CEBAF CRYOGENIC SYSTEM*

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I. INTRODUCTION

The CEBAF cryogenic system consists of three refrigeration systems: Cryogenic Test Facility (CTF), Central Helium Liquefier (CHL), and End Station Refrigerator (ESR), see figure 1 [1,2]. We now have 49,000 hours of CTF and 35,000 hours of CHL operation. The CHL is the main cryogenic system for CEBAF, consisting of a 4.8 kW, 2.0 K refrigerator and transfer line system (TL) to supply 2.0 K and 12 kW of 50 K shield refrigeration for the Linac cavity cryostats and 10 g/sec of liquid for the End Stations, see figure 2. This paper describes the nine year effort to commission these systems concentrating on the CHL with its high tech component the cold compressors (CC), see figure 3. The CC are a cold vacuum pump with an inlet temperature of 3 K which use magnetic bearings; they eliminate the possibility of air leaks into the subatmospheric He which could easily cause a multi-month down time for repurification.

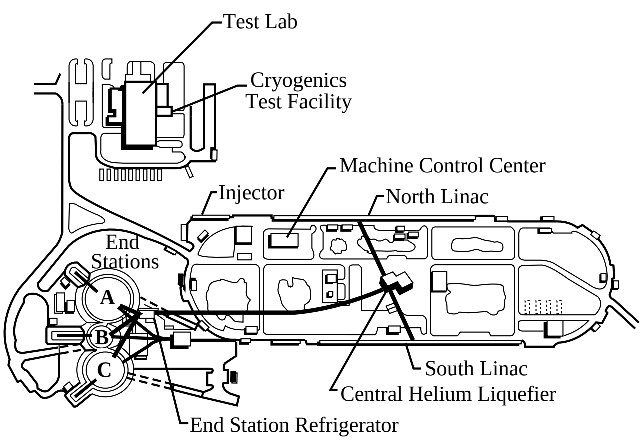

Figure 1. CEBAF Cryogenic Scope

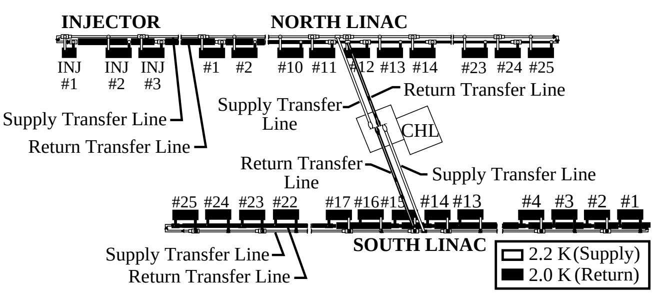

Figure 2. Linac Distribution System

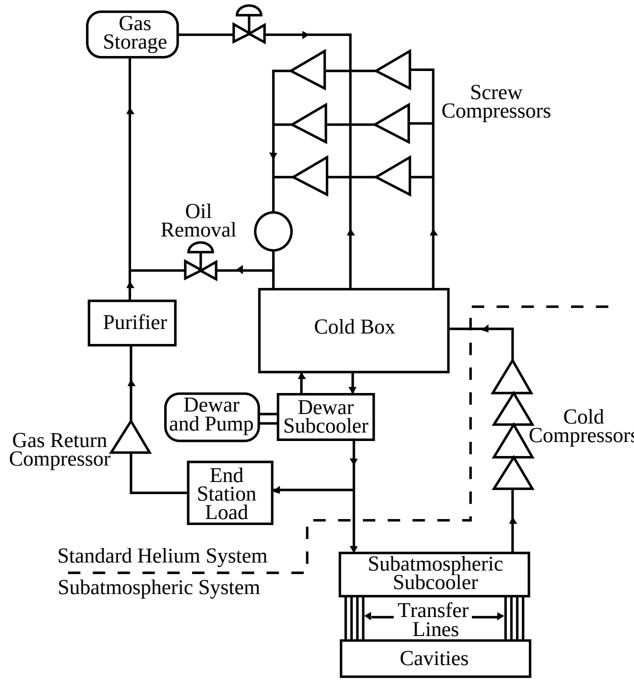

Figure 3. Block Diagram of Refrigerator

II. BACKGROUND

The cryogenic effort started with converting the Conceptual Design Report into the detailed specification for the CHL; this was the highest priority due to the long lead time associated with the CC and the need for a projected two year burn-in time to obtain 98% availability.

The process of awarding the contract took 11 months starting with the draft specification being sent to the vendors and ending with the award in January 1988. This was CEBAF's first major contract and still is the second largest technical contract (SRF cavities production is the largest). During the construction the contract appeared to be proceeding relatively smoothly except for the engineering personnel being repeatedly pulled off to prepare SSC bids. Problems surfaced during installation and commissioning; the 10 months scheduled installation and commissioning became $4\frac{1}{2}$ years. Table 1 is the project timeline.

III. He TRANSFER LINES

After writing the CHL specification, the emphasis was immediately on getting the CTF and its TL built, installed, and commissioned so that it could support cavity R&D and production. The CTF started operation in August 1988, and effort immediately shifted to the Linac TLs. The TL design was based on the Fermilab 6 km long, 168 mm

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diameter line with its eccentric shield. CEBAF has 2 km of TLs varying from 114 to 457 mm with 250 bayonets.

Table 1. Cryogenic Timeline

Feb. 86	CEBAF CDR
Feb. 87	CHL specification to vendors
Jan. 88	CHL contract awarded
Aug. 88	CTF operational
Dec. 89	Delivery 4.5 K system
Jul. 90	*****Scheduled 2 K acceptance test*****
Dec. 90	Screw compressor system operational
	Delivery 2.0 system
Feb. 91	First 4.5 K coldbox operation
	N. Linac supply TL cooldown
	**Start injector commissioning
May 92	N. Linac return TL cooldown
	**Start N. Linac commissioning
Aug. 92	T4 turbine operational
Mar. 93	S. Linac supply and return TL cooldown
	Rebuilt CC returned
Jul. 93	Unstable 2.9 K CC operation
Sep. 93	CEBAF assumes responsibility for CC commissioning
	New CC control concept
	30 min. run 2.2 K
Dec. 93	CHL contract closed
Jan. 94	Additional 4.5 K heat exchanger installed
	3750 W @ 2.1 K run
Feb. 94	Last of second stage warm compressors replaced
	Cool down first end station magnet
Apr. 94	Stable 2.3 K CC operation
May 94	**Start final beam commissioning
	Stable 2.1 K CC operation
Jul. 94	*****First beam on target*****
Aug. 94	32 day continuous CC run
Nov. 94	ESR operational
Mar. 95	Three end station cryogenic operation

The N. Linac Supply Transfer Line was cooled 15 minutes after the first drop of liquid was produced with the CHL. One of the 25 g/sec He vacuum pumps permitted commissioning of the injector to begin. The last of the Linac TL was cooled down 25 months later.

The operating schedule has not permitted detailed heat leak measurements, but based on operating performance they appear to be close to design. The static heat load for Linac TLs and 42 $\frac{1}{4}$ cryomodules is approximately 800 W at 2 K plus 8000 W at 50 K.

IV. 4.5 K SYSTEM

The 4.5 K system was delivered only two months behind schedule, but the commissioning had not started by the scheduled 2 K acceptance test date. At this time the system still has a large amount of remaining work. While there were several technical problems, the vendor did not want to complete the 4.5 K earlier than was required by the CC problems. The generalized problem was that work was not done on the 4.5 K system if a 2.0 K system component was broken and also converse; i.e., everything was in series in an attempt to minimize costs.

The initial 4.5 K problem discovered was incorrect assembly of the main screw compressor heat exchangers, permitting the oil to bypass the water cooling tubes. The second problem was that the coldest turbine bearings failed three times. Eighteen months later the root cause was found when the same seal failed in the next coldest turbine.

The last four problems caused trouble during the 4.5 K commissioning but became critical when we started to commission the CC.

1) The warm screw compressors were reduced in size after the initial design review. The contract required that we could run at full capacity with one of the three first stage compressors off or at reduced capacity with one of the three second stages off. We were unable to operate the CC with all six compressors on. In the winter of 1993/1994, we replaced the second stage compressor with the originally reviewed size. The motors had been sized for larger units and did not need to be changed. Replacing the first stage compressors is still a remaining task.
2) The heat exchangers between 30 and 4 K were sized for steady state only and have a pressure drop too high for CC starting, 4.5 K refrigeration, or off-design operation. Replacing these exchangers would require a three-month CEBAF shutdown and therefore is not planned for the near future.
3) In addition to the above problem, the 4.5 K subcooler has two problems: a) Two phase flow was attempted in a platefin exchanger; this causes major 60 second oscillations in the 4.5 K system. b) The exchanger is 80% deficient in heat transfer. In January 1994, a second 4.5 K subcooler was installed in the interconnect U-tube between the two coldboxes.
4) In an attempt to fix the previously discussed coldest expander problem, the flow nozzle was reduced by 8%, which then made it too small to support the CC. A spare turbine with the correct size was procured but not installed.

V. 2.0 K SYSTEM

The 2 K coldbox consists of the four stage CC and a small heat exchanger which lower the supply temperature from 4.5 K to 2.3 K. Each of the CC stages has a variable frequency drive with the motor cooled by liquid nitrogen. The bearing consists of a five degree of freedom magnet bearing system backed up by mechanical bearing (see figure 4).

The 2 K coldbox suffered a long series of electrical failures. The CC were based on Torr Supra's, scaled up a factor of 3 in size and 10 in power. The Torr Supra units

had run for 50,000 hours without a major failure while during commissioning CEBAF's had a MTBF of <<100 hours and a MTTR of >>1000 hours.

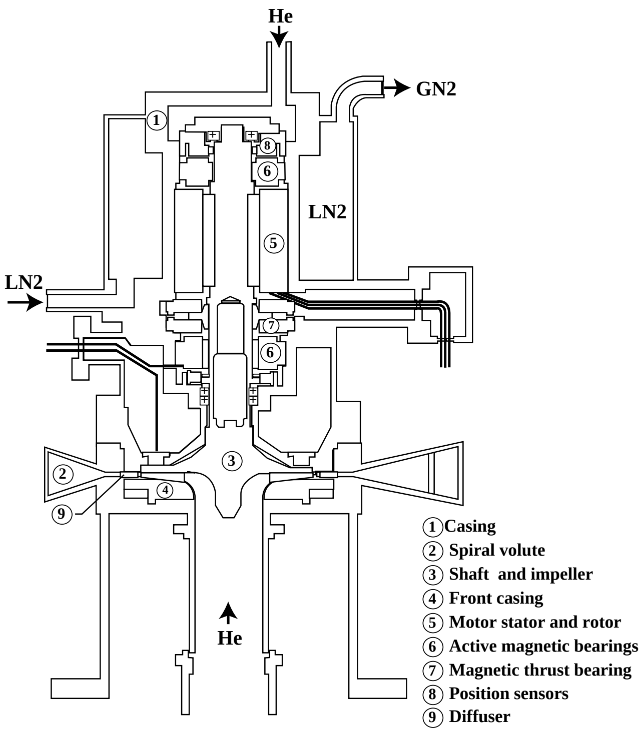

Figure 4. Cold Compressor

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There were eight major electrical failures; they were caused by two problems:

1) High voltage in low pressure He: 2 failures
2) Differential contraction: 6 failures

The problem of voltage breakdown in He is well known to superconducting magnet builders but not to industry in general. The Torr Supra CC were scaled by a factor of 3 in both voltage and current which led to 380 V in the third and fourth stages. In 1989 the third stage arced over during pre-delivery component testing. Isolation transformers and spike filters were added to the two highest stages. This was the primary reason the 2 K coldbox was delivered 14 months late.

The second arc occurred in 1992 at CEBAF in the fourth stage. This resulted in a complete redesign of the motors which lowered the voltage on the third and fourth stages to 170 V and took 8 months.

The second problem was in the potted fine wire position and speed sensing coils; these coils were reported to be identical to the Torr Supra coils except for a slight increase in diameter. The wire would open circuit upon cooldown and, in at least one case, healed itself on warmup. There were three failures in the position sensing coils which on the average took 1000 hours to repair. After the second failure all the upper position sensing coils were replaced with unpotted coils; upon recooldown the lower position sensing failed, leading to their replacement.

Two failures in the speed sensors did not stop testing; the speed request was wired to supply the actual speed signal. These were replaced during the motor rebuild.

The last failure occurred after the rebuilt motors were reinstalled and cooled down; the upward axial thrust coil was actually a dual coil unknown to us. It used another fine wire coil to provide the dc force to compensate for gravity; this coil was not replaced. This coil provided an intermittent ground fault. The electronics were modified to eliminate this coil and use the main coil to provide the dc biases as well.

In May 1993 the CC were finally ready for serious commissioning and they reached an unstable 3.35 K. The next run in July reached an unstable 2.9 K. The next run was in September; at this point two major changes occurred:

1) CEBAF assumed responsibility for commissioning in order to accelerate the commissioning progress.
2) A philosophic error was found in the CC control: a 30 minute run at 2.2 K was achieved September 13, 1993.

The remainder of 1993 was spent studying the system to find the four problems discussed in section IV. About 50% of the time through April 1994 was devoted to stable liquefaction to support cryomodule RF commissioning. As the date of accelerator turn-on approached, priority shifted from reaching lower temperature to developing reliable CC starting procedures. Accelerator operations at 2.3 K started on schedule.

After three weeks of beam operation, there was a concern that since we were operating above Lambda, bubbles in the He were causing cavity vibration problems beyond the control response of the RF system. Beam testing stopped, and three days were spent developing the procedures for 2.1 K operation.

Since July 1994, effort on the CC was spent on available, speedy reliable restarts, regulation, and finally fully automatic computer controlled restarting [3,4]. Figure 5 shows the last pumpdown; the repair took 0.8 hours, and restart took an additional 2.8 hours.

The refrigerator is now operating at full capacity at 2.08 K.

VI. COMPONENT RELIABILITY

The 35,000 hours of CHL operation have given reliability problems similar to those experienced by Fermilab during the first four years of Tevatron operation. Loss of utilities is the most painful of the problems because it shuts the system down completely. The utilities are configured for redundancy.

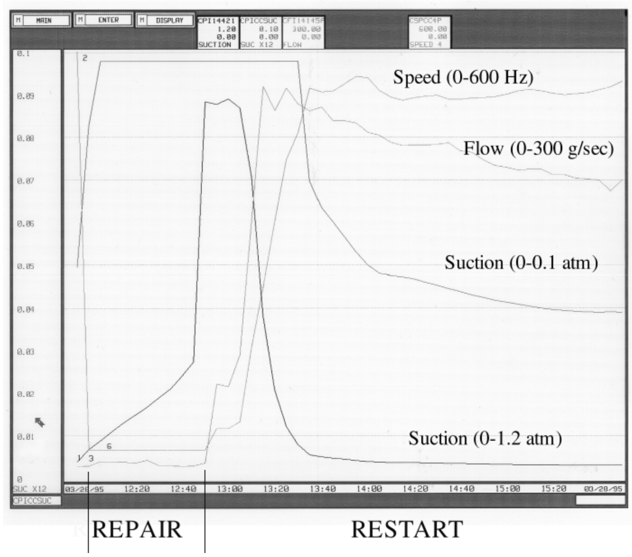

Figure 5. Repair and Pumpdown Cycle

The CEBAF site is fed by two taps to the power grid with a manual switch over. The high reliability tap feeds the CHL and ESR, and causes one or two outages per year. The CTF is fed from the second feed and has 10 to 15 outages per year, most less than a second in duration.

The CHL water system also averages one complete outage per year and several periods at reduced capacity. While the triply redundant compressed air system has not been down, moisture in the air has caused several downtimes annually. A system that has not caused downtime is the power for the CHL computers. The UPS has a triple redundant power feed: two power feeds from the site grid plus an automatically starting generator.

The 4 K system reliability has been good but still needs another factor of three improvement to reach our goal of 99.5%. The six main screw compressors are all approaching 30,000 hours. There were two premature failures at 10,000 hours of the main compressors' bodies believed due to initial misalignment during commissioning. The second stage oil pump bearings have all failed at about 25,000 hours. An annual failure has been a 1.7 MW motor lead connection loosening up and then arcing over; in theory this problem has been fixed by rebolting all the motor connections with Belleville washers. There have been two failures of the main butterfly valve linkages.

The 4 K coldbox has been relatively good. The bearings on the 25 K turbo expander have twice failed while jumping through the critical speed ranges during CC starting. The inlet filter to the 15 K turbo expander plugged with contamination, requiring localized warmup three times.

With only 8000 hours of CC operation including commissioning, it is too early to comment on the 2 K system reliability.

VII. AVAILABILITY

Cryogenic availability for the previous ten months has averaged 96.5%; the downtime and its cause are shown in figure 6. The cause is split between the 4 K system (1.4%), the 2 K system (0.7%), and the cryogenic controls (1.3%). The cryogenic controls category includes cryogenic software and hardware, as well as linac cryogenic instrumentation for the cavities. Not included in the downtime is another 1% of non-availability charged to other subsystems such as utilities; these included site power, city water, end station errors, and MCC problems.

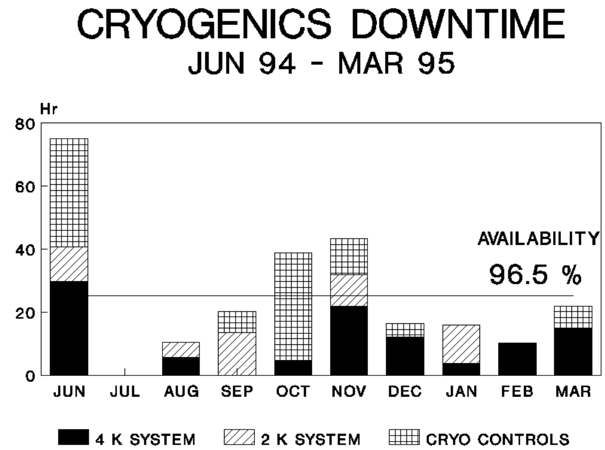

Figure 6. Cryogenics Downtime (June 1994–March 1995)

During this period there were 40 unscheduled CC trips plus two additional downtimes which did not trip the CC. This is a 174-hour MTBF and a 6.0 hour MTTR. The longest CC run was 766 hours, while the shortest was 5 hours. About half of the 6-hour MTTR was the response and repair time, while the other half was the accelerator pumpdown time.

The primary 4 K system downtime was caused by contamination tripping the 25 K and 15 K turbines; the turbine trip in turn causes a temperature transient, which would trip the CC. Other causes included the warm screw compressor trips and some control valves.

Only one of the 2 K system downtimes was associated with the CC hardware; with a valiant 14-hour all-night effort, it was possible to get the magnetic bearing electronics operational again. Five downtimes were due to excursions of the CC out of their stable operating regions, and not traceable to any equipment failures.

The unreasonably large cryo control downtime was due to three root causes: a) a failure of a supervisory LAN connection and/or board, b) intermittent failures of the linac serial highways which transmit load liquid level information, and c) overloading of memory allocations due to adding the third refrigeration system, ESR, to the network. The first was fixed by replacing several boards and reworking all the terminations, the second problem still remains, and the third has been partially fixed.

The effort on CC restarting procedures had major effects on availability. In June 1994 a very good CC restart took 5 hours, while bad ones took three or four times longer. During the fall, procedures improved and increased the probability of successfully pumping down. During the last four months, the average downtime was 4.7 hours, with the pumpdown time being 2.5 hours for CC trips lasting 3 hours or less. During the last two months, this was fully automated, including jumping of turbines through their critical speed range.

VIII. REMAINING TASKS

The primary need is to be able to shut down any one of the six warm screw compressors for maintenance or repair. With the previously discussed replacement of the second stage compressors, we have been able to operate reliably but have not reached either of the contractually-required modes of operation. We cannot operate the CC for more than two hours with a second stage off; we can operate with a first stage off but at reduced capacity. Therefore it is our highest priority either to install additional second stage compressor capacity or to develop the CC operation procedure for this mode.

The primary cryogenic weakness is the CC repair times. Even with the 50,000 hour compressor and 40,000 hour controller MTBFs, we cannot approach the 98% average availability goal. To achieve 98% we need to achieve one week repair on the compressors and eight hours on the controllers. While in one case we were able to get the controller operational again and our repair capability is steadily increasing, our best estimate of repair times are still an order of magnitude away from our needs.

Therefore CEBAF is in the process of procuring a complete redundant set of CC and controllers. During the following year these will be assembled into a redundant 2 K coldbox system.

The remaining major problem, the 4 K to 30 K exchangers, are costing efficiency and CC restarting delays. Since there are no planned 3-month cryogenic shutdowns in the next few years, work-arounds will continue. We are planning to order the replacement exchangers and store them for a future opportunity to install them.

IX. LESSONS LEARNED

This procurement contained one high tech element, the CC; CEBAF's initial planning was to make it a separate procurement. Due to the unanimous request of all the bidders, these two procurements were combined. In hindsight this appears to have been a major mistake. The contract did require two independent coldboxes, which permitted us to use the 4 K system to commission the accelerator with minimal impacts.

Two independent contracts, each with its own acceptance requirements, would have saved a minimum of two years of the nine year effort. The gains would have come primarily from the 4 K system:

1) The 4 K contract would have specified the interface flow rates, etc., eliminating some of the design errors.
2) The 4 K acceptance test would have flagged the 4 K problems in 1991 and forced their resolution at that time.
3) The commissioning would have been independent efforts eliminating delays in finishing the 4 K plant because a 2 K component failed.

The second mistake is that early in the contract when good progress was being made, the details of the contract were not always enforced. A full-time CEBAF inspector/engineer at the factory should have also been used.

X. ACKNOWLEDGMENTS

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XI. REFERENCES

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