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Performance of the MAGCOOL-Subcooler Cryogenic System After 50 mm SSC Dipole Quenches

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PERFORMANCE OF THE MAGCOOL-SUBCOOLER CRYOGENIC SYSTEM AFTER 50 MM SSC DIPOLE QUENCHES*

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ABSTRACT

The subcooler assembly installed in the MAGCOOL test area at Brookhaven National Laboratory has been used for testing SSC magnets since 1989. As part of the test program, magnets are quenched routinely in the system. The system description and steady state capacity have been given previously[1]. In this paper, the thermal behavior of the subcooler cryogenic system after quenches of the 50 mm SSC dipole magnet DCA207 are presented.

Pressures, temperatures and flow rates in the magnet cooling loop are given as a function of time. The heating/cooling and venting mechanisms are illustrated. The cooling rates and the total energy removed by cooling during quench recovery have been calculated for quench currents of 6000, 6883 and 7406 ampere at 4.35 K, and for 8413 ampere at 3.5 K. Results show that the total energy removed by cooling during quench recovery is in good agreement with the stored energy released by the magnet during the quench. No operating difficulties were encountered during the magnet tests. System recovery time varies from 50 minutes for a 6000 ampere quench to 90 minutes for an 8413 ampere quench.

INTRODUCTION

The thermodynamic process following a magnet quench is complex. When a superconducting magnet becomes normal, a large amount of stored energy is released into the magnet and the helium stream in a fraction of a second. The fluid is compressible, the phenomenon is transient and the geometry is complicated. The process depends both on the magnet and on the cooling system. Not only it is difficult to model the process, it is difficult to generate a well defined set of measurements for the thermal process after a magnet quench.

The subcooler assembly installed in the MAGCOOL test area at Brookhaven National Laboratory has been used to test successfully twelve 40 mm and two 50 mm SSC dipoles. These tests included several hundred magnet quenches. The cryogenic system recovers consistently after each quench. The assembly is operated by a CRISP process control computer with a real time data acquisition system which offers a unique opportunity to document the quench recovery process.

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SYSTEM DESCRIPTION

The cryogenic system for a single SSC magnet test consists of the HEUB/MAGCOOL helium refrigerator, the MAGCOOL distribution headers, the subcooler assembly, the feed can, the SSC magnet, and the return can. Fig. 1 shows the flow diagram for the subcooler assembly.

An important feature of the subcooler assembly is the use of a circulating compressor for closed loop circulation of single phase helium which obtains cooling from the subcooler helium pot and delivers it to the magnet. The flow rate, pressures and temperatures in the loop can be controlled independently of the refrigerator. There is no need to change the operating configuration of either the refrigerator or the subcooler assembly during a quench, and meaningful descriptions of the recovery process can be obtained.

The cold vacuum pump is used to adjust the pressure inside the helium pot and control magnet test temperature for steady state operation. During quench recovery, the cold vacuum pump restores the liquid helium level in the subcooler pot by establishing a flow from the pre-cooler pot. The wet expander, in Fig. 1, increases system efficiency by generating cooling at liquid helium temperature. Valves 307 and 300 are two valves used to control the loop pressure. When the loop pressure becomes higher than the set value during a quench, vent valve 307 opens to control the loop pressure. The makeup valve 300 is used to make up the vented helium when the magnet is cooled back to test temperature.

The subcooler assembly is well instrumented for purposes of computer control and system evaluation. There are fifteen sets of dual diode temperature sensors, five pressure transducers, two liquid level gages and one venturi flow meter. Real time pressure in atms, flow rate in g/s and speed in rpm are directly available. In Fig. 1, the temperatures are shown without units and are in Kelvin.

The volume for the circulating loop piping is approximately 290 liters and there is a warm line of 10 liter volume connected to the relief valve. Prior to a quench, the magnet is maintained at test temperature via circulation of 150 g/s of supercritical helium. There are 40,000 grams of helium in the loop, and it takes four and half minutes for the helium to travel through the loop. The amount of liquid helium stored in each of the subcooler and the precooler helium pots is 110 liters and each amount provides a cooling reserve of 240 Kilo-joules.

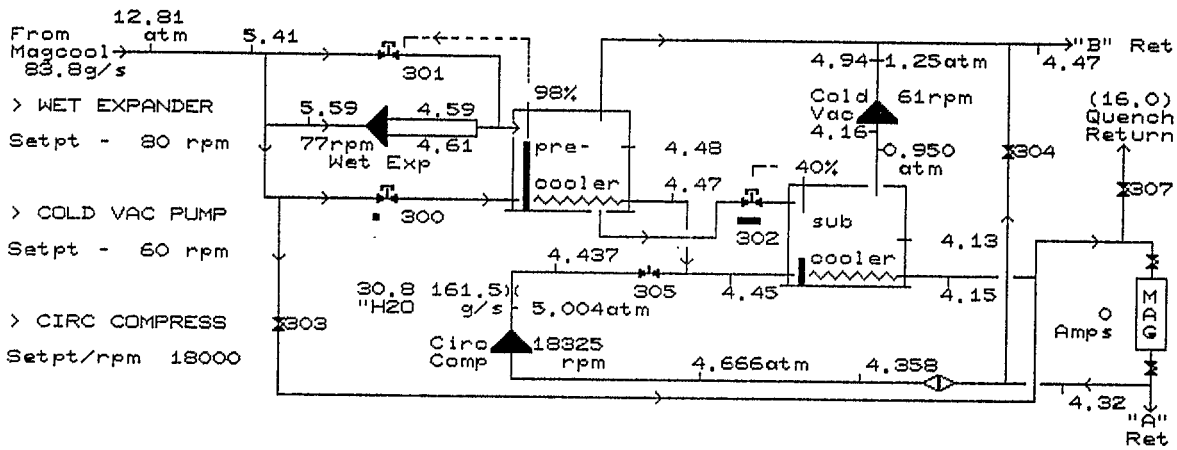

Fig. 1 Flow diagram for the subcooler assembly

PRESSURE, TEMPERATURE AND FLOW RATE AFTER QUENCH

The following results were obtained from quench of SSC DCA207 dipole installed in MAGCOOL test stand A. The magnet is maintained at 4.35 K and the quench current is 7406 amperes.

The loop pressure measured at the discharge of the circulating compressor by a strain gauge type transducer is given in Figs. 2 and 3 as a function of time. After the quench, the loop pressure increases quickly from 5 atm to about 8 atm in one second at a rate of 3 atm per second. Fortunately this initial pressure rise rate does not persist as the pressure increases further to 17 atm in about 20 seconds at an average pressure rise rate of 0.6 atm per second. It should be noted that 0.6 atm per second pressure rise is still very fast and 20 seconds is a very short time in cryogenic operations.

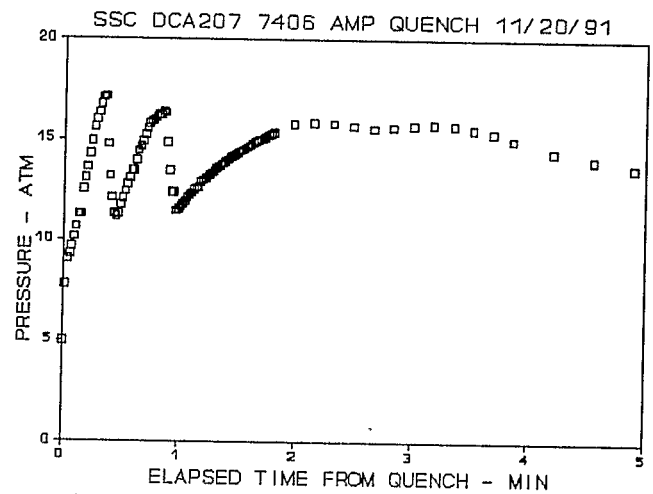

Fig. 2 Loop pressure after magnet quench

When loop pressure exceeds the set pressure of 16 atm, valve 307 opens to vent excess helium reducing the loop pressure to about 11.5 atm. The heating process continues with the loop pressure increasing at a slower rate and the venting repeats. Fig. 2 shows the first 5 min. of the pressure history with the vent valve opening twice during the first minute. After the second venting, the loop pressure first increases but soon decreases as the magnet is cooled back down. In about 15 minutes, the loop pressure falls below 5 atm and the makeup valve 300 opens to maintain the helium in the loop at 5 atm.

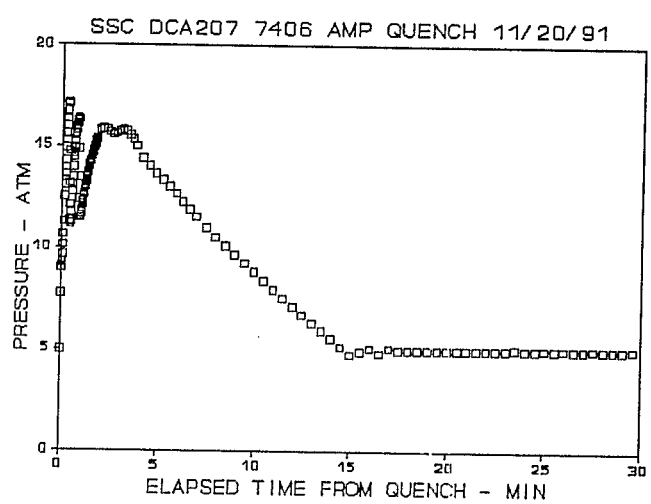

Fig. 3 Loop pressure after magnet quench

Temperatures recorded by calibrated diode sensors located at the supply and return lines of the subcooler assembly are given in Fig. 4. As can be seen, the temperatures respond more slowly than the pressure because it takes time for the heat to be transferred to the helium and carried to the subcooler by the flow.

The highest temperature recorded is 22.5 K occurring approximately 3.5 minutes after the quench. After the peak temperature is recorded, the return temperature decreases quickly to about 11 K in 3 minutes and then decreases at a slower rate. When the loop pressure reaches 5 atm 15 minutes after the quench, the supply and the return temperatures are 6.1 and 6.9 K respectively. Perturbations in temperatures near the subcooler helium pot occur due to the opening of the makeup valve.

The amount of helium vented can be calculated from the density difference between the test condition before the quench and the condition when loop pressure first returns to 5 atm. In the above case, approximately 92 liters of single phase helium was vented from the loop and the same amount was needed to make up the density difference when the loop was cooled to the operating temperature.

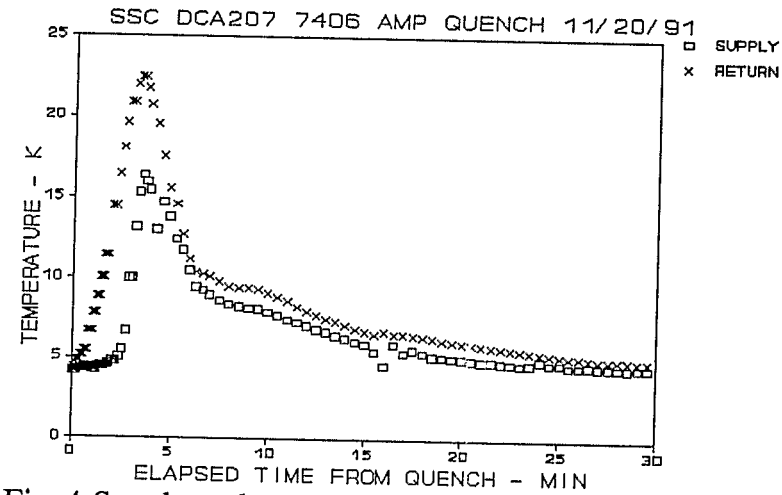

Fig. 4 Supply and return temperatures of the subcooler

In addition to pressures and temperatures, the flow rate through the loop must be known in order to evaluate the amount of cooling transferred during the recovery process. Using a venturi flow meter installed on the subcooler assembly, the mass flow rate maybe evaluated from the measured differential pressure and the density calculated from the measured pressure and temperature. During quench recovery, helium in the loop remains in single phase. With the circulating compressor maintained at constant speed, flow measurements are valid except during venting and make up.

The helium flow through the magnet as a function of time is given in Fig. 5. The mass flow rate after a quench first increases due to an increase in loop pressure but soon decreases as the return temperature increases. After the peak temperature is reached, the mass flow slowly increases to its original value. The momentary drop in flow occurring 15 minutes after the quench is caused by the opening of the makeup valve. Perturbations become smaller afterwards. The flow rate is a good indicator of the recovery in the circulating loop and the magnet. As can be see from Fig. 5, recovery of the magnet loop takes about 30 minutes.

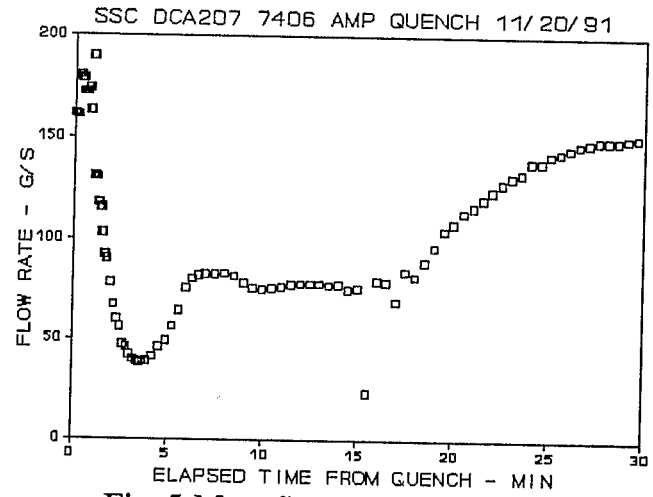

Fig. 5 Mass flow rate after quench

COOLING RATES

The cooling rate of the subcooler after a magnet quench is of great interest because the quench recovery is nothing more than a cooling process after the magnetic stored energy is released into the helium system. However, the exact cooling rate is difficult to calculate due to the transient nature of and the venting involved in the process. The system which started at test conditions is eventually cooled to the original conditions. The enthalpy flux difference between the supply and the return lines can be considered as the apparent cooling rate applied to the magnet. The net cooling for quench recovery equals the apparent cooling rate minus the background heat load. The total amount of cooling for quench recovery equals the integration of net cooling rates.

Apparent cooling rates to the magnet during quench recovery are given in Fig. 6. The apparent cooling rate peaks at 4500 watts 2 minutes after the quench and then decreases to about 800 watts in 5 minutes. There is an artificially wide variation in the cooling rate due to the opening of the makeup valve 15 minutes after the quench. The average cooling rate over the first 30 minute period is approximately 900 watts.

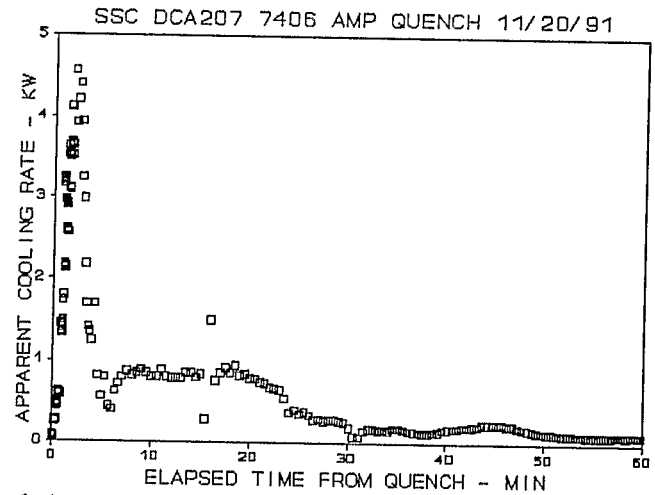

Fig.6 Apparent cooling rate during quench recovery

The integrated totals of net cooling as functions of time for the magnet are given in Fig. 7. As can be seen from Fig. 7, the cooling provided increases with time and is equal to 800, 1300 and 1500 kilo-joules at 10, 20 and 30 minutes after the quench occurred. At the end of the 60 minute quench recovery period, 1600 kilo-

joules of cooling have been provided with an estimated background heat load of 320 kilo-joules. Because the magnet system is fully recovered at the end of 60 minutes, the 1600 kilo-joule represents the amount of heat released from the magnet. The magnetic stored energy calculated from the inductance and the current, $1/2\ LI^2$, equals 2235 kilo-joules[2]. Thus the 1600 kilo-joule result as obtained from the integration of enthalpy flux equals approximately 72 per cent of the magnetic stored energy.

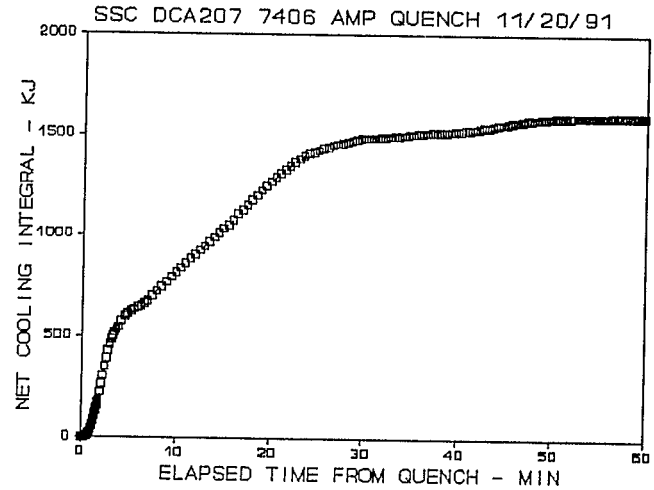

Fig. 7 Integrated totals of net cooling

RESULTS AT OTHER CURRENTS

Results for quench currents of 6000, 6883 and 8413 amperes have been investigated. In all cases, the characteristics of pressure, temperature and flow rate are similar to those given in Figs. 2 to 5.

Higher current quenches corresponds to larger stored energy releases. As shown in Fig. 8, the return temperatures as a function of time for 6000, 6683 and 7406 ampere quenches clearly suggest a higher peak temperature for a higher current. The 8413 ampere quench initiated at 3.5 K gives a peak temperature of 18.7 K which is lower than that of the 7406 ampere quench at 4.35 K.

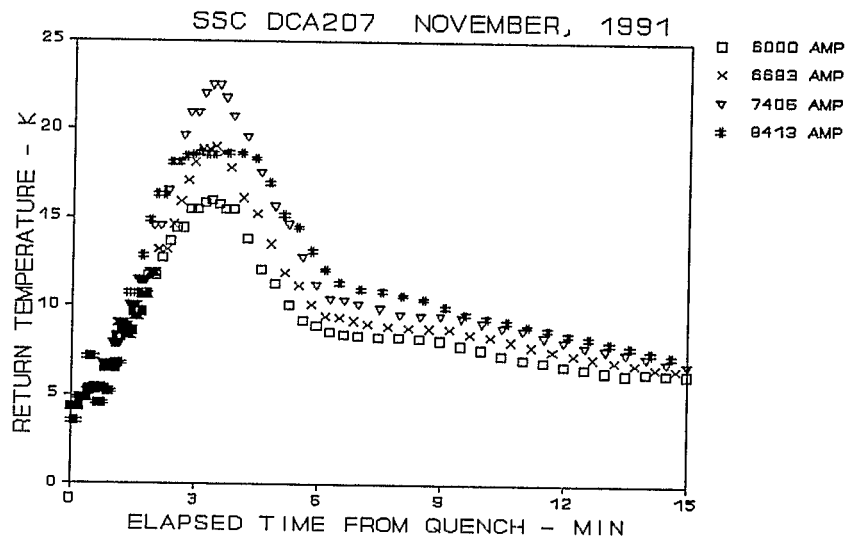

Fig. 8 Return temperatures for four currents

The pressure rise rate is fastest for the 8413 ampere quench, followed by the 7406 ampere quench, as can be seen from Fig. 9. For the 6000 and 6683 ampere quenches, the difference in rise rates is not as obvious. The first opening of valve 307

after the 6000 ampere quench occurs sooner after the quench than the first opening after the 6683 ampere quench. The second opening of 307 after the 6000 ampere quench occurs later after the quench than the second opening after the 6683 ampere quench. This suggests that even through higher energy releases in the magnet eventually translate to higher pressure rises, the process may depends on the details of the quench occurrence in addition to the quench current.

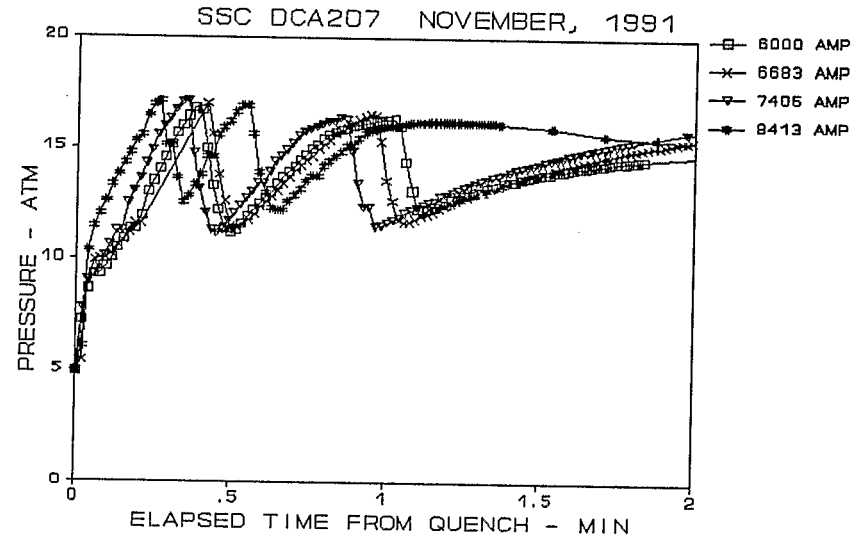

Fig. 9 Pressure history for four currents

The cooling rate and the total cooling provided are also found to be greater for higher quench currents. Fig. 10 shows the total cooling provided during quench recovery for different currents.

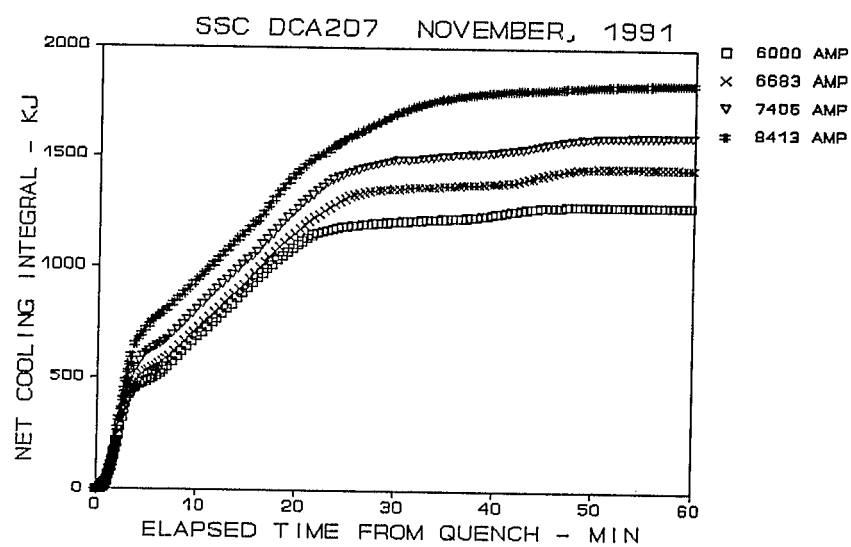

Fig 10. Cooling provided for four currents

The results for four quench currents are summarized in Table 1. The initial pressure rise rate used here is based on the pressure rise rate for the first five seconds after a quench. The recovery time is obtained when both the magnet temperature and the liquid levels in the helium pots are restored. The cooling integral and the corresponding magnetic stored energy are also given in Table 1. The ratio of the cooling integral to the magnetic stored energy varies from 87% at 6000 amperes to 64% at 8413 amperes.

Table 1. Results for four quench currents

Test Temp	Quench current	Init. pressure rise rate	Peak return temp.	Max. Cooling Rate	Total Cooling	½LI²	Ratio	Helium Vented	Recovery Time
K	ampere	atm/s	K	kw	kj	kj	%	liter	min.
4.35	6000	0.95	16	4.0	1280	1467	87	92	48
4.35	6683	1.02	19	4.3	1450	1820	80	113	52
4.35	7406	1.03	22.5	4.6	1600	2235	72	128	65
3.5	8413	1.53	18.7	4.9	1850	2884	64	133	86

DISCUSSION

The results given in this paper are only valid for a 50 mm SSC dipole magnet installed on MAGCOOL test stand A. The effect of the quench origin and details of quench phenomena are not considered. The effect due to the pressure control venting process is also neglected in the present study. If the venting process could be accounted for, the energy obtained from the enthalpy flux should agree better with the magnetic stored energy. The circulating loop is connected to a 1.5 inch relief line of 10 liter volume. It is believed this volume helps to slow down the pressure rise rate, but quantitative results are not available.

CONCLUSION

Quantitative results for the response of the MAGCOOL subcooler system after a magnet quench have been presented. The cooling/heating and venting mechanisms have been analyzed. The response time is of the order of seconds for pressures and longer for temperatures. Conventional instrumentation appears to be appropriate for data acquisition and process control. No operating difficulties were encountered with the subcooler assembly or any part of the cryogenic system during a magnet quench. Because the amount of helium vented outside the circulating loop is minimized by presetting the quench vent valve 307 to a high pressure value and because cooling is continuously provided to the magnet, operating test conditions are restored rapidly after a magnet quench. The subcooler assembly is capable of cooling the magnet back to test conditions in about 30 minutes and the liquid level in the helium pots are restored in one to one and half hour.

ACKNOWLEDGEMENT

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REFERENCES

1. K. C. Wu, D. P. Brown, J. H. Sondericker, Y. Farah, D. Zantopp and A. Nicoletti,"SUBCOOLER ASSEMBLY FOR SSC SINGLE MAGNET TEST PROGRAM", to be published in "Advances in Cryogenic Engineering", Vol. 37, 1992.

2. Private communication with A. Prodell, the inductance for DCA207 has been measured by P. Radusewicz to be 0.0815 Henry.