Fermi National Accelerator Laboratory

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Operations Aspects of the Fermilab Central Helium Liquefier Facility

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Abstract: The Fermilab Central Helium Liquefier (CHL) facility consists of helium and nitrogen reliquefier plants operated 24 hours-a-day to supply LHe at 4.6^{o}K and LN_2 for the Fermilab Tevatron superconducting proton-antiproton collider ring and to recover warm return gases. Operating aspects of CHL, including different equipment and systems reliability, availability, maintenance experience, safety concerns, and economics aspects are discussed.

INTRODUCTION

Supporting the world's largest proton/antiproton collider in high energy physics research, the Fermilab Tevatron cryogenic system consists of a hybrid system of a Central Helium Liquifier (CHL) feeding twenty four 1 kW satellite refrigerators through a 6.5 km transfer line and supplying the liquid helium for the superconducting magnets of the accelerator and liquid nitrogen for the thermo shielding (1). Helium Reliquefier plant consists of four parallel reciprocating compressors rated at 5.1 MW total power with extensive hydrocarbon removal and two independent cold boxes rated at 4000 liters/hour and 5400 liters/hour with LN_2 precool. Nitrogen Reliquefier is rated at 4680 liters/hour with three stages of compression and Refrigerant 22 precool. The original CHL system was built in 1979 and consisted of the helium reliquefier plant with one 4000 liters/hour helium liquefier (coldbox-I) and two 600 g/s reciprocating compressors (Compressor A, B) (2). The original design of the Tevatron cryogenic system envisioned redundancy of accelerator operations on either the CHL assisted satellite mode or stand-alone mode with twenty four dry expanders and LN2 precooling of the satellite system in periods when the CHL was off-line due to failure or trip. However, the refrigeration loads of the accelerator magnet system increased beyond the capacity of the stand-alone mode of the twenty four independent satellite refrigerators, thus making the CHL system vital for normal accelerator operations.

Over the years of operations, general upgrades were made to improve the reliability and availability of the system, including an addition of a third helium compressor (Compressor C) and 64,000 liters of liquid helium storage (3). Additionally, the 4680 liters/hour nitrogen reliquefier plant with three stages of compression and R22 precool was constructed in 1984 (4). Nevertheless, a significant impact on the accelerator physics program due to a major CHL failure pointed out the need for the CHL redundancy.

Another reason for CHL expansion is the Tevatron accelerator upgrade to 1 TeV operations. This will be accomplished via lower temperature operation of the accelerator system with 24 compressors cold operated at sub-atmospheric pressure. The net effect on the cryogenic system is the increase of the CHL load to 170 g/s, which is beyond the rated capacity of the Coldbox-I system. Therefore the CHL system has been recently upgraded to include the second cold box (Coldbox-II) and the forth compressor ("D") (5). Overall, the system has been configured to provide redundancy as well as increased capacity. The Coldbox-II design is generally identical to Coldbox-I. It is tied to the common compressor suction and discharge headers in parallel with Coldbox-I (see Figure 1). The oil bearing turbo-expanders are designed for three compressors flow capacity (1800 g/s) for an estimated liquid helium production of 190 g/s at 4.6°K. The equivalent refrigeration capacity can be assessed as 9.6 kW (coldbox-I), plus 12.5 kW (coldbox-II) at 4.6°K. Additionally, new distribution valves boxes and liquid helium pumps were added in parallel configuration allowing independent operations of either system. The option to operate both systems concurrently exists, thus allowing cool downs and engineering runs with the available compressors.

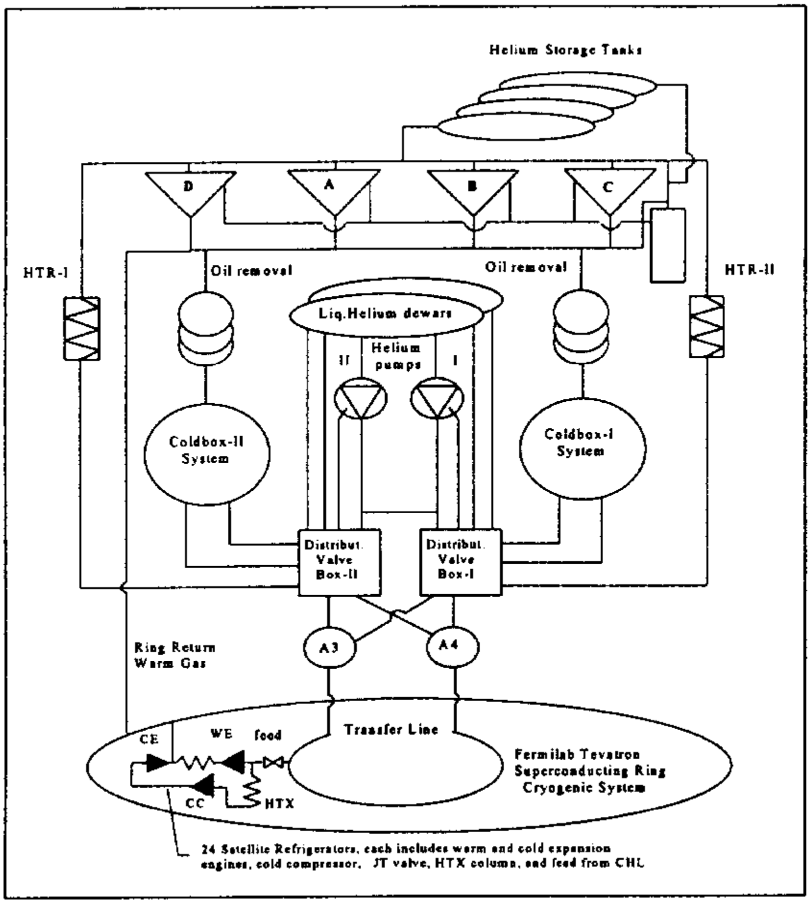

Figure 1. CHL Layout

CHL RELIABILITY AND AVAILABILITY FOR FERMILAB PHYSICS

CHL has recorded more than 76,000 hours of operational history. During first 19840 hours of operations (August 1980 to August 1985) CHL showed an average availability of 97% with an average accelerator downtime due to CHL problems around 20 hours/month (3). At the same time the historical trend has been always downward with 16 hours/month for the 1984 experimental run, and 11 hours/month for the 1985 experimental run. Since 1987 CHL has introduced numerous upgrades, together with improved control system and operator training. This has greatly improved the reliability and boosted the availability of the system to 99.5% with unscheduled accelerator downtime due to CHL problems never greater than 4 hours a month (see Figure 2). The closest in design, though later construction, HERA superconducting proton accelerator, Hamburg, Germany, has an average availability to the physics program of 98% with cryo plant's downtime ranging from 3.4 to 0.8 hrs/month in 1992 -1993 (6).

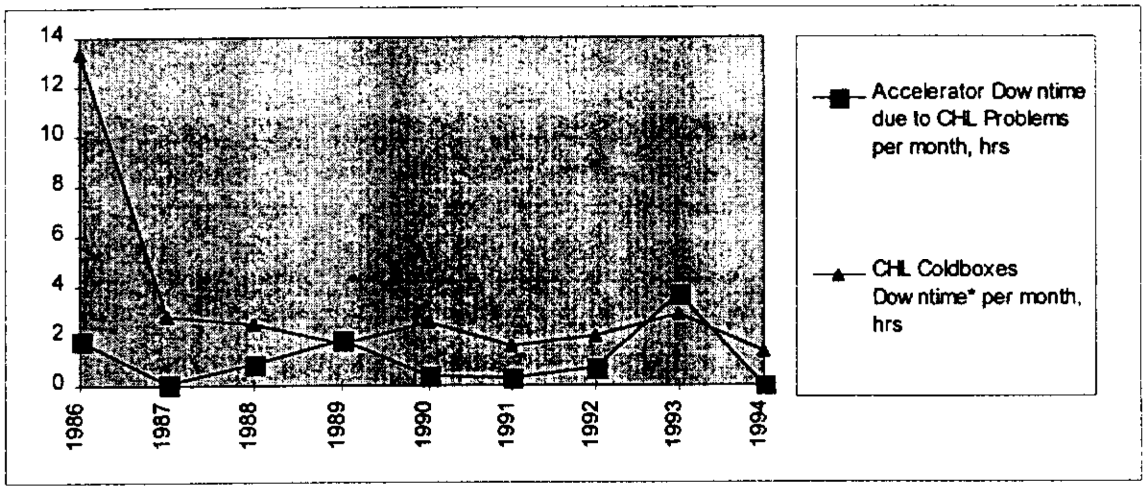

Figure 2. CHL Reliability vs Availability for Fermilab Accelerator Physics.
Average monthly downtime (*during scheduled operations, not related to power glitches)

The availability of the CHL for Fermilab Accelerator Physics has been improved greatly since 1986 when a liquid helium pump was installed in parallel with the coldbox to supply liquid helium from CHL dewars to the transfer line, thus providing uninterruptable temporary supply of cooling capacity for accelerator magnets. As Figure 1 shows, CHL stores its helium inventory in liquid helium dewars (maximum capacity is 64,000 liters) and 13 warm gas tanks (4700 kg total capacity). Therefore CHL can provide liquid helium to the transfer line with the liquid helium pump for 5 - 7 hours while coldbox is down for repairs or decontamination. This duration has proved to be sufficient for minor repairs or upsets, but not adequate if a major problem is encountered. In 1989 and 1993 the Coldbox-I oil skid failures led to Coldbox-I shutdown and consequently more than 10 hours repair resulting in disruption of accelerator physics (see Figure 3). At the same time CHL average contribution to accelerator cryogenics total downtime constitutes less than 10%, though its share of the accelerator total refrigeration capacity is more than 30% (see Figure 3).

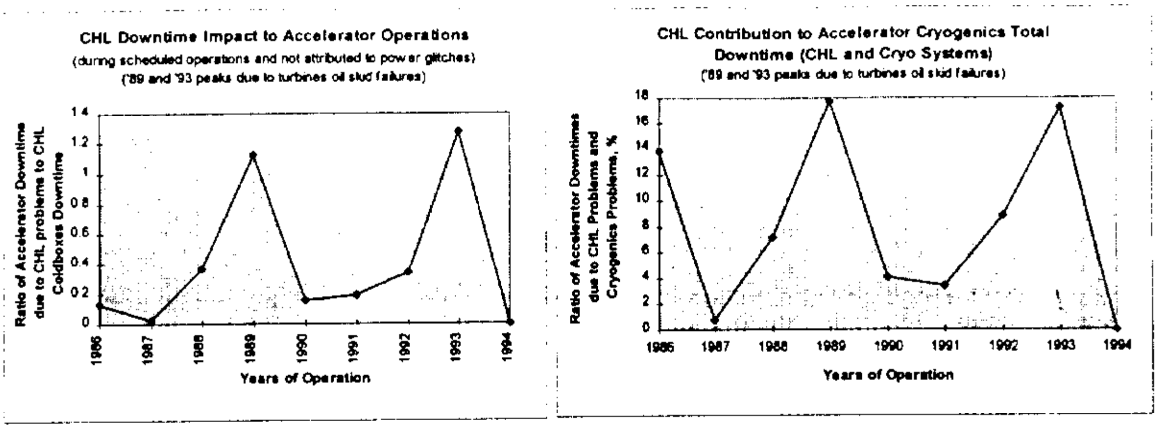

Figure 3. CHL Availability for Accelerator Physics

The Nitrogen Reliquefier (NRL) operations is generally decoupled from helium plant operations. Normally liquid nitrogen is readily available from vendor when the NRL is off-line. The low NRL availability of only 56% has been caused by major equipment failures, equipment deterioration, and manpower limitations. Recent interruption of liquid nitrogen delivery by vendor has affected accelerator operations since all helium plant operations ceased due to lack of precooling. Thermo cycling of the 6.5 km superconducting magnet system due to insufficient liquid nitrogen shielding risks undesirable stresses and resultant potential vacuum leaks. Thus focus on improving the liquid nitrogen availability through increased reserve capacity, improved NRL reliability and capacity is being addressed.

HELIUM COLDBOXES RELIABILITY

Though the availability of CHL for accelerator physics depends on failure-free operation of a variety of the equipment, the performance of the equipment associated with CHL helium coldboxes (Coldbox-I and -II) has proved to be most sensitive to process upsets, least accessible for regular diagnosis and maintenance, and most constrained to meet the accelerator demands in capacity and transient performance. Table 1 summarizes the causes which resulted in coldboxes' shutdown or crash during scheduled operations. Figure 4 represents graphically the monthly averaged number of shutdowns and crashes due to CHL equipment failures, human errors and power glitches for the last 9 years. It is noted that the number of shutdowns and crashes due to CHL equipment failures and human errors dropped and leveled off after initial years of operations. The upgrades of originally installed equipment and operator training played a significant role in the increased availability of CHL for accelerator physics. The equipment gradual wear and commence to operations of a new coldbox (Coldbox-II) are responsible for a relative increase in equipment failure rate and human errors. At the same time the total number of shutdowns and crashes have been steadily rising in years mostly due to increased rate of power glitches to CHL feeders.

Table 1. CHL Coldboxes Shutdowns/Crashes During Scheduled Operations (due to different equipment failures, problems, or human errors. 1986 - 1994)

Year of Operation	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**
Months a year with scheduled operations	**3**	**12**	**9**	**6**	**10**	**10.5**	**10**	**7**	**6**
Turbines oil skid (motor, pump, over-temperature)	0	0	3	1	2	1	1	2	0
Vacuum system	0	0	0	0	1	0	0	0	0
Valves, instrum-tion, power supplies, controls	1	1	0	0	0	0	5	1	3
Contamination	0	1	1	1	0	0	0	0	0
Power glitches caused by CHL equipment	0	1	0	0	1	1	0	0	0
Operations problem (due to other CHL equipment)	3	1	1	0	0	0	0	0	2
Total Coldbox crashes due to equipment failures	**4**	**6**	**5**	**2**	**4**	**2**	**6**	**3**	**5**
Human errors in operations and maintenance	**2**	**1**	**0**	**0**	**0**	**2**	**2**	**1**	**2**
Power glitches to CHL feeder/transformer	**0**	**1**	**2**	**2**	**2**	**3**	**5**	**2**	**4**
Total shutdowns/crashes	**6**	**8**	**7**	**4**	**6**	**7**	**13**	**6**	**11**

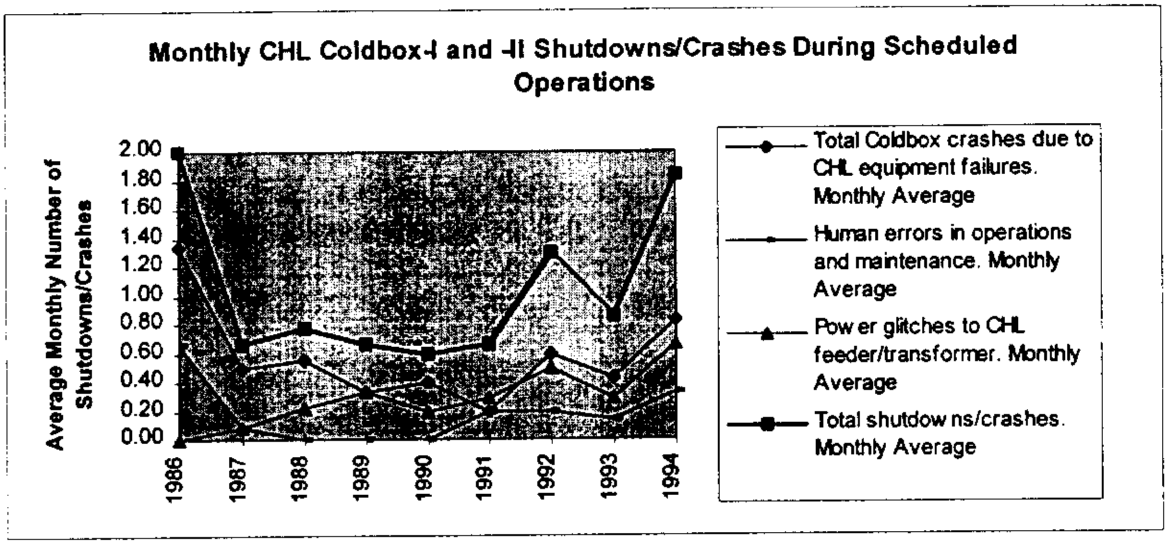

Figure 4. Monthly Average of CHL Coldboxes Shutdowns During Scheduled Operations [Monthly average downtime = (the annual number of downtime hours) / (number of months a year with scheduled operations)]

RECIPROCATING HELIUM COMPRESSORS RELIABILITY

The reliability of the CHL reciprocating compressors has a single most dramatic impact on the number of the monthly equipment shutdowns. Though CHL operates its helium coldboxes with only two (out of three existing) compressors, nevertheless a compressor failure leads to a temporary drop in liquefaction capacity, and if not given a immediate response may lead to operational instability and a coldbox crash. Three operational compressors are connected via the common suction and discharge header. The original three compressors are identical 537 g/s reciprocating 3-stage, double-acting, oil-lubricated, water-jacketed, inter-stage air-cooled machines operating between 15.2 psia and 180 psia. The fourth reciprocating compressor is a 4-stage machine with capacity of 750 g/s and it is currently being commissioned. The 1st and 2nd stage valves are the reed-type valves, and the 3rd stage valves are the plate-type ones. Since the 2nd stage discharge location had been historically the most failure-abundant one (see Table 2 and Figure 5), compressor "B" 2nd stage discharge valves were replaced with the poppet-type valves in 1991 to verify the manufacturer's recommendation.

Table 2. Registered Failures of Reciprocating Compressors Valves. 84 - 94
(failures include: broken, fractured, or heavily worn reed/button/spring/poppet, or loose, leaky, or defective valve)

Compression Stage	Compressor A	Compressor B	Compressor C
1st stage suction (6 valves)	3	3	7
1st stage discharge (6 valves)	3	3	5
2nd stage suction (10 valves)	0	1	0
2nd stage discharge (10 valves)	1	10	19
3rd stage suction (14 valves)	3	2	0
3rd stage discharge (14 valves)	6	2	2

The comparative analysis of CHL compressors' valves failure rate shows that the compressor closest to the operational coldbox (compressor "C" for Coldbox-I) produces the higher number of 1st stage valve failures, and the compressor outermost to the coldboxes (compressor "A") produces the higher number of 3rd stage valve failures.

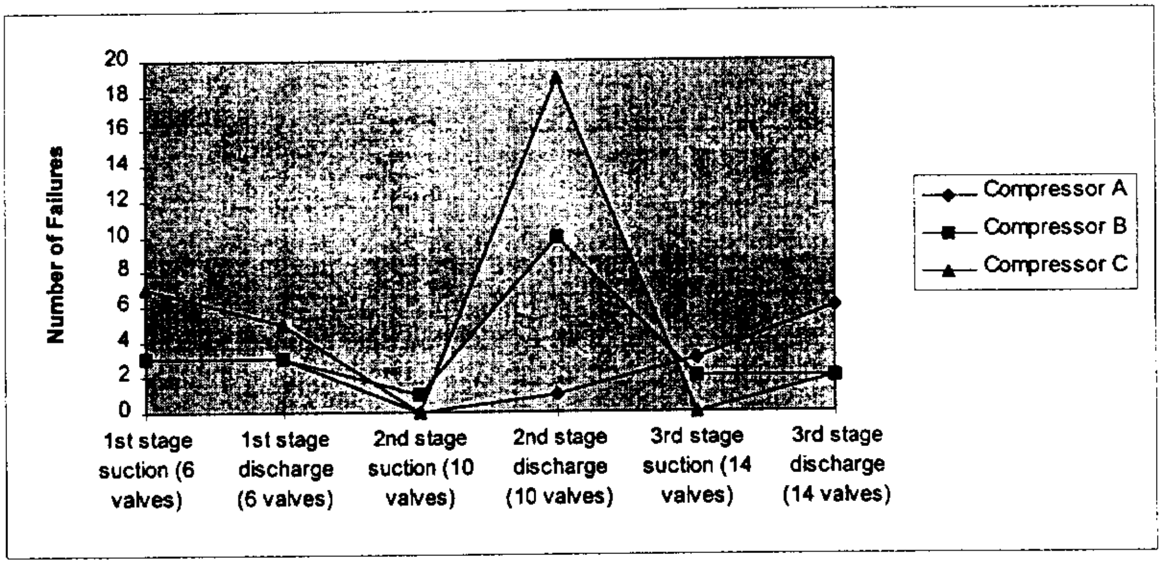

Figure 5. CHL Reciprocating Helium Compressors Valves Failures. 84 - 94.

The first phenomena may be attributed to the suction manifold pressure fluctuations, and the second phenomena to the slightly higher compression ratio. The 2nd stage valve failure rates were identical for "B" and "C" compressors for the period from 1984 to 1990 when both compressors had reed-type valves. Since

1990 compressor "B" has been operated with poppet-type valves in the 2nd stage. Two operating years of testing poppet-type valves has effectively proven their publicized (7) better performance for the most vulnerable 2nd stage of "B" compressor. The polyether ether keytone (PEEK) poppets are able to withstand temperatures up to 450°F, and have shown MTBF of 2.7 times higher than the one for the conventional reed valves installed at identical locations in compressor "C" (see Figure 6). Additionally, a poppet valve failure is normally a complete destruction of the poppet/spring, thus it is easier to diagnose a failure.

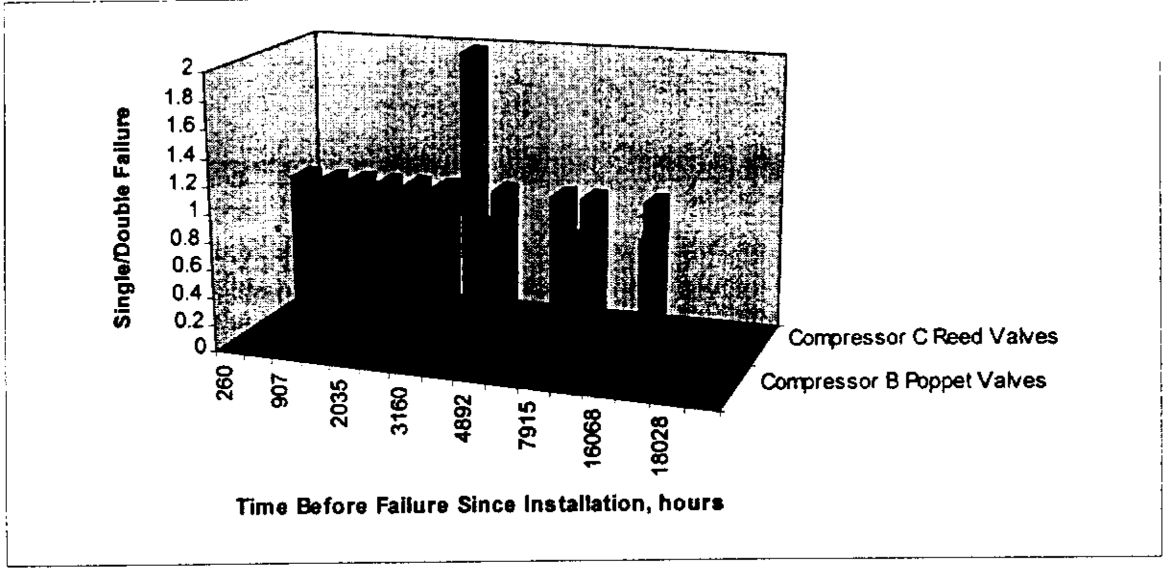

Figure 6. CHL Reciprocating Compressors "B" and "C" 2nd Stage Discharge Valves Failures. Poppet vs Reed Valves.

OPERATING COSTS

CHL reliquefaction cost for the average production of 140 g/s of liquid helium with two operating compressors is averaged at 0.141 \$/m^3 (0.004 \$/scf) based on FY94 data. The components, which constitute this cost are: electricity cost - 16.5%, manpower cost - 35.2%, operations expenses - 18.8%, and purchase LN2 used as a precool/shielding - 29.5%. These numbers can vary significantly from year to year with variations in market conditions for liquid nitrogen, electricity, and other services. CHL labor efficiency of 1.4 manhour/kiloliter

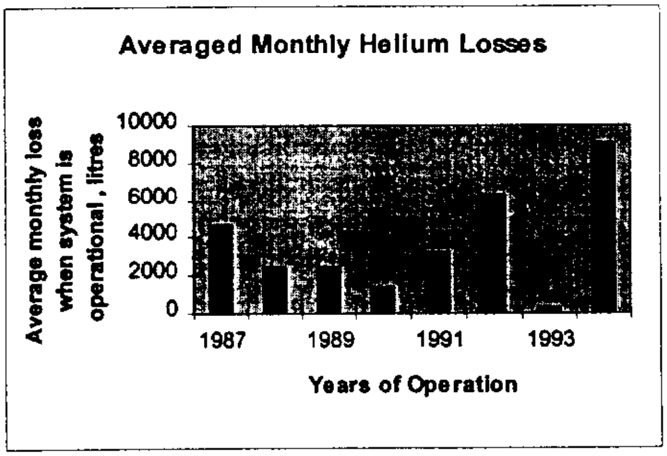

Figure 7. Monthly helium losses due to power outages

(52.8 manhours/mmscf) compares favorably with those of private sector plant operations (10). This does not include the cost of make-up helium purchased from outside vendors due to unrecoverable losses to atmosphere. The unrecoverable losses for the Fermilab helium cryogenic system average at the level of 1000 liters/day when the system is operational. Additional losses are attributed to unscheduled site power outages which results in partial or full loss of inventory. Those losses have been fluctuating through the years of Fermilab cryogenic system operations (see Fig. 7). Electric power consumption is 274 W per 1 W of refrigeration for Coldbox-I operation, and 300 W/W for Coldbox-II operation. This is comparable to Fermilab satellite system [270 W/W, (9)], HERA [285 W/W, (6)] and CERN LEP200 [287 W/W, (8)].

MAINTENANCE

Operational experience of CHL from 1981 to 1994 has served as a base to establish an effective conduct of operations guidelines and maintenance schedules. An established maintenance program ensures high CHL availability for the accelerator physics. Department of Energy (DOE) mandates implementation of a formalized maintenance management system for all DOE facilities (11). This is currently being commissioned across various laboratory organizations, including CHL. CHL does not have a maintenance-dedicated crew, but provides most of the maintenance using its own operations manpower resources. Predictive, preventive, or corrective maintenance is planned and supervised by CHL staff and done by available technicians when schedule allows them to be taken off from operational duties. CHL staff provides all necessary engineering and technical support, and is responsible for following manufacturers' recommendations, determining acceptance criteria, test requirements and procedures. Most of the CHL equipment and components are scheduled for planned or periodic maintenance, as well as for surveillance under predictive maintenance program. At the same time, maintenance activity at CHL is subjective to CHL programmatic mission, thus it is adjusted to fit Lab's planned shutdowns and Tevatron cryogenic system demand.

Most of the CHL equipment components are scheduled for preventive maintenance. Only a limited number of components can be planned rigidly for maintenance at predetermined intervals required by safety standards, or suggested by component's manufacturer or operation experience. These are components, which: a) may have environmental, safety, or programmatic impact; b) have an adequate stand-by backup to replace them for the duration of maintenance; c) if excluded from active service for the duration of maintenance, do not impact the programmatic mission of CHL facility. Deterioration of performance, engineering analysis, cost/benefit analysis, and reliability considerations are used as a basis to modify a frequency of the maintenance. A few examples of scheduled preventive maintenance are: Oxygen Deficiency Hazard system and emergency lights (monthly); purifier regeneration (weekly), reciprocating compressors bearing greasing (every 2300 hrs); coldbox-I/II turbines overhaul (every 18 months of continuos operations); cooling towers gear boxes maintenance; pressure relief valves inspection and testing (every 6 years). However, some equipment is operated until complete obsolescence or degradation requiring eventual replacement.

To ensure the timely maintenance CHL conducts an extensive surveillance program which consists of: a) operational equipment parameters monitoring, readings, and datalogging on a regular pre-defined time basis; b) operational equipment surveillance for deterioration indications by means of pre-defined walk-through paths; c) operational equipment periodical surveillance for vibration and temperature data; d) stand-by equipment tests and oil sampling. All of the CHL equipment characteristic parameters, including pressures, temperatures, flows, contamination, etc., are displayed locally and/or transmitted to dedicated process controllers for operator display in control room terminals, and datalogging. The characteristic parameters of CHL equipment critical for programmatic mission, such as coldboxes and dewars, are plotted and displayed at operator consoles at all times, thus providing for visual evaluation of equipment performance and need for corrective measures. Operators are trained to recognize a deviation from "normal" conditions, and standard operating procedures are developed to initiate further detailed investigation and preventive maintenance measures if required.

CHL rotating equipment critical for programmatic mission, such as coldbox turbo-expanders, oil skid pumps, liquid helium pumps, compressors and motors, etc. are included into vibration surveillance program. The vibration data for these equipment is collected on periodic basis, checked against the base line, and analyzed to detect any possible degradation of equipment. If a possible problem is detected then a detailed investigation is initialized through retrieving datalogged parameters and additional sampling. CHL reciprocating compressors' valves, which constitute the most frequent failure source, are monitored indirectly through compressors' process pressures and temperatures. Additionally, such important indirect indications of possible failures, as helium losses and helium inventory, are monitored and analyzed continuously. The set of "benchmark" readings is available for every major piece of equipment, and it is used as a base line to compare the current parameters for abnormal deviations. The hard copies of past readings, as well as the VAX archived logbook files, are always available for trend analysis and equipment history assessment.

SUMMARY

The experience in operating the world-largest stand-alone helium reliquefier system over the last eight years shows its high availability to Fermilab superconducting accelerator physics due to its system configuration, equipment reliability, extensive maintenance program, and personnel technical abilities.

LITERATURE CITED

1. C.H.Rode, Tevatron cryogenic system, "The Proceedings of the 12th International Conference on High Energy Accelerators" (1983).
2. G.A.Hodge, et al, Recent operating experience with the Fermilab Central Helium Liquefier, "Advances in Cryogenic Engineering" Vol.29, (1984).
3. R.J.Walker, et al, Recent operating experience with the Fermilab Central Helium Liquefier, "Advances in Cryogenic Engineering" Vol.31, (1986).
4. G.T.Milholand, et al, Design and performance of a 90,800 kg/day nitrogen reliquefier for Fermilab energy saver, "Advances in Cryogenic Engineering" Vol.31, (1986).
5. J.N.Makara, et al, Fermilab Central Helium Liquefier Upgrade, "Advances in Cryogenic Engineering" Vol.39A, (1994).
6. H.Berg, et al, Report on operational experience and reliability of the HERA cryogenic system, "Advances in Cryogenic Engineering" Vol.39A, (1994).
7. J.S.Bunn, Consider poppet valves for compressor retrofits, "Hydrocarbon processing" (Feb.1988).
8. W.K.Gistau, et al, The 6 kW at 4.5°K at CERN cryogenic test station, "Advances in Cryogenic Engineering" Vol.39A, (1994).
9. A Report on the Design of the Fermi National Accelerator Laboratory Superconducting Accelerator, May 1979, Fermilab, Batavia, IL
10. Helium Operations Reports for U.S. Bureau of Mines, J.R. Campbell & Associates, March 1988
11. Maintenance Management Program, DOE Order 4330.4A, U.S. Department of Energy, 1990