Fermi National Accelerator Laboratory

TM-1677

Trial Operation of Cold Compressors in Fermilab Satellite Refrigerators *

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September 1990

* Published in *Advances in Cryogenic Engineering*, Volume 35B, 1990.

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TRIAL OPERATION OF COLD COMPRESSORS IN FERMILAB SATELLITE REFRIGERATORS

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ABSTRACT

Reciprocating and centrifugal cold helium compressors have been incorporated into part of the Tevatron satellite refrigeration system on a test basis. Results to be presented include compressor performance and overall system behavior under steady state and upset conditions. The effects on quench current of reductions in magnet temperature are included for one sector (a sixth) of the Tevatron. The results of these tests will determine the effectiveness of adding cold compressors to all 24 satellite refrigerators, allowing for Tevatron beam energy increases up to perhaps 1 TeV. Also described are specific test results from individual machines from CCI, Inc., Creare, Inc., and IHI Co., Ltd.

INTRODUCTION

The Fermilab satellite refrigeration system provides cooling for the 1000 or so superconducting magnets and assorted cryogenic components that make up the Tevatron particle accelerator[1]. Together with the Central Helium Liquefier (CHL)[2], this system maintains peak magnet temperatures at about 4.9K, allowing the Tevatron to operate reliably at a beam energy of 900 GeV. One goal in Fermilab's upgrade scheme is the achievement of 1000 GeV (1 TeV) beam. The necessary increase in dipole magnetic field strength can be attained through a combination of weak magnet replacement and a reduction in magnet operating temperature. Figure 1 illustrates the expected gain in beam energy (above 900 GeV) as magnet temperatures are reduced. Replacement of weak or temperature insensitive magnets no doubt will be required to realize this performance prediction.

Cold compressors will be used to provide the required temperature reduction. One unit in each satellite refrigerator will reduce the pressure of the two-phase helium flowing through the magnets, thereby lowering their temperatures. Individual compressors have been tested extensively at Fermilab in order to verify performance; this work is reported by Peterson and Fuerst[3]. Further testing on a larger scale has since been completed, consisting of the installation and operation of cold compressors in one sector of the Tevatron (four refrigerator buildings). These tests confirmed earlier efficiency data and proved the ability of compressors to be integrated into the

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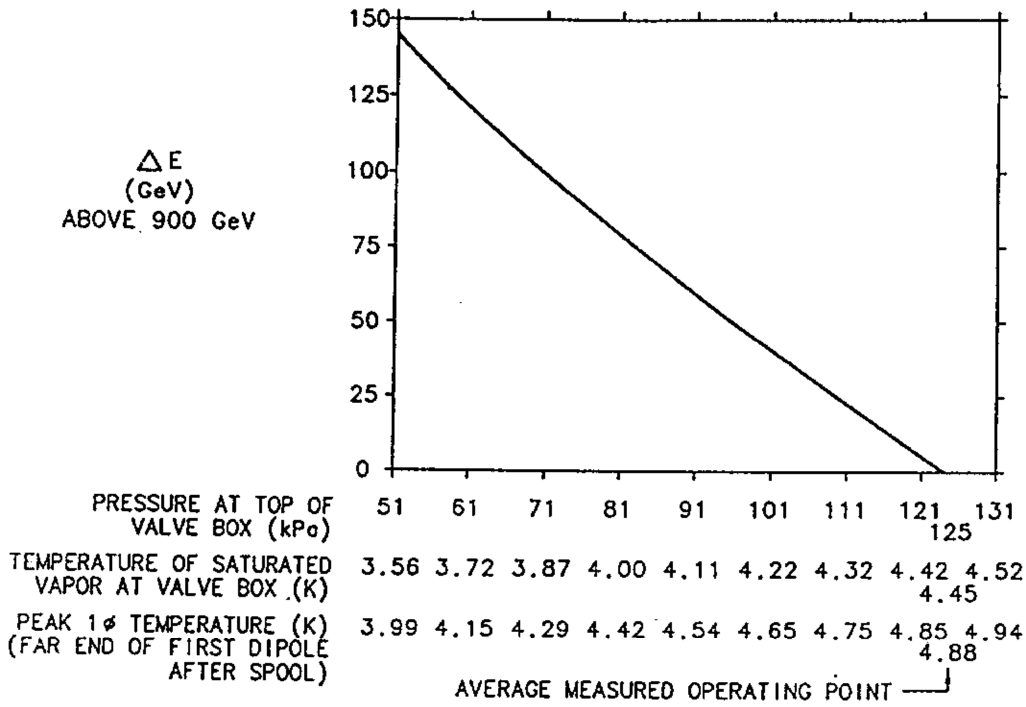


Fig. 1. Energy upgrade vs. magnet conditions

standard satellite refrigerator. This work took place while colliding beam physics was underway, thereby subjecting the modified refrigerators to a complete range of operating environments. To a certain extent reliability has also been demonstrated for both the Creare turbomachines and CCI reciprocating machines. All four units (two of each make) have run in their respective refrigerators for about 1500 hours without damage. Power testing of the sector has indicated a 82 GeV increase in magnet quench current for a 0.5K drop in magnet temperature.

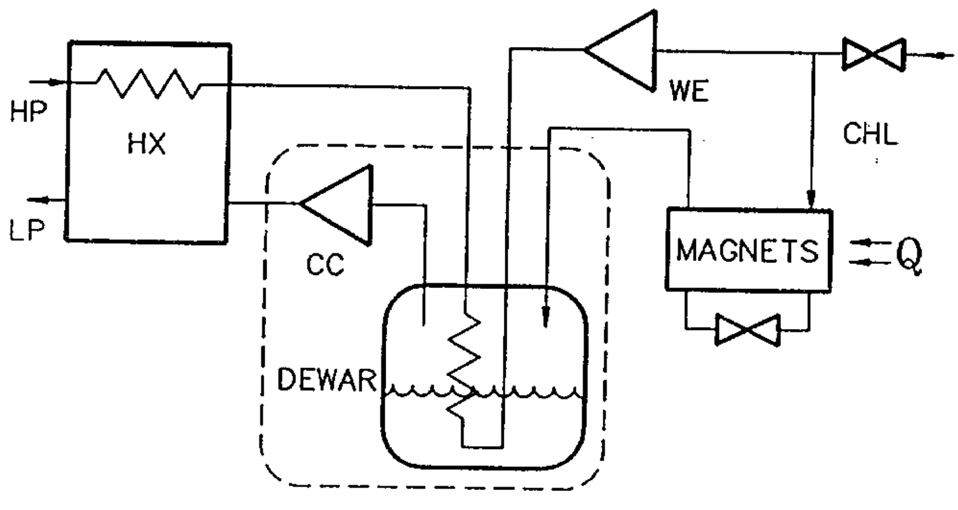


Fig. 2. Satellite refrigerator schematic (with cold compressor and dewar)

SYSTEM DESCRIPTION

General

As seen in Figure 2, each of the Tevatron's 24 satellite refrigerators consists of an above ground plant containing heat exchangers and expansion engines which feeds about 50 g/s of 219 kPa (2.16 atm), 4.6K helium to independent upstream and downstream magnet strings located in the accelerator tunnel 8 meters below. This "single phase" flow travels through the magnets until it reaches the ends of the strings. The flow is throttled into the 2-phase region and returns to the refrigerator in counterflow with the incoming fluid, boiling off along the way. A margin of 20 percent liquid typically is returned to the plant upstairs. Cold compressors serve to lower magnet temperatures by pumping on this return flow through a phase separator which collects returned liquid through which the wet expander intake flow is precooled. Thus the cold compressor must pump both the returned vapor from the tunnel and the liquid boiloff from the separator. Separator boiloff rate and hence, amount of liquid returned (assuming steady liquid level) are known through the amount of heat lost by the precooled wet expander intake flow. Without a cold compressor, a satellite's 2-phase pressure runs at about 136 kPa (1.34 atm, 4.55K) while the warm compressor suction header pressure is maintained at 108 kPa (1.07 atm). Differences in 2-phase temperature and peak magnet temperature reflect imperfect heat exchange between magnet coils and 2-phase helium. With cold compressors the 2-phase circuit typically is operated at 105 kPa (1.04 atm, 4.26K) with a tolerable level of added heat load due to the compressor. Current Tevatron refrigeration capacity and compressor technology (efficiency) limit 2-phase pressures to about 60 kPa (0.58 atm). However, operation of the Tevatron 2-phase circuits below atmospheric pressure can create a host of additional contamination related difficulties that are still being worked on.

Specific

With the conclusion of our tests of specific compressors from Creare[4], CCI, and IHI Co. Ltd.[5,6] at a designated remote test refrigerator, efforts were concentrated on those modifications necessary to adapt a cold compressor to our existing satellite refrigerators. Although three different units were tested, only the Creare and CCI units were considered for inclusion in our sector test. The IHI machine, while performing up to specifications, was not evaluated in time for inclusion. It is recognized that the IHI turbo-compressor has design differences that offer a real alternative should the Creare and CCI units prove incompatible with our system. Preparations for use included modification of control systems and instrumentation and, particularly for the Creare machines, design of an adequate phase separator dewar to be installed upstream of the compressor.

Earlier testing was performed under closely monitored conditions with compressors operating under local control. The Tevatron cryogenic system, on the other hand, operates via a remote, distributed network utilizing closed loop microprocessor control reporting to a central data acquisition/reduction system[7]. Thus each compressor was equipped with the following capabilities: local/remote toggle, remote start/stop, interlock trips, remote pressure and temperature readbacks, and remote speed readback for closed loop speed control. To this end a special digital-to-analog converter (DAC) circuit was developed to extend the otherwise saturated capabilities of the current Z80 based refrigerator microprocessors. Cold compressor loop control is set up such that machine speed is regulated by intake pressure. Tuning of PID loop parameters has provided intake pressure control to within a consistent plus or minus 1.4 kPa (0.014 atm), as shown in Figure 3. Both machines are able to handle the natural oscillations in flow and pressure during normal operation.

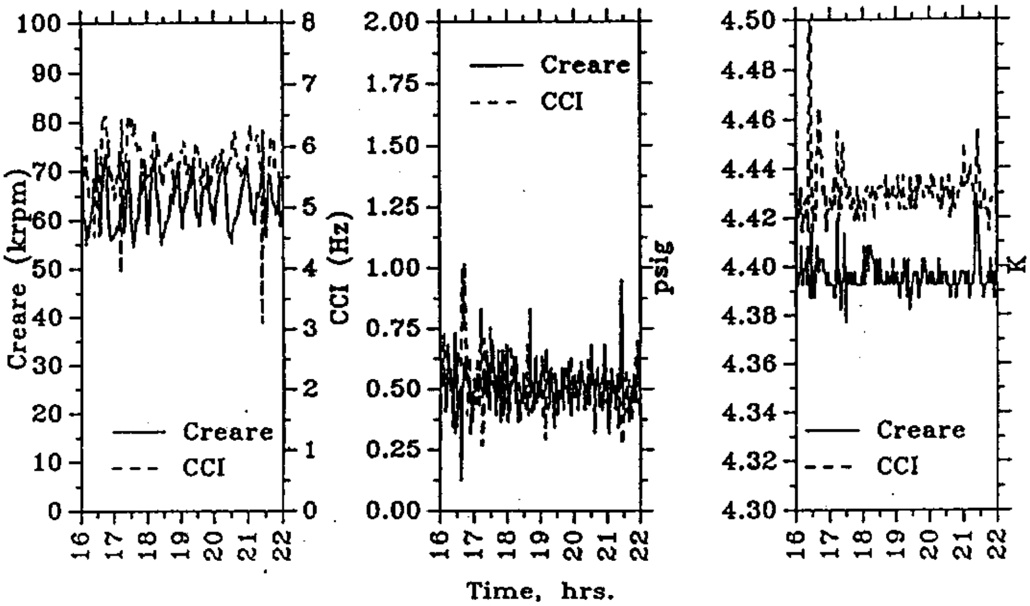
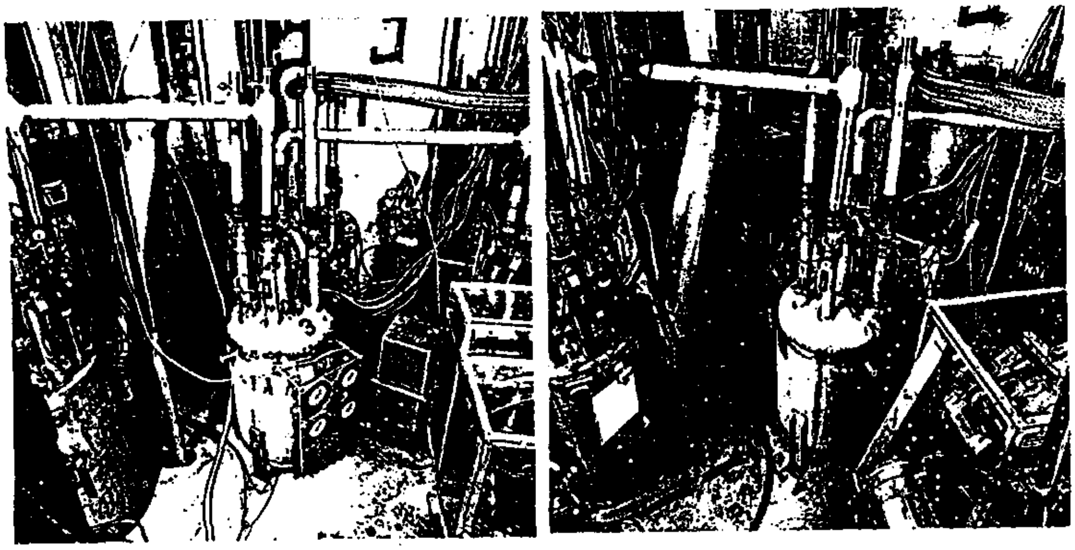


Fig. 3. Cold compressor performance: Typical operation showing (L-R) speeds, intake pressures and magnet feedcan temperatures.

With intake pressures of 105 kPa (1.04 atm), temperatures slightly superheated, and pressure ratios of 1.3, the CCI's run at about 275 rpm ±15 rpm while the Creare's run about 50,000 rpm ±7000 rpm, both with a period of around 1.5 oscillations per hour. Mass flow rates fell in the 40 - 50 g/s range.

A stand-alone phase separator of adequate size (100L) was designed and incorporated into the test. Whereas in a "normal" refrigerator configuration the 2-phase flow discharges directly into the cold end of the heat exchanger shell side, the sector test refrigerators deliver their 2-phase flow into the phase separator dewar. This tank is fitted with intake and exhaust vapor temperature thermometers (VPT's), a pressure gauge, and a superconducting liquid level probe. The cold compressor draws intake flow from the saturated vapor in the dewar; liquid level is actively controlled to prevent introduction of liquid at the compressor. The phase separator dewar also contains multiple passes of finned copper tubing through which the 2000 kPa (19 atm) wet expander intake flow is precooled. A carbon resistor thermometer at the intake and a VPT at the exhaust provide the information necessary to calculate the heat loss in this flow, giving dewar boiloff rate. The dewar static heat load is negligible relative to this heat transfer rate. Figure 4 shows photographs of the actual refrigerator installations, displaying both Creare/dewar and CCI/dewar configurations. Conditions are cramped but not unreasonable. Permanent installation of cold compressors ring-wide will take place with redesigned cryostats incorporating compressor and phase separator into one package.



(a) (b)

Fig. 4. Test refrigerator installations. With Creare cold compressors (a) and with CCI cold compressor (b)

TEST RESULTS

Refrigerator Behavior

The four refrigerators making up the sector test ran for about 3 months with cold compressors/phase separators installed in them. This testing period took place in the spring of 1989 prior to a five month scheduled accelerator downtime period. During that time there were no catastrophic equipment failures and only two compressor-created disruptions in the accelerator physics program. Earlier tests with a prototype phase separator dewar installed alone in a satellite refrigerator had confirmed our ability to maintain a stable (±5%) liquid level during normal operation. Quench behavior was also studied at that time; it was unclear whether or not the violent oscillations in refrigerator pressures and flow created by loss of superconductivity in the magnet strings caused liquid to exit the dewar. Time constraints did not permit further refinement of dewar design to exclude this possibility. It was decided that, rather than attempt to guarantee prevention of liquid transport out of the phase separator under all conditions, the cold compressor would simply have to tolerate 2-phase flow on rare occasions. This was not a problem for the CCI reciprocating unit. The Creare unit has undergone modification since initial testing aimed at making the machine more rugged and tolerant of modest amounts of 2-phase flow; this effort has been a success.

Installation of the two CCI units with their associated phase separators took place simultaneously during 6 hours of accelerator downtime. The equipment was connected without system warmup and quickly reached equilibrium with the rest of the refrigerator; complete recovery took about 3 hours. The compressors were left in the OFF condition for a few days while their physical impact on the refrigerators was evaluated. When it was apparent that, aside from some additional static heat load and increase in pressure drop due to the presence of the new devices, the refrigerators were behaving normally, permission was granted to start the two CCI's. With the machines running, control loops were tuned and interlock trips for low intake pressure (to prevent accidental subatmospheric operation), etc. were checked out. Shortly after startup it was noticed that one of the compressors was running inordinately fast relative to the other to maintain a similar pressure ratio. After thorough checkout of both refrigerators, the machine was taken off-line (leaving the phase separator in place) and the cold end returned to CCI for evaluation and repair. This was our original test unit with over 2000 hours of operation. CCI rebuilt the cold end and it was returned to service where it functioned normally. An improperly attached retaining wire was found that may have interfered with valve action. Both units have since shown performance in line with expectations (50-60% efficiency relative to Carnot) and function without incident in our refrigerators. The only change in refrigerator operating characteristics is an approximate 15% increase in CHL flow due to the added heat load of the running compressor. This is in accordance with earlier computer simulations performed on refrigerator models equipped with cold compressors. Refrigerator upsets have been of no consequence to these machines.

The two Creare cold compressors were installed with their phase separators a few weeks after the CCI's during another block of downtime. After connecting up one unit and starting refrigerator recovery it was observed that the compressor's impeller shaft began to spin on it's own, freewheeling in the high velocity, low density gas flow typical of refrigerator cooldown. The shaft speed quickly reached levels approaching or exceeding the first critical shaft speed (around 101 krpm). This was accompanied by a piercing whine and and intermittent high pitched squeal. Building flow was immediately halted and the unit spun down to a stop after a few minutes. The other installation team was contacted and told to cool down gradually and to power their compressor at minimum speed as soon as flow connections were made in the hope of controlling the shaft. These instructions were followed and no such similar events were reported from the other compressor. The first unit was then put on-line in similar fashion and appeared to be operational, freewheeling in the presence of flow and starting on command. However, the unit has shown consistently low efficiency (35% vs. the other Creare machine's 50-60%). Both cold compressor induced interruptions in Fermilab's physics program were generated by a bad speed readback in this less efficient Creare machine. Two failures of the capacitance-probe type speed transducer caused the unit to spin up to maximum speed upon receipt of the remote start command; this rapid drop in 2-phase pressure coupled with the jump in heat load from the running compressor overly disrupted the refrigerator and induced a magnet quench. The compressor survived both quenches in addition to other, non-refrigerator induced quenches over the course of this test period, although by the last month of testing the unit no longer freewheeled in the presence of flow. The other Creare unit has seen it's share of quenches also and freewheeled when OFF throughout testing. Inevitably, there was also one occurrence of phase separator dewar overflow at a Creare refrigerator due to corrupted control loop parameters. The machine tripped itself off due to a "high liquid level" interlock and, when restarted after proper level had been restored, functioned normally. Both Creare units have demonstrated extraordinary ruggedness compared to earlier performances at our dedicated test refrigerator. The Creare units have had generally the same effect on their refrigerators as have the CCI units with respect to normal operation and CHL usage (the latter being a function of machine efficiency).

Magnet Performance

Tests to determine the effect of lower magnet temperatures as produced by cold compressors on magnet quench current (peak Tevatron beam energy) were highly dependant on Fermilab's particle physics schedule. This was due to the long periods (about 18 hours each session) of accelerator downtime specifically required for the tests. The strategy for testing consisted of one session of sector quenches with cold compressors off to establish a datum for comparison. This level was found to be 940 GeV. Then followed a series of ramps up and down in magnet current with cold compressors maintaining 2-phase pressure at 105 kPa (1.04 atm), each ramp's maximum flat-top current being increased slightly above the previous ramp until a maximum quench current was reached. This current corresponded to a machine energy of 975 GeV. Repeating this step allowed for identification of the specific quenching magnet. Quench testing was then halted and a magnet replacement period began. During this time the offending magnet was replaced in the sector. The refrigerators were then recovered and round two began (see results, Figure 5). First, the 105 kPa cold compressor intake pressure condition was duplicated and the sector ramped in a manner identical to that of the previous test. This revealed a modest increase of 5 GeV in quench energy over the previous 975 GeV limit. After quench recovery, the cold compressor speeds were increased until a uniform minimum intake pressure of 91 kPa (0.90 atm) was reached. This subatmospheric operation did not cause any obvious contamination problems. At this lower temperature (about 4.3K in the single phase circuit), a maximum quench energy of 1022 GeV was reached. Additionally, a continuous 1 TeV ramp with 2 second flat top was established. This concluded the sector testing.

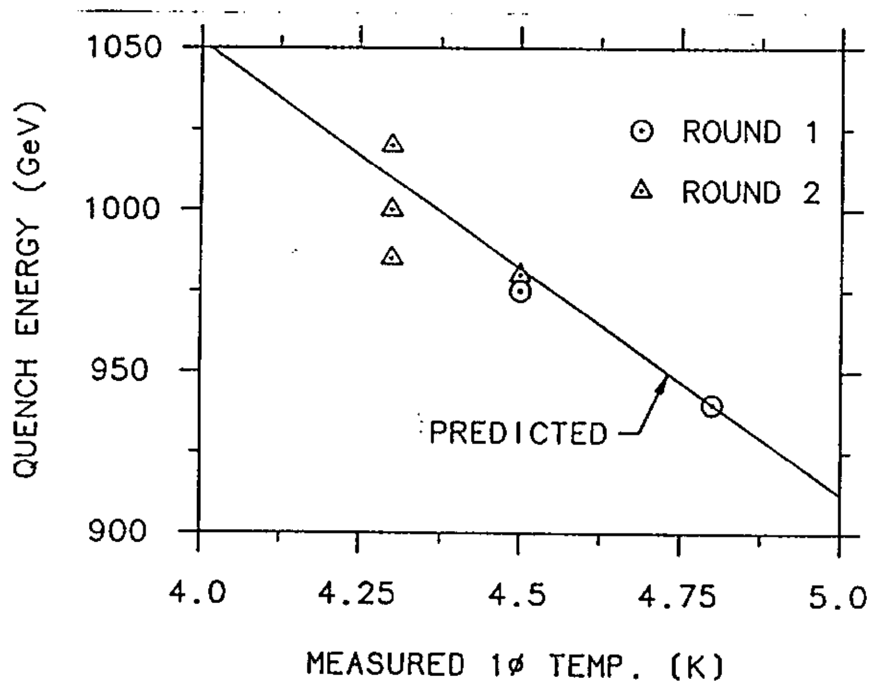


Fig. 5. Quench performance vs. magnet temperatures

CONCLUSIONS

Both reciprocating and centrifugal cold compressors are mechanically suitable for incorporation into Tevatron satellite refrigerators. Phase separation upstream of a compressor, while a requirement for a turbomachine, is useful in either case as a thermal buffer between a refrigerator and it's load. Except for initial maintenance on our older machine, the CCI units performed without incident over a wide range of process conditions. A regular maintenance program similar to that of our reciprocating expansion engines is required for continued operation. The Creare turbomachines proved themselves much more durable than their predecessor, withstanding quenches and an overflowing phase separator. Additionally, they were able to adapt to natural refrigerator rhythms, demonstrating responsiveness sufficient to maintain a constant intake pressure. As turbomachines with self-acting gas bearings they are essentially maintenance free (mechanically, not electrically); however, they are much more sensitive to process conditions performance wise. Some scuffing of the journals and intake shroud was observed upon disassembly of the low efficiency unit.

It has been proven that existing Tevatron magnets can take advantage of the lower operating temperatures provided by cold compressor operation and produce stronger magnetic fields. In fact, magnet behavior for the most part appeared to track the short sample predictions of the superconductor, although some higher energy "training" may have taken place during the course of the tests. The ability to operate one sector of the Tevatron with subatmospheric 2-phase circuits for an extended length of time (about 12 hours) with no noticeable harm is very encouraging.

ACKNOWLEDGEMENTS

Clyde Harmes of CCI, Dodd Stacy and John White of Creare, and Nobuyoshi Saji of IHI are to be thanked for their cooperation and advice. At Fermilab, mention must be made of Barry Norris, Mike Hentges, and the AD/Cryo electrical group for their tremendous achievement in fabricating and shaking down the compressor controls and interlocks. Gratitude also goes to the AD/Cryo engine group for overseeing day to day maintenance needs and to Jay Theilacker and Tom Peterson for guidance and counsel.

REFERENCES

1. C.H. Rode, Tevatron cryogenic system, in "12th Inter. Conf. of High Energy Accel.", 1983
2. G.A. Hodge, et al, Fermilab Central Helium Liquefier Operations, in: "Advances in Cryogenic Engineering", Vol. 29, Plenum Press, New York (1984), p.461.
3. T.J. Peterson and J.D. Fuerst, Tests of cold helium compressors at Fermilab, in: "Advances in Cryogenic Engineering", Vol. 33, Plenum Press, New York (1988), p. 655.
4. W.D. Stacy, Performance test results for a cold helium compressor, in: "AIChE Symposium Series, No. 251", Vol. 82, American Institute of Chemical Engineers, New York (1986), p. 45.
5. E. Tada et al, Performance Test Results of Cryogenic Pump System for Demonstration Poloidal Coil, "IEEE Trans. Magn." Vol. 24, No. 2, (1988) p. 1003
6. E. Tada et al, System Design and Verification Test results of Cryogenic system for Demonstration Poloidal Coil, in: "Advances in Cryogenic Engineering", Vol. 33, Plenum Press, New York (1988), p. 599.
7. J. Theilacker et al, Control of the Tevatron satellite refrigeration system, in: "Advances in Cryogenic Engineering", Vol. 29, Plenum Press, New York (1984), p. 437.