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Thermal Behavior of MAGCOOL Cryogenic System during Quenches of RHIC 009

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ABSTRACT

Thermal behavior of the MAGCOOL cryogenic system during quenches of RHIC 009 have been investigated for 6700 ampere and 5000 ampere currents. Pressures, temperatures and flow rates in the circulating loop are given as functions of time. The magnet's stored energy at 6700 amperes is approximately 80% more than that at 5000 amperes and produces a faster pressure rise rate and a higher peak temperature. The initial pressure rise rate has been found to be 17.5 atm/min for the 6700 ampere quench and 7 atm/min for the 5000 ampere quench. The peak temperature at the outlet of the magnet is found to be 13.2 K for the 6700 ampere quench and 10.9 K for the 5000 ampere quench. The net recovery cooling as obtained from the apparent cooling rate minus the background heat load has been found to be 650 KJ for the 6700 ampere quench and 375 KJ for the 5000 ampere quench. The quench recovery time is approximately 30 minutes. The time lag of the peak temperature in the circulating loop has been observed for each current value.

INTRODUCTION

The MAGCOOL magnet test facility at Brookhaven National Laboratory is used for testing both SSC and RHIC magnets. SSC magnets were tested using a Subcooler Assembly added to the MAGCOOL facility. RHIC magnets were tested using the MAGCOOL cold box alone. Both the Subcooler Assembly and the MAGCOOL cold box have a cold circulating compressor and the magnet test loop can be operated independently of the helium refrigerator.

The MAGCOOL facility is operated by a CRISP process control computer which has a real time data acquisition system capable of recording the thermal behavior of the cryogenic system during a magnet quench.

In August, 1991, a detailed investigation and analysis of the thermal behavior of the MAGCOOL - Subcooler Assembly during quenches of SSC dipole DD0028 were performed.

In a continuing effort to understand quench characteristics, an investigation of the thermal behavior of the MAGCOOL cryogenic system during quenching of RHIC dipole DRD009 was initiated. The results given below describe how MAGCOOL functions during a quench recovery.

SYSTEM DESCRIPTION

The flow schematic for the test and measure operation of the MAGCOOL cold box is given in Fig. 1. This cold box is connected to the 1500 watt HEUB/MAGCOOL helium refrigerator. The precooler and subcooler pots are liquid helium vessels each containing a heat exchanger coil inside. A helium ejector or jet pump, is used to keep the pressure and temperature in the subcooler helium pot lower than that in the precooler helium pot. The circulating compressor is used to circulate supercritical helium and deliver cooling from the helium pots to the magnet.

A surge tank located on the suction side of the circulating compressor is used for cooling loop pressure control. When the loop pressure exceeds the set value, helium will be vented into the surge tank and drained back to the low pressure side of the refrigerator for cooling recovery. Thus a quench induced heat load will be seen by the helium refrigerator as a refrigeration load rather than as a liquefaction load which would be seen if helium were vented out to warm return. The system efficiency is therefore higher.

The RHIC 009 dipole is installed in bay D of the MAGCOOL facility. 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 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. The volume of the circulating loop piping is approximately 210 liters, and the volume values for each component of the loop are given in Table 1. Figure 2 also shows the locations of dual temperature sensors at inlet to and the outlet from the RHIC magnet and at the outlet from the lead pot.

Fig. 3 shows the system flow diagram and the process controller on the computer console. Real time pressure in atm, flow rate in g/s and speed in rpm are directly available. The temperatures shown without units are in Kelvin. In Fig. 3, the Cooldown II heat exchanger is used in the MAGCOOL operation to cool the magnet from 80 K to 10 K and will not be considered in the present study.

Table 1 Liquid volume in the circulating loop

82 ft of 3/4 inch supply line	11 l
32 ft of 2.5 inch lin	37 l
return cap (can)	20 l
RHIC 009	25 l
cap	20 l
lead pot can	22 l
return line	
26 ft of 1.5 inch line	13 l
82 ft of 2.5 inch line	60 l
Total	208 liter

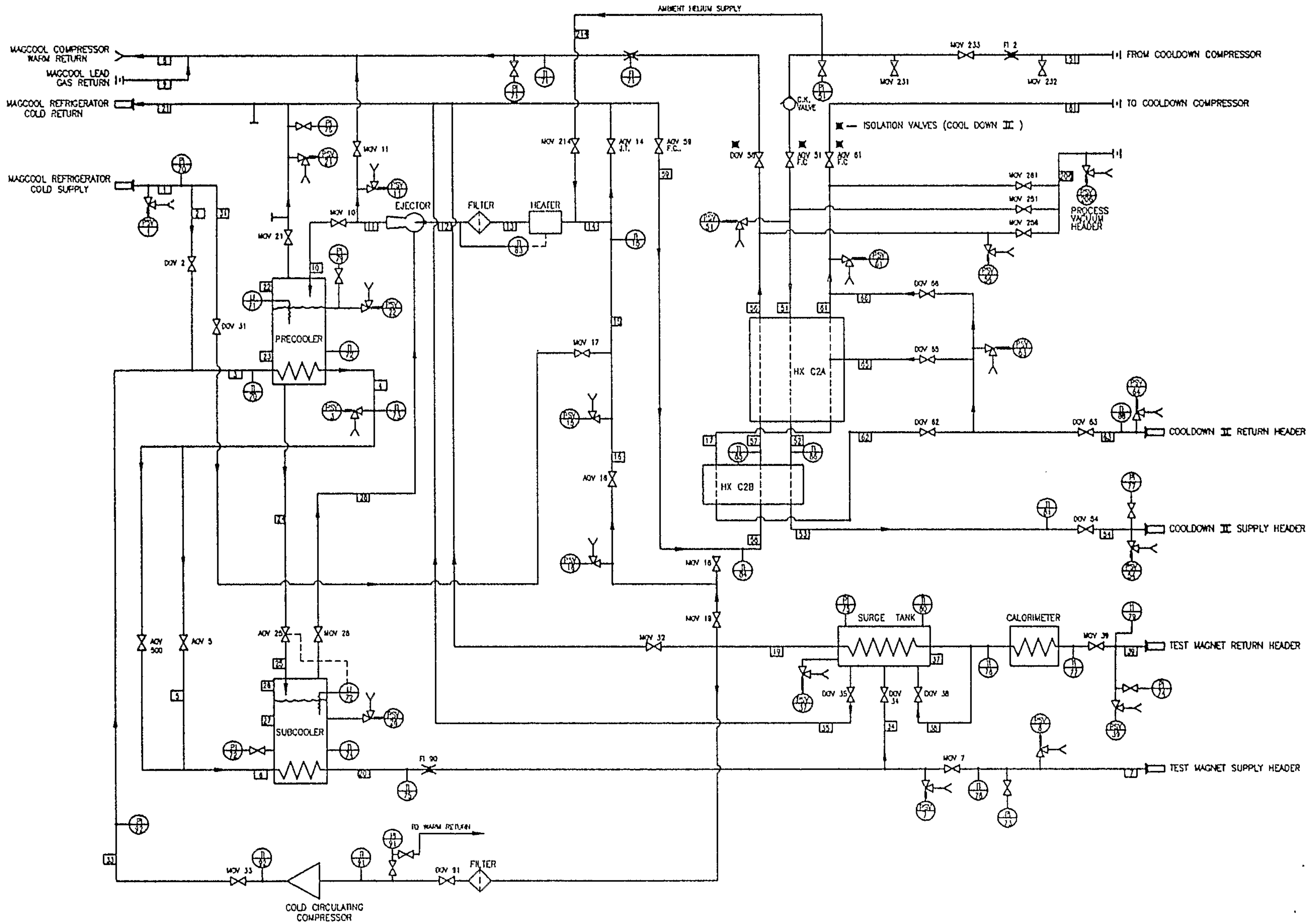

Fig. 1 MAGCOOL - test and measure flow schematic

Prior to a quench, the magnet is maintained at test temperature via circulation of 100 g/s of supercritical helium. There are 29000 grams of helium in the loop, and it takes five minutes for the helium to travel through the loop. The liquid capacity of the precooler is 200 liters and that of the subcooler, 270 liters. However, the amounts of helium stored in these pots during operation are roughly the same and about equal to 200 liters. The total cooling reserve in the pots is 880 KJ which is larger than the 650 KJ energy released during a 6700 ampere quench. The surge tank has a volume of 900 liters and is normally maintained at 3.5 atm and 4.9 K.

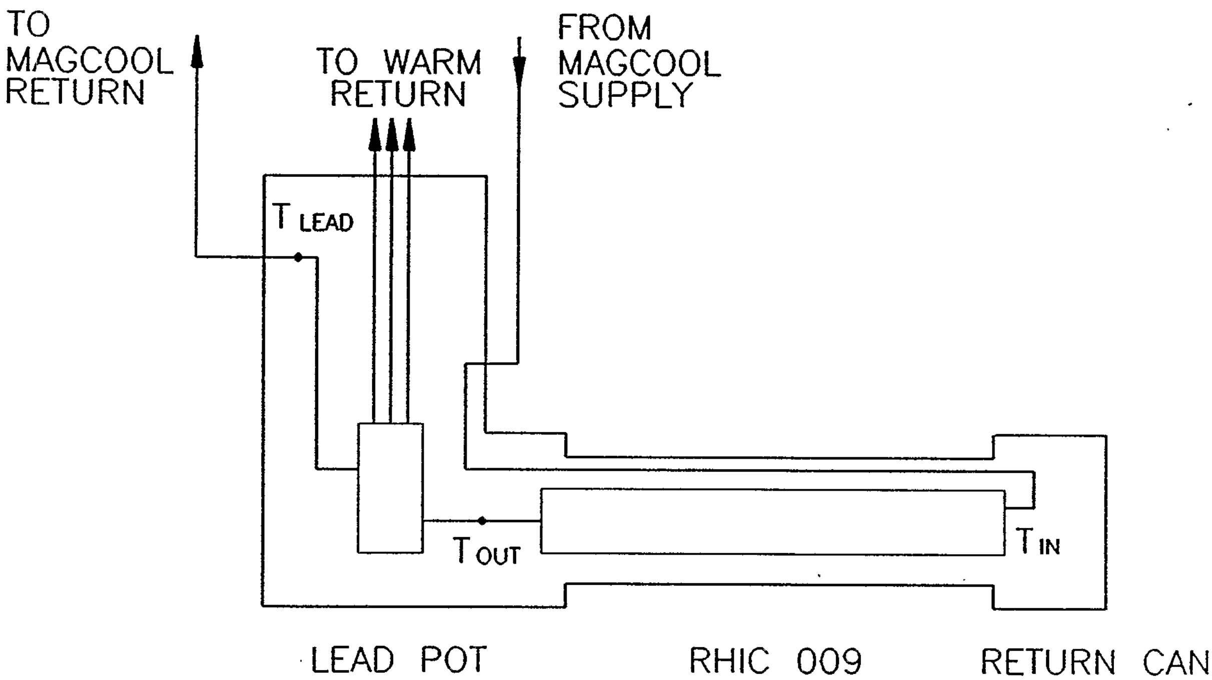

Fig. 2 Locations of temperature sensors on RHIC 009

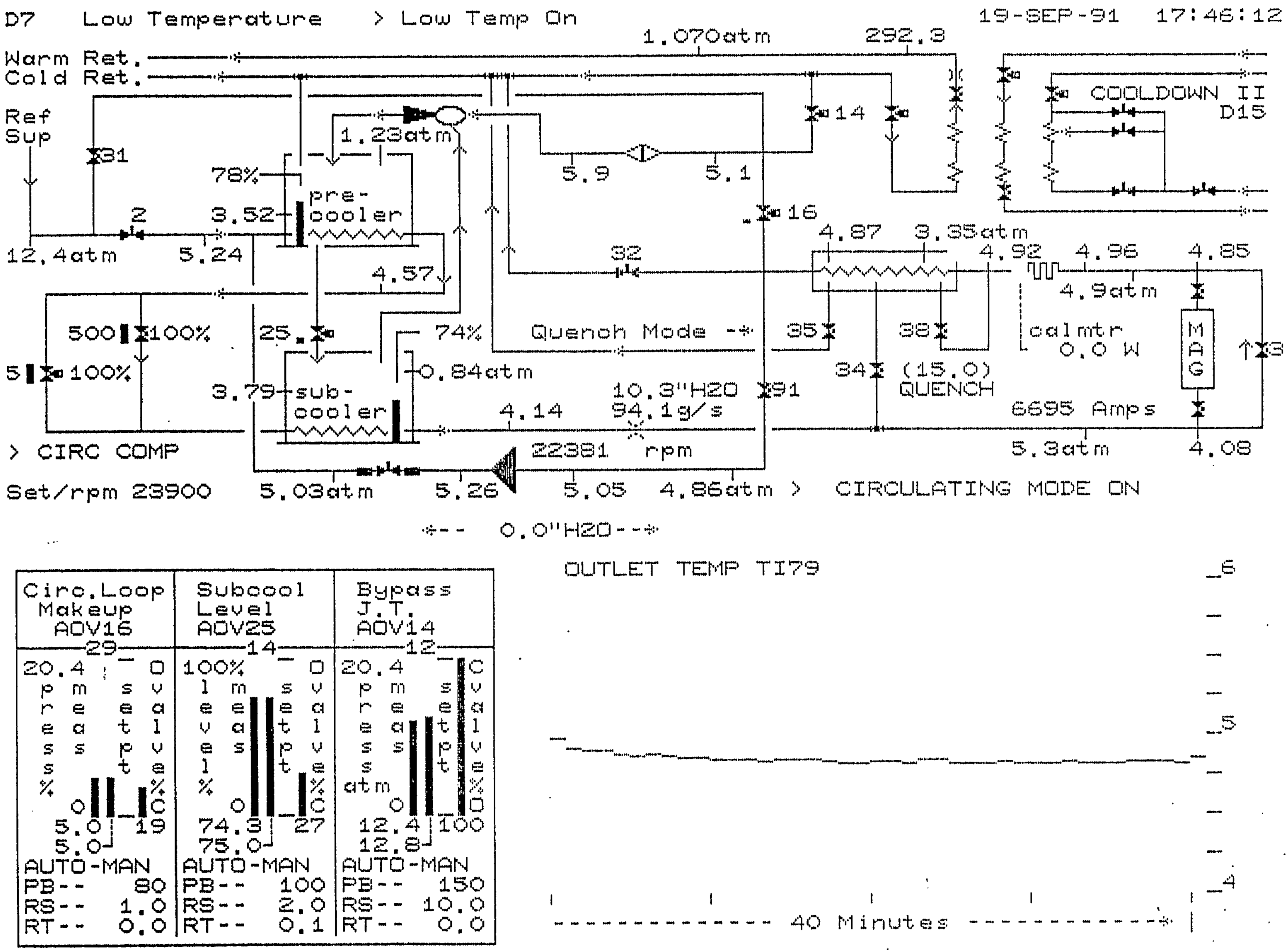

Fig. 3 MAGCOOL - test and measure flow schematic and process controllers

QUENCH BEHAVIOR

Typical process conditions after a 6700 ampere quench of RHIC 009 are given in Fig. 4a and 4b. The vent valve 38 is set at 15 atm to limit pressure in the loop by venting helium into the surge tank when the loop pressure exceeds that value. The drain valve 35 is used to drained the cold helium from the surge tank back to the refrigerator return. The makeup valve 16 is used to add helium to the loop when the magnet is cooled down. Valve 16 is also used to provide lead flow for power leads.

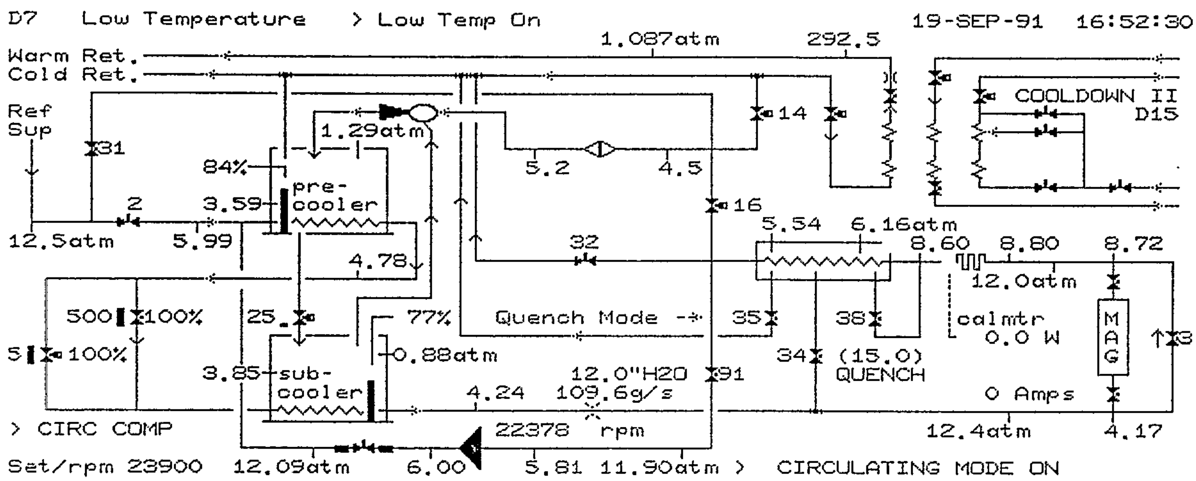

Fig. 4a Process conditions 1 1/2 min. after a 6700 ampere quench

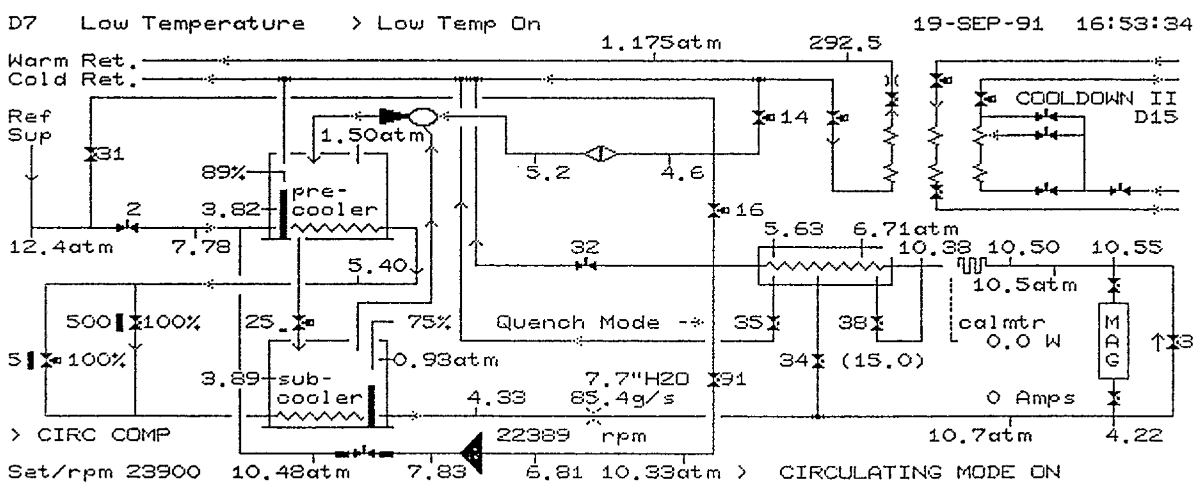

Fig. 4b Process condition 2 1/2 min. after a 6700 ampere quench

The loop pressure during the first two minutes after a 6700 ampere quench is given in Fig. 5a. The pressure increases quickly from 5 atm to 15 atm in about 0.5 minutes. Valve 38 then opens to vent helium to the surge tank and the loop pressure reduces to about 7 atm. The heating process continues and the loop pressure increases at a slower rate. Valve 38 will open again if the loop pressure exceeds the 15 atm set value. Fig. 5b shows the loop pressure after a 5000 ampere quench. The pressure rise rate for the 5000 ampere quench is about 7 atm/min which is substantially lower than the 18 atm/min rate after a 6700 ampere quench.

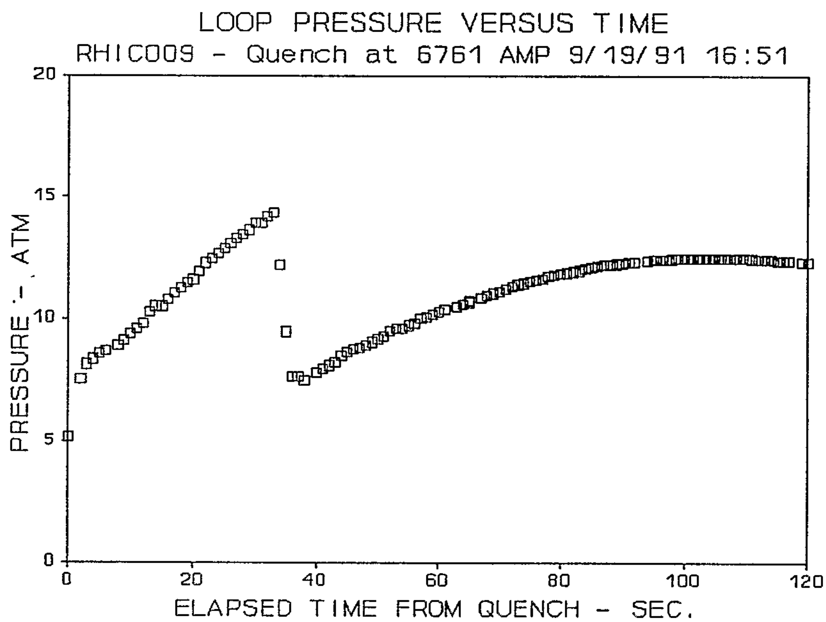

Fig. 5a First 2 min of loop pressure after a 6700 ampere quench

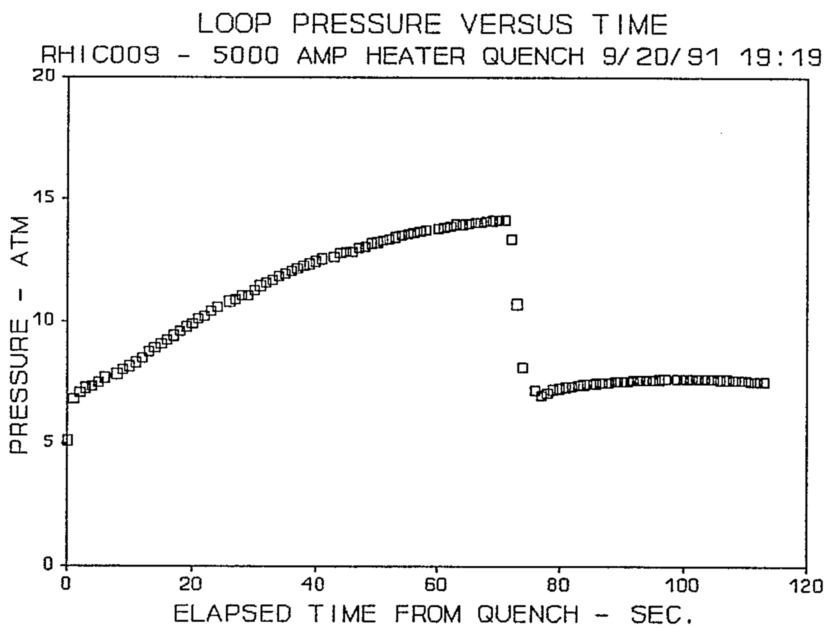

Fig. 5b First 2 min of loop pressure after a 5000 ampere quench

The pressure readings as a function of time during the 25 minute period after the 6700 ampere and the 5000 ampere quenches are shown in Figs. 6a nd 6b. In each case, the vent valve opens only once for approximately one second. After the vent valve is closed, the loop pressure first increases but soon decreases as the magnet is cooled back down. For the 5000 ampere quench, the loop pressure never goes beyond 8 atm after the venting. The loop pressure reaches 5 atm in about 4 minutes after the 6700 ampere quench and in about 3 minutes after the 5000 ampere quench. The makeup valve 16 then introduces high pressure helium into the loop. It takes about 15 minutes for the system to return to operating conditions and 30 minutes for liquid level in the precooler to be reestablished.

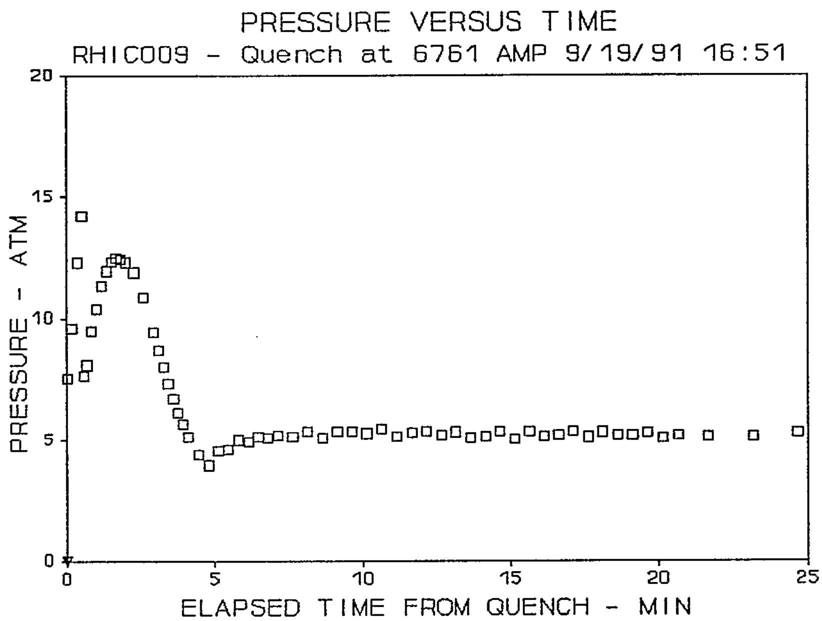

Fig 6a Loop pressure history for the 6700 ampere quench

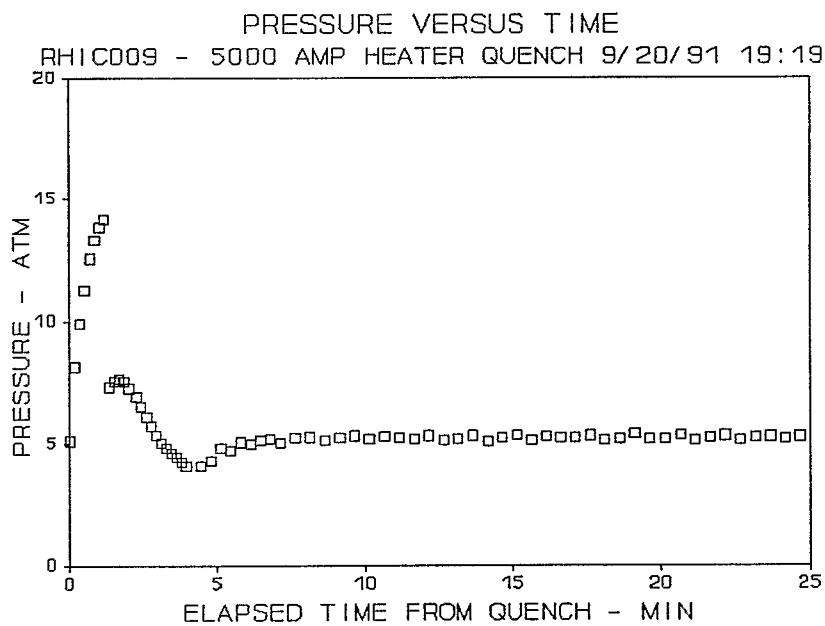

Fig 6b Loop pressure history for the 5000 ampere quench

The temperatures at the inlet and outlet of the magnet, the lead pot and the return header for the 6700 ampere and 5000 ampere quenches are shown in Fig. 7a and 7b. As can be seen, the inlet temperature varies only by a small amount during the entire recovery period because it is stablized by the large liquid inventory in the precooler and subcooler helium pots. The outlet temperature is higher as expected for the 6700 ampere quench due to the larger release of stored energy from the magnet.

For the 6700 ampere quench, the 13.5 K peak magnet outlet temperature is observed 1.35 min. after the quench. The peak temperature at the lead pot, 11.1 K, occurs 1.8 min. after the quench. The peak temperature at the return header, 10.8 K, occurs 2.7 min. after the quench. These results show a decrease and time lag of peak temperature as helium is circulated back to the MAGCOOL cold box.

For the 5000 ampere quench, the peak temperatures at the magnet outlet, the lead pot and the return header are 10.9, 9 and 8 K occurring at 1.28, 1.48 and 2.32 min. after the quench.

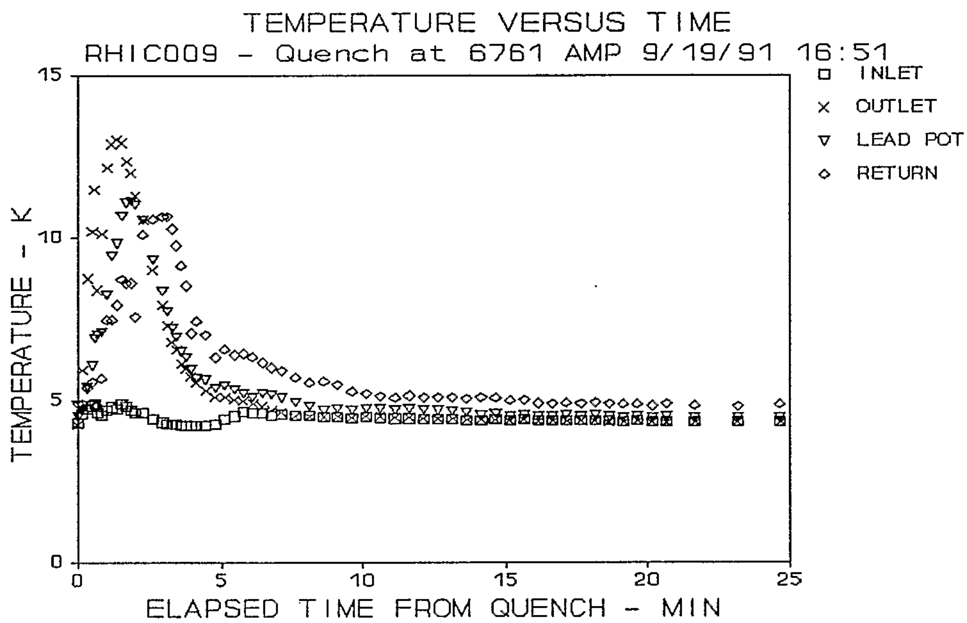

Fig. 7a Loop temperatures for 6700 ampere quench

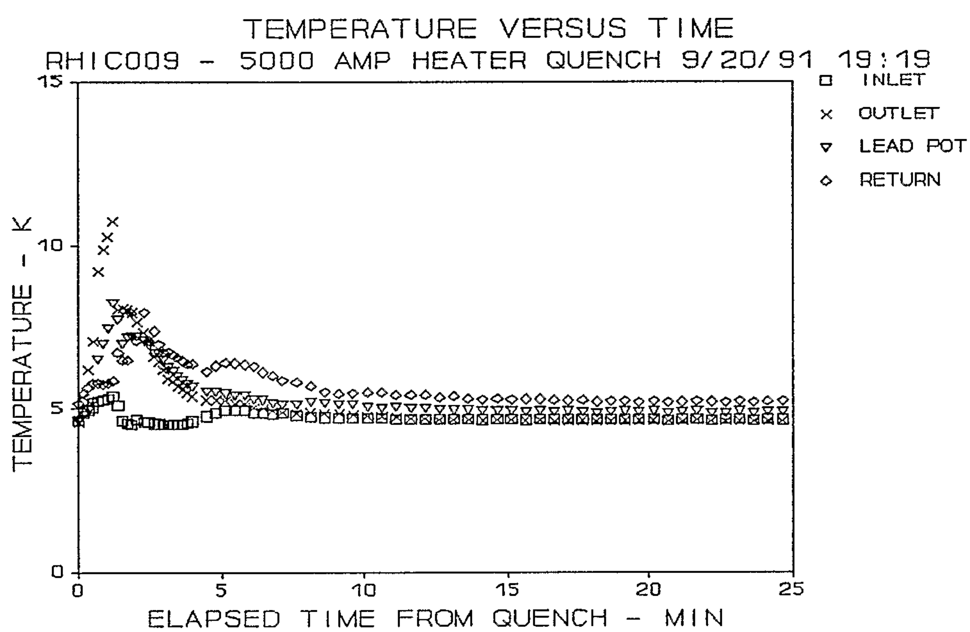

Fig. 7b Loop temperatures for 5000 ampere quench

The helium flow through the magnet as a function of time is given in Fig. 8a and 8b. The mass flow rate increases slightly after the quench. The momentary decrease in flow rate is caused by the opening of the vent valve. As the circulating compressor starts to see high temperatures, the flow rate decreases. The flow rate recovers after the peak temperature passes through the circulating compressor. Perturbations of the flow rate are seen when the loop pressure falls below 5 atm and the make up valve opens. About 10 minutes after the quench, the flow rate returns to its initial value.

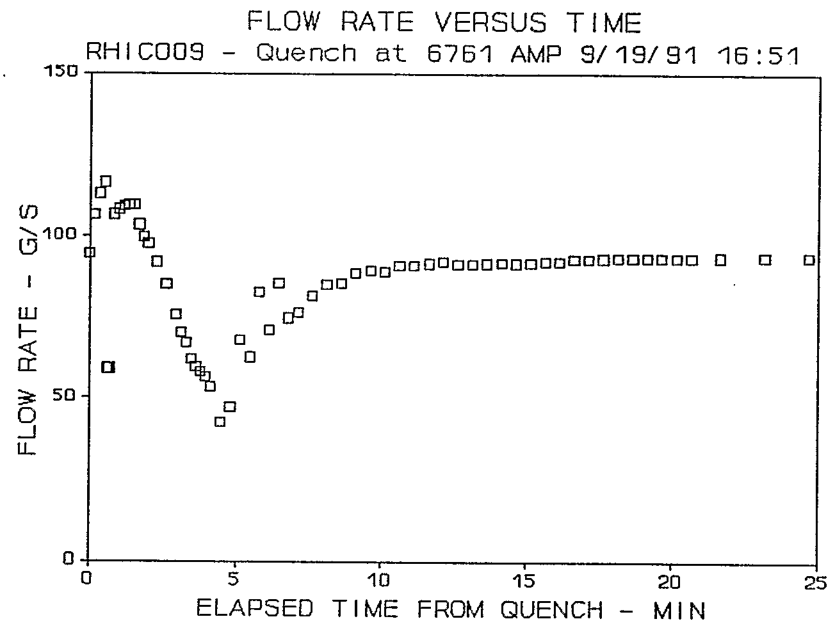

Fig. 8a Mass flow rate for 6700 ampere quench

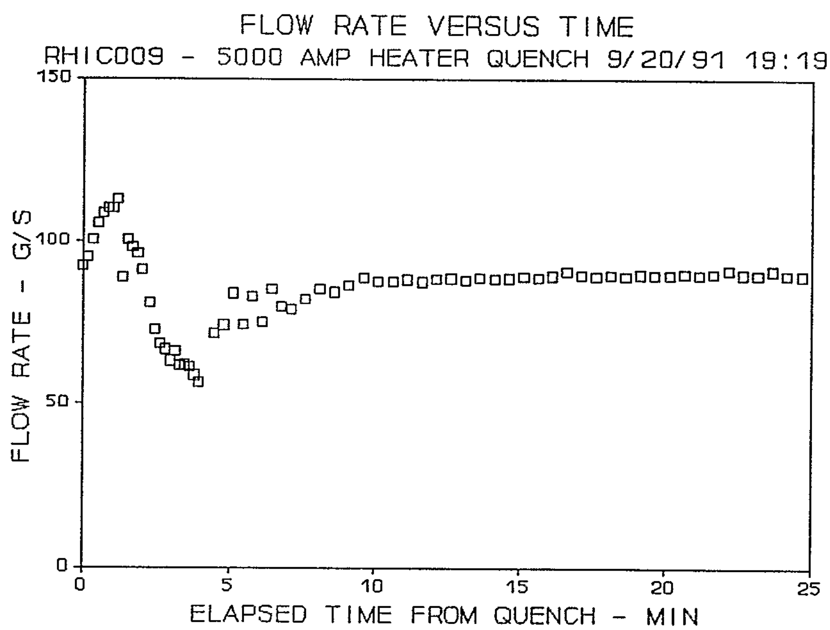

Fig. 8b Mass flow rate for 5000 ampere quench

COOLING CAPACITY

The heating rate of the magnet and the cooling rate of MAGCOOL during quench recovery are of great interest but the exact rates are difficult to calculate due to the transient nature of the process and the venting which occurs.

The MAGCOOL-magnet system which started at test conditions is eventually cooled back to the original conditions. The enthalpy flux difference through the magnet can be considered as the apparent rate at which the magnet releases heat energy. Likewise the enthalpy flux difference between the supply and the return of the MAGCOOL cold box can be considered as the apparent cooling rate MAGCOOL provides. The net useful cooling for quench recovery is equal to the above cooling rate minus the background heat load. The background heat load is small for the magnet but is about 280 watts for the circulating loop.

Fig. 9a and 9b show the apparent heating and cooling rates for the 6700 ampere and the 5000 ampere quenches. The peak heating rate for the magnet, 5.8 KW, occurs 1.3 minutes after the quench for the 6700 ampere case. The peak apparent cooling the MAGCOOL cold box provides, 3.4 KW, occurs 2.6 minutes after the quench. After about 10 minutes, most of the heat from the magnet has been removed and the apparent cooling rate for the MAGCOOL cold box approaches the steady state background heat load. The average cooling rate over a 25 minute period is 700 watts. Summing the circulator work, cold box internal heat leak, magnet lead flow, and the 700 watt cooling rate, give a total of approximately 1,000 watts of refrigeration. This number agrees with the operating capacity of the HEUB/MAGCOOL refrigerator.

For the 5000 ampere quench, the peak apparent magnet heating rate, 3.7 KW, occurs at 1.2 minutes. The peak apparent cooling rate for the cold box is 2.3 KW at 1.9 minutes.

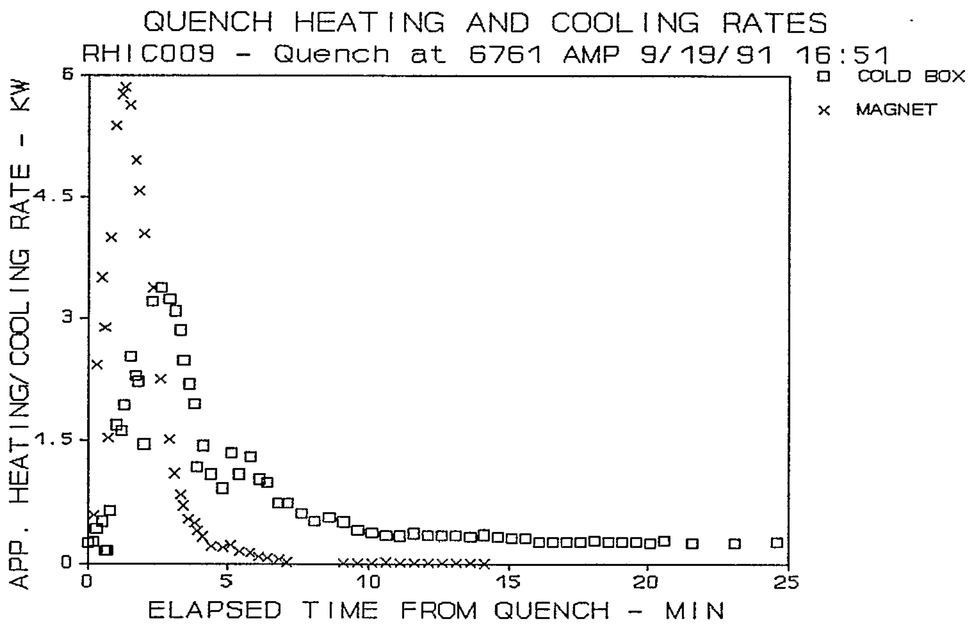

Fig. 9a Apparent heating and cooling rates for 6700 ampere quench

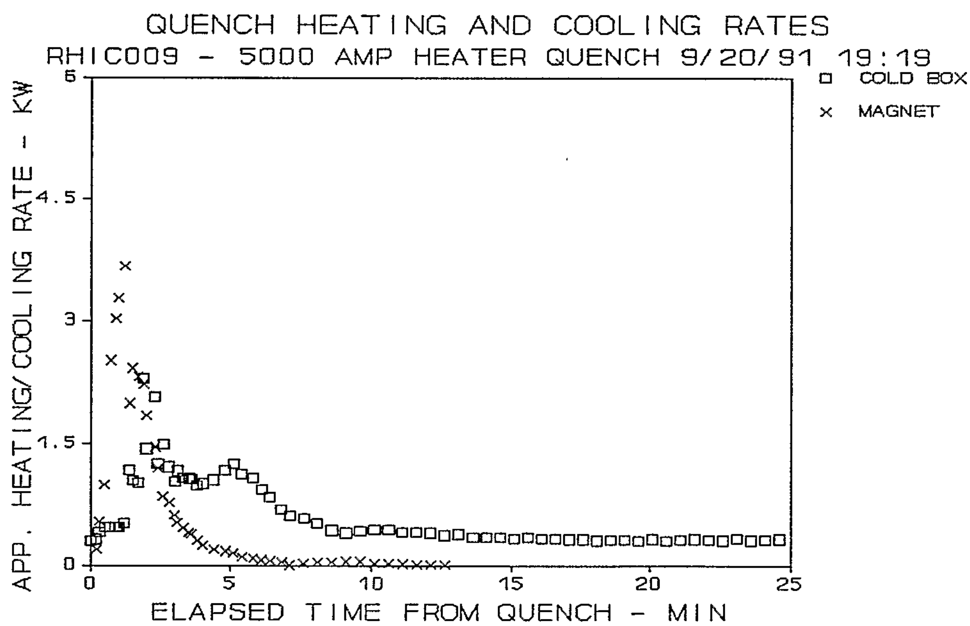

Fig. 9b Apparent heating and cooling rates for 5000 ampere quench

The integrated totals of apparent net cooling as functions of time for RHIC-009 and the MAGCOOL cold box for 6700 and 5000 ampere quenches are given in Fig. 10a and 10b. As can be seen, the apparent net cooling obtained for the magnet leads that of the cold box by about 3 minutes. The two curves approach each other after 12 minutes or so. The integrated total cooling equals 650 KJ for the 6700 ampere quench and equals 375 KJ for 5000 ampere quench. These values agree well with the calculated values of energy stored in the magnetic field of 351 KJ at 5000 amperes and 589 KJ at 6600 amperes given in the RHIC conceptual design.

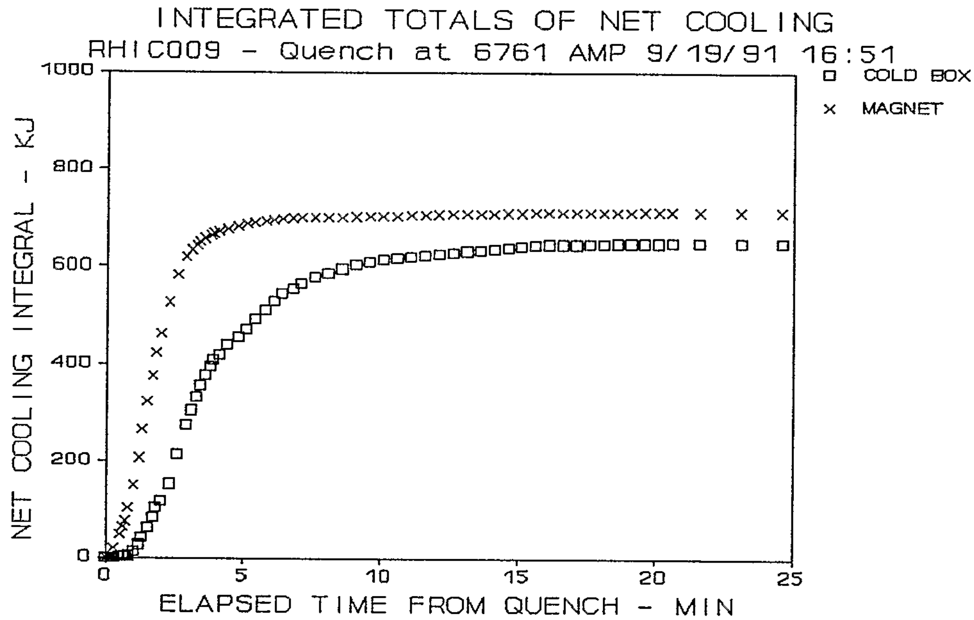

Fig. 10a Integrated totals of net apparent cooling for 6700 ampere quench

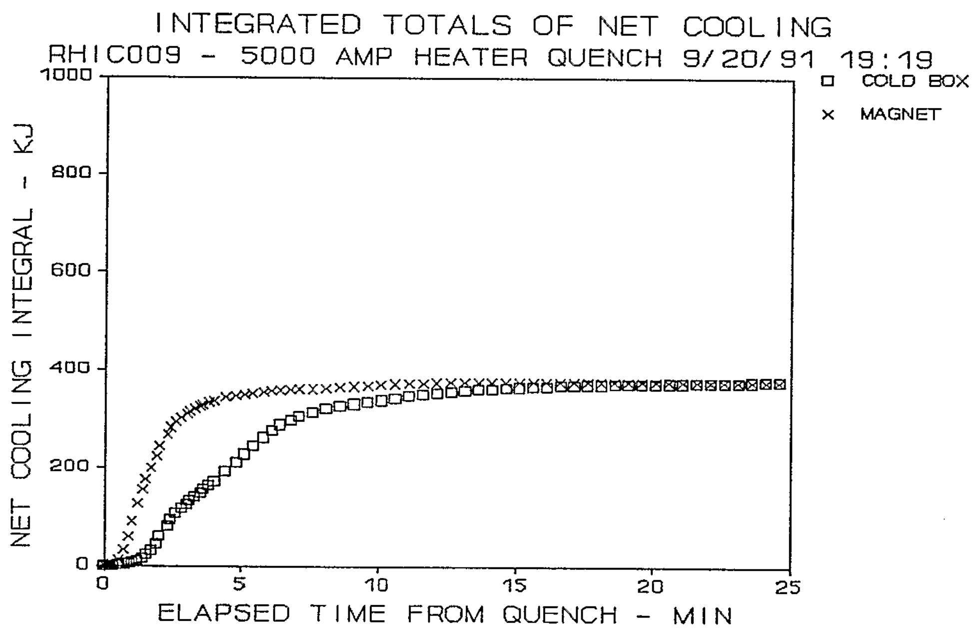

Fig. 10b Integrated totals of net apparent cooling for 5000 ampere quench

DISCUSSION

Fast quench recovery of RHIC magnet in MAGCOOL is attributed primarily to the use of the cold surge tank and ample cooling reserve in the helium pots. The cold surge tank is used as buffer volume to control test loop pressure. The quench induced heat is seen by the helium refrigerator as a refrigeration load rather than a liquefaction load. The large cooling reserve in the helium pots provide constant low temperature supply to the magnet after a quench. The cooling recovery rate is well within the capacity of the refrigerator.

During quench tests, no change in the liquid level of the subcooler helium pot was observed. For the 5000 ampere quench, the liquid level in the precooler was found to decrease by approximately eight inches. For the 6700 ampere quench, the liquid level in the precooler fell at least 12 inches to a level below the level gauge. In less than fifteen minutes, the liquid level once again reached the bottom of the gauge. Due to an over filling of the precooler, it is difficult to calculate the amount of liquid helium actually vaporized. Typically the liquid level in the precooler is reestablished in twenty minutes after the level appears.

CONCLUSION

Detailed thermal behavior of the MAGCOOL cryogenic system during quenches of RHIC 009 has beeen presented. The energy balance for the cooling and heating process was obtained. Higher current quenching deposits more energy in the system which translates into higher pressure rise rate and peak temperatures. No operating difficulties were encountered and the MAGCOOL cryogenic system recovered from a 6700 ampere quench in thirty minutes.

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