COMMISSIONING OF THE TEVATRON SATELLITE REFRIGERATION SYSTEM

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INTRODUCTION

Completetion of the new Fermilab 6 km circumference superconducting proton accelerator, the Tevatron, was in the summer of 1983. During the commissioning of portions of the accelerator, extensive refrigerator and magnet power testing have been performed. Considerable operating experience was acquired on a three refrigerator, 0.75 km magnet system (Jan. 1982)[1] as well as an eight refrigerator, two km magnet string system (Jan 1983). The entire refrigerator system was operational on May 28, 1983. The first beam was accelerated to an energy level of 512 GeV on July 3, 1983. Operational problems experienced during these tests are presented.

SYSTEM DESCRIPTION

Cooling of the Tevatron is provided by a 5000 L/h central helium liquefier (CHL) coupled with 24 satellite refrigerators (966W each).[2] Figure 1 shows the completed system configuration. The refrigeration system is divided into sectors each consisting of four refrigerators, 1 km magnet string and a compressor building. Startup of the ring was accomplished one sector at a time beginning with F sector and proceeding counterclockwise around the ring (Fig. 1). The system includes six compressor buildings which supply high pressure helium (20 atm) to the satellite refrigerators via a common 75 mm header. Each compressor building has four - two stage screw compressors, each with its own oil removal system. High

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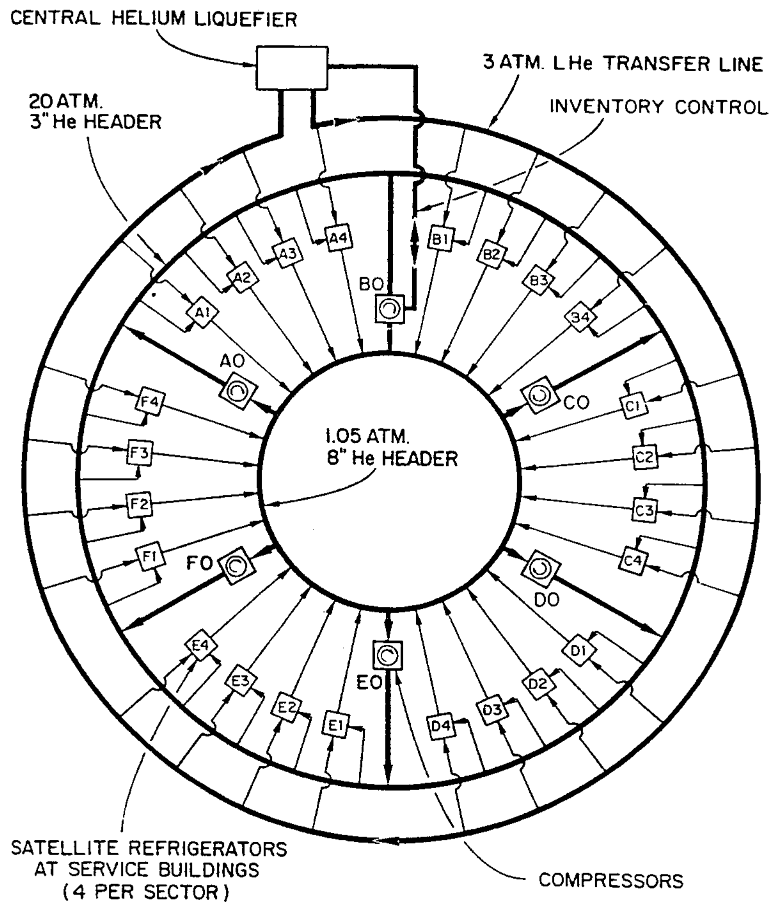

Figure 1 Tevatron Refrigeration System

pressure helium is then cooled in the satellite refrigerator in a series of four heat exchangers by cold, low pressure return gas from the magnet strings (Fig. 2). Supplemental shell side cooling can be supplied by a reciprocating 30 K expansion engine which is normally not used. Cold high pressure helium gas is then expanded through a reciprocating liquid expansion engine to a state of subcooled liquid at 1.8 atm. Additional liquid helium (LHe) is supplied to the system from the CHL, through a 6.5 km transfer line to the load, two 125 m long strings of magnets per refrigerator. The flow from the CHL results in a flow imbalance between the shell and tube sides of the heat exchanger. This additional shell side flow allows the satellite refrigerators to produce 4.5 K refrigeration without an intermediate temperature expander.

TRANSFER LINE OPERATION

The Tevatron Satellite Refrigeration system includes a liquid

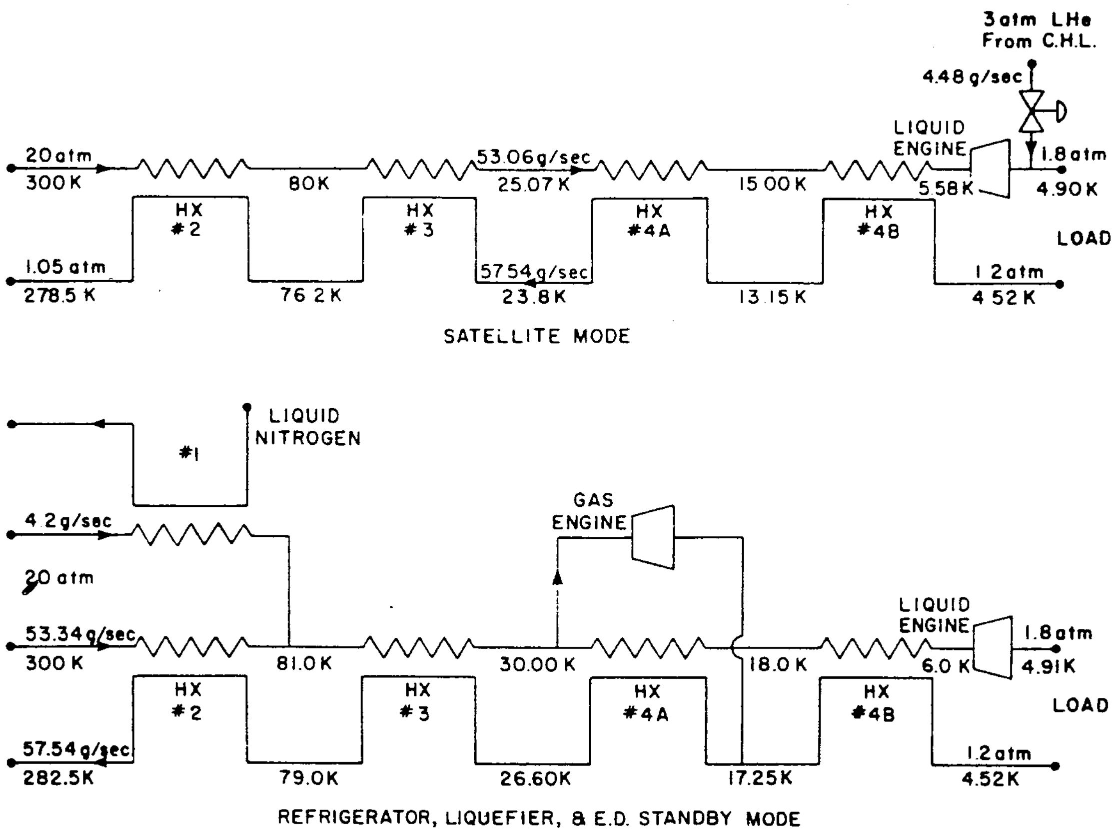

Figure 2 Satellite Refrigerator Operating Modes

helium/liquid nitrogen transfer line made up of twenty six-250 m long sections.[3] The line originates at the CHL, passes through each of the twenty four satellite refrigerator buildings and returns to the CHL (Fig. 1). Supercritical helium (4.6 to 5.5 K and 3 atm) and subcooled nitrogen pass through the line to each refrigerator. In Nov. 1982, the full ring transfer line was made operational.

Operational problems associated with the transfer line include:

1. Maintaining stable subcooled liquid nitrogen flow around the ring.

2. Maintaining stable helium temperature.

Excessive pressure drop and flow surging results if the nitrogen circuit is allowed to go two phase. If corrective actions are not taken, a gas bubble grows within the line. Consequently, the refrigerators become starved for LN_2 when this low density nitrogen reaches flow control valves.

Subcooled liquid nitrogen is maintained by subcooler heat exchangers located in the nitrogen U-tubes. This device must maintain enough subcooling to absorb the heat load of the next section of transfer line without going two phase. The main transfer line flow of subcooled LN_2 passes through the shell side of the subcooler. LN_2 is extracted at the top of the exchanger shell and is passed through a Joule-Thomson valve reducing the pressure to near 1 atm, thus decreasing its temperature to its boiling point at that pressure. This 2-phase mixture passes through the tube side of the finned tubing, exchanging its latent heat to subcool the 3 atm shell side nitrogen. The 2-phase nitrogen is finally transported to the #1 heat exchanger of the satellite refrigerator cold box, providing first stage cooling of high pressure helium. Some LN_2 is extracted at the bottom of the exchanger to provide magnet shield cooling; it flows through a vacuum insulated flexible line with two control valves. The remaining LN_2 passes toward the next refrigerator and provides shield cooling for the next section of transfer line.

Loss of subcooling is attributed to poor vacuum. The line has no permanently installed pumps or vacuum readouts. The vacuum is indirectly monitored by measuring the heat load (i.e. temperature rise). Helium at 5 K cryopumps the vacuum space within the transfer line. The absence of this cryopumping can increase the nitrogen heat load by over two orders of magnitude.

Vacuum decay within a section of transfer line shows up quickly on the line temperature profile. Temperatures are monitored at each of the twenty four refrigerators by vapor pressure thermometers. In most instances, poor vacuum was attributed to a leaking vacuum pumpout valve. Leak tight caps were put on the valves following repumping the line to cure the problem.

In one instance, the vacuum decay was attributed to an internal helium leak. Until we have a shutdown long enough to repair the leak, a continuously operating turbo pump has enabled us to run the line. The additional heat load due to the leak results in a 1 K temperature rise on this section, however.

Helium temperature instabilities in the line are caused by flow reversals or vacuum decay. The normal temperature gradient is 4.6 K at the inlet and 5.5 K at the outlet of the 6.5 km line. Pressure is maintained above the critical point with a back pressrue control loop on the return line to CHL. During periods of high ring usage (i.e. ring usage greater than CHL production) this regulation valve closes. Dead heading this last section of line causes it to warm and results in flow reversals. Closer monitoring of the ring usage to maintain usage levels below CHL production has enabled us to overcome this problem.

COMPRESSOR SYSTEM OPERATION

The six compressor buildings are equally spaced around the accelerator, as shown in Fig. 1. The compressor buildings are connected to the refrigerators via common suction (200 mmϕ) and discharge headers (75 mmϕ).[4]

Maintaining constant suction pressure was important to the system operation. A high suction pressure raises the operating temperature within the magnets due to the higher vapor pressure. Oscillations in the suction pressure resulted in severe refrigerator oscillations.

Suction regulation is accomplished by helium inventory control valves located at the BØ compressor building (Fig . 1). As the ring suction pressure increases, high pressure helium is sent back to the CHL or to storage tanks. Ideally, the mass of helium sent back to CHL equals the mass of liquid drawn from the transfer line during steady state operation. Stabilizing this control loop was the single most important operation for maintaining the entire systems stability.

A second problem associated with the suction was a pressure gradient along the header. The inventory controls maintained a proper suction pressure at BØ, depending on the mode of operation, suction pressures on the other side of the ring could vary from near relief pressures to sub-atmospheric. This was particularly true while the final refrigerators were being installed when the header was not continuous. At that time compressor buildings at the "ends" of the header operated in a suction regulation mode in order to keep the positive pressure in the header. Normally, the compressors regulate the discharge pressure while the inventory control valves regulate suction. With the full ring operating we are able to adjust the suction profile by choosing which compressors around the ring are allowed to regulate.

SATELLITE REFRIGERATION OPERATIONAL EXPERIENCE

Operational problems associated with the satellite refrigerators included:

1. Contamination effects
2. Expansion engine efficiency roll off at high rpm
3. Control loop stability
4. High pressure drop during periods of high capacity and/or low density.

Contamination

Helium contamination was a problem, particularly in early testing. Nitrogen was the most frequent contaminant. Sources of nitrogen included: System outgassing after initial helium purification, maintenance, and operational difficulties resulting in sub-atmospheric suction pressure.

Nitrogen is a particularly troublesome contaminant since it has a tendency to freeze out in the expansion engines, severly degrading their performance. Operating experience and more stringent procedures has increased expander mean time between failures to 3000-4000 hours.

Other contaminents found in the system include: Charcoal dust from adsorber vessels, oil from the screw compressors, argon from purchased helium, methane, and aluminum oxide dust. Upgrading the screw compressor oil removal system with larger oil coalescers and a final filter has eliminated the charcoal and oil problems. Reduction in argon contamination was accomplished by purchasing helium compressed from dewar boiloff. Sources of ethylene and methane have yet to be isolated. Aluminum oxide dust from an aluminum heat exchanger has, on occasion, plugged a CHL turbine inlet filter.

Expansion Engine Efficiency

Early in the refrigeration system testing it was found that the expansion engine efficiency reduced at high rpm. Cause of this rolloff appears to be due to flow restriction at the engine valves.[5] Since this was discovered we have restricted the maximum engine speed to maximize the refrigerator capacity.

Control Loop Stability

Each of the twenty four refrigerators has 14 active PID (Proportional-Intregal-Derivative) control loops.[6] Each compressor building has nine such loops while BØ has three additional loops for inventory control. Optimizing the performance is a long, tedious and sometimes controversial job. Much has been learned on this subject. However, the refrigerators are tuned at a higher than expected capacity to avoid unnecessary oscillations.

These control loops have been coupled with "smart" software to perform such tasks as automatic magnet cooldown, fast magnet quench recovery, and compressor suction pressure monitoring. Such software is essential to minimize the accelerator down time.

Pressure Drop

A high pressure drop during periods of high capacity and/or low density had been realized between the two phase side of the magnets and compressor suction.[1] Pressure measurements isolated an unexpectedly high pressure drop in a 5 K magnet return U-tube and a room temperature exchanger suction line. Pressure drops in these locations drive the two phase side of the magnets to higher pressures, and thus higher temperatures. In the area of interest, a 0.5 K decrease in magnet temperature will allow ~10% increase in magnet current. As a result, operating at excessively high capacities actually had adverse overall effects.

MAGNET SYSTEM OPERATIONAL EXPERIENCE

Each satellite refrigerator cools two 125 m long strings of magnets. Operational problems associated with the refrigerator load include: Magnet cooldown problems, vacuum deficiencies, and magnet excitation.

Magnet Cooldown

During our "A" sector test (Jan. 1982) we had considerable difficulty filling the magnet strings in stand-alone mode (without the CHL).[1] This has been attributed to a combination of higher thermal loading and satellite refrigerator inefficiencies. The higher magnet heat load was expected due to a modification in the last generation of dipole magnets. Also, new correction elements with higher heat loads were incorporated.

Inefficiencies within the refrigerator are thought to be the result of expander efficiency roll off at high rpm and system contamination. When the CHL came on line we were able to fill the magnets. Once the magnets were full, the satellite refrigerators were able to keep them cold while in stand-alone mode. In recent test we have been able to fill the magnets in stand-alone mode, presumably due to our gains in contamination prevention and lowering maximum expander speeds.

Vacuum Deficiencies

Localized areas of poor vacuum have been sources of higher magnet heat loads. The leaks are usually from a helium C-seal joint between components. The addition of a turbo pump near the leak location usually allows the refrigerator to overpower the added heat load. However, in one instance the magnet string had to be warmed up and the leak repaired.

Heat leaks of this type are particularly troublesome when the magnet string is allowed to warm above 7 K, such as after a quench.

Temperatures above this point can result in a vacuum avalanche and subsequent re-cooldown of the string can be difficult. There is evidence of sufficient cryopumping below 7 K to avoid this effect.

Magnet Excitation

Applying the time-varying current ramp to a cold magnet string can result in large refrigerator oscillations. The steady state temperature of a ramping magnet string is slightly higher, and the associated liquid helium density changes releases some inventory out of the magnets through the return side of the heat exchanger. The resulting cold heat exchanger deceives the control loops into reducing the refrigerator capacity at the most inopportune time. As the magnets reach a steady state temperature, this release of inventory ceases and the refrigerator must suddenly respond.

The application of a 500 GeV - 60 second cycle ramp on a cold system often resulted in oscillations which warmed the magnets to the point of tripping off the ramp. Procedures were changed to give the refrigerator more time to respond. Longer cycle time ramps were applied first. As the refrigerator begins to warm, a shorter cycle time ramp is applied. Again, as the refrigerator begins to warm, the normal cycle ramp is applied. The procedure prevents the refrigerators from reducing capacity to a point from which it is unable to recover.

CONCLUSION

The Fermilab Tevatron accelerator is now operational and considerable operating experience has been acquired. The resulting refrigeration system problems and solutions have been presented. The satellite refrigerator concept has proven to be a reliable design for the Tevatron.

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