NASA TECHNICAL MEMORANDUM

NASA TM X-52928

NASA TM X-52928

USE OF HEAT PIPES FOR ELECTRICAL ISOLATION

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TECHNICAL PAPER proposed for presentation at
Thermionic Conversion Specialist Conference sponsored by
the Institute of Electrical and Electronics Engineers
Miami, Florida, October 26-29, 1970

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Abstract

Some of the problems of electrical isolation of the emitter from the heat source in out-of-core thermionics can be circumvented by the use of long heat pipes as electrical resistive elements. The various relations governing electrical resistance, heat pipe geometry, heat pipe pumping limits, and temperature losses were used to estimate the performance of heat pipes used in this manner. The design variables are the form of the electrical network, heat pipe length, heat pipe diameter, wall thickness, the wick design in the adiabatic section of the pipe, and heat pipe materials. First order calculations project the attainment of 28 volts with small penalties in system performance.

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Introduction

A variety of recent developments in the thermionic converter and related areas has indicated that out-of-core thermionics should be considered for advanced space power systems; improved thermionic converter performance;[1, 2] high-strength, high-temperature, ductile alloys;[3] better understanding of high temperature corrosion resistance;[4] new compact reactor concepts;[5, 6] and perhaps most important the development of a high intensity heat transfer device, the heat pipe.[7] But a major problem yet remains. Fundamental to the nuclear-thermionic out-of-core power system is the requirement of electrically isolating the emitter from the energy source in order to develop voltages practical for large power systems. A variety of techniques have been proposed and reviewed in an unpublished report.[8] Most prevalent are radiant coupling, the use of refractory oxide insulators, and isolation of nuclear fuel elements in conjunction with isolation of the local heat transfer elements. Each of these approaches has its disadvantages as discussed in Ref. 8. This report treats still another method, the use of long heat pipes as electrically resistive elements. The application takes advantage of the low-voltage, high-current characteristics of thermionic converters to secure a degree of electrical isolation by controlled current leakage through metallic elements and does not attempt complete electrical isolation.

The idea of using metallic elements to achieve a degree of electrical isolation is not new. Further, it is not new in thermionics; some of the first thermionic converters used thin refractory metal elements to isolate the emitter from the collector before the cesium compatibility problem of ceramic-to-metal seals was adequately solved.[9] Also the problem of high neutron flux and cesium attack on insulators was side-stepped in early tests at the Plum Brook reactor test facility of NASA-Lewis by the use of thin metal sleeves that acted as a resistive load and provided a degree of electrical isolation between the emitter and collector.[10] More recently the use of long liquid metal loops meandering in and out of the core of an externally fueled in-core thermionic reactor has been suggested as a method of obviating the need of electrical insulators in the collector coolant loop.[11]

So what does this paper contribute? Simply a recognition that a long heat pipe may provide a unique degree of electrical isolation: The metallic walls used in heat pipes are thin. The energy transport is by a nonconductive metal vapor. And from a design standpoint if the converters are located in or near the radiators long heat pipes provide a natural and convenient means of locating the converter away from the troublesome environment of the reactor. As suggested in Refs. 8 and 12 these long heat pipes may provide a surprisingly effective method of electrical isolation. Some of the compromises among heat transfer, wall stress, and electrical leakage are illustrated in this paper.

Analysis

The system assumed is a group of heat pipes that are metallically (and thus electrically) coupled to a heat exchanger in or adjacent to a nuclear reactor (fig. 1). If the reactor is split as in Refs. 8 and 12, then two sets of electrically independent heat pipes may be put in-series to double the system voltage. In principle a reactor may be subdivided to continuously build the series voltage, but then this requires the electrical isolation of fuel elements with the attendant problem of poor thermal communication of the fuel elements in the reactor. Thus on the basis of thermal stability, this analysis is limited to a split reactor with a maximum of two independent sets of coupled heat pipes.

Each set of heat pipes may be arranged as shown in Fig. 2. A common ground centrally located in the interconnected pipes minimizes the electrical leakage. At the end of each heat pipe several converters tied in parallel with their emitters grounded to the heat pipe generate a voltage. The voltage is increased by connecting adjacent heat pipe heated converter assemblies in series. The electrical leakage along the heat pipe is proportional to V^2/R, so as can be seen in Fig. 2, those heat pipes farthest away from the common ground contribute the largest electrical loss.

Also it is obvious that in order to minimize the electrical leakage the joule heat loss should be made small with respect to the thermal flux through the pipe. Further it should be noted that some of the joule heat loss is recoverable since it feeds back as energy supplied to the emitter of the thermionic converter. By definition, a 100% efficient conversion device will recover all of the joule heat loss.

A detailed optimization study requires a complex treatment of each heat pipe with respect to location, power matching, armor requirements for meteoroid protection, stress analysis, and reliability, all of which are intimately related to the mission selected. The scope of the present paper is much less ambitious and is limited to a first order treatment of this form of electrical isolation. In keeping with the restricted scope the following assumptions are made.

All heat pipes in a set have the same length, outside diameter, axial throughput, wall thickness, and diameter of fluid return. Since the heat exchanger and the converters

Presented at the 1970 Thermionic Conversion Specialists Conference, October 26 through 29, 1970, Miami, Florida.

determine the characteristics of the evaporator and the condenser of the long heat pipe (respectively), the design variation resides in the adiabatic section.

The temperature of interest is in the range of 1750° to 1850° K. (In absence of detailed biaxial creep data in presence of lithium, this temperature range is based on demonstrated performance of lithium heat pipes reported in refs. 13 and 14).

Lithium is the heat pipe fluid and the electrical resistance of the heat pipe wall and screen is typified by tantalum.

Additional assumptions will be identified as introduced. The electrical power that can be generated by the converters at the end of each heat pipe is (a list of symbols appears at the end of this paper)

$$P = P_o + \eta q_j - q_j$$

where

$$P_o = \eta q_o$$

$$\frac{P}{P_o} = 1 + \frac{q_j}{q_o}\left(\frac{\eta - 1}{\eta}\right)$$

or

$$\frac{\Delta P}{P_o} = \frac{q_j}{q_o}\left(\frac{1 - \eta}{\eta}\right)$$

Also the joule loss for a group of heat pipes referenced to the common ground is

$$I^2R = \frac{1}{R}\left[\left(\frac{1V_o}{2}\right)_1^2 + \left(\frac{3V_o}{2}\right)_2^2 + \left(\frac{5V_o}{2}\right)_3^2 + \left(\frac{7V_o}{2}\right)_4^2 \ldots\right]$$

If the number of heat pipes biased from the common ground is 6 or greater then the average joule heat loss determined by the series above can be approximated to within 1% by

$$q_{j,\,ave} = \frac{V_{eff}^2}{3R}$$

where V_{eff} is the voltage imposed on the n^{th} heat pipe plus one-half the individual diode voltage; or simply one-half the voltage of an entire set, i. e., two groups with a centrally located common ground, for example, 7.32 volts in the case of Fig. 2.

The average fractional power loss is then

$$\frac{\Delta P}{P_o} = \frac{V_{eff}^2}{3Rq_o}\left(\frac{1 - \eta}{\eta}\right)$$

The fractional power loss is minimized by increasing the electrical resistance and by increasing the heat flux q_o through the pipe. The electrical resistance is increased by increasing the length or reducing the cross sectional area of the liquid and the solid metallic elements. Since the wall stress requires that the tube diameter be reduced as wall thickness is reduced, and since the heat flux per pipe is often based on powerplant design constraints, the minimization of the power loss is simply achieved by using an adiabatic section of a heat pipe that is operating at or near its pumping limit for the particular length and heat flux required. The length of the heat pipe is usually dictated by distance required to move from the reactor to a location where there is sufficient area available for the heat rejection requirements of the radiator or for other powerplant or vehicle requirements.

Figure 3 illustrates several possible vapor and fluid passages that can be used in the adiabatic section. The diameters of the liquid and vapor sections in configurations (a) and (e) that yield a minimum pressure drop can easily be determined by the usual pressure drop relations since symmetry allows analytical simplifications. But configuration (a) introduces a large liquid volume that in turn contributes to a significant electrical leakage. Configuration (e) tends to reduce the liquid volume but does not return wall condensate to the evaporator. The other configurations (b), (c), and (d) do not lend themselves to convenient analytical forms of the fluid flow optimization procedures, but nonetheless were selected for several first order evaluations. Configuration (d) was finally chosen because of the following reasons; the liquid volume is the smallest for a given liquid pressure drop; the vein like return tube is easy to fabricate; contact with the wall is sufficient to provide for the return of the wall condensate to the evaporator; and also corrosion of the external wall of the adiabatic should be less than configurations (a), (b), and (c) since the shearing action of the fluid of the liquid return is confined to the interior surfaces of the vein used to return the liquid lithium.

Several heat fluxes, outer tube diameters, vein diameters, and tube lengths were examined to assess the general properties of the fluid flow and electrical leakage. It was observed that at the conditions of most interest the Reynolds number of the vapor corresponded to turbulent flow, whereas the liquid was generally laminar. Also it was determined an optimization procedure based on minimizing the pressure drop and electrical resistance was highly questionable because of the uncertainty of the coefficients of friction for both the vapor and fluid for the configuration and materials used. In both cases the fluids were in or near the transition condition between laminar and turbulent flow. Furthermore the practical problem of building a small-diameter long liquid-return tube composed of small-pore material tended to dominate all other considerations. No simple analysis yielded the information required; so it was decided to resort to empiricism. Several attempts to make small diameter porous tubes finally resulted in a degree of success. On the basis of this experience it was assumed that the vein diameter would be allowed to vary as

$$D_{vein} = \left(\frac{D_p}{10} + 0.15\right), \text{ inches}$$

This variation in diameter is based on the practical observation that the longer veins are associated with the larger pipe diameters and that at present the fabrication problems of the longer veins are eased by going to slightly larger diameters.

Using the relation for the diameter and restricting the smallest diameter of the heat pipe to 0.4 inch yielded estimated liquid pressure drops less than 15% of the vapor pressure drop. Since the uncertainty of the friction coefficient of the vapor is greater than 15% the liquid pressure drop was neglected in subsequent calculations.

The pressure drop of the vapor was based on turbulent flow and was calculated from the

$$\text{pressure drop} = \frac{1}{2} \frac{w_t}{\rho_v} \frac{f_o l_a}{D_v^5}$$

The Reynolds numbers for the vapor were at or near the transition region for all conditions examined. In absence of experimental pressure drops for the configuration a constant value of $f_o = 0.035$ was used for all calculations. The effect of the blockage of the vein was introduced by assuming that the flow area was 90% of interior of the pipe and by adjusting the diameter in equation to correspond to the reduced area.

With these simplifying assumptions and simple analytical forms the electrical leakage of a variety of heat pipes were examined. The conditions examined were

Axial throughput, kW	10 to 30
Outer diameter of heat pipe, in. (cm)	0.4 to 0.9 (1.02 to 2.29)
Wall thickness, mils (cm)	20 to 50 (0.0508 to 0.127)
Adiabatic pressure drop (pumping capacity required), torr	20 to 120
Veinous wick wall thickness (material tantalum or tungsten alloy), mils	7

Results

Since

$$\frac{\Delta P}{P} = \frac{V_{eff}^2}{3Rq_o}\left(\frac{1-\eta}{\eta}\right),$$

the results can be compacted by plotting $1/3Rq_o$ as a function of heat pipe length for various values of heat pipe diameter and pressure drop. Figures 4, 5, and 6 are representative plots. The log of power loss parameter plotted against the log of heat pipe length for the specified diameters are straight lines with a slope of minus 1. In the range of interest the pumping limits are also nearly straight lines. The intersection of a line of constant diameter and a line for a constant pressure drop of the adiabatic section establishes the maximum length and minimum power loss for the assumed values of temperature, heat flux, wall thickness, diameter, and allowed pressure drop. For example, a tube with a 0.6-inch outside diameter, 30-mil wall thickness, operating at 1800° K, and an axial heat flux of 20 kW has a minimum value of $1/3Rq_o$ of 3.0×10^{-4} and a maximum length of the adiabatic section of 410 cm if the pressure drop of the adiabatic section is limited to 20 torr. Using an estimated conversion efficiency of 15% and an effective voltage of 7 volts results in a power loss of

$$\frac{\Delta P}{P} = V_{eff}^2\left(\frac{1-\eta}{\eta}\right)\left(\frac{1}{3Rq}\right)$$

$$\frac{\Delta P}{P} = (7)^2\left(\frac{0.85}{0.15}\right)(3\times10^{-4}) = 0.0833 \text{ or } 8\tfrac{1}{3}\%$$

The powerplant produces 28 volts for a split reactor with two sets of the heat pipes in series for this case of V_{eff} of 7 volts. If the V_{eff} were reduced to 3.5 volts and the corresponding circuit voltage were 14 volts the loss would be about 2.1%.

As stated previously, the power loss parameter was determined for several wall thicknesses and heat pipe temperatures. Figures 4, 5, and 6 represent only a small part of the results yet illustrate the general trends. Although the change in wall thickness alters the vapor flow area and thus pressure drop, the effect of wall thickness appears primarily in the resistance of the heat pipe. Since the electrical conductance of the heat pipe wall is usually greater than that of the vein used to return the liquid to the evaporator for the range of values treated, wall thickness has a large effect but not quite linear influence on power loss. Heat pipe temperature influences the specific electrical resistance of materials, liquid and vapor density, viscosity, and latent heat of vaporization. The result is a small reduction in power loss with increased operating temperature for a heat pipe of fixed wall thickness. But since an increase in temperature alters creep strength and the internal pressure of the heat pipe, the net effect of increasing temperature appears to be deleterious particularly where the wall thickness must exceed 30 mils to withstand the internal pressure. Other factors such as fabrication reliability and intergranular corrosion may limit wall thicknesses to 30 mils or greater. In any event the final resolution of the effect of temperature on electrical leakage awaits additional engineering information on creep strength and corrosion.

Perhaps the greatest assurance of the feasibility of heat pipes operating in the temperature ranges selected in the study resides not in specific values of creep strength, nor in detailed corrosion studies, but in the surprising success of the few attempts to operate heat pipes in this temperature region cited in Refs. 13 and 14. Freedom from failure of our Lewis Research Center tests of tantalum alloy heat pipes (yet in the short duration test category) also supports the projected use of heat pipes at these temperatures.

Combining the various observations in the literature and our limited experimental experience on heat-pipe reliability plus the relatively simple analysis of electrical leakage and pressure drops suggests that a reasonably effective electrical isolation of the emitter of an out-of-core thermionic system might be obtainable. Figure 7 illustrates the magnitude of the penalty associated with a network voltage of 20 and 28 volts. As can be seen in Fig. 7, losses are low; and indeed if compared with losses projected for the use of a refractory oxide insulated emitter at this voltage, actually a heat pipe may be more effective than the oxide insulator. This is true because an overall evaluation of leakage currents, temperature drops, and voltage drops along the emitter favors the heat pipe isolated emitter.

Concluding Remarks

A first order analysis of the use of long heat pipes as a method of providing electrical isolation of the emitters of out-of-core thermionic systems suggests that system voltages of the order of 28 volts can be achieved with relatively small electrical leakages. Problems of startup and corrosion of the long heat pipes await experimental exploration but are amenable to simple, quick, low cost assessment, as are the fluid flow and electrical behaviors of the long heat pipes.

Symbols

D_p outer diameter of the heat pipe

D_v effective diameter of the vapor flow passage

D_{vein} outer diameter of the liquid return duct

f_o friction coefficient

l_a length of adiabatic section of the heat pipe

P output power of the assembly of diodes and the end of the heat pipes

P_o output power of the assembly of diodes for zero loss in the heat pipes

ΔP power loss caused by electrical leakage of the assembly of the heat pipes

q_j joule heat contribution of the leakage current of the heat pipe

q_o heat flux through the heat pipe from the heat source

R resistance of the adiabatic section of the heat pipe

w_t mass flow of vapor towards the condensor section of the heat pipe

η conversion efficiency of the assembly of converters

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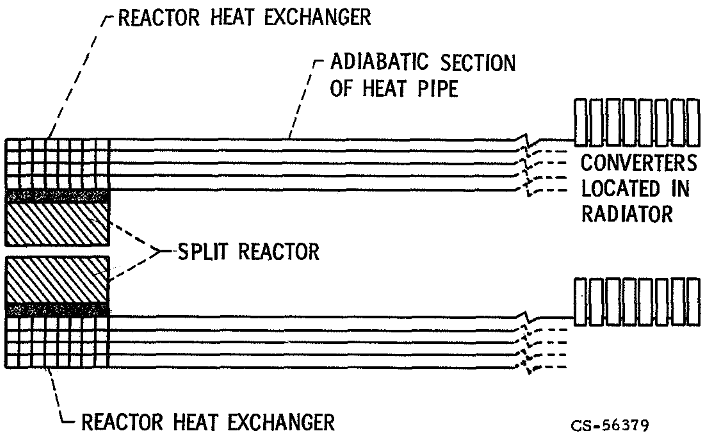

Figure 1. - Schematic arrangement of reactor, heat exchanger, and long heat pipes used for electrical isolation.

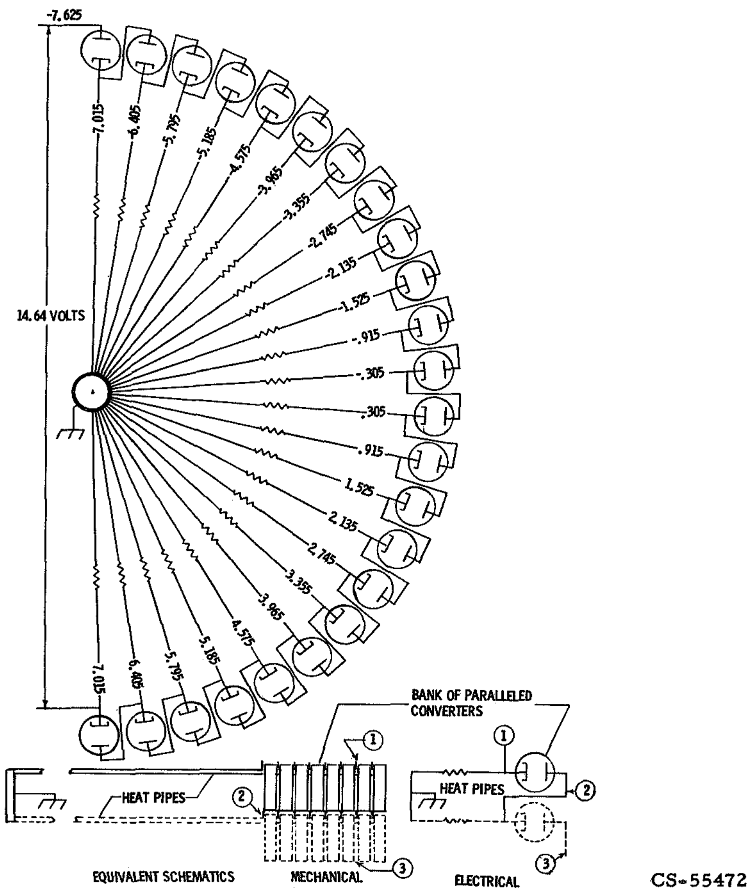

Figure 2. - An example of how heat pipes can be used for electrical isolation. Four sets of 12 heat pipes provide 29.28 volts.

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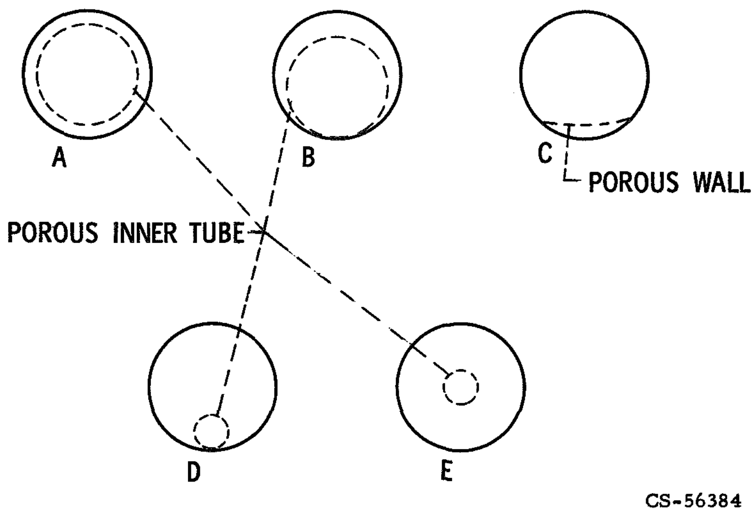

Figure 3. - Various configurations of the adiabatic section of a long heat pipe showing type of liquid return passage.

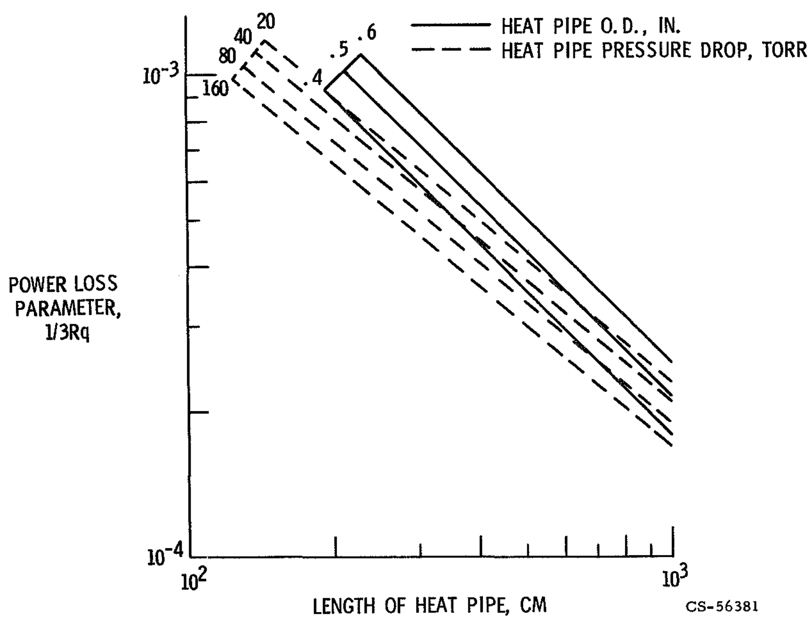

Figure 4. - Effect of heat-pipe length, diameter, and pressure drop on electrical power loss of an assembly of heat pipes used for electrical isolation. Axial heat flux per pipe, 10 kilowatts; vapor temperature, 1800° K; and wall thickness, 30 mils.

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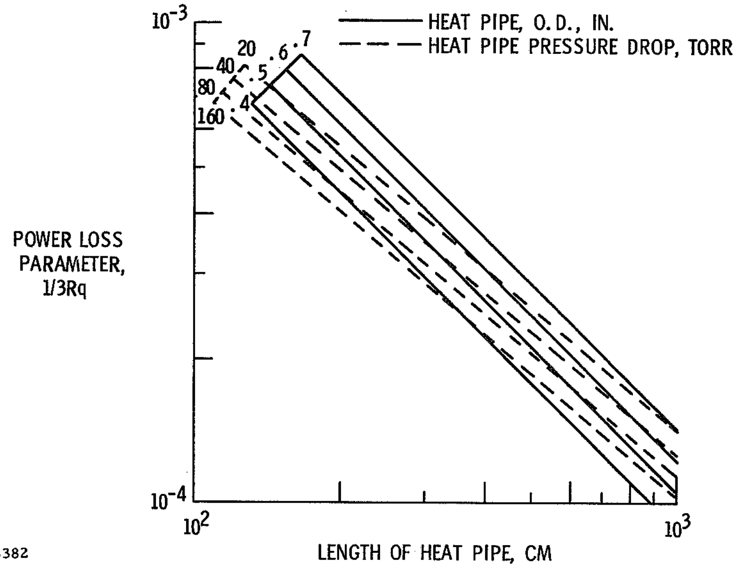

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Figure 5. - Effect of heat-pipe length, diameter, and pressure drop on electrical power loss of an assembly of heat pipes used for electrical isolation. Axial heat flux per pipe, 20 kilowatts; vapor temperature, 1800° K; and wall thickness, 30 mils.

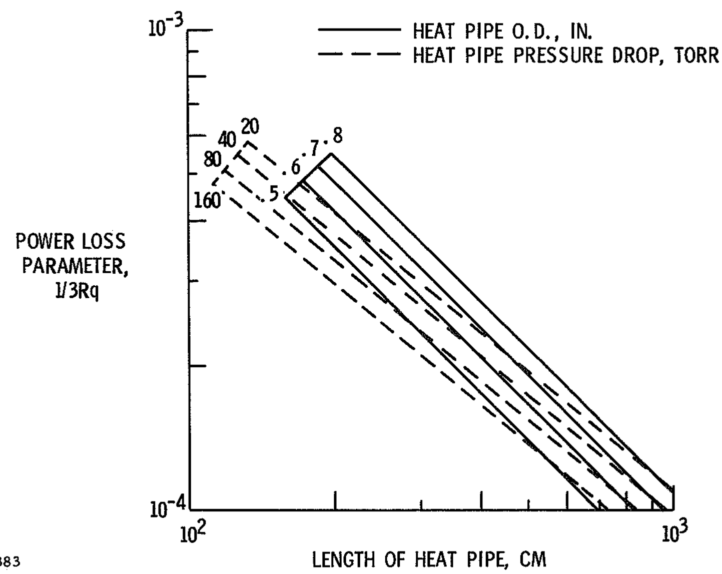

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Figure 6. - Effect of heat-pipe length, diameter, and pressure drop on electrical power loss of an assembly of heat pipes used for electrical isolation. Axial heat flux per pipe, 30 kilowatts; vapor temperature, 1800° K; and wall thickness, 30 mils.

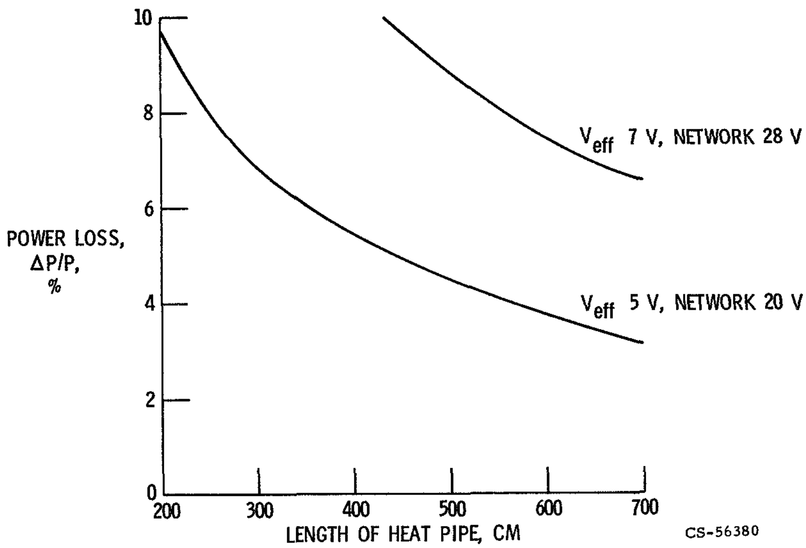

Figure 7. - Minimum power loss for an array of tantalum alloy heat pipes with a 30 mil wall thickness operating with lithium at a temperature of 1800° K, an axial heat flux of 20 kilowatts per pipe, and a pressure drop of 20 torr in the adiabatic section. The conversion efficiency assumed is 12.5 percent.