TEVATRON CRYOGENIC SYSTEM

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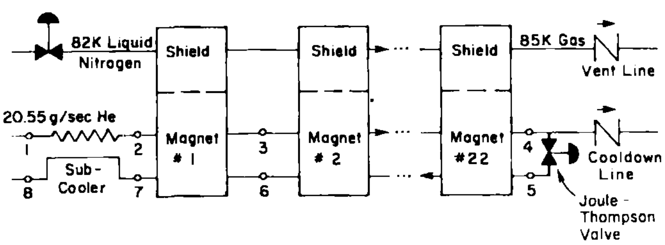
INTRODUCTION

The Tevatron Cryogenic System consists of a 6500 meter ring of super conducting magnets in the existing Fermilab Main Ring Tunnel with a distributed refrigeration system above grade. The magnet ring is comprised of 777 dipoles, 216 quads, 204 spools, and 86 specialty components. The spool pieces contain the safety leads and voltage taps for quench protection, three relief valves, vacuum instrumentation and connections, Helium temperature indicator, and superconducting correction coils with their power lead. The speciality components include 24 refrigerator interface feed cans (half with power supply connections), 30 Joule-Thompson valve boxes, 24 cryogenic bypasses around warm equipment and eight miscellaneous adaptors. The ring is broken up into 48 strings of magnets, which are cooled by 24 satellite refrigerators. [1]

To cool long superconducting magnet strings one cannot use the standard bubble chamber pool boil technique; one must use a force feed system. One can use either a pump, Joule-Thompson valve, or wet expander, to drive either subcooled liquid helium, 2-phase helium or supercritical gas. We chose the wet expander driving subcooled liquid with 2-phase conterflow heat exchange.

The temperature and pressure distribution for 1/48 of the Tevatron ring is shown in Fig. 1. The liquid He is sub-cooled by a small heat exchanger located in the feed can. It then reaches equilibrium after the first magnet, point 3. There is a small increase in temperature, .05 K, from point 3 to point 4, due to the 2-phase pressure drop from point 5 to point 6. The heat generated by the coil located in the 1Ø chamber is heat exchanged, vaporizing the liquid in the 2Ø chamber. The flow is controlled by the Joule-Thompson valve to maintain point 8 at .1 K of superheat. The shield is cooled with 2Ø N_2 with the discharge as 85 K gas.



POINT	T(K)	Patm	HJ/g	% LIQUID
1	4.90	1.8	14.22	100.
2	4.50	1.8	11.20	100.
3	4.55	1.8	11.47	100.
4	4.60	1.8	11.75	100
5	4.47	1.25	11.75	96.
6	4.42	1.2	27.49	13.
7	4.42	1.2	27.99	10.
8	4.52	1.2	31.01	0.1K Super Heat

Figure 1. Details of the cooling loop for a string of cryogenic magnets (1/48 of the ring)

* Operated by Universities Research Association, under contract with the U.S. Department of Energy.

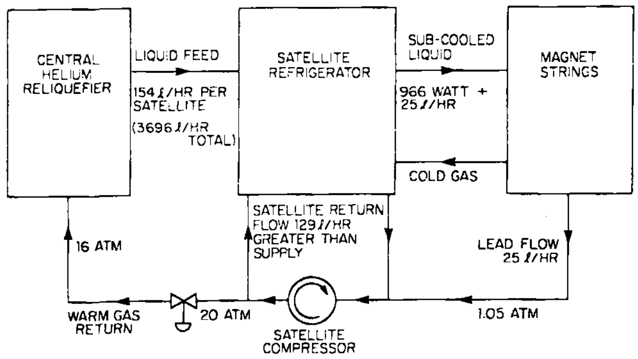


Figure 2. Helium Flow Schematic

SYSTEM DESCRIPTION

The Tevatron magnets are cooled by a hybrid system which consists of a 5000 liters/hr central helium liquefier (CHL) coupled with a small-diameter liquid transfer line connecting twenty-four satellite refrigerators (Fig. 2). The transfer line supplies liquid helium for both the satellite refrigerators and the magnet lead flow as well as liquid nitrogen for the magnet shields. The satellites act as amplifiers with a gain of twelve by using the enthalpy of the helium supplied by the central liquefier as liquid, converting it to 4.5 K refrigeration, and returning it as 300 K gas. This arrangement combines advantages of a single

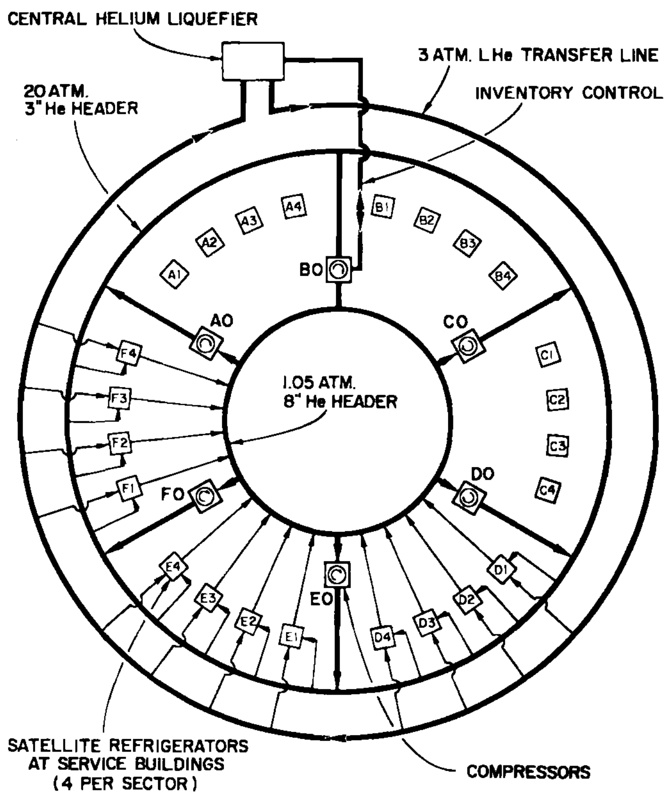


Figure 3. Layout of the Refrigeration System

central facility with those of individual stand-alone units stationed around the ring. The central liquefier has the high efficiency associated with large components, but requirements for distribution of cryogenic liquids and electric power to the service buildings are reduced. The likelihood of continued operation in the event of equipment failure is also significantly improved.

The six compressor buildings supply 20 atm helium to the twenty-four refrigerators through a 9.0 cm discharge header located on the berm and a 22.0 cm i.d. suction header located in the tunnel (Fig. 3). The suction header is also used as the cooldown line as well as quench relief. Also located in the tunnel is the nitrogen collection and relief header.

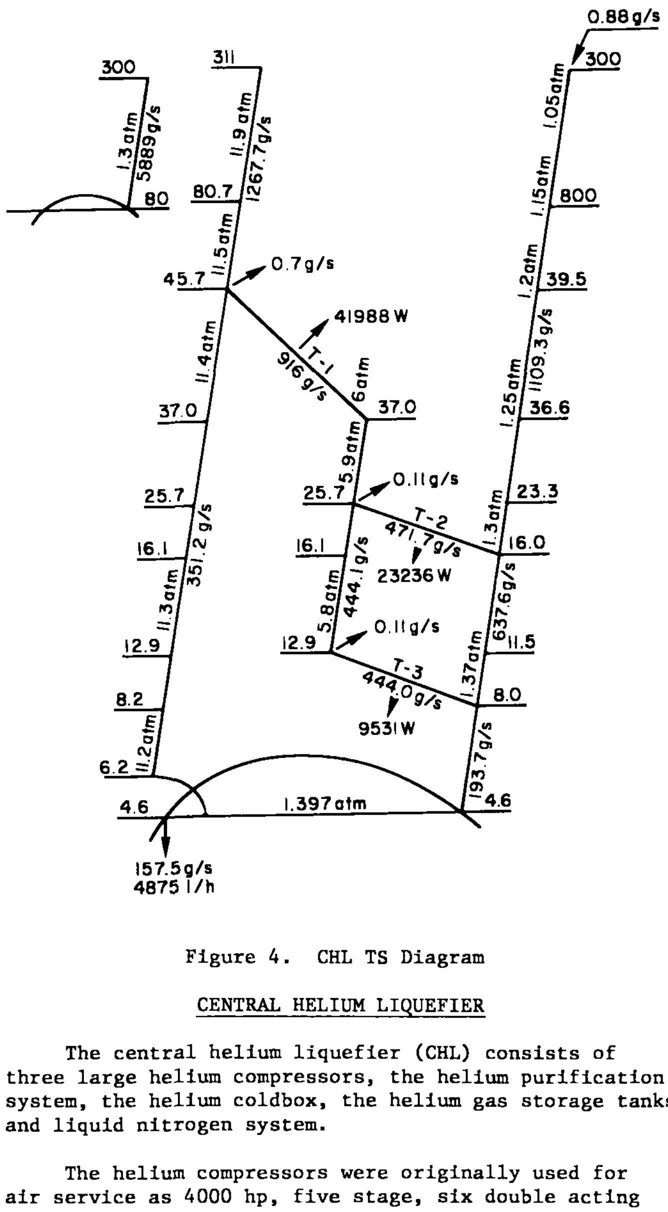


Figure 4. CHL TS Diagram

CENTRAL HELIUM LIQUEFIER

The central helium liquefier (CHL) consists of three large helium compressors, the helium purification system, the helium coldbox, the helium gas storage tanks and liquid nitrogen system.

The helium compressors were originally used for air service as 4000 hp, five stage, six double acting cylinder units. They were reconditioned and converted to helium service. The helium design used only three stages and a lower compression ratio; the first stage throughput was reduced by blanking off one half of a first stage cylinder and the third stage throughput was increased by putting the third, fourth and fifth stages in parallel. The pistons were modified to accept graphite carbon-filled Teflon rings, two per piston. The rest of the compressor was rebuilt and used in its original form.

The gas purification system consists of two separate systems. One purifies the process flow whose main contaminant is oil, and the second purifies the compressor packing blow-by or seal gas which is contaminated by air and oil.

The compressors are lubricated with Rarus 427, which must be removed from the helium. This is done using a commercially bought full-flow oil mist removal system having a collection efficiency of 100% on all particles greater than 3 microns and 99.5% on particles less than 3 microns. The gas is then further purified in an activated carbon adsorber vessel containing 9000 lb. of type BPL 4 x 10 mesh granular activated carbon. Once it leaves the adsorber, it is final filtered through a 2 micron cartridge filter before entering the cold box.

The seal gas purification system is designed to remove contaminants from the helium blow-by past the pistons. This gas is collected in the distance pieces which are at atmospheric pressure. The contaminated helium gas is then piped to the suction of 280 scfm 265 psia screw compressor. This feeds a commercially bought cryogenic helium purifier, which reduces contamination level to 1. ppm air impurity. The gas is then routed to discharge before the oil removal system and then to the cold box.

The cold box is designed to accept 1268 g/sec of helium at 300 K and 12 atm and produce 4875 ℓ/hr at 4.6 K and 1.4 atm. The first stage of cooling is provided by liquid nitrogen counter flowing with high pressure helium. Not more than .64 ℓ of nitrogen is used for each liter of liquid helium produced. The flow divides with 916 g/sec going to the turbines and 351 g/sec to the high pressure side of the heat exchangers. Of the turbine flow all is expanded in turbine #1. The flow is divided again and 471 g/sec goes to turbine #2, with the remainder going to turbine #3. The 351 g/sec of high pressure helium is cooled to 6.2 K by return helium flow in heat exchangers 3 through 8. By means of a J.T. valve, it is then expanded to 1.4 atm at 4.6 K. Fig. 4 shows the T-S diagram.

The liquid gas mixture passes through a phase separator, 194 g/sec of cold gas is returned to the low pressure side of the cold box and 157 g/sec of liquid collects in a 5000 gallon dewar. From the dewar the helium will be pumped to the feed transfer line. Our current operating configuration expands the high pressure helium with the J. T. valve to 3.5 atm where the flow is split with half going through a subcooler to feed the transfer line. The remainder of the flow is expanded to 1.4 atm, the liquid is vaporized in the subcooler, and the cold gas is then returned to the low pressure side of the cold box.

The dewar and pump have not been commissioned at this time. The helium inventory is stored in fourteen 15 atm "propane" tanks which will hold 30,000 liquid liters equivalent.

The nitrogen system currently consists of a 14,000 gal. liquid nitrogen dewar, supplying liquid to the helium coldbox and a subcooler which in turn supplies the transfer line. A closed loop nitrogen liquifier (CNL) has been designed and is currently being procured.

When the CHL and CNL are finished the helium and nitrogen returns from the feedline will dump any excess liquid into two storage dewars. These two dewars which are the only two in the entire system serve a dual function: a) they provide system stability and b) they provide liquid for a few hours if the centrals have to be shutdown for minor repair.

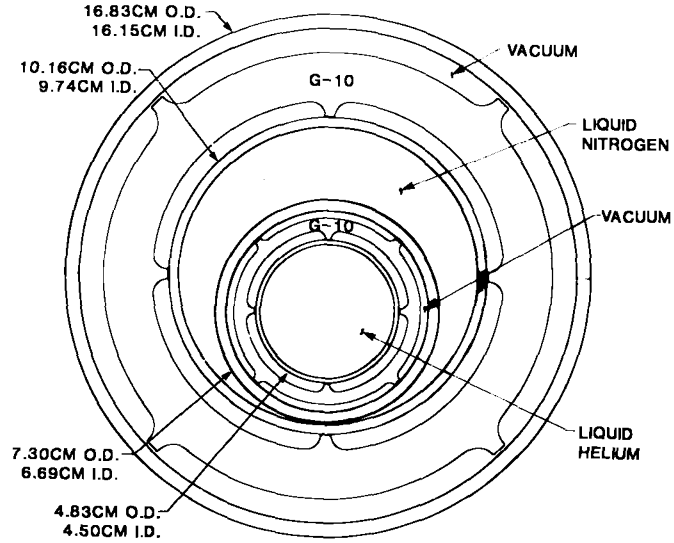


Figure 5. Transfer Line Cross Section

FEED TRANSFER LINE

The key to success of a hybrid system is the transportation of cryogens. The initial design used three 42,000 liter tankers to truck the helium from CHL to ring refrigerators. This conservative approach was soon replaced by the feed transfer line due to both winter environmental problems and operating costs.

The Tevatron transfer line consists of twenty-six 250 meter sections interconnected with vacuum jacketed U-tubes forming a loop.[2] Fig. 5 gives the cross section of the line. The line is made out of commercial 304 stainless steel, schedule 5 & 10 pipe with G-10 supports. The inner pipe has an i.d. of 4.50 cm and contains super-critical helium at 4.6 to 5.5 K 3 atm. This pipe is wrapped with 15 layers of superinsulation (aluminized mylar and dexter paper). A G-10 support is located every three meters.

The second and third pipes, 7.30 cm o.d. and 9.74 cm i.d., form the shield for the transfer line as well as the liquid nitrogen supply for the refrigerators and magnets. The shield operates at 3 atm subcooled liquid with the last section breaking into the two phase region. The flow area of the shield is 32.60 cm.[2] The third pipe is wrapped with 60 layers of superinsulation with G-10 suspensions again located every three meters. The fourth pipe, 16.83 cm o.d., is the outer vacuum jacket.

The schematic of one section of the line is given in Fig. 6. At each end is located a bayonet can, a 45.72 cm diameter vertical pipe, which contains a helium and a nitrogen female bayonet for inter-connecting to the next section as well as to the local refrigerator. In the middle is the expansion and relief box.

Completing the cryogenic transfer line system are 24 helium and nitrogen vacuum jacketed U-tubes, Fig. 7. They connect the various sections of the transfer line and provide branch taps to the refrigerator and magnet systems. Each U-tube has a vapor pressure thermometer which can be read locally, or remotely, through a pressure transducer. The nitrogen U-tube contains, in addition, a subcooler heat exchanger which removes the shield heat leak of the previous 250 m transfer line section.

The transfer line itself has no isolation valves

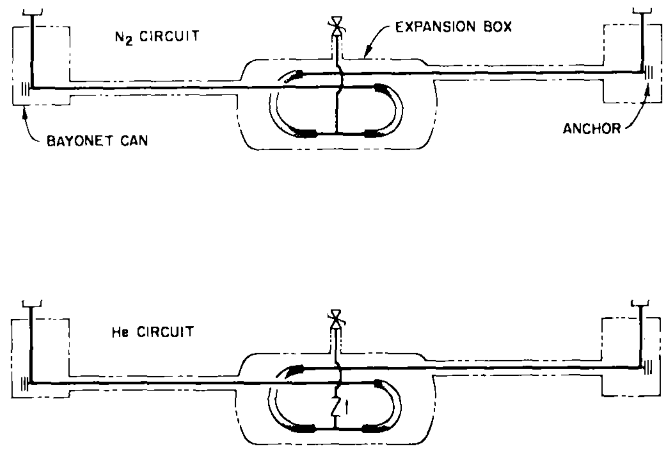


Figure 6. One Section Tevatron Feed Transfer Line (1/26 ring)

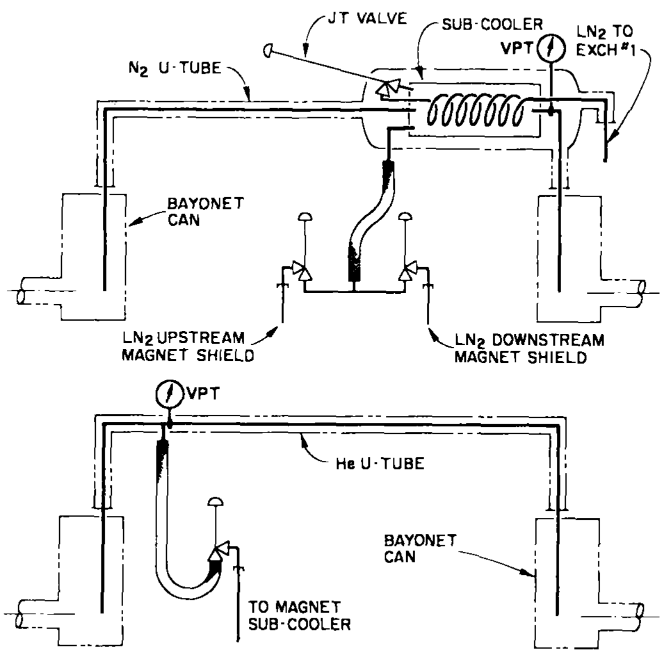


Figure 7. One Pair Tevatron U-Tube

in the system. Any isolation required will be done by lifting the U-tubes until the bottom of the male bayonet clears the warm ball valve; the chevron seals will prevent a large leakage flow. The ball valves are then closed and the U-tube removed.

Transfer lines in 24.4 m lengths were fabricated at a specially designed facility. Fabrication was performed on four subassembly lines, each of which produced one of the four pipe sizes. Almost all of the pipe is seam weld pipe in 12.2 m lengths. Three other assembly lines were used to fabricate the expansion boxes, the bayonet cans, and the helium and nitrogen U-tubes.

Prior to installation of the subassemblies around the 6250 m ring, supports for the transfer line, expansion boxes, and bayonet cans were installed and surveyed level. Positioning of the transfer line sections and the expansion boxes was carried out by a helicopter. Two hundred three assemblies were positioned around the ring from seven staging areas in 16 hours. The bayonet cans are installed in the refrigerator buildings and anchored firmly to the floor. Alignment is critical since the helium and nitrogen U-tubes are rigid with no bellows.

Welding of the subassemblies in the field begins with the inner line, starting at the bayonet can and ending at the expansion box. The other lines are moved as required and the bellows in the outer vacuum jacket at the bayonet cans are compressed to provide access to the inner pipe weld area. The finished line is cold shocked and leak tested. Similarly, the two liquid nitrogen shield lines are welded, cold shocked, and leak tested in sequence. Finally, the vacuum jacket line is welded by extending the bellows. The inner lines are then pressurized to 5 atm of helium and a final leak test is conducted on the total system.

Preliminary testing indicated that due to the number of vertical legs in the system, including road crossings, operating with two-phase helium or nitrogen, would cause severe flow oscillations. We therefore decided to operate both with single-phase cryogens. The helium circuit operates with a back pressure regulator set at 2.8 atm; i.e., above the critical point. The nitrogen circuit operates as subcooled liquid with a a small heat exchanger every 250 meters.

There have been six transfer line runs; the first was a single section run in May 1980. In November 1982, the full ring transfer line was cooled down. Table I gives the major parameters.

TABLE I Tevatron Transfer Line

	Helium	Nitrogen
Flow Rate	5000 l/hr	3000 l/hr
Input Pressure	3.5 atm	3.0 atm
Input Temperature	4.6 K	85 K
Output Pressure	2.8 atm	2.0 atm
Output Temperature	5.5 K	90 K
Length	6.5 KM	6.5 KM
Flow Area	15.9 cm^2	32.6 cm^2
Heat Leak	240 w	3600 w

SATELLITE REFRIGERATORS

The twenty four satellite refrigerators consist of the compressor, the warm distribution piping (previously described, Fig. 3), a cold box, a liquid reciprocating expander, two flow splitting subcoolers, two Joule-Thompson valves, and a stand-by 30 K gas reciprocating expander.[3,4,5,6]

The compressor system consists of four Mycom screw compressors located in each of six buildings. The compressors are 350 hp 58 g/sec, 20 atm, two stage, oil flooded units, each with its own independent oil removal system. The rotors are internally coupled and operate at 3600 rpm. The oil removal starts with the bulk oil separator with an output coalescer which lowers the oil levels to < 5000 ppm. The gas then passes through a small water cooled heat exchanger. This is followed by three Monsanto Coalescer De-misters; the first two of which have an automatic oil return to the compressor. The third stage is a guard unit for malfunctions, the normal input level being about .01 ppm. This is followed by a charcoal bed for oil vapor, a mole sieve bed for water vapor, and a final filter to remove any dust generated by the beds.

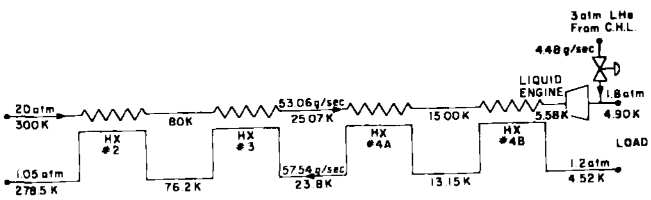
The schematic of the cold boxes and expanders is shown in Fig. 8 and the capacities are given in Table I. In the satellite mode the unit is continuously supplied 4.48 g/s liquid helium (plus .87 g/s power lead flow) from the central liquefier. This causes an imbalance in the heat exchanger flow (53.06 g/s supply vs. 57.54 g/s return) giving us a double pinch at 25 K and 5 K. The liquid engine expands from 20. atm to 1.8 atm, producing slightly subcooled liquid. The cold end refrigeration comes from three sources: 44% from the heat exchangers flow imbalance, 48% from the liquid expander, and 8% from the central liquefier flow.

Table II Refrigerator Capacity

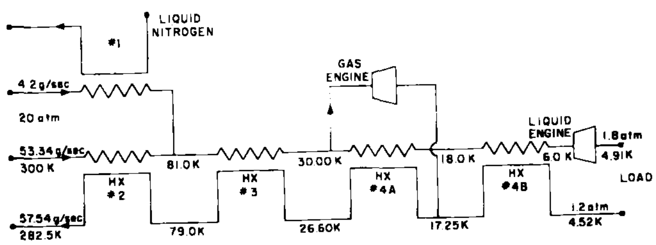
	Consumption		Production	
Mode	LN_2 ℓ/hr	LHe ℓ/hr	P watts	LHe ℓ/hr
Satellite	5	154	966	25
Stand-alone	60	---	500	25

Flow 57.5 g.sec 20 atm He

In the stand-alone mode liquid nitrogen is used instead of liquid helium. The stand-by gas engine is now operated at 30 K, while the liquid engine produces a two phase liquid gas mixture. The stand-alone mode is a mixture of refrigeration and liquefication with a trade off ratio of 5.0 watt to 1.0 ℓ/hr. This mode is designed to cool strings of magnets without the aid of the CHL both during initial construction and later during failures of the CHL. This mode was used for all the initial magnet runs. There are many additional mixtures of satellite and stand-alone modes that can be used if the central is operating at reduced efficiency.



Satellite Mode



Stand Alone Mode (Refrigeration Values)

Figure 8. Satellite Refrigerator Flow Schematic

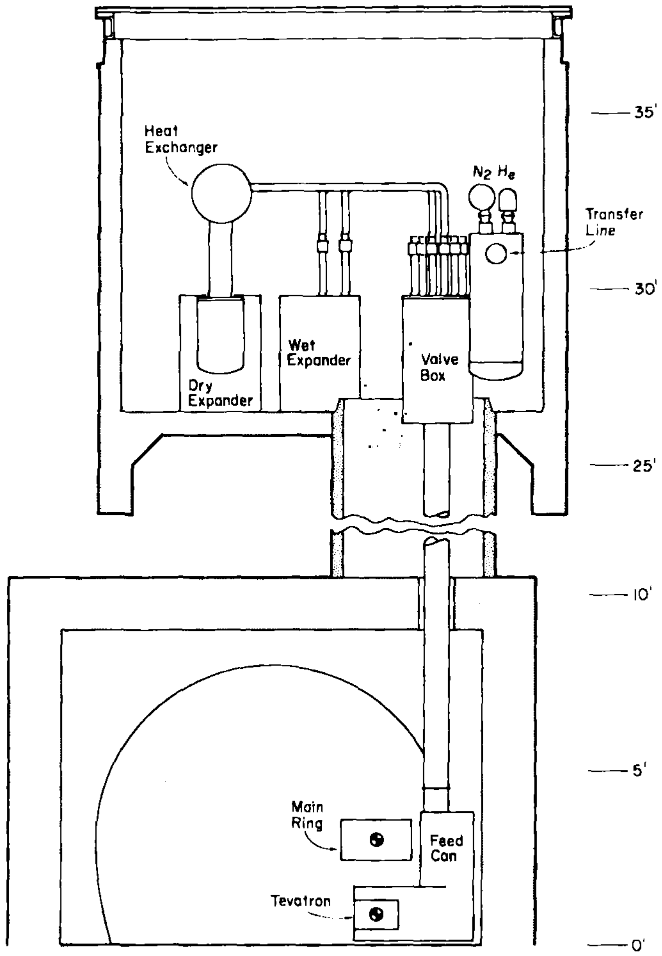


Figure 9. Cross Section of Satellite Refrigerator and Cryogenic Feed to the Superconducting Magnets in the Tunnel

The output of the liquid expander passes through the valve box to the feed can which contains a subcooler for each of the two strings; the cross section of the refrigerator and tunnel is shown in Fig. 9. At the end of each string, 125 m away, is the flow control valve which expands the 1Ø liquid into the 2Ø return passage of magnets (Fig. 1). This module also contains a cooldown line for the string.

Cooldown is accomplished by a single pass flow through the magnets with the Joule-Thompson valve closed and a cooldown valve used to control the flow. In stand-alone mode, the flow is 4 g/sec of 20 K gas per string while in satellite mode, the flow is 12 g/sec at 10 K. When the ends of the strings are cold, we switch from single pass flow to loop flow. The cooldown takes four days in stand-alone mode and less than two days in satellite mode.

Commissioning

The conceptual testing started in 1973 with the 400 ft. He pump loop runs; they tested the concept of pumping liquid He and the effects of long lines.[7] In May 1975 we started up our B12 test facility, originally cooled by only one little CTI 1400 refrigerator, and ran an extraction beam through a .8 m long prototype magnet.[8]

The next phase was full scale, prototype testing. We built the prototype satellite cold box and expanders, and made calorimeter runs in February 1976. We then modified a series of reciprocating compressors for He service, and finally ended with the testing of the Mycom screw compressor.

In December 1977 we moved the prototype refrigerator and the second prototype reciprocating compressor to the ring at the A1 service building. In August 1978, we cooled down a 60 m long magnet string. We then connected a 90 m long string on the upstream side of the refrigerator and ran an extracted beam through it. This was then followed by a series of two 125 m long magnet strings at both the A2 and A3 refrigerators, including one where the A1 refrigerator was run as a liquifier (CHL) and A2 was operated in satellite mode cooling the magnets. The goal of these runs was to measure magnet heat loads, investigate cool down problems, and understand the dynamic characteristics of the refrigerators.

On January 3, 1982 we started the "A-sector test" to gain general operating experience as well as to study subsystem interaction.[9] We ran two of our six compressor buildings (AØ and BØ)to supply five of the twenty-four refrigerators (A1 through B1). The A1, A2, and A3 refrigerators each had two 125 m magnet strings to cool, while the A4 refrigerator was connected to the transfer line as a liquefier replacement for the CHL. The fifth refrigerator B1, running as a stand-alone, cooled a single 125 m magnet string in our above ground B12 test facility.

We were totally unsuccessful in stabilizing the transfer line A4 refrigerator system, and after two weeks this was abandoned. We attempted to cool the magnets in stand-alone mode; with one exception this also failed. On February 1, we started up CHL using the brute force approach of 250 ℓ/hr helium consumption per building. We filled the magnets in three days. Subsequent tests showed that we could operate in stand-alone mode easily but could not cooldown. No progress was made on the transfer line stability until the second half of the run when we lengthened it to 3 km and spent a month studying the oscillations.

The system operating difficulties in order of severity were:

1. Expander Problems and 2. Contamination: Two kinds of thermal performance problems appeared. One was low efficiencies most often due to valve leaks appearently caused by contaminants in the helium, but some instances of low efficiency were caused by leaking seals. The second thermal performance problem was the dropping off of expander performance with increasing speed above two-thirds of maximum speed due to a high pressure drop across the engine inlet valve. Large pressure drops through the heat exchanger train due to contaminattion aggravated this problem.

   Mechanical problems including broken gas expander driveshafts and bad piston shaft seals resulted in mean times between major maintenance of about 1000 hours for gas expanders and 2000 hours for liquid expanders.

3. Controls during the early part of the run we were plagued with microprocessor reboots. In addition the communication link would fail if any one of the service buildings would get out of the range of 55 to 90°F.

4. Expander Loads: The problem included poor regulation on the liquid expander, blown fuses, and SCR's

not firing when they were too cold, causing expanders to run away and trip their emergency brakes.

5. Transfer Line Oscillations: There were independent oscillations in both the helium and nitrogen circuits. The nitrogen oscillation occured because we were trying to operate the end of the transfer line with two-phase flow and we have a large number of vertical legs in the system, including road crossings.

   The helium oscillation was actually a flow reversal oscillation; it would rush into the pipe, warm up, and flow back to CHL. The line was stabilized by putting in a full flow back pressure regulator on the output vent and a fixed inlet pressure drop orifice.

6. Power Lead Warm End Seals: The warm end of the power lead contained several epoxy joints and one O-ring. After repeated leaks, the warm end was completely redesigned using threaded epoxy joints and a welded flange.

   Extensive power testing was performed during the A-sector run.[10] The 0.75 km string of magnets was powered from a single supply to a level of 4200 amperes (950 GeV equivalent). A total of 116 hours was spent ramping at lower currents. Testing associated with the magnet ramping included:

   1. Quench protection system tests.
   2. Magnet and quench relief header pressure studies.
   3. Power leads studies.
   4. Magnet heat load measurement.
   5. Quench recovery.

On June 10 1983 the "A-sector test" ended together with the 400 GeV High Energy Physics Program. The tunnel installation crews started installing the rest of the ring on a two shift basis. On December 3, 1982 E and F sector cooldown started.[11]

The AØ, FØ and EØ compressors were used to supply the eight E and F sector refrigerators each with its two 125 m magnet strings. The full ring transfer line was commissioned one month before the test.

This run was again made in stand-alone mode, but this time we were successful in cooling down 15 of the 16 strings of magnets. The most important difference from the A-sector test was that we did a much better job in initial decontamination (1 to 2 ppm) and maintained a cleaner system. The clean helium, some expander design improvements, and a program of closely monitoring and carefully maintaining the expanders resulted in much improved expander efficiencies and much less expander downtime than in the A-sector test. Also, we learned for various operating conditions to keep expander speeds below those at which performance drops off, thus optimizing performance and minimizing wear.

The major problem on this run was magnet vacuum leaks; after several weeks the E1 and E2 refrigerators were shutdown. Two major leaks and several small ones were repaired. At F3 we installed three mobile pumps to control another large leak. On January 15, 1983 we restarted E1 and E2 in stand-alone mode.

The second most severe problem was microprocessor reboots which crashed the refrigerators. This was caused by four independent problems which together caused nine 12-hour or longer down periods. The first problem was the more than thirty self reboots over a six week period. The cause of the reboots was never found but after six weeks the reboots stopped. The second problem was that there was no alarm system to notify the operator when a microprocessor rebooted or an expander tripped off. We are now running with a temporary alarm scan. The third problem was a bad set of default parameters in the microprocessor ROM which choked the high pressure flow to the expanders; these have been replaced. The fourth problem was an overly sensitive power reversal safety circuit in the expander load; this has not been changed.

On February 1, 1983 we switched E and F sector to satellite mode. We started an additional sector, D, on February 18, 1983 in stand-alone mode. The next two weeks were spent on E and F sector power testing, during which we reached a 2000 amp 60 sec ramp using four power supplies.

We warmed up the system to 88 K on March 7,1983 for re-purification; a procedural error had contaminated the helium system with a large quantity of nitrogen. On April 11, 1983 we started a four sector cooldown including C-sector; B-sector following on May 6, 1983. C-sector contained a magnet with a shorted turn, therefore one house was warmed up to 300 K and two houses were warmed to 30 K. On May 29, 1983 the complete ring was cold and operating. On June 11, 1983 we achieved 13 turns of 90 GeV beam, on July 3, 1983, after repairing two magnet solder joints and a number of minor problems we achieved 512 GeV accelerated beam.

The system has been operating very smoothly, due largely to the experience gained on previous runs. We have a scheduled 16 to 28 hour weekly maintenance period during which all expanders are checked and greased, instrumentation is repaired, the #3 and #4 exchangers of a single satellite are derimed and occasionally CHL is derimed.

The major problem on this run is contamination detection, prevention, and shifting. We are operating with a back ground level of about 1/2 ppm with 5 min. long spikes; two and three orders of magnitude higher during maintenance, quenches, and control oscillations. This makes all our commercially bought detection useless; we are working on more sensitive detectors capable of being continuously data logged by the computers. CHL is having a great deal of trouble with its 40 K turbine inlet filter plugging. It appears to be aluminum oxide left over from the initial construction and not removed in the cleaning process. In addition there is a contaminent aggravating the problem; most likely a hydrocarbin bellow 1/2 ppm.

The second most serious problem is failures of our main Mycom compressor motors; the problem is not understood and is still being investigated. There have been nine burn outs to date. The third problem is continued magnet vacuum leaks. The helium leaks, other than causing an increased heat load, are no problem since they can be controlled by the 48 permanently installed turbo pump plus a half dozen mobile ones for the large leaks. The growing problem is the increasing quantity of cryopumped air and/or nitrogen which can cause a vacuum avalanche due to a quench or refrigerator crash.

The final serious problem is a combination of control stability, efficiency, and operating cost. Fig. 10 and 11 show the power, helium and nitrogen usage. By switching to a superconducting accelerator we are saving \$10. M per year on our power bill. The power consumption is as listed in the Design Report but the Helium and Nitrogen consumption are a factor of two higher than design. The helium consumption of \$1.2 M per year is caused by three equally significant problems: many very small leaks, system upsets due to

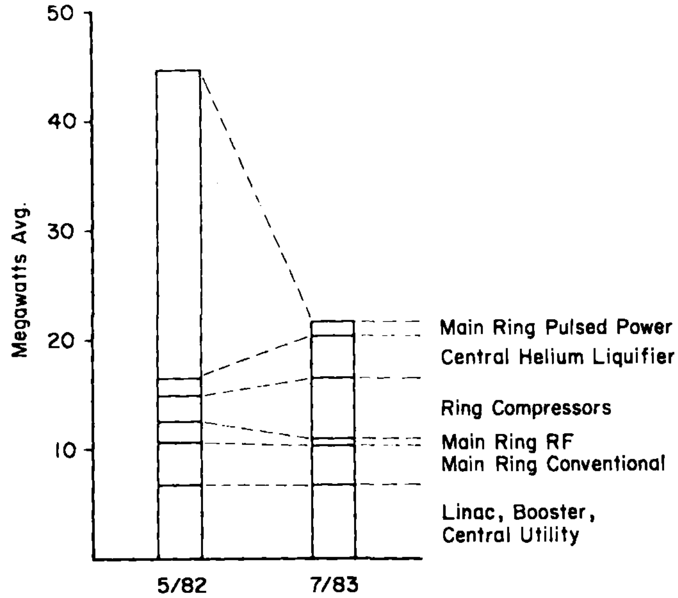


Figure 10. Monthly Power Consumption

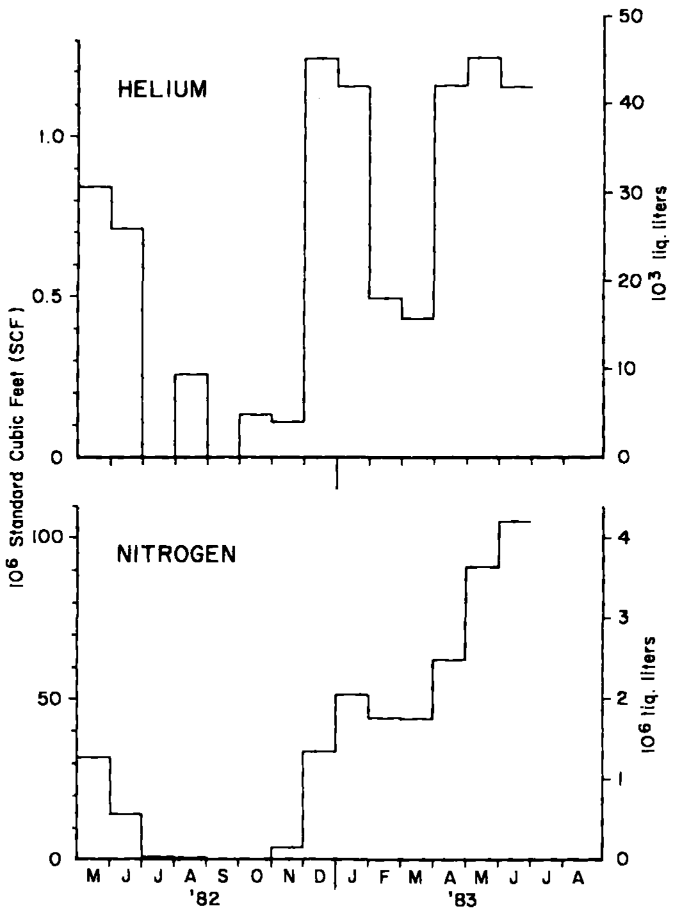


Figure 11. Tevatron Monthly Helium and Nitrogen Consumption

controls, quenches etc. and purges for maintenance. As we switch from the commissioning phase to the the operating phase, we expect to see a significant decrease in this usage.

The nitrogen usage of $3. M per year appears to be a serious problem. The magnet shield heat leak increased significantly when the anchor system was strengthened, but this component only accounts for $.6 M. CHL usage should be less than $1.6 M. In order to achieve stable system operation, many of the control loops have been permitted to freeze out their control variables while the magnet shield control loops badly over shoot dumping liquid into the collection header. As soon as data logging and upgraded software is available, we intend to start a major effort to tuneup and optimize the refrigeration system. We hope to reduce the nitrogen consumption by $.5M and the ramp cycle time by 1/3.

We are currently adding a seventh compressor building with start up planned in September. This will give us another 100 w per building in stand-alone mode (150 w in satellite mode). The system heat load is too close to 500 w per building for us to operate the full ring in stand-alone mode when CHL is down for repairs.

ACKNOWLEDGEMENT

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