A HELIUM-3 REFRIGERATOR EMPLOYING CAPILLARY CONFINEMENT OF LIQUID CRYOGEN

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ABSTRACT

A condensation refrigerator suitable for operation in a zero-gravity space environment has been constructed. Unlike conventional cryostats, the condensed liquid refrigerant is confined by surface tension inside a porous metal matrix. Both helium-4 and helium-3 gases have been successfully condensed and held in a copper matrix. Evaporative cooling of confined liquid helium-4 has resulted in a temperature of 1.4K. Using a zeolite adsorption pump external to the cryostat, a temperature of 0.6K has been achieved through evaporative cooling of liquid helium-3. The amount of time required for complete evaporation of a controlled mass of liquid helium-4 contained in the copper matrix has been measured as a function of the applied background power. For heating powers below 18 mW the measured times are consistent with the normal boiling of the confined volume of liquid refrigerant. At background powers above 18 mW the rapid rise in the temperature of the copper matrix- the signature of the absence of confined liquid- occurs in a time a factor of two shorter than that expected on the basis of an extrapolation of the low-power data.

INTRODUCTION

Refrigerators operating at cryogenic temperatures on the order of 1K or less will be required for several classes of future NASA space missions. Cooled infrared detectors will be used in conjunction with infrared astronomical telescopes- notably the Shuttle Infrared Telescope Facility (SIRTF) and the

Large Deployable Reflector (LDR), Earth resources remote sensing satellites, and high-frequency commercial communications systems. In addition, spaceborne physics experiments studying liquid helium critical phenomena will require a cryogenic working surface. By performing such experiments in space improvements in temperature resolution of several orders of magnitude can be achieved [1].

Possible refrigeration processes compatible with the zero-gravity space enivironment are helium-3/helium-4 dilution, adiabatic demagnetization, and liquid helium evaporation [2]. Dilution refrigeration in space presents difficulties since no gravitational field is present to maintain the crucial cooling interfaces. Recent proposals for circumventing this problem have concentrated on determining the effect of a controlling electric field on the phase boundary [3]. Gravity-independent adiabatic demagnetization refrigerators show promise for space applications and are an active area of research, but engineering problems- including magnetic torques and power/mass requirements- still remain [4].

Ground-based helium-3 evaporation refrigeration technology is not directly transferable to space refrigeration since the Earth's gravitational field is used to direct and confine the liquid cryogen during and after condensation from the gas phase [5]. A proposed alternate approach replaces the gravitational force with liquid/metal surface tension to confine the cryogen. Theoretical calculations [6] have addressed the feasibility of this approach and preliminary experimental research with various liquid cryogens in a porous metal matrix have been successfully performed [7].

In this paper, a low-temperature cryostat in which surface tension forces confine the liquid helium cryogen to the micron-sized capillaries of a copper sponge is described. Both helium-3 and helium-4 gases have been successfully condensed; evaporative cooling of the resulting liquids have resulted in temperatures of 0.5 K and 1.4 K respectively. Since in any realistic experimental or astronomical application the low temperature working surface will be subject to a background power load, the response of confined liquid helium-4 to a range of heat loads was measured. As discussed in detail below, it was found that for heating powers less than 18 mW, the liquid cryogen underwent normal evaporation but that for powers above this value the temperature of the copper sponge rose in a time faster than the evaporation time suggesting a possible physcial ejection of the liquid cryogen from the sponge interior.

INSTRUMENT DESCRIPTION

Figure 1 is a schematic diagram of the capillary confinement cryostat. The critical component of the system is the porous copper matrix or sponge (A). In operation, the liquid cryogen is held in the interstitial spaces of the sponge by the surface tension between the copper strands and the liquid helium. Foametal Inc. manufactures the sponges by sintering a granular powder into a reticular celluar structure. The results reported in this paper were obtained with a sponge having 60% the density of pure copper and containing an average pore size on the order of 9 microns. The cylindrical sponge is indium soldered along its rim to a copper working surface.

Surrounding the copper sponge and working surface is the transfer gas volume (B). The gas in this volume acts as a thermal switch between the sponge and helium-4 reservoir (D). The sponge and working surface are attached to the end of the U-shaped test gas delivery tube (E) through which the gas to be condensed flows from an external gas supply to the sponge. To insure that the test gas will condense at the sponge and at no other point along the length of the delivery tube, the tube must not be in thermal contact with the helium reservoir. For the bottom part of the tube, the thermal isolation is provided by an inner vacuum can (C). The remainder of the tube which passes through the dewar is double-walled. As a further step to prevent condensation in the delivery tube, a heating coil was attached to the horizontal section of the U-tube (see Figure 1). Finally, conventional liquid nitrogen and outer vacuum jackets provide a thermal shield to the room temperature laboratory environment.

Also shown in Figure 1 as black dots are the locations of the sensors used to monitor the status of the cryostat. Thermometry is provided by germanium resistance thermometers in thermal contact with the helium reservoir, working surface, sponge, and test gas delivery tube. With liquid helium in the sponge, it was found that the temperature of the working surface was typically only 10% higher than the sponge temperature, thus indicating that the thermal conductance between these points was as high as desired. The purpose of the test gas delivery tube thermometer was to verify that no helium gas had condensed in the tube as opposed to in the sponge. Three manometers were also employed to measure the helium gas pressure over the helium-4 reservoir, in the transfer gas volume, and over the copper sponge. A plumbing manifold connected to the top of the cryostat enabled the evacuation of the test gas delivery tube, the transfer gas volume, and the inner vacuum can. Both the pressure of the helium gas above the sponge and in the helium-4 reservoir were maintained at a fixed value by automated, motor-driven valves.

It should be pointed out that the ultimate application of a refrigerator employing capillary confinement would be in the low-gravity space environment. Although, of course, this situation cannot be simulated in an earth-based laboratory, the geometrical configuration of the cryostat shown in Figure 1 represents a more stringent test of the surface tension confinement principle. This is due to the fact that the flow of the condensing gas is opposite to the gravitational vector; the confined liquid must be held by the surface forces against a gravitational acceleration of 1 g.

EXPERIMENTAL RESULTS

In this paper, two sets of experiments will be described each aimed toward characterizing the performance of the capillary confinement technique for zero-gravity helium refrigeration. The first experiment was to establish that helium gas could both condense on the copper fibers and that surface tension could confine the resulting liquid cryogen during evaporative cooling. During condensation the transfer gas volume was filled with helium-4 gas to a pressure of 4 torr, thereby allowing the sponge to attain the temperature of the helium-4 reservoir (2.5 K). The test gas was delivered to the sponge at a controlled pressure greater than the helium condensation pressure. It was established that the test gas had condensed when the sponge temperature and the test gas pressure were consistent with the known helium vapor pressure relation. Both helium-4 and helium-3 gases have been sucessfully condensed. For helium-4 the gas supply used was the boil-off from a commercial helium-4 dewar. For helium-3 a closed cycle control system was constructed in which high pressure gas is expanded into low-pressure volumes before passage into the test gas delivery tube.

To achieve the desired low-temperature performance, the liquid cryogen in helium refrigerators must undergo evaporative cooling by lowering the pressure of the gas in equilibrium with the liquid. In order to enable evaporative cooling of the liquid held in the sponge, the transfer gas volume was evacuated and the test gas delivery tube was attached to a pump. For helium-4 the pump used was a conventional diffusion pump. For helium-3 a zeolite absorption pump cooled to 4.2 K was employed. The lowest pressures and temperatures achieved with the present system are shown in Table 1. These temperatures are consistent with the the operating temperatures of germanium bolometers presently used for ground and air based far-infrared/millimeter obeservational astronomy [8,9]. It should be noted that the limiting factor in achieving the lowest sponge temperature for the present system is the pumping capacity of the zeolite in the adsorption pump. Increasing the volume of the present external pump should allow temperatures of 0.3K to be obtained.

The second set of experiments involved establishing the performance of the capillary confinement technique when the copper sponge was subjected to a range of background heating powers. The first step in the experimental procedure was the condensation of a controlled volume of helium-4 gas. This input volume was regulated at 3.0 liters using a conventional dry gas meter. Heating loads were applied to the sponge through Joule heating of three sets of resistors attached to the working surface (schematically shown in Figure 1). After condensation of the test gas, the heating power was applied and the gas pressure above the sponge was maintained at 50 torr which corresponded to a sponge temperature of 2.5 K. For a given heating power, P_H, the time, t_e, between the onset of heating power application and the point at which liquid cryogen was no longer present in the sponge was measured with a strip chart recorder. The signature that the sponge no longer contained liquid helium was a rapid sponge temperature increase. A secondary indicator was the sudden decrease in the rate of gas flow leaving the sponge as measured with a flowrate meter attached to the test gas delivery tube.

In Figure 2 the results obtained from heat load experiments performed on four separate days are presented. For each day the inverse of t_e is plotted against heating powers ranging from 2 to 20 mW. The error shown in t_e is dominated by the finite time width of the temperature rise signature. As is illustrated by Figure 2, the data obtained for low heating powers- $P_H < 18$ mW are well fit by the solid lines shown. The slope and intercept of these lines were obtained from a least squares analysis. In the second column of Table 2, the reduced chi-squared resulting from this analysis are shown; the values obtained reflect the excellent quality of the fit of the data to a straight line.

A linear relationship between inverse t_e and P_H pertains if the liquid confined to the sponge is undergoing evaporation due to the heating power. Specifically, energy conservation gives the following equation

$$1/t_e = (1/LV_o)\, P_H + P_R/LV_o \tag{1}$$

where L is the latent heat of evaporation of helium-4, P_R is the residual or parasitic power continually absorbed by the sponge from its surroundings, and V_o is the volume of confined liquid cryogen. This liquid volume is converted into the volume of gas evaporated- V_G - by the liquid/gas density ratio. In Table 2 the values of V_G and P_R calculated, respectively, from the slope and intercept of the least-squares fit lines are presented. As required by mass conservation, the value of V_G agrees well with the input gas volume of 3.0 NTP liters. The negative values of P_R obatained on two days probably reflect the inadequacy of the assumption that all of the power applied to the heating resistors is transferred to the liquid helium.

It is apparent in Figure 2 that for each of the days shown the high heating power data points deviate significantly from the evaporation line. For applied heating powers above 18 mW, t_e is considerably shorter than the anticipated evaporation time; the sponge temperature increases on a faster timescale. In Figure 3 the data from all four days have been plotted on the same graph. It can be seen in Figure 3 that there is reasonable agreement between data obtained on various days. The larger reduced chi-squared obtained for the composite data (see Table 2) is a reflection of the variation of the parasitic power from run to run. More importantly, the data shown in Figure 3 indicate that deviation of t_e from the evaporation value has a sharp dependence upon the heating power; the effect cuts-on quite rapidly at 18 mW. The possible physical explanations of the observed effect- such as the ejection of the confined liquid during the transition between nucleate and film boiling at high powers- will be discussed in a future paper.

FUTURE WORK

In terms of fully investigating the capillary confinement technique for zero-gravity helium refrigeration, several avenues and questions still remain open. In addition to theoretically understanding the physical processes involved in the high heating power effect discussed above, more experimental data - especially at $P_H > 20$ mW- is required. Heat load data using liquid helium-3 have been obtained and are presently under analysis. In addition, the effect of the variation of sponge parameters such as composition, interior geometry, and pore size on cryostat performance needs to be established.

Actual operation of the capillary confinement refrigerator in a zero-gravity environment would completely establish its performance. This could be especially critical if the high power heating effect is a boiling phenomenon since, unlike the situation on earth, the role of buoyancy forces is diminished by several orders of magnitude in the space environment. Aircraft parabolic trajectories and ground-based drop towers can produce low-gravity simulation but are severly time constrained. For extended testing a space shuttle or space station experiment is required.

Table 1. Capillary refrigerator performance.

CAPILLARY REFRIGERATOR PERFORMANCE

CRYOGEN	PRESSURE (TORR)	TEMPERATURE (K)
HELIUM-4	1.8	1.4
HELIUM-3	0.3	0.55

Table 2. Evaporation data.

EVAPORATION DATA

DATE	χ_{ν}^{2}	$V_G(\ell)$	P_R(mW)
5/11/82	1.3	2.7±0.3	-3.0±1.2
5/3/82	0.1	3.2±0.2	-0.8±0.3
5/12/82	0.4	3.2±0.5	1.4±2.0
3/29/82	-	3.4±0.3	0.2±0.6
COMPOSITE	6.0	3.1±0.1	-0.8±0.2

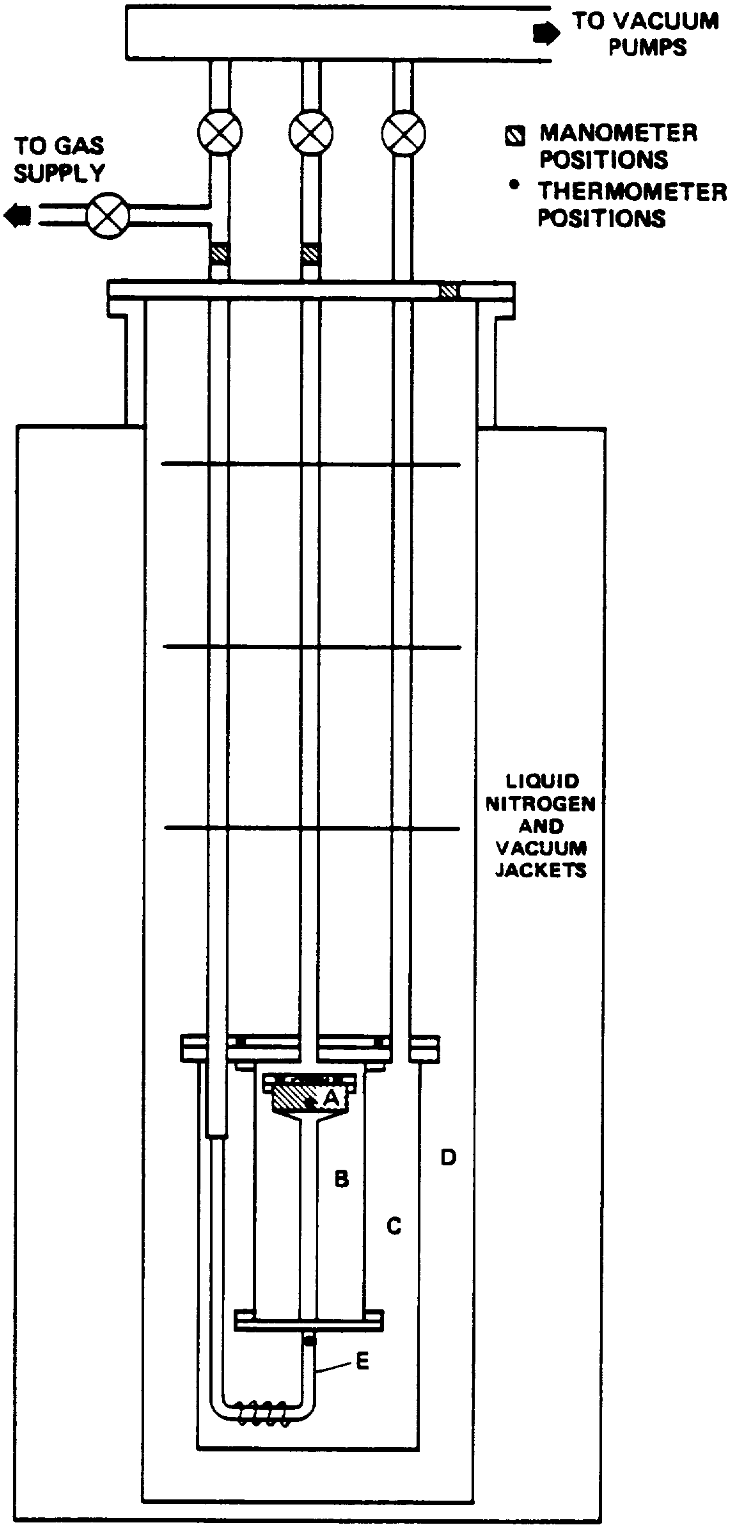

Figure 1. Schematic diagram of the capillary confinement cryostat

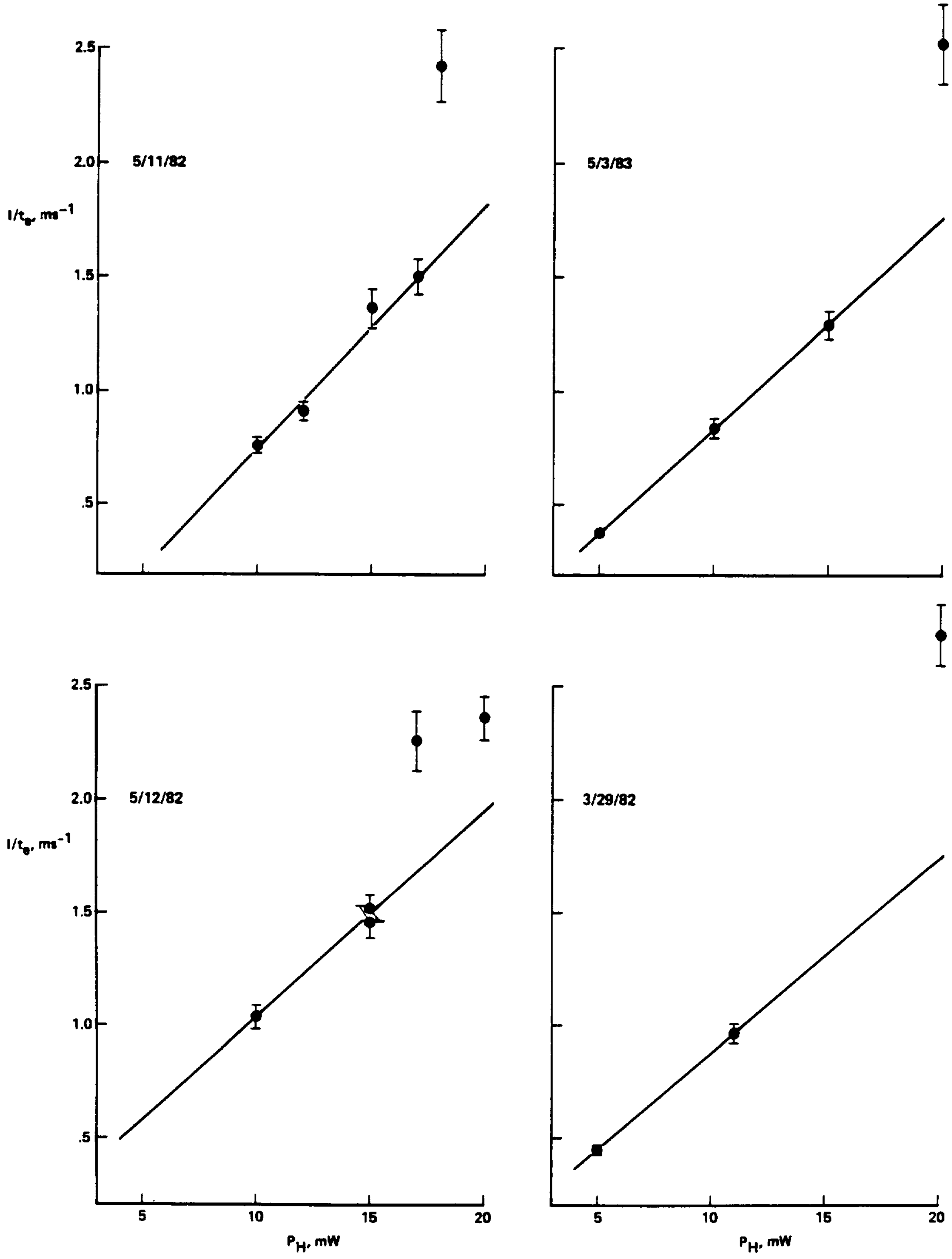

Figure 2. Inverse evaporation time versus applied heating power for four runs

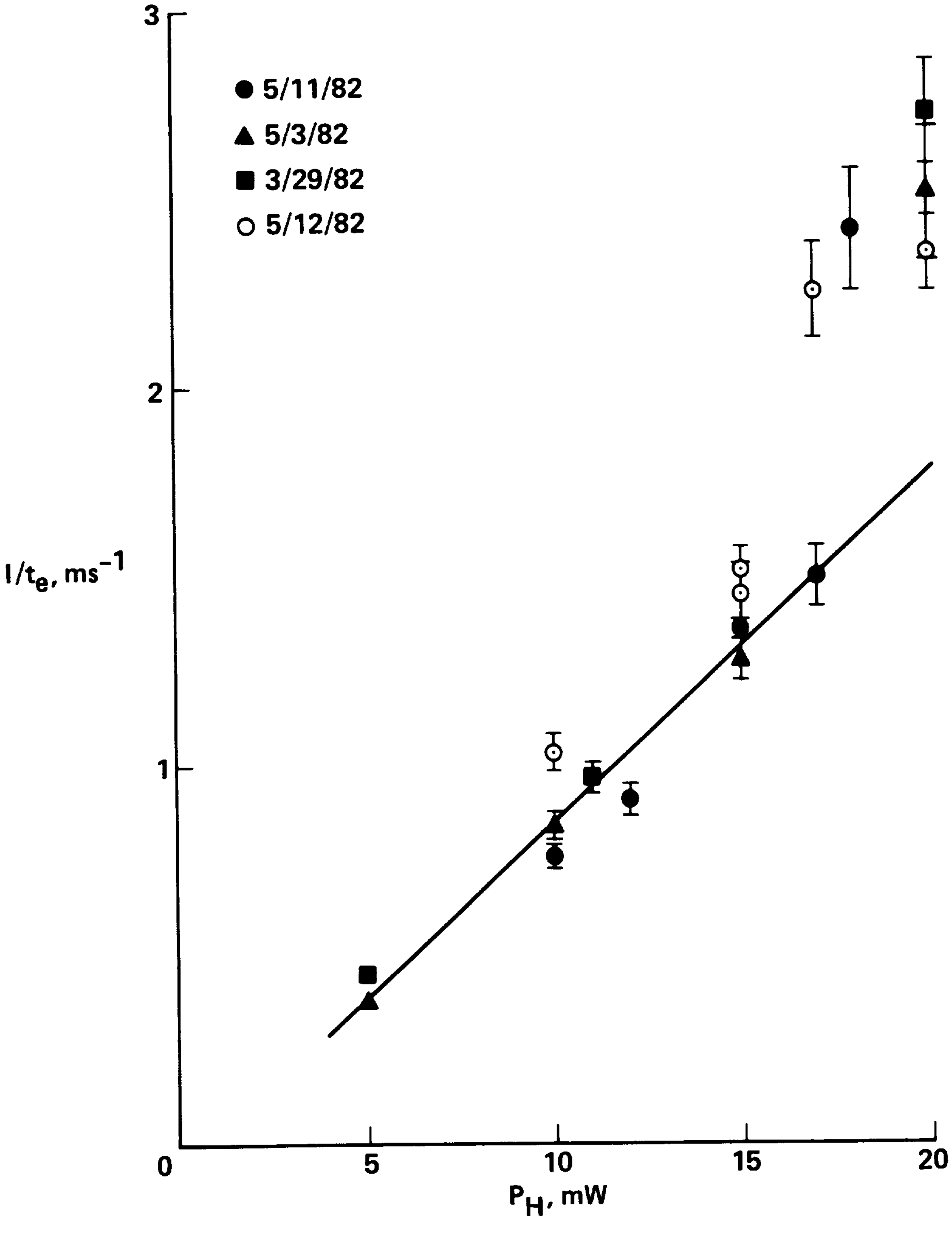

Figure 3. Composite Evaporation Curve

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