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TITLE

ESTABLISHING LOW-POWER OPERATING LIMITS FOR LIQUID METAL HEAT PIPES

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SUBMITTED TO

The 8th International Heat Pipe Conference
The Institute of Engineering Thermophysics
Chinese Academy of Sciences, P.O. Box 2706
Bejing, CHINA 100080

September 14-18, 1992
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MASTER

FORM NO. 836 R4
ST. NO. 2629 5/81

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Executive Summary

Liquid metal heat pipes operated at power throughputs well below their design point for long durations may fail as a result of the working fluid migrating to a cold region within the pipe, freezing there, and not returning to the evaporator section. Eventually sufficient working fluid inventory may be lost to the cold region to cause a local dry-out condition in the evaporator.

A joint experimental and analytical effort between the Air Force Phillips Laboratory and Los Alamos National Laboratory is underway to investigate this phenomena. Experiments include both high temperature liquid metal and low temperature organic heat pipes. To date, a low temperature working fluid has been selected and its performance in a heat pipe validated. Additionally, a low-temperature heat pipe has been fabricated and is presently being tested.

Background

Laboratory tests have demonstrated that in operating radiative coupled heat pipes below their heat throughput design point, a part of the condenser will operate near the evaporator exit temperature, essentially isothermal. At the end of this region, the temperature falls sharply and can reach values below the fusion temperature for the working fluid. This temperature decline occurs over a length corresponding to a few heat pipe diameters.

To illustrate this, Figure 1 shows a temperature profile for a potassium heat pipe operated well below its design point. This heat pipe is constructed of niobium-1.0% zirconium; has an annular screen wick; and is 1.52 centimeters in diameter and is approximately 1.0 meter long. The heated length was 11 cm. Heat removal was by radiation over the entire length. The heat pipe was operated at steady state, with an approximate power throughput at the evaporator exit of 65 Watts. It was designed to transport 650 Watts at 800 K.[1]

A heat pipe operating well below its design point will slowly deplete its inventory of usable working fluid as a result of liquid freezing in the condenser and not being cycled back to the evaporator. For long-term, low-power operation of heat pipe radiator elements in space power systems, this mode of operation may lead to system failure.

In order to determine the rate at which the working fluid migrates from the molten region to the frozen region, it is necessary to establish the point where freezing begins. To do so by analytic means requires the use of a model for the flowing vapor in the condenser. The heat pipe wall temperature is strongly dependent upon the vapor stream temperature, and freezing will start to occur at the point along the wall where the temperature is equal to the working fluid fusion temperature. A useful model must account for the changing nature of the vapor as it travels down the condenser, progressively becoming more rarefied. The vapor stream as it leaves the evaporator exit is in continuum flow. Eventually a sufficient amount of vapor condenses out of the stream so that the assumption of zero velocity for the vapor at the wall is no longer valid.[2] This type of flow is termed slip flow, or

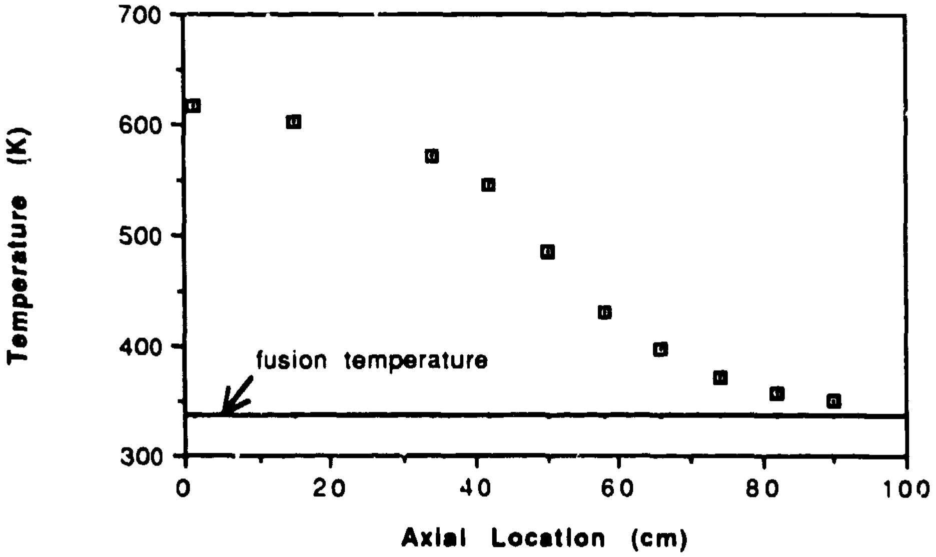

Figure 1. Low Power Temperature Profile Data for a Potassium Heat Pipe

transition flow. The manner in which the vapor hydrodynamics are modeled must be changed when going from continuum to slip flow. Eventually, the flowing vapor becomes so rarefied as to be in free molecular flow. Molecular flow occurs when the mean free path for the molecules is approximately equal to the characteristic dimension for the channel,[3] in this case the heat pipe inside diameter. Again the manner in which the vapor is modeled must be changed. It is in these regions of slip flow and free molecular flow that the sharp temperature decline along the outside heat pipe surface is observed.

Introduction

A joint experimental and analytic investigation of the performance of heat pipes operated well below their design points is being undertaken jointly by the Air Force Phillips Laboratory and Los Alamos National Laboratory. The objectives of this effort are to experimentally observe and measure the rate of mass migration into the frozen region within heat pipes and develop a combined analytical and empirical model capable of predicting those rates for liquid metal heat pipes operating well below their design points. As a result, the operating parameters for heat pipes intended for this type of operation, such as is the case for some spacecraft radiators, will be defined. This will ultimately lead to the formulation of heat pipe designs not subject to failure as a result of internal migration of working fluid.

Experiments include both high temperature liquid metal heat pipes and low temperature heat pipes. The first series of experiments, which are the focus of this paper, are for the low temperature heat pipes.

Low Temperature Experiments

The purpose of the Low Temperature Experiments (LTE) are twofold. First, the use of a low temperature (i.e., less than 475 K operating temperature) working fluid allows for the design of a transparent heat pipe; thus, the phenomena of mass migration from the molten region to the frozen region of an operating heat pipe can be observed directly. Second, the requirements for instrumentation, insulation and experimental procedure are simplified over those for the high temperature liquid metal heat pipes. Data from the LTE will be used in the development of the computer code used to model mass migration phenomena. Conclusions derived from that data will be used when designing the high temperature experiments (HTE).

LTE Working Fluid Selection

Prior to conducting the LTE experiments, it was necessary to select a working fluid and to validate its usefulness through preliminary heat pipe performance tests. Selection of the LTE working fluid was made with the objective of achieving operation in a similar manner to a liquid metal in a heat pipe.

Criteria for selecting a low temperature heat pipe working fluid are listed below:

- Useful operating temperature below 470 K in order to facilitate bench testing. Instrumentation requirements and insulation requirements are greatly simplified as the operating temperature approaches room temperature. In addition handling and data collection are simplified, requiring no specialized equipment. Thermophysical properties affecting useful operating temperature include vapor pressure, liquid and vapor kinematic viscosities, latent heat of vaporization, surface tension and liquid density.

- Free molecular flow behavior near the triple point. The working fluid vapor pressure and density must be very low near the triple point (i.e., on the order of 10^{-7} atm.).

- Triple point above the dew point. This prevents mass accumulation on the outside of the heat pipe while under operation as a result of condensation of water from the surroundings.

- Relatively low saturation vapor pressure at the operating temperature. This helps to minimize the mass required for the containment structure. A saturation pressure slightly below atmospheric is preferable because this mitigates the hazard to the experimenters in the unlikely event of a rupture or leak in the containment vessel.

- Compatible with materials of construction. A useful working fluid must be nonreactive with the selected materials of construction.

- Low toxicity, hazard potential and nuisance factor.

Hundreds of candidate fluids were screened based on the criteria established above. Those with greatest merit are listed in Table 1 along with some of their notable properties and characteristics.

Of the candidates listed in Table 1 nonadecane, octadecane and polyethylene glycol E600 were considered most favorable. Because more property data were available in the literature for octadecane than for the other two, octadecane was selected for use in the low temperature heat pipe experiments. Octadecane appears to satisfy all of the design criteria.

Preliminary Heat Pipe Tests

The intent of the preliminary heat pipe tests was to determine whether the selected working fluid would perform satisfactorily in a heat pipe, in particular, to determine whether it would transport sufficient heat and exhibit sufficient wicking capability. For these experiments, a simple transparent heat pipe was constructed. It comprised a quartz envelope and a homogeneous, 250 mesh stainless steel wick. The heat pipe was operated at steady state for successively greater static lift heights. The temperature profile at each orientation was recorded. A heat pipe performance limit was indicated when the evaporator temperature rose sharply. Such a condition is a result of insufficient fluid circulation. This condition is often termed a capillary limit.

TABLE 1 CANDIDATE HEAT PIPE WORKING FLUIDS.
(Temperatures in degrees Centigrade)

Candidate Working Fluid	Tmp	Tbp	Tc	vapor pressure
Cesium	29	397	1777	
Dowtherm A	12	258	528	
Nonadecane	32	330		1 torr @ 133 °C
Octadecane	28	317		1 torr @ 120 °C; 001 torr @ 41 °C
Pentadecane	10	271		1.7 torr @ 100 °C
Methyl myristate	18.5	295		1 torr @ 115 °C
Hexadecane	18.5	287.5		1 torr @ 105°C; 95E-6 torr @ 20 °C
Lauryl alcohol	24	257		
Diphenyl methane	26.5	265		3.5 torr @ 100 °C
Diphenyl ether	27	259		1 torr @ 66 °C
Anethole	22.5	235		1 torr @ 63 °C
Phorone	28	197		1 torr @ 42 °C
Methyl palmitate	30.5	196		1 torr @ 135 °C; decomposes
Ethyl furoate	34	195		1 torr @ 38 °C
Tribromomethane	8.5	150		20 torr @ 10 °C
Phenyl salicylate	42.5	172.5		1 torr @ 54 °C
Polyethylene glycol E600	22			5E-6 torr @ 100 °C

Data from these preliminary tests are shown in Figures 2 and 3. These figures show temperatures along the main axis of the heat pipe for various static lift heights while at a constant power throughput. The heat pipe performance limits are indicated by the "dryout" points. The static lift heights shown in Figures 2 and 3 are dial indicator readings showing the differences in elevation between the furthest spaced ends of the evaporator and condenser along the top surface of the heat pipe. Therefore, these readings are not direct measurements of static lift height, since they do not include the pipe diameter and the influence of the puddle resulting from excess fluid inventory. The calculated dryout points, once these factors are accounted for, are plotted in Figure 4. The line connecting these points is useful for determining the operating characteristics for this particular combination of heat pipe working fluid and wick structure. It is evident from this figure that this particular combination can achieve in excess of 150 Watts in a horizontal position and can achieve a static lift, with no power throughput, of a little more than 2.0 inches. It may be concluded that the working fluid, octadecane, is capable of reasonable power throughputs and is not overly sensitive to gravitational effects. Octadecane was found satisfactory for use in the LTE.

LTE Approach

The experimental approach being used for the LTE is as follows. A series of heat pipes are being constructed and operated as part of the test matrix shown in Table 2. Currently one of these heat pipes is complete and testing has begun. The second heat pipe is under construction, with the others soon to follow.

Upon completion of a given test, the heat pipe will be allowed to cool, then disassembled, and measurements of the mass distribution along the pipe will be made. From the mass distribution measurements, and the operating time measurement, the mass migration rate will be determined. Upon completion of the entire test matrix, the functional dependence of mass migration rate on temperatures and power throughputs will be analyzed.

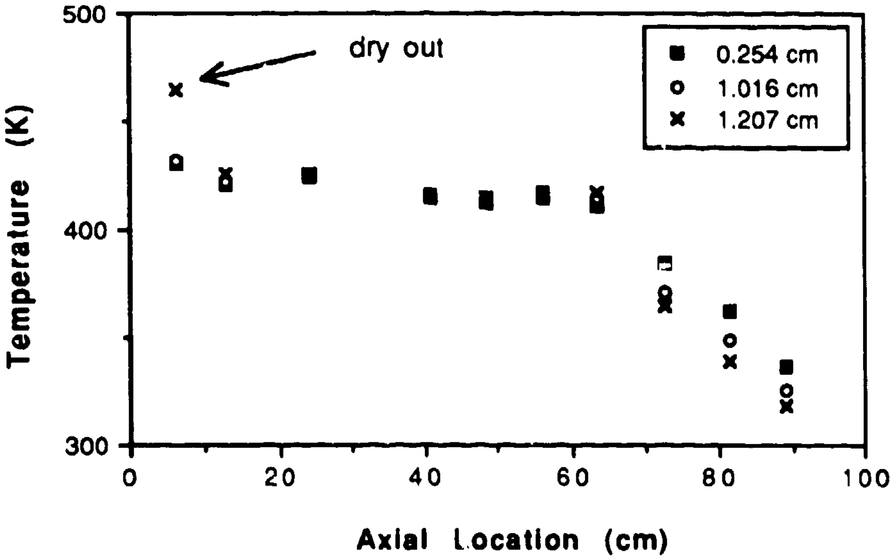

Figure 2. Capillary Performance Limit Test at 31 Watts for an Octadecane/Quartz Heat Pipe with a 250 mesh Homogeneous Stainless Steel Wick.

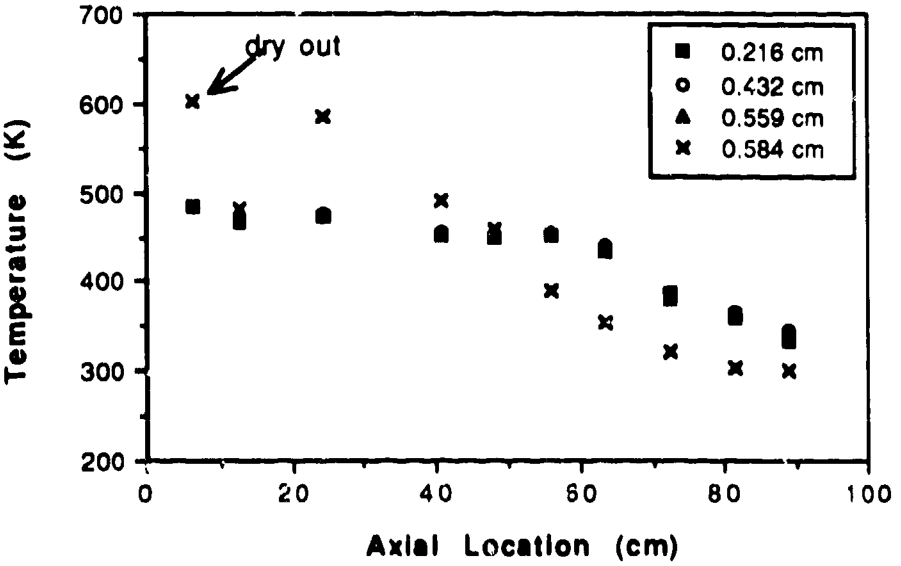

Figure 3. Capillary Performance Limit Test at 55 Watts for an Octadecane/Quartz Heat Pipe with a 250 mesh Homogeneous Stainless Steel Wick.

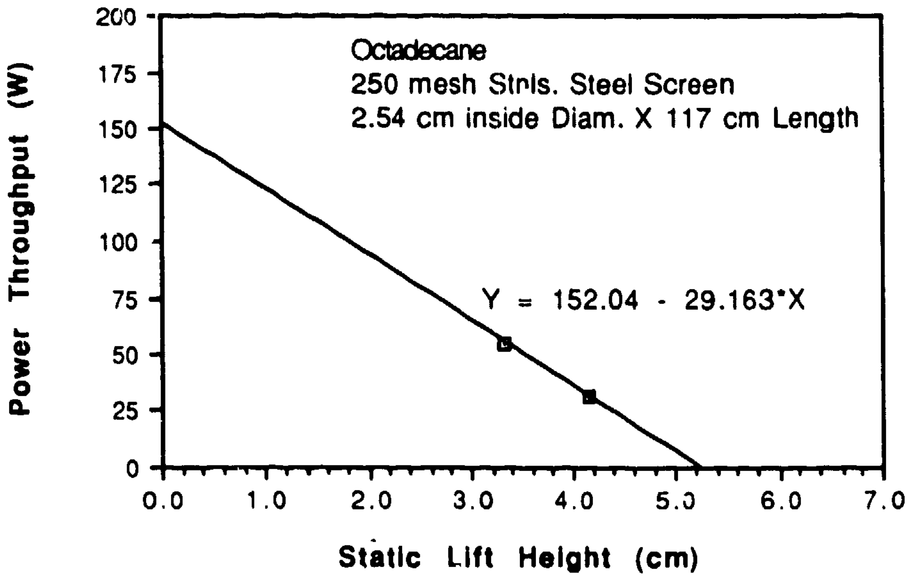

Figure 4. Power Throughput as a Function of Static Lift Height for an Octadecane/Quartz Heat Pipe with a 250 mesh Homogeneous Stainless Steel Wick.

Table 2 Low Temperature Experiment Heat Pipe Test Matrix

Pipe Description	Test Duration HRS	Heat Load	Temp.
LTHP1	500	15 W	370 K
LTHP2	1000	35 W	370 K
LTHP3	500	15 W	340 K
LTHP4	500	35 W	420 K

A detailed description of the LTE heat pipe, test set-up and experimental procedure follow.

LTE Heat Pipe Description

Figure 5 illustrates the heat pipe design being used in the LTE. This heat pipe is composed of an outer pyrex envelope, an inner pyrex tube cut into several smaller cylindrical sections and a homogeneous stainless steel wick. The use of pyrex as a containment material make visual observation of the mass migration phenomena possible. The sectioned pyrex tube allows for direct measurement of the mass distribution along the pipe.

Preparation of the heat pipe components and assembly of those components into a working heat pipe are accomplished as follows. First, all inner pyrex cylinder sections are numbered sequentially using a diamond tipped scribe. Next, all of the pyrex components, including the envelope, are carefully cleaned in Freon and rinsed in deionized water and ethyl alcohol. The parts are then dried in warm air. Each inner pyrex cylinder is weighed to an accuracy of ± 0.0001 grams. The weights of these sections are logged. A representative cylinder section is 2.0 centimeters long and weighs between 2.9400 and 3.0400 grams. The wick structure is fabricated by wrapping four layers of 400-mesh stainless steel screen around a copper mandrel. The screen wraps are spot welded and the mandrel is etched away using nitric acid to leave a screen tube properly sized to fit snugly within the inner pyrex tube. After the screen is thoroughly rinsed in deionized water and then ethyl alcohol, it is vacuum fired for four or more hours at approximately 700 K. The wick is fitted inside the heat pipe envelope. The cylinder sections are then stacked sequentially inside the envelope. A pyrex nipple section is fused to the end of the envelope and then the whole assembly is heated to approximately 400 K in a vacuum of less than 10^{-5} torr to remove all water. The final step is to charge the heat pipe with working fluid and seal it by fusing the nipple end shut with a torch.

LTE Set Up

Figure 6 illustrates the test set-up for the LTE. It shows the heat pipe, the heat sink, the heat source and the various necessary instrumentation. The heat source is a Kapton foil resistance heater, 30 centimeters long, wrapped about the full outside pipe diameter, which allows for uniform heating of the evaporator. The heater is rated for 150 Watts at 115 Volts. Insulation is applied over the heater. The heat sink is a water-cooled gas-gap calorimeter. Temperature control on the water is 273 to 323 K. The gas is a mixture of argon and helium in any desired proportions from all argon to all helium. Mass flow measurements of the gas are made using a Hastings Linear Mass Flowmeter. Water flow rates are made with a stop watch and graduated cylinder. Finally, temperatures are measured with chromel-alumel thermocouples. Temperature measurements are made at various locations along the heat pipe, both in the evaporator and the condenser sections. Temperature measurements are also made of the cooling water and the surrounding ambient air.

Heat is applied to the pipe. The gas mixture and water temperature in the heat sink are adjusted until the freeze front is located at some conveniently observable location on one of the numbered pyrex cylinder sections. Temperatures and times are then recorded periodically during the duration of the test while visual observations are made of the mass migration phenomena.

After the heat pipe has operated for the prescribed period, it will be allowed to cool below the fusion temperature of the working fluid. Then it will be disassembled and each numbered cylinder section will be weighed. The mass accumulation for each cylinder will be recorded, along with its physical location within the heat pipe. The result will be a mass distribution profile for the working fluid.

Summary

Data for a potassium heat pipe was presented that illustrates, by way of its axial temperature profile, the kind of operation that can, in time, lead to heat pipe failure. This kind of failure is caused by the progressive migration of working fluid to the frozen region of the heat pipe. A program was described that investigates this phenomena and determines the operating parameters for low power, extended duration heat pipes. Octadecane was selected as a working fluid for a series of low temperature heat pipe experiments (LTE). Selection was based on certain similarities to liquid metal heat pipe working fluids, particularly on low vapor pressure at the triple point. Heat pipe performance tests verified the usefulness of octadecane as a working fluid for the LTE. Finally, the design of and execution of the LTE was described.

Following the successful completion of the LTE, a series of high temperature experiments (HTE) are planned. The results of the LTE and HTE will be used to derive a model for predicting working fluid migration rates in heat pipes. This model will be useful for determining and evaluating heat pipe performance and ultimately for assisting in the design of heat pipes required to operate well below their design point for extended durations.

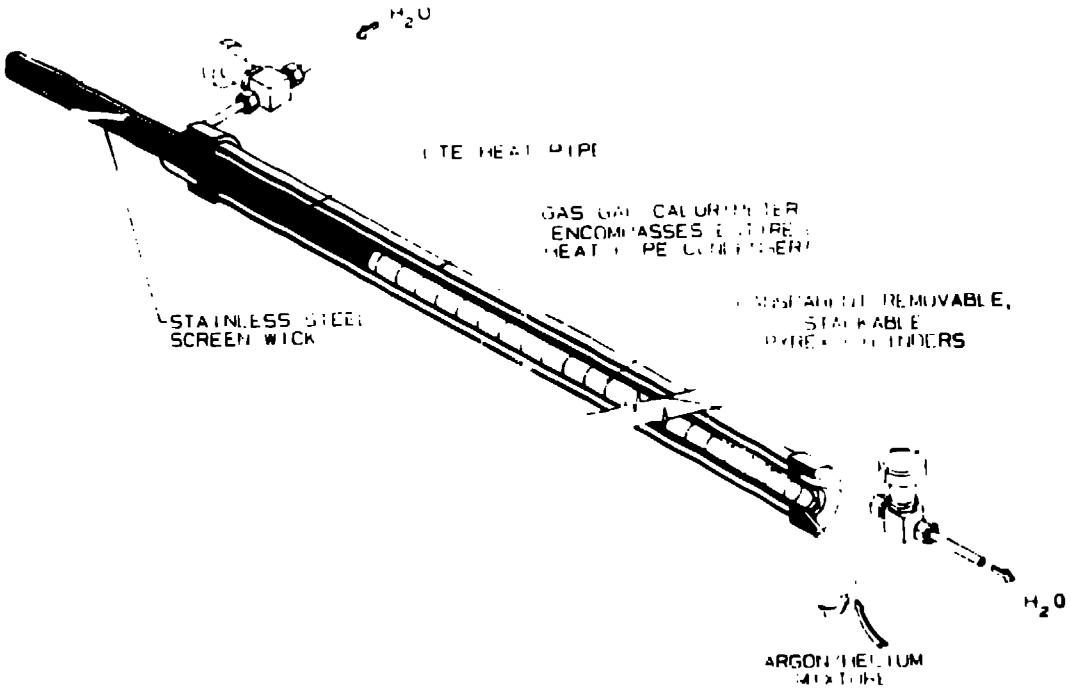

Figure 5. Low Temperature Heat Pipe Design Showing Gas-Gap Calorimeter

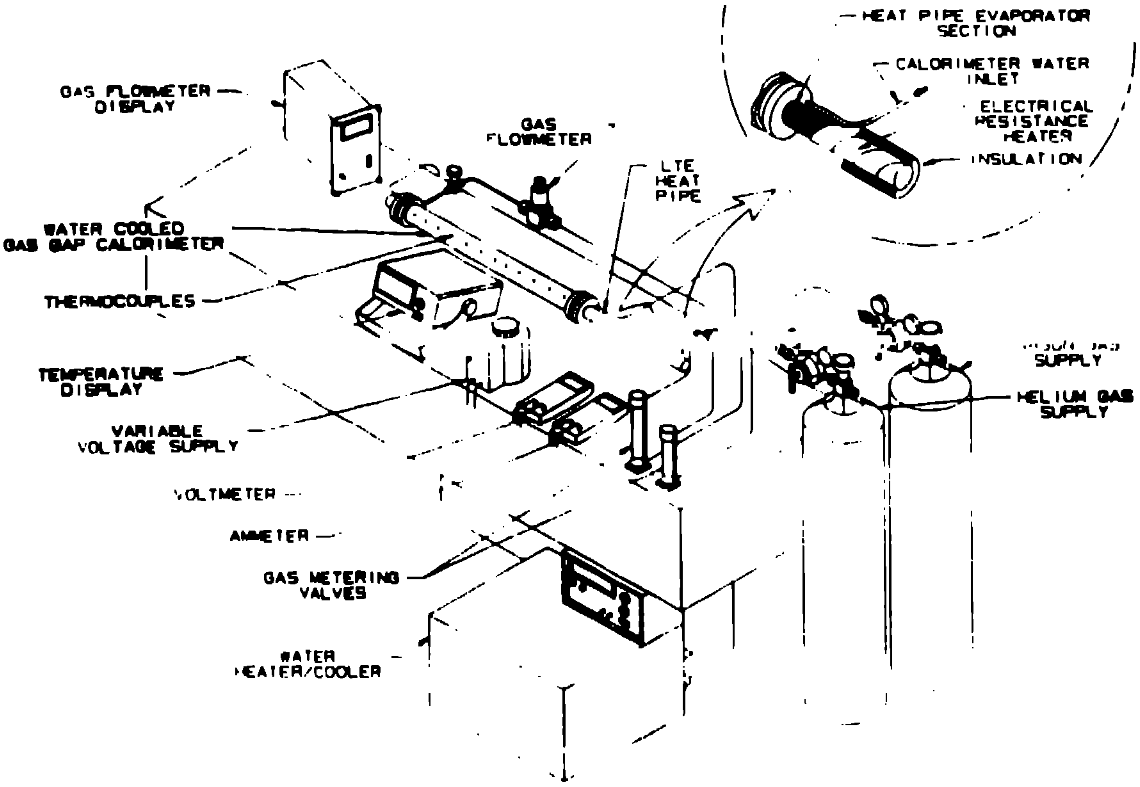

Figure 6. Low Temperature Experiments Equipment Layout

References

1. Woloshun, K. A.; Sena, J. T.; Keddy E. S.; and Merrigan, M. A., "Radial Heat Flux Limits in Potassium Heat Pipes: An Experimental and Analytical Investigation," *Proceedings of the 7th Symposium on Space Nuclear Power Systems, The Institute for Space Nuclear Power Studies*, Chemical/Nuclear Engineering Department, University of New Mexico, Albuquerque NM 87131, January 7-11, 1990.

2. Brown, G. P.; DiNardo, A.; Cheng, G. K.; and Sherwood, T.K., "The Flow of Gases in Pipes at Low Pressure," *Journal of Applied Physics*, Vol.17, 1946, pp. 802-813.

3. Perry, R. H. and Green, D., *Perry's Chemical Engineers' Handbook.*, Sixth ed., Sec. 5, McGraw-Hill Publishing Co., NY, 1984.

4. Dunn, P. D. and Reay, D. A., *Heat Pipes*, 3rd ed., Pergamon Press, NY, 1982.

5. Chi, S. W., *Heat Pipe Theory and Practice*, Hemisphere Publishing Corp., Washington, DC, 1976.