BNL-101832-2014-TECH

AD/RHIC/RD/50;BNL-101832-2013-IR

An Experimental Study of Catastrophic Loss of Vacuum for RHIC DRD-009 in MAGCOOL

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December 1992

Collider Accelerator Department

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U.S. Department of Energy

USDOE Office of Science (SC)

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RHIC PROJECT

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An Experimental Study of Catastrophic Loss of Vacuum for RHIC DRD-009 MAGCOOL

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ABSTRACT

A heat load on the order of 20 kilowatts, 0.17 watt/cm^2, was identified for the loss of vacuum experiment of RHIC dipole magnet DRD-009 in MAGCOOL. In response to this enormous heat load, the pressure and the temperature increase quickly. In approximately three minutes, 50% of the single phase cooling helium was vented to prevent the helium containment from over pressured. In twenty minutes, the magnet was heated to 70 K. Since the majority of heat load comes from condensation of air on the surface of the magnet, the heat load reduces to a lower value when the magnet is above 77 K. Unlike a magnet quench, the impact from loss of vacuum to the helium cryogenic system is cumulative and non-recoverable. However the impact to the vacuum tank and to the heat shield from air entering the vacuum are relatively mild.

INTRODUCTION

One of the worst accidents that could occur in a helium cryogenic system is the sudden loss of vacuum. Accidental structure failure due to a ruptured pipe or cryostat causes a large quantity of air to flow into the vacuum space. Condensation of air on the cold surface combined with pressure increase in the insulating vacuum lead to a heat load several orders of magnitude larger than normal. As a result, the pressure and temperature for the cryogen increase rapidly. Adequate relief system must be provided to prevent the pressure build up.

For the RHIC cryogenic system, the problem is further complicated by the subsequent quench of the superconducting magnets which leads to an even higher pressure rise rate. In order to understand the response of the cryogenic system to the loss of vacuum, a test was performed on the MAGCOOL magnet test facility.

RHIC magnet DRD-009 was cooled to 4.5 K operating temperature and powered to the 5000 Ampere design current. Ambient air is introduced into the vacuum space through a 3/4 inch line, 2.85 cm^2 cross sectional area, to simulate the accident. Current through the magnet, insulating vacuum, pressures, temperatures and flow rate for the cooling helium, liquid level in helium pots, temperatures on the vacuum tank and on the heat shield were recorded as a function of time. The heat load was found to be on the order of 20 kilowatt based on estimation from 1). the sum of heat into the magnet and the helium system and heat removed by the MAGCOOL cold box and the vented helium, 2). the vaporization of liquid helium, and 3). the air flow through a 3/4 inch orifice.

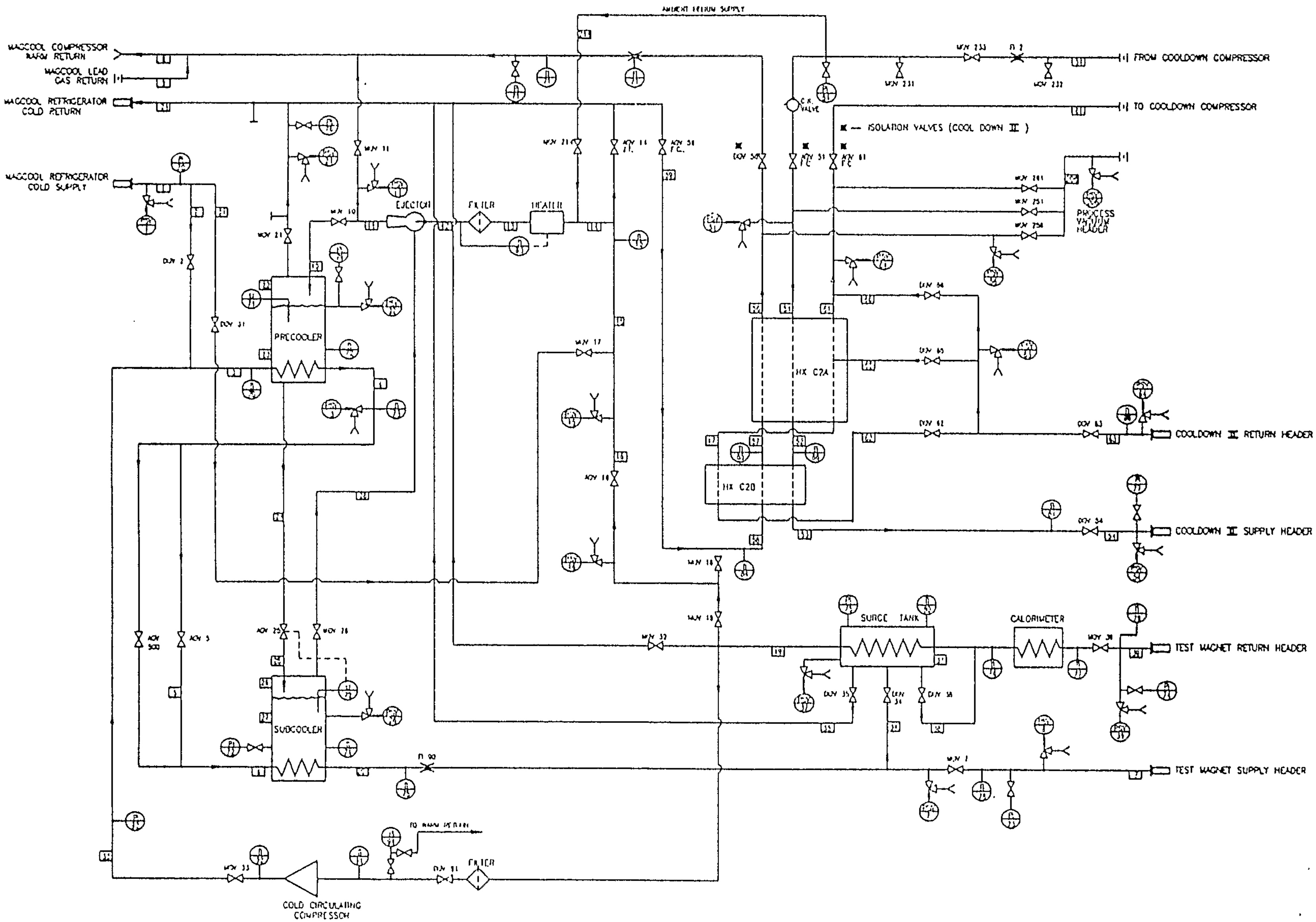

Fig. 1 MAGCOOL - test and measure flow schematic

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, single phase helium will be vented, through valve 38, into the surge tank to prevent the loop from over pressurized. 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 DRD-009 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-009 and at the outlet from the lead pot.

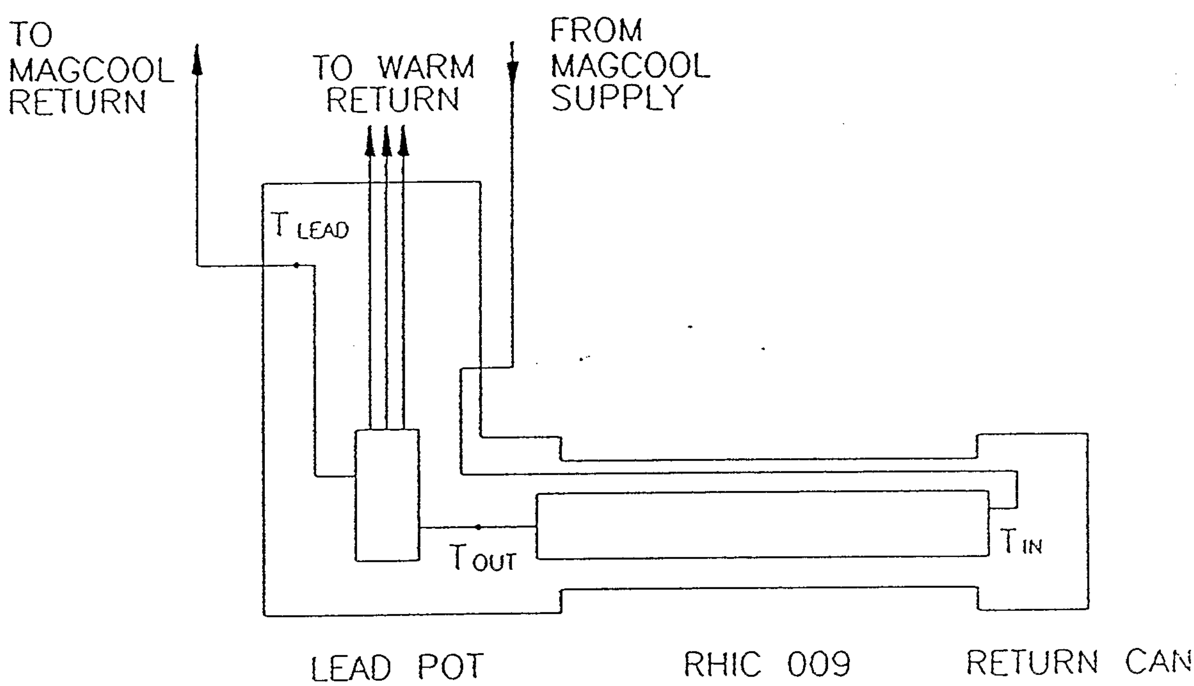

Fig. 2 Flow schematic and locations of temperature sensors for DRD-009

The insulating vacuum space for DRD-009, the lead pot can and the return can are common. Its volume was found to be 104 cubic feet from a vacuum gage measurement. Ambient air was introduced into the vacuum space through a 3/4 inch penetration on the lead pot can to simulate the maximum credible vacuum failure in RHIC. The reactions of the MAGCOOL cryogenic system were recorded for investigation.

Prior to the introduction of air, DRD-009 was maintained at a nominal operating condition 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 the opposite side of the heat shield. Not shown in Fig. 3 is T13 which is mounted on the shield of the middle support leg. These six temperatures will be used to estimate the heat input to the vacuum tank and to the shield.

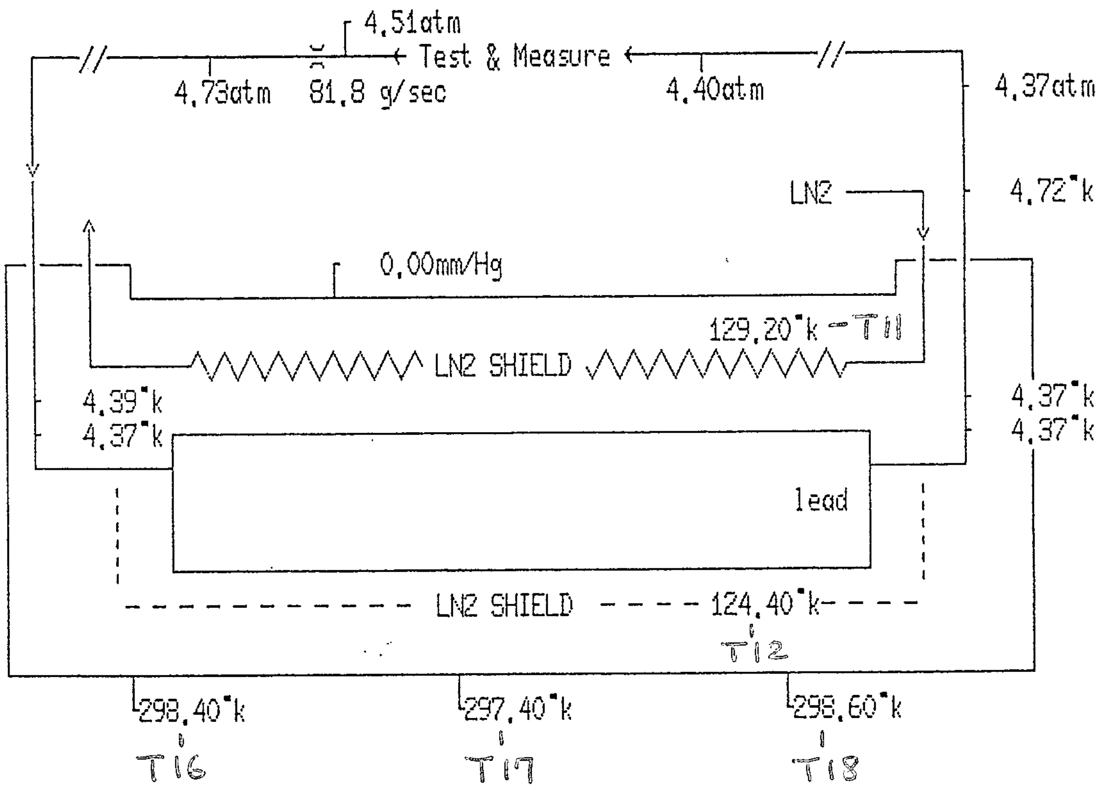

Fig. 3 Nominal operating conditions of DRD-009

PARAMETERS FOR RHIC DIPOLE

The cross sectional view of the RHIC dipole is given in Fig. 4. The carbon steel vacuum tank is 24 inch O.D. with a 1/4 inch wall. The aluminum heat shield is 21 inch O.D. with a nominal thickness of .090 inch on the cylindrical shell and .125 inch on the bottom flat portion. The dipole magnet consists mainly of superconducting coil and iron yoke in an 11 inch stainless steel helium containment vessel. Sixty layers of superinsulation were installed between the vacuum tank and the heat shield. Fifteen layers of superinsulation was installed around the dipole. In addition, 30 layers of superinsulation was wrapped around the 4.5 K line and the dipole. Total layers of superinsulation between the heat shield and the magnet equals to 45.

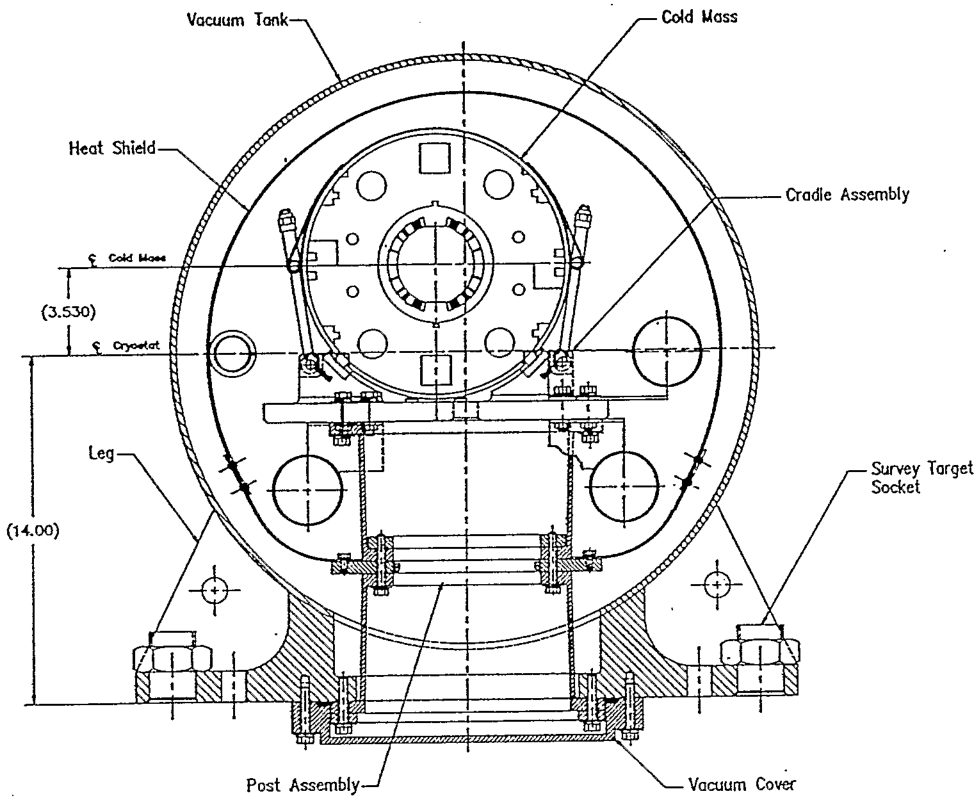

Fig. 4 Sectional view of RHIC dipole magnet

The weight, the surface area, the specific heat and the thermal capacity for the vacuum tank and for the heat shield for DRD-009 including lead pot and return can are given in Table 1.

Table 1 Parameters of the vacuum tank and heat shield

	Weight	Surface area	Temper-ature	Specific heat	Thermal capacity
	kg	m^2	K	J/g-K	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 for the dipole cold mass is 3600 kilogram. The specific heat of the iron yoke as a function of temperature below 80 K are shown in Table 2. The enthalpy and the thermal mass of the dipole are also given in Table 2. The surface area are 8.4 m^2 for the helium containment vessel and 3.5 m^2 for the four helium cooling passages. The 2 1/2 inch supply line in the cryostat is approximately 12 meters long. The thermal mass for the supply line is insignificant but the surface area equals to 2.6 m^2. There are two caps, with a surface area of 0.6 m^2, attached on the ends of dipole for magnet test purpose. Total surface area that exposes to single phase helium is 6.7 m^2. 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 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 the single phase helium in the cooling loop is 210 liters and the surge tank has a 900 liter volume. Total helium prior to the vacuum failure is 150 kilogram.

AIR FLOW, MAGNET RESPONSES AND HEAT TRANSFER

Prior to the introduction of air into the vacuum space, the magnet current was powered to 5000 amperes with 350 kilojoules stored energy in the magnetic field. Ambient air flowed into the insulating vacuum through a 3/4 inch penetration at sonic speed. Seconds after air was introduced, DRD-009 quenched and the current became zero as shown in Fig. 5. The exact time lag, however, was not known.

A large volume of air flowed into the vacuum space at sonic velocity. The intake volume of air was many times the volume of the vacuum space, but pressure in the insulating vacuum did not reach ambient pressure instantaneously because the intake air was quickly condensed on the cold surface of the magnet. The insulating vacuum increased slowly with time as shown in Fig. 6. It took about 10 minutes for the insulating vacuum to reach 90 mm Hg, i.e., 0.12 atm. In about 20 minutes, the vacuum reached 280 mm Hg. After 20 minutes, the vacuum was above the full scale of the pressure gage. Based on the extrapolation of Fig. 6, the insulating vacuum would reach 1 atmosphere in 30 minutes.

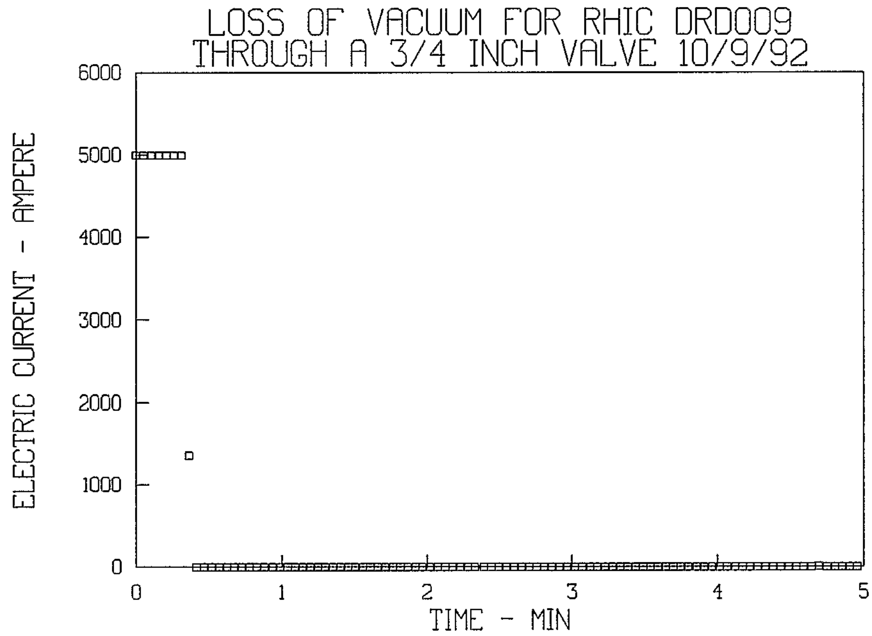

Fig. 5 Current as a function of time after air is introduced

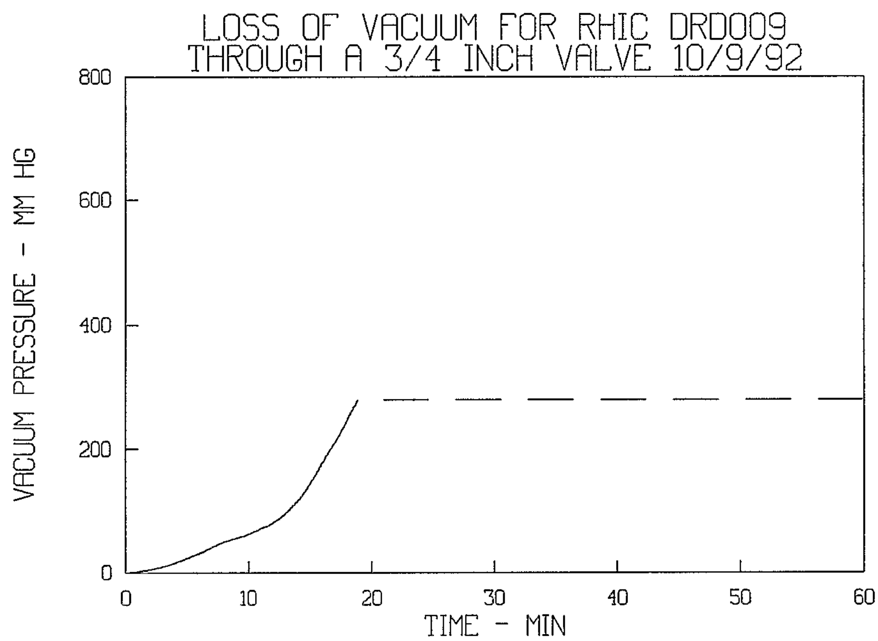

Fig. 6 Insulating vacuum of RHIC DRD-009 after air is introduced

The maximum air flow through a 3/4 inch orifice with upstream pressure at 1 atm and downstream pressure less than 0.5 atm is 57 liter/sec or 120 ft^3/min. Actual air flow in the present study is less than the maximum flow due to restrictions from both the upstream and downstream piping and fitting. Air continuously flowed into the vacuum space at sonic speed for about 20 minutes and then decreased as the insulating pressure increased. At the same time, the magnet was warmed up above the air condensing temperature. Some time later not only the air flow stopped, in fact air was leaving the vacuum tank at a rate of 5 cubic foot per minute as air was released from the cold surface. This is similar to the regeneration process for a cryopump. Total outflow air was found to be approximately 1100 ft^3.

There is a great uncertainty among the measurements for the air flow, the pressure and the exact timing for the sonic flow to stop, outflow air to begin and stop. Based on the 120 ft^3/min flow rate for 20 minutes, the air flow would be 2400 ft^3 rather than 1100 ft^3. The 1100 ft^3 was measured by a gas meter with some extrapolation.

If the air flow is assumed to be 100 ft^3/min, the heat load from condensing the air would be on the order of 25 kilowatt. Total heat from 2000 ft^3 of air equals to 30,000 kilojoules. Total heat for the 1100 ft^3 air equals to 16,400 kilojoules only. These values will be used to check against the heat input calculated from heat absorbed by the dipole magnet and the helium coolant, and heat removed by cooling through the MAGCOOL cold box.

The thermal mass for the dipole magnet is substantially smaller than the helium coolant at 4 K. As temperature increases the ratio of thermal capacity between the magnet and the helium coolant reversed. Therefore, all heat deposited will be absorbed by the helium initially. A larger percentage of heat input will be absorbed by the magnet as temperature increases.

Because of this enormous heating rate, liquid helium in the precooler and subcooler pots in MAGCOOL was vaporized quickly as soon as the heat was carried from the magnet to the cold box. The vaporization rate of liquid helium in the precooler and subcooler pots can be used as an estimation for the initial heat load.

PRESSURE, TEMPERATURE AND FLOW RATE IN THE HELIUM COOLING LOOP

The pressure, temperature and flow rate in the helium cooling loop are of great interest in this study. Since the helium containment is a rated pressure vessel, helium must be vented through the relief system to prevent the vessel from being over pressurized. The pressure, temperature and flow data will also be used to calculate the amount of heat carried to the MAGCOOL cold box.

The 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 20 seconds due to the very large heat load associated with the air intake. Vent valve 38 opened to release helium from the cooling loop into the cold surge tank. The pressure in the surge tank also reached 15 atm quickly. Vent valve 35 was manually open to release helium from the surge tank to the low pressure return. After 10 minutes, a large portion of helium was vented out of the loop. Although the loop was continuously heated, the heat transfer rate became smaller as we shall see later in this study, the loop pressure declined slowly to 8.5 atm in 60 minutes due to helium flow through the magnet power leads and leakages associated with valves connecting the loop to the low pressure lines.

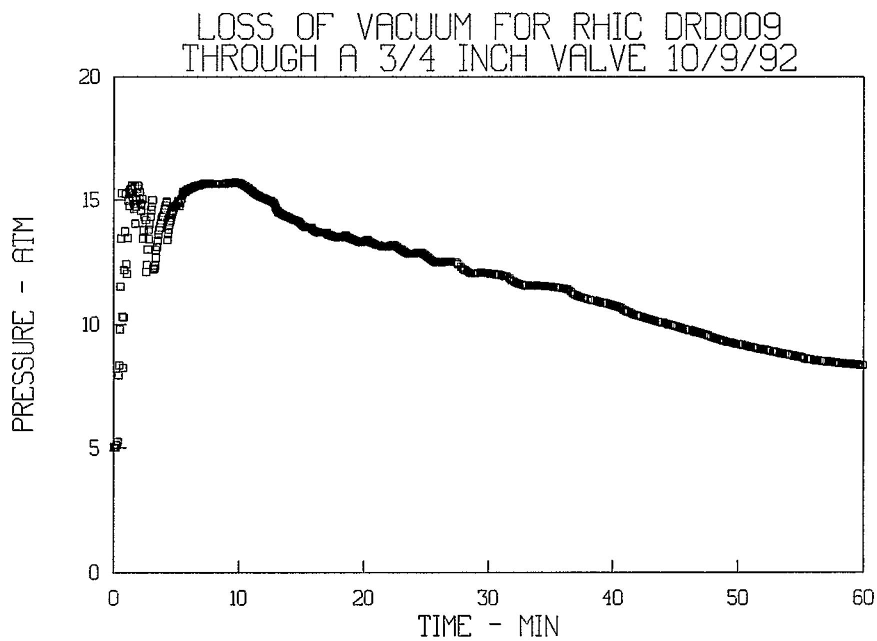

Fig. 7 Loop pressure as a function of time after air is introduced

Besides being used for the heat balance calculation, the temperature readings can be used to characterize the heat transfer process. Temperatures recorded at the inlet of the magnet, the outlet of the magnet and the lead pot are given in Fig. 8. As seen, these temperatures increase quickly rising from 4.3 K to 20 K in just 2 minutes. In 15 minutes, the magnet reached 70 K. The temperature rise became slower from here on as the cold surface of the magnet can no longer cryopump the air.

In Fig. 8, the inlet temperature is not always lower than the outlet temperature because the inlet sensor is located at the exit of the 4.5 K supply line shown in Fig. 2. Air condensed both on the magnet and on the 4.5 K supply line. The results from Fig. 8 suggest that it takes about two minutes for the 4.5 K line and fifteen minutes for the magnet to loose their cryopump capacity. The inlet temperature shall not be used for the heat input calculation. When the magnet was warmed up to 70 K, the heat input became smaller as we shall see in the heat input analysis.

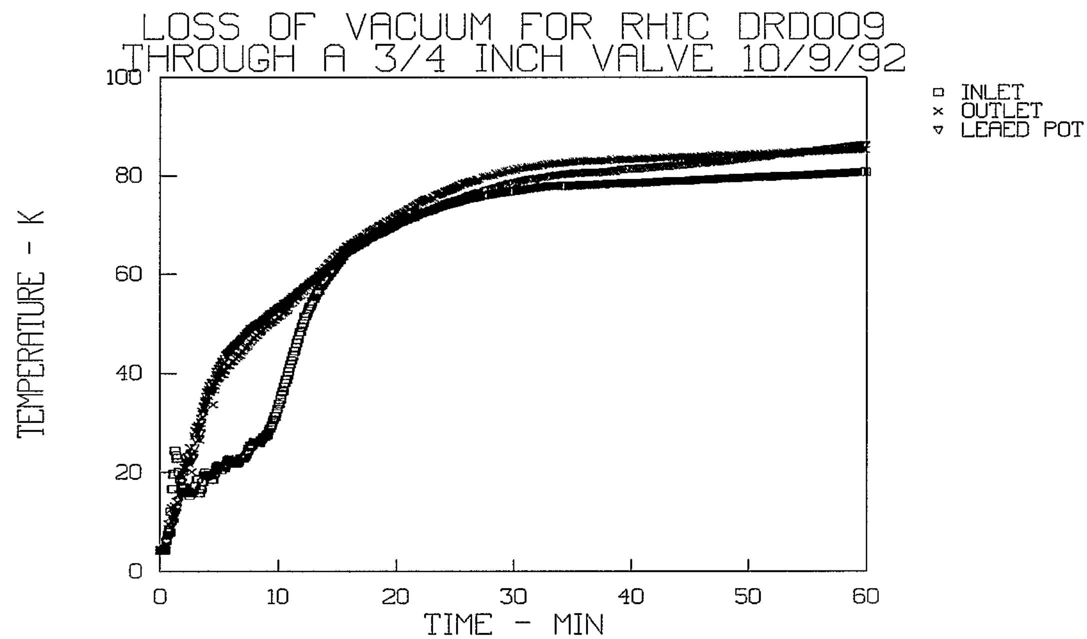

Fig. 8 Temperatures at the inlet of the magnet, the outlet of the magnet and the outlet of the lead pot after air is introduced.

Temperatures recorded at the supply, at the return and at the surge tank as a function of time are given in Fig. 9. As seen, temperature at the return line went up quickly as air is introduced into the vacuum space. But the supply temperature and the tank temperature went up much slower than the return temperature because there was a substantial cooling reserve in the two liquid helium pots and the surge tank.

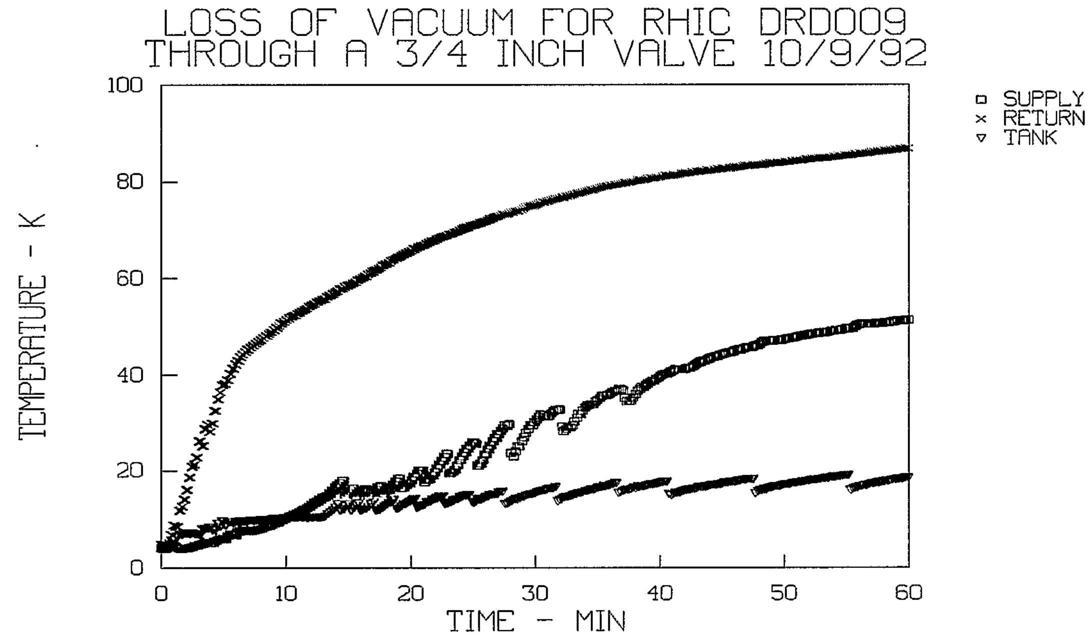

Fig. 9 Temperatures at the supply, the return and the surge tank in the cold box after air is introduced.

The flow rate in the cooling loop is used in the heat balance calculation and is given in Fig. 10. Except for minor scatter when air is first introduced, the flow rate essentially decreases with time because helium density in the loop decreases quickly as the loop is warmed up.

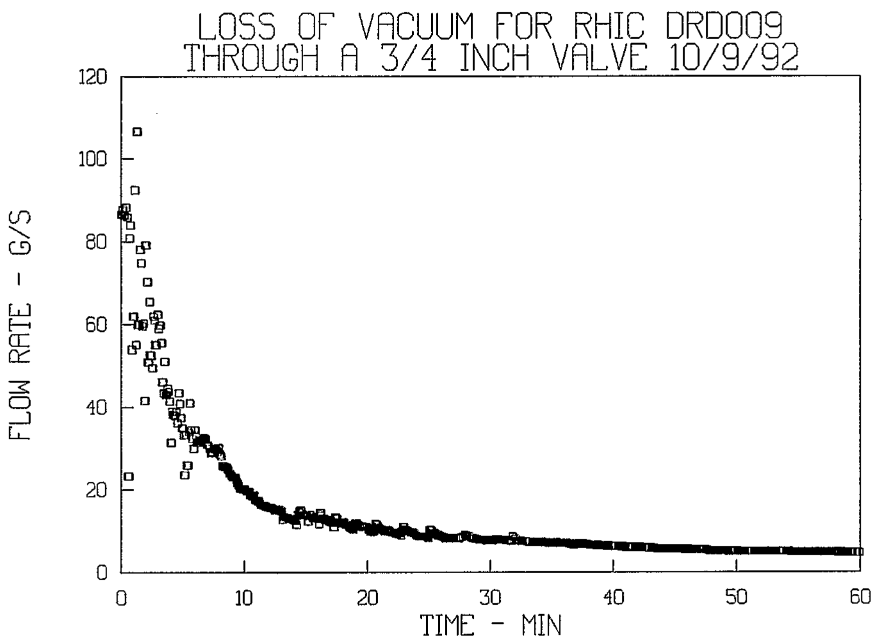

Fig. 10 Loop flow rate after air is introduced

HEAT INPUT ANALYSIS

Four major area in which the heat input can be accounted for are 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 equals to the change of 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. This probably will underestimate the heat input as the surface of the magnet may reach the liquid air temperature.

The amount of heat absorbed by the helium coolant equals to the change of internal energy of the helium. Total single phase helium consists of that in the loop and that in the cold surge tank. In the present study, the surge tank is assumed to have uniform temperature whereas the cooling loop is divided into eleven segments. The density and the internal energy of helium are calculated from the pressure and averaged temperatures in each segment.

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 between the supply and the return of the cooling helium.

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 helium coolant, removed by the MAGCOOL cold box, carried away by the vented helium, and their sum are given in Fig. 11.

As can be seen from Fig. 11, the initial heat input is absorbed primarily by the helium coolant. As the magnet was warmed up, more heat was absorbed by the magnet. Total heat input is linear with time for approximately twenty minutes. The average heating rate as a function of time is given in Table 3.

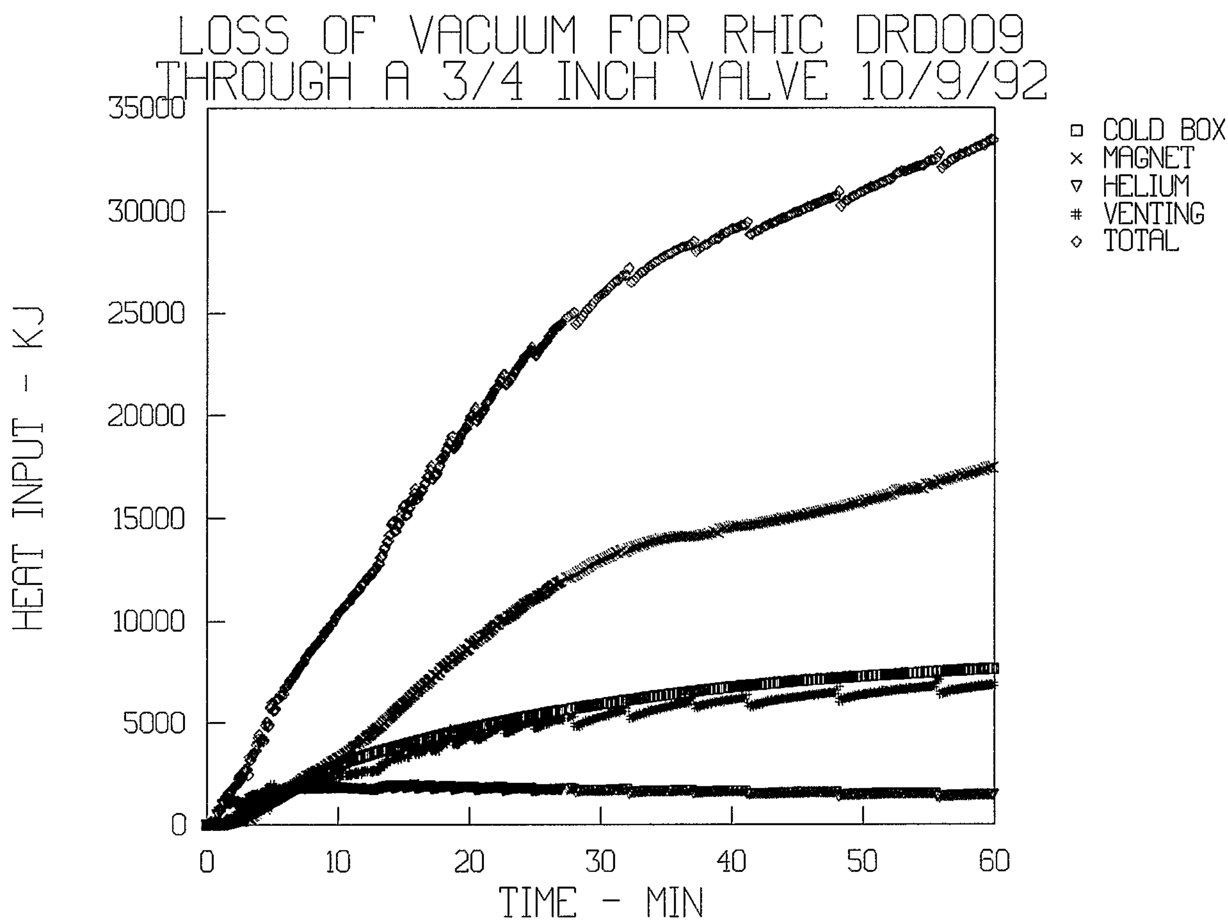

Fig. 11 Heat input to the helium system

Table 3. Average heating rate

Time period min	Magnet temperature K	Heating rate kW
0-10	4.3 - 44	17.3
10-20	44 - 71	15.7
20-30	71 - 79	11.4*
30-40	79 - 81	6.6*
40-50	81 - 82	4.3*
50-60	82 - 83	5.3*

*Addition of an estimated 1.2 KW for vaporization of liquid air

For the initial 10 minutes, the average heating rate is 17.3 kilowatts. The heating rate decreases with time as the magnet temperature increases. When the magnet reached 77 K at which air condensation can not take place, the heat input is about 6 kilowatts. In table 3, 1.2 kW has been added to correct the vaporization of liquid air when air outflow was observed. From this analysis, it is clear that the heating input is dominated by the condensation of air.

LIQUID HELIUM LEVELS IN THE POTS

Since the heat input is very large for the present test and a complete heat balance modelling is prohibited, the rate of vaporization of liquid helium in the precooler and the subcooler helium pots is presented for an independent heat input calculation.

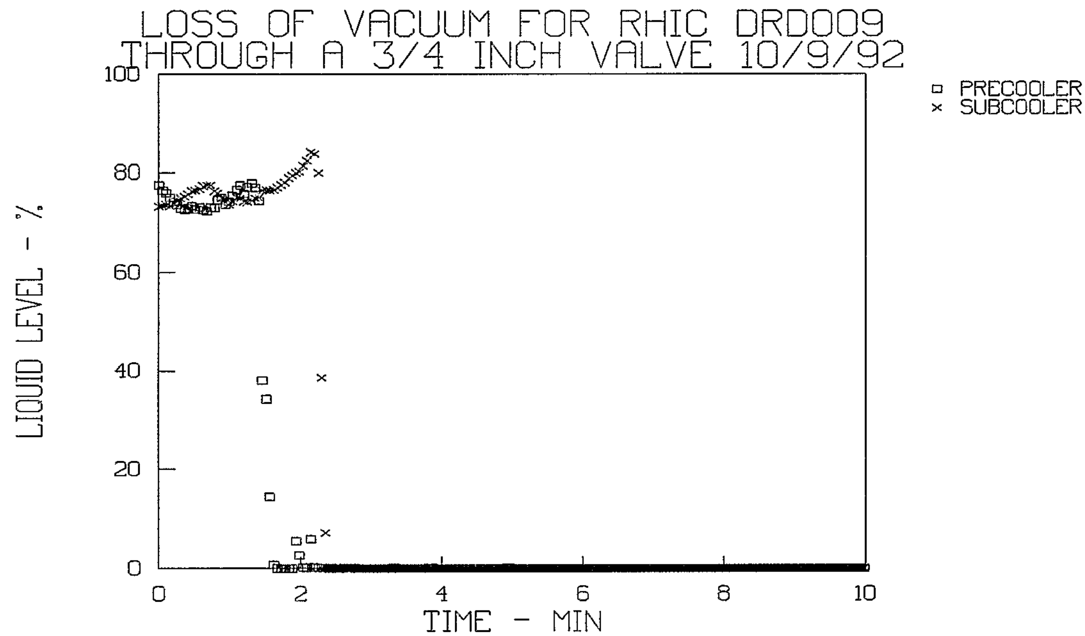

Fig. 12 Liquid level in helium pots after air is introduced

The liquid helium level in the precooler and subcooler pots are given in Fig. 12. As seen, the liquid levels were not effected for about two minutes after air is introduced since the heat input has not been carried back to the liquid helium pots yet. As soon as the heat reached the pots, liquid helium in the precooler vaporized quickly followed by the subcooler. The rate of vaporization is estimated at 7 liter per second, equivalent of 15 kilowatt.

MASS OF HELIUM IN THE COOLING LOOP

As a consequence of air flowing into the vacuum tank, loop pressure and temperature increase and helium must be vented through the relief. The amount of helium to be vented and the venting rate will be given below.

Total 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 is divided into eleven segments with temperature in each segment evaluated from measurement. The density of helium is calculated from the pressure and averaged temperatures in each segment. The helium mass is obtained from the density and the volume and is given in Fig. 13.

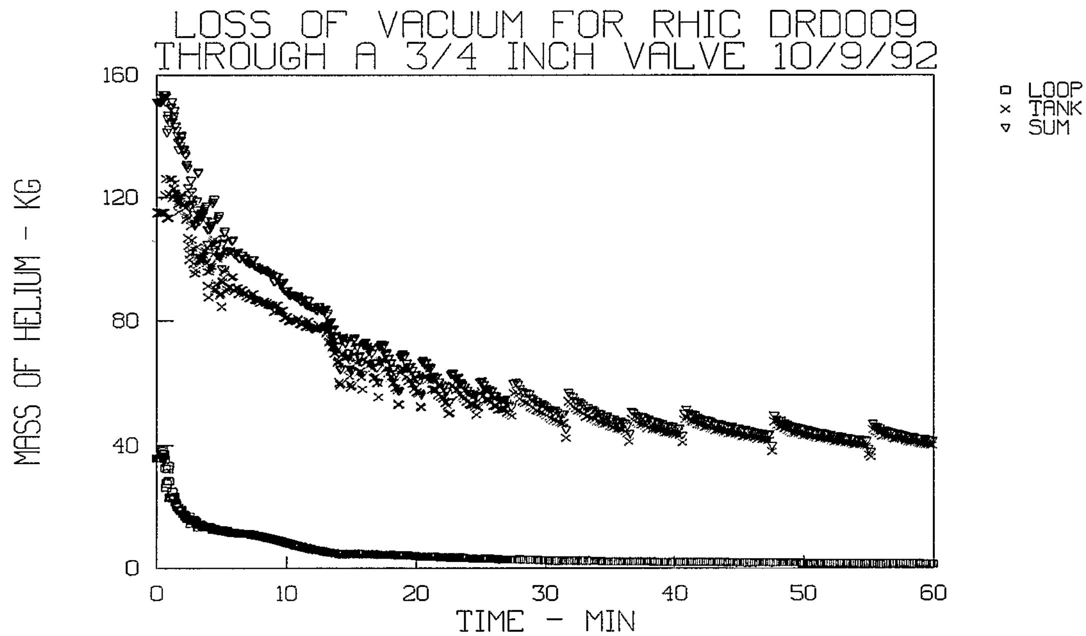

Fig. 13 Mass of helium in the system

As seen, 50% of the 40 kilogram single phase helium in the loop has to be vented in less than 3 minutes with an average venting rate of 110 g/s. 50% of the 160 kilogram total helium has to be vented in 13 minutes with an average venting rate of 100 g/s. The initial venting rate may be higher than the above values.

TEMPERATURES OF THE VACUUM TANK AND THE HEAT SHIELD

The heat transfer process after air is introduced into the vacuum tank is much more complicated than given above. Besides the condensation of air and the very fast changing nature of the process, RHIC DRD-009 has a heat shield. Heat transfer occurs between the magnet and the shield, and between the shield and the vacuum tank. Temperatures on both the magnet, the shield and the vacuum tank vary with time.

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 air intake, the magnet is maintained at 4.5 K by single phase helium. The shield is maintained at 90 K by liquid nitrogen. The vacuum tank is at ambient temperature of 297 K. For protection purpose, three fans were used to blow ambient air around the vacuum tank to prevent the tank from possible freezing.

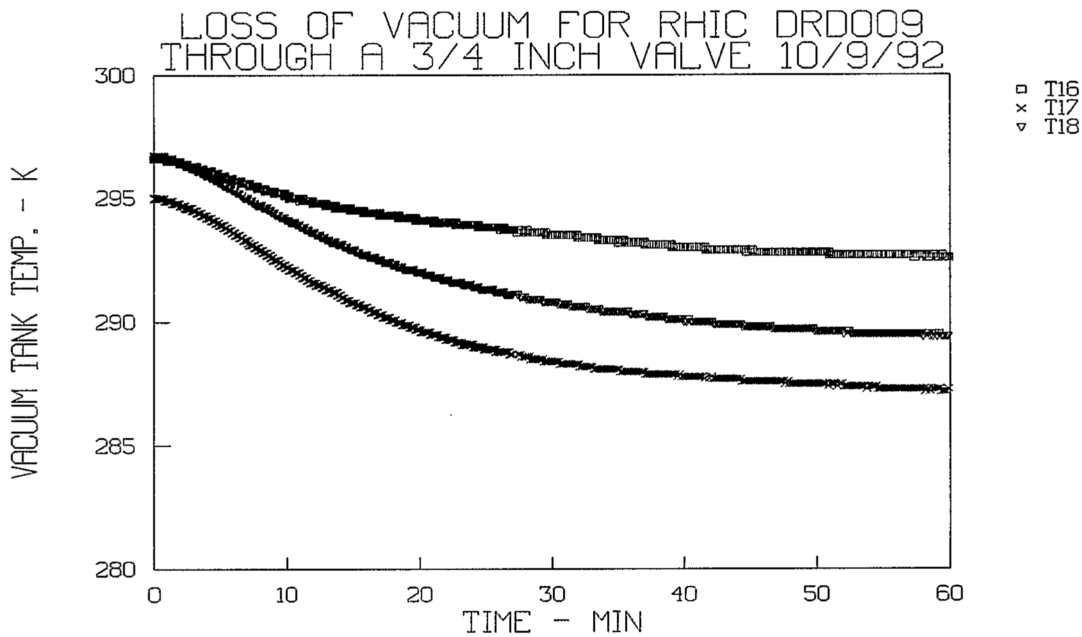

Fig. 14 Temperature of the vacuum tank after air is introduced

After air is flowing into the vacuum space, the temperature readings on the surface of the vacuum tank are given in Fig. 14. As seen T16, T17 and T18, track each other and decrease approximately 7 K over a one hour period. Without the cooling transferred into the surrounding air, the heat input from the vacuum tank into the cryostat equals to approximately 1.1 kilowatts. It is believed the heat input from the vacuum tank remains small even if cooling transferred into the surrounding air were taken into account. This illustrates that the air condensation process, rather than the heat conduction and convection through the insulating vacuum, dominate the heat input.

Unlike the vacuum tank, the heat shield temperature responses quickly because the thermal mass for the shield is much smaller than that of the vacuum tank. As shown in Fig. 15, the temperature for the heat shield increase from 90 K to about 150 K in 30 minutes. During this period, the nitrogen flow rate is not known. Fortunately in the MAGCOOL operation, the liquid nitrogen supply valve remain closed until temperature at the exit of the shield reached 130K. Therefore, for the first 15 minutes, heat deposited on the shield will be mainly absorbed by the thermal mass of the aluminum shield. Assuming the average thermal capacity equals 80 kilojoule/K for the present case, the heat input into the shield equals to 2.7 kilowatt which is much smaller than the heat input to the helium system. This also suggests that the heat input is dominated by the air condensing process which occurred below the shield temperature.

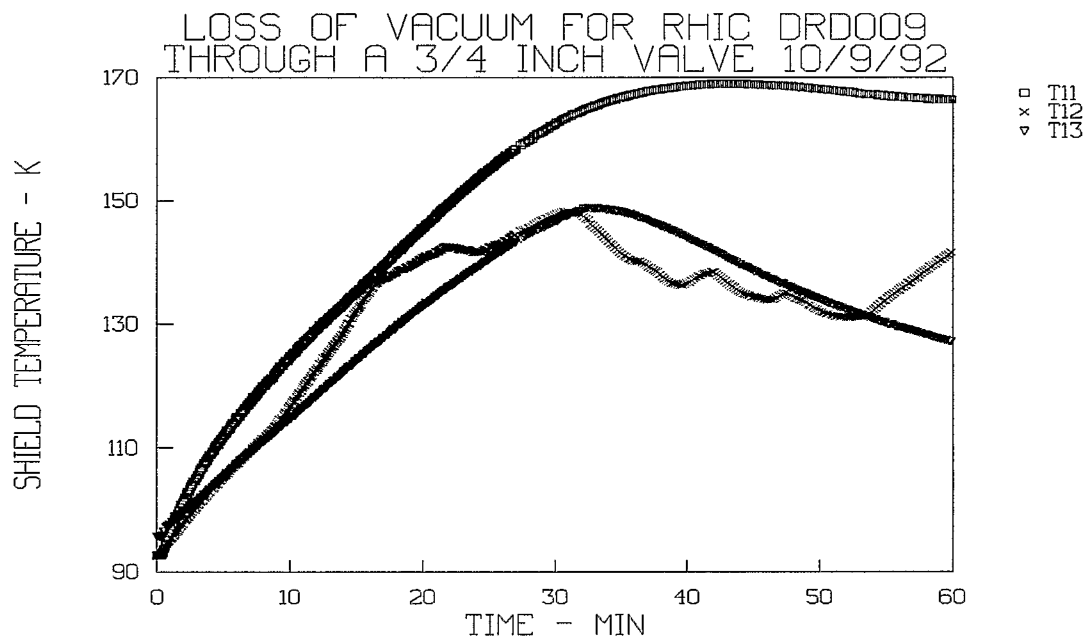

Fig. 15 Temperature of the heat shield after air is introduced

CONCLUSION

A test was performed in MAGCOOL for investigating the most credible loss of vacuum scenario for RHIC DRD-009. The heat input to the system has been estimated from 1). the heat absorbed by the magnet and the helium coolant and, removed by the MAGCOOL cold box and by the helium vented, 2). the vaporization rate in the liquid helium pots, and 3). the enthalpy changes from the condensation of air. The process is very violent and the heat load is estimated in the neighborhood of 20 kilowatts. The required venting rate for cold helium is on the order of 110 g/s.

ACKNOWLEDGEMENTS

The author would like to thank H. Hilderbrand, R. Picinich, W. DeJong, M. Sardzinski, F. Cullen, W. Kollmer, A. Gwilt, W. DeVito, D. Campbell, D. Pate, R. Davis, M. Leheccka and S. Agnetti from the RHIC Collider Ring Division for their supporting effort.