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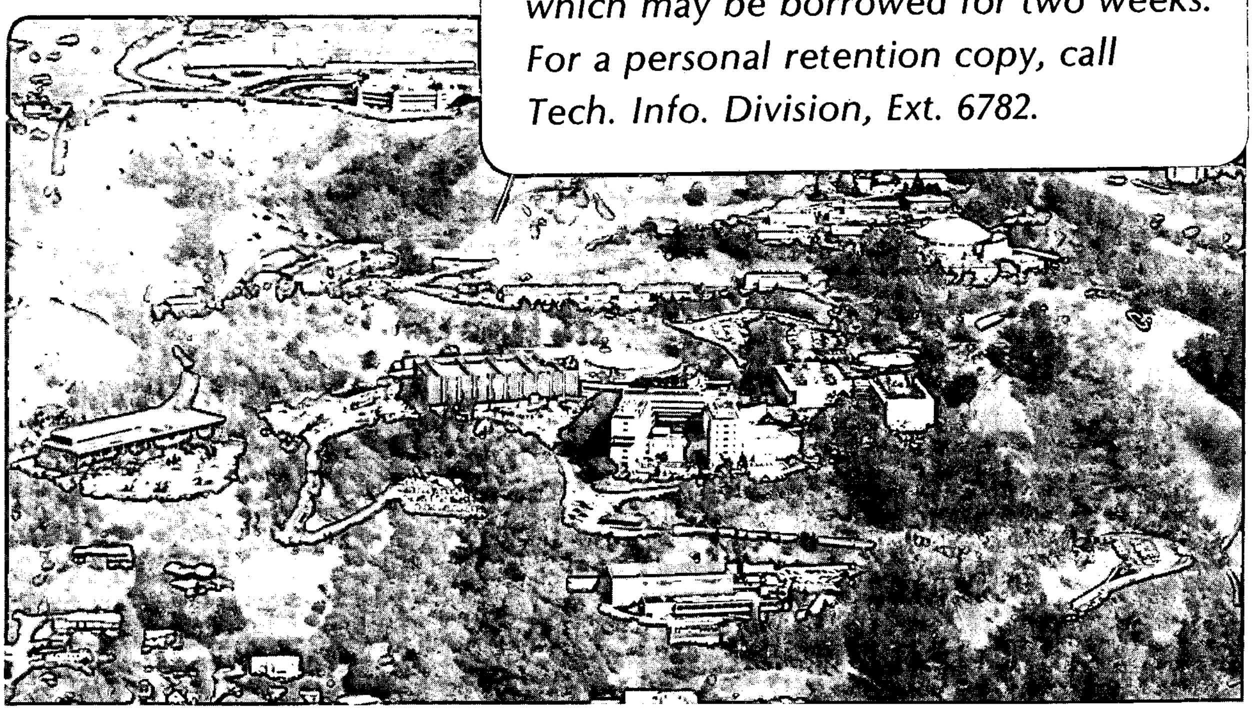

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DISCLAIMER

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ABSTRACT

This paper describes the cryogenic tests of the TPC 2-meter-diameter superconducting solenoid on a 200 W refrigerator with gas-bearing turbines. The solenoid is cooled with two phase helium in forced flow around the superconducting winding. The two-phase helium was circulated using either the J-T circuit flow or a bellows type liquid helium pump. The particular problems associated with running a variable load on a gas-bearing turbine refrigerator are discussed.

THE TPC MAGNET CRYOGENIC SYSTEM

The TPC superconducting solenoid which has been installed as part of a high energy physics experiment at the Stanford Linear Accelerator Center SLAC includes the following major components: 1) The gaseous helium compressor system, 2) the CTi Model 2800 cold box, 3) the control dewar and transfer lines, 4) the conditioner system, and 5) the two phase cooled superconducting magnet. The helium compressor system is separated from the other four components by 400 meters of helium supply and return piping. The remaining four components, which are located at the interaction region of the experiment, are shown in Figure 1.

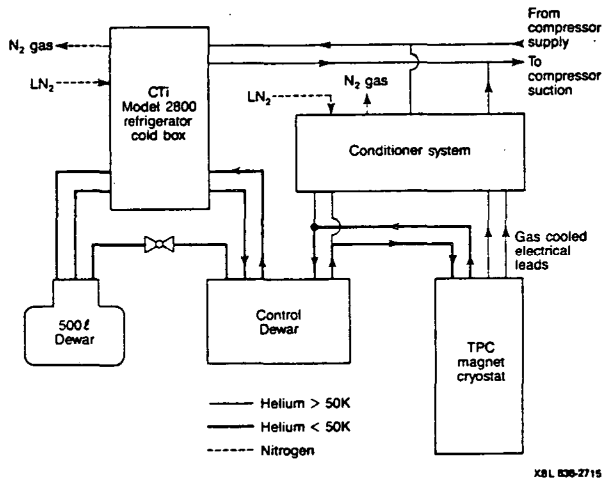


Fig. 1. An overall TPC magnet cryogenic system schematic diagram.

The helium compressor system consists of a single Sulair screw compressor with oil removal equipment. This compressor can deliver up to 54 gs^{-1} to the refrigerator. Included in the compressor system is the helium makeup and recovery system and a full flow liquid nitrogen temperature helium purification station. Helium is delivered to the refrigeration system at a pressure of up to 1.65 MPa (240 psia) and the helium is returned to the compressor at a pressure of around 0.11 MPa (16 psia).

The refrigerator cold box is a CTi Model 2800 refrigerator with two Sulzer gas bearing turbines which are in series with a heat exchanger between them. The high temperature turbine operates at a nominal pressure ratio of 2.5 to 3. The lower turbine operates at a pressure ratio of around 5. The gas bearings in the turbines are self actuating which in theory require no external gas source. The refrigerator can supply refrigeration to the TPC magnet and liquify helium into a 500 liter dewar simultaneously.

The control dewar is a 175 liter open mouth helium dewar which contains a heat exchanger and a liquid helium pump (see Figure 2). The use of a control dewar permits one to use either the refrigerator J-T circuit or the liquid helium pump to circulate helium to the magnet. About 70 percent of the TPC magnet liquid helium inventory is in the control dewar. The heat exchanger within the control dewar shifts the two phase cooling process from the gas side to the liquid side of the two phase dome. This permits one to refrigerate a load which is up to 150 percent of the output of the refrigerator for a short period of time. The pressure drop through the magnet cooling tubes is also reduced. The liquid helium pump can be used to circulate two phase helium through the magnet in the event the refrigerator shuts down for a short time (i.e., a cold shut down of the turbines).

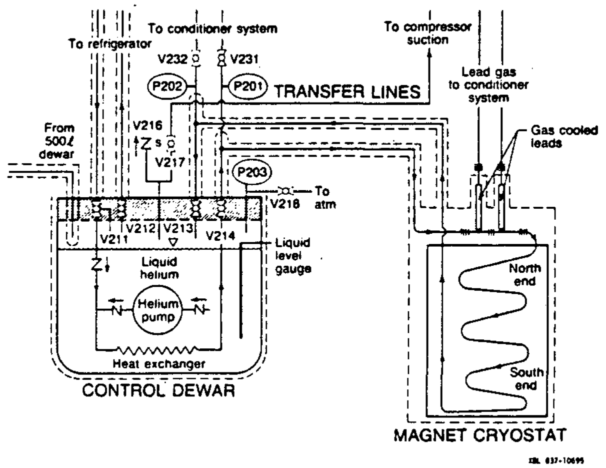


Fig. 2. A schematic diagram of the helium circuits for the control dewar, transfer lines and the magnet.

The conditioner system is used for cooldown and warmup of the magnet. The magnet can be cooled from 300 K to 85 K using the liquid nitrogen to helium heat exchanger which is part of the conditioner system. Gas can be injected into the magnet system from the conditioner from any temperature between 85 and 350 K. Heat exchangers and heaters within the conditioner system can heat the gas returning from the magnet during a warmup or cooldown before it returns to the compressor suction. The conditioner can hold the TPC magnet at 85 K while repairs are made on the helium refrigerator cold box.

The TPC thin superconducting solenoid is connected to the control dewar-conditioner system by 32 meters of liquid nitrogen shielded transfer lines. These lines are semi flexible so that the magnet can be easily installed in its iron shield. During the test reported here, an additional 38 meters of transfer line was added so that the stray field of the magnet would not affect the TPC experiment computers (the magnet was tested outside the iron). The transfer lines and the magnet cooling circuit are sized so that 12 to 15 gs^{-1} of two phase helium can be carried with a pressure drop of 0.03 MPa (4.5 psi) or less.[1]

The TPC thin solenoid has a warm bore diameter of 2.04 m. Its outside diameter is 2.44 m at the ends (2.36 m in the center) and its length is 3.83 m. The cold mass of the superconducting coil and its cooling circuit is 2330 kg.[2] The cooling circuit, which is 300 m long, consists of 43 turns of finned aluminum tube epoxied to the magnet coil package. The gas cooled electrical leads are cooled directly off the two phase flow circuit. The cross-section of the cooling tube was chosen so that phase separation is avoided. The total cold mass of the magnet, transfer lines and control dewar is approximately 2600 kg. The flow circuit was designed to cool this mass from 300 K to 4 K in 24 hours.

CALORIMETRY AND MEASUREMENTS OF REFRIGERATOR PERFORMANCE

Several methods for measuring the cryogenic system performance were used. The calorimetry methods used included 1) direct measurement of helium boil off with a gas meter, 2) measurement of liquid level drop in the control dewar, 3) mass and energy balance on the system with cold gas leaving, and 4) relative liquifaction and refrigeration based on a known performance curve. Measurements of magnet system performance were made while the helium pump circulated helium. Measurements were made at different pump speeds in order to separate out the pump work.[3]

Table 1 shows the measured heat loads for the TPC cryogenic system. The indicated error represents one standard deviation of the various measurements. The magnet system loss was measured both with and without liquid nitrogen in the magnet cryostat shields. The CTi model 2800 refrigerator while operating on the SLAC compressor system is capable of delivering 250 to 260 W of refrigeration or 3 gs^{-1} of liquid helium. During a portion of the test, the refrigerator did not liquify to its full potential.

Table 1. A comparison of measured heat loads in the TPC magnet system with and without LN_2 in the magnet cryostat shields.

Source	Heat Load (W) Without LN_2	Heat Load (W) With LN_2
Magnet Cryostat	56 ± 7	16 ± 2
Control Dewar	3 ± 0.4	6 ± 1*
Refrigerator to Control Dewar Transfer Lines	6 ± 2	6 ± 2
TPC System Transfer Lines	37 ± 3	37 ± 3
TOTAL HEAT LOAD	102 ± 9	65 ± 8

*Includes an estimated 3 to 4 W thermal acoustic oscillation heat leak.
NOTE: A helium liquifaction rate of 0.3 to 0.4 gs^{-1} is required to gas cool the electrical leads.

The reduced capacity (still above 220 W) is believed to be due to some of the automatic control functions and/or damage to one of the turbines.

COOLDOWN OF THE MAGNET SYSTEM TO 10 K

The TPC magnet system was cooled from room temperature to helium temperature three times during the magnet system test. Numerous cooldowns were made from 70 to 4.5 K. One cooldown was made using the model 2800 refrigerator; two cooldowns were made using the conditioner system to cool to 85 K. There was no limit placed on the end to end temperature gradient in the magnet. A limit was placed on the difference between the entering temperature of the cold gas and the temperature of the cold end of the magnet. This limit was 25 K when the magnet was at 300 K and there was no limit once the cold end of the magnet reached 150 K (Ref. 3).

The cooldown using the 2800 refrigerator alone took 36 hours from the start until the magnet turned superconducting. The magnet was ready to operate 6 hours later. The maximum end-to-end temperature gradient was 140 K; the maximum mass flow through the flow circuit was 10.8 gs^{-1}; and the maximum pressure drop across the flow circuit was 4.8 atm. The peak refrigeration delivered from the cold box was 4800 W.

The cooldowns using the conditioner took 24 to 28 hours (see Figures 3 and 4). The refrigerator was not turned on until the warm end of the magnet reached 100 K. Once the magnet had become superconducting, liquid helium could be transferred so that magnet operation could proceed. The maximum end-to-end temperature gradient was 150 K; the maximum mass flow through the flow circuit was 12.5 gs^{-1} and the maximum pressure drop across the flow circuit was 8.5 atm during a conditioner assisted cooldown. A maximum refrigeration rate of 7500 W was generated by the conditioner (see Figure 4).

The 2600 kg of cold mass in the TPC magnet cryogenic system was cooled to 4 K in just over 24 hours using the conditioner and liquid from the 500 liter storage dewar. Depending on when liquid helium is added the overall cooldown time could be reduced to 20 to 22 hours.

OPERATION OF THE TPC CRYOGENIC SYSTEM

The transition of the magnet from the normal to the superconducting state took 10 to 20 minutes. It took another 30 minutes to establish two phase flow in the magnet cooling loop. Two

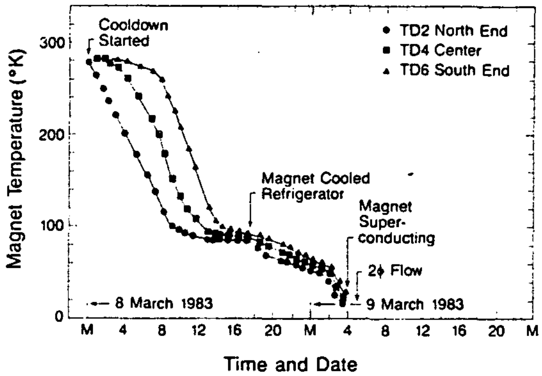


Fig. 3. The temperature at the north end, center, and south end of the TPC magnet versus time of day during a cooldown using the conditioner for the above 100K portion of the cooldown.

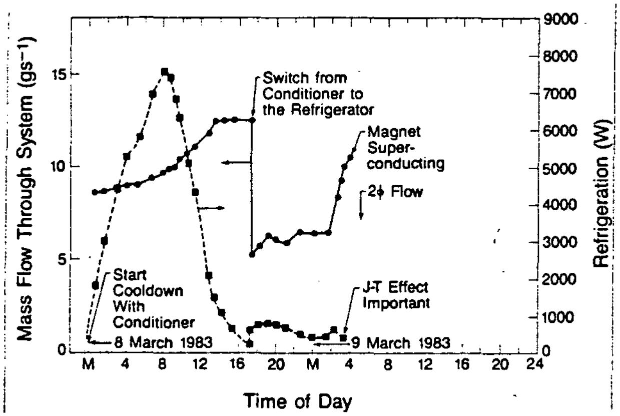
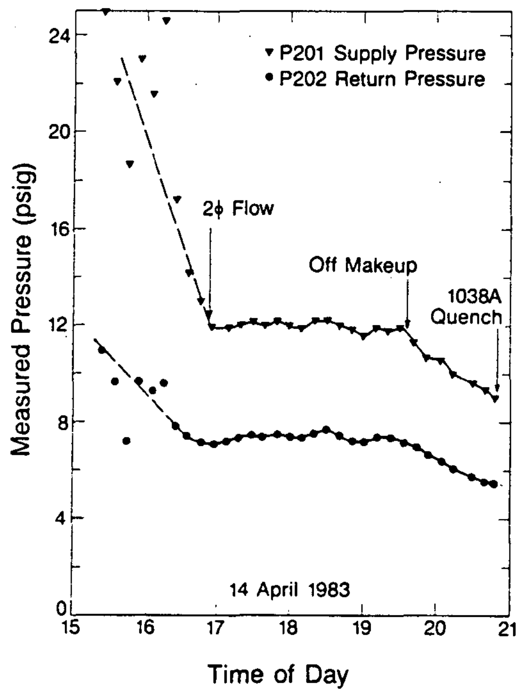


Fig. 4. Calculated circuit mass flow and refrigeration rate delivered to the magnet cold mass versus time of day during a cooldown using the conditioner down to 100K.

phase flow is characterized by a drop in control dewar pressure and a marked reduction in the pressure drop across the flow circuit. Fluctuations of the inlet and outlet pressures are also reduced when the system is in two phase flow (see Figure 5).

When the refrigerator is operated in the off make up mode (make up helium to the refrigerator is shut off), both the inlet and outlet pressures of the flow circuit are reduced. Liquifaction in the control dewar slows, then ceases. Once the system reaches equilibrium (it takes several hours), pressures in the control dewar as low as 0.128 MPa (3.5 psig) were recorded. The maximum pressure in the flow circuit (with LN_2 in the magnet shield) reached values as low as 0.153 MPa (7.5 psig). In most cases, the operating temperature of the magnet at the high pressure end was between 4.7 and 4.9 K (see Figure 6). The TPC magnet was operated on the two phase cooling system at its design operating current of 2260 A without quenching on May 17, 1983.

The TPC magnet was also kept cold using the liquid helium pump as a two phase helium circulator. The helium pump can pump up to 50 gs^{-1} (Ref. 4) but it was used at nominal helium flow rates of 10 to 25 gs^{-1}. The amount of liquid helium in the flow circuit was usually higher when the system operated on the helium pump. One could switch back and forth from the pump to the refrigerator but operation with the pump required additional refrigeration to handle the pump work.



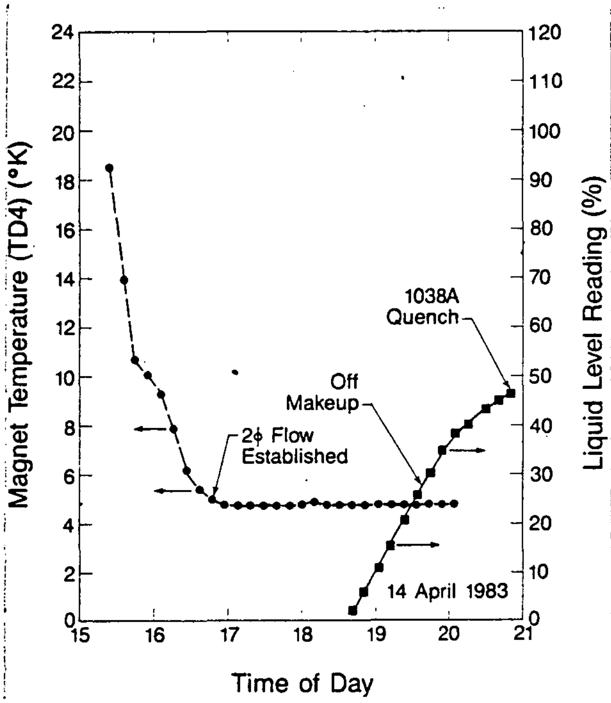


Fig. 5. Measured inlet and outlet of day at the end of pressures PT201 and PT202 versus time of day at the end of the cooldown and during filling of the control dewar.

Fig. 6. Measured magnet temperature (TD4) and measured liquid level in the control dewar versus time of day at the end of cooldown and while filling the control dewar.

The major operating problem on the TPC magnet was the Sulzer gas bearing turbines. During the test, two first stage turbines failed. The root of the problems with the gas bearing turbines is weak thrust bearings. A pressure unbalance across the turbine causes the thrust bearings to scrub. One of the turbine failures was caused by a quick shut down of the inlet gas flow to the turbine. One turbine failure and several bearing scrubs, which did not result in turbine failures, were caused by sudden cooling of the lower heat exchangers of the refrigerator, which changes the pressure ratio across the upper turbine.

Unlike many helium systems, where the refrigerator makes liquid into a constant pressure dewar, the TPC cryogenic system is a dynamic system which changes its pressure and temperature in response to the load and control of the J-T valve. As a result, a number of modifications of the cryogenic system had to be made so that one could have a system one could live with. These changes include: 1) an automatic J-T valve which uses the entry temperature of the number two turbine as a control function,

2) an automatic spoiler control to inject warm gas into the entry of the second turbine in the event the J-T valve control is not adequate, 3) an automatic pressure control at the inlet of the first turbine, and 4) an automatic quick shut off valve between the control dewar and the refrigerator on the return line (see V212 in Figure 2).

The automatic shut off valve is very important when the magnet quenches. Unlike refrigerators with piston expanders (some other turbine machines as well), the 2800 with the Sulzer turbine can not tolerate a sudden burst of cold gas back through the heat exchangers. The automatic shut off valve is actuated by: 1) a detected magnet quench, 2) a pressure drop across the flow circuit greater than 0.11 MPa (16 psig) when the system is in two phase flow, and 3) a control dewar pressure greater than 0.21 MPa (16 psig). In addition to the shut off valve, the liquid level in the control dewar was dropped to about 70 percent full. Using the automatic shut off valve, one can quench the TPC magnet at its full design current without turbine failure.

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