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AN EXPERIMENTAL STUDY USING HELIUM TO PRODUCE A CATASTROPHIC LOSS OF VACUUM IN A RHIC DIPOLE MAGNET CRYOSTAT

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ABSTRACT

A heat load of approximately 10 kilowatts was measured when the insulating vacuum of a RHIC dipole magnet operating at 4.5 K in MAGCOOL was spoiled by introduction of helium to the magnet cryostat. This heat input is more than 1000 times the heat load on the cryostat under good vacuum, but is less than the heat input when air was introduced in a previous experiment.[1] The response of the cryogenic system is very fast although slower than in the previous test with air. The heat transfer mechanism is different for air as compared to helium. When helium is introduced, the pressure in the insulating space increased rapidly causing the vacuum tank to become colder and the heat shield warmer as heat is transferred primarily by conduction. When air is introduced, the air initially is cryopumped on the cold surfaces and the pressure in the insulating space increases more slowly which inhibits the heat transfer by conduction between the vacuum envelope and the cold surface. The initial impact on the 4.5 K system by conduction through helium gas is less than that from condensation of air. However the heat conduction by helium gas eventually becomes larger than that by air. Because the maximum rate at which heat is introduced to the magnet is greater with air than helium, the relief system shall be sized for an air leak.

INTRODUCTION

A sudden loss of vacuum experiment using air was performed in October 1992. A heat load of approximately 20 kilowatts was reported.[1] In a continuing effort to understand the effect of loss of vacuum, a study was performed on RHIC dipole DRD-010 in MAGCOOL during which helium gas at ambient temperature was introduced into the insulating space.

As in the previous test, the RHIC magnet was cooled to 4.5 K and powered to 5000 Amperes prior to the introduction of helium. Since helium gas will not be cryopumped, a small amount of helium spoils the vacuum.

Parameters of the system including current through the magnet, insulating vacuum, pressures, temperatures and flow rates for the helium coolant, liquid levels in helium pots, temperatures on the vacuum tank and the heat shield were recorded as a function of time. The heat load was found to be about 10 kilowatts from the sum of heat into the magnet and the helium system, and heat removed by the MAGCOOL cold box and the helium vented from the cooling system. The results agree well with the rate of the vaporization of liquid in the helium pots.

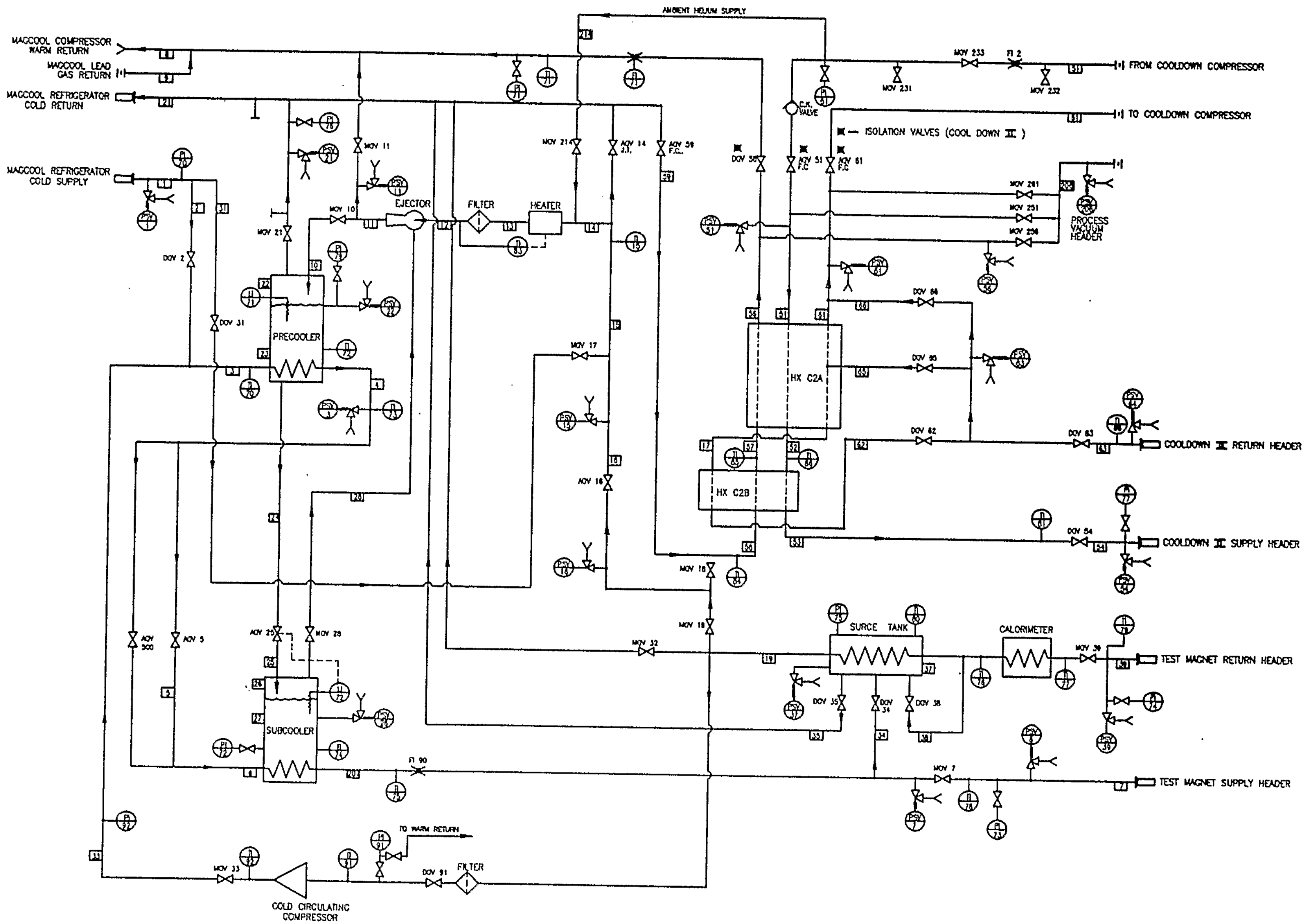

Fig. 1 MAGCOOL - test and measure flow schematic

SYSTEM DESCRIPTION

The cooling scheme for testing a RHIC magnet in MAGCOOL is shown in Fig. 1. A circulating compressor is used to circulate single phase helium in the cooling loop. Cooling is delivered from the precooler and subcooler liquid helium pots to the magnet.

The surge tank located on the return side of the MAGCOOL cold box is used for controlling cooling loop pressure. In the event that the loop pressure exceeds a predetermined value of 15 atmosphere, single phase helium will be vented, through valve 38, into the surge tank to prevent loop overpressure. Valve 35 is used to maintain surge tank pressure below a predetermined value by draining helium to the low pressure return line of the refrigerator.

The RHIC dipole magnet DRD-010 is installed in Bay D of MAGCOOL. A lead pot and a return can are installed at the ends of the magnet to connect electrical wiring, cryogenic piping and room temperature instrumentation. Cold helium flows from the MAGCOOL supply header through the lead pot can, the 4.5 K supply line inside the magnet cryostat, the return can, the magnet, the lead pot can and back to the MAGCOOL return header as shown in Fig. 2. Fig. 2 also shows the locations of dual temperature sensors at the inlet to and the outlet from DRD-010 and at the outlet from the lead pot.

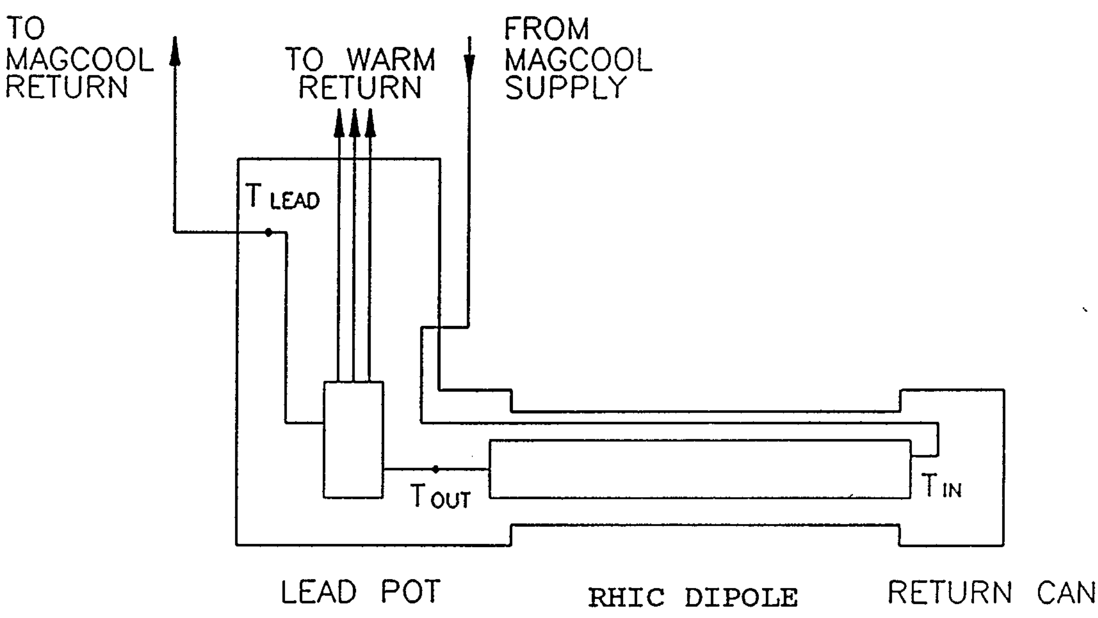

Fig. 2 Flow schematic and locations of temperature sensors for RHIC dipole

The insulating vacuum space for the RHIC dipole, the lead pot can and the return can are common. Its volume was previously determined to be 104 cubic feet from the earlier test of DRD-009. Ambient helium was introduced into the vacuum space through a 1/2 inch line with flow area restricted by three 1/4 inch lines with a total flow area of 0.53 cm^2. The reactions of the MAGCOOL cryogenic system were recorded for analysis.

Prior to the introduction of helium, DRD-010 was maintained at nominal operating conditions as shown in Fig. 3. In Fig. 3, there are three temperature sensors T16, T17 and T18 mounted on the surface of the vacuum tank from non-lead end to the lead end. There are three temperature sensors mounted on the heat shield. T11 is mounted on the liquid nitrogen pipe and T12 is mounted on 180 degrees from the pipe on the heat shield. Not shown in Fig. 3 is T13 which is mounted on the shield of the middle support leg. These six temperatures were used to estimate the heat input to the vacuum tank and to the shield.

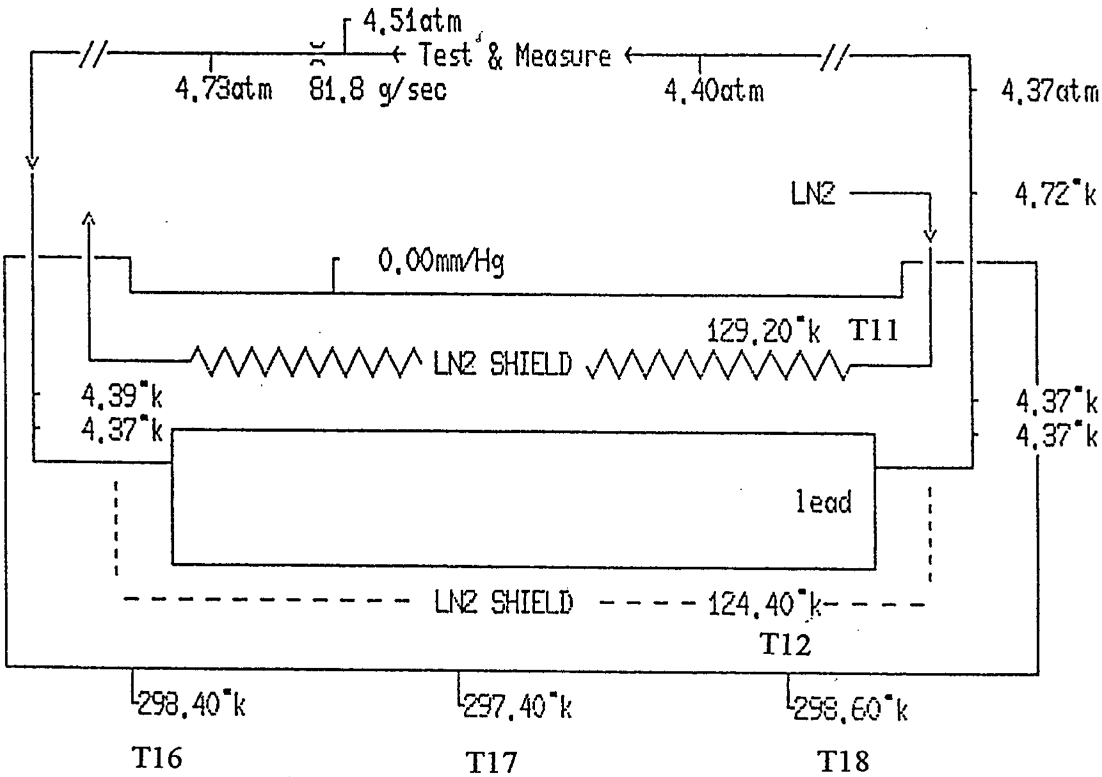

Fig. 3 Nominal operating conditions of RHIC dipole

PARAMETERS FOR RHIC DIPOLE

The cross sectional view of the RHIC dipole is given in Fig. 4. The carbon steel vacuum tank has a 24 inch O.D. with a 1/4 inch wall. The aluminum heat shield has a 21 inch O.D. and a nominal thickness of .090 inch on the cylindrical shell and .125 inch on the bottom flat section. The dipole magnet consists mainly of superconducting coils and an iron yoke in an 11-inch diameter stainless steel helium containment vessel. Fifteen layers of superinsulation are initially installed around the dipole helium vessel and an additional 30 layers of superinsulation are then wrapped around both the 4.5 K lines and the dipole vessel making the total number of layers of superinsulation between the heat shield and the magnet equal to 45. Sixty layers of superinsulation are finally installed between the vacuum tank and the heat shield.

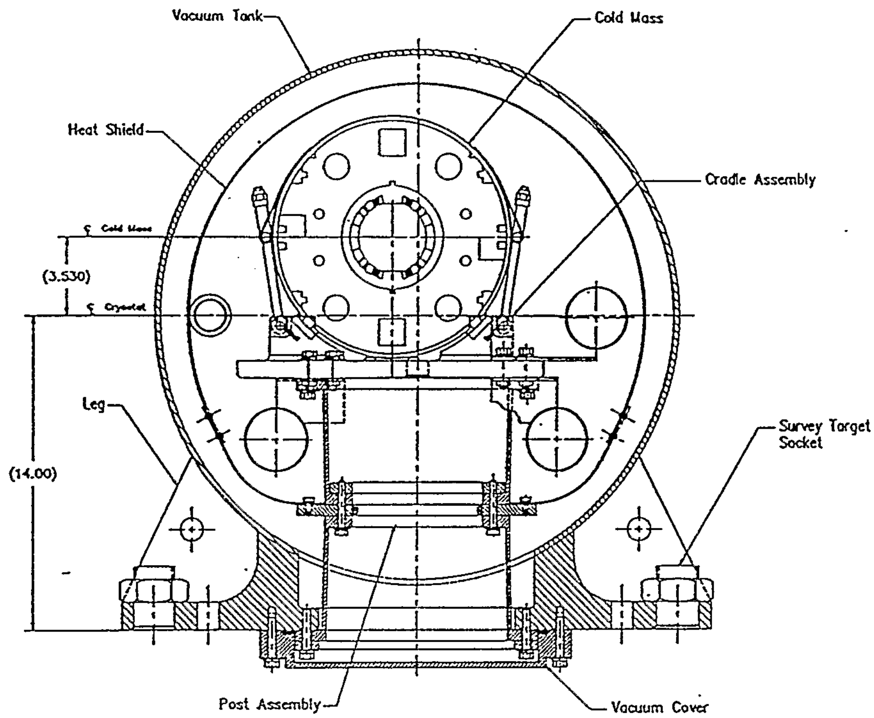

Fig. 4 Sectional view of RHIC dipole magnet

The weight, the surface area, the specific heat and the thermal capacity of the vacuum tank and the heat shield for the RHIC dipole test system which includes the lead pot and return can are given in Table 1.

Table 1 Parameters of the vacuum tank and heat shield

	Weight kg	Surface area m^2	Temperature K	Specific heat J/g-K	Thermal capacity kJ/K
Vacuum tank	1260	25.5	290	0.44	554
Heat shield	145	21.1	90	0.422	61
			160	0.713	103

The weight of the dipole cold mass is 3600 kilograms. The specific heat of the iron yoke as a function of temperature below 80 K is shown in Table 2. The enthalpy and the thermal mass of the dipole are also given in Table 2. The surface areas are 8.4 m^2 for the helium containment vessel and 3.5 m^2 for the four helium cooling passages in the magnet yoke. The 2 1/2 inch diameter supply line in the cryostat is approximately 12 meters long. The thermal mass of the supply line is insignificant but the surface area equals to 2.6 m^2. There are two caps, with a total surface area of 0.6 m^2, attached to the ends of dipole for magnet test purposes. The total surface area that is exposed to single phase helium is 6.7 m^2. The total surface area for the helium containment vessel and the supply line equals to 11.6 m^2. These surface areas will be used in the heat flux calculation.

Table 2 Specific heat, enthalpy and thermal mass of the RHIC dipole

Temperature K	Specific heat J/g-K	Enthalpy J/g	Thermal mass kJ/K
4	.000382	.000742	1.4
10	.00124	.00537	4.5
20	.0045	.0316	16.2
40	.029	.31	104
80	.154	3.83	554

The volume for single phase helium in the cooling loop is 210 liters and the surge tank has a 900 liter volume. The total mass of helium prior to the vacuum failure is 150 kilograms.

MAGNET RESPONSE AND INSULATING VACUUM

Prior to the introduction of helium into the vacuum space, the magnet current was raised to 5000 amperes at which value 350 kilojoules of energy are stored in the magnetic field. Helium gas was then introduced into the insulating vacuum space until the pressure in the space reached 15 psia. Seconds after the helium flow was started, DRD-010 quenched and the current decreasing rapidly to zero as shown in Fig. 5. The exact time delay, however, is not known.

Rather than rising to atmospheric pressure instantaneously as the flow of helium proceeded, the insulating vacuum pressure increased linearly with time as shown in Fig. 6. It took about 17 minutes for the pressure in the insulating vacuum to reach 15 psia. After 17 minutes, the helium flow reversed direction and began venting from the insulating vacuum space. A total of 105 ft^3 of helium was found to have vented from the insulating vacuum space after the system was warmed to ambient temperature. The volume of helium entering the insulating vacuum volume was greater than this volume, because the entering helium became cold.

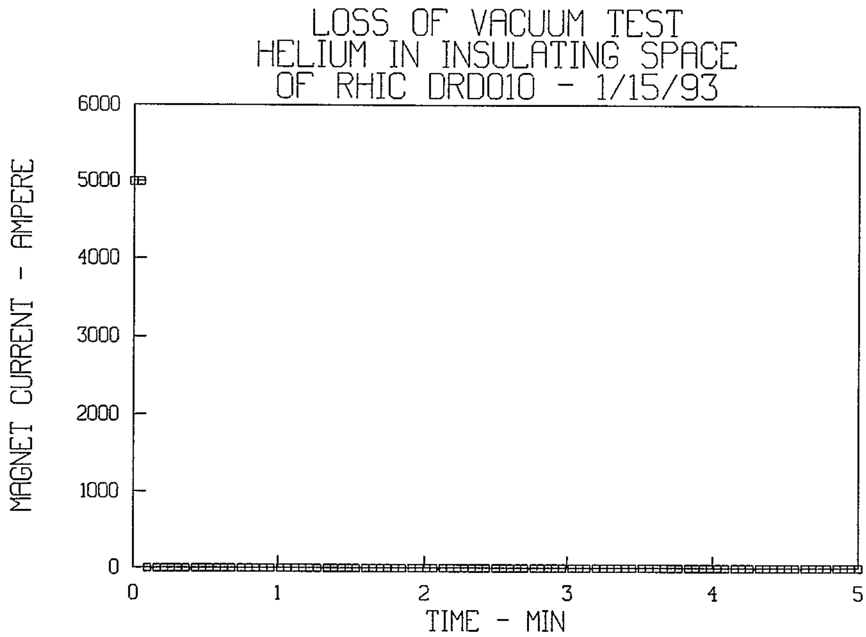

Fig. 5 Current as a function of time after helium is introduced to the insulating vacuum

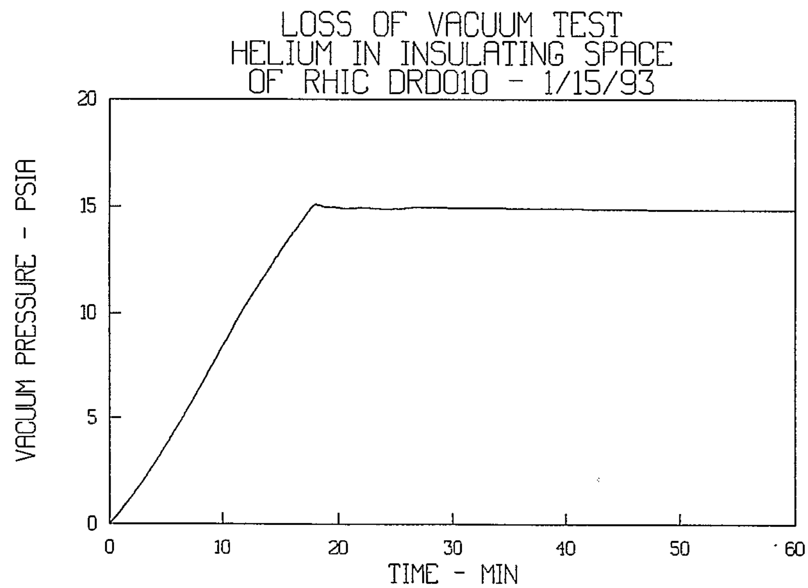

Fig.6 Insulating vacuum of RHIC DRD-010 after helium is introduced to the insulating vacuum

PRESSURE, TEMPERATURE AND FLOW RATE IN THE HELIUM COOLING LOOP

The pressure, temperature and flow rate in the helium cooling loop are essential in calculating the cooling provided by the MAGCOOL cold box. The pressure rise rate and the helium venting rate are important to the design of the relief system for the magnet helium containment. These results will be given below.

The cooling loop pressure as a function of time is given in Fig. 7. As can been seen, the loop pressure increased quickly from 5 to 15 atmosphere in 40 seconds as compared to the 70 second rise time after a magnet quench and 20 second rise time for the air condensation test observed in previous investigation.[2,1] Vent valve 38 opened to release helium from the cooling loop into the cold surge tank. Vent valve 35 opened to release helium from the surge tank to the low pressure return. This venting process continued for about 25 minutes. The loop pressure then declined slowly to 5 atm.

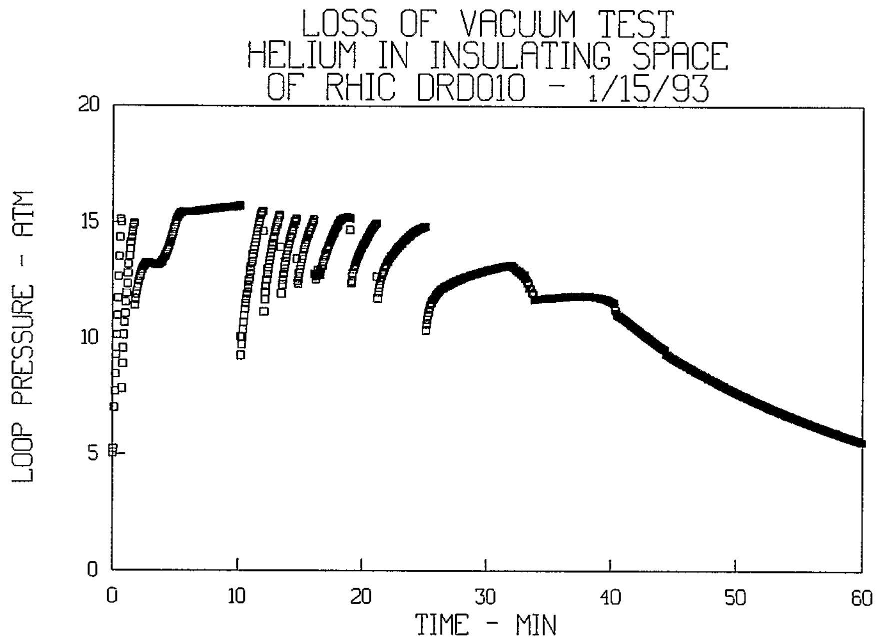

Fig. 7 Loop pressure as a function of time after helium is introduced to the insulating vacuum

Temperatures recorded at the inlet of the magnet, the outlet of the magnet and the lead pot are given in Fig. 8. Unlike the loss of vacuum due to air during which these temperature reached 20 K in less than 2 minutes, it took more than 10 minutes for these temperatures to increase from 4.3 K to 20 K. This suggests the initial heat load due to conduction through helium gas is much smaller than that due to condensation of air on the cold surfaces. From 20 K on, the magnet temperature increases linearly with time. In 60 minutes, the magnet temperature reached approximately 90 K at a rate of 1.5 K degrees per minute.

In Fig. 8, the inlet temperature is not always lower than the outlet temperature because the inlet sensor is located at the connection of the 4.5 K supply line to the magnet which could be warmed faster than the magnet because of its low thermal mass. This inlet temperature was not used for the heat input calculation. The outlet temperature was used as the mean temperature of the magnet.

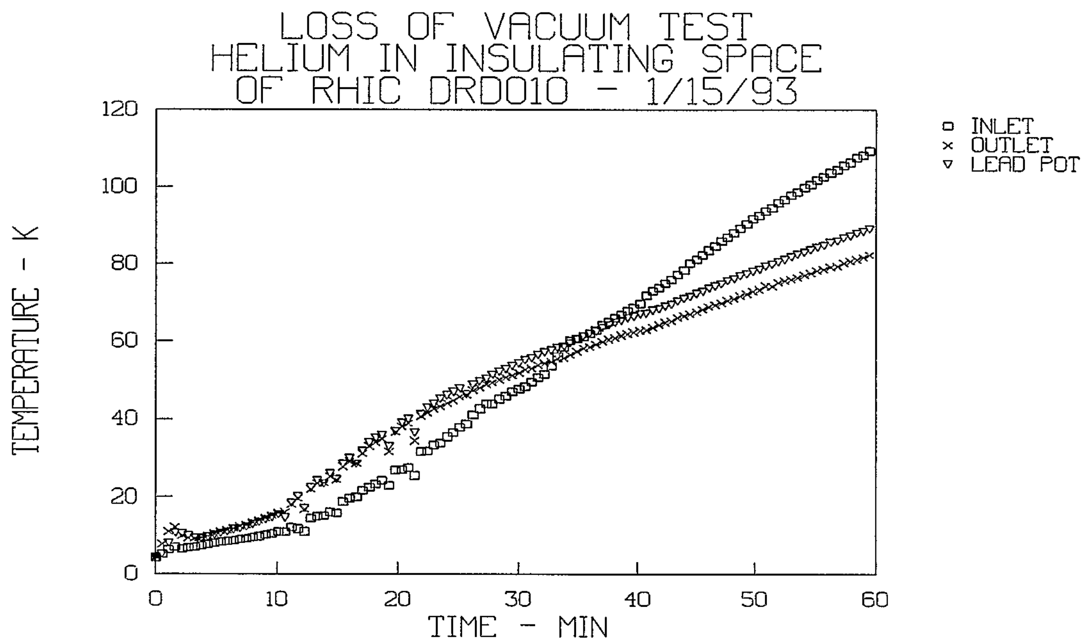

Fig. 8 Temperatures at the inlet of the magnet, the outlet of the magnet and the outlet of the lead pot after helium is introduced to the insulating vacuum

Temperatures recorded at the supply from and the return to the MAGCOOL cold box and at the surge tank as a function of time are given in Fig. 9. As seen, the temperature at the return line increased immediately after helium was introduced to the vacuum space. The supply temperature and the tank temperature increased more slowly than the return temperature because there was a substantial cooling reserve in the two liquid helium pots and the surge tank.

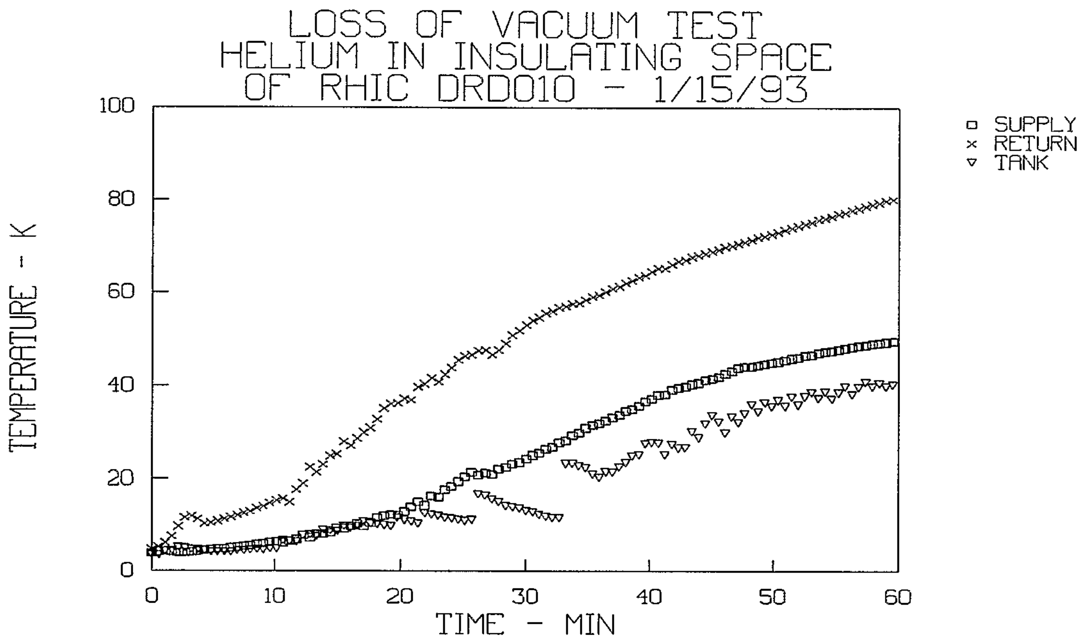

Fig. 9 Temperatures at the supply, the return and the surge tank in the cold box after helium is introduced to the insulating vacuum

The mass flow rate in the cooling loop was used in the heat balance calculation and is given in Fig. 10. Generally speaking, the mass flow rate decreases with time because the helium density decreases quickly as the loop is warmed.

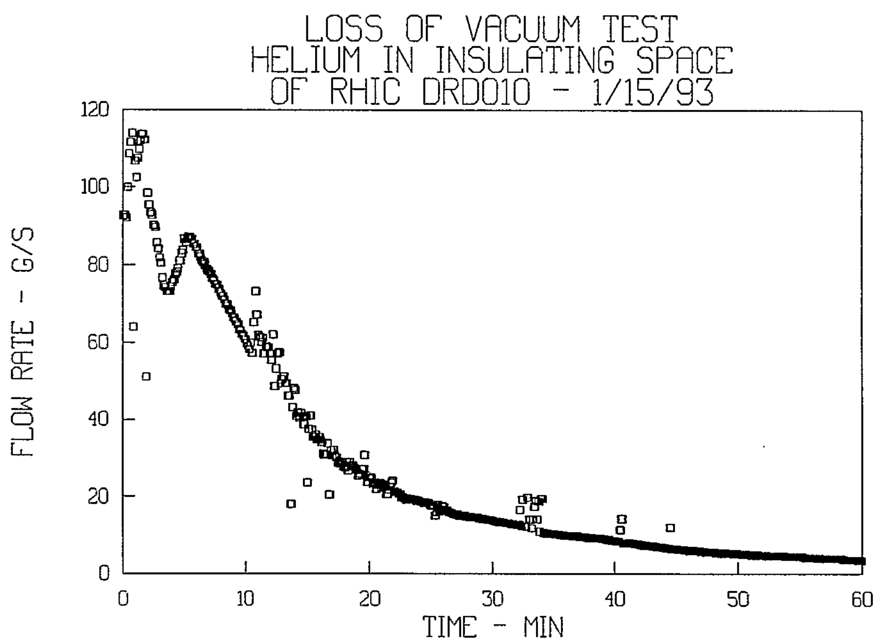

Fig. 10 Loop flow rate after helium is introduced to the insulating vacuum

HEAT INPUT ANALYSIS

The total heat input to the system can be accounted for as 1). heat absorbed by the magnet, 2). heat absorbed by the helium coolant, 3). heat removed by the MAGCOOL cold box and 4). heat carried away by the vented helium.

The heat absorbed by the magnet is equal to the change in enthalpy of the iron yoke. Since there are no temperature sensors installed on the magnet, the helium temperature at the outlet of the magnet is used to determine the change in enthalpy. This method probably will underestimate the heat absorbed by the iron as the surface temperature of the magnet is probably higher than the outlet temperature.

The amount of heat absorbed by the helium coolant is equal to the change of internal energy of the helium. The total mass of single phase helium consists of that in the loop and that in the cold surge tank. In the present study, a uniform temperature is assumed for the surge tank and a temperature distribution consisting of eleven segments is assumed for the cooling loop. The density and the internal energy of helium in each segment are calculated from pressure and averaged temperature in each segment and then summed over the segments.

The amount of heat removed by the MAGCOOL cold box is obtained from the integration of the apparent cooling rate defined as the mass flow rate multiplied by the enthalpy rise of the helium between the supply and the return lines at the box.

The amount of heat carried away by the vented helium is calculated from the amount of helium vented multiplied by the enthalpy of helium in the surge tank.

The amount of heat input absorbed by the magnet, absorbed by the single phase helium, removed by the MAGCOOL cold box, carried away by the vented helium, and their sum are given in Fig. 11.

As can be seen, the initial heat input rate is relatively low. Ten minutes elapsed before the heat input reached the level of 2500 kilojoules, yielding an average rate of 4.6 kilo-watts. The heating rate after this period increased to a constant value suggesting a conduction mode heat transfer. The total heat input then is in direct proportion to time. The average heating rate as a function of time is given in Table 3.

The amount of helium entering the vacuum space was found to be about 210 cubic foot at standard conditions and has a 1 kilogram mass. Cooling this mass of helium from ambient temperature to 150 K corresponds to 800 kilojoules heat load which is small compared to the total heat load on the system.

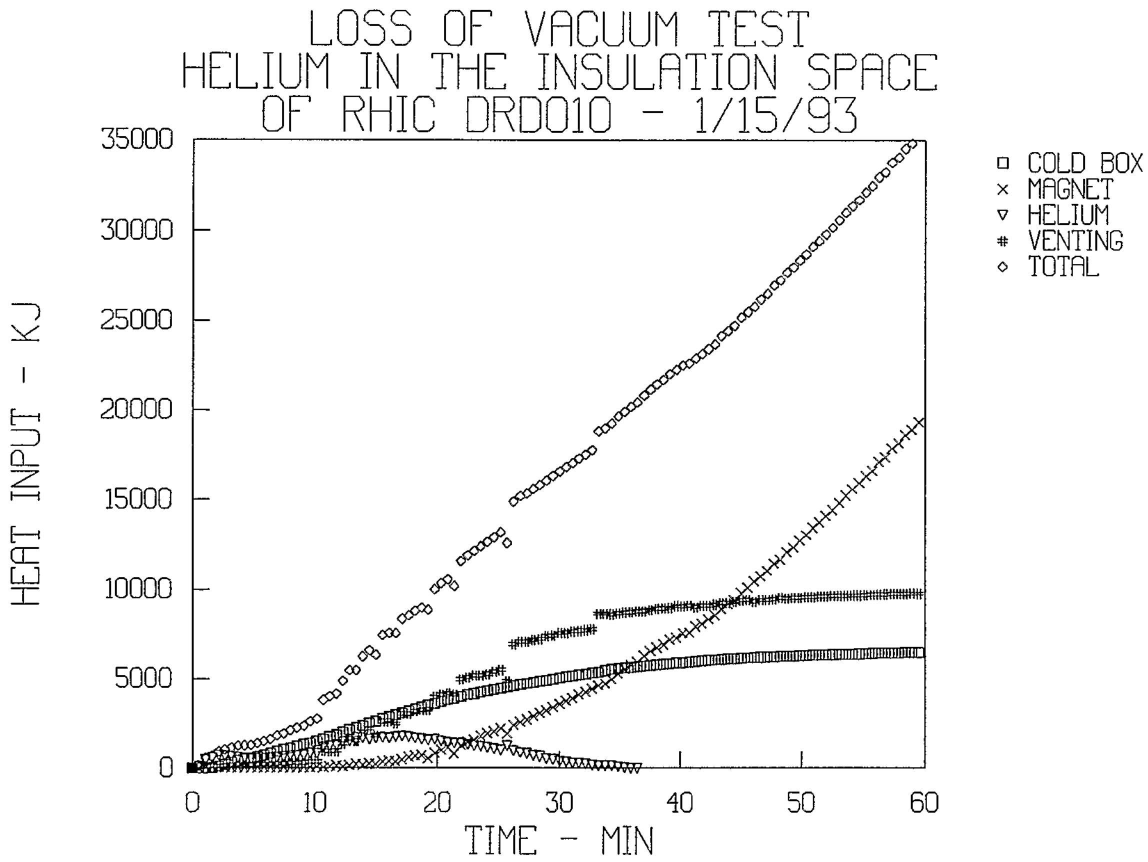

Fig. 11 Heat input to the helium system

Table 3. Average heating rate

Time period min	Magnet temperature K	Heating rate kW
0-10	4.3 - 15	4.6
10-20	15 - 38	12.3
20-30	38 - 54	10.7
30-40	54 - 67	9.7
40-50	67 - 78	10.2
50-60	78 - 90	11.8

LIQUID HELIUM LEVELS IN THE POTS

Since the present test involves a very large heat input over a very short period of time, it is very difficult to accurately calculate the heat input. The rate of vaporization of liquid helium in the precooler and the subcooler helium pots presented in Fig. 12 is used as an independent check on heat input calculation.

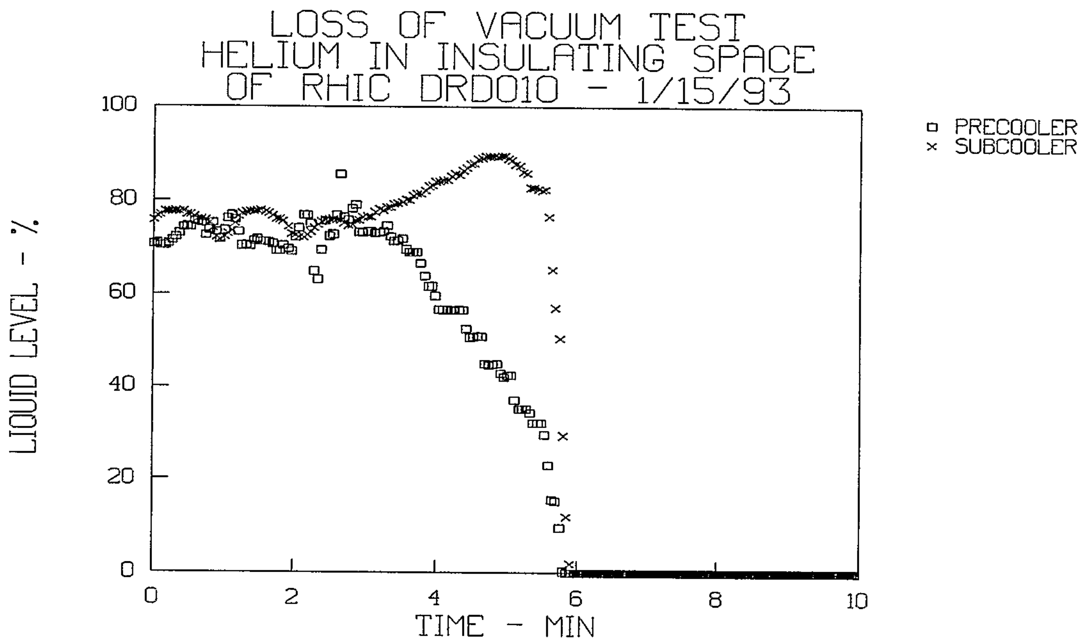

Fig. 12 Liquid level in helium pots after helium is introduced to the insulating vacuum

As seen from Fig. 12, the liquid levels were not effected for almost four minutes after helium was introduced to the insulating vacuum because the heat input has not yet been carried back in the circulating loop to the liquid helium pots. As soon as the heat reached the pots, liquid helium in the precooler vaporized quickly followed by that in the subcooler. The liquid helium stored in both the precooler and the subcooler was vaporized in about 6 minutes. This rate is about three times slower than the 2 minute rate for the air test. The rate of vaporization in this case is estimated at 2 liters per second, the equivalent of 5 kilowatts power input.

MASS OF HELIUM IN THE COOLING LOOP

As a consequence of helium flowing into the vacuum tank, the loop pressure and temperature increase and helium is vented from the cooling loop. The amount of helium vented and the venting rate are given below.

The total amount of single phase helium in the system consists of that in the loop and that in the cold surge tank. The surge tank is assumed to have uniform temperature whereas the cooling loop, for purpose of calculation, is divided into eleven segments with temperatures measured at the inlet and outlet of each segment. The density of helium is calculated from the pressure and average temperature in each segment. The total helium mass is obtained by summing the mass in the segments which are calculated from the density of the helium in and volume of each segment. The total helium mass is plotted in Fig. 13 as a function of time.

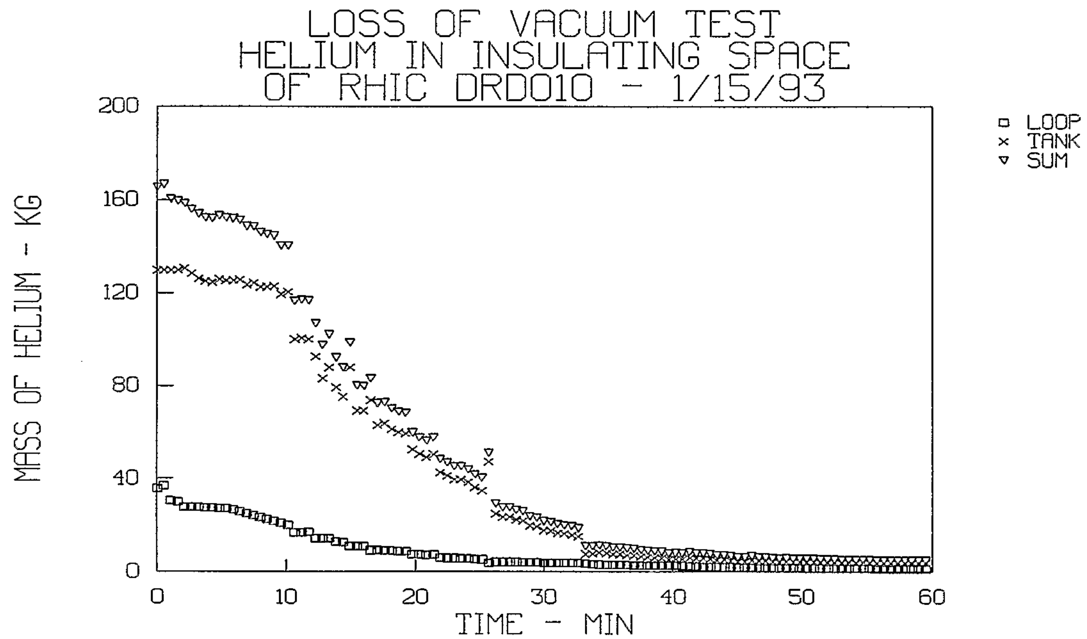

Fig. 13 Mass of helium in the system

In the first minute, about 3.7 kilograms of the 36 kilograms of single phase helium in the loop is vented corresponding to a venting rate of 62 g/s. Over a ten minute period, 24 kilograms of the 165 kilograms of helium in the cooling loop and surge tank vented corresponding to a 40 g/s venting rate. Between ten and thirty minutes, the venting of helium is controlled manually and corresponds to a higher rate of 80 g/s.

TEMPERATURES OF THE VACUUM TANK AND THE HEAT SHIELD

The heat transfer process is very complicated because the RHIC dipole in this test has a liquid nitrogen heat shield and a cold supply line at liquid helium temperature. Heat transfer occurs between the magnet, the shield and the cold line, and between the shield and the vacuum tank. The heat transfer to the shield and the vacuum tank are estimated based on the rates of change of temperature of these components.

As shown in Fig. 3, T16, T17 and T18 are temperature sensors located on the surface of the vacuum tank. T11, T12 and T13 are sensors located on the heat shield. Prior to the loss of vacuum, the magnet is maintained at 4.5 K by single phase helium. The shield is maintained at about 100 K by liquid nitrogen. The vacuum tank is at the ambient temperature of 297 K. For safety reasons, three fans were used to blow ambient air around the vacuum tank to prevent the tank from being cooled to a temperature at which the tank material might become brittle.

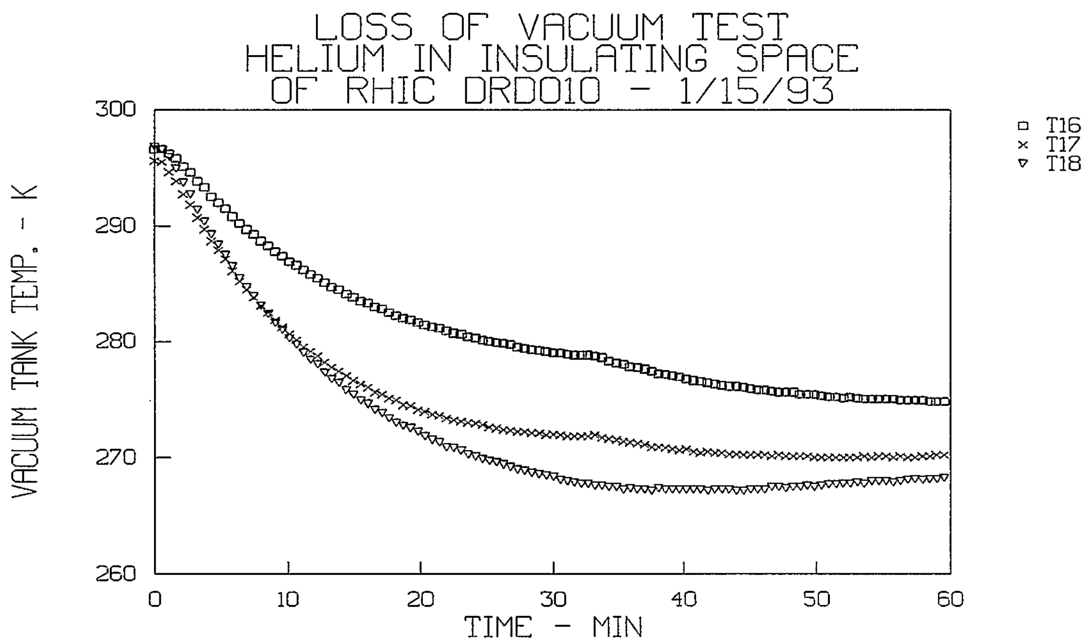

Fig. 14 Temperature of the vacuum tank after helium is introduced to the insulating vacuum

The surface temperature of the vacuum tank as a function of time, after helium was introduced into the insulating vacuum space, is given in Fig. 14. As seen, the temperatures at T16, T17 and T18, track each other and decrease quickly at a rate of approximately 1.5 K degrees per minute for 20 minutes and then stabilize at about 270 K. Neglecting the heat transfer from the surrounding air, the heat input from the vacuum tank to the cryostat is almost 13 kilowatts for the initial 20 minutes. This process is very different than that for the air leak in which the cold magnet system is capable of maintaining a good insulating vacuum until the cryopumping capacity is exhausted. The 13 kilowatts yields an order of magnitude estimate of the heat conduction between the heat shield and the vacuum tank.

The heat shield temperature also changes quickly. As shown in Fig. 15, the temperature of the heat shield increases from 100 K to approximately 150 K in about 10 minutes. During this period, the liquid nitrogen flow rate is not known. In the MAGCOOL system, the liquid nitrogen supply valve remains closed until the temperature at the exit of the shield reached 130K. Therefore, for the first 5 minutes or so, heat deposited on the shield will be mainly absorbed by the thermal mass of the aluminum shield. Assuming the average thermal capacity of the shield equals 80 kilojoule/K, the heat input to the shield equals to 6.7 kilowatts. If the heat input due to warm helium is neglected, then the heat into the 4 K system would be the difference between 13 kilowatts and 6.7 kilowatts.

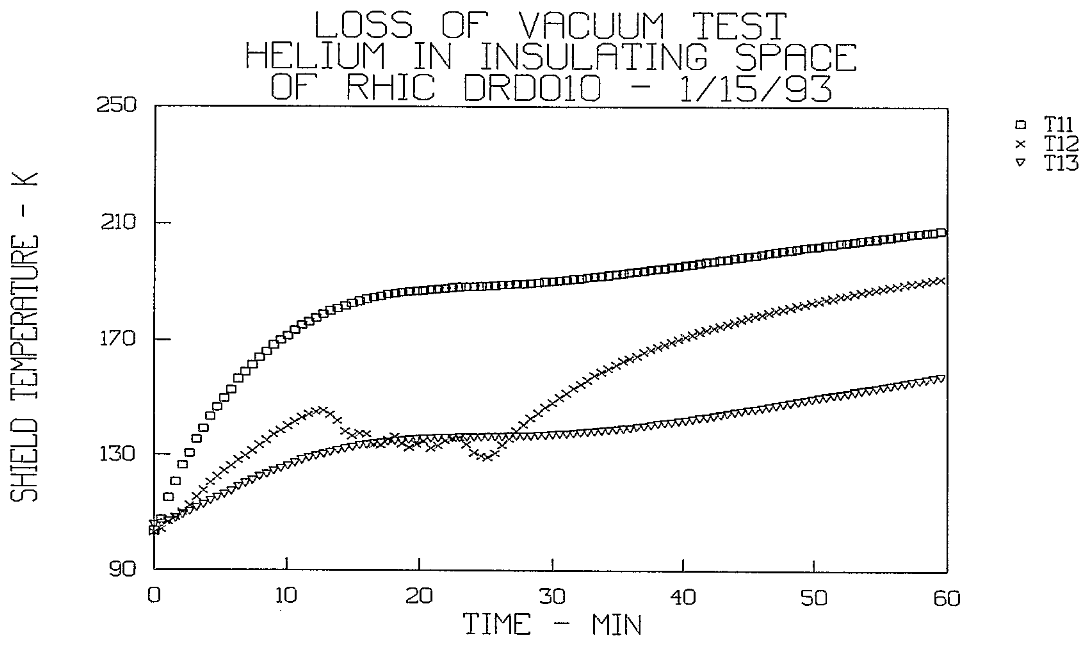

Fig. 15 Temperature of the heat shield after helium is introduced to the insulating vacuum

CONCLUSION

A test was performed in MAGCOOL investigating the consequences of the loss of vacuum due to a helium leak using RHIC DRD-010. The heat input to the system was calculated from the heat absorbed by the magnet and the helium coolant, removed by the MAGCOOL cold box, and by the helium vented. The heat input is very large when the vacuum deteriorates, but the 10 kilowatt heat input for the present study with helium is less than the 20 kilowatt heat load due to a large air leak. The relief valve shall therefore be sized to accommodate the loss of vacuum due to air.

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