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Initial Performance of Upgraded Tevatron Cryogenic Systems

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ABSTRACT

Fermilab began operating a re-designed satellite refrigerator system in November 1993. Upgrades were installed to operate the Tevatron at a magnet temperature of 3.5K, approximately 1K lower than the original design. Refrigerator upgrades included new valve boxes, larger reciprocating expanders, the installation of cold vapor compressors, new sub atmospheric instrumentation and an entirely new distributed controls system.

Cryogenic system reliability data for Colliding Physics Run 1B is presented emphasizing a failure analysis for each aspect of the upgrade. Comparison to data for Colliding Physics Run 1A (previous to the upgrade) is presented to show the impact of a major system overhaul. New operational problems and their solutions are presented in detail.

INTRODUCTION

After 10 years of successful operation, from 1983 to 1993, the Tevatron Cryogenic Satellite Refrigeration System was re-designed to lower the operating temperature of the Tevatron magnet system down to a two-phase temperature of 3.56K from the original 4.45K temperature. The Low Temperature Upgrade, as this work is referred too, is required to increase the operating colliding beam physics energy of the Tevatron to 1000 GeV from the nominal 900 GeV energy. Modifications to the satellite refrigeration system included the installation of new valve boxes, installation of cold compressors, hardening of the two-phase circuit to make it leak tight for subatmospheric operation, conversion of wet expanders to 7.5 cm piston machines, installation of 5.6 kW AC variable frequency drive for wet expander continuous braking, and installation of a new distributed control system. These modifications have been discussed in detail elsewhere[1] and will not be discussed here. A flow diagram of a satellite refrigerator is shown in Figure 1.

To maintain reliable accelerator operations, it is imperative that the satellite refrigeration system downtime be minimized. This paper attempts to compare the statistics of the last two colliding beam physics runs: a before and after look at reliability. The statistics shown are a comment on how well the Low Temperature Upgrade was designed, installed and operated.

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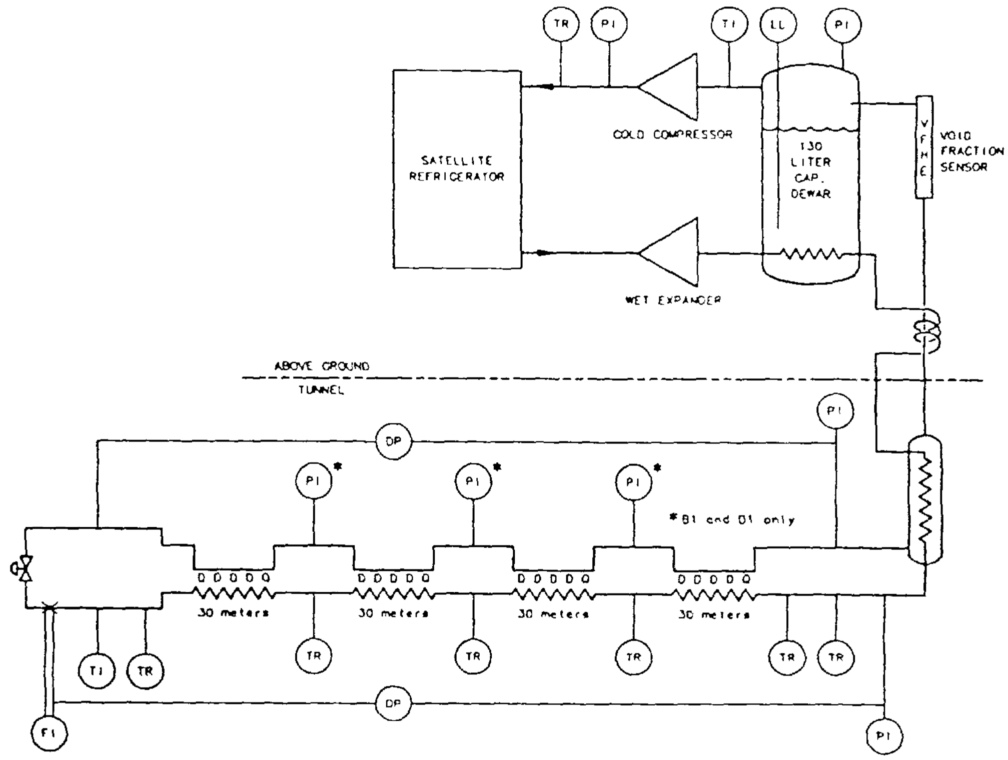

Figure 1. Flow diagram showing satellite refrigerator and one half of magnets (D = dipole magnet, Q = quadrupole magnet)

LOW TEMPERATURE/HIGHER ENERGY STATUS

After the installation of the Low Temperature Upgrade equipment in the Summer and Fall of 1993, a series of power tests were performed to get to 1000 GeV operation.[2] The conclusion of these tests proved we could achieve 975 GeV operation with a cold compressor inlet temperature of 3.84K. This energy was attained in a DC condition (a "STORE") for over an hour. Attempts to go higher in energy resulted in a quench.

Before achieving this one hour "STORE" condition, we had attempted to ramp the machine to 1000 GeV and found that we experienced a significant number of training quenches. The highest energy we achieved at any time during these studies was 997 GeV (this was on ramp up; flattop was never achieved).

Because of the uncertainty in being able to easily get to 1000 GeV and because of a desire to proceed with Physics Run 1B, laboratory management decided to continue with accelerator physics at 900 GeV. Thus cold compressor and low temperature operation have not been of a "critical" nature to this Run. We have, however, operated cold compressors as we could. All of this means that the statistics for cold compressor reliability and impact to operations are not yet well established. Although we intend to perform more studies to understand how to attain 1000 GeV operation, Low Temperature operation will not become an everyday reality until Collider Run 2 presently scheduled for 1998-9.

RELIABILITY DATA BEFORE AND AFTER UPGRADES

A real concern that we recognized throughout the design process for all aspects of the Low Temperature Upgrade was continued high reliability. Our goal was to better our downtime numbers where possible.

The Accelerator Division Operation Department keeps statistics on all aspects of accelerator downtime. This data has been used as the basis for the statistics shown in this paper. To better understand the impact of the Low Temperature Upgrade on cryogenic reliability, data in Table 1 shows the present run, Run 1B, and the last pre-Low Temperature Upgrade run,Run 1A. Table 1 is broken down into major categories of cryogenic failures. These categories have been chosen based on experience of typical Tevatron failures over the years. Each failure category will be discussed individually in the paper.

Table 1 includes the amount of calendar time and Tevatron availability time. The Tevatron availability time during Run 1B is about twice that of Run 1A. (Note that problems such as power outages or failed Tevatron magnets are accounted for in the Tevatron Unavailable Category.) However the total cryogenic downtime for Run 1B has been the same amount as the previous pre-Upgrade Run, about 1.0-1.2%. This translates into averaging approximately two hours of satellite downtime per week. As shown in Figure 2, both Runs began with significantly higher Average Weekly Downtime but converged to the two hour level over a number of weeks. After the installation of the Low Temperature Upgrade equipment, it has taken longer than the previous Run to converge to the two hour point. This is explained by two issues: a learning curve needed for operators on the new equipment and a much higher than normal failure rate with our wet expanders (see section on expansion engine failures).

The fact that the last two Runs have the same general weekly downtime average is quite encouraging and illustrates that a major Tevatron system upgrade can be successfully implemented without adding to the overall downtime of the accelerator. Of course, only after Low Temperature Operation becomes an everyday reality will we truly be able to determine how well we have done in terms of reliability.

WET EXPANDERS

The refrigerator cycle for the Upgrade was studied in detail and a special Fermi designed Macintosh simulator was used to understand the best cycle we should create.[3] This work led to the wet expander exhausting into a subcooled dewar of liquid rather than exhausting directly into the single phase of the magnets. With the cold compressor in use, the expander now operates with an inlet temperature of 7-8K where in the past the expander operated with an inlet <5K. The supply-side density change forced an increase from 5 cm to 7.5 cm diameter pistons. This increase translated into a need to have a motorized brake sized for 5.6 kW (up from the old 1.5 kW). To accomplish this we purchased AC variable frequency drives from Mitsubishi that included a regenerative unit for converting the energy of the expander into 60 Hz electrical energy and placed back onto the power grid.

Table 1. Comparison of Reliability Data for Run 1A and Run 1B

	Run 1A June 15, 1992-May 31, 1993		Run 1B Dec. 15, 1993 - June 11, 1995	
Category of Failure	% Of Cryogenic Downtime	Total # Of Hours Down	% Of Cryogenic Downtime	Total # Of Hours Down
Expanders (Mechanical)	18.80%	15.1	50.6%	61.1
Expanders (Electrical)	10.70%	8.6	3.1%	3.7
Kautzky Reliefs	35.70%	28.9	11.1%	13.4
Distributed Controls	6.90%	5.6	4.5%	5.4
Cryo Control/Electronic	1%	0.8	5.5%	6.7
Cold Compressors	NA	NA	0.4%	0.6
Instabilities	4.3%	3.4	18.8%	22.7
Power Lead	22.6%	18.3	6.0%	7.3
Total Cryo Downtime	NA	80.7	NA	120.9
Total Calendar Time	NA	6720.0	NA	13,032.0
TeV Unavailable		336.0		1632.0
TeV Available		6384.0		11,400.0
Cryo Downtime Total %		1.2%		1.0%

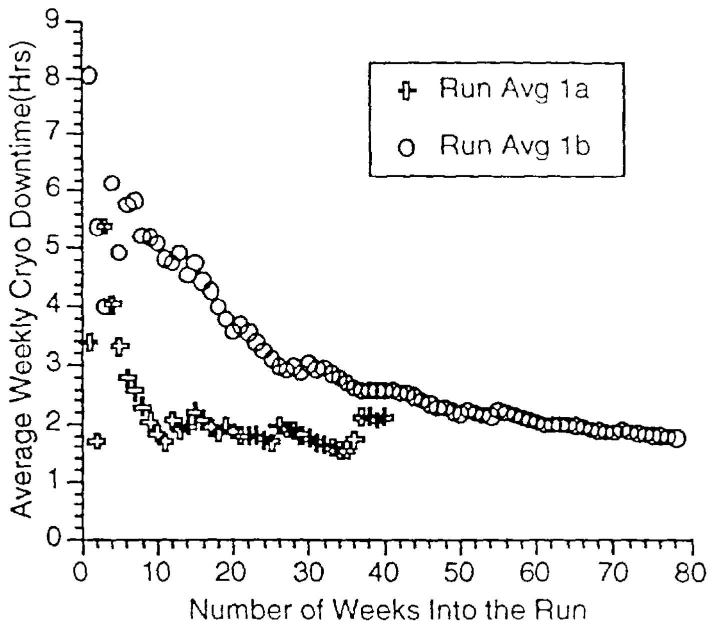

Figure 2. Comparison of average weekly downtime for Run 1A and Run 1B

Mechanical Statistics for Expanders

At the start of Run 1B, we experienced an abnormally high number of mechanical failures with the expanders.[4] There were five failures that caused downtime within the first two months of the run. These failures were caused by cyclic metal fatigue of the main crankshaft. An independent study showed we were experiencing fretting of these crankshafts. The failures were brought on by upgrading to the larger piston machine. The same outside study suggested using a higher strength steel and surface treating the shafts, either ion-nitriding or a special chroming. Since doing so we have experienced only one other broken crankshaft and this shaft had been treated with an inferior surface treatment soon realized to be inadequate.

Besides this rash of crankshaft failures, our expander downtime has increased in general. This increase seems to be a result of the larger piston diameter which places more force and stress on bearings, shafts, and frames overall. All of these items are warm-end failures. Cold-end failures such as o-ring blowby, piston, connecting rod, or internal leak problems have remained about the same. Figure 3 shows the weekly downtime average for this category.

Electrical Statistics for Expanders

The motor and motor drive system used on the wet expander are used as a continuous brake. A PID closed loop tries to maintain the proper speed for pressurizing the magnet's single phase pressure to 0.22 MPa. This loop outputs a speed setting to the Mitsubishi drive which then "brakes" the expander to the correct speed. This speed is adjusted, if necessary, every two seconds. The motor is allowed to make maximum speed changes each sample time of 100 rpm.

Since we began using the new drives in November, 1993, we have accumulated approximately 329,000 hours of time on the motors and drives. As shown in Table 1, this category of downtime amounts to 3.1% of our total cryo downtime and is a significant

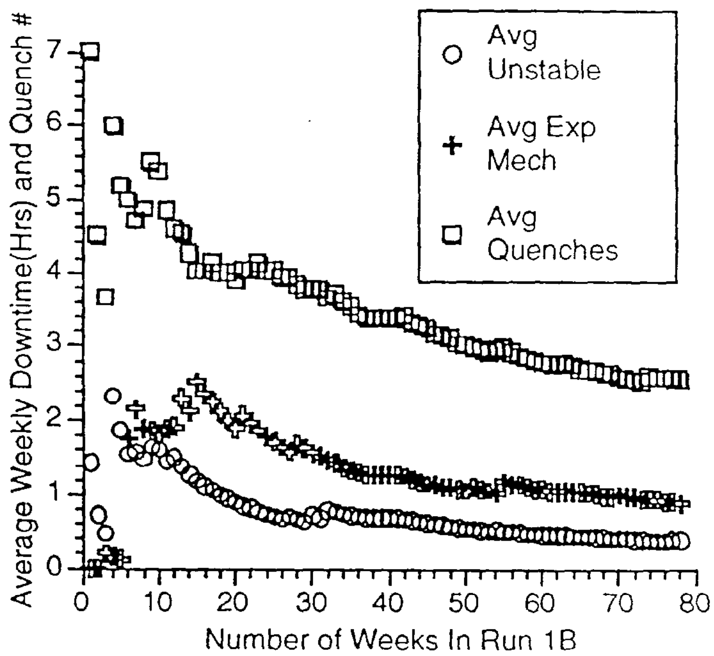

Figure 3. Average weekly statistics for expanders (mech.), instabilities, and quenches.

improvement from our previous motor drive systems in Run 1A. We have had one catastrophic motor failure and had to replace one Mitsubishi Drive system after a lightening storm appeared to have damaged some open-collector transistors used for status. There have been no failures of an in-house built interface box used to connect the Mitsubishi drive to the new distributed control package.

KAUTZKY RELIEFS

The Tevatron uses a bellows operated relief valve, known as a Kautzky valve, on the single-phase, two-phase, and nitrogen circuits of the Tevatron magnet system. All circuits are relieved at 0.3 MPa. During the low temperature upgrade, the two-phase circuit of the system had to be made leak-tight, including the Kautzky valves. These valves now use a low pressure helium guard and a double o-ring configuration. A total of 250 valves were modified. We did not alter reliefs on the single-phase or nitrogen circuits.

These valves have a history of high failure rate. These failures generally occur in two ways. The first way is that something (a physical object like a loose screw) gets lodged in the valve and forces it to stick open. If the object cannot be dislodged the valve must be changed out at 20K or greater temperature conditions. The second common failure is that the bellows tears typically at its first convolution, and control pressure gas used to set the relieving pressure, cannot seal the valve. This problem is caused by repeated cycles of the bellows.[5]

Nothing that we did in the upgrade would explain the statistical differences seen between the two Runs. We did not change the bellows nor enhance the performance of these reliefs in anyway. Even more, the failures are normally single-phase Kautzkys as these experience the very high cyclical stress placed on them during quench episodes (see Figure 3 for average number of quenches). It is believed that we simply do "accelerator maintenance" on reliefs in a better way. That is, when the accelerator is down for scheduled maintenance we actively look for reliefs that may have a damaged bellows and replace as necessary. Doing this means we remove damaged reliefs before they catastrophically fail and cause accelerator downtime. It also means we have the same number of failures as in Run 1A, we just aren't causing unscheduled downtime because of them.

DISTRIBUTED CONTROLS

To reliably control all the old and new cryogenic equipment used in the Tevatron, it was necessary to upgrade our distributed control system. Fermilab engineers designed and installed a new system based on a Multibus II platform using Intel 80386 and 186 processors. Token ring is used as the link between 6 primary crates while Arcnet is used as a LAN between the primary crate and individual I/O crates located at each refrigerator or compressor building (there are 32 such buildings in the Tevatron). This control package has been detailed by Norris.[6,7]

In terms of actual downtime, the new distributed control system has been a success. In fact, it wasn't until the week of March 13, 1995 (the 66th week of the Run) that this control system accounted for any downtime.

The downtime listed in Table 1 is three separate events. Two of these events were related to a loss of communication from Token Ring to the 386 processors of the refrigerators. In both situations, the cryogenic system continued to operate properly because the communication from 386 to the local I/O crate was not disturbed. Only when rectifying the problem by rebooting the master crate and thus the Token Ring board did we encounter problems. Both cases were situations where software bugs were discovered on boot-up. These bugs have since been fixed. The third downtime event has been charged to our control system but may, in reality, not be a control system failure. During the week of April 17, 1995 we had a magnet JT valve suddenly step closed. This valve controls the flow through the magnet string of half of the house. This resulted in a quench. All other possibilities were pursued but an exact conclusion was never reached. This has been charged to the controls category simply because it is the most probable mechanism for such a valve action. Software has been upgraded to prevent such an occurrence in the future. This event accounts for over 71% of the distributed controls downtime. If you assume there was not a controls failure in this case the distributed control system downtime would be reduced to a total of 1.5 hours.

CRYO CONTROL/ELECTRONIC

The category of Cryo control/electronic was created to encompass all the electronics that is not a part of the distributed control system but is required to operate these systems. These devices include all types of cryogenic transducers, electric motor actuators with LVDT readbacks for power lead solenoids used to manipulate flow, plus many other monitoring and control devices.

As can be seen in Table 1 the total number of downtime hours is significantly higher in Run 1B. However this is only two downtime events. In the first case a tunnel valve had a damaged position readback and led to inaccurate valve positioning and finally a quench. This problem arose after work had been done in the same area as the valve so it is believed this work led to the problem. The second problem led to more serious work by the engineering staff.

A key element in the operation of a satellite is to maintain proper dewar level. This dewar is located between the refrigerator and the magnet single-phase and two-phase circuits. It acts to buffer the load from refrigerator upsets and the level of this dewar is an indicator of how well the refrigerator is performing overall. Liquid level is measured in 2 different ways, with a differential pressure measurement (DP) across the dewar and with a superconducting liquid level probe (LL). In the case of the downtime event, we were using the DP as a level measurement. Based on its value a control valve opens and closes adding liquid helium from the Tevatron's transfer line system. On this occasion the DP cell began to oscillate wildly causing growing instabilities in the dewar and finally a quench of the magnet strings. It was recognized early that this it is imperative to have adequate level sensing for refrigerator stability and protection of the IHI cold compressors. Ingestion of liquid droplets will at a minimum cause the cold compressor to trip on overload and potentially damage the turbo machine.

A lot of time was spent understanding our superconducting LL probe behavior. In the case above, we had been using the DP cells because we did not trust the signal the probes were giving out. After weeks of studies it was determined that the probes we were using were becoming noisy whenever a fill valve would spay liquid into the dewar. It was realized that the LL probe, which has holes along it's G-10 structure, could be rotated in a direction away from the spray to help it's performance. All of this work led to us putting a sheath around the probe and establishing small pin holes in the sheath. This simple idea has proven very reliable and has led us to sheath all 24 probes that we use. There has been no more downtime related to this control issue.

COLD COMPRESSORS

In January of 1994 the lab decided to continue Physics at 900 GeV and not pursue higher energies until later. That decision, plus a decision to limit the amount of compressors that were to be operated at the Central Helium Liquefier for budgetary reasons, limited how many cold compressors we could operate and at what speed. Therefore, the downtime category for the cold compressors is really not a true representation of what downtime rate we might have had we run at lower temperatures.

However it must be noted that we have put many hours on these machines. Beginning in January, 1994 we operated 3 to 5 cold compressors at all times to understand their behavior in quench conditions. During earlier power testing we discovered the cold compressors would sometimes trip when their exhaust side pressure was quickly elevated, as happens in a Tevatron quench. We found this could be controlled by changing the rate of which the IHI was allowed to change speeds. This testing lasted until August 1994.

In August 1994, the lab experienced a delivery problem with liquid nitrogen and was forced to go into an extended maintenance period. At this time we decided to install new journal bearings from IHI that could be operated at lower speeds (20,000 rpm instead of 40,000) that would cause less of a perturbation to the refrigerator on startup. From early September until April of 1995, we accrued >93,000 hours on these new bearing machines (the original bearings had accrued >27,000 hours). However during that period we experienced 3 machine failures, all experiencing bearing problems on startup. At this point these failures are not completely understood and Fermilab and IHI are working to resolve this issue.

INSTABILITIES

The instabilities' category is used to account for any downtime that isn't necessarily an equipment failure. This includes items such as unstable refrigerators, low warm compressor discharge, plugged cryogenic instrumentation used to measure magnet pressures, or human error situations.

In reviewing the statistics for this category it is apparent we suffer mostly from two failure conditions, both cold instrumentation. The first failure is a plugging of the capillary tubing used for sensing the single-phase pressure at the feedcan in the tunnel. This is the process variable the wet expander tries to maintain. Any partial plugging of this line and the refrigerator becomes unstable. The second instrumentation failure is similar to the first in that we have plugged instrumentation. In the Tevatron we use a differential pressure gauge to compare two-phase pressure and two-phase temperature (using a vapor pressure bulb). This reading is an indicator of the amount of subcooling in the magnets two-phase. If the pressure measurement tubing plugs we get inaccurate readings that cause magnet JT valves to be positioned inaccurately.

These two failures dominate this category of downtime and reinforce our need to have a clean helium system. During each period of scheduled long term maintenance we warm-up to 80K and purify the system to <5 ppm Nitrogen in Helium. See Figure 3 for the average weekly downtime of this category.

POWER LEADS

This category of failure has before this run been a constant problem. Our 5000 amp power leads require cooling taken from the single phase of our magnet strings. This flow can be selected to be three different flow rates depending on the energy of the machine. Solenoids are used to control pre-defined flow orifices and give the 3 ranges of flow. In Run 1A we spent a lot of time adjusting flows for various houses. This led to a significant amount of downtime. During Run 1B, we have had minimal downtime due to these lead flows. In fact, all of this downtime is related to special low beta quadrupole leads at the B0 and D0 interaction areas. There have been six total downtime entries.

FUTURE WORK

In late July 1995 we plan to continue low temperature testing with five days dedicated to understanding higher energy operation. This second test period should give us enough data to understand if and how we can achieve 1000 GeV energy levels. Until we accomplish this goal, engineering time will continue to be spent on perfecting the equipment we installed for this upgrade. Note, Run 1B is scheduled to continue until February 15, 1996.

CONCLUSION

We have shown during the last year and a half that a major cryogenic upgrade could be undertaken on the Tevatron without significantly altering the average downtime of the machine. Although lower temperature operation on a continuous basis is not yet a reality, this work and the reliability it has accomplished is encouraging to us and should offer others in the field encouragement about their success chances when the time comes for them to upgrade major cryogenic facilities.

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