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MEASURING HEAT LEAK WITH A HEATMETER*

M. Kuchnir, J. D. Gonczy, and L. Tague

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M. Kuchnir, J. D. Gonczy and J. L. Tague

Fermi National Accelerator Laboratory*

Batavia, Illinois

ABSTRACT

The heatmeter or more precisely the heat flow meter is a device based on thermal conductivity measuring techniques. It consists of a thermal conducting body between two thermometers, with provisions for thermal connections and calibration. The paper describes the design, construction details, calibration and performance of one such heatmeter for use with heat reservoirs at either 4.2 K or 78 K. Near 4.2 K it has a sensitivity of 10 μ W and requires less than a minute to reach steady state. Near 78 K its sensitivity is 10 mW and requires 25 minutes to reach steady state.

INTRODUCTION

We have developed a new method for accurate and expeditious heat-leak measurements of the Superconducting Super Collider cryostat components now being designed. Instead of the more traditional methods for measuring heat-leaks (boil-off, enthalpy change) we make what amounts to a thermal conductance measurement which we later use with the measured temperature difference across it to determine the heat flowing through it. The thermal conductance in question is that between two thermometers in the body of the thermal link connecting the part under test to the cold reservoir. This technique has been used before^{1,2,3} where the heatmeter was designed for the particular test. Here we emphasize that such an instrument can be designed with transportability in mind and reused in different test setups.

The advantages of this technique are higher sensitivity, better accuracy, shorter waiting times and a dependence on only electrical measuring equipment (constant current sources, microvoltmeter, switches, electronic temperature controller and a recorder). The higher sensitivity results from the use of resistance thermometers (platinum, carbon or germanium), while the better accuracy comes from the direct comparison with electrically generated heat, which can be accurately measured.

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The shorter waiting times are the result of the technique depending only on the temperature of the cold liquid reservoir, not on the steadiness of its vaporization rate or on its usually high heat capacity (i.e. large equilibrium time constant). Therefore, the time constant involved in a measurement depends mainly on the properties of the component under test since the heat capacity of the heatmeter itself leads to relatively short time constants. The portability of the heatmeter is possible due to the relatively good thermal contact one can have between threaded copper parts when greased with copper powder loaded compounds now commercially available.*

DESIGN CONSIDERATIONS

Since most thermal properties of materials vary considerably over the temperature range 300 K to 4 K, a heatmeter with a specified sensitivity must be designed for a limited temperature interval. Fortunately the temperature intervals of interest are not many, for our purpose just two: near the boiling points of liquid He³ and liquid N₂. Therefore in this design we use, at each of the two temperature sensing spots, two types of thermometers: platinum resistors for the interval near 78 K and Allen-Bradley carbon composition resistors for the interval near 4.2 K. The provisions for calibration included in the heatmeter make the use of carbon-composition resistors uncontroversial since no reliance is placed on their temperature calibration or their long term stability. Besides the sensitivity and the temperature interval one must also specify the magnitude of the expected heat flow. Because the coldest spot of the sample under measurement is at the temperature of the hot end of the heatmeter and not at the temperature of the reservoir, a correction to the measured heat leak must be applied. In order for this correction to be a simple linear extrapolation, the temperature drop across the heatmeter for the expected heat flow must be small relative to that across the sample. The temperature drop across the ends of the heat meter, including the threaded copper contacts must also be kept small.

As an example, we calculate the thermal conductance of a heatmeter with a sensitivity of 10 μW near 4.6 K. For a 100 Ω , 1/8 W Allen-Bradley carbon composition resistor the temperature coefficient between 4.2 K and 5.0 K is approximately 250 Ω/K .⁶ Reading it with a current of 10 μA (that does not heat it up) and a voltmeter sensitive to 1 μV , we are able to detect temperature changes of: $1 \mu\text{V}/(10 \mu\text{A} \times 250 \Omega/\text{K}) = 0.4 \text{ mK}$. For a detectable temperature drop of 1 mK to be due to 10 μW flowing through the heatmeter, its thermal conductance, $\kappa\ell/l$, should be

$$\kappa\ell/l = 10 \mu\text{W}/1 \text{ mK} = 10 \text{ mW/K} ,$$

where A is the cross section area, ℓ the length and κ the average thermal conductivity of the heatmeter material in the temperature interval considered. Since we are not sure of the thermal conductivity at 5 K of the copper to be used, we chose stainless steel for the heatmeter material. This stainless steel cylinder is silver-soldered between the copper parts containing the sensing spots and threaded ends; see Figure 1. The thermal conductivity of stainless⁷ is approximately $0.3 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, resulting in an aspect ratio $A/\ell=33.3 \text{ mm}$ or a cylinder with length $\ell=8.5 \text{ mm}$ and diameter $D=19 \text{ mm}$. Near 79 K, $\kappa=8.1 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and the thermal conductance will be 0.27 W/K . Using 100 Ω platinum resistor⁸ (which at these temperatures has a sensitivity of $0.43 \Omega/\text{K}$) with a 100 μA current, the 1 μV sensitivity of the voltmeter results in a measurable

* Cryocon Grease - Manufactured by Air Products & Chemical Inc., P. O. Box 528 Allentown, PA 18105

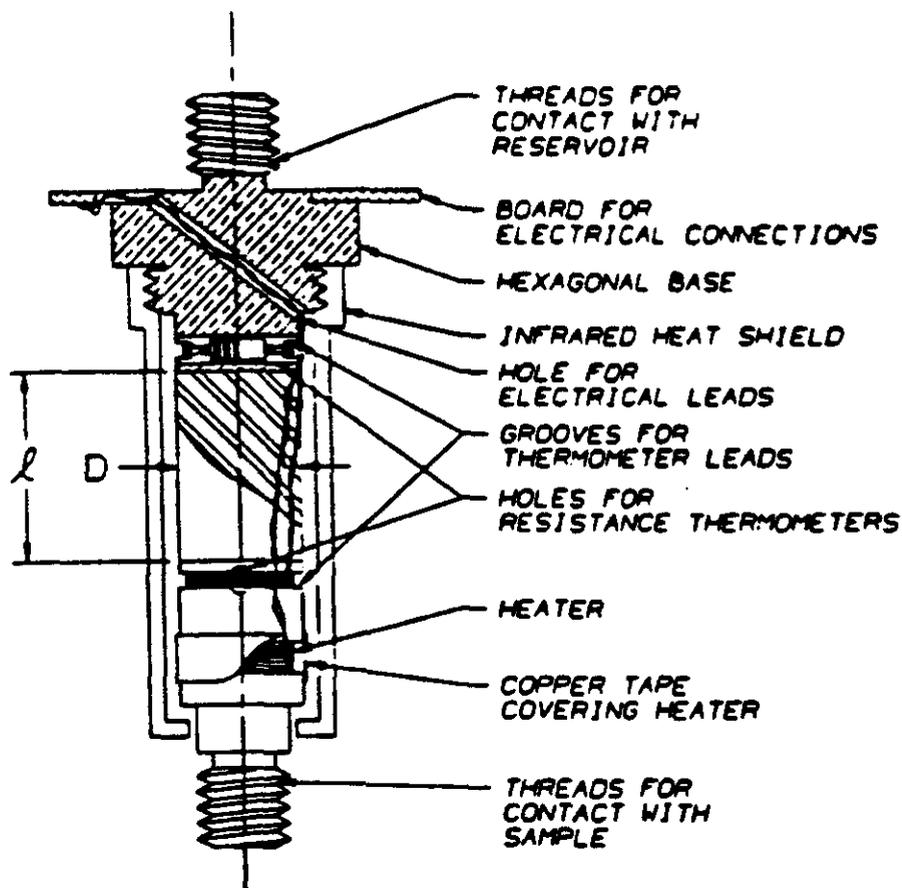


Fig. 1. Assembly drawing of a heatmeter

temperature change of 23 mK or a detectable heat leak of 6.3 mW. The determination of the actual sensitivity is presented in the calibration section.

Figure 1 shows many of the details involved in properly sensing the temperatures, shielding from infrared radiation, routing the electrical leads and providing for portability. In order to simplify the drawing, only one resistor instead of two, is shown tucked in a hole transversal to the heat flow direction and through the cylindrical groove which contains eight leads varnished with GE7031** to the surface for thermal contact. Although the drawing shows only one twisted pair leaving the the hot-side groove, each resistor has four enamel coated, 0.1 mm-diameter manganin leads, two for current and two for voltage. All leads go as twisted pairs to a printed circuit connecting board through the diagonal hole shown in the drawing. The connecting board is located near the cold end of the heatmeter so that the heater and thermometer leads coming from the hot end have their thermal conductance automatically included in the calibration process. The outside shield, made of copper, and threaded to the cold side of the heatmeter, prevents it from exchanging infrared radiation with the exterior. A copper tape over the groove containing the heater traps the radiation from the heater wires. The 99 Ω heater is made of 0.20 mm diameter, enamel insulated manganin wire varnished in its groove with GE7031 and has eight leads, each current lead consisting of 3 wires to reduce the dissipation along the body of the heatmeter to a negligible value. The cold end of the heatmeter has a hexagonal section for screwing into the reservoir.

** GE7031 - Varnish manufactured by General Electric Corp. Schenectady, N.Y.

CALIBRATION

The main calibration of the heatmeter is done by attaching the cold end to the cold reservoir leaving the hot end free. A radiation shield at the temperature of the reservoir is used to enclose the heatmeter preventing its unshielded part from absorbing heat. With the vacuum established and the reservoir filled with cold liquid the calibration proceeds by dissipating a constant power into its heater and recording the appropriate sensor temperatures T_C and T_H when steady state condition is reached.

The linearity of the platinum resistors near 78 K and of the carbon composition resistors for low enough powers allow us to calibrate the power dissipated directly in terms of the difference in the voltages across the hot and cold resistors. The same current of $10 \mu\text{A}$ provided by a Keithley Model 225 current source flows through all resistors. Each voltage measurement is the result of two readings corresponding to opposite current directions in order to cancel thermal E.M.F.s. A Hewlett Packard, Model 6181C DC, current source is used for powering the calibration heater which is in series with a precision resistor permitting the measurement of the current to be done with the same instrument that measures and records all the voltages in the test facility, a Kaye Model DR-3C Digistrip II Data Logger.

Figure 2 presents the low power end (up to 0.19 mW) of the calibration data for this heatmeter near 4.2 K . The scatter of the data is contained in the band drawn and indicates that a heat leak of $100 \mu\text{W}$ will be known within $\pm 5 \mu\text{W}$. For this heat leak, $T_H = 4.439 \text{ K}$ and $T_C = 4.397 \text{ K}$ indicating that the 42 mK across the heatmeter is $\sim 5\times$ smaller than the 200 mK between T_C and the liquid He. This calibration curve extends to heat flows as high as 200 mW . Above 20 mW , however, one should convert the voltage differences into temperature differences due to the non linearity of the carbon resistors. For the 200 mW heat flow the measured temperatures were $T_C = 6.9 \text{ K}$ and $T_H = 13.5 \text{ K}$.

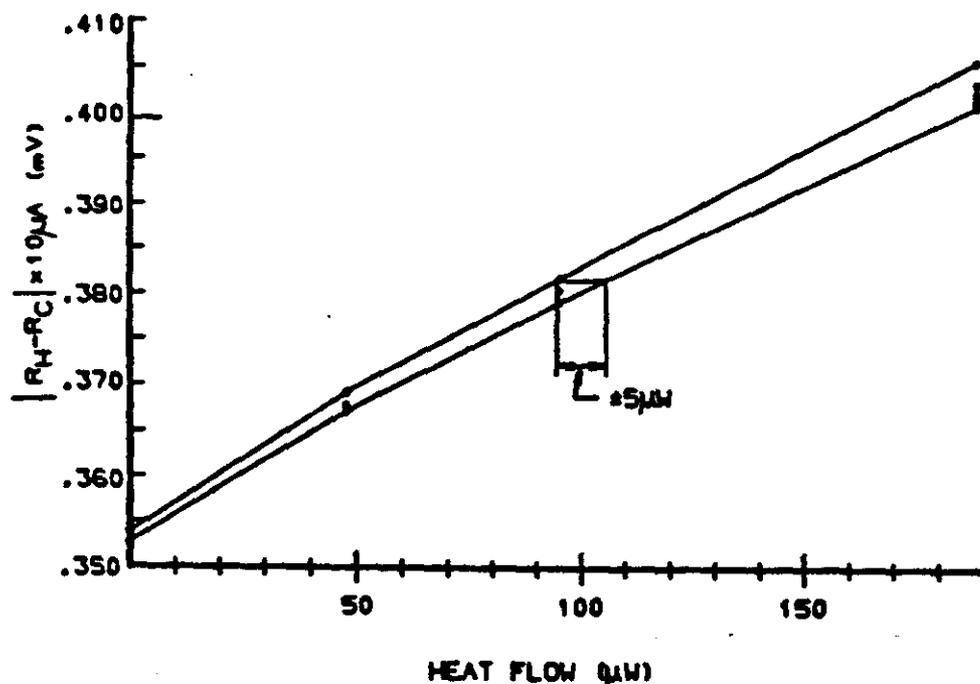


Fig. 2. Heatmeter calibration near 4.2 K

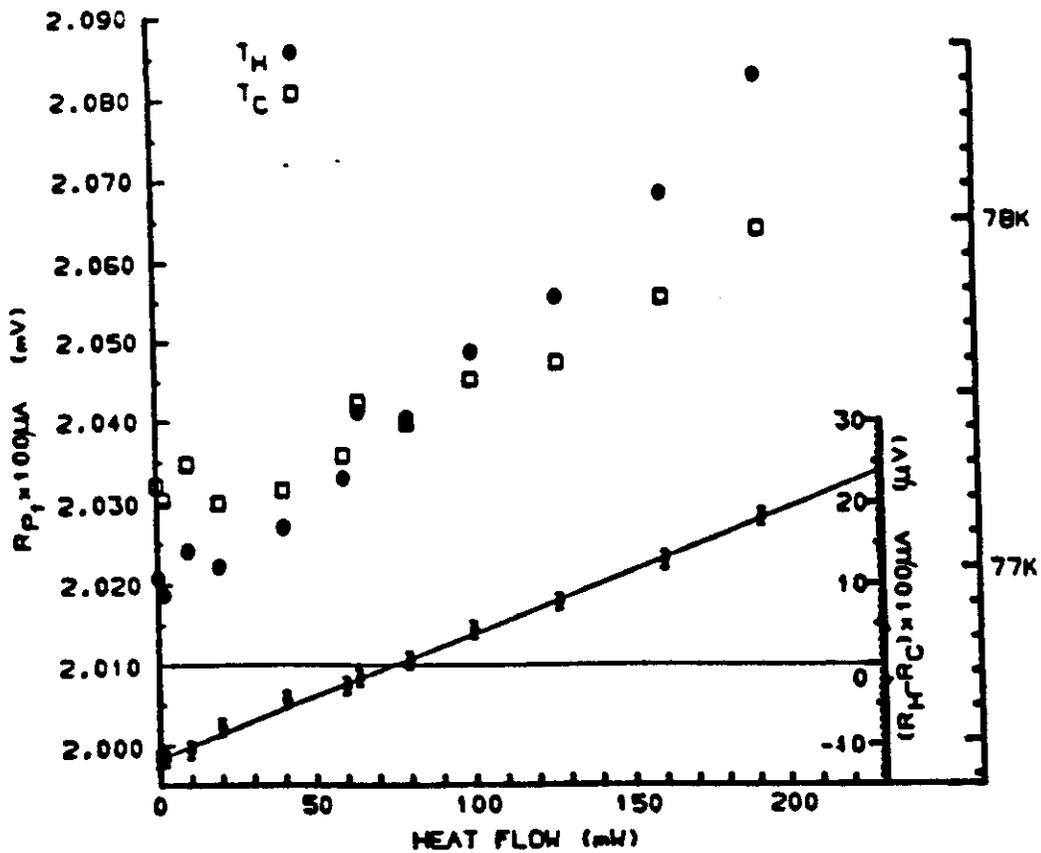


Fig. 3. Heatmeter calibration near 78 K

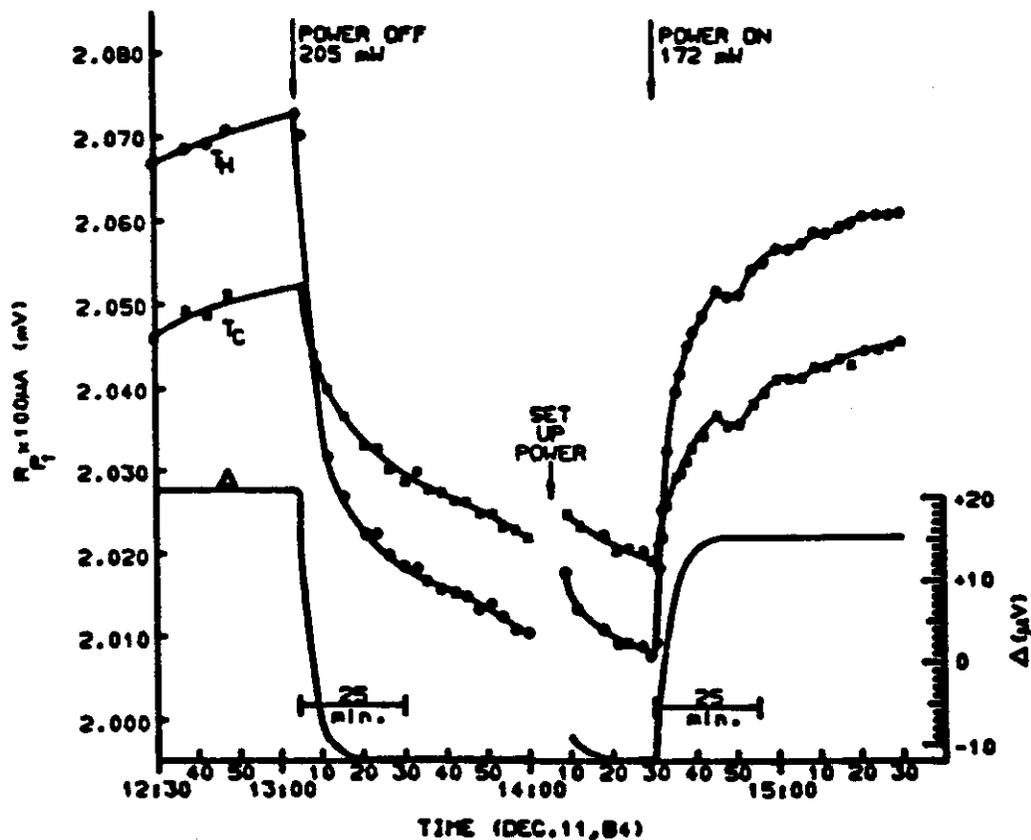


Fig. 4. Data showing time constant during calibration near 78 K

The calibration data for the low power end (up to 200 mW) near 77 K is presented in Figure 3 where the two vertical scales are the voltage across the platinum resistors and the corresponding temperature. Their difference (the calibration curve) is included as an insert. A discrepancy of 0.11 Ω in the values of the resistors causes the curve to cross zero for a heat leak of 75 mW. For a 100 mW heat flow $T_H - T_C = 0.36$ K and the average value of the heat meter temperature is 77.6 K which differs from the liquid nitrogen boiling temperature of 77.4 K by 0.2 K. Thus for 100 mW heat leak the temperature drop in the heatmeter is of the same order of magnitude as that across the thermal contacts. This curve has been continued for powers up to 3 W, where $T_C = 83.7$ K and $T_H = 94.2$ K. Repetition of both calibrations at several occasions separated by cyclings of the cryostat show that they don't change.

Figure 4 shows the data acquired as a function of time while the calibration heater was dissipating 205 mW, 0 mW and again 172 mW. The 25 minutes needed to reach steady state near 78 K for the heatmeter alone, as in this calibration procedure, is also indicated in this figure. It can be clearly seen that, although the average temperature of the heatmeter was not stationary, following the reservoir drift towards equilibrium, the voltage difference between the two platinum resistors (curve labelled Δ) takes no more than 25 minutes to reach a steady state that remains unperturbed even while the reservoir recovered from a liquid N_2 transfer at 14:45 hours. Near 4.2 K the heat capacity of the heatmeter is much smaller and the time to reach steady state is measured in seconds.

CONCLUSION

The heatmeter as built is slightly different from the one shown in Figure 1. It has larger threads for thermal contact, no hexagonal section at the base and the shield, instead of threaded to the base is press fitted squeezing an indium gasket. The heat-leak measuring facility described in reference 7 used this heatmeter to measure the heat leak of a superconducting magnet suspension member for several temperatures of its intermediate temperature heat sink, and also to measure the mean apparent thermal conductivity of a multilayer insulation blanket. In the process of commissioning the facility there was a comparison between the method using the heatmeter and the more traditional boil-off method which lead to a decisive preference for the former.

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