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CRYOGENIC TESTING OF THE TPC SUPERCONDUCTING SOLENOID

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Lawrence Berkeley Laboratory
University of California
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F. Barrera, H. Petersen, C. E. Rago, R. I. Rinta
D. Talaska and R. D. Watt

Stanford Linear Accelerator Center
Stanford University, Stanford, CA

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ABSTRACT

This report describes the results of a series of tests on the TPC superconducting magnet cryogenic system which occurred during the winter and spring of 1983. These tests occurred at interaction region 2 of the PEP colliding beam facility at the Stanford Linear Accelerator Center (SLAC). The TPC Magnet Cryogenic System which was tested includes the following major components: a remote helium compressor with a full flow liquid nitrogen purification station, 400 meters of high pressure supply and low pressure return lines; and locally a CTi Model 2800 refrigerator with two Sulzer gas bearing turbines, the TPC magnet control dewar, 70 meters of transfer lines, and the TPC thin superconducting solenoid magnet. In addition, there is a conditioner (liquid nitrogen heat exchangers and gas heaters) system for cooldown and warmup of the magnet.

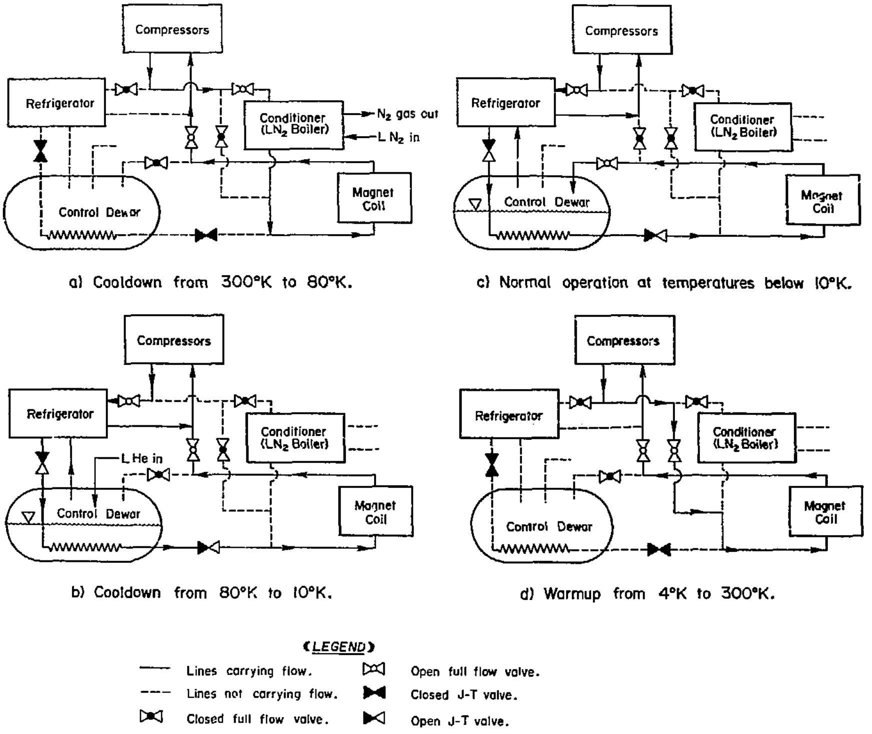
This report describes the local cryogenic system and describes the various steps in the cooldown and operation of the TPC magnet. The tests were successful in that they showed that the TPC magnet could be cooled down in 24 hours and the magnet could be operated on the refrigerator or a helium pump with adequate cooling margin. The tests identified problems with the cryogenic system and the 2800 refrigerator. Procedures for successful operation and quenching of the superconducting magnet were developed.

1. Description of the TPC Magnet Cryogenic System

Figures 1 and 2 illustrate, in simple schematic form, the procedure used to cooldown, operate, and warmup the TPC forced two phase cooled superconducting solenoid. Figure 1 illustrates the cooldown and operation of the TPC magnet using the conditioner and the refrigerator. Figure 2 illustrates the use of transfered liquid helium for the cooldown and operation of the TPC system.

Figures 1 and 2 show in schematic form the basic elements of the TPC magnet cryogenic system. The five major components can be found in Fig. 1. They are: the compressor system, the 2800 cold box, the control dewar system, the conditioner system, and the magnet. This section will delve into the cryogenic components of the TPC system.

The TPC cryogenic system is located in two places on the SLAC site. The helium compressors, gas clean up, and gas storage are located within the SLAC experimental area at the end of the accelerator. The model 2800 cold box, the control dewar, a 500 liter storage dewar, the conditioner system, and the magnet with its transfer lines are located within IR-2 at PEP. The two areas are connected by approximately 400 meters of room temperature helium piping. The control dewar, 500 liter dewar, refrigerator cold box, and conditioner system are permanently installed on top of the PEP-4 electronics house. During the test, the magnet coil without iron was located just outside the double doors of the IR2 staging hall. The control dewar conditioner system was connected to the magnet through about 70 meters of



a) Cooldown from 300°K to 80°K.

c) Normal operation at temperatures below 10°K.

b) Cooldown from 80°K to 10°K.

d) Warmup from 4°K to 300°K.

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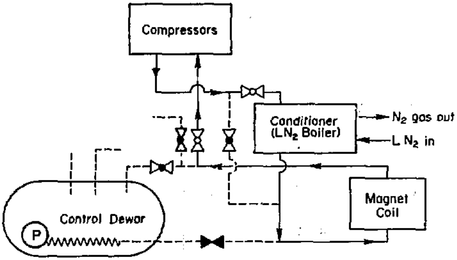
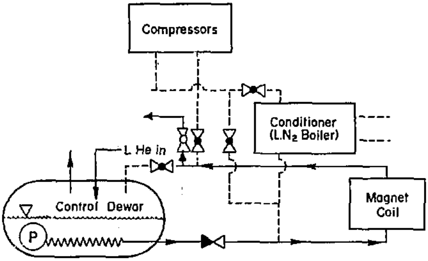
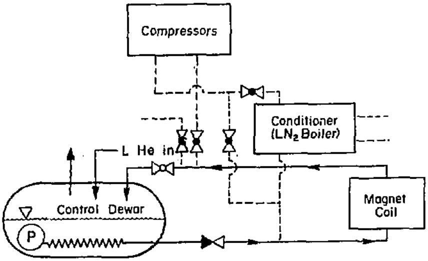
Fig. 1. A simplified schematic diagram showing various stages of the cool-down and warm-up of the TPC magnet system.



a) Cooldown from 300°K to 80°K.



b) Cooldown from 80°K to 10°K.



c) Normal operation at temperatures below 10°K.

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Fig. 2. A simplified schematic diagram showing various stages on the cooldown of the TPC magnet using liquid helium from the control dewar.

liquid nitrogen shielded helium transfer lines. When the magnet is installed in its permanent position, the transfer lines will be much shorter.

The design concepts of the TPC magnet cryogenic system are described in a number of LBL reports (see Refs. 1-6). The estimated design performance specifications are given in Ref. 1, which also describes the 1980 test of the cryogenic system. Since 1980, a number of changes have been made to the cryogenic system. Most of these changes are described in this section of this report.

An overall schematic of the TPC cryogenic system is shown in Fig. 3. Not included in Fig. 3 is the compressor and purification station. Figures 4 through 6 show in schematic form the major subsystems. Figure 4 shows the basic helium piping in the refrigerator cold box. Figure 5 shows the magnet, the transfer lines, and the control dewar. The conditioner system for cooldown and warm up is shown in Fig. 6.

a) The Model 2800 Refrigerator[7]

The CTi model 2800 refrigerator is one of several such machines built by CTi. Each of the machines has two Sulzer gas bearing turbines which are in series. The refrigerators have slightly different helium circuits. All have been troubled with turbine failures. (CTi no longer makes the 2800 refrigerator with Sulzer gas bearing turbine expanders. The turbines have been replaced by two piston expansion engines.)

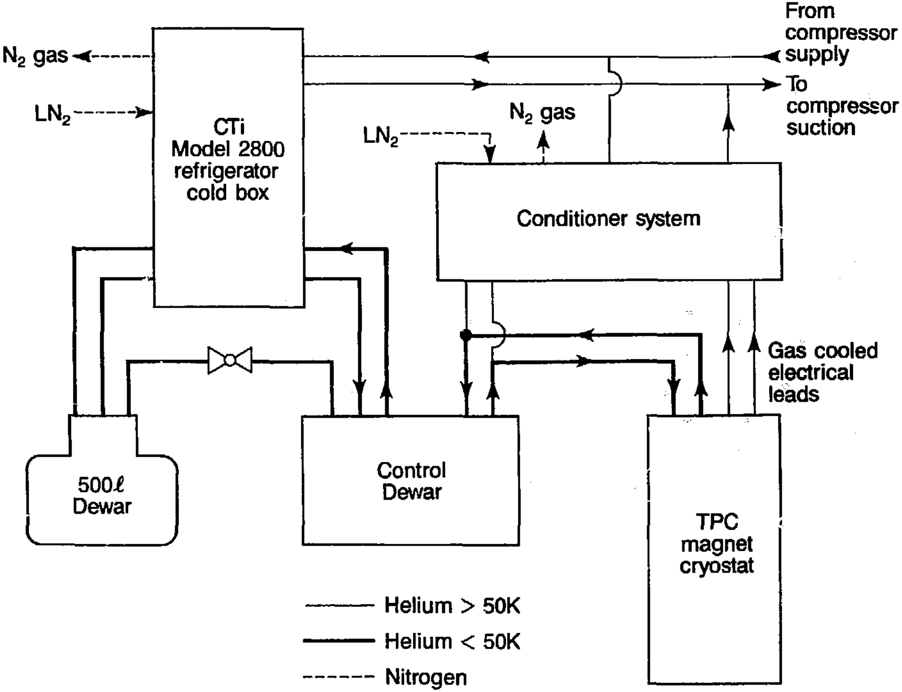

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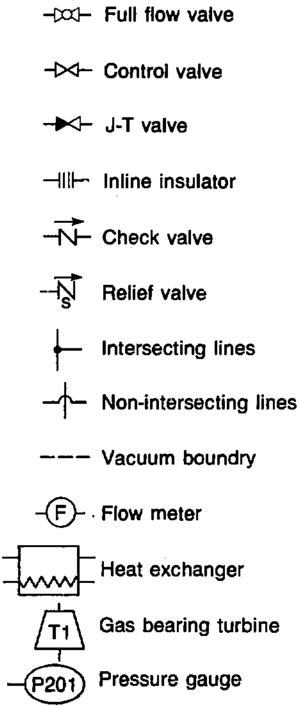
Fig. 3. An overall TPC magnet cryogenic system schematic diagram.

LEGEND


Full flow valve
Control valve
J-T valve
Inline insulator
Check valve
S
Relief valve
Intersecting lines
Non-intersecting lines
Vacuum boundry
F
Flow meter
Heat exchanger
T1
Gas bearing turbine
P201
Pressure gauge

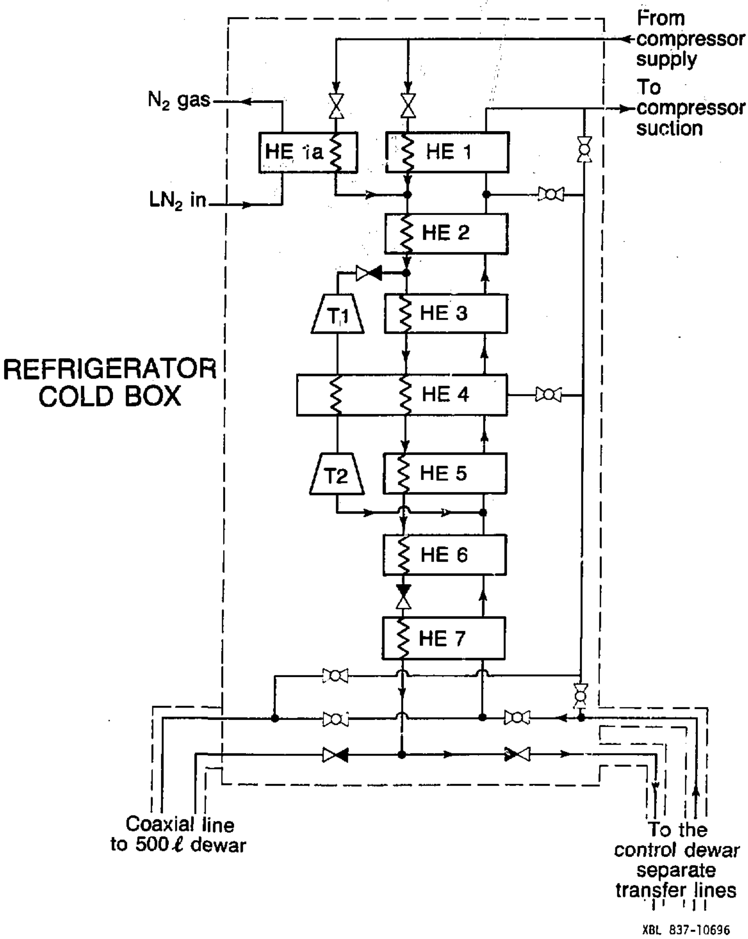


Fig. 4. A basic flow circuit diagram for the SLAC CTi model 2800 refrigerator.

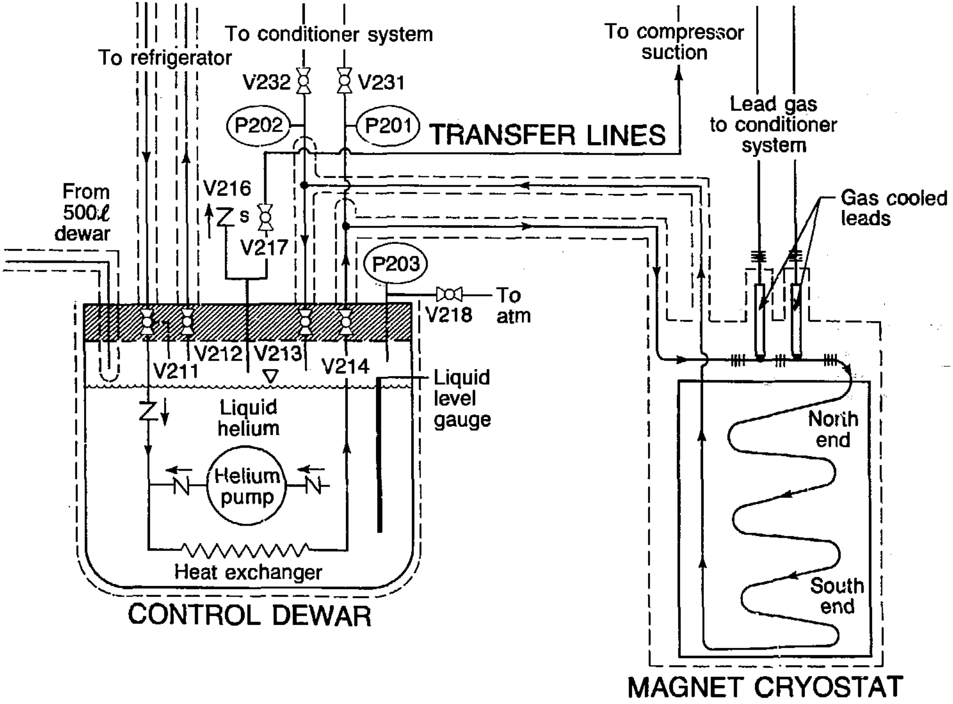


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Fig. 5. A schematic diagram of the helium circuits for the control dewar, transfer lines and the magnet.

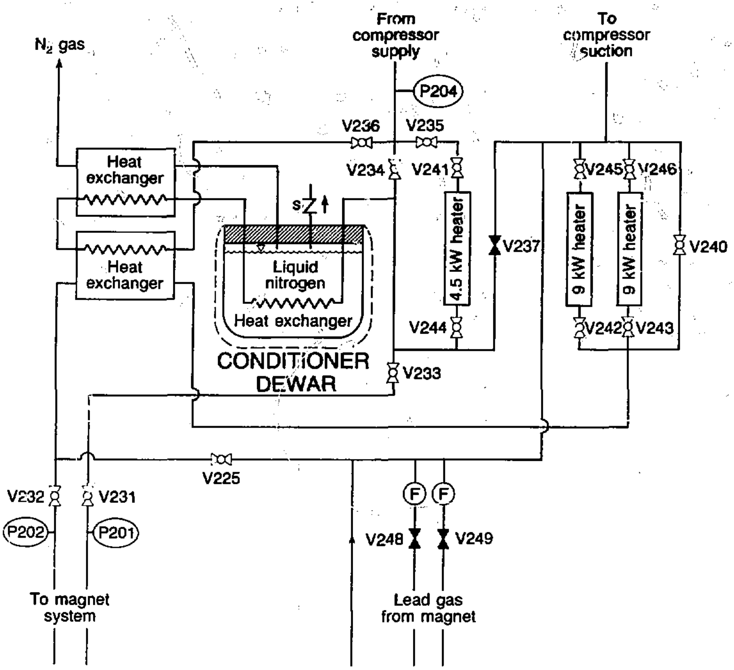

Fig. 6. A schematic diagram of the conditioner system for cooldown and warm up of the TPC magnet.

The basic flow circuit for the SLAC 2800 refrigerator is shown in Fig. 4. The cold box has seven helium to helium heat exchangers and one helium to liquid nitrogen heat exchanger. The turbines are in series and are separated by a three pass helium heat exchanger which is at about 20 K. The design pressure ratio across the upstream turbine is about 2.5; the design pressure ratio across the down stream turbine is around 5. During operation with helium makeup, the turbine circuit carries from 35 to 45 gs^{-1} and the J-T circuit carries between 10 and 15 gs^{-1}. The maximum compressor throughput is 54 gs^{-1} at a pressure ratio of 15. When the machine operates in the low pressure off makeup mode, the compressor mass flow drops to maybe 30 gs^{-1}.

The root of the turbine failures on the 2800 refrigerators is weak thrust bearings. The turbine failures experienced at SLAC have been due, for the most part, by an inbalance in the thrust forces on the self-activated thrust gas bearings (see Ref. 8). SLAC has had two failures of the number one turbine. One of these failures was caused by a sudden cooling in heat exchangers 4 and 5. This increases the pressure ratio across turbine number one. The first turbine failure was caused by a pressure inbalance across the number one turbine during an overly fast shutdown.

There has been considerable modification of the refrigerator controls by SLAC in order to prevent turbine failures. These steps include the following.

1) An automatic J-T valve controller uses the entry temperature of the number two turbine as a control function. As this temperature goes down, the J-T circuit opens up increasing the flow of warm gas in the J-T circuit.

2) An automatic spoiler control was installed to inject warm gas directly into the second turbine inlet. The spoiler is used when the J-T valve circuit control is ineffective in keeping the number two turbine inlet temperature above about 8.5 K.

3) An automatic shut off of the flow between the LBL control dewar (see valve 212 in Fig. 5) and the refrigerator cold box was installed. This valve is triggered by the detection of a quench, by a flow circuit pressure drop exceeding 16 psi (indicating over heating in the magnet circuit) and by a control dewar pressure of 16 psig or greater. (The flow of cold supercritical helium back through the refrigerator should be avoided.)

The use of the automatic controls has prevented further turbine failures. In the meantime there is an effort to replace the Sulzer turbines with some designed and built by SLAC which incorporate externally energized thrust bearings. The final coil test was run on such a turbine.

b) The Control Dewar System

The control dewar is the key element in the TPC magnet cryogenic system. It performs the following functions: 1) it holds most of the liquid helium in the cryogenic system and all of the reserve liquid helium (176 liters versus about 50 liters in the TPC magnet and transfer lines); 2) it insures that there will be liquid in the two-phase cooling coil in the magnets even when the short-term heat load at the magnet coils is as much as 50 percent greater than the rate of refrigeration; and 3) it insures that the pressure drop through the magnet cooling tubes is minimized. (The control dewar minimizes the quality of the helium flowing in the cooling circuit, which reduces the pressure drop by a factor of 2 or more. Quality is defined as it is in steam system. A quality of zero is all liquid; a quality of one is all gas.)

Two kinds of systems can be used to circulate low-quality (high liquid - low gas content) helium through the magnet cooling tube. They are: 1) a liquid-helium pump used as a circulator, or 2) the refrigerator compressors used as a circulator. Both systems use a heat exchanger to insure that the helium will enter the system at or near the saturated liquid line.

The heart of the cooling system, the control dewar is a wide-mouth cryostat with evacuated multilayer insulation and forced-cooled liquid nitrogen shields. It contains the helium pump, the heat exchangers and the control valves. (The control dewar with its helium pump heat exchanger and control valves are shown in Fig. 5.)

The inner vessel of the control dewar has a 508 mm OD (20 inches) with 1.75 mm thick 304 stainless steel walls that are 1076 mm high (42.375 inches). The dewar has a rounded bottom. The top of the dewar is connected to a thick stainless steel plate that connects to a 305 mm OD (12 inches) 304 stainless steel neck 0.75 mm thick and 305 mm (12 inches) high. The inner vessel was pressure-tested to a pressure of 175 psi, and is connected to the liquid nitrogen shield about 5 inches from the top of the neck.

The liquid helium pump for the cooling system utilizes two four inch diameter bellows, each consisting of 30 hydroformed 347 stainless steel convolutions, which are caused to compress and expand by a reciprocating mechanism driven by a variable-speed, torque-controlled dc gearmotor.[9] There is a cam assembly which permits the pump to be driven with strokes of 0.5 inch, 0.75 inch and 1.0 inch. The bellows pump is designed to be double acting. Each chamber can act independently. The pump is designed to deliver liquid helium at rates up to 50 g s^{-1} at a speed of 50 one inch strokes per minute with a pressure drop thru the coil of 0.5 atm or less.

The control dewar's two helium to helium heat exchangers remove heat from the helium that has been pumped or expanded through a J-T valve. The heat exchangers insure that the helium will enter the magnet at the lowest possible quality (highest possible liquid content). The heat exchanger which consists of rolled up copper tube has a nominal heat transfer area of two square meters.

The plug assembly which fills the neck of the control dewar has a number of ports in it. Four of these ports contain the female part of a bayonet valve assembly. These ports include: 1) a bayonet, two-way valve for helium entering the control dewar from the refrigerator

(Valve V211); 2) a full-flow bayonet valve for helium returning to the refrigerator (Valve V212); 3) a full flow bayonet valve for helium being delivered to the TPC magnet system (Valve V214); 4) a full flow bayonet valve for helium returning from the TPC magnet system (Valve V213); 5) a vent and fill line which is attached to a relief valve, a rupture disc and a helium fill port with ball valve; 6) various instrumentation ports; and 7) the helium pump drive shaft port.

c) Transfer Lines and the Magnet

Also shown in Fig. 5 are the TPC magnet helium transfer lines and the superconducting magnet with it's forced two phase cooling tube. The cryogenic system used for the noniron magnet test included 70 meters of transfer line, two transfer boxes and the magnet cooling circuit. The extra 38 meters of transfer line was required in order to move the magnet coil far enough away from the TPC experiment so that the strong magnetic field doesn't affect the computers.

The transfer lines contain both liquid nitrogen and liquid helium flow circuits. The helium is carried in two 12.7 mm OD (1/2 inch) OD tubes; the liquid nitrogen is carried in a single 12.7 mm OD tube. The helium lines are bound together with a woven glass tube containing molecular sieve. The helium carriers are insulated with aluminized mylar and bridal veil netting. The nitrogen carrier is put beside the wrapped pair of helium tubes and the three tubes are in turn wrapped with twenty more layers of superinsulation. The TPC magnet transfer lines are designed to be semiflexible capable of bends with a one meter radius.

The transfer lines used for the TPC magnet tests without the iron include the following segments; 1) a pair of semi flexible lines which are 5.5 meters long connect the control dewar and the first transfer box. These lines are designed to pass through the shielding between the electronics house and the TPC experiment. 2) For the test, 26 meters of rigid LBL transfer line, 12 meters of semiflexible transfer line, and a second transfer box were added between the first transfer box and the magnet pigtails. The additional 38 meters of transfer line plus the transfer box were needed so that the magnet could be tested well away from the computer for the TPC experiment. 3) The pig tails for the magnet, which are 10 meters, connect the second transfer box to the magnet. These lines will penetrate the iron when the magnet is in its final position. The first transfer box, the second transfer box and the transfer lines between the first transfer box and the magnet share a common vacuum with the magnet. The transfer lines between the control dewar and the first transfer box each have their own vacuum.

The helium and nitrogen transfer lines enter the magnet cryostat at the north end near the 6:30 position (see Fig. 7). The helium which enters the magnet goes clockwise around the north end (as one faces the north end looking south). Helium is bled off the flow circuit to cool the two 2300 A gas cooled leads which are on either side of the 11 o'clock support block.[10] The helium cooling circuit of the superconducting coil starts at the 2 o'clock position on the north end.

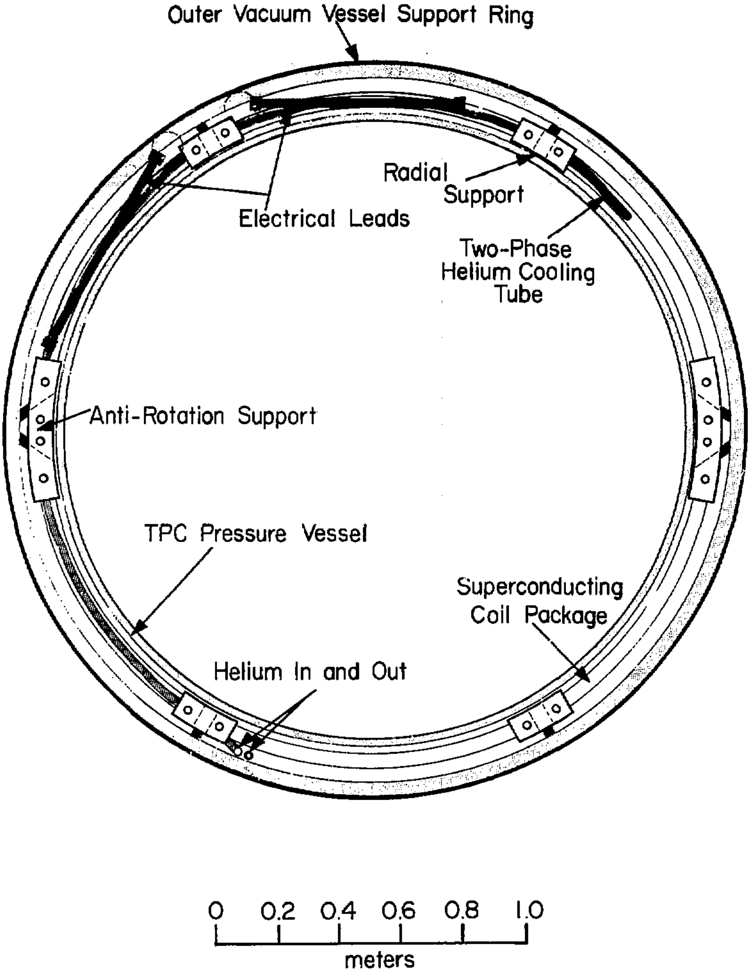

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Fig. 7. An end view of the TPC magnet from the north, showing the location of the major services.

The magnet cooling tube consists of 43.3 turns of 12.7 mm (1/2 inch) ID finned tube[11] wound on the outside of the coil on 76.2 mm (3 inch) centers. The magnet cooling circuit, which is 300 meters long exits at the south end of the magnet at the 6 o'clock position. The tube which comes back to the north end comes back along the outside of the coil package at the 6:30 position (as one looks at the north end).

Figure 5 shows the magnet leads, the magnet cooling circuit, and the transfer lines which connect to the control dewar through the bayonet valves V213 and V214. The transfer lines have standpipes which connect the helium circuit to the conditioner system shown in Fig. 6. At the bottom of these standpipes is a shut off valve (see valves V231 and V232) which keep the standpipes from having thermal-acoustic oscillations. Pressure taps for pressure gauges and pressure transducer are located under the standpipe valves.

The cryogenic transfer lines and control dewar were tested separately from the magnet. The second transfer box contained a coil of 0.190 inch ID tube 9.6 feet long which was used to simulate the magnet cooling circuit. The coil of copper tube had a 200 watt heater attached to it in order to simulate heat load at the magnet.

d) The Conditioner Circuit

The conditioner system was developed in order for the TPC magnet to be cooled down and warmed up in 24 hours or less. The conditioner has proved to be very useful on a number of occasions. For example, the conditioner has been used to maintain the magnet temperature at 85K in the event of a turbine failure. During the 1980 test of the magnet, the conditioner and 1600 liters of liquid helium pumped by the helium pump was used to cool down the magnet. (A Sulzer turbine on the LBL refrigerator had failed.)

The conditioner circuits contain the cooldown heat exchangers and the heaters for warming up gas entering and leaving the magnet. The conditioner system has three heat exchangers which serve the following functions: 1) The first heat exchanger is a nitrogen boiler which can be used to cool the helium gas to 85K. This heat exchanger permits gas flows of up to 12 gs^{-1} during the cooldown. 2) The second heat exchanger precools the helium entering the boiler by exchanging it's heat with the nitrogen boil off from the conditioner dewar. 3) The third heat exchanger exchanges heat between the warm helium from the compressor and cold helium exiting from the magnet system. The second and third heat exchangers will reduce the liquid nitrogen consumption and most of the time will eliminate the need for warm up heaters.

The conditoner system includes a 160 liter Minnesota Valley liquid nitrogen dewar. Contained within this dewar is the liquid nitrogen boiler for precooling helium used for cooldown. The dewar also has a liquid nitrogen pump which was supposed to circulate liquid nitrogen through the shield. The liquid nitrogen pump did not work well, so it's use has been curtailed.

Also included with the conditioner system are three chromalox heaters. Two are rated at 9 kW and one is rated at 4.5 kW. The smaller heater is used for heating gas entering the magnet during warm-up. The 9 kW heaters were designed to be used to preheat helium gas going back to the compressor. Operation of the system at SLAC has shown that the heaters are not needed.

Using valves V234 and V236 one can mix warm gas with cold gas so that one can control the temperature of the gas entering the magnet. This has proved to be necessary in order to prevent possible cracking of the epoxy under the finned cooling tube which is wrapped around the coil package. (The old TPC Magnet had no temperature restriction on gas entering the magnet.)

2. A Cryogenic System Test Without Magnet

A cryogenic systems test completed in January Of 1983 was to test the Model 2800 refrigerator and the TPC magnet cryogenic system except for the magnet. The components tested included; 1) the compressor and purification system, 2) the 2800 cold box, 3) the conditioner system, 4) the control dewar with the helium pump and 5) the transfer lines.

The magnet cooling circuit pressure drop was simulated with 9.6 feet of coiled 0.190 inch ID copper tube. A heat load at the magnet was simulated by a 200 W heater attached to the copper tube coil. No attempt was made to simulate the 2500 kg of magnet cold mass or the up and down motion of the helium in the magnet cooling tubes. These tests would have to await the installation of the magnet itself. The flow of gas through electrical leads could be simulated by bleeding gas off the top of the control dewar.

The cryogenic test at SLAC was supposed to accomplish the following tasks: 1) the whole system was to be tested to see that all components fit together [except for the coil itself]; 2) basic calorimetry was to be done on the control dewar, transfer lines and the helium pump; 3) the system was to be cooled down with the refrigerator both alone and with a liquid helium assist; 4) measurements of excess refrigeration were to be made on the system while it was operating on the refrigerator in various operating modes; 5) a test on emergency procedures and a test of the refrigerator performance under excess return gas flow was made.

All of the objectives were met during the January 1983 test. The cryogenic system was cooled down using both the refrigerator and the conditioner as was set forth in the cryogenic system test procedure set forth in Ref. 12. The detailed results of this test can be found in the TPC magnet log book (see Ref. 13) and the refrigerator log book (see Ref. 14).

Before the January cryogenic system test was completed successfully, there were various kinds of vacuum and heat leak problems which had to be dealt with. The January test was the second cryogenic system test. The first which was in November of 1982 found problems which prevented cooldown with liquid helium. These problems included; 1) vacuum leaks at transfer boxes, 2) a small helium leak into the vacuum space on one of the lines, 3) a liquid nitrogen leak, and 4) a thermal short on the supply and return transfer lines. We found that the liquid nitrogen pump did not circulate liquid nitrogen through the system in a reliable way. Problems with the nitrogen pump were also observed in Berkeley in 1980, but they were not as severe as those encountered in the 1983 SLAC test. As a result, the liquid nitrogen pump loop was abandoned. We also found problems with the liquid nitrogen fill system on the conditioner and the seal gasket on the liquid nitrogen dewar.

The most important results of the January 1983 test were the various calorimetry measurements and a measurement of a performance curve for the CTi model 2800 refrigerator as it runs on the TPC magnet cryogenic system. The refrigerator performed reasonably well during the test. This gave us a false sense of security because even the emergency procedures tests did not uncover the turbine problems which would be found while the refrigerator operated on the TPC cryogenic system with the superconducting magnet.

Calorimetry was done using the helium boiloff gas flow measurement method and a method which involves measuring the liquid level drop in the control dewar. In most cases the two methods could be made to agree within 10 percent. An attempt was made to separate the heat leak in the control dewar from heat leaks in the transfer lines and heat put into the system from the work put into the helium from the pump. The calorimetry can be summarized as follows:

1) Control dewar

   Liquid level below heat exchanger <1.8 W

   Liquid level from 30 to 70% 2.7 ± 0.5 W

   Liquid level full near the plug ~4.9 W

2) Helium transfer lines 37 ± 3 W

3) Helium pump work

   at 17 strokes per minute ≈ 15 ± 2 W

   at 24 strokes per minute ≈ 29 ± 3 W

   at 28 strokes per minute ≈ 41 ± 4 W

   at 30 strokes per minute ≈ 45 ± 5 W

A refrigerator liquifaction characteristic curve was measured for the 2800 refrigerator running on the TPC cryogenic system without the magnet but with the dummy load. This measured operating curve is shown in Fig. 8. The measurements shown in Fig. 8 were taken quickly so perhaps the heat exchanger time constants were not fully accounted for. As testing proceeded further we became aware of the various time constants in the system. For example, the lowest heat exchanger (number 7 in Fig. 4) might have a time constant of a few seconds (when it is cold); but the upper heat exchangers (numbers 1 and 2 in Fig. 4) might have time constants as long as four hours. The characteristic curve shown in Fig. 8 agrees in magnitude with other measurements made by the SLAC refrigeration group. On a good day (both good days) the CTi 2800 refrigerator can make as much as $88\ell h^{-1}$ of liquid helium or produce as much as 260 W refrigeration at the cold box.

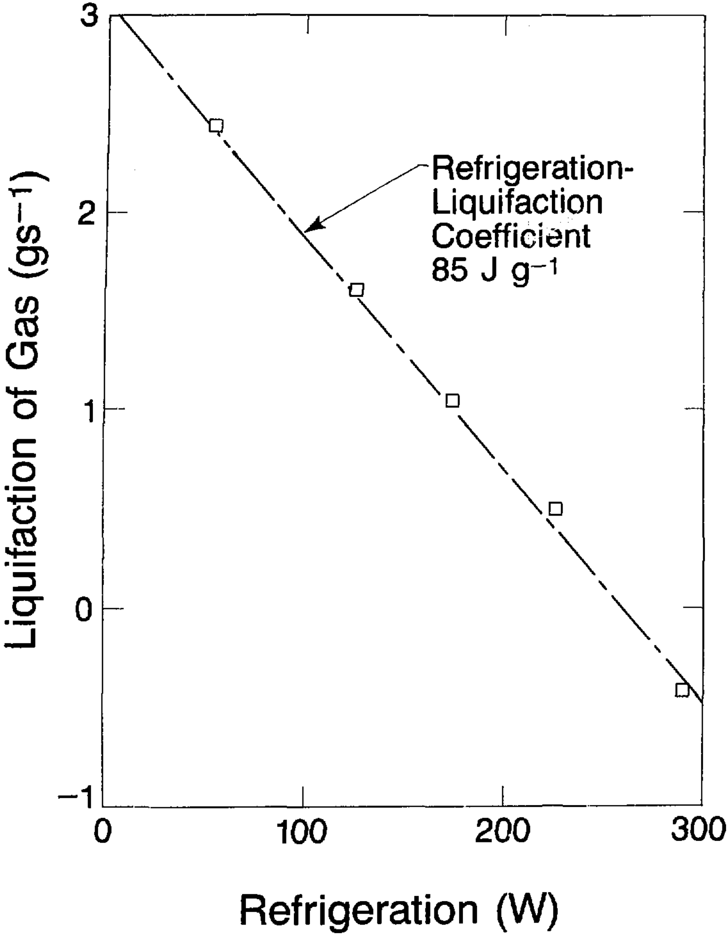

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Fig. 8. The refrigeration liquifaction characteristics of the CTi 2800 refrigerator connected to the TPC magnet cryogenic system (data was taken in January 1983).

3. Cooldown of the TPC Superconducting Magnet and the Helium Supply System

During the spring 1983 test of the TPC magnet, the magnet was cooled down from 280K to 5K three different times. The magnet was also cooled from 60-80K to 4K on a number of occasions. The first cooldown took 36 hrs; the second cooldown took 28 hrs; and the third cooldown took 24 hours. The first cooldown used the 2800 refrigerator alone to provide the cooling. The second and third cooldowns involved the use of the conditioner to cool the magnet from 280K to about 90K.

The TPC magnet cold mass is about 2330 kg.[15] The cold mass in rough terms can be broken down as follows; copper and superconductor 750 kg, aluminum in various forms 1170 kg, and various plastic type materials 410 kg. The thermal energy which must be removed from the TPC coil package during cooldown is approximately 280 MJ. The thermal energy stored in the magnet coil package (energy is zero at absolute zero) versus temperature as shown in Fig. 9. A method for estimating the cooldown time for the coil package is presented in Ref. 16.

The temperature of the TPC magnet during cooldown could be measured directly from seven silicon diodes attached to the coil package and the inlet and outlet cooling tubes. The location of these temperature sensors is shown in Fig. 10. The helium enters the magnet at the north end and it exits from the magnet at the south end. (The north-south orientation was determined by the ultimate direction of the coil in the TPC experiment.) Temperature sensors TD1 and TD7 on the helium circuit are located in the first transfer box which is

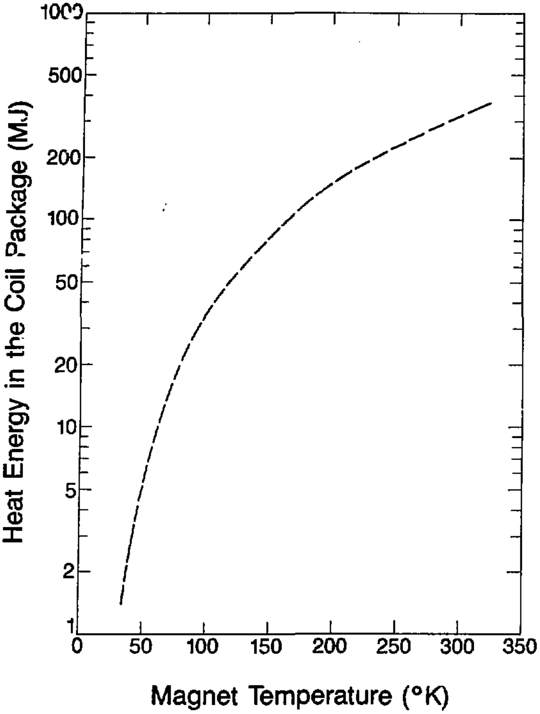

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Fig. 9. The thermal energy in the TPC magnet cold mass versus temperature (energy = 0 when the temperature = 0K).

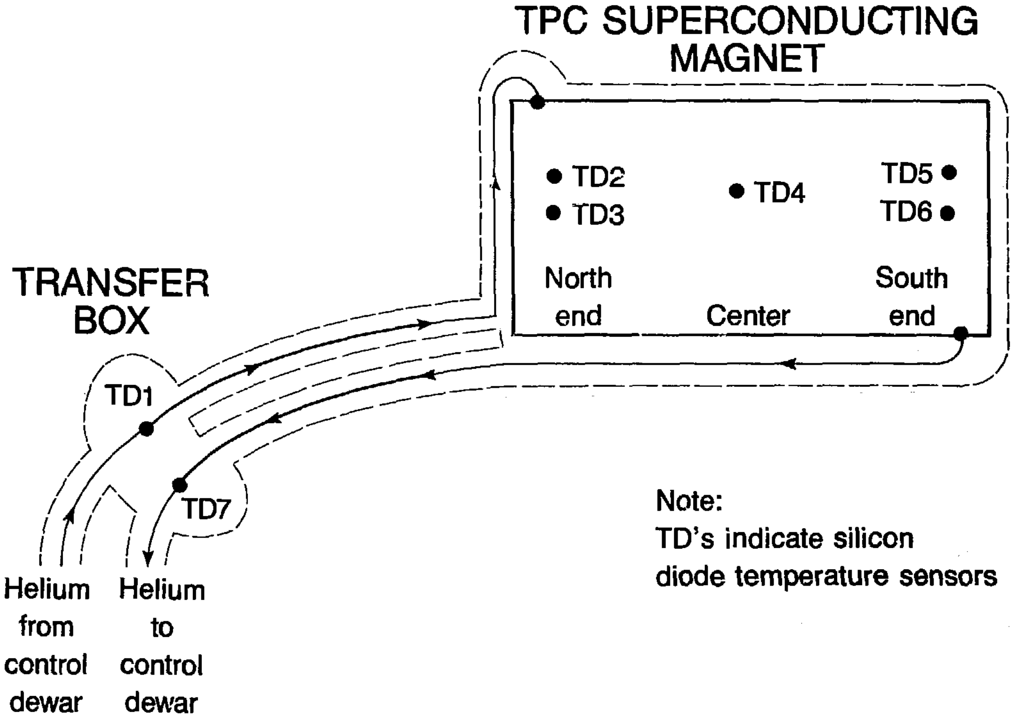

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Fig. 10. The locations of the silicon diode temperature sensors TD1 through TD7 on the transfer lines and on the magnet bore tube.

some distance from the magnet coil package. Temperature sensors TD2 through TD6 are on the magnet bobbin. An alternative method for measuring the magnet temperature is to measure the resistance of the coil and the ultra pure copper (UPC) circuit (see Figs. 17 and 23).

Before cooling the magnet, the effects of possible thermal strains were calculated. In the three test coils and the previous TPC magnet, the gas was allowed to enter the cooling system at any temperature. The new TPC coil uses the thin fin cooling tube approach; there was considerable concern about cracking between the finned cooling tube and the coil package itself. As a result, the temperature of the helium entering the magnet as measured by TD1 in transfer box number one is kept at a temperature which is a certain number of degrees below or above (depending on whether one is doing a cooldown or warm up) the temperature measured at the north end of the magnet coil (at TD2 or TD3). Table 1 shows the allowable temperature differences between the transfer box (TD1) and the north end of the magnet (TD2 or TD3) during a cooldown or a warm up.

During all three cooldowns, the temperature differences were kept less than those shown in Table 1. When the magnet was cooled using the refrigerator along, the pressure at the inlet to the flow circuit P201 was limited to 100 psig or less. This limitation is imposed by a small relief valve which was used to protect the bellows of the helium pump. When the conditioner was used for the early phases of the cooldown, this pressure limitation did not apply. (Valve V214 between the control dewar and the supply transfer line was closed.)

Table 1. The allowable temperature difference between the north end of the coil (TD2) and the helium entering the magnet (TD1) as a function of north end magnet temperature during a cooldown or a warm up.

North End Temperature TD2 (K)	Temperature Difference TD2–TD1 (K)	
	Cooldown	Warm Up**
20	20*	-140
50	50*	-115
100	100*	-80
150	150	-70
200	80	-60
250	60	-50
300	50	-40

*There is no temperature limit.

**NOTE: This column has negative temperature differences because TD1 is greater than TD2 (see Fig. 10).

a) Cooldown with the Refrigerator Alone

The first full magnet cooldown occurred on January 31 and February 1, 1983. The refrigerator alone supplied cold gas to the system. During much of the cooldown warm gas was brought back through the control dewar to the internal bypass within the refrigerator. Early in the cooldown the heat transfer with the warm gas in the control dewar was good enough to reduce the cooldown rate. Later in the cooldown, gas from the magnet was sent back through the conditioner warm up circuits. During the last part of the cooldown, when the south end of the magnet was at 80K or below, the return flow was routed through the control dewar back through various heat exchangers in the refrigerator. A by-pass of the control dewar between valves V213 and V212 would permit a faster cooldown with the refrigerator. Figure 11 shows the temperature versus time at TD2 TD4 and TD6 during the cooldown.

The helium mass flow can be calculated using the pressure drop equation;

$$P_1 - P_2 = \frac{8}{\pi^2} \frac{\dot{m}^2}{\rho} f \frac{L}{D^5} \qquad (1)$$

where P_1 is the inlet pressure (Nm^{-2}), P_2 is the outlet pressure (Nm^{-2}), m is the mass flow of helium (kgs^{-1}), ρ is the density of helium ($kg\ m^{-3}$), L the length of the circuit (m) and D the inside diameter of the round tube (m). f the friction factor is defined for turbulent flow by the following relationship;

$$f \approx 0.184 \left[\frac{4\dot{m}}{\pi D \mu}\right]^{-0.2} \qquad (2)$$

where D is the hydraulic diameter (in this case D is the same as D in equation 1) and μ is the viscosity (kg $m^{-1}s^{-1}$). The viscosity is a function of the helium temperature. If one assumes that ρ and μ are functions of the average temperature T_{AVE} (K) then the mass flow through the TPC magnet can be calculated using the following relationships in an iterative way:

$$\dot{m} \approx 1.52 \times 10^{-8} \left[\frac{P_1^2 - P_2^2}{T_{AVE} f}\right]^{1/2} \tag{3}$$

$$f = 0.184 \left[\frac{4\dot{m}}{\pi D \; \mu(T_{AVE})}\right]^{-0.2} \tag{4}$$

Equations 3 and 4 can be applied iteratively to calculate the flow circuit mass flow up until two phase helium starts to flow in the tubes. (There is no easy way to measure or calculate the mass flow in two phase flow.)

Figure 12 shows the calculated value of mass flow through the cooling circuit and the calculated rate of refrigeration delivered during the cooldown as a function of time of day during the cooldown using the refrigeration alone. The refrigeration rate can be calculated using the following relationship:

$$Q = \dot{m} \; Cp \; (T_7 - T_1) \tag{5}$$

where m is the mass flow rate through the flow circuit (kg s^{-1}); Cp

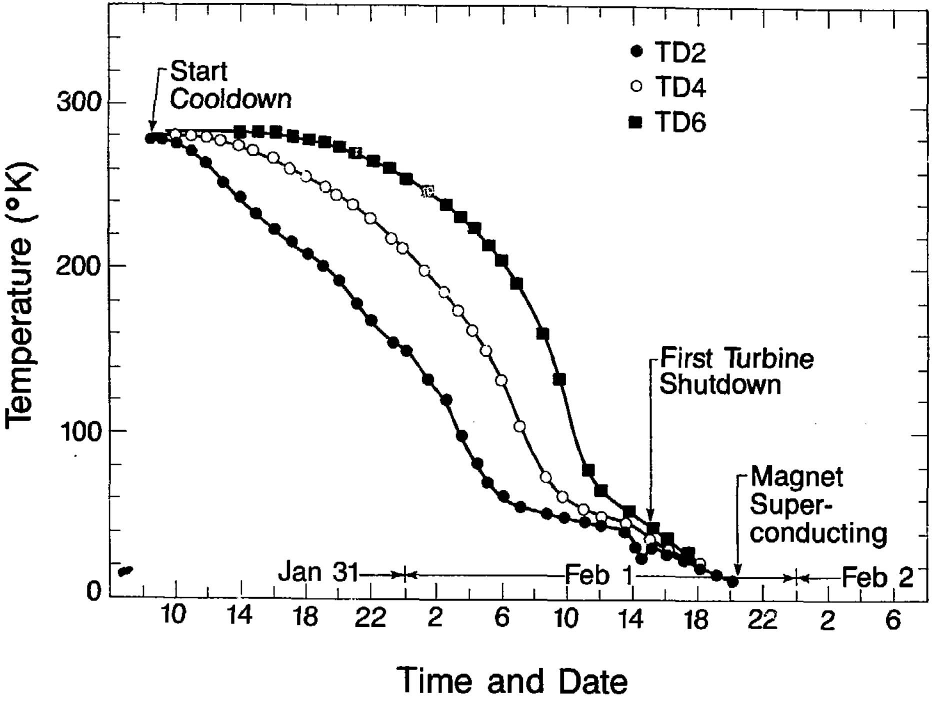

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Fig. 11. The temperature of the north end, center, and south end of the TPC magnet versus time of day during a cooldown using the refrigerator alone (see Fig. 12).

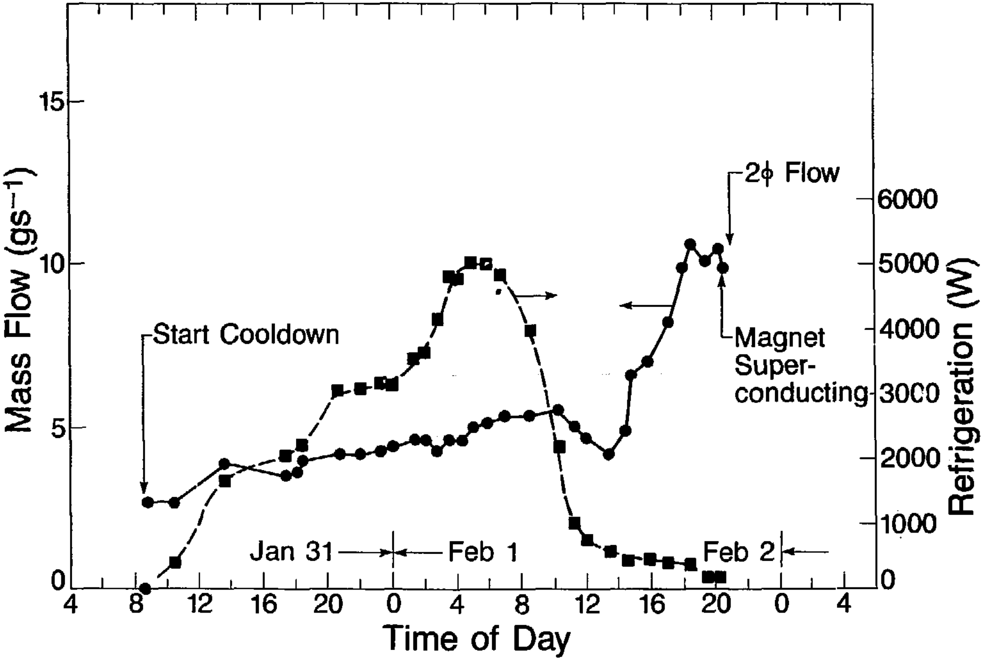

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Fig. 12. Calculated flow circuit mass flow and refrigeration rate delivered to the magnet cold mass versus time of day during a cooldown using the refrigerator alone (see Fig. 11).

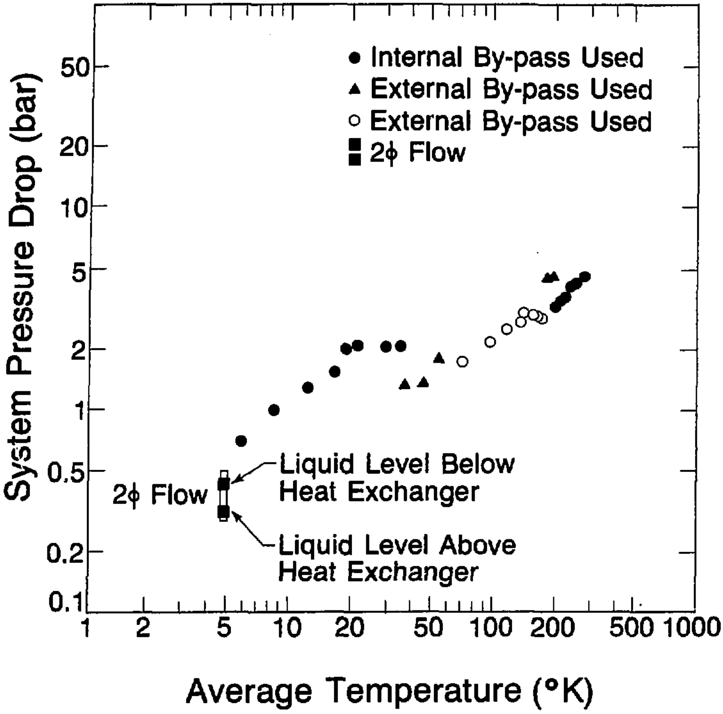

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Fig. 13. The pressure drop across the flow circuit (P201-P202) versus the temperature at the center of the magnet (TD4) during a cooldown using the refrigerator alone (see Fig. 11).

is the specific heat at constant pressure for helium gas (J kg^{-1} K^{-1}) (Note: for helium Cp = 5200 J $kg^{-1}K^{-1}$); T_7 is the temperature measured by TD7; T_1 is the temperature measured by TD1 (K); and Q is the rate of refrigeration (W).

Figure 13 shows the pressure drop across the flow circuit in (bar) as a function of average temperature in the magnet as measured at TD4. At high temperatures, the pressure drop is limited by the relief valve on the flow circuit. The pattern shown in Fig. 13 is not a consistent one because various flow circuit changes were made (see Ref. 17). It is interesting to note that maximum flow rates did not occur until the magnet was fully cold. The maximum rate of refrigeration occurred relatively late in the cooldown when the temperature differences from end to end in the coil approached 135 K. It is quite possible that the cooldown time using the refrigerator alone can be reduced from 36 hours to as low as 32 hours. (Installation of a by-pass valve between valve V213 and V212 will reduce cooldown time even more.)

b) Cooldown Using the Conditioner

Two full cooldowns and a partial cooldown of the TPC magnet were made using the conditioner to cool the magnet to below 100K. The two full cooldowns were made on 8 March 1983 and 12 May 1983. The first cooldown took 28 hours; the second took 24 hours. In the first cooldown, the refrigerator started cooling the system 17 hours after the start of the cooldown. In the second cooldown, the refrigerator became part of the cooldown process 11 hours after the start of the cooldown. During the first of the conditioner cooldowns, the magnet had no liquid nitrogen shield; during the second cooldown, the shield was operating. It is believed that the shield had little effect on the cooldown time.

Figure 14 shows the temperature at the north end (TD2), center (TD4) and the south end (TD6) as a function time during the March 8 cooldown of the TPC magnet. A maximum temperature gradient from end to end of 150K was reached 8.5 hours after the start of the cooldown. The end to end temperature difference is not much different than in the January 31 cooldown (see Fig. 11), but it occurs much sooner in the cooldown (8.5 hours after the start instead of 22 hours after the start.)

Figure 15 shows the calculated mass flow through the flow circuit and the calculated refrigeration rate through the flow circuit as a function of time. During the second cooldown, maximum mass flow occurred 14 hours after the start of the cooldown and the maximum refrigeration rate occurred 8 hours after the start of the cooldown. (It should be noted that the temperature limitation at TD1 prevents maximum refrigeration rate to be obtained at or near the start of the cooldown.) It is interesting to note that if one integrates the refrigeration rate vs time in Figs. 12 and 15 one comes up with an integrated energy removal of around 280 MJ.

Figure 16 plots system pressure drop versus average magnet temperature for the March 8 cooldown. This curve is much more consistent than the curve given in Fig. 13. The mass flow was high during the

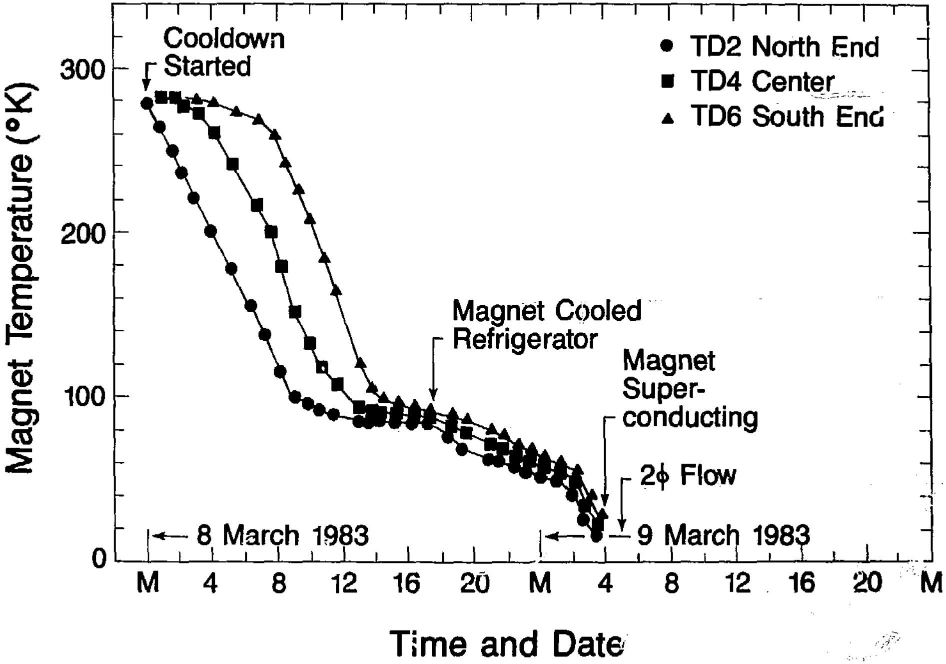

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Fig. 14. The temperature at the north end, center, and south end of the TPC magnet versus time of day during a cooldown using the conditioner for the above 100K portion of the cooldown (see Fig. 15).

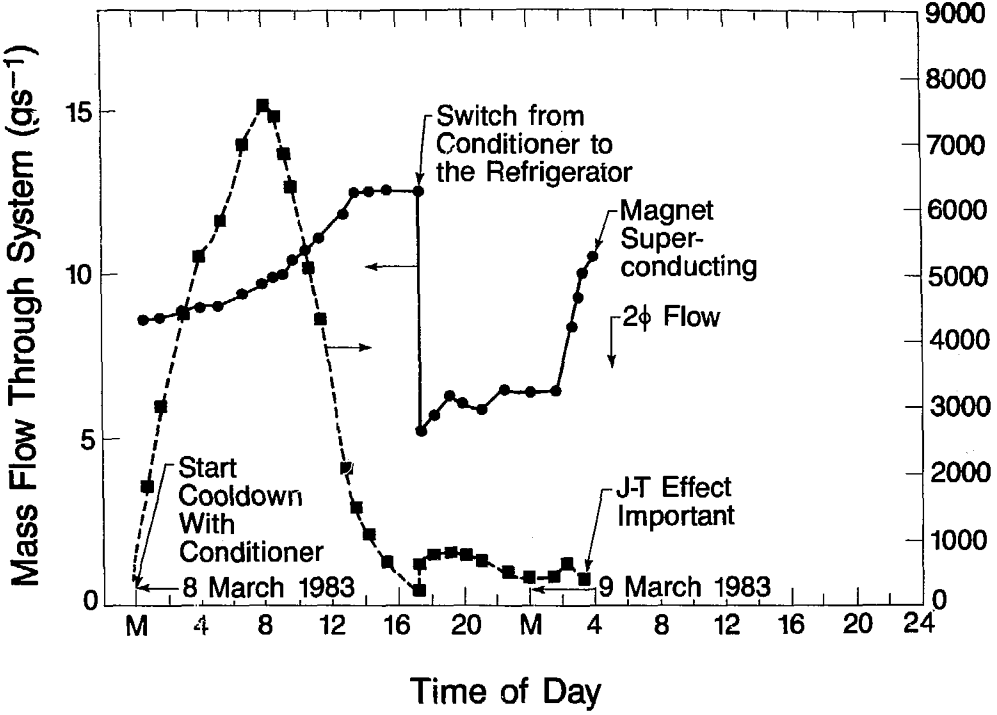

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Fig. 15. Calculated circuit mass flow and refrigeration rate delivered to the magnet cold mass versus time of day during a cooldown using the conditioner (see Fig. 14).

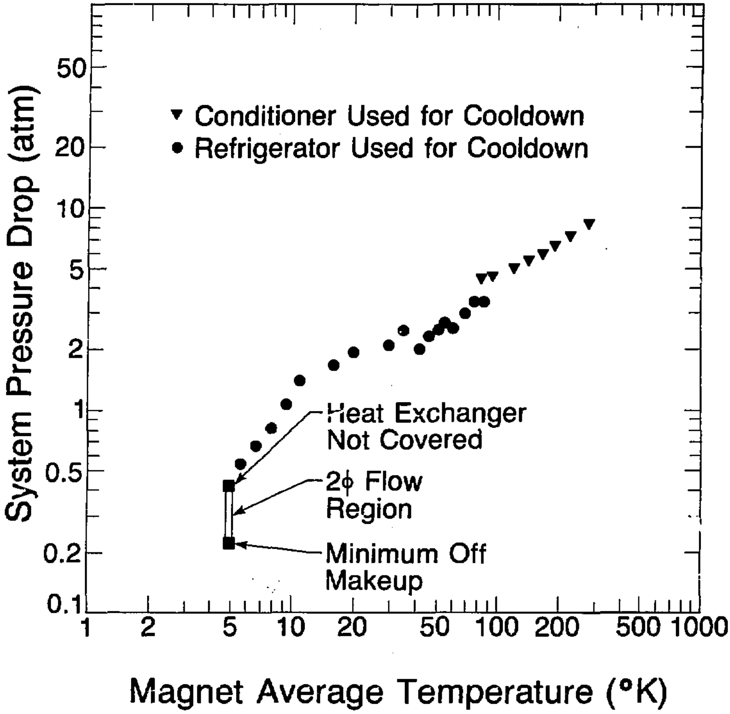

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Fig. 16. The pressure drop across the flow circuit (P201-P202) versus temperature at the center of the magnet (TD4) during a cooldown using the conditioner (see Fig. 14).

conditioner phase of the cooldown. The mass flow during the phase where the refrigerator was used (below 80K) was about the same as it was during the January 31st cooldown. The May 12 cooldown was faster than the March 8th cooldown primarily because the refrigerator was switched into the flow circuit earlier in the cooldown. If the refrigeration was properly optimized and external bypasses were used early in the refrigeration phase of the cooldown, the cooldown time for the TPC magnet could be reduced to 20 to 22 hours. (A by-pass of the control dewar would reduce the cooldown time even more.)

Figure 17 demonstrates that temperature measuring diodes are not needed to monitor the magnet cooldown. The figure shows the measured resistance of the superconducting coil circuit and the ultra pure copper (UPC) circuit as a function of the temperature on the bore tube at the magnet center (TD4). The characteristic knees in the resistance curves at 75K and 40K are quite apparent. These knees could be used as control points for the cooldown process.

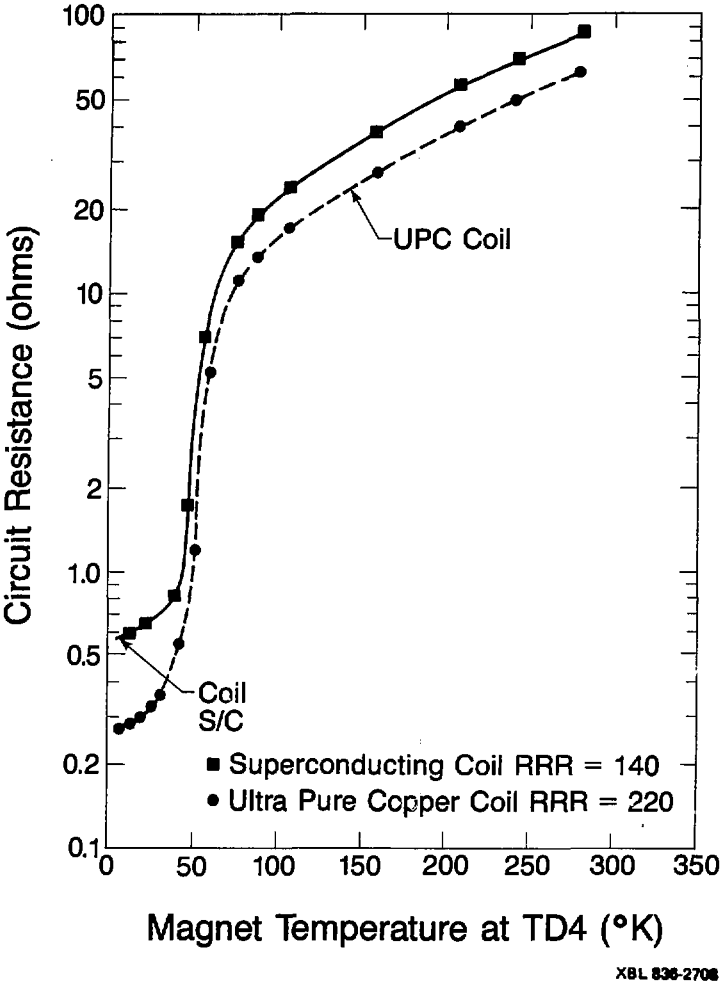


Fig. 17. The measured superconducting coil resistance and the ultra pure copper (UPC) coil resistance versus the temperature at the center of the magnet (see Fig. 23).

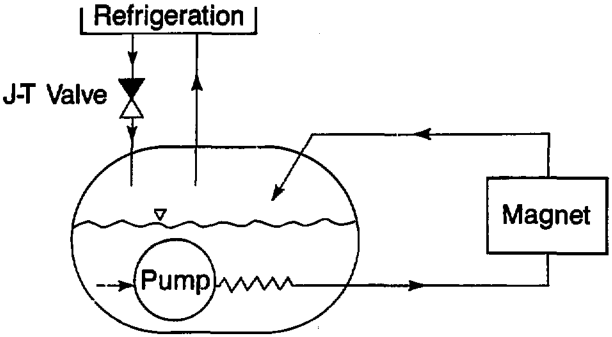
4. Filling the System with Liquid Helium and Normal Operation of the System

As the TPC magnet becomes superconducting, liquid helium is being produced by the J-T value in the refrigerator. In about one hour, the helium cooling tube around the magnet becomes filled with two phase helium and liquid helium returns to the control dewar. Once two phase flow has been established, if takes 1 to 1-1/2 hours for the liquid level in the control dewar to rise up to the bottom of the heat exchanger and the bottom of the liquid level gauge. When the heat exchanger is fully covered, full low pressure drop two phase flow is established.

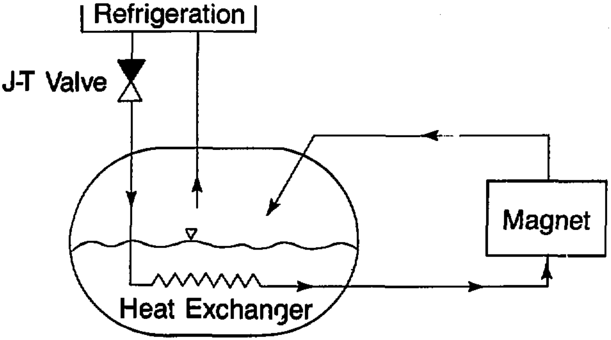
Figure 18 shows the two means by which the TPC magnet two phase cooling can operate. Figure 18a shows a simple helium pump loop; Figure 18b shows how the magnet and control dewar circuits can operate directly off of the refrigerator. The original design concept described in Refs. 1, 3, 4 and 18 calls for a second expansion valve after the control dewar heat exchanger. Originally valve V214 in Fig. 5 was designed to act as a throttling valve. The 1980 test of the TPC system showed this was not necessary so valve V214 was changed to a soft seated shut off valve.

a) The Januray 31st Cooldown

The Process of transition from single phase flow to two phase flow is illustrated in Fig. 19. Figure 19 presents the pressure data measured at the supply and return pressure transducers (PT201 and



a) LIQUID HELIUM CIRCULATION WITH PUMP



b) LIQUID HELIUM CIRCULATION WITH REFRIG. COMPRESSOR

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Fig. 18. The two basic two-phase flow circulating systems for the TPC magnet using the control dewar (see Fig. 5).

PT202). The onset of two phase flow is characterized by a drop in control dewar pressure (despite increased mass flow through the J-T circuit) and a sudden decrease in the pressure drop through the magnet cooling circuit.

During the first cooldown, illustrated in Figure 19, two phase flow started at 21:30 on February 1. It took just over 2-1/2 hours to fill the control dewar up to the bottom of the liquid level probe and the heat exchanger. About 43ℓ of liquid was made in the 2-1/2 hours (note: cold dense gas is replaced with liquid). The rate of liquifaction was 0.38 gs^{-1} (10.9 standard liquid liters per hour).

When the heat exchanger became covered at just after midnight on February 2 (see Fig. 19), the pressure drop across the coil circuit dropped to about 0.3 atm (4.5 psi). The control dewar pressure also dropped. Liquifaction into the control dewar continued at the rate of about 0.4 gs^{-1} until the turbine cold shut down at 2:00 in the morning on February 2. The magnet stayed cold during the cold shut down but a considerable amount of liquid was lost in the control dewar.

Liquifaction started once again just after 2:00 on Feburary 2. Liquid could be seen on the liquid level meter at 3:45 on the morning of February 2 (see Fig. 20). The rate of liquifaction had now increased to 0.60 gs^{-1} (17.3 standard liquid liters per hour). The increase rate of liquifaction could be attributed to the cooling of superinsulation, the molecular sieve canisters, and other attachments.

The rate of change of the liquid level with time during the February 2 cooldown shown in Fig. 20 was not even. The liquid level

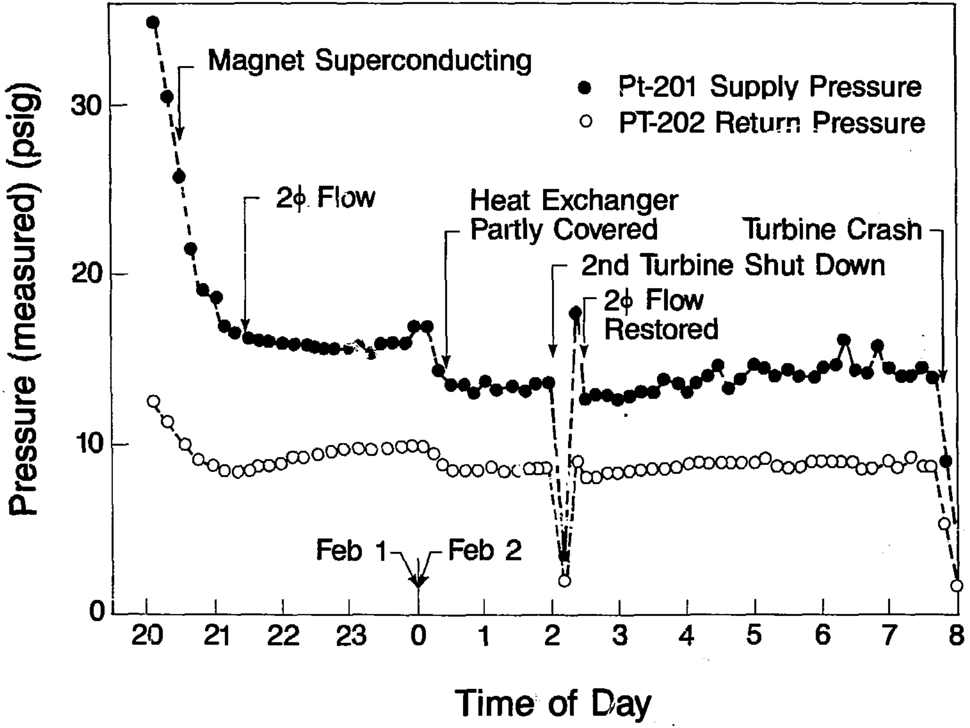

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Fig. 19. Pressure at the entrance to the flow circuit PT201 and the exit to the flow circuit PT202 versus time of day during the transition from single phase to two phase flow and filling the control dewar with liquid (the refrigerator runs on makeup) (see Fig. 20).

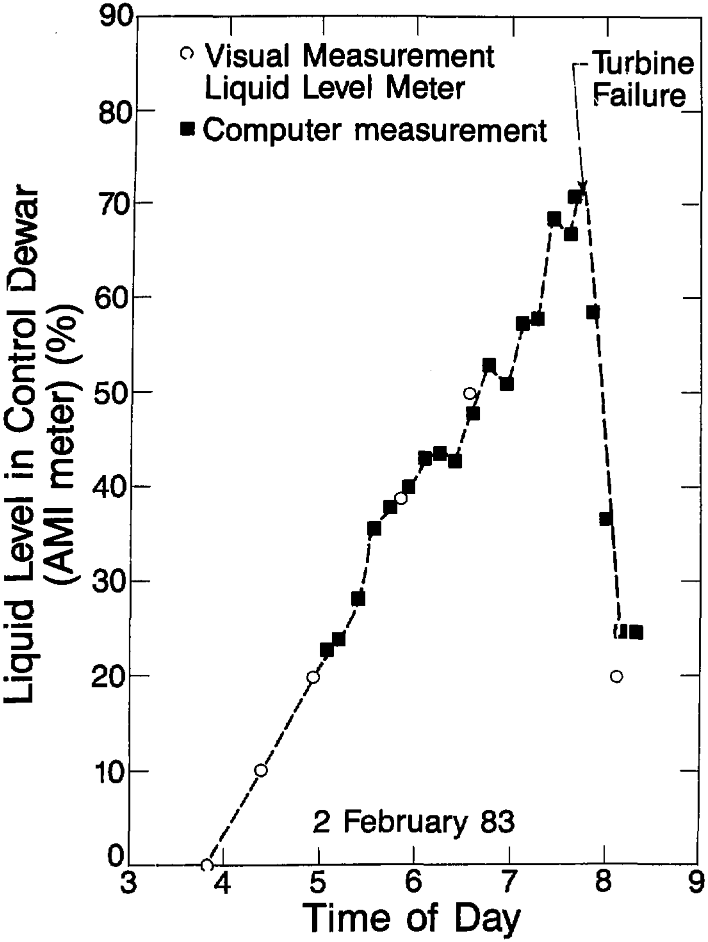

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Fig. 20. Measured liquid level in the control dewar versus time of day on February 2, 1983 (see Fig. 19). Note: Each percent below 50 percent corresponds to 1.59 liters. Each percent above 50 percent corresponds to 1.76 liter. Zero percent corresponds to 43 liters in the control dewar.

rose and fell then rose even higher than before. At 7:39 in the morning, on February 2, the turbine went into a cold shutdown. This shut down resulted in a scrubbing of the thrust bearings of the number 1 turbine. This turbine failure shut the experiment down for a month.

At the time of the turbine crash, it was felt that the turbine failure was related to the oscillations of liquid level shown in Fig. 20. This oscillation represents a periodic filling and unfilling of the coil tubes with liquid helium. Two scenarios have emerged as a possible cause for this filling and dumping of the coil circuit with liquid helium: (1) the refrigeration J-T valve was manually controlled in reponse to changes in the inlet temperature of the number two turbine. These adjustments caused the fluctuations in the inlet pressure shown in Fig. 19. (2) The helium vacuum leak in the supply transfer line loaded the moledular sieve in the supply transfer line. In response to changes in temperature (due to changes in pressure at the inlet), the molecular sieve was unloaded and loaded with helium gas which caused rapid changes in the supply line vacuum and rapid changes in the heat leak. Regardless of the cause or causes, there had to be a number of changes in operating procedure.

b) The March 8th Cooldown and Subsequent Cooldowns without the LN_2 Shield

Between February 2 and March 8 a number of changes were made on the refrigeration controls and the TPC magnet cryogenic system. These changes are outlined on pages 3 and 4 in the first section of this report. In addition, two operating procedures were set up. These include; (1) the control dewar liquid level was to be set at least 40 liters below the return pipe inlet to the refrigerator. (The return to the refrigerator is at about 90 percent liquid level. The operating liquid level was set at 67 percent or below.) (2) The off make up mode was developed. When the liquid level had risen to around 40 percent on the cryostat level gauge, the helium makeup to the compressor system was shut off. As a result, the inlet pressure for gas to the refrigerator went down until the amount of refrigeration produced by the refrigerator matches the load. A side benefit of the off make up mode was lower control dewar pressures and reduced pressure drop across the flow circuit (the J-T circuit flow was automatically cut back).

Figure 21 shows the system inlet and outlet pressures as a function of time of day. The system was under full J-T valve automatic control as the transition from single phase to two phase flow was made. Figure 22 shows the magnet temperature and the liquid level measured by the level gauge for the same operation shown in Fig. 21. Once two phase flow had been established, the magnet temperature stayed constant. The inlet pressure was about 12 psig; the exit pressure was a bit over 7 psig (the exit pressure is very close to the control dewar pressure). The system was taken off make up when the liquid level approached 30 percent. The system responded by a reduction of both the inlet and outlet pressures to 9 psig and 5.5 psig respectively. It takes 4 or 5 hours for the liquid level and pressures to reach equilibrium. This is believed to be caused by the time

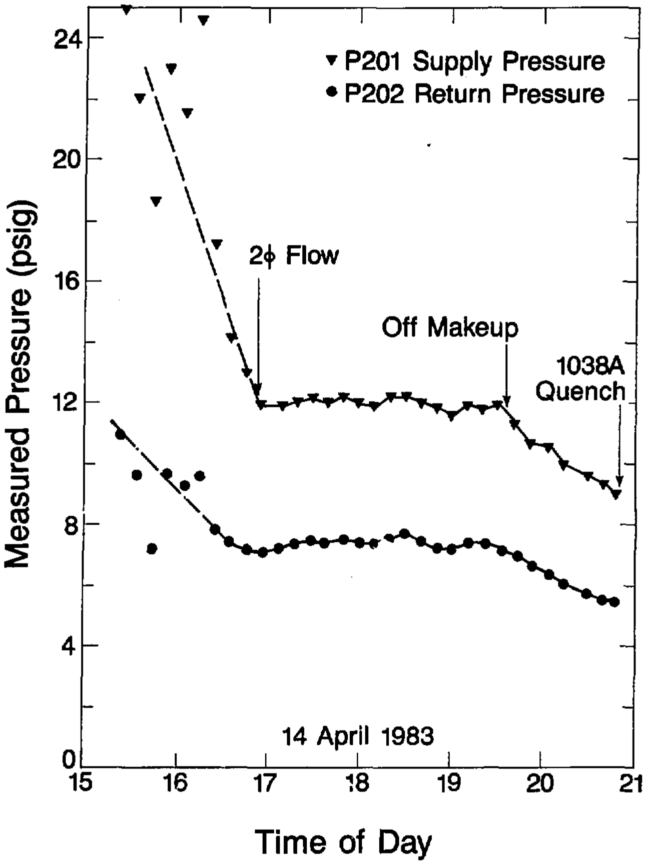

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Fig. 21. Measured inlet and outlet pressures PT201 and PT202 versus time of day at the end of the cooldown and during filling of the control dewar. The refrigerator was switched to off make-up and the J-T valve was under automatic control (see Fig. 22).

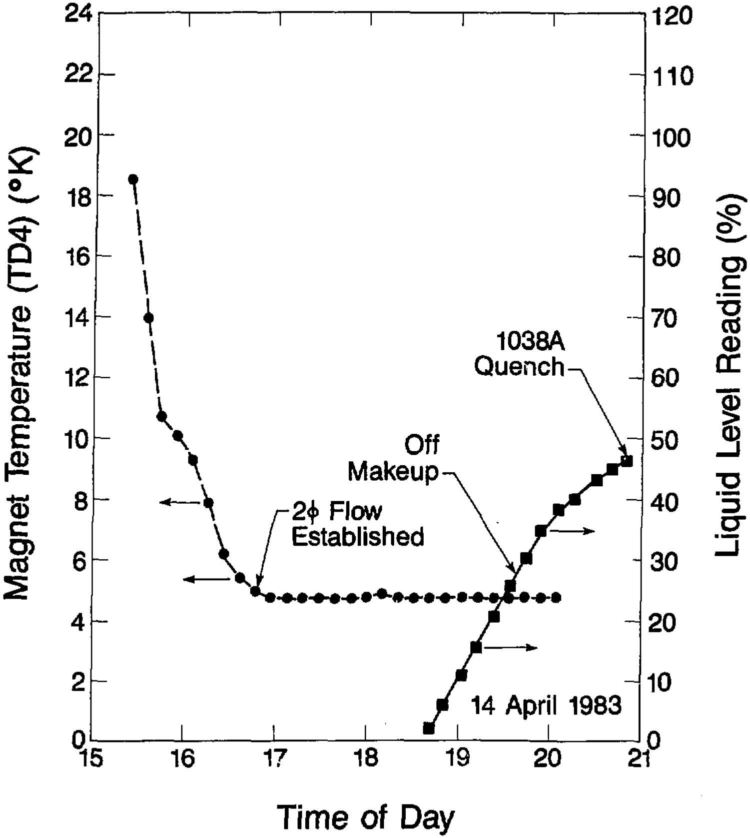

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Fig. 22. Measured magnet temperature (TD4) and measured liquid level in the control dewar versus time of day at the end of cool-down and while filling the control dewar. The J-T valve is under automatic control and the helium system was switched to the off make-up mode (see Fig. 21).

constants associated with the upper heat exchangers of the 2800 refrigerator cold box.

From the cooldown of March 8 on, the J-T circuit flow was controlled by the temperature measured at the inlet to the number 2 turbine. The inlet and outlet pressures stayed quite constant under this type of control. The J-T valve opened and closed constantly but the changes were smooth. As a result, temperature changes in the coil package were minimal as expected. As time progressed the heat leak into the cryogenic system decreased. This was evident from an increased liquifaction rate when the system was run off make up. On March 9 the liquifaction rate was 0.65 gs^{-1} (18.6 standard liquid liters per hour); by April 16 the liquifaction rate had increased to as high as 1.04 gsi^{-1} (30.0 standard liquid liters per hour). This difference probably reflects a soaking in of the cold into the superinsulation with time.

The transition of the superconducting coil from the normal to the superconducting state is illustrated in Fig. 23. This figure plots the coil resistance and UPC circuit resistance versus the corrected coil temperature measured by TD4. Before the coil became superconducting the resistance of the superconducting coil plateaud at 0.60 ohm (note: The superconducting coil resistance was 86 ohms at 280 K.). By the time the TD4 temperature has dropped to 7 K, the coil had zero resistance. A plateau in the UPC coil resistance was reached at 13 K at a value of 0.27 ohms (The UPC coil resistance was 61 ohms at 280 K.).

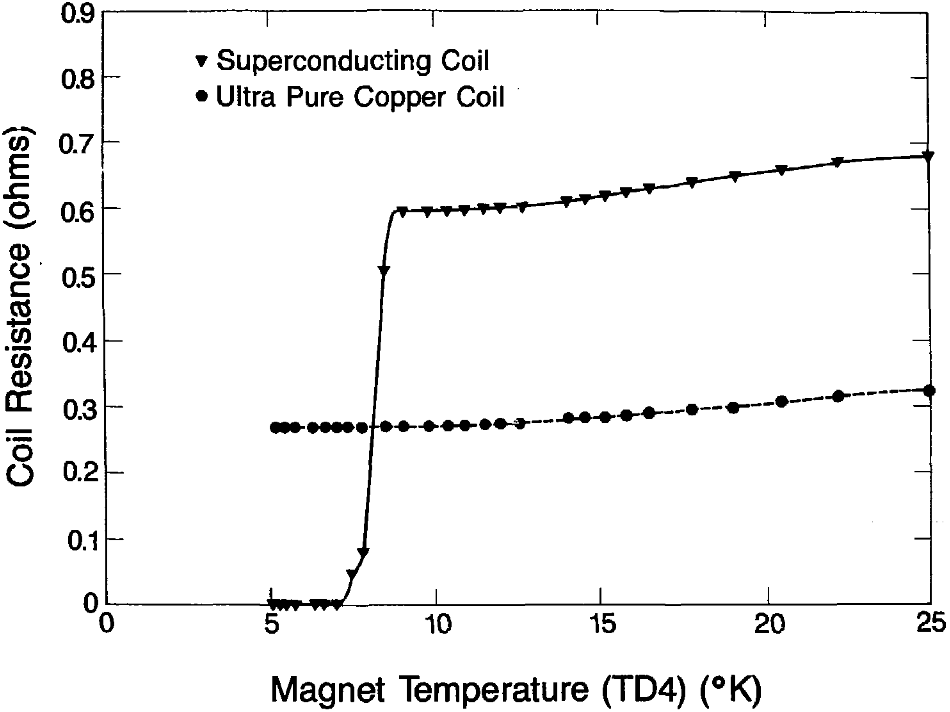

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Fig. 23. The transition of the TPC magnet from the normal to the superconducting state. The superconducting coil and UPC coil resistance versus temperature (TD4) at temperatures below 25K.

c) Operation of the System with the Liquid Nitrogen Cooled Shields Cold

Extensive testing without the liquid nitrogen shield occurred during March and April of 1983. The magnet was quenched using the Q coils at currents of around 100, 200, 400, 800 and 1000A. At about 1300 A the first spontaneous quench occurred. There were several spontaneous quenches between 1300 and 1540 A. This was far short of the designated magnet design current of 2260 A. The cause of the spontaneous quenching was thought to be due to heat leaking into the high field region of the superconducting coil through the UPC leads. This heat leak and high temperature point (6.5 to 7.0 K) in the magnet was traced directly to operating the magnet without a liquid nitrogen shield.

A temperary patch was put on the leak in the nitrogen circuit. (We were lucky because the bellows, which had a hole in it, could be pulled out and be repaired without further leaks developing in the circuit.) On May 12, 1983, the cooldown with the liquid nitrogen shield was started. The magnet was completely cold 24 hours later.

The immediate response was an increased rate of liquifaction while the refrigerator was operating on make up. The first time the magnet was cold with nitrogen in the shields the rate of helium liquifaction in the control dewar was 1.34 gs^{-1} (38.6 standard liquid liters per hour. While the system was operating on makeup, the inlet pressure was 9.9 psi and the control dewar pressure was 5.7 psi.

When the system was switched to the off make up mode, the circuit inlet pressure dropped to pressures as low as 8.4 psig. The control dewar pressure dropped to around 3.5 psi. The reduction in control dewar pressure was due to a lower mass flow in the J-T circuit. (Note: The turbine flow was also reduced.) The pressure drop across the flow circuit appears to be higher than when the system was operated without liquid nitrogen in the shield even though the apparent mass flow through the flow circuit (measured just before two phase flow is established) is reduced. The quality of the helium leaving the flow circuit appears to be higher (more gas and less liquid), and there could be some phase separation occurring in the flow circuit due to the reduced mass flow.

The off make up mode of operation saw larger changes in the J-T valve opening. This was accompanied by larger changes in circuit inlet pressure. Changes in the temperature measured at TD1 suggest that the temperature at this point has a pattern which follows the changes of inlet pressure. While operation in the off make-up mode was satisfactory, one might want to increase the mass flow through the flow circuit in order to smooth out the flow. (One might also vary the J-T valve control time constant.)

On May 16 the magnet quenched spontaneously at 1735 A. This was a disappointment. On the evening of May 16 the magnet quenched at 2194 A. The quench was caused by a misfire of the quench protection circuit. (The magnet did not quench spontaneously.) On May 17, 1983, the magnet reached its design current of 2200 A. The magnet operated at this current for about an hour. (The stored energy of the TPC magnet at design current without iron is 9.0 MJ.) The magnet current was brought back down until the magnet quenched spontaneously at around 1200 A. This quench was suspected to be related to changes in lead gas flow.

It was decided on May 18 that the magnet should be brought back to Berkeley for a permanent repair of the liquid nitrogen shield and modifications of the ultra pure copper (UPC) lead bus bars. The latter changes would probably permit the TPC magnet to operate at full current even if the liquid nitrogen shield were warm. The heat leak into the TPC magnet is estimated to be 16 ± 3 W with the liquid nitrogen shield as compared to 56 ± 7 W without the liquid nitrogen shield (see Section 5 on the magnet calorimetry).

5. Operation of the System on the Helium Pump, Calorimetry of the System

The TPC magnet cryogenic system is designed to run either on the refrigerator or a liquid helium pump (see Fig. 18 and Refs. 1, 5, and 9). The original reason for having the helium pump was to provide backup refrigeration in the event of a turbine shut down or a refrigerator failure. The pump was expected to operate no more than a few hours. Figure 24 shows the helium pump and control dewar heat exchanger. Figure 25 shows a helium pump schematic.

During the TPC magnet test the pump served two functions.

1) The pump was operated on the TPC magnet in several different modes both without and with current in the magnet. The problems of switching in the pump and switching the system back to the refrigeration mode were investigated.
2) The helium pump was used to circulate helium through the system while calorimetry was done to measure basic system heat leaks.

Both uses of the pump have demonstrated that two phase cooled superconducting magnets can be cooled using a helium pump. At least one of the future thin solenoids intends to use a helium pump as the means of circulating helium through the flow circuit.[19]

a) Operation of the Superconducting Magnet on the Liquid Helium Pump

On April 26 and 27, the TPC magnet was cooled by flow from the helium pump while it carried currents of 100 A and 1000 A. (Note:

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Fig. 24. The helium pump and its heat exchanger.

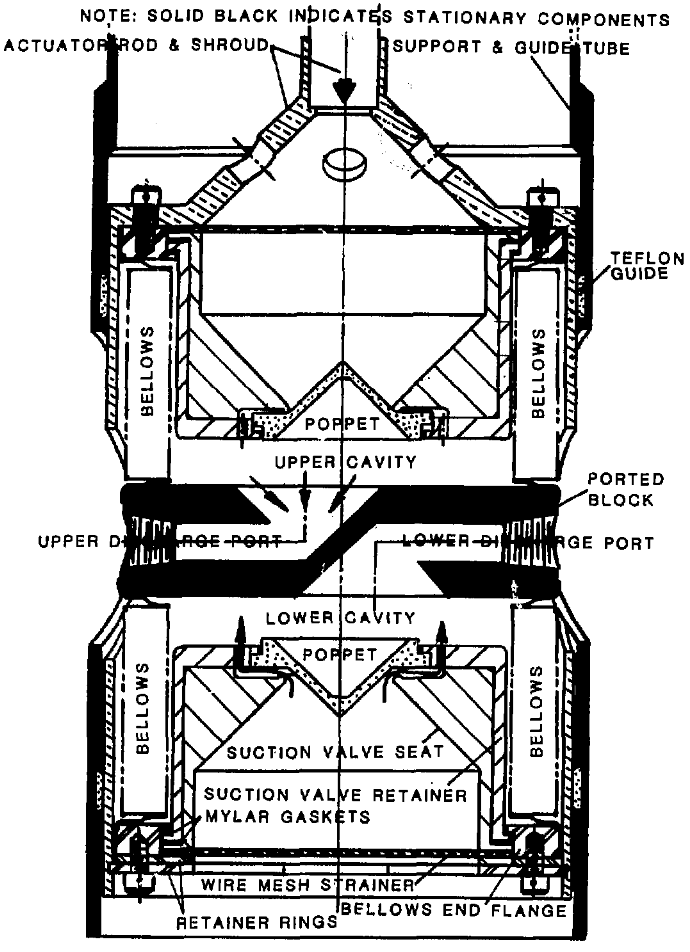

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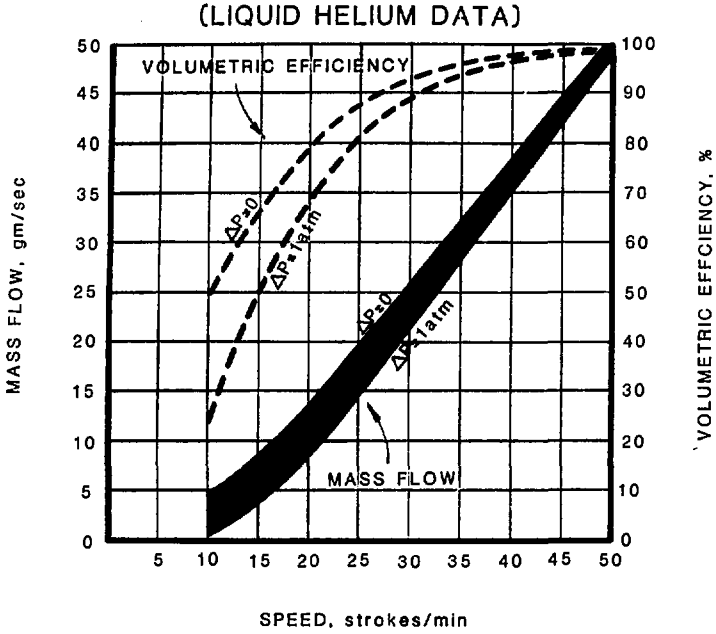
Fig. 25. A cross-section of the helium pump showing the double acting bellows system and intake valves.

This is before the shield was fixed; the magnet critical current was 1300 to 1500 A.) The low current test done on April 26 went through the following steps: 1) The pump was turned on and run at a speed of 24 strokes per minute. The pump flow is added to the flow from the refrigerator. 2) The control dewar valve V211 was switched from the refrigerator to the pump mode while the pump operated at 24 strokes per minute. The pump supplied all the helium to the magnet. 3) The pump speed was increased from 24 strokes per minute to 32 strokes per minute. 4) The pump speed was decreased from 32 strokes per minute to 16 strokes per minute. 5) The pump speed was increased from 16 to 24 strokes per minute. The pump was switched off and valve V211 was switched back to the refrigerate mode.

The measured mass flow versus pump speed with the one inch cam is shown in Fig. 26. (These measurements were made in 1979.) The estimated mass flow through the circuit while off make up (with no liquid nitrogen in the shields) was estimated to be 7.5 gs^{-1}. When the pump was turned on at 24 strokes per minute the mass flow was increased to about 22 gs^{-1}. Operation on the pump alone at 24 strokes per minute yielded an estimated mass flow of about 15 gs^{-1} (see Fig. 26). Operation of the pump at 32 strokes per minute resulted in an estimated mass flow of about 24 gs^{-1}, and a pump speed of 16 strokes per minute yielded a mass flow of about 8 gs^{-1} (see Fig. 26).

Figure 27 shows the measured pressure at the inlet and the outlet of the flow circuit. There was a lot of fluctuation in the pressures (the inlet pressure was the worst) so Fig. 27 shows a range of



ONE INCH FIXED STROKE,
DUAL CHAMBER RECIPROCATING BELLOWS,
POSITIVE DISPLACEMENT,
CRYOGEN CIRCULATING PUMP

XBL 803-8751

Fig. 26. The helium pump volumetric efficiency and pump mass flow as a function of the pump speed for the one inch can.

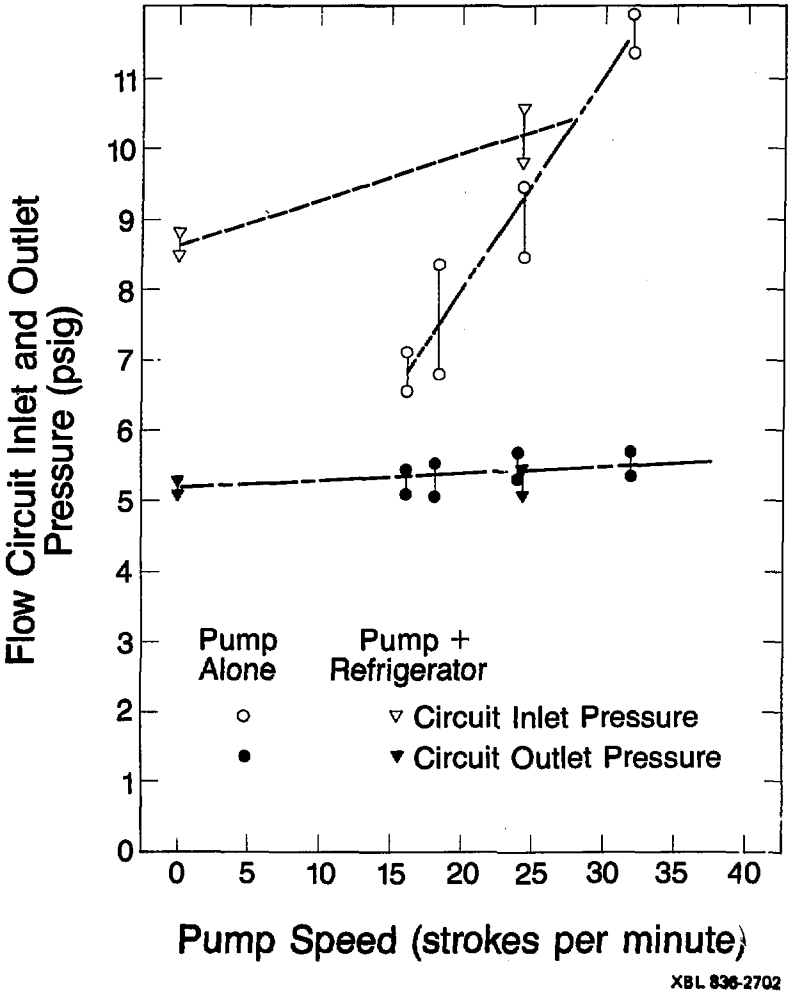


Fig. 27. Measured flow circuit inlet pressure PT201 and outlet pressure PT202 as a function of pump speed.

pressures which represents the highs and lows of pressure measured by the computer monitoring system. When one trys to calculate pump work from these pressure measurements, one ends up with a low value. (The pressures which count are those which occur within the bellows.)

When the system operates on the refrigerator alone while it is off make-up, the mass flows were reduced to around 7.5 gs^{-1}. The estimated quality change as the helium flows through the flow circuit was estimated to be about 70 percent. The helium entered the flow circuit at a quality of around 15 to 20 percent and exited at a quality of 85 to 90 percent. (Quality is defined in the same sense as it is for steam; all liquid is zero and all gas is one.) When one turned on the pump at 24 stroke per minute and added the pump flow to the refrigeration flow the quality change across the circuit was reduced to a 26 percent change. The entering quality was estimated to be from 5 to 7 percent. The exiting quality was estimated to be from 31 to 33 percent. Thus, even through the flow circuit carried much more mass flow (about a factor of three) the pressure drop only goes up a factor of around 1.5.

The pressures shown in Fig. 27 were measured only a short time after changes were made. The upper heat exchangers of the refrigerator have not had time to react. The low pressure drop measured while the pump was operated at 16 and 18 strokes per minute started to increase as the upper heat exchangers in the refrigerator begin to change in temperature.

The TPC magnet was operated at 1000 A for about 3 hours while two phase cooling was supplied by the pump. The refrigeration system was switched from refrigeration to pump mode and the pump was turned on and off as the magnet carried current. Operation of the TPC magnet was stable. The cryogenic system settled to an equilibrium operating condition when the pump was running.

b) Calorimetry of the Entire Magnet Cryogenic System

The TPC cryogenic system including the magnet was measured for total heat load using helium boil off measurements. Two sets of measurements were made with no liquid nitrogen in the shields. One set of measurements was made with liquid nitrogen in the shield. Three methods of calorimetry were used: 1) Direct measurements of helium boil off were made with a room temperature positive displacement gas flow meter. 2) Calorimetry was done by measuring liquid level changes in the control dewar. 3) An overall mass and energy balance was made on the flow circuit with cold gas leaving the system through the refrigerator heat exchangers.

The first set of calorimetry measurements was made on March 11, 1983. The measurements were made using the gas flow and liquid drop methods. The magnet had no liquid nitrogen in its shields. The second set of measurements (also with no nitrogen) was made on April 26, 1983. This set of measurements used the overall mass and energy balance method. On May 18, 1983 calorimetry using the mass and energy balance method was made on the TPC magnet while liquid nitrogen flowed in the magnet shields.

Table 2 compares the results of calorimetry measurements on the magnet with and without the liquid nitrogen system. The use of the liquid nitrogen system reduces the heat leak into the TPC magnet cryogenic system by about 40 watts. Table 3 compares the May 18, 1983 heat load measurement with the May 1980 heat load measurements. The largest differences in the two were due to changes in pump work and the transfer line heat leak.

Table 4 presents an estimate of the refrigeration requirements for the TPC magnet system with and without liquid nitrogen in the shields of the magnet. If the results of Table 4 were plotted, on Fig. 8, a different charactoristic line would be created. This line would not be parallel to the line shown in Fig. 8. The line would intercept the x axis at 250 W instead of 257 W and it would intercept the Y axis at 2.24 gs^{-1} (64.5 standard liters per hour) instead of 3.06 gs^{-1}. There are two explanations for this; 1) the automatic J-T valve chooses a different operating line which is farther from the maximum liquifaction refrigeration line, and 2) the turbines were less efficient than they were when the line in Fig. 8 was created. (During one of the turbine failures, a turbine blade was damaged.)

The measured heat loads compare favorably with the predicted values given in Ref. 1. The TPC magnet system should perform even better when it is in the iron. The transfer lines will be shorter and liquid nitrogen will be used in the magnet shields. The predicted refrigeration requirements for the magnet in the iron is 50 ± 6 W plus about 0.4 gs^{-1} liquifaction for the electrical leads at full current.

Table 2. A heat load estimate for the TPC magnet cryogenic system with and without liquid nitrogen in the magnet cryostat shields.

System Component	Heat Load (W) Without LN_2	Heat Load (W) With LN_2
Magnet Cryostat	56 ± 7	16 ± 3
Transfer Lines	37 ± 3	37 ± 3
Control Dewar	3 ± 0.4	6* ± 1
Helium Pump Work 24 RPM	29 ± 4	---
Helium Pump Work 28 RPM	---	41 ± 4
TOTAL	125 ± 10	100 ± 7

*This includes a thermal acoustic oscillation of about 3 watts.

NOTE: The values given are mean values. The deviations are standard deviation values of various measurements.

Table 3. A comparison of the measured heat loads, with the liquid nitrogen in the shield on the magnet cryostat, May 1983 and May 1980 tests.

System Component	Heat Load (W) May 1983 Test	Heat Load (W) May 1980 Test
Magnet Cryostat	16 ± 2	16 ± 2
Control Dewar	6 ± 1*	3 ± 0.5
Transfer Lines	37 ± 3**	28 ± 3**
Helium Pump Work	41 ± 4+	33 ± 3++
TOTAL	100 ± 7	80 ± 7

*There is an acoustic oscillation heat load of about 3 W.

**The transfer lines for the 1983 test were 70 meters long; the transfer lines for the 1980 test were 45 meters long.

+Helium pump speed 28 strokes per minute.

++Helium pump speed about 25 strokes per minute.

NOTE: The deviations of the values are one standard deviation of the various measurements.

Table 4. A comparison of measured refrigeration and liquefaction for the TPC magnet with and without liquid nitrogen in the magnet shield.

	Without LN_2	With LN_2
Refrigeration Loads (W)		
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 REFRIGERATION (W)	102 ± 9	65 ± 8
Liquifaction Loads (gs^{-1})		
Lead Gas Flow	0.30	0.30
Maximum Measured Liquifaction in the Control Dewar	1.04	1.34
TOTAL LIQUIFACTION (gs^{-1})	1.34	1.64

*Includes an estimated 3 to 4 W thermal acoustic oscillation heat load.

NOTE: The uncertainty represents one standard deviation of the calorimetry measurement. The error on liquifaction is unknown.

6. The Response of the TPC Magnet Cryogenic System to Quenches and Other Transients

A series of transient response tests were made on the TPC magnet system without the magnet on January 14, 1983. The 900 watt heater in the control dewar was used to provide cold gas to the lower end of the refrigerator. The 900 watt heat pulses were put into the liquid helium in the control dewar for time intervals of 30, 45, 60, 90 and 120 seconds. The response of the refrigerator depended on the liquid level at the start of the pulse and the length of the pulse.

At a 90 percent liquid level, the control dewar is full. Liquid helium will start to flow back to the refrigerator when the liquid is at this level. (The refrigerator could be adjusted to permit this kind of operation but our tests suggest this is not advisable.) The first heat pulse which was put into the system was a 60 second pulse with the liquid level at about 89 percent. The pressure within the control dewar rose rapidly. As soon as critical pressure was reached (2.245 atm or 18.3 psig), the refrigerator became very cold and the turbines went into a cold shut down. Gas flowed through the refrigerator raising the pressure in the line to the compressor suction from 15.5 psia to over 18 psia. The liquid level in the control dewar dropped to 58 percent with a loss of 55 liters of liquid helium. The excess energy put into the system beyond what the refrigerator could remove was 42 kJ which under normal circumstances would boil away only about 18 liters of liquid. It is clear that 37 liters of liquid were transported out of the control dewar into the refrigerator before it boiled away.

When the 60 second pulse test was repeated (at 900 W) when the liquid level was at 66 percent, the results were much more favorable. In this case, the peak dewar pressure was 11.8 psig (below critical pressure). The refrigerator turbines did not shut down. The pressure in the suction line to the compressor rose to 16.15 psia and only about 4 liters of liquid was lost. This amount of liquid is less than the 18 liters which might be lost under normal circumstances. Sensible heat was recovered from the helium as it went up the return side of the heat exchangers.

Low liquid level pulses of 30, 45, 90 and 120 seconds were made. In all cases the peak pressure in the control dewar was below the critical pressure for helium; the system remained operational without a turbine shutdown. The amount of liquid consumed in the control dewar was less than one would expect from open pot boil off indicating that sensible heat was being recovered in the refrigerator heat exchangers. The January 14, 1983 tests indicated that the control dewar pressure must be kept below the critical point in order to prevent the transport of a large mass of helium through the refrigerator back to the compressor return line.

Large pulses of helium back through the refrigerator will cool the heat exchanger between the two turbines, decreasing the pressure drop across the number two turbine and increasing the pressure drop across the number one turbine. The number one turbine is very sensitive to changes in pressure drop and absolute pressure. Sudden changes in pressure can result in turbine failure.

As a result of the February 2, 1983 turbine failure and an analysis of the January 14, 1983 test data, the quick shut off valve between the control dewar and the refrigerator and the control dewar was installed. This valve (V212) will close quickly under the following circumstances: 1) The pressure drop across the circuit from P201 to P202 exceeds 16 psi; 2) the control dewar pressure exceeds 16 psig (2 psi below critical pressure); 3) a quench signal from the OR module (which fires the coil quench protection system) is detected; and 4) there is a signal from a turbine shut down. In addition, improved control of the turbine inlet pressure will be achieved with a better valve plug and a development program is proposed to develop a new turbine with a stronger thrust bearing system.

Quenching of the TPC magnet started in March of 1983. The first quenches were at currents of around 100 A, 200 A and 400 A. The first series of quenches did not have the full protection of valve V212. It was decided that the valve would be closed manually so that one could see how the refrigerator reacted to the quenches. In all cases during these early quenches, the magnet was run on the refrigerator with liquid levels in the control dewar below 60 percent. The refrigerator had no problem with the 100 A (18 kJ of magnetic energy released), but the 200 A quench caused a turbine shut down. The upper turbine was restarted but it ran roughly with considerable noise being generated. A quench of the magnet at 433 A (300 kJ of stored magnet energy) was made without shuting the turbine down. A short time later the turbine shut down. After several attempts at restarting the turbine, it was pronounced dead.

All other quenches occurred with the full protection of the automatic shut down circuit on valve V212. The valve closed immediately upon a signal from the quench protection circuit. Pressures in the control dewar rose quickly. Within seconds the control dewar relief valve vented to the atomosphere. One of the changes made in the system was the replacement of the circle seal type elastimer gasket relief valve with an all metal seal, pressure actuated relief valve developed by Fermi Lab. This relief valve opens fully with only a small pressure difference between just cracked and fully open. The relief valve performed very well. It resealed immediately and did not require a heat gun to thaw it out. The relief valve is set to around 18 psig. (The control dewar rupture disc is set to 125 psig.)

The first series of quenches (up to 1030 A) were induced in the TPC magnet using a Q coil (a small coil through which a 1000 μF capacitor is discharged generating a normal spot about 1 cm in diameter through superconductor AC losses). Spontaneous quenching started at 1320 A (3.07 MJ stored magnetic energy). There were a series of these quenches between 1300 and 1540 A. (It was later determined that the spontaneous quenches probably were caused by heat leaking into the coil through the ultra-pure copper leads. This heat was put into the coil at the maximum field point. Activating the nitrogen shield reduced the heat leak by a factor of five and permitted the coil to be charged to full design current.)

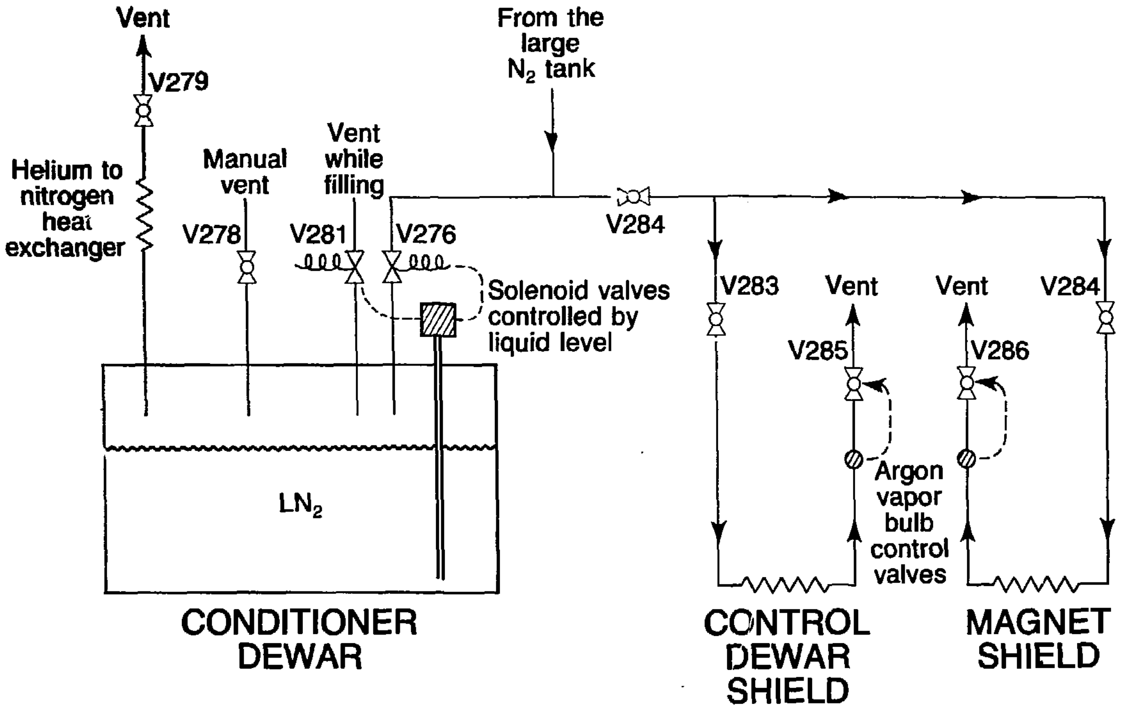
As the quench current increased, two things happened. The pressure in the control dewar rose faster and the maximum pressure measured by the inlet pressure gauge P201 increased. Under no circumstances was this measured pressure above 300 psig. Operation with the helium pump increased the P201 pressure and shortened the time required for the control dewar relief valve to relieve. (The liquid content of the helium in the tubes is higher when the pump is used to circulate the helium.) The maximum pressure during a quench was not affected by the presence or absense of liquid nitrogen in the shields.

During low current quenches, starting the helium pump and using left over liquid in the control dewar appeared to help speed up quench recovery. During high current quenches, the J-T valve was closed and gas was vented from the control dewar. Once the control dewar pressure reached 5 psig, one could vent the gas back to the refrigerator and through the by-pass of the lower heat exchangers. Recovery from even very high current quenches took less than 5 hours. On one occasion the process was speeded up by adding liquid helium from the 500 liter storage dewar to the control dewar.

7. Operation of the Liquid Nitrogen Circuit

The liquid nitrogen system described in Ref. 1 consisted of the control dewar shield, the supply transfer line, the magnet coil shield, and the return transfer line as a single series circuit. Flow through the circuit was to be supplied by a contrifugal pump in the conditioner dewar. During tests of the liquid nitrogen system in November 1982 and January 1983, we could not get the system to work in a satisfactory way. The liquid nitrogen pump constantly lost its prime. Once the pump prime was lost, the pump was difficult to restart. (We don't understand why the pump gave us problems. SLAC successfully operated a nitrogen pump on LASS for several years.)

The liquid nitrogen pump was abandoned in late January 1983. The series pump loop was replaced by two parallel nitrogen loops which were run directly off the liquid nitrogen tank. A separate circuit controlled by an automatic fill mechanism kept the conditioner dewar full when it was in use for cooldown. The modified nitrogen flow circuit, shown in Fig. 28, consists of a separate flow circuit for the control dewar and a separate foow circuit for the supply transfer line, magnet shields, and the return transfer line. (It should be noted that supply and return transfer lines carry both helium and nitrogen to and from the magnet coil package. The nitrogen circuit serves as a shield for the transfer lines.) The flow through the control dewar nitrogen circuit and the magnet nitrogen circuit is controlled by Argon vapor bulb controller valves. When the Argon



XBL 836-2716

Fig. 28. A schematic diagram of the liquid nitrogen system for the TPC magnet.

pressure is high (the circuit is too warm) the valve opens. When the Argon pressure is too low the control valve closes.

The operation of the liquid nitrogen circuits was surprisingly smooth. The major operational problems were caused by the liquid nitrogen tank being empty. There was one or two occasions when the liquid nitrogen tank pressure was either too high or too low. The former caused relief valves on the nitrogen circuit to relieve. (These valves were reset to relieve at a higher pressure.) The latter caused a warming of the nitrogen shields. The TPC magnet system could not be run on the refrigerator without liquid nitrogen, when there was no nitrogen in the shields. A reduced heat load due to the magnet nitrogen shields operation and shorter transfer lines may permit operation of the refrigerator without nitrogen.

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References

1. M. A. Green, W. A. Burns, J. D. Taylor and H. W. Van Slyke, "The TPC Cryogenic System," Lawrence Berkeley Laboratory Report LBL-10352, UC-38, March 1980.
2. M. A. Green, "The Large Superconducting Solenoid for the MINIMAG Experiment," Advances in Cryogenic Engineering 21, 24 (1975), LBL-3677.
3. M. A. Green, "The Development of Large High Current Density Superconducting Solenoid Magnets for Use in High Energy Physics Experiments," Ph. D. Thesis, University of California, Berkeley, LBL-5350, May 1977.
4. M. A. Green, W. A. Burns, and J. D. Taylor, "Forced Two Phase Helium Cooling of Large Superconducting Magnets," Advances in Cryogenic Engineering 25 (1979), LBL-9701.
5. M. A. Green, et al., "The Operation of a Forced Two Phase Cooling System on a Large Superconducting Magnet," Proceedings of the ICEC-8 Conference, Genova, Italy, p. 72, June 1980 (LBL-10976).
6. M. A. Green, "Quench Protection and Design of Large High Current Density Superconducting Magnets," IEEE Transaction on Magnets, MAG-17, No. 5, p. 1793, Sept. 1981 (LBL-12233).
7. KOCH Process System report on the CTi Model 2800 Refrigerator.
8. M. A. Green, "Foreign Travel Report 1980," LBL Engineering Note M5818, Nov. 1981.

9. W. A. Burns, M. A. Green, R. R. Ross, and H. W. Van Slyke, "The Construction and Testing of a Double-Acting Bellows Liquid Helium Pump," Proceedings of the ICEC-8 Conference, Genova, Italy, p. 383 (LBL-10977).

10. R. G. Smits, et al., "Gas Cooled Electrical Leads for Use on Forced Cooled Superconducting Magnets," Advances in Cryogenic Engineering 27 (August 1981), LBL-12783).

11. A. O. Dubois, "PEP4, TPC Magnet, Flanged Cooling Tube," LBL Spectification M637A, February 1982.

12. M. A. Green, "Cryogenic System Test," an unnumbered LBL note, Nov. 9, 1982.

13. "TPC Rebuild Coil, Log 2 Beginning with Wire Inspection, Cryogenic Log Book, End May 1983," see P. H. Eberhard or J. D. Taylor for details.

14. "SLAC Cryogenic Log Book for the CTi 2800 Refrigerator," see H. Petersen or R. D. Watt for details.

15. A. Dubois and M. A. Green, "PEP4, Magnet, Basic Parameters of the Cryostat and coil as Fabricated in 1983," LBL Engineering Note M6018, January 1983.

16. M. A. Green, "Large PEP Detector, Large Thin Superconducting Solenoid Magnet, Cooldown of the TPC Thin Solenois," LBL Engineering Note M5034, March 1977.

17. M. A. Green, "Cryogenic Tests of the TPC Magnet," an unnumbered LBL note, January 20, 1983.

18. M. A. Green, "MINIMAG Experiment, Large Superconducting Solenoid Magnet, the Cryogenic System," LBL Engineering Note M4834, June 1975.

19. Private communication with A. Yamamoto of KEK on the TOPAZ experiment proposed thin superconducting solenoid.