and will also operate at 910 K. One of the capsules will, however, be placed nearer the center of the reactor core with an input flux of 5-1/2 W/gm so the total specimen weight will be reduced to maintain the same overall heat transfer required.

V. TEST PROCEDURES

The test specimens in a capsule are heated externally by the high flux radiation of a reactor; it is therefore not feasible to build a laboratory test apparatus to determine the operating characteristics of a complete capsule before inserting it into a reactor core. It is possible, however, to determine the operating temperature and control capability of the heat pipes before they are assembled into the capsule. The ability of the heat pipe to establish and control the operating temperature is the main factor for the thermal control of irradiation capsules. Therefore, if the test of a heat pipe is satisfactory, adequate performance of the complete capsule assembly is reasonably assured.

An apparatus for testing heat pipes to mockup reactor conditions is shown in Fig. 8. Heat input to the heat pipe is provided by an rf induction coil to simulate the external radiation input flux of the

Fig. 8. Heat pipe test apparatus.

reactor. Heat rejection to the reactor sodium coolant stream is simulated by a split copper block clamped to the heat rejection section of the heat pipe which is temperature controlled by a water-cooled, gas-gap calorimeter. The heat rejection rate to the calorimeter is controlled by adjusting the thermal conductivity of the gas in the gap between the copper block and the calorimeter with various mixtures of argon and helium. The upper and lower limits of heat transfer for a given block temperature are fixed by having either all helium or all argon in the gap. The temperature of the copper block heat sink, to simulate the temperature of the reactor coolant sodium, can be set by controlling the heat rejection rate for any given input heat flux. This is done by varying the mixture of argon and helium in the gap. To extend the heat rejection range beyond the capability of the gas mixture, the gap spacing can be changed by lining the inner wall of the calorimeter with various thicknesses of pure silver sheet. Temperatures of the copper block were measured with clad thermocouples inserted into wells bored into the block. The heat pipe temperatures are measured by thermocouples spot welded onto the heat pipe wall at various points.

The heat transfer rate of the heat pipe is measured by the calorimeter. A ΔT meter indicates the temperature rise of the water through the calorimeter and a rotameter is used to measure the flow rate. The heat rejection rate of the heat pipe can be calculated utilizing these two factors.

A valve is attached to the fill tube of the heat pipe for the preliminary tests so that the quantity of inert control gas can be varied to obtain the desired control temperature. This also enables studies to be made of the effects of different control gas pressures on the control temperature. The operation of a heat pipe with three different gas pressures is shown in Fig. 9. Each of the curves has the same slope, but as the gas loading is increased, the control temperature is increased. This graph also indicates that a more stable control over the temperature range results when the gas pressure is higher.

When the tests have been completed and the proper operating temperature established, the valve is removed by making a pinch-off weld. This is done by flattening the fill tube in three stages with

Fig. 9. NRL gas-controlled heat pipe.

hydraulically driven anvils and annealing the tube between each stage. After the final flattening stage, the tube is held under full hydraulic pressure and burned through with a heli-arc torch as shown in Fig. 10. This procedure provides a permanent seal weld.

After the valve has been removed, another temperature control test is made to determine the final operating characteristics of the heat pipe. Removing the valve and a section of the fill tube reduces the volume of the gas-control section. This results in an increase in operating temperature after the pinch-off weld is made, the magnitude of which, depends upon the relative size of the gas-control volume. A typical example of this effect is demonstrated by the test results of a heat pipe used in an NRL irradiation capsule (see Fig. 11).

Fig. 10. Hydraulic pinch-off apparatus.

Fig. 11. Effect of pinch off on control temperature.

VI. HEAT PIPE DEVELOPMENT FOR HIGH INPUT FLUX CAPSULES

The early capsule development work at LASL was directed toward the irradiation of thermionic diode materials at relatively low radiation fluxes and high temperatures (970 - 1020 K). More recently, efforts have been confined to the development of capsules for irradiation of reactor structural and control rod materials for the fast breeder reactor program. These capsules must operate at a lower temperature (870 - 920 K) and high radiation input fluxes. Operation at lower temperatures and high heat transfer rates introduces several problems in the design of heat pipes for these capsules. The heat pipe diameter should be as small as possible so that the maximum number of test specimens can be irradiated. However, at lower temperatures a large vapor passage is required or the pipe will be sonically limited due to the lower vapor density.⁶ This problem is accentuated at high heat transfer rates because of the need for a thicker wick structure, to avoid a liquid limit, which decreases the vapor passage. Potassium as a working fluid has a much higher sonic limit than sodium and can transfer approximately three times as much heat as sodium at 920 K (see Fig. 12). However, as potassium requires a thick wick structure to accommodate the liquid flow, the liquid inventory is relatively large. This, combined with the low wicking height of potassium, can result in startup problems because of a large pool at the bottom of long pipes operating in the gravity-assist mode. If there is a heat input at this pool section, boiling in the wick can occur at relatively low input fluxes. This can be a violent action forcing all the liquid out of the pool area and cause a startup failure and even permanent distortion of the wick structure. Experiments have also shown that if a heat pipe has a liquid excess, the excess may be at the bottom or forced to the top of the pipe. As this causes a change in control-gas volume, two modes of operation have been noted with different control temperatures.

Operating at lower temperatures and high heat transfer rates also increases the possibility of failure because of vapor-liquid interaction. As the vapor density is relatively low, the velocity is very high, which can disrupt the flow of liquid to the evaporator and cause failure. In this respect,

Fig. 12. Sonic limit for sodium and potassium.

potassium is more suitable than sodium because it has a higher vapor density and therefore a lower vapor velocity in the lower temperature range (see Fig. 13).

Another advantage of using potassium as a working fluid is that it has a much higher vapor pressure than sodium. Consequently, the control gas will also be at a higher pressure and if there is any gas generation in the heat pipe due to radiation, the effect on the control gas pressure (and the control temperature) would be less for potassium than sodium. Recent tests of a sodium pipe have shown that for an operating temperature of 920 K, a loading of 4-mm pressure of argon was required, whereas 26-mm pressure was needed when potassium was the working fluid.

Although the present capsule design has been satisfactory for recent irradiation of reactor structural materials, it is restricted to the lower fluxes of the outer rows of the EBR-II core. This requires a long irradiation period to accumulate

Fig. 13. Vapor pressure and density of sodium and potassium.

the desired number of megawatt days. To shorten this period, the capsule can be placed near the center of the core and receive a higher radiation flux input. However, this necessitates a reduction of the total specimen weight because the heat rejection rate of the present system cannot be increased. The gas-gap is 0.025 cm, and it is not feasible to increase the radial heat rejection by reducing this gap further as it would require the high cost of precision-machined capsule dewars. The axial heat rejection rate of the heat pipe cannot be increased with its present diameter and sodium as the working fluid. Tests were made of a sodium heat pipe with the same dimensions and wick structure to determine the maximum heat transfer limits of this system. There was no control gas in the pipe and it was operated in the gravity assist mode from 830 K to 1070 K. Several failure points were obtained and, as shown in Fig. 14, four different types of limits were established - the sonic limit, the entrainment limit, the liquid limit, and the boiling limit. The liquid limit was also determined for horizontal operation and the results indicated that the heat transfer capability was almost double for this limit

Fig. 14. Limit curves for NRL sodium heat pipe.

when the pipe was operated in the vertical position with gravity-assist liquid flow.

In the application of gravity-assist heat pipes for irradiation of reactor materials, the temperature range of interest is 870 - 920 K. As shown in Fig. 14 by the shaded area under the limit curves, the maximum capability of this heat pipe is set by the sonic and entrainment limits. These limits for this heat pipe geometry cannot be increased except by using a fluid with a higher sonic limit and lower vapor velocity. Potassium has the potential as a high capacity heat pipe fluid with regard to these limits; however, because of its relatively low wicking limit, a different type of wick structure must be used as tests have shown that a normal homogeneous screen wick structure is not satisfactory for operation in the gravity-assist mode.¹⁰

VII. WICK DEVELOPMENT FOR GRAVITY-ASSIST HEAT PIPES

A program was undertaken to develop a wick structure suitable for potassium as the working fluid so that high heat rejection rates could be obtained for irradiation capsules. The main considerations in the design of the wick structures were:

1. Maintain present heat pipe dimensions - diam 2.22 cm - length 54 cm.
2. Pipe to operate in gravity-assist mode.
3. Low liquid flow resistance.
4. Maximum vapor passage diameter.
5. Minimum interaction between liquid and vapor flow.
6. Good distribution of liquid in evaporator.
7. Minimum liquid inventory.

The most suitable design which would meet the above consideration appeared to be a helical liquid return structure to provide a low resistance liquid flow by gravity. A multiple helix system could provide adequate liquid flow without utilizing a very large portion of the cross-sectional area of the pipe. By placing two layers of fine mesh screen against the wall, a high liquid wicking height is obtained and two or three layers of coarser mesh screen could provide distribution of the liquid from the helical flow elements to all sections of the evaporator. This type of wick structure provides a low liquid flow resistance, minimum liquid inventory, good distribution, and a relatively large vapor passage area. The helical liquid return also provides a means for reducing the liquid-vapor interaction.

Seven different wick structure assemblies were constructed and tested in an effort to develop a high capacity heat pipe for the lower irradiation temperature range. All of these heat pipes were to use potassium as the working fluid and to operate in the gravity-assist mode so it was designated as the GK Series.

GK-1 Helical Arteries

4 helical arteries - 2 turns per helix - 0.16-cm i.d. 100 mesh screen. Screen cut on bias, formed on copper wire mandrel, and spot-welded along seam then drawn through a die for sizing.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 3 layers #160 mesh screen.

GK-2 Helical Wires (Fillet Flow)

6 helical wires - 6 turns per helix - 0.23-cm-diam wire.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 3 layers #160 mesh screen.

GK-3 Helical Arteries

8 helical arteries - 2 turns per helix - 0.16-cm i.d.

Artery construction same as GK-1.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 2 layers #160 mesh screen.

GK-4 Helical Troughs

4 helical troughs - 2 turns per helix - 0.32 cm high x 0.16 cm wide - 100 mesh screen.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 3 layers #160 mesh screen.

GK-5 Helical Troughs

4 helical troughs - 6 turns per helix.

Trough construction same as GK-4.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 3 layers #160 mesh screen.

GK-6 Helical Troughs

4 helical troughs - 2 turns per helix - 0.32 cm high x 0.16 cm wide - 0.051-cm sheet stock.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 3 layers #160 mesh screen.

GK-7 Helical Troughs

4 helical troughs - 6 turns per helix - 0.32 cm high x 0.16 cm wide - 160 mesh screen.

Wall wick - 2 layers #250 mesh screen.

Distribution wick - 4 layers #250 mesh screen.

VIII. HEAT PIPE CONSTRUCTION

The wall wick and distribution wick were constructed the same for all heat pipes. First the wall wick was rolled on a copper mandrel, inserted into an oversize heat pipe tube and then drawn down to the final heat pipe diameter to obtain compression of the screen and good contact with the wall. With the mandrel still in, the heat pipe was fired at 1170 K for 1 hour to sinter the screen and bond it to the wall. After firing, the mandrel was dissolved by nitric acid. The distribution screen was then rolled on a second mandrel and inserted into the heat pipe. This undersized assembly was expanded against the wall screen by driving plugs through the mandrel or by hydraulic pressure. The assembly was again fired at 1170 K to obtain bonding and then the mandrel dissolved. All of the helical liquid flow channel systems were assembled by a similar technique. The helical system was assembled on an undersized nickel mandrel with the proper spacing and number of turns per helix. Each helix was spot-welded to the mandrel to maintain its position and the entire assembly inserted into the heat pipe. The mandrel was then expanded to press the helices against the distribution-screen and the heat pipe

fired at 1170 K for 4 hours to obtain good bonding of the helical members. After firing, the mandrel and all helical forming wires were dissolved by nitric acid and the assembly thoroughly rinsed and sonically cleaned. End caps were welded in to complete the assembly and it was given a final out-gassing by firing at 1170 K for 1 hour before loading with potassium.

IX. TEST RESULTS

Each of the heat pipes was tested with a gas gap calorimeter to establish its maximum heat transfer capability. These were comparative tests to determine which type of wick structure was best and, if possible, what factors had the greatest influence on its capability. No control gas was used and the pipes were operated to sonic limits or failure points over the temperature range of interest. The test results of the last four pipes are shown on the heat transfer vs temperature graph in Fig. 15.

GK-1 - Relatively low heat transfer capability.

Arteries apparently did not fill even after

an extended period of operation. Operation was primarily wick limited. Apparently part of liquid return was by fillet flow on top of arteries.

GK-2 - Lower performance characteristics than GK-1.

Also liquid limited. Fillet flow not adequate.

GK-3 - Performance was slightly higher than GK-1 but very erratic and unstable. Arteries apparently did not fill and the pipe was wick limited.

GK-4 - Much higher heat transfer capability than first three wick structures. The pipe was not wick limited and had relatively linear-slope limit curve up to 930 K where the slope suddenly decreased and was distinctly concave upward. This condition was maintained up to 1050 K where a typical boiling limit curve was established. A maximum heat transfer of 7.8 kW was obtained at 1050 K.

GK-5 - The results obtained from this test produced a slightly concave upward limit-curve up to 1115 K where a maximum heat transfer rate of 9.8 kW was reached. When the temperature was increased further, a boiling limit resulted. There was no sudden change in slope before the boiling limit was reached as experienced with GK-4.

GK-6 - Performance very similar to that of GK-4 but the sudden change of slope occurred at a temperature 20 K higher and the change was not as pronounced. The pipe was not operated to a high enough temperature to obtain a boiling limit curve. In the high temperature range a heat transfer rate was obtained which was about 1 kW higher than GK-4 at 1050 K.

GK-7 - This pipe had the highest heat transfer capability of all the pipes tested. It was operated only up to 990 K, but at that temperature a heat transfer rate of 9.4 kW was obtained. At 870 K the slope increased, indicating an increase in performance, but returned to its original value at 910 K when a second inflection point occurred. No boiling limit curve was established.

Fig. 15. Performance of GK heat pipes.

X. DISCUSSION

The results of the first three heat pipes indicated that the artery or fillet liquid return is

not a satisfactory method for gravity-assist operation. All three pipes were liquid limited and the artery systems were not stable because of the inability to maintain the arteries full of liquid.

The best system appears to be the helical trough which can fill easily without the possibility of flow interruption due to vapor or gas bubbles forming as encountered in a closed system. The troughs provide low impedance flow paths, small liquid inventory, and protection from vapor-liquid interaction which can disrupt or stop flow. The tests indicated that the amount of protection depends upon the pitch of the helix. At higher heat transfer rates, both GK-4 and GK-6 indicated a sudden decrease in performance as they had only two turns per helix which provide less protection of the liquid flow from the counter-current vapor flow. The decreased performance in this region appeared to be a result of turbulence, but the turbulent effect was not as pronounced for GK-6 which had troughs made from sheet stock instead of wire mesh screen. Another possible cause of the lower performance of structures with two turns per helix is that the liquid distribution from the troughs to the wall screen in the evaporator is not as good as for structures with more turns per helix. Increasing the number of turns per helix results in better protection from vapor-liquid interaction and more efficient liquid distribution; however, too many turns would result in insufficient liquid flow and performance would be liquid limited.

The results of the tests of GK-5 and GK-7 indicate that high capacity potassium heat pipes can be constructed to operate in the gravity-assist mode in a lower temperature range than is possible with sodium. Heat transfer capability of these two pipes is indicated in Fig. 16 by a narrow cone starting at the sonic limit curve of potassium and extending up to about 10 kW. Because the vapor passage area could not be readily calculated, an "effective area" was determined experimentally by measuring the heat transfer rates at low temperatures where the heat transfer could not be increased by increasing the heat rejection rate at the condenser. At this point the vapor flow is sonic and the effective area was then calculated from the equation for sonic flow developed by Busse¹¹ and used for plotting the sonic curves. The sonic limit of sodium for the same

Fig. 16. Limit zone for GK-5 and GK-7.

vapor passage area is also shown and, as indicated by the operational zone for the two potassium heat pipes, a relatively high heat transfer operation was obtained which would not be possible with sodium as the working fluid in the temperature range of interest. A heat transfer rate of approximately 7 kW at 910 K was achieved, which is about 1 kW above the sonic limit for sodium at this temperature. As a further comparison of the two working fluids, the potassium was removed from heat pipe GK-5 and it was loaded with sodium. The pipe was then tested and its performance curve did not equal that of the potassium operation until a temperature of almost 1000 K was reached. At high temperature, however, the sodium performance exceeded that of potassium and a heat transfer rate of over 11 kW was obtained, which was the upper limit of the power supply and not the heat pipe. The tests show, however, that for lower temperatures, potassium must be used as the working fluid and that a wick structure consisting of helical troughs does

provide high heat transfer capability for gravity-assist operation.

One of the most important results of these tests was the revelation of a heat pipe limit which has not been previously considered. As shown in Fig. 17, the limit curves for all four helical trough heat pipes fall in a very narrow zone from the sonic limit curve at 730 K up to 920 K. Above this temperature, each pipe then displayed individual characteristics depending upon the wick structure design. However, in the narrow limit zone below this temperature, the type of trough material, the number of turns per helix, or the mesh of the distribution wick had no apparent effect upon the heat pipe limit. In the past, limit curves with a similar slope were often encountered in heat pipe tests which was determined to be a function of vapor velocity. This was considered to be an "entrainment" limit as the impingement of liquid particles, swept out of the wick by the vapor, was audible when failure occurred. These recent tests, however, seem to indicate that entrainment is not a limit but the result of a limit. A study of the

test results shows that a limit was reached which was a function of the vapor pressure gradient and similar to that described by Wallis¹² for counter-current two-phase flow in a vertical duct. This theory states that for an upward vapor flow, a downward liquid flow can occur only if the gravity gradient in the liquid exceeds the pressure gradient in the vapor. If the vapor pressure gradient equals the gravity gradient, liquid flow will stop. In a heat pipe system this would result in operational failure as no liquid could return to the evaporator. When the vapor pressure gradient exceeds the gravity gradient, the liquid flow can reverse direction and, as the condenser of a heat pipe is still supplying a downward flow of liquid, an excess would be formed at some point and forced out of the wick structure. This condition could lead to liquid particles being swept to the condenser end of the heat pipe by the vapor stream and has been called "entrainment." However, the limiting factor which causes the heat pipe failure could be considered as a "pressure-gradient limit" and the entrainment is a result of this condition. Further studies are being made to establish suitable equations to define this limit and investigate the parameters which influence it.

Fig. 17. Pressure-gradient limit for GK heat pipes.

XI. CONCLUSIONS

As the energy shortage is becoming more critical, increasing emphasis is being placed on the development of fast breeder reactors. This development requires extensive irradiation testing of reactor structural materials. Because the present facilities for irradiation of specimens preclude the measurement or control of testing conditions, the only apparent recourse is to incorporate heat pipes in the test capsules for the establishment and control of test temperatures. It has been shown that the gas-controlled, gravity-assist heat pipe is capable of providing good temperature control with high heat transfer rates for this purpose. Similar thermal control systems could be used for a variety of other applications over a wide temperature range using different working fluids.

Considerably more work must be done to perfect this system and provide information to predict its performance and limitations. Further work is also planned to study the heat pipe limit involving

pressure gradient effects in two-phase, counter-current flow.

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