OPERATION OF LARGE CRYOGENIC SYSTEMS

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Introduction

This report is based on the past 12 years of experience on R & D and operation of the 27 kW Fermilab Tevatron Cryogenic System.[1] In general the comments are applicable for all helium plants larger than 1000W (400 ℓ/hr) and non mass-produced nitrogen plants larger than 50 tons per day.

The start up of any large system can be broken into three phases: 1) component debug, 2) commissioning and 3) operations. The component debug phase consists of getting the rotating machinery working reliably as well as getting major subsystems operational such as coldboxes. In addition, for computer controlled systems, one must get the control software and a significant fraction of the application diagnostics operational. It is often argued that with a "turn key" plant one can skip the component debug phase. Due to the small quantities of rotating machinery produced for cryogenics and the lack of manufacturers' full scale helium testing capabilities for design "improvements" or even "fixes", rotating machinery must be debugged. In the case of the Tevatron, the only quazi "turn key" component was the central helium liquefier cold box. We had a ten year R & D program; during the later half of this period a significant effort was put into improving the M.T.B.F. of the rotating machinery. In the case of the ring screw compressors this was so successful that they never affected the commissioning.

The commissioning phase consists of getting all of the subsystems functioning together, followed by a lengthy process of finding the system weaknesses, followed by component modifications or system redesign (1-2 years). In the case of the Tevatron during the latter half of this phase the high energy physics program was in progress.

The final phase, operations, continues to require a significant effort in improving the M.T.B.F. The problems of contamination and helium leakage are still significant, but a new problem of quality control for maintenance and repair parts becomes significant.

For the Tevatron Cryogenic System the dates for the various phases are shown in Table I.

Phase	Dates	References
0) R & D	1973 - 1982	2,3,4
1) Component Debug	Feb 76 - June 82	5,6,7
2) Commissioning	Dec 82 - July 84	1,8,9,10,11,12, 13,14
3) Operation	Oct 84 - Present	--

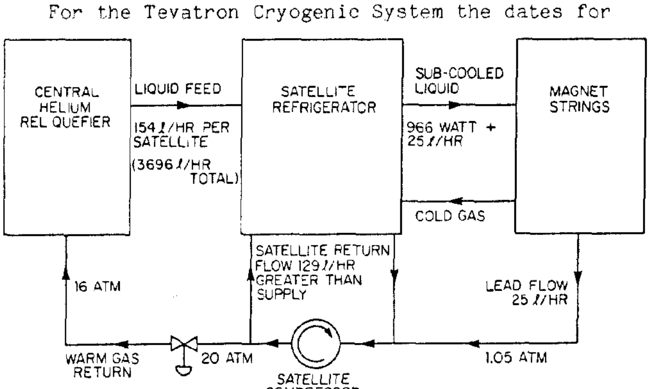

Figure 1

The primary installation period was June 1982 through May 1983; the commissioning started when one third of the ring was installed. In previous years R & D and component debug runs were made on 1/24 through 1/8 of the ring (A-sector run).

System Description

The Tevatron magnets are cooled by a hybrid system which consists of a 5000 ℓ/hr central helium liquefier (CHL) coupled with a small-diameter liquid transfer line connecting twenty-four satellite refrigerators (Fig.1). The transfer line supplies liquid helium for both the satellite refrigerators and the magnet lead flows as well as liquid nitrogen for the magnet shields. The satellites act as amplifiers with a flow gain of twelve by using the enthalpy of the helium supplied by the central liquefier as liquid, converting it to 4.5K refrigeration, and returning it as 300K gas.

The six compressor buildings supply 20 atm helium to the twenty-four refrigerators through a 9.0 cm ID discharge header located on the berm, (Fig. 2). A

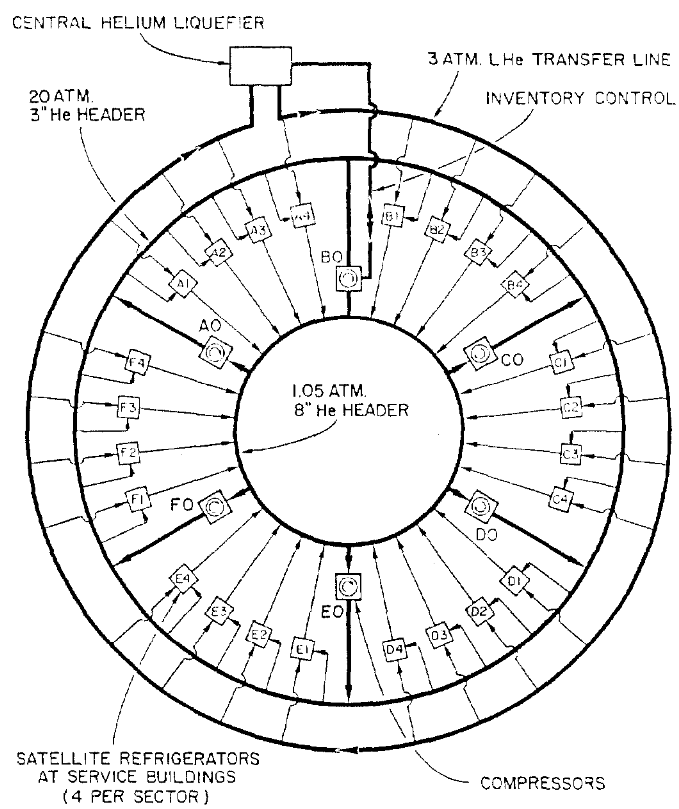

Figure 2

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

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22.0 cm ID suction header located in the tunnel is also used as the cooldown line and quench relief vent. Also located in the tunnel is the nitrogen collection and relief header.

This arrangement combines advantages of a single 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 central helium liquefier (CHL) consists of three large 2000 hp reciprocating helium compressors, the helium purification system, the helium coldbox, the helium dewar, the helium gas storage tanks and the liquid nitrogen system.

The twenty-four satellite refrigerators consist of the compressor, the warm distribution piping (previously described, Fig. 2), a coldbox, a liquid reciprocating expander, two flow splitting subcoolers, two JT valves, and a stand-by 30K gas reciprocating expander. The capacities are given in Table I. The requirement for dividing the magnets into 48 separate strings is due to the extremely small passages in warm iron magnets (i.e. high pressure drops). This together with relatively high heat leak are the fundamental disadvantages of warm iron magnets; their advantages are low cold mass and good field quality.

Table I. Refrigerator Capacity (Flow 57.5 g/sec atm He)

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

The compressor system consists of thirty-two Mycom screw compressors located in 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 the drive rotor operates at 3600 rpm.

Research and Development

The conceptual testing started in 1973 with the 400 ft He pump loop runs; they tested the concepts of pumping liquid He and the effects of long lines. In May 1975 we started up our B12 test facility, and originally using only one CTI 1400 refrigerator sent an extracted beam through a .8 m long prototype superconducting magnet.

Component Debug

This phase started with the construction of the prototype satellite coldbox and expander; the calorimeter runs started in February 1976. We then modified a series of reciprocating compressors for helium service; the last of these was retired from service in June 1982.

In December 1977 we moved the prototype refrigerator and the second prototype reciprocating compressor to the ring at the A1 service building. We continued component testing but also gained operating experience with long magnet strings.

The testing of our Mycom screw compressors started in 1978. Since the compressor is the first component required and in many ways the most critical from an upset standpoint, it received a great deal of attention to make it reliable. At the same time we continued testing and finalized a highly reliable oil removal system; on many occasions we had pumped oil and/or charcoal into one of our coldboxes.

CHL started running their compressors in January, 1980, and after some initial turbine trouble produced over 3500 ℓ/hr in March, 1981.

On January 3, 1982 we started the "A-sector test" to gain general operating experience as well as to study subsystem interactions. 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 refrigerator, cooled a single 125 m magnet string in our above ground B12 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 magnet strings 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 apparently 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 contamination aggravated this problem. During this period the primary contaminants were water, nitrogen, and to a lesser degree particulates.

Mechanical problems including broken gas expander drive shafts 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^{o}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.

Extensive power testing was performed during the A-sector run. The 0.75 km string of magnets was powered from a single supply to a level of 4200 amperes (950 GeV equivalent). 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, 1982 the "A-sector test" ended together with the conventional 400 GeV High Energy Physics Program. The tunnel installation crews started installing the rest of the Tevatron ring on a two shift basis.

Commissioning

The commissioning started on December 3, 1982 with the start of the cooldown of E and F sector which were the first two of the six sectors finished. CHL had started up in November and cooled down the 6 km transfer line; the liquid nitrogen for E and F sector as well as nitrogen for dehydration was taken from the transfer line. In February 1983, the liquid helium valve between the transfer line and satellite refrigerator were opened, connecting CHL to the ring. As additional sectors were finished they were decontaminated and also cooled down; the full ring was cold and operating on May 29, 1983.

The E and F sector run was successful in cooling the magnets in stand-alone mode. The most important difference from the A-sector test was that we did a much better job in initial decontamination (1 to 3 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 during the first part of this run was magnet vacuum leaks. Two major leaks and several small ones were repaired. The second most severe problem was microprocessor reboots which crashed the refrigerators. The cause of the more than thirty self reboots over a six week period was never found, but after six weeks the reboots stopped . This problem was compounded by the absence of an alarm system to notify the operator when a microprocessor rebooted or an expander tripped off.

In June, warm component installation was completed and a number of problems repaired. On July 3, 1983 beam was accelerated to 512 GeV. In September 400 GeV beam was being delivered to the experimental areas; the energy was increased to 800 GeV in March 1984. Figure 3 shows the downtimes during this period for CHL, satellites, and quench recovery.

The system operating difficulties in order of severity were:

1. Contamination/wet expander efficiency: Twice during the installation the ring was crashed due to nitrogen leaking through a closed valve into the helium system. In general during the commissioning phase, contamination was less of a problem in the ring; the major contaminants being nitrogen and particulates. The CHL had major problems with contamination; a mixture of aluminum oxide, water, and nitrogen would plug the 40K turbine inlet filter. The aluminum oxide was a by-product of the brazing of the plate-fin exchanger; the water was a 0.7 ppm leak in one of the compressors. The nitrogen primarily

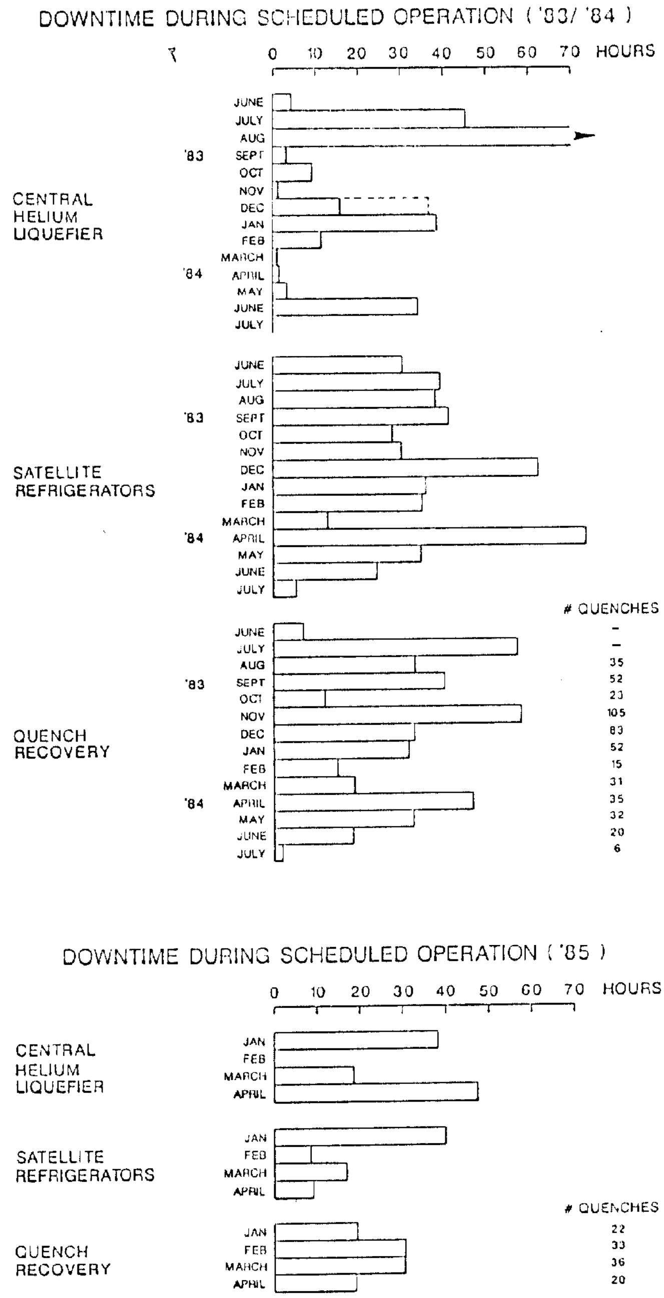

Figure 3

came from the ring, where it circulated at 1.0 ppm through the magnets in the liquid. An additional contaminant tentatively identified as CO_2 would plug the purifier coldbox.

The contamination in the ring was kept under control by a series of about 20 three-hour individual exchanger derimes on accelerator maintenance days, and by one full ring warm-up to 80K during the three week February 1984 magnet installation shutdown. The wet expander efficiency was intermittently affected by contamination (primarily nitrogen and particulates) causing valve leakage, necessitating expander derimes. The exchanger and expander derimes were concentrated in one half of the ring. During the latter part of the run exchanger derimes were not needed and the number of expander derimes decreased significantly.

2. Ramp Permit/Control Stability: We require the entire 6 km ring to be subcooled in order to turn on the main power supply. The system breathes about 1000ℓ when the ramp is turned on due to a lack of heat transfer between the inner and outer single-phase flows in the dipoles. This liquid in turn freezes out the refrigerator causing it to cut back to minimum capacity for 20 min. instead of doubling its capacity to compensate for the AC heat load. When the ramp is then turned off or trips off, the magnets demand 1000ℓ extra in a period of four minutes. This in turn overloads the CHL transfer line system since the CHL dewar system was not operational.

Two or three ramp trips in a short period would make the system oscillate badly causing more ramp trips and several hours of downtime.

3. Main Power Leads: After the February 1984 shutdown we switched to 800 GeV; previously we had been ramping from 150 to 400 GeV. Inadequate lead cooling and flow oscillation accounted for a large fraction of the April downtime.

4. Magnet Quench Reliefs: Access to the tunnel to change magnet relief valves occurred on many occasions. About half of these were due to broken valve bellows. The other valves were stuck open due to magnet superconductor lead clamps loosening and becoming caught in the valve poppet.

5. 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-pumps plus a half dozen mobile ones for the large leaks. The growing problem was the increasing quantity of cryo-pumped air and/or nitrogen which can cause a vacuum avalanche following a quench or refrigerator crash. This problem was controlled by speeding up and fully automating quench recovery.

6. Mycom Motor Failures: We had 16 motors burnout with field windings shorted to ground. One to two showed signs of possible overload. We replaced all of one manufacturers 350 hp motor with high efficiency 400 hp motors.

Operations

After a summer of civil construction, the ring was restarted in October 1984 with CHL starting up in mid November. The start-up went extremely well. Two problems were quickly obvious: 1) Our effort to reduce He leakage had failed; 2) Our expander lifetime had dropped by almost an order of magnitude.

He Leakage/Contamination: During the summer shutdown we had redesigned and replaced every warm high pressure valve stem in the ring. While the re-design was completely successful, our first indication that we had not improved the overall helium leakage was that we measured 2 ppm nitrogen circulating in the ring helium. During the previous running period we started with 0.8 ppm which increased to 2.0 during the run. At these levels nitrogen is not removed by the ring coldboxes but only by the CHL coldbox turbine filters.

After the monthly He usage data confirmed that the usage had not changed, we initiated another major leak hunting effort. We also carefully kept lists of leaks that need to be fixed on maintenance days or during shutdowns. The improvement was first seen in early February when the contamination in the bulk of the ring dropped to below 0.5 ppm. The usage in late February and early March of 1000ℓ per day is the best we have been able to achieve. The bulk of this is steady state leakage, but the usage for maintenance and decontamination is significant.

A major problem is detecting stuck open reliefs after quenches. Because the Tevatron Magnets are low pressure rated components, we have 100 suction reliefs. Since the system breathes 1000ℓ when ramp is turned on, we often do not know that a relief is leaking for several days.

Liquid Expander: For the running period from June, 1983, through July, 1984, the mean time between major maintenance for liquid engines (i.e., warmup) increased from about 3000 hours to about 4200 hours, and liquid engine efficiencies averaged 71%.

From December 1984, through April, 1985, liquid engines have averaged 77% efficient. Two factors reducing the frequency and severity of valve leaks have contributed to this improvement. First, the system is cleaner than in 1984. Secondly, measurements of valve spring force and calculations based on our valve seat diameter and peak inlet pressures occasionally seen at liquid engines indicated that the exhaust valve spring stiffness might be marginal. Slightly stiffer exhaust valve springs were installed by January, 1985.

The mean time between major maintenance was dominated by the piston O-ring lifetime. Like the Model 1400 expander, all of Fermilab's liquid reciprocating expanders have a phenolic plunger-type piston with warm, lubricated O-rings as piston seals at the top (warm) end. We experimented with several types of O-rings, T-rings, and lubricants. From January, 1984, through July, 1984, we used primarily teflon-coated O-rings and the standard grease-impregnated felts supplied by Koch Process Systems.

During the shutdown from July, 1984, through October, 1984, all the expanders were overhauled and new felts and teflon-coated O-rings were installed. From the startup through February, 1985, our piston O-rings lasted an average of about 1300 hours, with some failing after only a few hundred hours. After a typical failure the O-rings looked dry and worn and the felts and grease were partially gone.

In January, after it was apparent that we had an O-ring problem, we began installing high-quality Nitrile (70 durometer, uncoated) O-rings and carefully selected firm, fresh felts. Also we were very careful to keep everything clean and follow a good procedure. Almost all the engines that had not yet received the new O-rings and firm felts were overhauled during planned maintenance periods in February. Engines now (May 1, 1985) all have between 2000 and 3000 hours without one failure since February.

We have concluded that our drop to almost 1000 hours MTBF early in 1985, had several causes:

1. A switch to a different vendor for teflon-coated O-ring (based on price) in May, 1984, resulted in our receiving lower quality O-rings.

2. During the long shutdown from July through October we did not have the feedback which would have told us we were using a poorer quality O-ring.

3. During the long shutdown less experienced people did not have the feedback required or adequate training. Some procedures may not have been up to par; of the first 20 O-ring replacements, 14 were done in one half of the ring, six in the other. Different groups of technicians had overhauled the two halves of the ring during the shutdown.

The high energy physics run started again on Jauary 3, 1985. Figure 3 shows the downtime during the first four months of the run. Downtime is defined as the number of hours of scheduled high energy physics which were interrupted due to a subsystem problem. Scheduled preventive maintenance is not included. Typically the Tevatron system has one day of scheduled maintenance every two weeks, with a four hour necessary repair period on the alternate week.

Problems resulting in downtime for the Cryogenic System in order of severity include:

1. CHL-Water Contamination in Helium: During April, the CHL system had to be shutdown for a system derime due to water contamination. Water from the compressor cylinder cooling jacket leaked into the cylinder. The leak was at an oil injector which passed through the water jacket. Nine days were required to dehydrate the charcoal adsorber bed, coldbox, and bring the system back on line. All of this time is not reflected in the April downtime since part of it coincided with a scheduled one week installation shutdown.

2. CHL-Unknown Contaminants in Helium: During January and March the CHL suffered reduced capacity due to contamination in the helium stream resulting in partial coldbox plugs. During the previous runs all the plugging had been in the 40° turbine inlet filters therefore during the summer shutdown a pair of large parallel switchable filters were added upstream of the existing one. During January a plug appeared in the 25K piping; after several partial warmups, CHL was completely warmed-up to room temperature.

The March plugging appeared in several locations in the 5 and 10K piping. It appears to have been at least two different contaminants; one with the freezing point near "CO_2" and the other either Neon or Hydrogen. Several partial warm-ups to 125K and 300K extended the running by several weeks (most on maintenance days) but finally we did a complete warmup of CHL. The Neon or Hydrogen has also caused six "instantanious" plugs in the 5K piping of the satellite system; because of the smaller component size and modularity of the system these usually can be removed in less than an hour.

3. Wet Expanders: The previously discussed O-ring problem accounted for almost half the satellite downtime in January.

4. Leads: The lead overheating and oscillations problem which caused the April 1984 downtime reappeared in January. This was cured by reducing the minimum flow during maintenance, and increasing the minimum flow and lowering the regulation set point during operation.

5. Ramp Permit: The ramp permit problems of the past year continued especially when CHL was running at reduced capacity. In order to reduce the problem we raised the maximum temperature limit from 4.9 to 5.0K.

6. Controls: As the ring satellite operation stabilized to about 10-15 hours per month downtime in February, control component failures started to become significant. In addition one micro processor location gave us a great deal of trouble for a few weeks; the second total replacement got the problem under control.

7. Human Error: Human error can always be counted on for a few hours of downtime per month; this includes: Forgetting procedures, omitting a step in written procedures, forgetting to close a valve after opening it manually, etc.

Conclusions

1. The most significant problem, by far, is contamination detection, prevention, and shifting. Commercial on-line process contamination detection equipment is not available at the 0.1 ppm level. We therefore have been investing a large amount of effort into sensitive detectors capable of being continuously data logged by the central computer. Our large helium usage adds contamination in two ways: First by reverse diffusion though the leak and secondly contamination in the makeup helium.

2. With a proper component debug period, one can get the rotating machinery reliable before the commissioning.

3. One successful year-long running period of a component does not guarantee another. Constant vigilance is required to be sure that replacement components and maintenance procedures are indeed those that have proven successful. This is especially true when routine maintenance is done during a shutdown period since the feedback is delayed regarding the performance of the equipment after maintenance.

4. For the SSC, in order to have stable systems, one must have a very tightly coupled integrated magnet and cryogenic design effort followed by a vigorous string test program, starting with early 50 m strings expanding to 1 km strings.

References

1. "Tevatron Cryogenic System", C.H. Rode, Proceedings of the 12th Inter. Conf. on High Energy Accel., 529, (Aug. 1983).
2. "Cooling of a System of Superconducting Magnets by Means of Pumped Subcooled Liquid Helium", P.C. Vander Arend, et al., IEEE Trans. on Mag., Vol-MAG-11, No. 2. (March 1975).
3. "Operation of Superconducting Magnets in Fermilab Extracted Beams", C.H. Rode, et al, IEEE Trans. on Nuc. Sci., NS-22, No. 3, 1185, (June 1974).
4. "Operations of Multiple Superconducting Energy Doubler Magnets in Series", G. Kalbfleisch, et al, IEEE Trans. on Nuc Sci., NS-24, No. 3, (June 1977).
5. "Fermilab Energy Saver Refrigeration System Test", J. Theilacker, et al, IEEE Trans. on Nuc. Sci., NS-28, No. 3, 3257, (June 1981).
6. "Fermilab Tevatron Five Refrigerator Tests", C.H. Rode, et al, Adv. in Cryo, Eng., Vol. 27, 549, (1981).
7. "Fermilab Tevatron Transfer Line", C.H. Rode, et al, Adv. in Cryo. Eng., Vol-27, 769, (1981).
8. "A-Sector Power Test Report", P. Martin, et al., Fermilab Report, TM-1134, (1982).
9. "Fermilab's Satellite Refrigerator Expansion Engines", T. Peterson, Adv. in Cryo. Eng. Vol-29, 443, (1983).
10. "Control of the Tevatron Satellite Refrigeration System", J. Theilacker, et al., Adv. in Cryo. Eng. Vol-29, 437, (1983).
11. "Fermilab Satellite Refrigerator Compressors With Oil and Moisture Removal Systems", J. Satti, et al., Adv. in Cryo. Eng., Vol-29, 453, (1983).
12. "Commissioning of the Tevatron Satellite Refrigeration System", J. Theilacker, et al., Adv. in Cryo. Eng., Vol-29, 429, (1983).
13. "Operation of the Tevatron Six Kilometer Long Transfer Line", C.H. Rode, et al., IEEE Trans. on Nuc. Sci., NS-30, No. 4, 2769, (Aug 1983).
14. "Fermilab Central Helium Liquefier Operations", G.A. Hodge, et al., Adv. in Cryo. Eng., Vol-29, 461, (1983).