

**ACCURATE SURFACE TEMPERATURE MEASUREMENTS AT LIQUID
HELIUM CONDITIONS IN SPACE ENVIRONMENT FACILITIES**

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Abstract

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An accurate temperature sensor, consisting of a germanium resistance thermometer, a lead-wire heat sink, and a high thermal conducting epoxy fastening method is available for measuring wall temperatures of large liquid helium cooled space environment facilities. Indicated wall temperature measurements have errors less than $+0.03^{\circ}$ K at liquid helium conditions. Cycling tests from 473° K to 4.2° K demonstrated stability of germanium resistors in vacuum facilities using a mild bake-out. A high thermal conductivity epoxy minimizes the vacuum thermal contact resistance between the sensor envelope and the wall. The lead-wire heat source into the sensor was minimized by using a thin fiberglass-copper heat sink in the voltage and current measuring circuit. Error determinations were made by referencing the sensor temperature to the liquid helium temperature in the Lewis Research Center's 6'x10' Space Environment Facility. The helium vapor pressure data was used to determine the liquid helium temperature in the space simulator.

I. Accurate Surface Temperature Requirements in Large Liquid Helium Cooled Space Environment Facilities

The effectiveness of liquid helium cooled walls in providing high pumping speeds for many gases of interest is recognized. If hydrogen is the gas resulting from products or combustion or deliberately introduced into the space simulation chamber then the resulting environment pressure strongly depends on wall temperature. For instance, if the wall temperature changes from 4.4° K to 4.8° K then the steady-state pressure, with a hydrogen in-flow, changes by an order of magnitude⁽¹⁾. Another reason for this sensitivity is that the sticking coefficient, for all gases, is surface temperature dependant. The control of cryopumping speed of a facility therefore depends on accurate temperature measurements.

In facilities that are used to find the low temperature optical properties of various materials, at space environment conditions, the need also exists for accurate surface temperature measurements. In this case the temperature of the cryo-surface is the back-ground radiation temperature. Consequently, knowing the correct wall temperature and hence the input from this background is more critical at lower specimen temperatures.

For these reasons, a study was started at the NASA, Lewis Research Center to develop an accurate and reliable surface temperature sensor. The successful sensor system was then applied to measure the wall temperature of a large liquid helium cooled space environment chamber.

II. Statement of the Problem

Surface temperature measurements with accuracies greater than $+0.01^{\circ}$ K are common in calibration cryo-stats, small super-conducting magnet chambers, or laboratory low temperature physics vessel. Applying these laboratory techniques, with high measuring accuracies, to large space environment facilities however, is difficult. The reasons are:

(1) Large radiant and conduction heat sources to the sensors are present in space environment facilities.

(2) Wiring the temperature sensor, in a large facility, to the signal read-out system involves long lengths and feed-throughs from the vacuum to atmospheric conditions.

(3) The presence of large amounts of "thermal noise."

All of these factors are present in the Lewis Research Center 6'x10' Space Environment Facility (Fig. 1). Two 32-in. diffusion pumps, a booster pump, and mechanical vacuum pump are used to pump the 6'x10' high vacuum chamber. The walls of the chamber can be cooled with liquid helium, refrigerated helium gas (5° K to 70° K), or liquid nitrogen. With the cryopumping produced by the cold walls, the pressure in the chamber can be varied from atmosphere to less than 1×10^{-15} mm Hg. Liquid helium is conserved by using an insulating vacuum chamber and a cooled radiation shield between the helium jacket and outer steel wall. A mild bake-out condition (400° K) is available by passing warm helium gas through the liquid helium jacket. Consequently, the wall temperature varies from 400° K to 4° K. Solar simulation is achieved by using a carbon arc, a lens, and a collimating mirror. This 5'x19' optics section is placed on top of the vacuum chamber and can provide solar radiation intensities up to three solar constants. Model instrumentation, electric power, and vacuum chamber instrumentation pass through the instrumentation section feed-throughs. This section also contains a quartz window which separates the vacuum chamber from the optics section. The optics, combined with the model and its supports, provide large thermal radiation sources to the liquid helium cooled walls.

A temperature sensor installation technique had to be devised that minimized several major error sources. A first error source is the vacuum thermal contact resistance between the sensor envelope and the wall. Large radiant heat sources combined with the vacuum thermal contact resistance can force the sensor to indicate a temperature many degrees above the true wall temperature. A second error source is the conduction heat source into the sensor through the signal measuring lead-wires. Since the lead-wires are near room temperature at the feed-through ports and are at liquid helium temperatures near the sensor, large heat fluxes can appear at the sensor.

Consequently, if a good heat sink is not available to absorb this heat then again the sensor will indicate erroneously high temperatures. The third error source can occur by choosing a temperature sensor with low sensitivity. If the sensor sensitivity is low then thermal noise in the long lengths of lead wires and wire connections could be mistaken for wall temperature readings. A fourth error source is an undetected shift in calibration of the temperature sensor. Repeated 400° K to 4° K cycling could cause a calibration shift resulting in errors of tenths of degrees. A sensor requiring a calibration after each run would not be useful for most test programs. The temperature measuring system to be described tends to minimize these four error sources.

III. Procedures and Methods

A. Sensor Selection Base on Sensitivity

Choosing a temperature sensor for maximum sensitivity, at liquid helium conditions, included comparisons between thermocouples and resistance thermometers. Sparks, Powell et al.⁽²⁾ have investigated many thermocouple combinations for use at cryogenic temperatures. Their results indicated a maximum sensitivity of 13 microvolts per degree for chromel versus gold 7% iron. However, in this combination, and under laboratory conditions, thermal noise sources of 2 to 16 microvolts are possible. The thermal noise was expected to be much higher in a large facility. Inhomogeneity of alloy composition through long lengths of thermocouple wire combined with many kinks and mechanical strains would account for signals greater than the sensitivity of the thermocouple signal. If the objective is to measure fractions of a degree then the low thermocouple signal requires very high resolution and accuracy in the read-out instrumentation.

Germanium, platinum, and carbon resistors have been used as low temperature resistance thermometers. Sinclair, et al.⁽³⁾, have demonstrated good sensitivity and accuracy of platinum resistors to liquid hydrogen temperatures. However, the platinum resistor sensitivity falls to about 0.5 ohm per °K at 4.2° K. Using a current of 100 microamps, which avoids Joule heating effects, results in a signal of 50 microvolts per degree. This sensitivity could be equal to the thermal noise signal in the system. However, Germanium and carbon resistors have higher sensitivities at 4° K. The germanium resistor has a sensitivity of 450 ohms per degree. This compares with 750 ohms per degree for a 100 ohms, 0.1 watt carbon resistor. Based on sensitivity, the germanium and carbon resistor seems best suited to a large facility.

B. Sensor Selection Based on Stability and Reliability

Several investigators⁽⁴⁾⁽⁵⁾ have noticed a shift in the temperature versus resistance calibration for carbon resistors. This shift is caused by repeated cycling from room temperature to liquid helium conditions. Errors of 0.1° K can be expected after a few cycles. Sachse⁽⁴⁾ noticed that this instability varied from resistor to resistor. Similar results, for carbon resistors, were obtained in our 370° K to 4° K cycle tests. However, one resistor in the group did not change its indi-

cated liquid helium temperature by more than 0.01° K after 22 cycles.

Stability investigations for germanium resistors were available from room temperature to liquid helium temperatures⁽⁶⁾. However, the literature did not contain higher temperature cycling data that would be necessary for large liquid helium facilities using a mild bake-out (400° K to 500° K). Several germanium resistors were placed in an oven and heated to 473° K. The resistors were then slowly immersed into a wide mouth 100 liter liquid helium Dewar. Precautions were taken to immerse each resistor 5 or 6 in, below the liquid helium level since Sinclair⁽³⁾ had noticed liquid-gas surface temperature gradients in similar bath experiments. The germanium resistor indicated a temperature which was compared with the helium vapor pressure-temperature scale. Deviations less than +0.007° K, at 4.2° K, were noticed after 20 cycles from 473° K to 4.3° K. The germanium resistor with its high sensitivity and repeatability seemed ideally suited to large facility temperature sensing tasks.

C. Measurement Circuit and Interpolation of Temperature-Resistance Calibration Data

The measurement circuit includes a constant current power supply, the four wire germanium resistor with V^+ , V^- , I^+ , I^- , lead-wires, and an integrating digital voltmeter. A precision 1000 ohm resistor ($\pm 0.002\%$) is used to establish and measure the current through each resistor. A current level of 10 microamps, corresponding to a resistor power of 0.1 microwatt, minimizes the Joule heating effect. The voltage drop across the germanium resistor and the precision current resistor is measured on a six place integrating digital voltmeter. The voltmeter has a resolution of one microvolt and an accuracy of $\pm 0.01\%$ of reading. In addition, a pre-amplifier at a gain setting of unity increases the system resistance to 10^{10} ohms. This combination yields negligible loading errors and has the resolution and accuracy necessary for measurements of 0.01° K.

Each germanium resistor is supplied with an eight point calibration between 6.5° K and 4.0° K. Edlon and Plumb⁽⁷⁾ found that a polynomial of the form:

$$\log_{10} R = \sum_{N=0}^M A_N (\log_{10} T)^N \quad (1)$$

was sufficient to describe the resistor calibration. A seventh order polynomial was used in a double precision computer program to present the temperature versus resistance data at every 0.01° K interval between 4° K and 6.5° K. The accuracy of the calibration-curve fitting program was ± 0.001 ° K.

D. The Vacuum Contact Resistance Problem

Each calibrated germanium resistor is supplied with a copper surface mounting button that screws into a cryo-surface (fig. 2). The snap ring holds the copper envelope to the button. Inside the envelope, a doped germanium resistance element is strain-free attached to a bulk head containing the four lead wires. An environment of helium gas provides a thermal path between the element and the envelope. Two sources of vacuum thermal contact resistance can occur with this attaching arrange-

ment. The first source is between the button surface (threads and shoulder) and the cryo-surface. A second source is the interface between the envelope and the button. This total effect of vacuum contact resistance can cause the indicated temperature to be considerably higher than true wall temperature.

Six germanium resistors and their buttons were placed at various stations in the 6'x10' solar space environment simulator (fig. 3). This arrangement gives a complete facility temperature profile along its height. To minimize the vacuum contact resistance effect the optics section and the model support struts were removed from the facility. However, each station receives a room temperature radiant flux depending on the view factor with respect to the top of the facility. A series of tests were performed to determine the contact resistance effect on indicated wall temperature.

Fig. 4 is a time history curve of a resistor at each station. All resistors indicated a wall temperature of 2 to 10 degrees above the temperature of the liquid helium in the jacket. The jacket pressure is recorded on an accurate pressure gauge, and when combined with the helium vapor pressure data, defines the lowest possible wall temperature. Fig. 4 shows that after 5 hours from the start of liquid helium flow into the jacket, each sensor is reading above the liquid helium jacket temperature. The location of the maximum and minimum difference did not correspond to station elevation. Station F, having the poorest radiant heat flux view factor should yield the minimum temperature difference. The measuring discrepancies shown in fig. 4 are probably due to the variation in contact resistance from sensor to sensor. These variations, in turn, are probably due to differences in the interface contact pressure between the snap ring and the sensors envelope or between the button and the wall at each station.

Since a vacuum contact resistance effect seemed to exist a series of tests were performed to determine its magnitude. An indium "O" ring was placed between each button and the chamber wall. Also, the envelope-button contact pressure was changed for the resistor at Station F. The snap ring was replaced with a small set screw located in the top of the button and a thin film of silicon grease was applied to the envelope. The test program (fig. 5) consisted of the following sequence of space simulator environment pressure changes. At time "zero" the liquid helium flows into the jacket. After 1 hour from the start of liquid helium flow, the space simulator pressure falls from 1×10^{-6} mm Hg to $1 \times 10^{-1.5}$ mm Hg. 7 hours later the indicated wall temperature appears constant with time and is 2 to 5 degrees above the jacket liquid helium temperature. At 8 hours from the start of liquid helium flow, a gaseous helium leak was started and continued until the simulator pressure increased to 1×10^{-3} mm Hg. The purpose of this leak was to fill the interface surface void volume with a gas. Consequently, the thermal contact resistance would be reduced by the heat transported through the gas in the interface voids. The reverse effect of removing gas from the voids was created by stopping the gaseous helium leak and pumping the facility from 1×10^{-3} mm Hg to 1×10^{-8} mm Hg.

The results, contained in fig. 5, show two distinct contact resistance effects. First, with the presence of gas in the voids, the temperature difference at the top and bottom of the facility falls below 0.4° K. Removing the gas from the voids causes the temperature difference to return to approximately its value before the leak influx. From this result the conclusion follows that vacuum contact resistance causes the sensors to read above true wall temperature. A second effect in fig. 5 was noticed at Station D. An explanation of the peculiar time history curve of Station D is as follows. A cold cathode magnetron vacuum gauge was located 2 in. from the wall at this station. Before the start of the gaseous helium leak the vacuum gauge temperature is considerably higher than the stainless steel wall temperature of the simulator. Once the gas is introduced, and the pressure rises above 1×10^{-5} mm Hg, a new conduction path exists which cools the gauge and locally heats the sensor's button. The indicated temperature rises until the gauge surface temperature falls to about the wall temperature. Thus, the radiant and conduction heat flux coming from the gauge to the button is reduced and the wall temperature decreases. When the gas is removed the conduction heat flux is eliminated causing the indicated wall temperature to fall at a different rate. With all of the gas removed, the vacuum gauge once again applies an increased radiant heat flux to the sensor's button. The temperature difference increases to the value which existed before the leak. These changes in the space simulator environment pressure together with the presence of a heat source demonstrate the existence of a vacuum thermal contact resistance effect for Station D sensors. The germanium resistors at Station A and D were interchanged and the test results were identical to fig. 5 which shows that the time history data was not a function of the resistor itself.

The set screw and silicon grease reduced the contact resistance effect by 5 degrees (fig. 4 and fig. 5 - Station F) but was reduced an additional order of magnitude with the helium leak. Thus, it seemed more important to reduce the radiant heat flux by shielding than to consider further changes in contact pressure.

To determine the effect of the radiant heat flux and the vacuum contact resistance on temperature errors a liquid helium cooled copper baffle was placed in the space simulator (fig. 6). Three germanium resistors and their buttons were mounted at Stations G, H, and J to record the baffle temperature. Each resistor was on the chamber side of the baffle. Fig. 7 shows the baffle, liquid helium fill and vent lines, and the top flange of the simulator. The resistor lead-wires were strapped tightly to the bottom of the baffle and the fill line. All vacuum gauges were removed from the space simulator. In this configuration, with the baffle at liquid helium temperature, no radiant heat sources existed in the test chamber.

Fig. 8 shows a time history of the resistor readings at Stations A, D, and F. After 9 hours, liquid helium entered the copper baffle. 2 hours later, the indicated wall temperature reaches a new equilibrium value of 0.55 to 2.3 degrees above the liquid helium temperature. Introducing the gaseous helium leak decreased the temperature difference to 0.04° K. Since the vacuum gauge had been removed

from Station D the germanium resistor had the same helium leak characteristics as the other sensors. Comparisons with the results in figs. 5 and 8 shows a considerable drop in the temperature difference with the helium leak. However, liquid helium cooling of the baffle had only a small effect on the temperature difference. Similar results were noticed with the three resistors on the copper baffle. With liquid helium in the baffle, temperature differences of 0.15° K above the liquid helium temperature existed at all positions. The gaseous helium leak reduced this difference to less than 0.05° K. Consequently, eliminating the radiant heat sources did reduce the vacuum thermal contact resistance effect. However, the 1° K to 4° K initial equilibrium temperature differences were above the desired accuracy.

To minimize further the effects of thermal contact resistance, a new sensor attaching method was used. Fig. 9 describes this method. The germanium resistor's envelope is inserted into the space simulator wall with a hole center-line 30° from the vertical. Thus each sensor has a very low view factor for all radiant heat flux sources. With the resistor placed in the wall, the vacuum thermal contact resistance is also reduced by eliminating the interface between the button and the wall. The remaining contact resistance interface, between the wall and the envelope, was decreased by fastening the envelope with a high thermal conductivity epoxy. This epoxy (Epibond, Furane Plastics, Inc.) contains 95% silver which accounts for its high thermal conductivity at liquid helium conditions. The resistor lead-wires were epoxied to the simulator wall for a strain-free condition.

E. The Lead-Wire Heat Conduction Problem

Since the surface-jacket helium temperature difference was much smaller on the copper baffle than on the simulator wall it was evident that other thermal sources were affecting the sensor. Gordon⁽⁸⁾ had shown that at liquid helium conditions, sizable conduction heat fluxes were possible in sensor lead-wires or model support wires. A second liquid helium baffle, located at Station D, was used to determine if the temperature difference depended on wire fastening techniques. The baffle (fig. 10) was instrumented as follows. The resistor normally located at Station D was epoxied to the small baffle at Station K. However, its lead-wires were still fastened to the simulator wall. A temperature referencing resistor was placed on the small baffle at Station L, and its lead-wires were attached to the baffle and the liquid helium fill line. The wires attached to the baffle should not experience the same thermal gradients as the simulator wall wires.

Fig. 11 shows the baffle test results and the results with resistors at Stations A and F placed in the simulator wall. Comparisons with previous results indicated that the contact resistance effect was reduced to its lowest value. However, at the initial equilibrium condition, the wall temperature was 0.57° K to 1.6° K above the jacket liquid helium temperature. The temperature difference was still too large even with liquid helium in the large and small baffles. Fig. 11 shows that the baffle indicated surface temperature to liquid helium temperature differences varied between 0.2° K to 0.8° K. Also, the resistor, with its wire

strapped to the simulator wall had the higher value. This result indicated that the lead-wires were not at wall temperature and were sources of heat flux to each resistor. Introducing the gaseous helium leak dropped all temperature differences below 0.06° K. A major reason for this order of magnitude reduction could be the cooling of the lead-wires by providing a conduction path to the wall.

The lead-wire heat conduction source was next minimized by using a heat-sink near the germanium resistor. Fig. 12 shows the design and final assembly with each resistor. The objective of the heat sink is to drop the wire temperature to the wall temperature while providing a large electrical resistance between the wire and the wall. The basic component which achieves these results is a 15 mil thick fiber-glass printed circuit board having a copper layer of 5 mils. The circuit board was cut into 1.25×4 in. strips and the fiberglass was milled down to a thickness of 0.010 in. All of the copper was milled off except for four rails with a width less than 8 mils (fig. 13).

A vacuum contact resistance effect at the interfaces, could also limit the efficiency of the heat sink. The vapor deposited copper gives excellent bonding to the fiberglass. The high thermal conductivity epoxy was used at the interface between the fiberglass and the simulator wall. Three studs provide good contact pressure on the heat sink and an aluminum foil radiation shield reduces the radiant heat flux.

Additional thermal resistance into the sensor is achieved by using 2 in. lengths of No. 30 gauge manganin wire between the heat sink and the resistor. The teflon covered manganin wires are sandwiched between mylar tape and epoxied to the wall. No. 28 gauge manganin wires are used as lead-wires between the heat sink and the read-out instrumentation. Additional lead-wire cooling is obtained by nichrome strapping the wires, at 8 in. intervals, to the wall. The original lead-wire was No. 30 gauge solid copper wire which resulted in an all copper system. A thermal noise, corresponding to 50 to 100 microvolts, occurred. Operating with zero current in the germanium resistor circuit and measuring the voltage drop across the germanium resistor defined the magnitude of thermal noise. However, the thermal noise, using the manganin wire, is only 2 microvolts. Similar low thermal noise occurred if 30 gauge stranded copper wire was used. All electrical or wire connections were made with crimped mechanical connectors as every combination of soldering gave high thermal noise. Fig. 14 shows the final installation in the space simulator.

A final test was made using the heat sink system and manganin lead wires. A liquid helium reservoir, positioned at Station B (fig. 3), was used as a reference temperature source. Fig. 15 shows the liquid helium reference cylinder and its location in the space simulator. The reference temperature was determined by placing a calibrated germanium resistor inside the cylinder and using the helium vapor pressure data. The sensor, normally located at Station B, was attached to the reference cylinder. The reservoir pressure was measured by attaching a separate 0.25 in. dia. tube from the cylinder, through a feed-through, and to an accurate pressure gauge. All of the original instrumentation and the large

copper baffle (without liquid helium) were placed in the space simulator.

Fig. 16 shows the results of the final test. The time history curve shows that after 3 hours the temperature difference was 0.04° K. With liquid helium in the reference cylinder the temperature difference between the resistor, with heat sink and manganin lead-wires attached to the wall and the liquid helium temperature was less than 0.03° K. Several similar tests indicated equilibrium temperature differences between 0.04° K and 0.02° K. Calculations of the heat flux to the liquid helium jacket, using an average wall temperature of 0.04° K, agreed with the recorded liquid helium usage rate.

IV. Summary and Conclusions

With the techniques described in this paper, accurate wall temperature measurements can be made in large liquid helium cooled space environment facilities. Measurements as little as 0.04° K above the liquid helium temperature were achieved. The main factors in achieving this measuring accuracy were as follows:

(1) Germanium resistors were used because they have excellent sensitivity and the best stability of all low temperature sensors.

(2) Vacuum contact resistance effects were minimized by using a high thermal conductivity epoxy and positioning the germanium resistor with a low radiant heat flux view factor.

(3) A lead-wire heat sink was found to be necessary to eliminate wire conduction heat sources into the sensor.

(4) No. 28 gauge manganin lead-wire was used to reduce conduction heat sources to the sensor and minimizes thermal noise.

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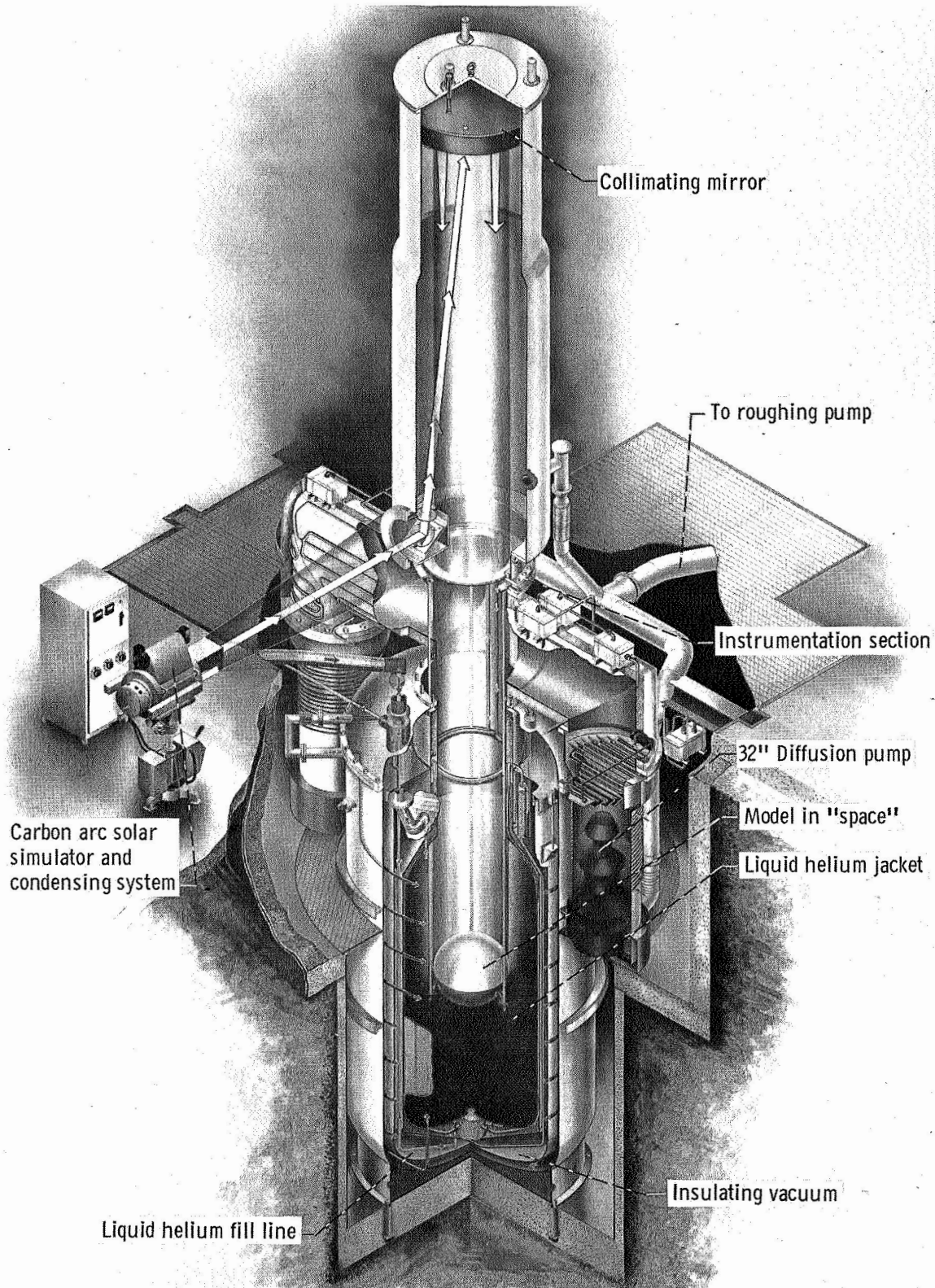


Figure 1. - 10' x 6' Solar space simulator.

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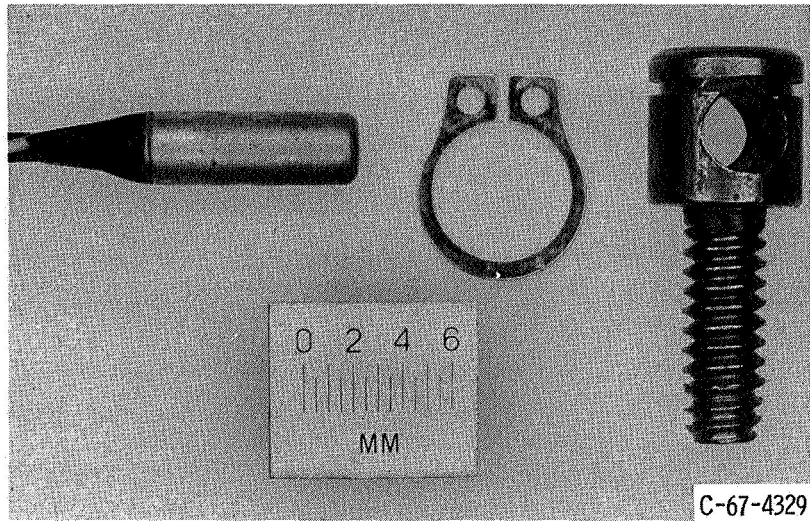


Figure 2. - Germanium resistor and button.

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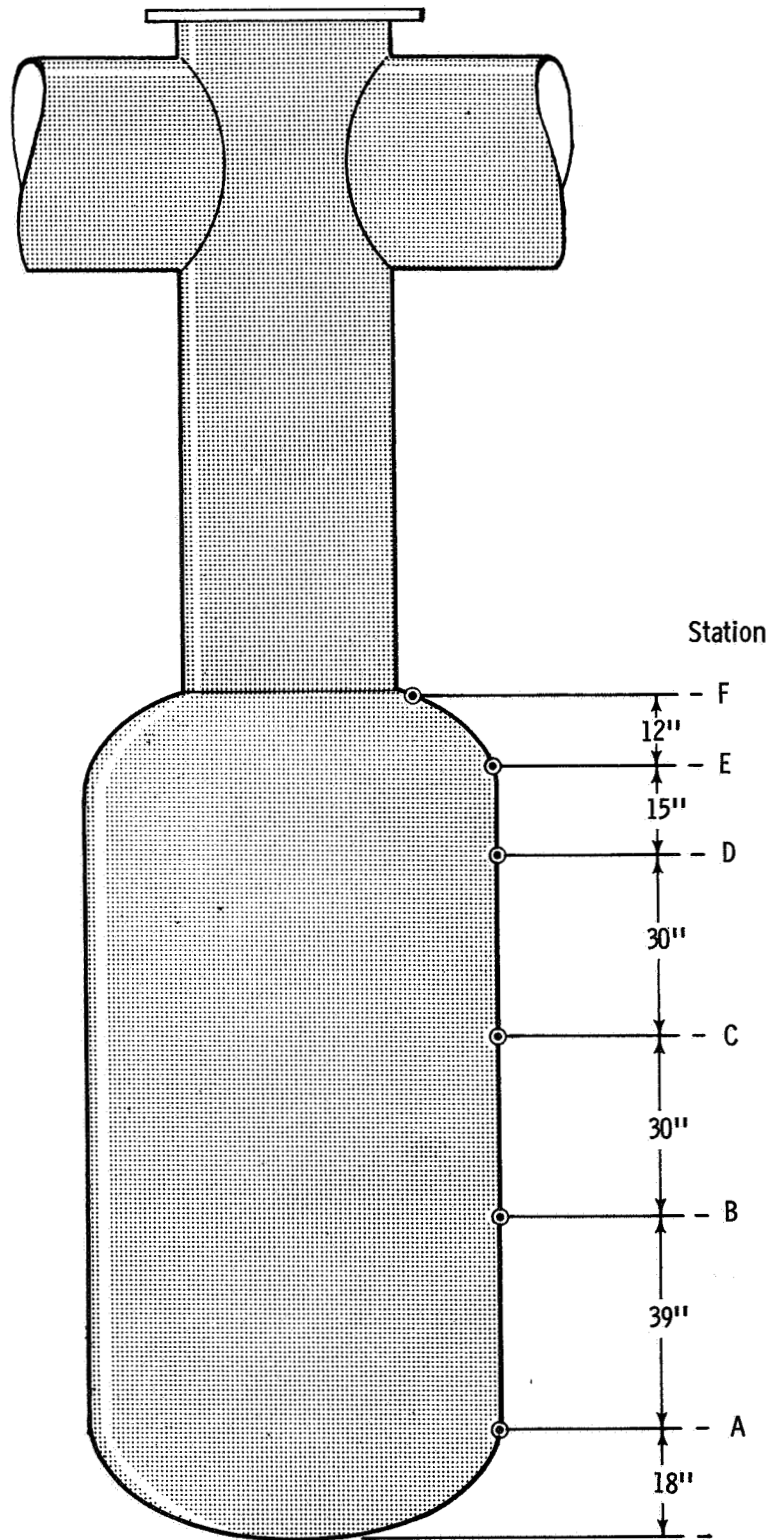


Figure 3. - Germanium resistor location in the space simulator.

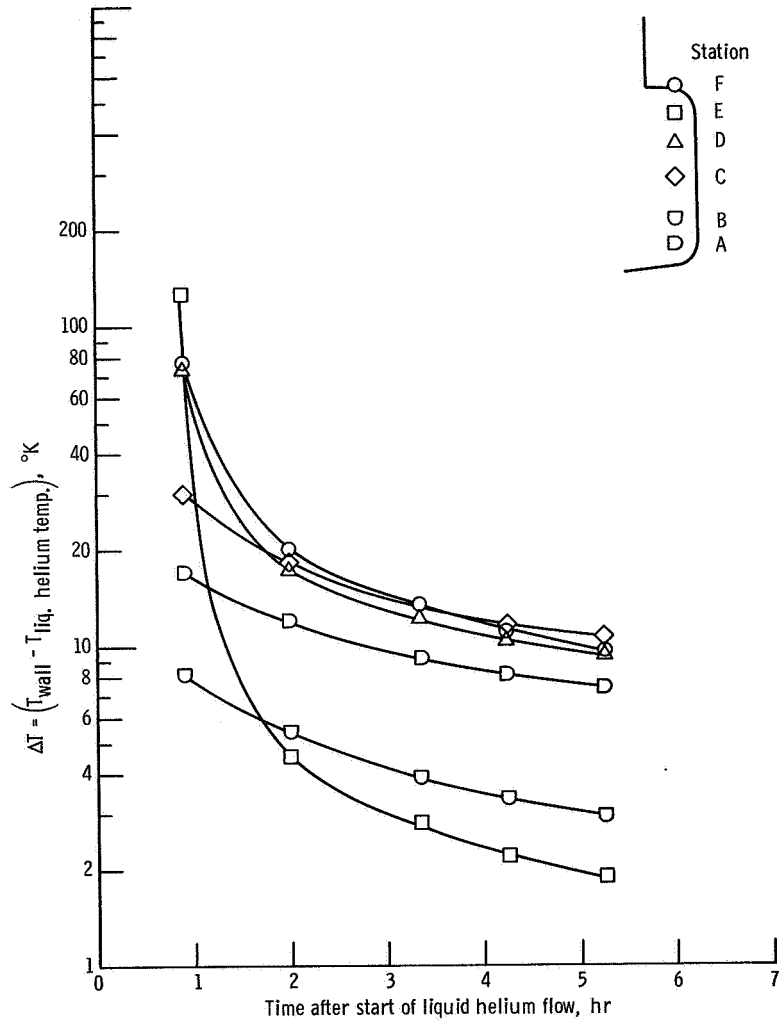


Figure 4. - Germanium resistor-time history curve.

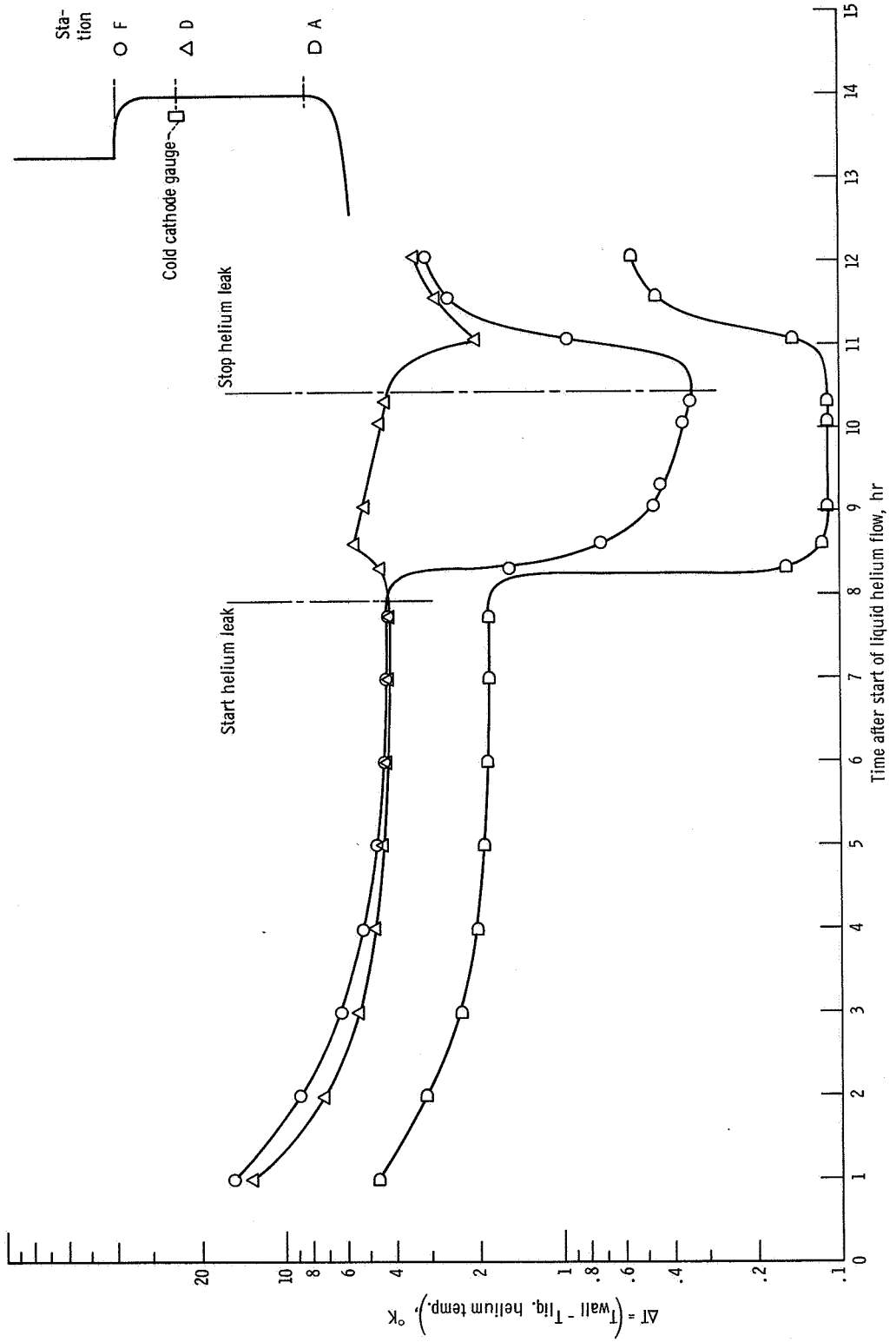
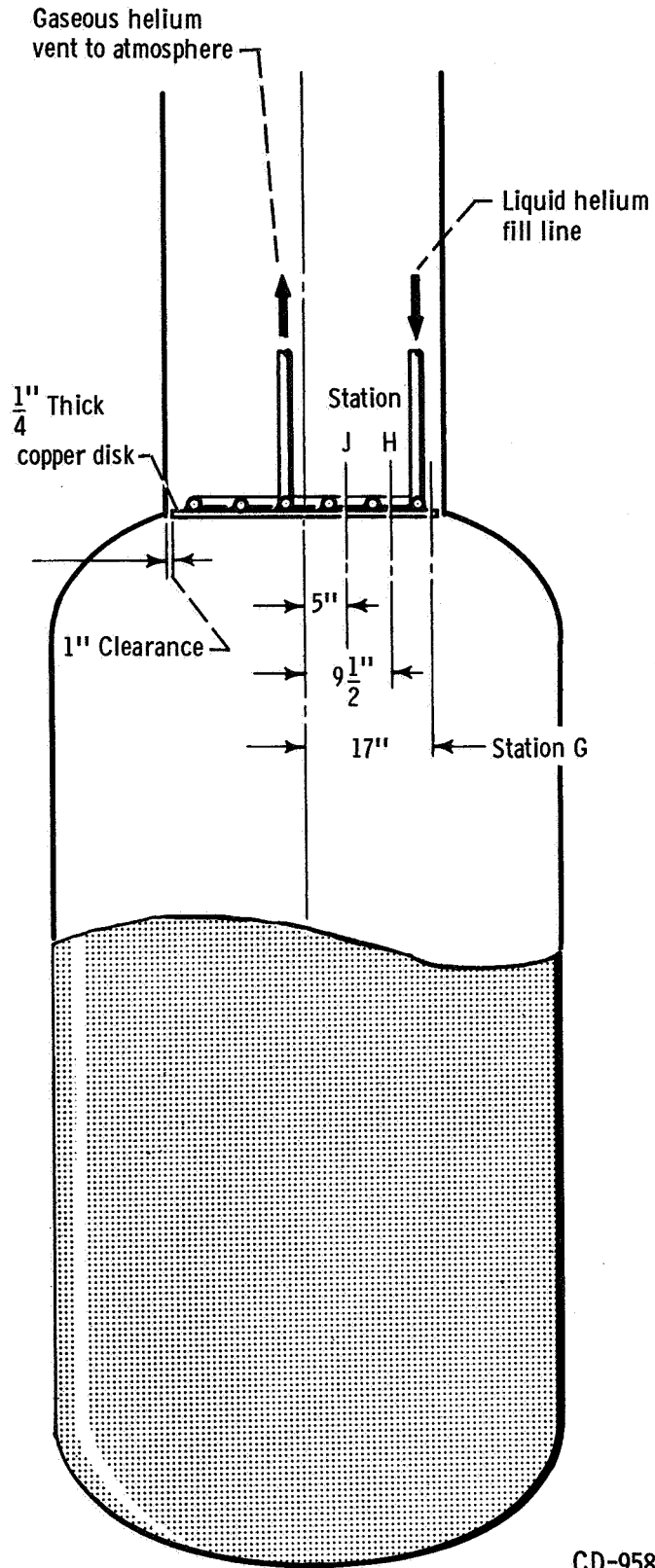


Figure 5. - Effect of environment pressure on vacuum contact resistance.

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Figure 6. - Large liquid helium cooled baffle in space simulator.

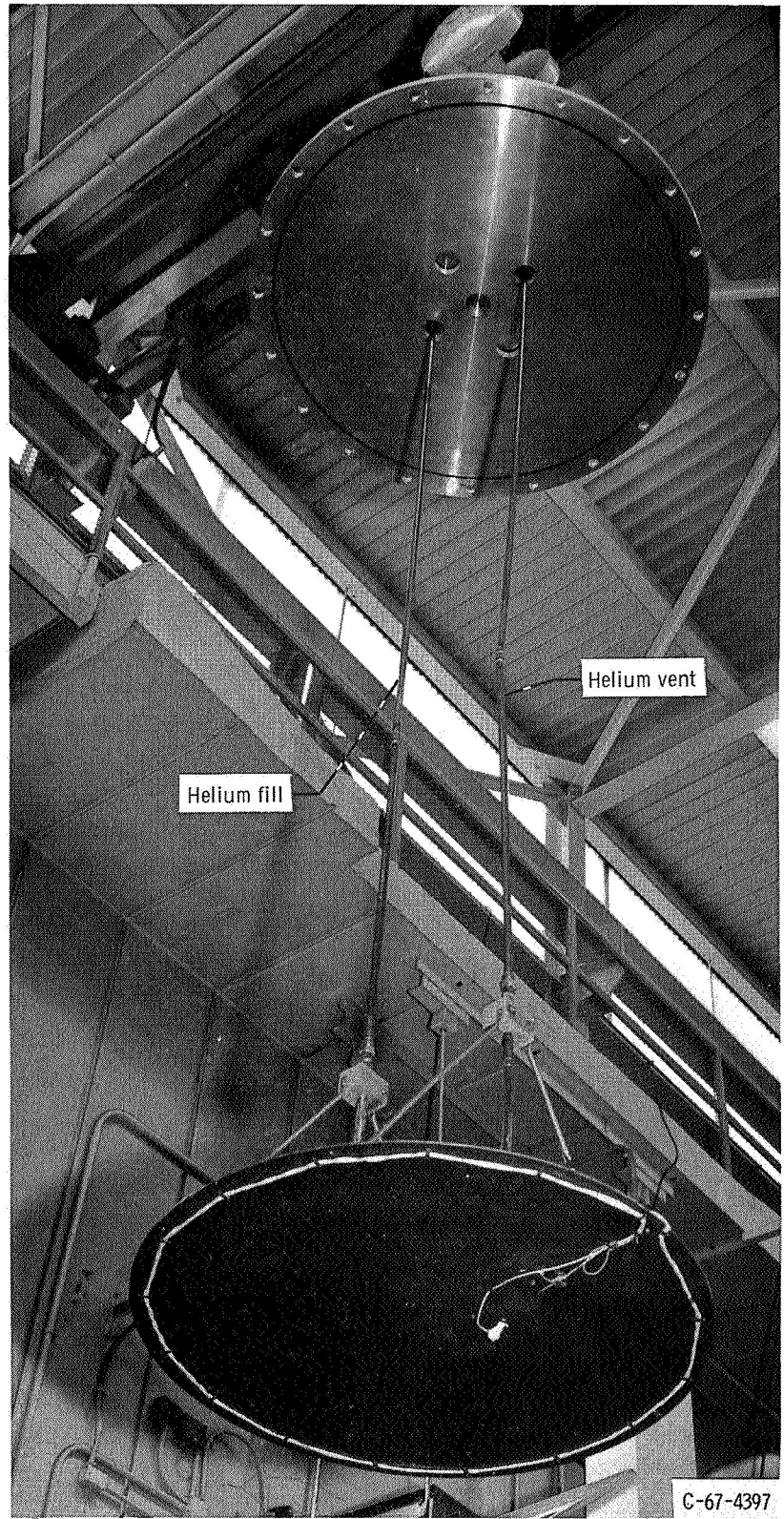


Figure 7. - Large liquid helium cooled baffle.

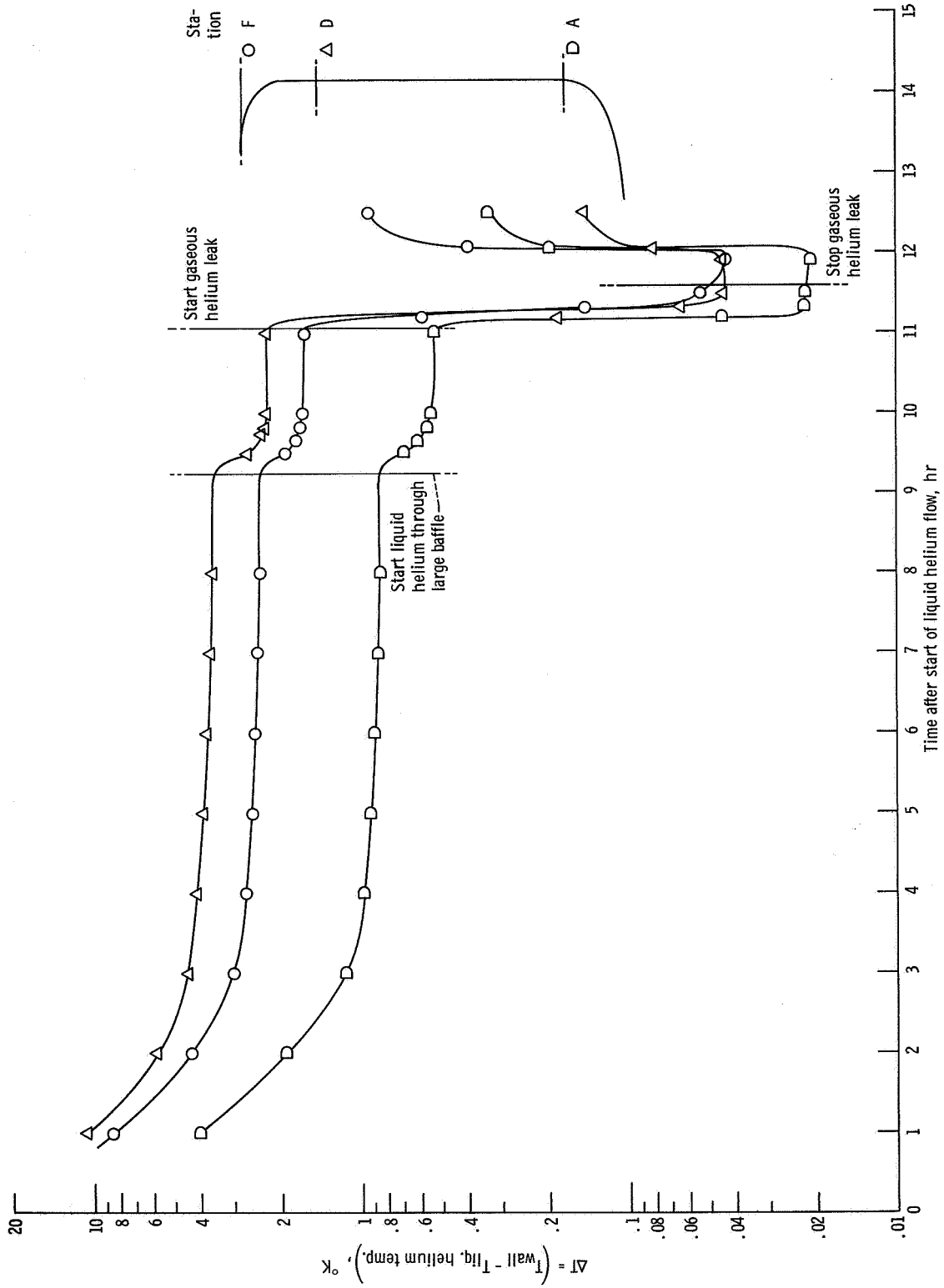
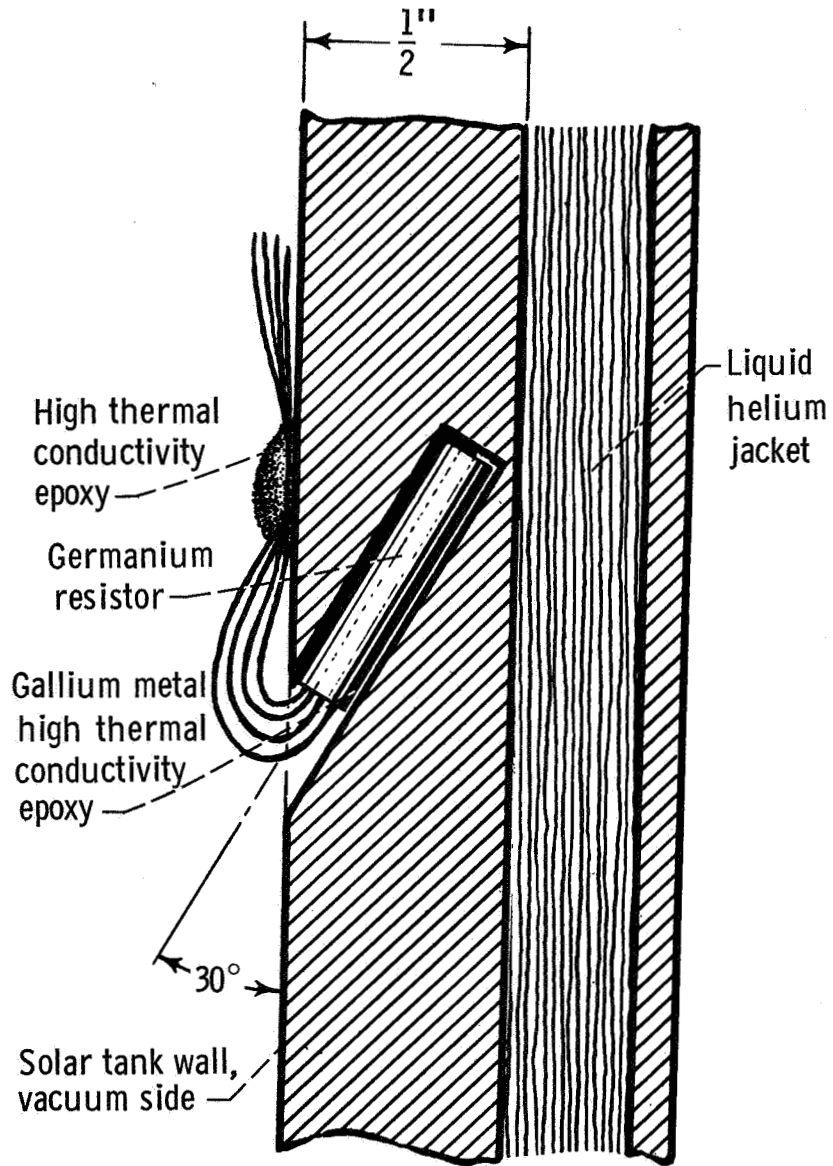


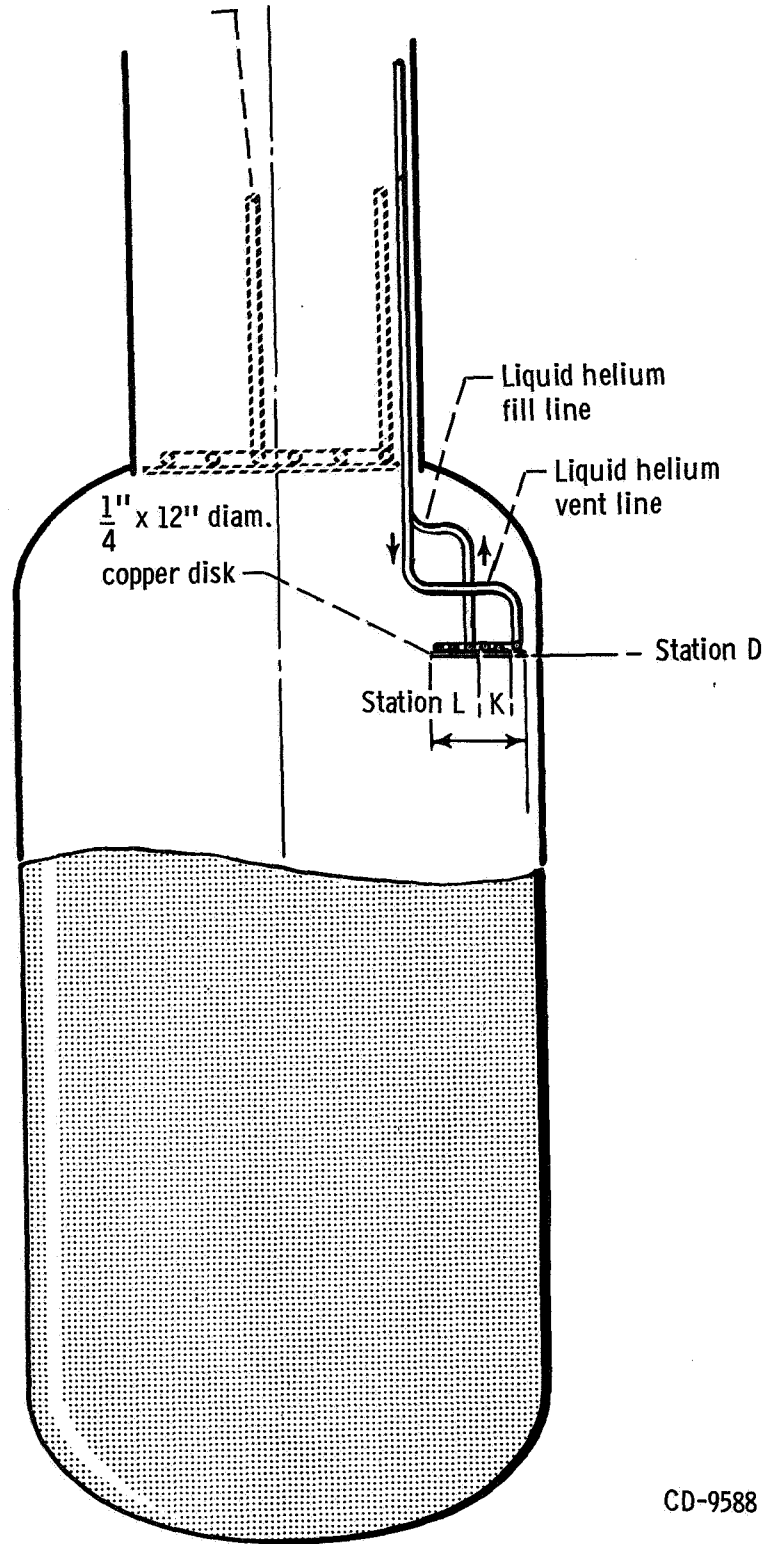
Figure 8. - Effect of reducing the radiant heat flux and the effect of environment pressure on vacuum contact resistance.



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Figure 9. - Germanium resistor installation.

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Figure 10. - Small liquid helium reference baffle at Station D.

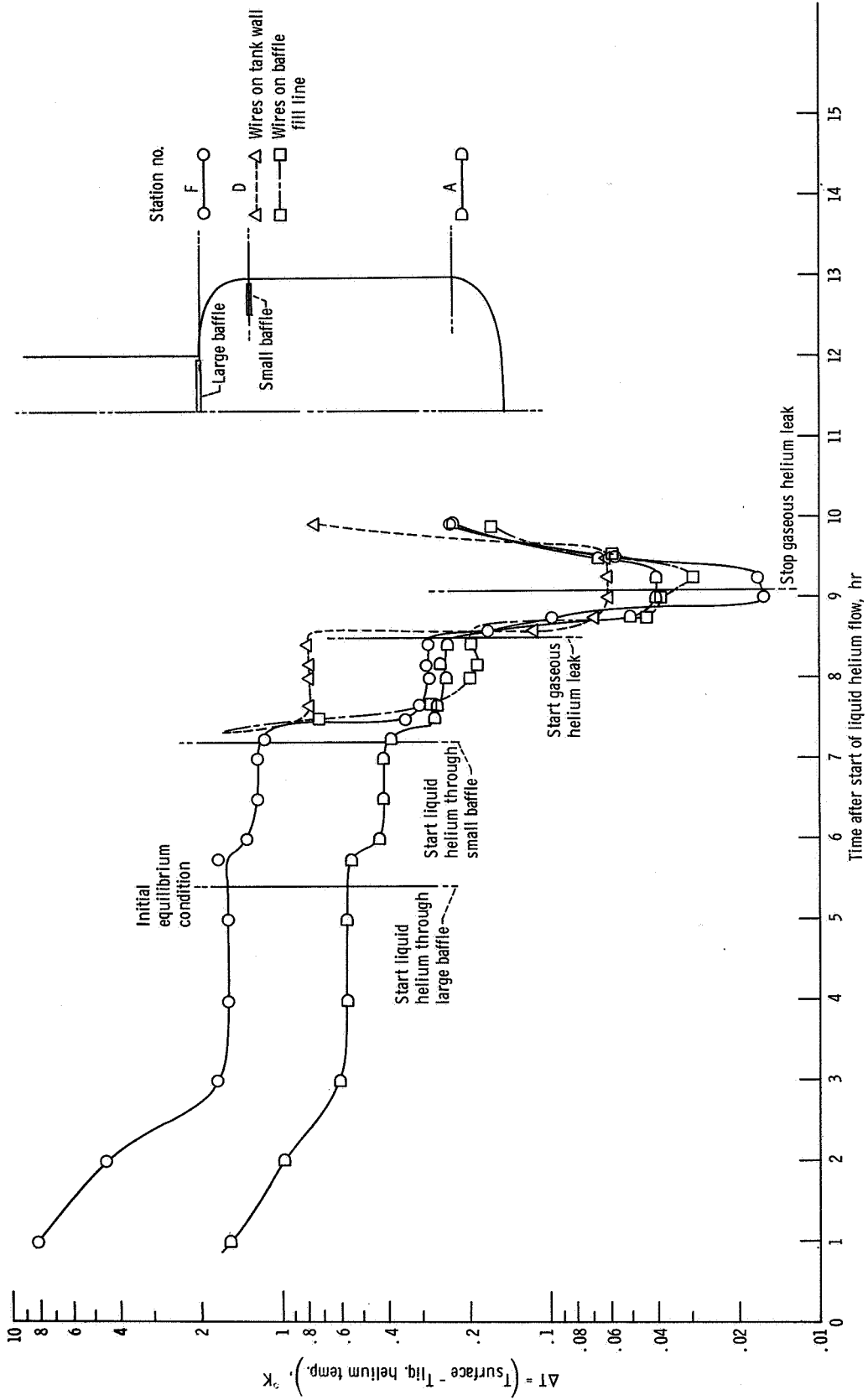


Figure 11. - Effect of lead wire conduction heat source and reduction in radiant heat source on germanium resistor sensing accuracy.

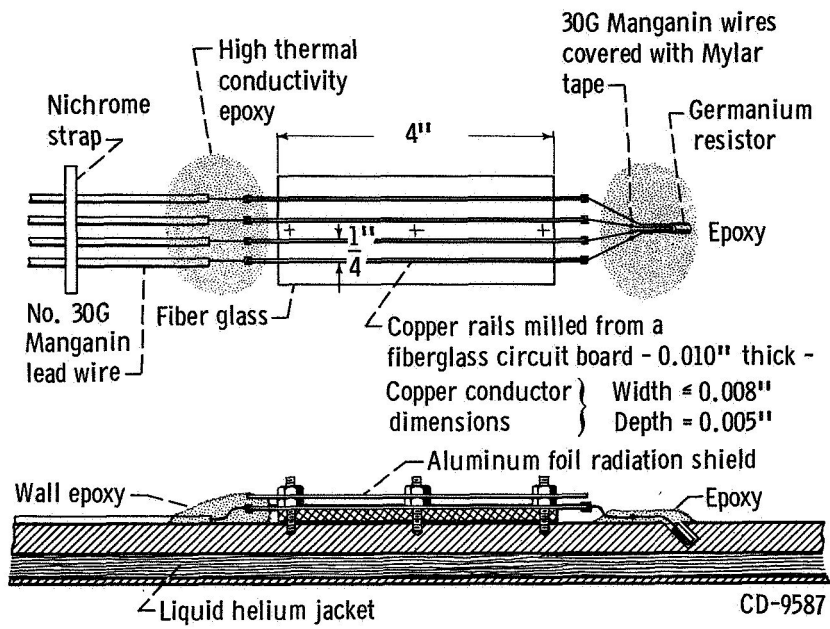


Figure 12. - Typical heat sink for resistors.

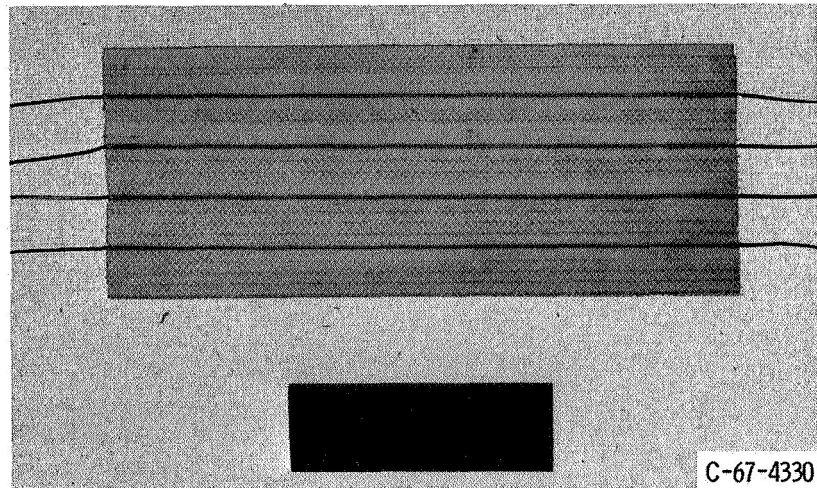


Figure 13. - Fiberglass-copper rail heat sink.

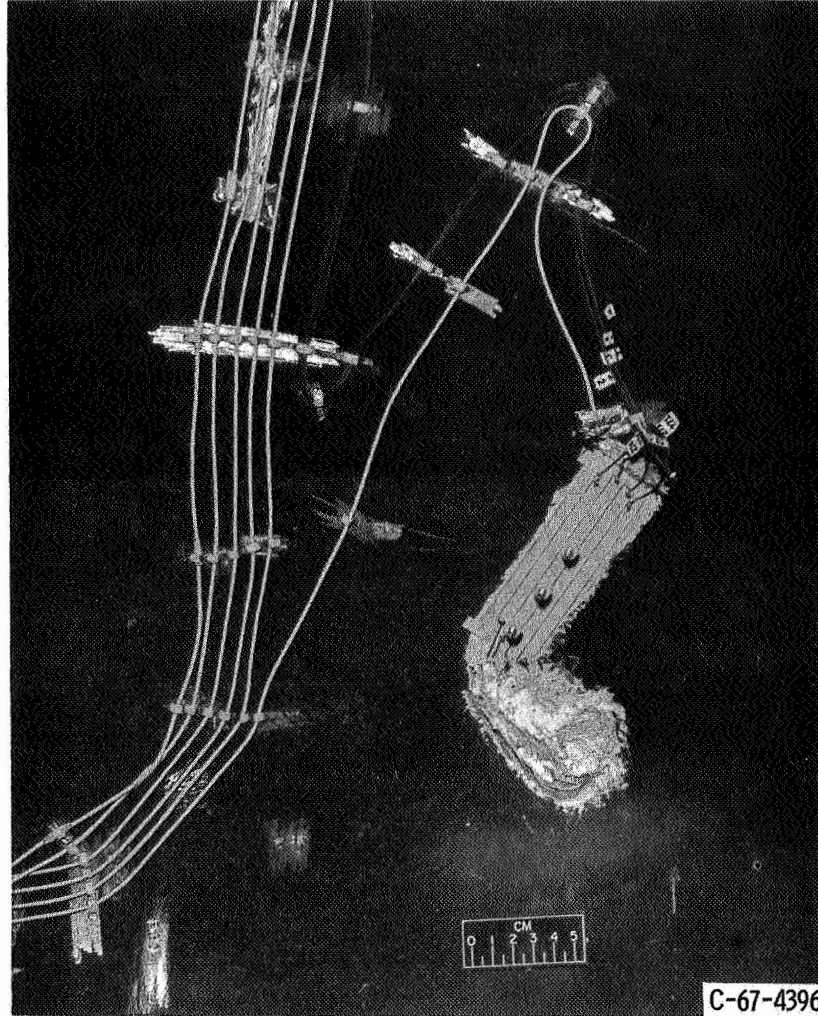


Figure 14. - Heat sink wire strapping, and high conductivity epoxy at typical resistor station in a space environment facility.

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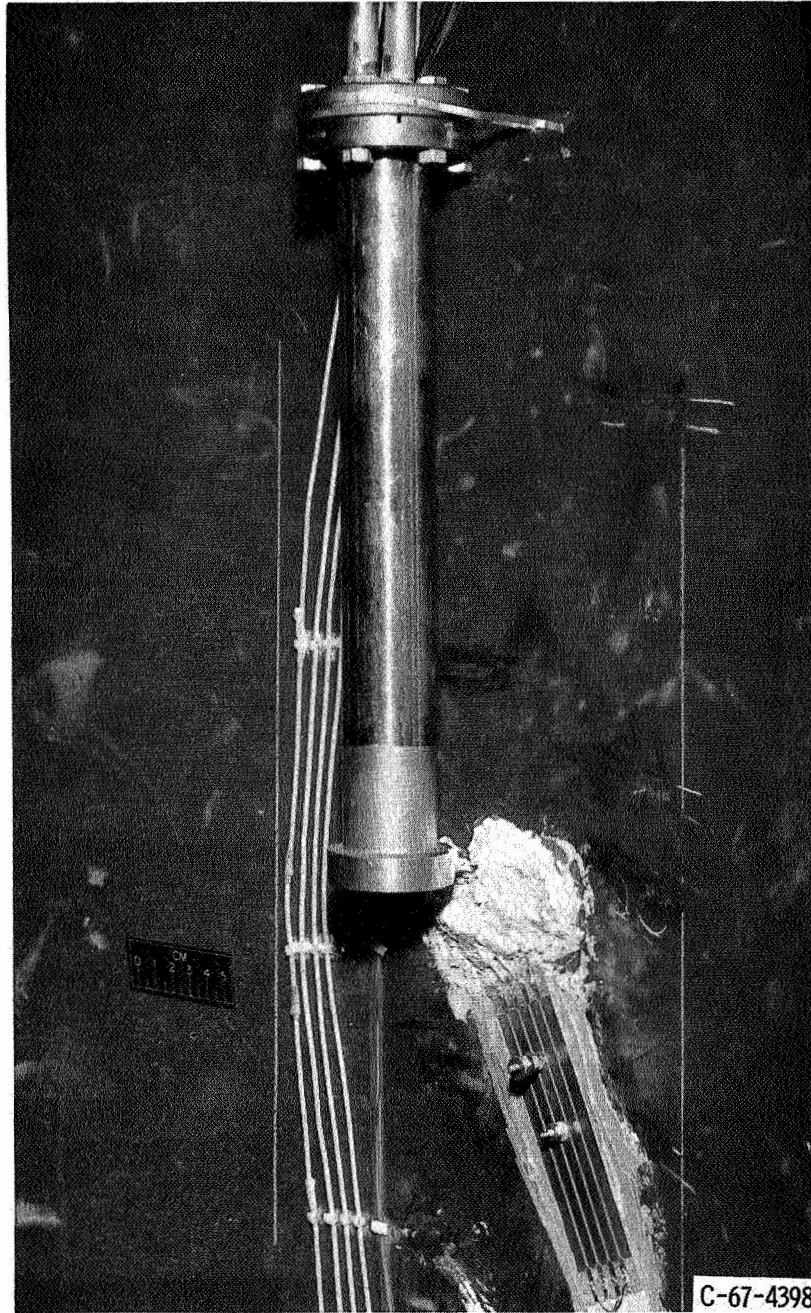


Figure 15. - Liquid helium reference cylinder.

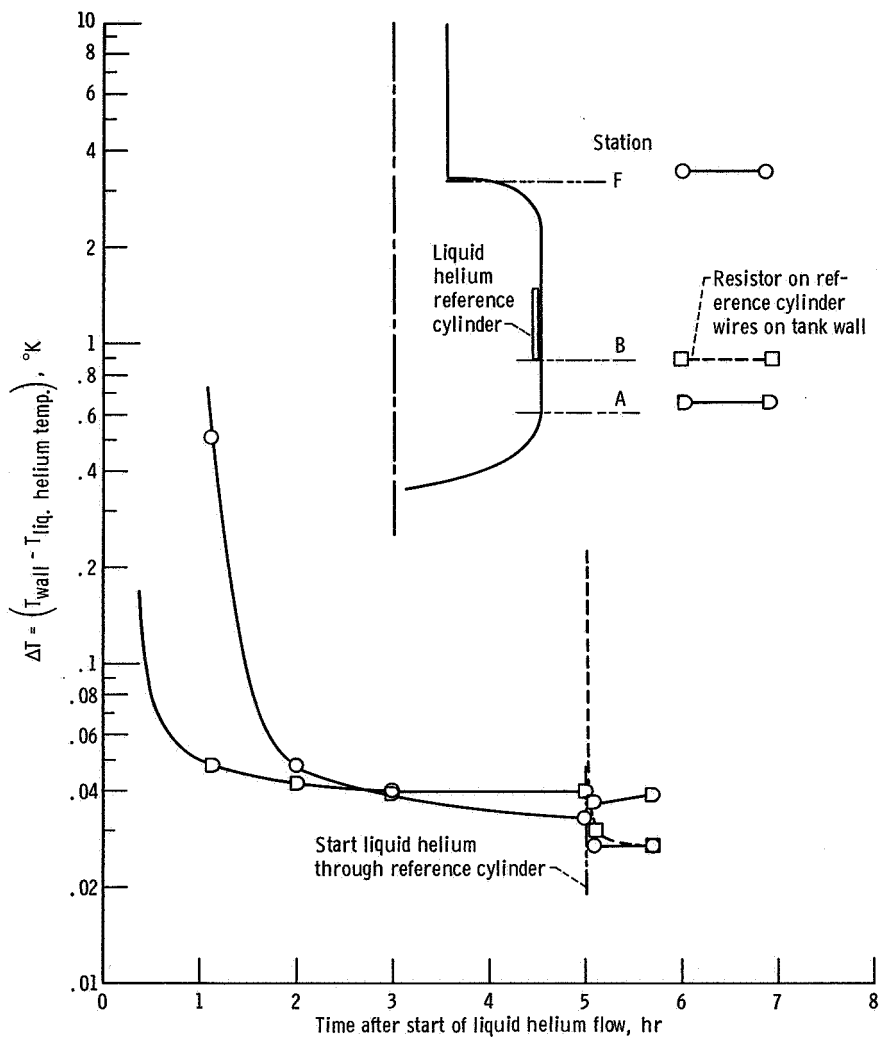


Figure 16. - Final effect of reducing vacuum contact resistance and lead wire conduction heat source on germanium resistor accuracy.