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# Design and Calibration of a Test Facility for MLI Thermal Performance Measurements Below 80K

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# DESIGN AND CALIBRATION OF A TEST FACILITY FOR MLI THERMAL PERFORMANCE MEASUREMENTS BELOW 80K

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## ABSTRACT

The design geometry of the SSC dipole cryostat includes active thermal radiation shields operating at 80K and 20K respectively. Extensive measurements conducted in a Heat Leak Test Facility (HLTF) have been used to evaluate the thermal performance of candidate multilayer insulation (MLI) systems for the 80K thermal shield, with the present system design based upon those measurement results. With the 80K MLI geometry established, efforts have focused on measuring the performance of MLI systems near 20K. A redesign of the HLTF has produced a measurement facility capable of conducting measurements with the warm boundary fixed at 80K and the cold boundary variable from 10K to 50K. Removing the 80K shield permits measurements with a warm boundary at 300K. The 80K boundary consists of a copper shield thermally anchored to a liquid nitrogen reservoir. The cold boundary consists of a copper anchor plate whose temperature is varied through boil-off gas from a 500 liter helium supply dewar. A transfer line heat exchanger supplies the boil-off gas to the anchor plate at a constant and controlled rate. The gas, which serves as cooling gas, is routed through a copper cooling tube soldered into the anchor plate. Varying the cooling gas flow rate varies the amount of refrigeration supplied to the anchor plate, thereby determining the plate temperature. A resistance heater installed on the anchor plate is regulated by a cryogenic temperature controller to provide final temperature control. Heat leak values are measured using a heatmeter which senses heat flow as a temperature gradient across a fixed thermal impedance. Since the thermal conductivity of the thermal impedance changes with temperature, the heatmeter is calibrated at key cold boundary temperatures. Thus, the system is capable of obtaining measurement data under a variety of system conditions.

## INTRODUCTION

A cryogenic measurement facility at Fermilab has been instrumental in measuring the thermal performance of various components for the SSC collider dipole cryostat[1-4]. In use since the early days of the cryostat development program, the Heat Leak Test Facility (HLTF) has experimentally verified the thermal performance of candidate support structures and multilayer insulation (MLI) schemes for the cryostat[5]. Results from measurements made in the HLTF have facilitated the evolution of the support system to its present state. Moreover, the design of the MLI system for the 80K thermal shield evolved as a direct result of measurements made in the HLTF.

With the design of the 80K MLI system complete, attention has focused on measuring the thermal performance of candidate MLI systems for the innermost thermal radiation shield of the cryostat. To this end, substantial modifications made to the HLTF have led to a cryogenic measurement facility capable of measuring heat loads under a variety of system conditions, including boundary temperatures between 300K and 4K as well as variable insulating vacuum levels. The system has been modified and calibrated, and is presently in use conducting thermal measurements on MLI systems below 80K.

## DESIGN OF THE HEAT LEAK TEST FACILITY

The HLTF is shown in its present configuration in Figure 1. The top portion of the HLTF, from the vacuum can adapter up, has remained fixed since the inception of the facility. This area is comprised of two inner vessels designed to contain either liquid nitrogen ($LN_2$) or liquid helium (LHe), depending on experimental parameters. The inner vessels are surrounded by a third vessel containing $LN_2$ which serves as a thermal radiation shield. An intermediate-temperature flange is mounted to the bottom of the He reservoir, and serves as the refrigeration source for intermediate shields under certain test configurations. The operating temperature of the flange is established by routing boil-off gas from the LHe/$LN_2$ inner reservoir through the flange; the flange temperature is varied by controlling the flow rate of the gas through the flange. MLI blankets encompass all vessels to minimize the background heat load into the cryogen reservoirs.

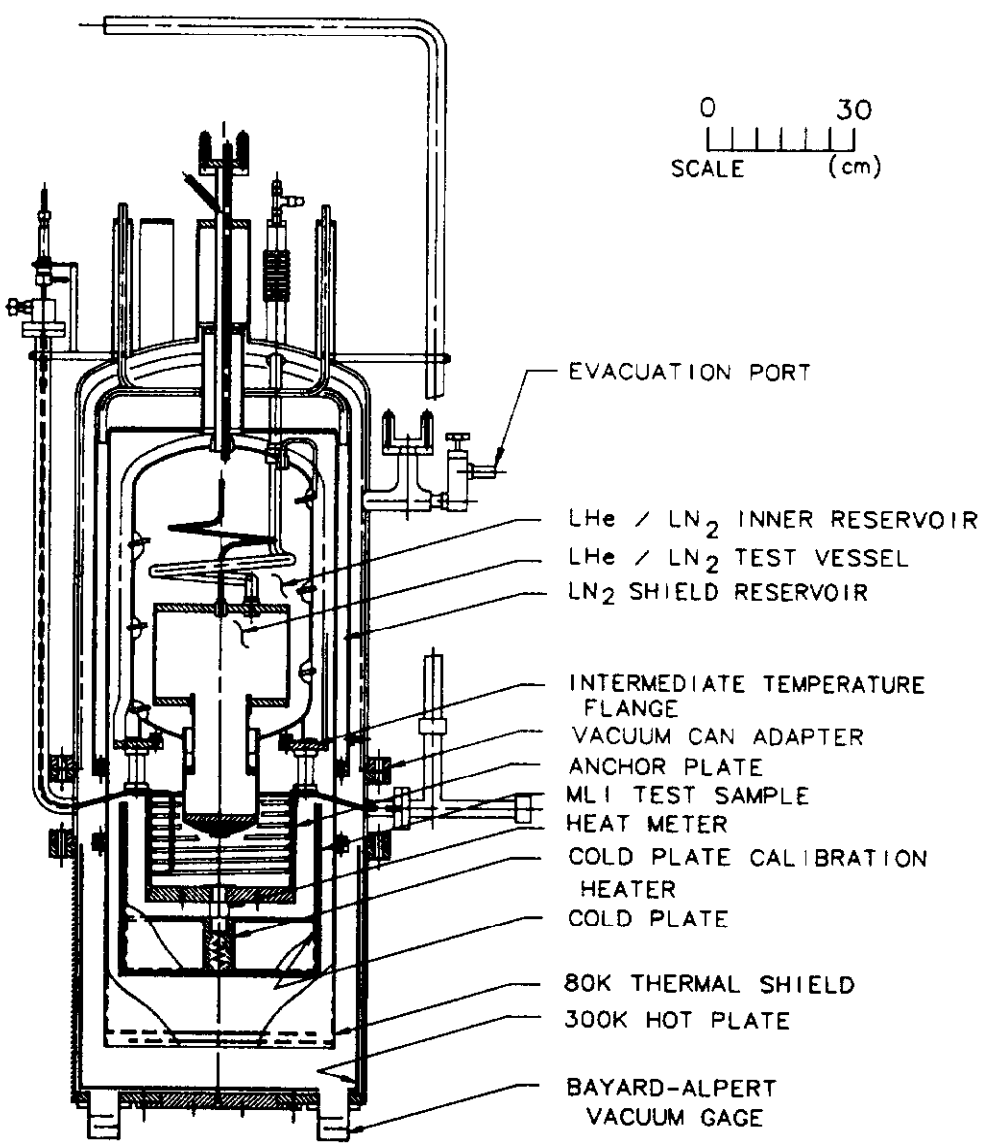


Fig. 1. Heat Leak Test Facility for MLI measurements below 80K

For the measurements previously referenced, the cold boundary temperature was fixed at either 77K or 4.2K depending on the cryogen in the Test Vessel volume. Given that the nominal operating temperature of the SSC cryostat inner shield is 20K, a means of providing a constant cold boundary temperature of 20K was needed to simulate cryostat conditions in the HLTF. Further, under changing conditions in the cryostat, the inner shield may in reality operate over a temperature range from 10K to 40K. Thus, the HLTF should ideally be capable of also varying the temperature of the cold boundary over this temperature range. These parameters have been met through the design and inclusion of a component named the Anchor Plate.

Heatmeter Anchor Plate - The Anchor Plate, shown in Figure 1, is comprised of a 26 cm. diameter OFHC copper cylinder with a wall thickness of 0.95 cm. The Anchor Plate is flanged on one end to permit attachment to the HLTF. The opposite end of the Anchor Plate consists of a 2.54 cm. thick disc of OFHC copper for substantial thermal mass. In an effort to reduce thermal communication between the Anchor Plate and the HLTF, a set of four insulated stand-offs were fabricated and placed between the Anchor Plate and the intermediate temperature flange of the HLTF. The stand-offs are constructed of 2.54 cm. diameter G-11 tubes, 1.2 mm. wall thickness, with shrink-fit joints[6] at either end. The stand-offs work exceptionally well to thermally isolate the Anchor Plate from the HLTF.

The temperature of the Anchor Plate is varied through boil-off gas from a 500 L helium supply dewar. Boil-off gas from the dewar is routed through a 0.64 cm. diameter copper tube that is coiled against the inner wall of the assembly. The spiralled tube is soft-soldered to the copper wall for solid thermal contact. Varying the flow rate through the tubing varies the temperature of the assembly; increased flow provides increased cooling.

Final temperature control is achieved through a resistance heater varnished into a milled groove on the outer wall of the Anchor Plate. The heater wire is Formvar-insulated 38 AWG manganin wire that is fabricated in a ten-wire ribbon. Nominal resistance of the ten-strand wire is 5.95 ohms/meter; total resistance of the heater is approximately 50 ohms. The heater wire is connected to a commercial cryogenic temperature controller capable of controlling the temperature to better than 1 mK for temperatures below 30K. As an example of Anchor Plate operation, if a temperature of 20K is desired, then the boil-off gas flow rate is set to provide a temperature of approximately 17K. The temperature controller is then used to power the heater and maintain the temperature at the desired set point of 20K.

Critical to attaining stable thermal equilibrium in the system is the ability to maintain constant flow rate and temperature of the supply gas. To sustain constant flow, the pressure of the supply dewar is maintained near 3.0 psig. Initial operating experiences found it very difficult to establish and maintain constant flow rates and gas temperatures. Lowering a conventional transfer line stinger into the He bath caused "slugs" of liquid He to enter the transfer line at these pressures and flow rates. The result was temperature oscillations in the Anchor Plate of magnitude and frequency beyond the control capability of the controller. Positioning the stinger in the gas volume above the liquid worked fine until the liquid level dropped and the stratified gas at the transfer line inlet changed temperature, thereby providing less cooling to the Anchor Plate. An innovative solution was found that provided constant temperature inlet gas at a constant pressure and flow rate.

Description of the Transfer Line Heat Exchanger - The controlled-temperature heat exchanger, shown in Figure 2, consists of a long cylindrical tube with a valve assembly at the warm end and a bulb assembly at the cold end. The 2.54 cm. o.d. thin-wall tube is comprised of glass-epoxy reinforced plastic (GRP) of low thermal conductivity whose length positions the bottom of the bulb assembly 2.54 cm. from the bottom of a 500 L storage dewar. Vent holes in the tube allow boil-off gas from the dewar to enter the tube and descend to the bulb assembly. A liquid helium level probe mounted along the tube immediately above the bulb provides information on liquid level in the dewar during operation.

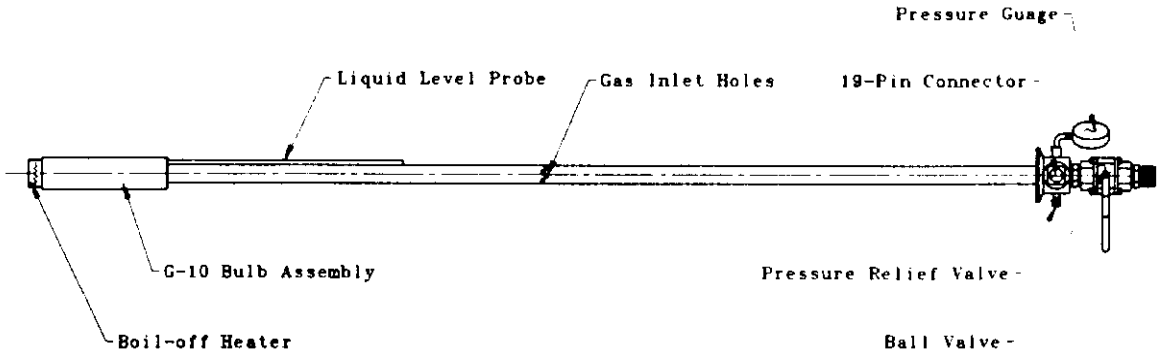


Fig. 2. Controlled temperature heat exchanger for cryogenic transfer lines

The bulb assembly, illustrated in Figure 3, consists of a short length of GRP tube whose diameter is slightly greater than the main tube. The bulb houses a cylindrical heat exchanger comprised of a large number of thin copper fins which provide a large surface area through which the vent gas must pass. A resistance heater is thermally-anchored to the heat exchanger and provides the means of varying the temperature of the exit gas. The heater is coiled around the heat exchanger to provide good thermal transfer along the entire heater length. Temperature of the vent gas exiting the device is measured by a precision cryogenic thermometer located near the transfer line inlet. The thermometer is suspended in the gas stream to measure the temperature of the gas and not of the heat exchanger or bulb.

A resistance heater mounted on the outside of the bulb assembly is used to generate boil-off gas in the dewar. The heater is mounted on a thin-wall GRP cylinder that is in poor thermal contact with the bottom of the heat exchanger bulb. Varying the power into the heater varies the boil-off rate in the dewar, which varies the flow rate of gas exiting through the transfer line.

The top portion of the transfer line heat exchanger is illustrated in Figure 4. The transfer line stinger is inserted through a ball valve equipped with Teflon seals to maintain a leak-tight seal at low temperatures. Internal pressure of the storage dewar is monitored with a pressure gauge installed on the top housing. Maximum pressure in the dewar is determined

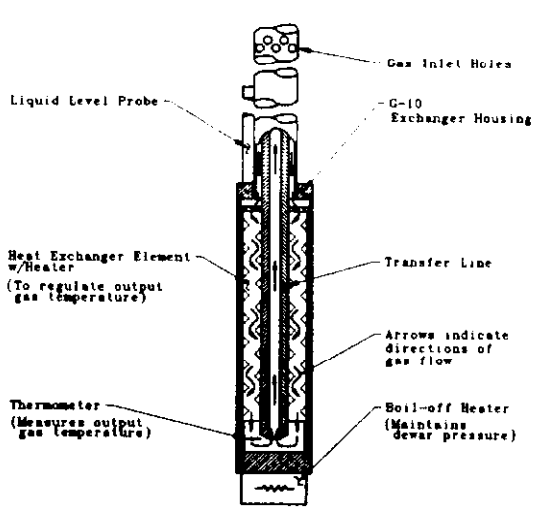


Fig. 3. Bulb assembly of transfer line heat exchanger

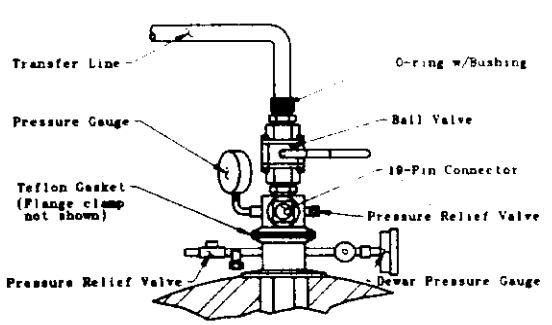


Fig. 4. Top portion of transfer line heat exchanger

by a self-sealing pressure relief valve that is set to relieve at 3.0 psig; operating experience has shown this to be the preferred pressure. Finally, a hermetically-sealed pin connector is used to bring out the instrumentation wires associated with the heat exchanger. These include lead-wires for the two internal heaters, the precision cryogenic thermometer, and the liquid level probe.

Operation of the Transfer Line Heat Exchanger - The transfer line heat exchanger is installed in a 500 L He dewar before transfer operations begin. For safety, the dewar must be stable with an internal pressure not exceeding 0.5 psig. In one continuous operation, the standard cover of the helium dewar vent is removed and the transfer line heat exchanger slowly inserted into the liquid bath. The device is designed so as not to interfere with existing relief valves on the storage dewar, thereby maintaining the safety designed into the dewar by the manufacturer.

After the transfer line heat exchanger assembly is installed, the transfer line stinger is inserted into the heat exchanger following commonly-practiced procedures for inserting a stinger into a helium dewar. The stinger length should be such that it extends to within 1.3 cm. of the bulb bottom; this positions the inlet of the stinger in the coldest gas region. At this point the outlet of the transfer line should be closed.

With the transfer line in place, the 0.5 psig relief valve is closed to allow pressure in the dewar to build to approximately 3.0 psig. The relief valve on the heat exchanger assembly is set to relieve at this pressure to avoid dewar over-pressurization. It should be noted that, provided the heat exchanger is installed slowly into the bath, the pressure rise is at a slow and constant rate and does not pose a danger due to rapid pressure rise.

Once pressure in the dewar reaches operating pressure, the transfer line vent is opened to begin gas flow. Cold gas from the dewar enters the heat exchanger through vent holes in the extension tube. Since the dewar vent is now through the transfer line at the bottom of the tube, the gas begins to descend into the bulb of the device. Cooling of the gas occurs as the gas flows through the tube due to the liquid helium in contact with the walls of the tube. This cooling causes some condensation of the gas as it flows through the tube; however, this condensation is flashed back to a gas as a small amount of power is applied to the heater encompassing the heat exchanger assembly. Subsequently, a pocket of gas exists at the mouth of the transfer line that is of constant temperature; varying the power applied to the heater varies the temperature of this gas. As long as the level of the helium bath in the dewar remains above the bulb assembly, the temperature of the gas pocket remains constant. Hence, the transfer line is always located in a pocket of constant temperature gas.

Thermal Boundaries for MLI Measurements - The parameters for MLI measurements currently underway in the HLTF call for a warm boundary at 80K and a cold boundary variable from 10K to 40K. The warm boundary is established by a thermal shield of OFHC copper that is bolted to the $LN_2$ reservoir of the HLTF. Thermal contact is provided between shield and reservoir through copper-laden grease suitable for use in a high vacuum environment. The inner surface of the shield is covered with 3M No. 850 aluminum tape to lower the surface emissivity and simulate the condition of the aluminum 80K shield in the SSC dipole cryostat. The inner surface area of the 80K shield is approximately 0.68 $m^2$.

The cold boundary consists of a 30.5 cm. diameter copper drum, 28 cm. tall, with an outer surface area of approximately 0.36 $m^2$. The drum, referred to as the Cold Plate in Figure 1, is thermally anchored to the Anchor Plate through the heatmeter. Copper-laden grease is used to assure good thermal contact. Varying the temperature of the Anchor Plate subsequently varies the temperature of the Cold Plate. All MLI test configurations are wrapped around the Cold Plate.

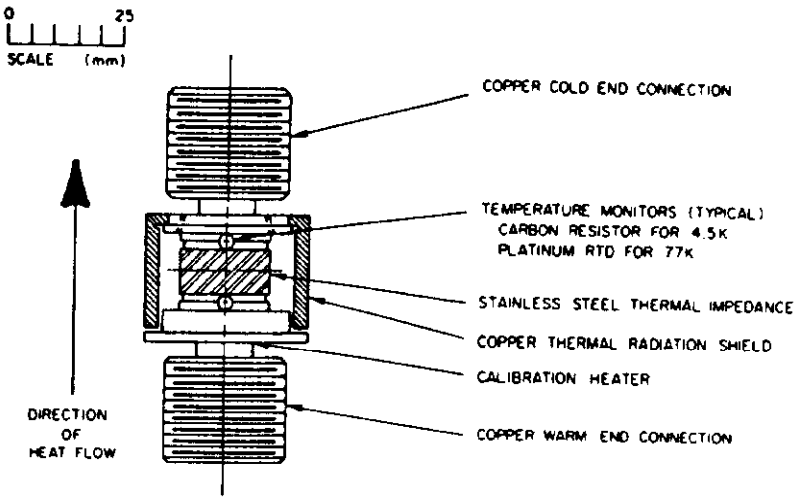


Fig. 5. Cross-section view of heatmeter

METHOD OF MEASURING HEAT LOAD

Heat loads are measured in the HLTF with a heatmeter illustrated in Figure 5. The heatmeter, described in detail elsewhere[7], consists of threaded copper ends separated by a stainless steel disc. The stainless steel disc serves as a thermal impedance to heat flowing through the device. Thermometers on either side of the disc measure the thermal gradient across the disc as a function of heat flow. Since the degree of temperature drop across the heatmeter is a function of the thermal conductivity of the stainless disc, and given the fact that thermal conductivity changes with temperature, then it is necessary to calibrate the device for each cold boundary temperature desired.

The heatmeter is calibrated by powering a resistance heater attached to the warm end of the device and measuring the corresponding temperature drop across the stainless disc. For the present series of measurements, the heatmeter was calibrated for temperatures between 10K and 50K. The calibration curve for 20K is presented in Figure 6. The heatmeter is very sensitive to heat flow with a resolution of 1.0 milliwatt to 20K. Figure 7 is an example of a heat load measurement made to 20K in the present HLTF configuration.

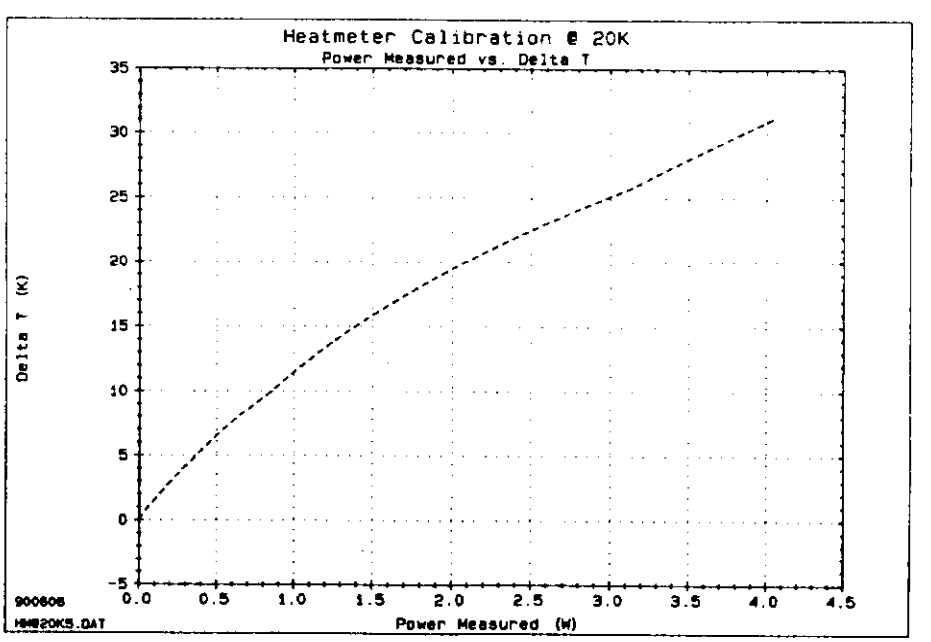


Fig. 6. Heatmeter calibration curve for measurements to 20K

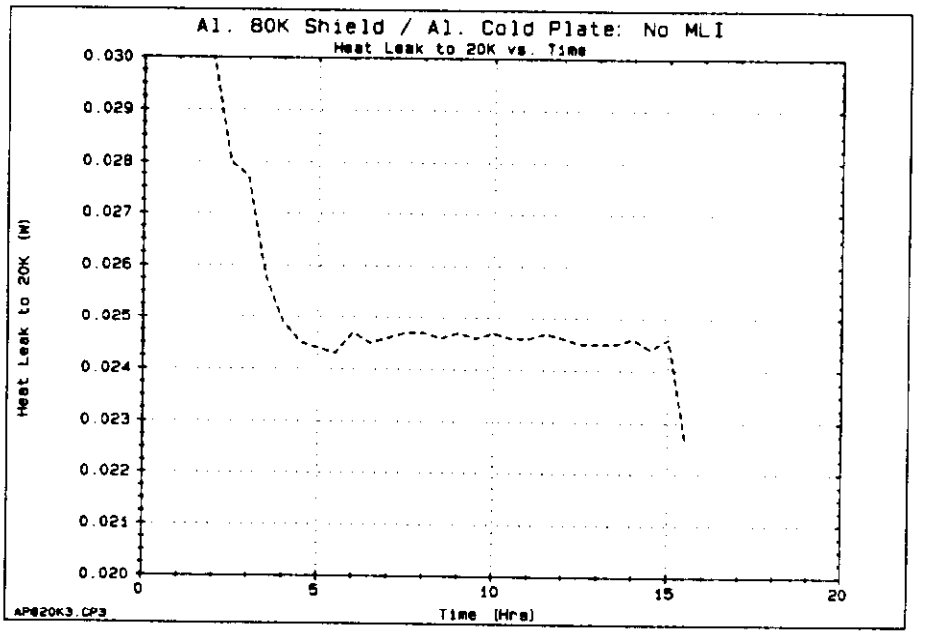


Fig. 7. Measurement data of heat load to 20K using the heatmeter

## VACUUM SYSTEM CHARACTERISTICS

Insulating vacuum in the HLTF is provided by a turbo-molecular pump with a pumping speed of 160 L per second. Due to the substantial amount of MLI in the top portion of the HLTF, along with the conductance of the system, the lowest pressure typically achieved in the HLTF is approximately $10^{-6}$ torr. With the recent acquisition of a getter pump, insulating vacuum in the $10^{-7}$ torr range should be achieved. To degrade the vacuum and study the effects of gas conduction on MLI performance, the valve between the turbo pump and the HLTF is closed. With the valve closed, pressure in the HLTF typically increases to approximately $10^{-4}$ torr.

To fully understand the effects of varying pressure on MLI performance, the capability to vary pressures between $10^{-6}$ and $10^{-4}$ torr is required. This has been achieved with the inclusion of a servo-driven valve regulated by a flow/pressure controller. The pressure controller senses system pressure from the output of an ion gauge controller and opens or closes the servo valve as necessary to maintain the insulating vacuum at the desired pressure. When operating the pressure controller system, the main valve between the HLTF and the turbo pump is closed; pumping occurs solely through the servo valve. This allows an infinite degree of control over system pressure in the $10^{-6}$ to $10^{-4}$ torr range.

## ADDITIONAL CAPABILITIES OF THE HEAT LEAK TEST FACILITY

The HLTF is presently configured for MLI measurements between 80K and 20K. However, the system as built could be easily adapted for a variety of thermal measurements including heat loads through solid support structures and thermal conductivities of sample materials. For thermal conductivity studies below 80K, the sample could be placed between the 80K shield and the heatmeter. Varying the temperature of the Anchor Plate would produce integrated thermal conductivity values over the temperature range below 80K. Removing the 80K shield would permit measurements with the warm boundary anchored near 300K. The cold boundary temperature could be varied by either flowing gas from a $LN_2$ dewar through the Anchor Plate to provide cold boundaries in the range above 80K or LHe dewar through the Anchor Plate to provide cold boundary temperatures below 80K.

SUMMARY

The Heat Leak Test Facility has been successfully reconfigured for MLI thermal performance measurements below 80K. After an initial period of learning and understanding the subtleties of the system, the behavior of the system has become repeatable and predictable. Preliminary test results show the system to be stable and very sensitive, with heat load measurement resolutions of 1 mW to 20K. Finally, due to the versatile design of the system, minimal hardware modification would be required to convert the system for thermal conductivity measurements.

ACKNOWLEDGEMENTS

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