CONTROL SYSTEM FOR FERMILAB'S LOW TEMPERATURE UPGRADE

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Abstract

Fermilab recently upgraded the Tevatron Cryogenic Systems to allow for lower temperature operation. This Lower Temperature Upgrade grew out of a desire to increase the Colliding Beam Physics energy from 900 GeV to 1000 GeV. A key element in achieving this goal is the new cryogenic control system designed at Fermilab and installed in 24 satellite refrigerators and 8 compressor buildings. The cryogenic improvements and addition of hardware like cold compressors exceeded the capability of the original distributed controls package. The new distributed controls package uses a Multibus II platform and Intel's 80386 microprocessor. Token Ring is used as the link to the systems 6 primary crate locations with Arcnet used as the connection to the systems numerous I/O crates. I/O capabilities are double the capabilities of the original system. Software has also been upgraded with the introduction of more flexible control loop strategies and Finite State Machines used for automatic sequential control, like quench recovery or cold compressor pump down.

I. INTRODUCTION

Since the fall of 1993, a new cryogenic control system has been operational in Fermilab's Tevatron accelerator. This control system was one of numerous upgrades to assist with the lowering of the Tevatron magnet temperature from the original 4.45K 2ϕ temperature to 3.56K. The need for a new control package was driven by the addition of a cold vapor compressor, the addition of instrumentation, and a need for upgraded software capabilities.

The project was broken into two parts referred to as Phase I and Phase II. Phase I resulted in the package being installed at each cryogenic site and operating with equivalent software to the old control system. Phase II is a period dedicated to enhancing the capabilities of the new controls system. These enhancements include imbedded software filters for analog channels used in control loops, development of multiple alarm scenarios for all devices, and ability to link real-time data to engineering software (for, example, helium property routines) to generate real-time cryogenic properties.

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II. REVIEW OF TEVATRON CRYOGENIC SYSTEM

The Tevatron and the Cryogenic System, initially commissioned in 1983, now consists of two large liquefiers known as CHL I and CHL II and 24 satellite refrigerators. These satellite refrigerators are arranged in six sectors, each comprised of four refrigerator buildings and one compressor house. Equipment in each satellite includes a series of heat exchangers, two expansion engines, a valve box/dewar package with connection to the magnet system, a cold vapor compressor, electric valve actuators and a large array of cryogenic instrumentation. Compressor buildings include four 480 volt soft starters, four 300 kW motors and associated screw compressors, oil pumps, a water pump, and a wide variety of electric valve actuators and instrumentation.

The satellite refrigeration system is supplemented with liquid helium and liquid nitrogen transported around the 6.5 Km ring via a transfer line system connected to the CHL complex. Control of the CHL complex is completely separate from the satellites and is not discussed here.

III. LOW TEMPERATURE OPERATIONAL COMPLEXITIES

The mechanism for lowering the temperature of the Tevatron magnets is, at first glance, quite simple (see Figure 1). The details and impact to overall reliability issues are quite complex.

The backbone of the temperature reduction is a cold vapor compressor. This is a centrifugal machine manufactured by IHI of Japan. It is a high speed, gas bearing turbo machine capable of a maximum speed of 95,000 rpm with flow rates varying from 40-70 g/s and a minimum inlet pressure condition of 0.4 atmospheres. This machine is driven by a 1.5 kW induction motor.

First, operating a turbo machine under these conditions is non-trivial. Control loop algorithms must be chosen and tuned properly so that conditions of overcurrent, stall, or surge are avoided. Understanding the control requirements of this machine and integrating it into our PID control strategies has been key to achieving reliable operations. Transient conditions, such as quenches, translate to high outlet pressures for all 24 turbomachines. Control loops are adjusted for this and automatic sequential programs turnoff the machines at the quenching house.

The cold compressor pumps on the gas head of a 130 liter dewar and must not be allowed to ingest liquid or liquid droplets as damage may occur if it does. Special control loops (fill valve and dewar heater) are required to maintain dewar level. Automatic sequential algorithms are running all the time to sense such upsets such as a dewar overfill and in such a case, the cold compressor is turned off and a bypass valve is opened.

Second, using these machines adds heat of compression to each refrigerator‘s cycle. This can only be overcome by using more liquid helium supplied to each refrigerator via CHL and the transfer line. Conservation of CHL liquid helium usage is imperative since overuse of liquid helium will effect our ability to maintain constant, reliable lower temperatures and, in return, not allow higher energy operation. It is vitally important that refrigerators are tuned well and efficiency problems are recognized early. These issues have led us to consider global tuning concepts and have required meaningful engineering units (efficiencies, mass flow) to be available in real-time to cryogenic engineers. Phase II of this project addresses those needs.

Third, using the cold compressor to pump down from the original 4.5K state to a lower temperature requires sophisticated control strategies. As we begin to pump down and the 2ϕ circuit gets colder, total refrigerator mass flow increases. If we make no corrections for this mass flow increase, we run a risk of running out of available warm compressor capacity and we also cause unnecessary pressure drop conditions leading to warmer magnet temperatures. This issue forces us to use complicated sequential programs in which we reduce the 2ϕ pressure and compensate for higher mass flows by simultaneously closing the Joule-Thompson valves on each magnet string. All of this must be accomplished while maintaining adequate liquid level in the refrigerator dewar, an indication of refrigerator stability.

These and other issues have resulted in the control system described here.

IV. CONTROL SYSTEM HARDWARE DESCRIPTION

The new control system has been developed in a six sector configuration identical to the layout of the cryogenic hardware. A Multibus II platform using Intels 20 MHz 80386 processor is at the heart of each sector’s system. Each Multibus II Crate can house as many as eight 80386's. A typical crate contains five processors, one for each refrigerator/compressor building in a sector. In the original Multibus I arrangement, each refrigerator/compressor building had a dedicated crate and processor which was interfaced to a CAMAC serial link.

The use of the Multibus II platform grew out of a project for an Upgraded Tevatron Front End [1]. Selecting this platform was based on having the right hardware and software people already in place to address the issues. The ability to easily interface to Fermilab’s existing integrated accelerator control system, and the need to design, build, and install a system in a very short time frame all led to the choice of this system. (The time period from initial funding request until completion of Phase I was three years.)

The main distributed network is Token Ring, connecting each sector’s Multibus II crate. Ethernet and a Tevatron Clock Event system are supported at each crate as well. Ethernet is used to communicate to an embedded DOS PC which is, in turn, used for system initialization and diagnostics. An example of Ethernet usage is to download default files for control loops onto a local hard-drive.

Every sector uses an Arcnet local area network to communicate to the I/O subsystems located at each refrigerator and compressor building. Each refrigerator has 2 I/O subsystems, a Cryogenic Thermometry I/O and a Cryogenic Device I/O. (Compressors only use Cryogenic Device I/O.) Each subsystem I/O uses an Intel 16 MHz, 80C186 processor to control all the activity such as settings and readings.

The Device I/O subsystem provides support for transducer input, valve actuator controls, automatic control for magnet relief valves, power lead digital control, vacuum gauge readbacks, and various motor driven devices such as expansion engines or cold compressors. The Thermometry I/O subsystem provides support for 96 channels of pulsed current, resistance Thermometry and also acts as a link to the Tevatron Quench Protection system (QPM). A summary of the total Device I/O and Thermometry I/O hardware capabilities is outlined in Table 1.

It was recognized in the early specification stages of this project that some support for data acquisition greater than a 1 Hz rate was necessary. Although most cryogenic processes are slow (seconds to minutes), entering into the age of higher energy and lower temperatures created a number of questions about transient conditions such as quench analysis and cold compressor performance during upset conditions. These transient needs spawned a “snapshot” 16.3 second wide circular buffer operating at 1 KHz and capable of handling up to 16 channels. It is triggered by a programmed TCLK event or a dedicated digital input wired at the refrigerator/compressor building. With this board we have been able to analyze quench behavior of Tevatron magnets and reliefs at lower temperatures and higher energies to study the mechanical soundness of our system.

V. SOFTWARE DESCRIPTION

The 80386 processor software is a three tier system [2]. The chosen operating system is MTOS. The intermediate tier is OOC++ and is used for supporting standard ACNET communication. The final tier is the data acquisition tier. The data acquisition tier will be described here.

Table 1. Summary of Tevatron Refrigerator Input/Output Capabilities. [1]

Card Type	Analog Capabilities	Digital Capabilities	Max No. of Cards per Refrigerator
A/D Board	64 channels, 10 volt, 12 bit	—	2
Actuator Board	1 A/D channel, 10 volt, 12 bit, plus 24 volt DC drive control and LVDT instrumentation	4 T^2L Status	35
Engine Board	2 A/D channels, 10 volt, 12 bit plus 1 DAC channel	3 Momentary relays and 16 optical coupled status bits	6
Resistor Board	96 channels, 10 volt, 12 bit	Link to TeV QPM	1
Vacuum Board	12 channels, 10 volt, 12 bit	—	1
Relay Board	—	8 Latching relay and 8 T^2L status	4
Digital Board	—	30 T^2L Status	2

1 The difference in the compressor I/O is a special board interfaces to the oil injection slider valves and Thermometry is not used.

The data acquisition tier of the 386 processor consists, in itself, of three layers. The first layer is a set of device drivers each built to support ACNET messages to that specific device. Types of messages include reading, setting, reading a setting, basic status, basic control, and both analog and digital alarms. With this layer we communicate to standard ACNET pages used for parameter display and application programs used for real physical control of equipment. The second layer is used as the primary control feature for cryogenic valves, engines, cold compressors, and motors. This layer is our closed loop control. Console applications allow cryogenic engineers to interface to this layer and effectively tune each cryogenic component. This second layer supports all combinations of PID control, operates at 1 Hz, and is set up so that each cryogenic loop is de-coupled from all others. As many as 32 control loops per house are supported.

The final and most powerful layer is the Finite State Machine layer. This software is used to handle routine procedures such as automatic cooldown, quench recovery, and cold compressor pump down to lower temperatures. These FSM's are coded at the console application level by Cryogenic engineers and then downloaded as necessary. There are 32 FSM's presently supported per refrigerator house. As will be described in the Phase II portion of this paper, FSM's are being used to expand our capabilities and make our system more flexible.

VI. PHASE I - INSTALLATION AND COST

The entire cryogenic control system had to be installed and made functional in a period from June 1, 1993 to Oct. 1, 1993. This included all refrigerators and the majority of compressor buildings. (Redundancy in compressors allowed us to do them at a slower pace.) This was a successful effort done by a combination of Accelerator Cryogenic and Accelerator Controls people. After initial installation, the month of October was used to shakedown system bugs. A significant amount of effort was required on the software end. By November, 27 new nodes were fully operational. Since that time, the remaining compressor houses have also been converted to the new scheme.

The total project cost for Phase I was approximately $2232K. The breakdown for this cost is as follows:

Salaries & Fringes		1158K
Administration	23K	
Hardware	857K	
Software, Micro	185K	
Software, Applications	93K	
Cards, connectors, electronic components		542K
Enclosures, panels		109K
Multibus II crates, PC boards, assembly		187K
Electrician Labor		118K
Miscellaneous		118K

VII. PHASE II

Initially we felt it was too ambitious for us to attempt implementing entirely new control software that was not absolutely necessary. Phase II, which is an on-going project, was established to pursue to new specialized needs (mainly software oriented tasks). Although work continues on this phase, we have defined and begun implementation of a few of these new capabilities. These features include: 1) creation of software filters for use as control devices within loop algorithms, 2) creation of a mechanism to allow for multiple alarm states that are a function of the actual state the Tevatron Cryogenic System is in, and 3) the ability to link real time data to specialized engineering software to create, for example, thermodynamic or fluid calculations.

Filtering software has been created with two types of programmable filters, smoothing and Butterworth. These filters are created as a database device and defined via an ACNET application page. Filters can be used for process variable readbacks, analog output board settings, and readings for output devices such as motor or expander driver cards. All of these can be used in our normal control loop algorithms. Filters can be set, read, plotted and alarmed.

In an accelerator magnet cryogenic system it is quite often necessary to operate the system different than the steady state, powered condition. Events such as quenches, cryogenic maintenance, and shutdown periods make it necessary to handle temperature variations from 3.5K to 300K. This also requires a flexible alarm strategy. Until Phase II work was started, each cryogenic device had one alarm block associated with it (the operating state). In periods of non-operations, these alarms are sometimes masked and become useless. Created in Phase II is an automatic alarm strategy that understands the state a device is in and points to one of many alarm blocks residing in a tabloid on the refrigerator processor. A Finite State Machine is running on each refrigerator processor that determines which alarm state devices should be in. This alarm message, and messages for all refrigerator processors, are passed to a dedicated front end (Micro VAX that is referred to as a Virtual Machine Front-end) that checks the message for correctness, and then reflects back to a device resident in the refrigerator processor. This device, in turn, points to the proper alarm block. The Virtual Machine FE was used as a method for approaching global needs, such as disabling of the process or automatically choosing a specific alarm block independent of what a Finite State Machine is doing.

Another new feature is the ability to create real devices that have more meaningful engineering units. An example of this is helium mass flow in a refrigerator. It is typical in cryogenic systems to use a venturi that measures pressure drop as a measure of mass flow. Engineers find themselves using units that are mixed and not real meaningful to their system, e.g. In w or psid. If enough instrumentation and cryogenic fluid properties exist, more meaningful units (to a cryogenic engineer) such as grams/second (or efficiencies) can be calculated. To accomplish this goal, we purchased “HEPAK” source code for helium properties from Cryodata, Inc. and are running it as part of a process named GLFRIG on a Micro VAX. This process can poll each refrigerator node every 2 seconds and provide data to console applications via a RETDAT process. The uses of this mechanism are enormous. It makes operating and diagnosing this system much easier and it allows us to start thinking in terms of global controls for overall refrigerator and compressor tuning. For example, at present an operator determines whether he has too little or too many 300 psig compressors operating. It takes daily attention and leads to us not optimizing our compressor usage. If we operate one compressor too many, we cost ourselves about $150,000 over a year. These new control features should help us with issues of these sorts.

VIII. RELIABILITY

As stated earlier, completion of Phase I for 27 nodes was finished by November 1, 1993. On December 15, 1993 Colliding Beam Physics Run 1B began and is scheduled to continue until July 24, 1995. Accelerator downtime is tracked in an effort to understand problem areas. Since the beginning of this physics run the cryogenic control system has been charged with three hours of downtime occurring in a total of three events. This accounts for 2.5% of the total downtime charged to Cryogenic Systems. Two of the downtime events were caused by a loss of communication to a 386 processor and the third was a bad power supply in a Multibus crate. Other minor problems have occurred with I/O boards but none has led to an interruption in the physics program.

Besides the work on-going with Phase II, Fermilab controls personnel continue to work on problem areas of the design. Loss of communication via Token Ring has been one of two continuing problems. Because of the ability to continue local control of cryogenics during a Token Ring problem we have been able to survive numerous loss of communication situations. Controls personnel continue to work on this problem. The second continuing problem is a lack of reliability with Ethernet downloads. The problem has caused us the inability to download default files at times from a console. This reliability problem as well as a desire on our part to automatically update our default files on a daily basis are also being worked on.

IX. CONCLUSION

A new distributed cryogenic control system has been fully operational since November 1993. This system was specified, designed, built, and installed by Fermilab Controls and Cryogenic personnel. The system has operated well throughout Colliding Beam Physics Run 1B, having been responsible for only three hours of downtime over a 18 month period.

This new system has given the Cryogenic system personnel much more flexibility than the original package. Hardware capabilities are double that of the original system and it has added such features as snapshot circular buffers to study transient conditions related to Low Temperature Operations.

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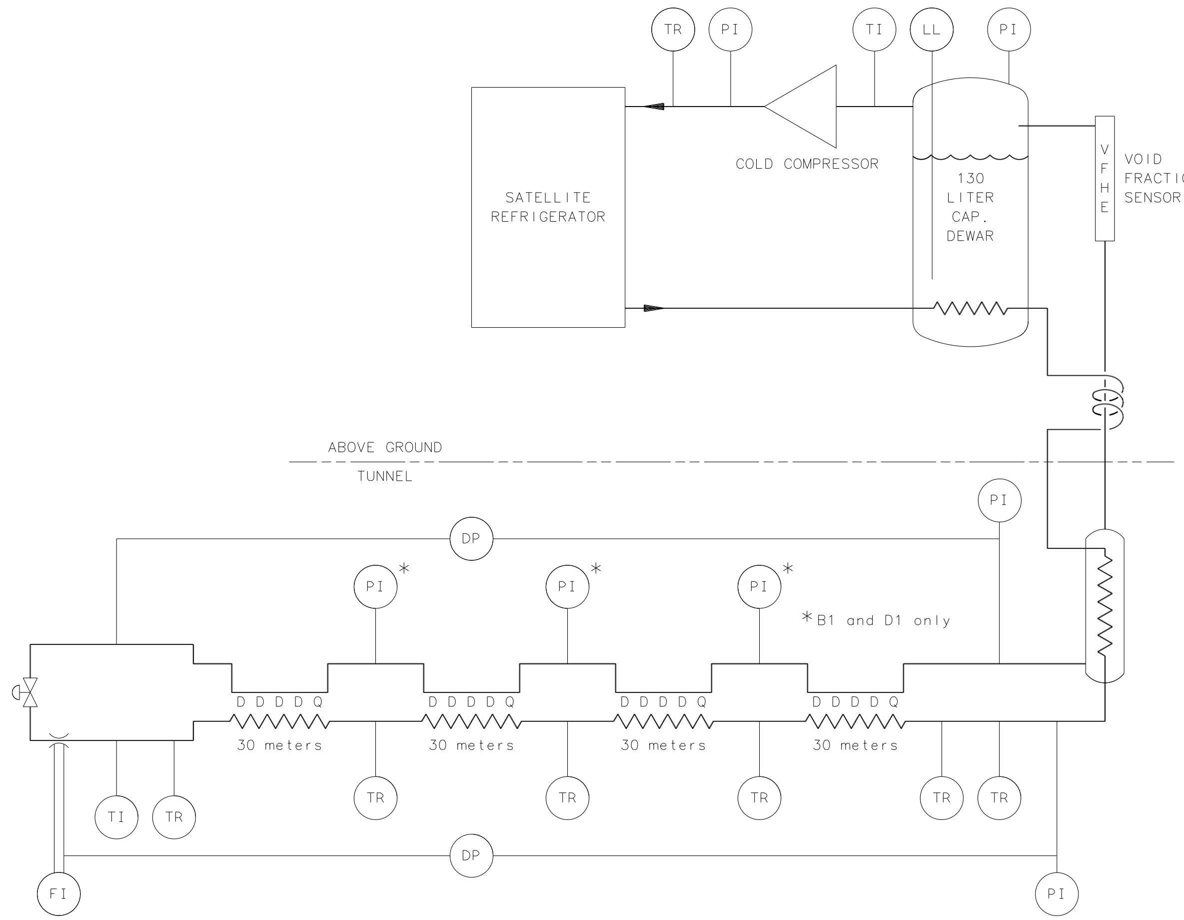

Figure 1: Satellite refrigerator layout after low temperature upgrade
Note: Only half of magnets shown (D=dipole magnet, Q= quadruple magnet)

Software capabilities have been enhanced by adding more flexible PID control strategies, more versatile alarm blocks, and a method for creating real-time thermodynamic properties.

This control system has played and will continue to play a heavy role in Fermilab achieving higher energy operation.

XI. REFERENCES

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