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Thermal Behavior of MAGCOOL Cryogenic System after Low Current Quenches of RHIC Magnet DRD-009

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ABSTRACT

The performance of the MAGCOOL cryogenic system after 2000, 3000, 4000 and 5000 ampere strip heater quenches of RHIC magnet DRD-009 was investigated to verify the accuracy of the thermal measurements and to understand the heating/cooling process after a magnet quench. In these tests, the amount of energy released into the helium stream was small and perturbation to the cryogenic system was mild. Uncertainties associated with the venting of helium were eliminated. Peak loop pressure and peak temperatures in the magnet loop were found to be linearly proportional to the energy released during a quench. The apparent cooling rate and total cooling provided for quench recovery were evaluated for each quench current and agreement between total cooling and the magnetic stored energy was reconfirmed. Pressures, temperatures and flow rates through the magnet cooling loop are given as a function of time and characteristics of the cryogenic system are summarized.

INTRODUCTION

The performance of the MAGCOOL cryogenic system after the 6700 ampere and the 5000 ampere quenches of RHIC magnet DRD-009 was previously investigated and reported[1]. The cooling/heating and venting mechanisms of the system were described. The total cooling provided during quench recovery was found to agree with the energy stored in the magnetic field of the magnet. However in this previous study, helium was vented from the cooling loop because the loop pressure exceeded the vent relief pressure. There was, therefore, an uncertainty associated with the cooling calculation. The peak loop pressure and temperature could not be identified.

In the present study quenches were initiated at lower currents and the vent relief pressure was set at a higher value than in the earlier tests to contain the helium in the cooling loop. For the 5000 ampere quench, the peak loop pressure is slightly lower than in the previous study due to a slightly lower initial operating temperature.

A detailed system description including a break down of the liquid volume in the circulating loop was given in reference 1. The total loop volume given in this reference is 208 liters. However, a 10 liter by-pass line on the MAGCOOL system was not included in the total. The temperature of this by-pass line is somewhere between 4 K and 300 K. It is believed this by-pass line buffers the loop pressure somewhat, but no quantitative results are available.

PRESSURES, TEMPERATURES AND FLOW RATES AFTER LOW CURRENT QUENCHES

The following results were obtained from quenches of DRD-009 in MAGCOOL test stand D. The magnet was maintained at 4.3 K prior to a quench. Quenches were initiated at 2000, 3000, 4000 and 5000 amperes by the No. 4 strip heater located on the mid-plane of the coil at the return end of the magnet[2]. The corresponding magnetic stored energies are 56, 126, 224 and 350 kilo-joules.

The loop pressures as a function of time are given in Fig. 1. As can be seen, the loop pressure increases right after a quench to a peak value and then decreases as the loop is cooled down. In the present study, the loop was cooled back to 5 atm in about 5 minutes.

The peak pressures are 6.8, 8.6, 11.8 and 14.8 atmospheres, occurring at 53, 87, 93 and 82 seconds respectively after the quench, for quench currents of 2000, 3000, 4000 and 5000 amperes. The value of the peak loop pressure increases linearly with the amount of energy released as shown in Fig. 2.

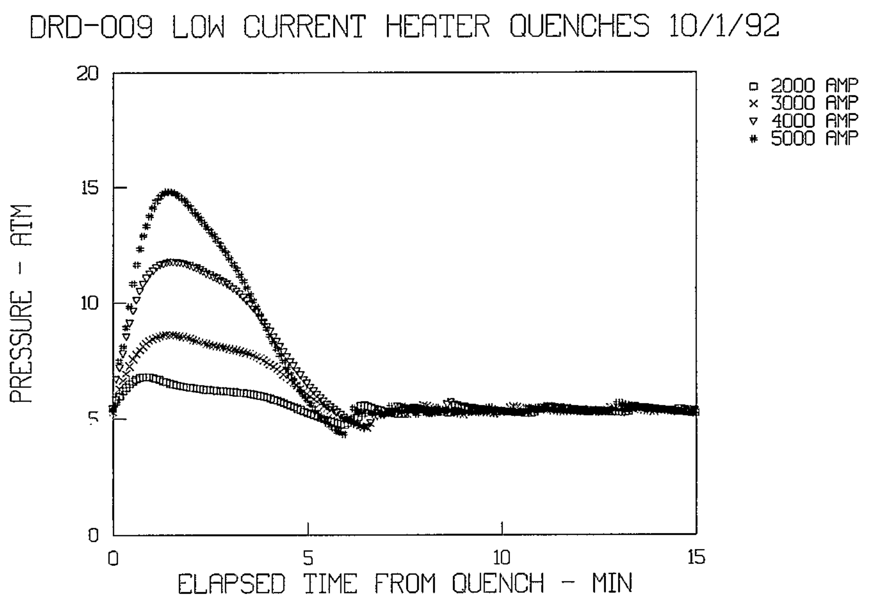

Fig. 1 Loop pressures after magnet quenches

Prior to a quench, the magnet is maintained at 4.3 K. After the quench, the supply temperature changes very little. Temperatures recorded at the inlet of the magnet increase slightly for a short period.

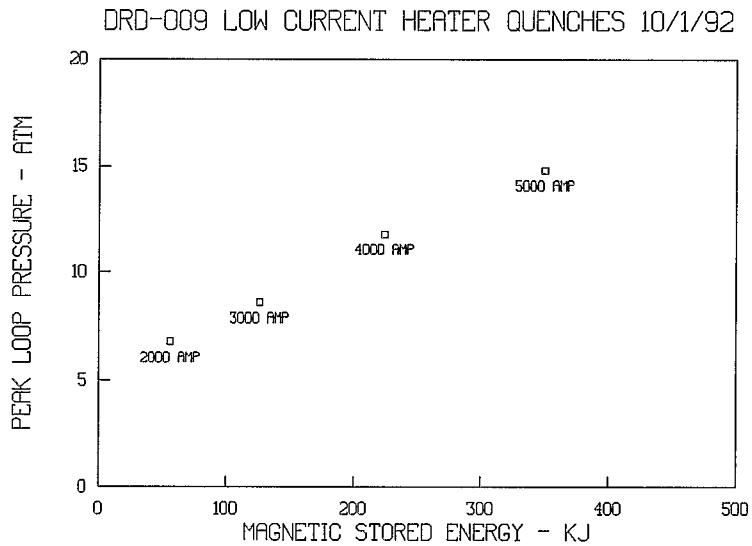

Fig. 2 Peak loop pressures versus magnetic stored energy

Temperatures recorded at the return to the MAGCOOL cold box are given in Fig. 3. The return temperatures are higher for higher current quenches. The peak temperatures recorded are 5.5, 6.29, 7.46 and 8.27 K, occurring 164, 162, 142 and 175 seconds respectively after the quench, for the 2000, 3000, 4000 and 5000 ampere quenches. The times at which the peak temperatures were recorded depend primarily on the flow rate of the helium in the cooling loop and are approximately 3 minutes after a quench for all cases. For the 4000 and 5000 ampere quenches, temperature fluctuations around the peak return temperature are believed to be not real.

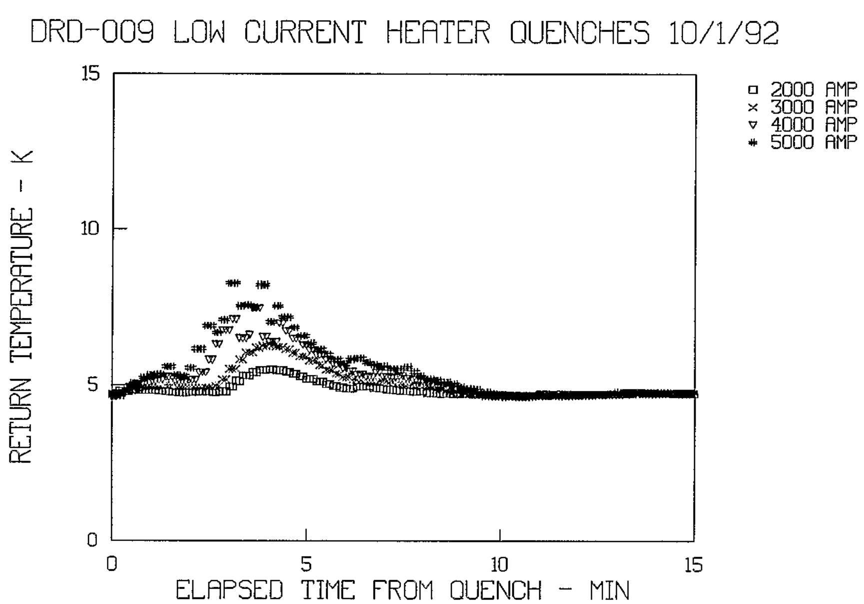

Fig. 3 Return temperatures in the MAGCOOL cold box

Temperatures recorded at the outlet of the magnet and the lead pot are given in Fig. 4 and 5. The time lag due to the circulation of helium can be found by super-imposing Figs. 3, 4 and 5. The peak temperatures and their times of occurrence are given in Table 2 of the Summary. The highest temperature occurs at the outlet of the magnet as expected. The peak temperatures observed at the return, the magnet outlet and the lead pot outlet are proportional to the magnetic stored energy as shown in Fig. 6. As can be seen from Fig. 6, the peak return temperatures for the 4000 and the 5000 ampere quenches are on the low side.

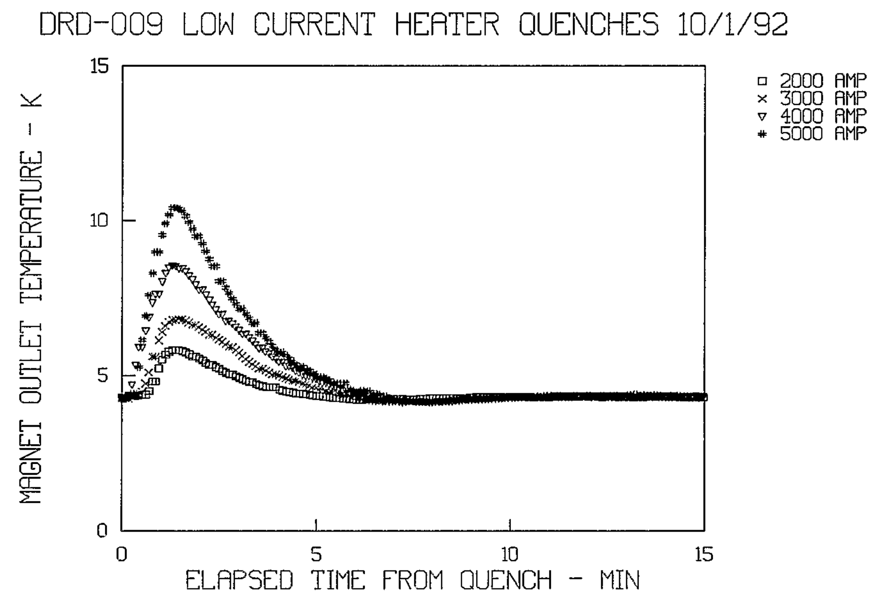

Fig. 4 Temperatures recorded at the outlet of the magnet

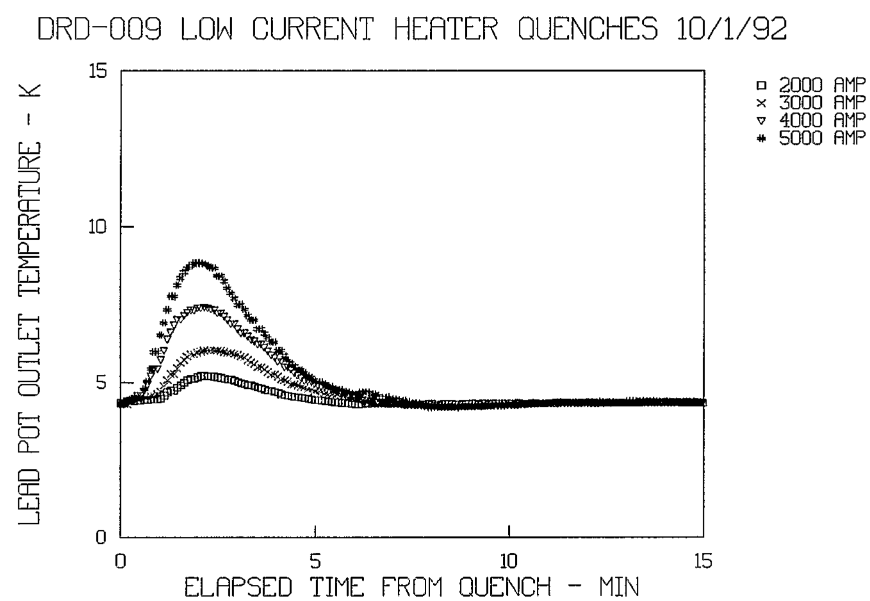

Fig. 5 Temperatures recorded at the outlet of the lead pot

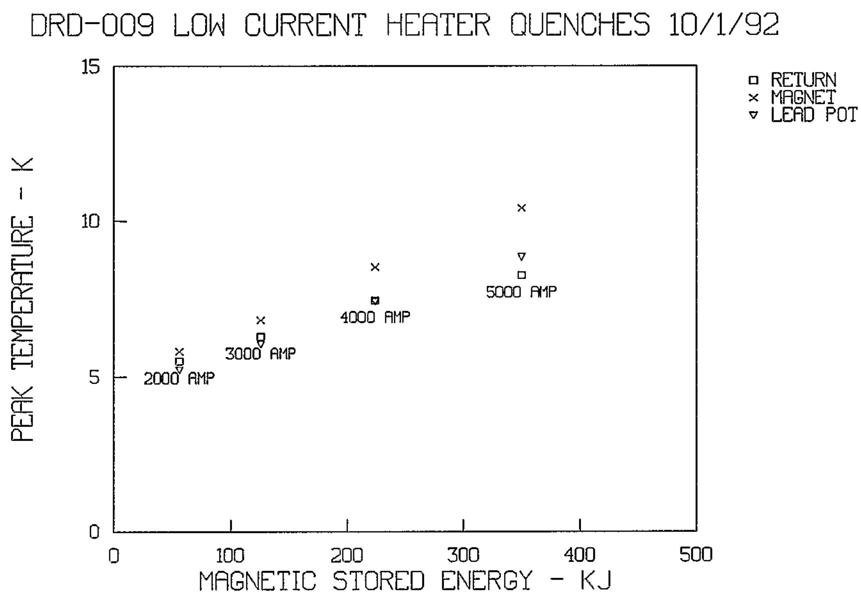

Fig. 6 Peak temperatures at the cold box return, the magnet and the lead pot

Helium flow rates through the magnet as a function of time are given in Fig. 7. The mass flow rate increases slightly after the quench due to an increase in loop pressure. As the circulating compressor starts to see the higher return temperature, the flow rate decreases. The flow rate recovers after the peak temperature passes through the circulating compressor. Perturbations of the flow rate are caused primarily by the opening of the helium make up valve. About 10 minutes after a quench, the flow rate returns to its initial value.

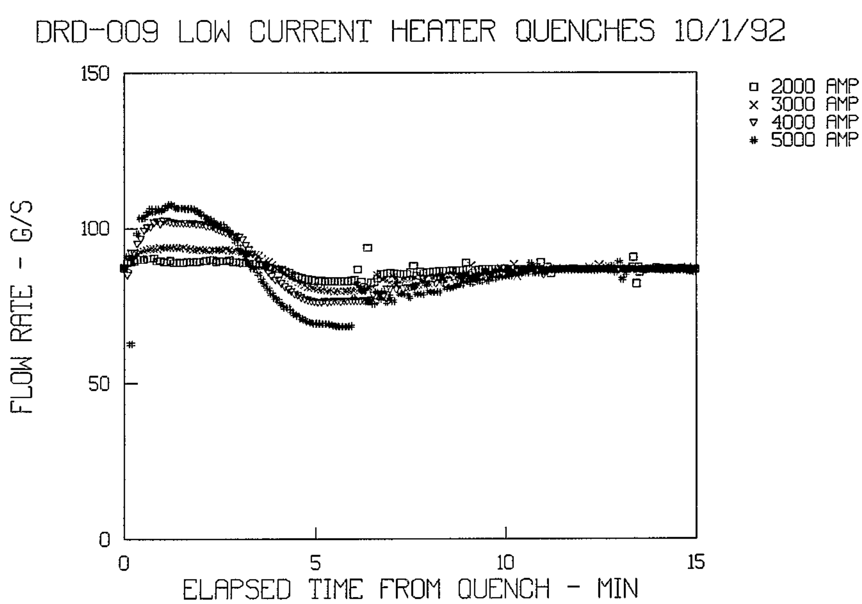

Fig. 7 Mass flow rates in the cooling loop

COOLING CAPACITY AND TOTAL COOLING FOR QUENCH RECOVERY

The apparent cooling rate applied to the magnet, the lead pot and the distribution headers is defined as the difference of enthalpy flux between the supply and the return lines. The net cooling rate for quench recovery equals the apparent cooling rate minus the background heat load. Because the system which started at test condition is cooled to the original condition after a quench, the integration of the net cooling rate represents the total amount of cooling provided for quench recovery and should be equal to the stored energy released by the magnet.

Previous investigations for the low current quenches of SSC dipoles and quadrupoles in MAGCOOL test stand B confirm that the total cooling determined by such integration is in excellent agreement with the magnetic stored energy[3,4].

The apparent cooling rates during quench recovery are given in Fig. 8. The maximum apparent cooling rates are 0.54, 0.90, 1.47 and 1.92 kilo-watts for quench currents of 2000, 3000, 4000 and 5000 amperes respectively. The maximum apparent cooling rates evaluated from the temperature sensors located at the inlet and the outlet of the magnet are higher than the above values, ranging from 10% higher for a 2000 ampere quench to about 50% higher for a 5000 ampere quench.

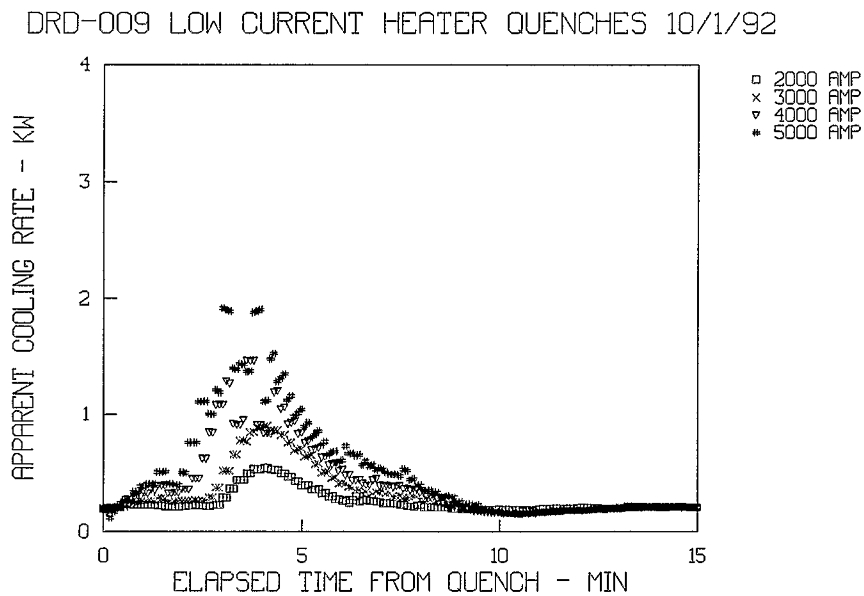

Fig. 8 Apparent cooling rates during quench recovery based on cold box temperatures

Total net cooling provided during quench recovery for the 2000, 3000, 4000 and 5000 ampere quenches is given in Fig. 9. The cooling provided increases with time and reaches a plateau when the loop is cooled to conditions existing prior to the quench. The total cooling provided is found to be 57, 116, 208 and 303 kilo-joules for the 2000, 3000, 4000 and 5000 ampere quenches respectively. Fluctuations in the temperature readings for the 4000 and 5000 ampere quenches caused the cooling in each case to be too low by an estimated 15 kilo-joules. The inductance for DRD-009 has been measured to be 0.028 Henries[2]. After adding 15 kilo-joules to both the 4000 and 5000 ampere quenches, the difference between the total cooling and the magnetic stored energy in each case is less than 10% as shown in Table 3. The total net cooling based on the temperature sensors located at the inlet and outlet of the magnet is higher by about 30% than the results shown in Fig. 9. Since both the venturi flow meter[5] and the temperature sensors are believed to be accurate, the discrepancy in cooling as evaluated from sensors located at the MAGCOOL cold box versus sensors located near the magnet requires further study.

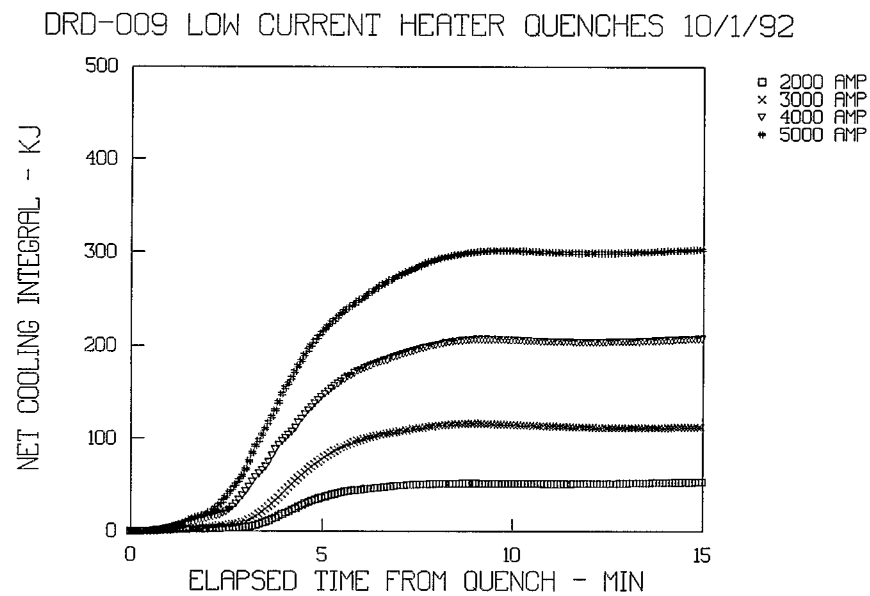

Fig. 9 Total cooling provided to the magnet for quench recovery based on cold box temperatures

SUMMARY

Characteristics of the MAGCOOL cryogenic system for the low current quenches for DRD-009 are summarized in Tables 1 through 3.

Table 1. Peak pressures and times of occurrence for the low current quenches

Quench current ampere	Nominal temperature prior to quench K	Nominal pressure prior to quench atms.	Peak loop pressure atms.	Time to peak pressure second
2000	4.3	5	6.79	53
3000	4.3	5	8.61	87
4000	4.3	5	11.8	93
5000	4.3	5	14.8	82

Table 2. Peak temperatures at the outlet of the magnet, at the outlet of the lead pot and at the cold box return for the low current quenches

Quench current ampere	Nominal temp. prior to quench K	Peak magnet outlet temp. K	Time to peak magnet outlet temp. second	Peak lead pot temp. K	Time to peak lead pot temp. second	Peak return temp. K	Time to peak return temp. second
2000	4.3	5.82	88	5.22	129	5.50	164
3000	4.3	6.83	87	6.05	132	6.29	162
4000	4.3	8.53	77	7.42	128	7.46	142
5000	4.3	10.42	69	8.85	118	8.27	175

Table 3. Maximum cooling rates, total cooling provided and the magnetic stored energies for the low current quenches

Quench current ampere	Nominal temp prior to quench K	Maximum cooling rate KW	Total cooling provided KJ	Magnetic stored energy KJ	Ratio of total cooling provided to magnetic stored energy
2000	4.3	0.54	57	56	1.02
3000	4.3	0.90	116	126	0.92
4000	4.3	1.47	223*	224	1.00
5000	4.3	1.92	328*	350	0.94

* Add 15 KJ to compensate fluctuation in temperature reading

CONCLUSION

The thermal behavior of the MAGCOOL cryogenic system after low current quenches of RHIC magnet DRD-009 has been investigated. Both peak loop pressures and peak temperatures are found to be in proportion to the stored energy released to the cooling helium. Although there are discrepancies between results evaluated based on temperature sensors located on the MAGCOOL cold box as compared to sensors located on the magnet, general agreement between the cooling provided and the magnetic energy released has been obtained.

ACKNOWLEDGEMENT

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