Fermi National Accelerator Laboratory

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NEW CRYOGENIC CONTROLS FOR THE TEVATRON LOW TEMPERATURE UPGRADE

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INTRODUCTION

Fermilab's Tevatron accelerator is undergoing a major cryogenic system upgrade. This upgrade project is necessary to lower coil temperature of the accelerator's magnets by approximately 1K. The new system configuration utilizes a new valve box containing a 130 liter subcooling dewar and a Cold Compressor at each of the 24 satellite refrigerators. Each Cold Compressor pumps on a dewar to maintain the two-phase pressure at 50.7 kPa (0.5 atm) producing 3.56K helium in the dewar and magnet strings.

The valve box and cold compressor installations, coupled with the need for new wet expander controllers and the addition of a significant amount of instrumentation, forced the immediate need for additional cryogenic control capabilities, which could only be met by major hardware and software upgrades.

The additional requirements of the new cryogenic system doubled the number of I/O terminations per satellite,[1] exceeding the capability of the original Multibus I, Z80-based distributed controls package. The original controls package,[2] although highly successful over the last 10 year period, had already reached the upper limits of its capabilities with the many previous changes the cryogenic systems had undergone (i.e., Low Beta Magnet installations). The need for more digital and analog hardware, along with the desire for further control loop and automated controls features guided the new design.

CRYOGENIC CONTROLS OVERVIEW

The Tevatron Cryogenic Control system is required to control 24 satellite refrigerators and eight compressor buildings (each compressor building containing four, 298 kW (400 hp) Mycom compressor packages). This system is distributed over a 6.0 Km area and is required to be controllable from remote control room areas and be easily operated in the local environment. Cryogenic instrumentation is quite expansive, so that on the order of 700 data points must be readback at each of the refrigerators. Data acquisition is required at the rate of 1 Hz for all data. Each of the refrigerator and compressor buildings operates relatively free of human intervention as special PID loop control software has been developed for these systems. These control loops are easily modified and updated by the operator at a console level. Automatic operations are further improved by the use of specialized finite state machine software to automatically cooldown a refrigerator and string of magnets from room temperature or to recover the house after a quench occurrence.

* Operated by Universities Research Association, Inc. Under contract with the U.S. Department of Energy.

New Controls System Hardware

The new distributed controls package uses a Multibus II platform and Intel's 32 bit, 80386 microprocessor. This arrangement was selected because of previous use on Accelerator Division front end computers.[3] It was realized early in the development stage that 90% of the existing cryogenic hardware (valve actuators, motor controls, etc.) would remain intact and thus a substantial amount of hardware and software could be replicated for the new architecture.

The Tevatron Cryogenic System is a ring built into six sectors, each containing a minimum of one compressor building and four satellite refrigerators. Due to the need for extra compressors, two sectors have an extra compressor building. Also, various refrigerators not necessarily an active part of the Tevatron Cryogenic system use the same controls, and are piggy-backed onto the Multibus II system.

The new controls were partitioned into six sectors, following the same physical layout of the cryogenic system. This is a significant difference from the original system, in which each satellite and compressor system had its own Multibus I crate. In the new design, each Multibus II crate houses every 386 single board computer needed for a sector (five typically; four refrigerators and one compressor). One Multibus II chassis can support as many as eight 80386's.

The Multibus II system is beneficial in that it interfaces well with the ACNET control system used at Fermilab. Here, Token Ring is used as the link between Multibus II crates of different sectors. Two other services, Ethernet and a Tevatron Clock system, are supported as well. Ethernet is used as an interface between ACNET and an embedded DOS PC for each crate. This embedded PC is used for system initialization and various diagnostic tools. Downloading of refrigerator defaults parameters for control loops is a prime example of Ethernet usage.

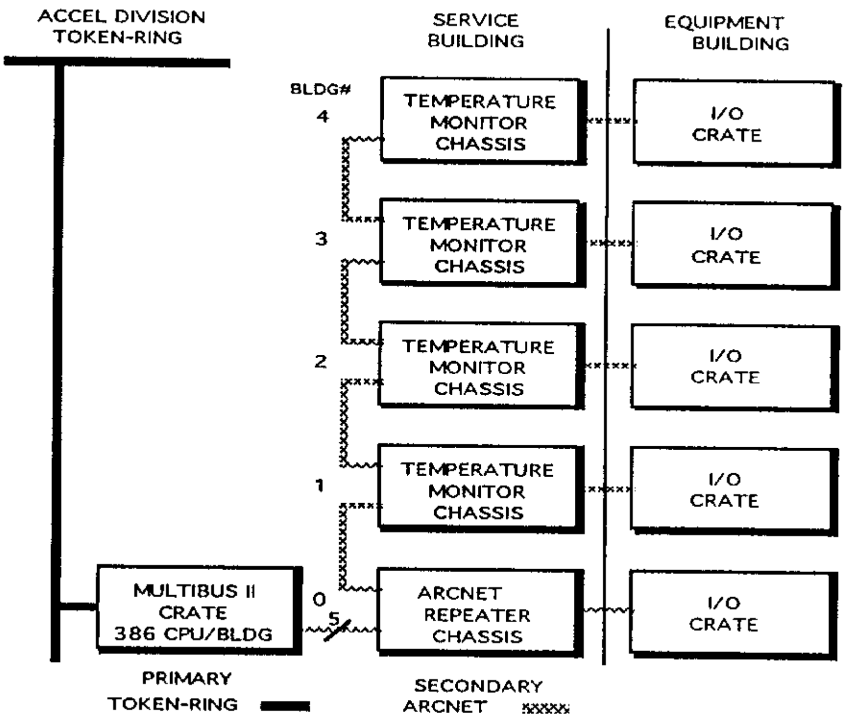

Figure 1. Cryogenic controls network

Each sector is designed so that it operates as a small local area network using Arcnet technology with each having a Multibus II/Token Ring interface located at Compressor buildings. The Arcnet system is used to communicate to two I/O subsystems per refrigerator building, a Cryogenic Thermometry I/O and a Cryogenic Device I/O. (Compressors only use Device I/O). This network, as shown in Figure 1, provides the needed communication link for the entire sector. Arcnet, established via coax, can support as many as 255 nodes and operates at a 2.5 Mbit/second data rate.[1]

Each of the Thermometry I/O and Device I/O subsystems uses a 16 Mhz Intel 80C186EB as a processor for I/O. This processor controls all of the activity within the subsystem crate such as device settings and readings. In the case of the Device I/O subsystem, this processor also provides fast data logging facilities, Tevatron clock decoding abilities, and an Arcnet interface. The Device I/O crate layout is shown in Figure 2.

The Device I/O subsystem provides support for transducer input, actuator valve 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.

A special feature requested by the Cryogenic Department was to incorporate the use of a high speed data acquisition service for obtaining snapshot data during triggered events. This controls scheme allows data collection of as many as 16 channels for a 10 second period at a rate of 1KHZ. Each refrigerator or compressor house can have its own dedicated trigger established via digital input channels or Tevatron clock events. This circular buffer can be used to study such items as the dynamics of high field quenches or of cold compressor operations.

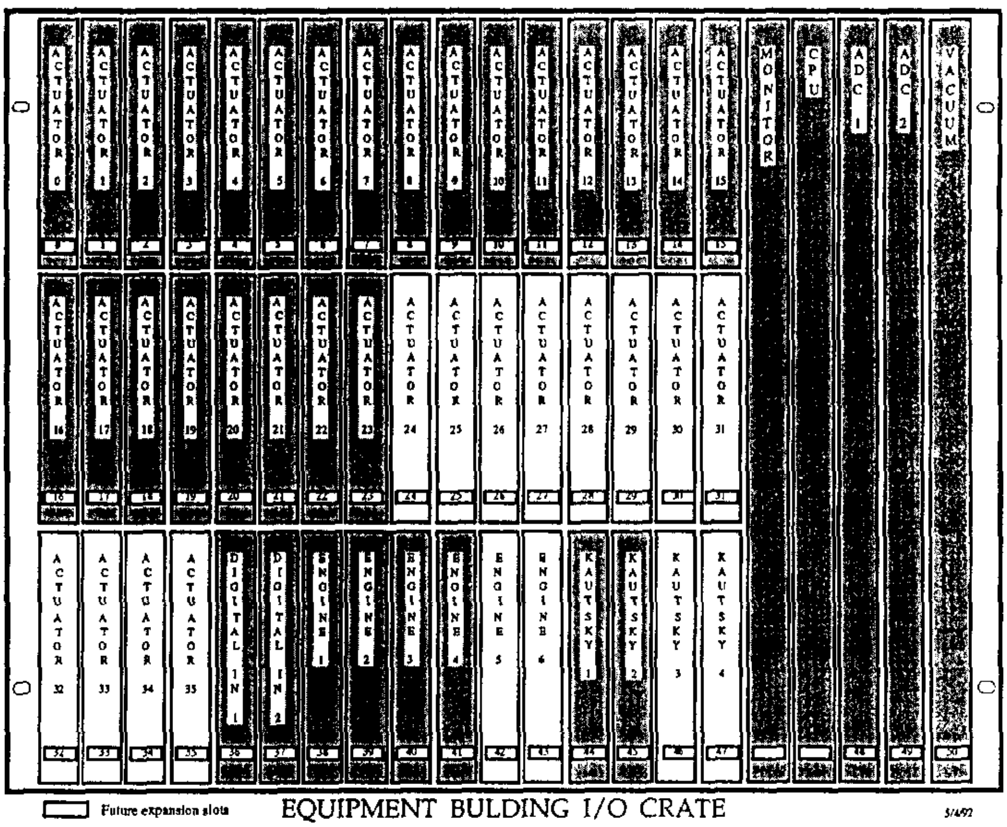

Figure 2. Device I/O crate layout.

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	—	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 was designed to interface to the oil injection slider valves and Thermometry is not used.

Cryogenic Software

Two very powerful sets of software are written for the operator of the Tevatron cryogenic systems: specialized loop control and finite state machines (FSM's).[4] Each of these is supported with a VAX application to allow interaction at a console level between any operator and any refrigerator or compressor.

The loop control presently supports as many as 32 loops per building (easily increased if needed), an increase of 12 over the original system. This software is written to establish any combination of classical closed-loop PID control or open-loop control. The software operates at 1 HZ. Using this software, cryogenic parameters such as pressure, temperature or liquid level are easily controlled via output devices such as valves, engines, or cold compressors. Loops may be tuned or altered by an operator changing any or all variables via the VAX application page.

The FSM software is the highest level of software in the cryogenic control system. It is used for creating sequential cryogenic control algorithms to handle such conditions as quench recovery or cooldown from ambient temperature. Each system presently supports 32 FSM's, an increase from the original systems 15, each of which can contain 16 states. As in the case of the loop software a VAX application was written to allow operators to program their own algorithms.

EXPANSION ENGINE CONTROLLERS

The lower temperature satellite refrigerators contain a liquid expansion engine, a gas expansion engine, and a cold compressor package. Each of these machines is motor driven and requires a special controller/motor for its specific application.

Liquid Expansion Engine

The Tevatron Wet expander used in the upgrade requires a mechanism for continuously braking the expander and a method for accurately controlling its speed to achieve a specified flow of liquid for cooling. In the past, a regenerative DC motor/generator system has been used on both the liquid and gas expansion engines. These DC machines required significant maintenance, e.g., motor brush replacement and controller board failures. One significant problem with the original controllers was that regenerative power was dissipated through resistors internal to the controller and thus generated a significant amount of potentially damaging heat. These headaches, coupled with the fact that the new cryogenic system configuration needed a 5.6 kW (7.5 hp) wet expander rather than the original 1.5 kW (2 hp), led to our pursuit of a new controller/motor device.

The new wet expander controller is an AC Variable Frequency Drive with a regenerative unit made by Mitsubishi. This arrangement resides in two separate chassis, the FREQROL Z300 Transistor Inverter and the FREQROL RC Regenerative Converter Unit. This package is rated at 5.6 kW (7.5 hp), 480 volts, and controls the speed of an AC 3-phase induction motor that is the main expander drive/brake. The regenerative unit takes advantage of the expander being overdriven by the cryogenic process and stores that energy in a DC bus system. When the DC bus is fully charged, the system converts DC to AC and synchronizes itself with the incoming power.

This controller package uses Insulated Gate Bipolar Transistors (IGBT's) that switch at 15 KHZ. This high frequency switching reduces the audible motor noise, since this frequency is at the upper limit of human hearing. Pulse width modulation control is used to achieve a speed accuracy to within 1% using a slip compensation feature. The unit is extremely versatile in that 80 user programmable parameters may be entered through a touchpad interface called a Parameter Unit. Alarms, digital I/O and other operations may be programmed from this unit.

To thoroughly instrument the Z300 we designed a separate electronic package as an interface between the motor controller and our device I/O subsystem. This package incorporates the use of Xilinx Field Programmable Gate Array (FPGA) technology and allows the user to monitor 16 digital outputs, manipulate the start, stop, reset functions of the unit and control/monitor the speed of the AC motor from 0-1750 rpm.

Before investing into this technology a prototype unit was operated at the BR test refrigerator in the same configuration it was to be used in the TeV. This test lasted for a 10 month period with virtually continuous usage. There were no known failures of the Z300 or the Regenerative Brake Unit. One negative aspect of this setup is that the transistors operating at 15 KHZ generate a significant amount of electrical noise. Special attention has been given to the cabling of the actual installation. Power line filters have been used to guarantee clean power returned to the 480 volt, 60 Hz feeder.

Dry Expansion Engine

The new gas engine is only used in emergency conditions or as a supplement to the liquid drawn from the Tevatron Transfer line system. Since it is less critical, we are re-using the original 1.5 kW (2 hp) dc controller previously used on the wet expanders.

This 30K gas expander uses a General Electric 6V7F3229 Speed Variator to regulate outlet temperature. This controller was modified to incorporate safety interlocks for overspeed, emergency flywheel brake, emergency stop button, and power reversal (should the controller drive the flywheel/piston assembly). Motor speed is controllable from 350 rpm to 1800 rpm and the machine can be stopped, started, and reset either remotely or locally.

Cold Compressor

The centrifugal cold compressor unit being used in the upgrade is manufactured by Ishikawajima-Harima Heavy Industries (IHI).[5] This turbo machine is driven by a small 1.25 kW (1.68 hp), 208V, 3-phase induction motor. A Toshiba inverter controller was incorporated into a control package developed by IHI under specification by Fermilab, and the package was provided as part of the cold compressor contract. This unit was built to easily interface to the new Device I/O boards. Remote and Local operation allow for stop, start, reset functions, and speed controls up to a IHI physical limit of 95,000 rpm.

As an added feature a special board was built and FSM software was written to help protect the IHI machine. The board is used to automatically open a cold compressor bypass valve each time the cold compressor is turned off (for whatever reason.) This same bypass valve will close upon cold compressor turn-on after a small time delay. FSM software, running continuously, will automatically turn off the cold compressor should a quench occur or if the dewar that the IHI is pumping on overfills. These safety features are intended to limit the probability of the IHI turbo having liquid or 2-phase helium at its intake.

New Cryogenic Instrumentation

A significant amount of instrumentation was either added or modified for the upgrade. The new valvebox was instrumented in much more detail than the original[2], and the operations at lower temperature forced modification of the 2-phase circuit for subatmospheric operation.

Figure 3 outlines the basic layout of each satellite refrigerator highlighting the new or modified instrumentation included in this design. Table 2 summarizes the additional devices in terms of manufacturer, range and purpose.

It should be noted that no additional instrumentation is added at compressor buildings at this time.

Table 2. Summary of instrumentation changes.

Tevatron Pneumonic	Manufacturer, Range	Subatmospheric[1]	Process Measurement
PI11	Setra, 0-0.34 MPa (0-50 PSIA)	Yes	Cold Comp. Inlet Press
PI16	Setra, 0-0.34 MPa (0-50 PSIA)	Yes	Upstream 2-phase Press
PI19	Setra, 0-0.34 MPa (0-50 PSIA)	Yes	Downstream 2-phase Press
DP16	Setra, 0-34.4 kPa (0-5 PSID)	Yes	Upstream 2-phase Diff Press
DP19	Setra, 0-34.4 kPa (0-5 PSID)	Yes	Downstream 2-phase Diff Press
DP11	MKS, 0-1.24 kPa (0-5 in W.C.D)	Yes	Dewar Diff Press
PI3	Setra, 0.1 MPa-0.27 MPa (0-25 PSIG)	No	Exchanger Shell Out Press
PIEX	Setra, 0.1 MPa-0.27 MPa (0-25 PSIG)	No	Wet Engine Exhaust Press
PICX	Setra, 0.1 MPa-0.27 MPa (0-25 PSIG)	No	Cold Comp Exhaust Press
FILH	Setra, 0-12.4 kPa (0-50 in W.C.D.)	Yes	CHL LHe flow to Dewar
TISH	Setra, 0.1-0.79 MPa (0-100 PSIG)	No	Dewar Subcooler Out temp
TICI	Setra, 0-0.69 MPa (0-100 PSIA)	Yes	Cold Comp Inlet Temp
DT16	Setra, 0-34.5 kPa (0-5 PSID)	Yes	Upstream Outlet Superheat
DT19	Setra, 0-34.5 kPa (0-5 PSID)	Yes	Downstream Outlet Superheat
FI12	Setra, 0-24.8 kPa (0-100 in. W.C.D.)	No	Wet Engine Inlet Flow
FI3	Nice, 6.10-48.8 m/s (20-160 FPS)	No	Exchanger Shell Side He Flow
LL11	Cryomagnetics, 0-0.89 m (0-35 in LHe)	Yes	Dewar Liquid Level
TREX	Allen Bradley, 18Ω, 1/8 W carbon composite resistors	No	Wet Engine Exhaust Temp
TRCX	Allen Bradley, 18Ω, 1/8 W carbon composite resistors	No	Cold Comp. Exhaust Temp

1 All subatmospheric devices excluding LL11 are delivered to Fermilab with deformable metal gasket fittings and all-welded internal construction.

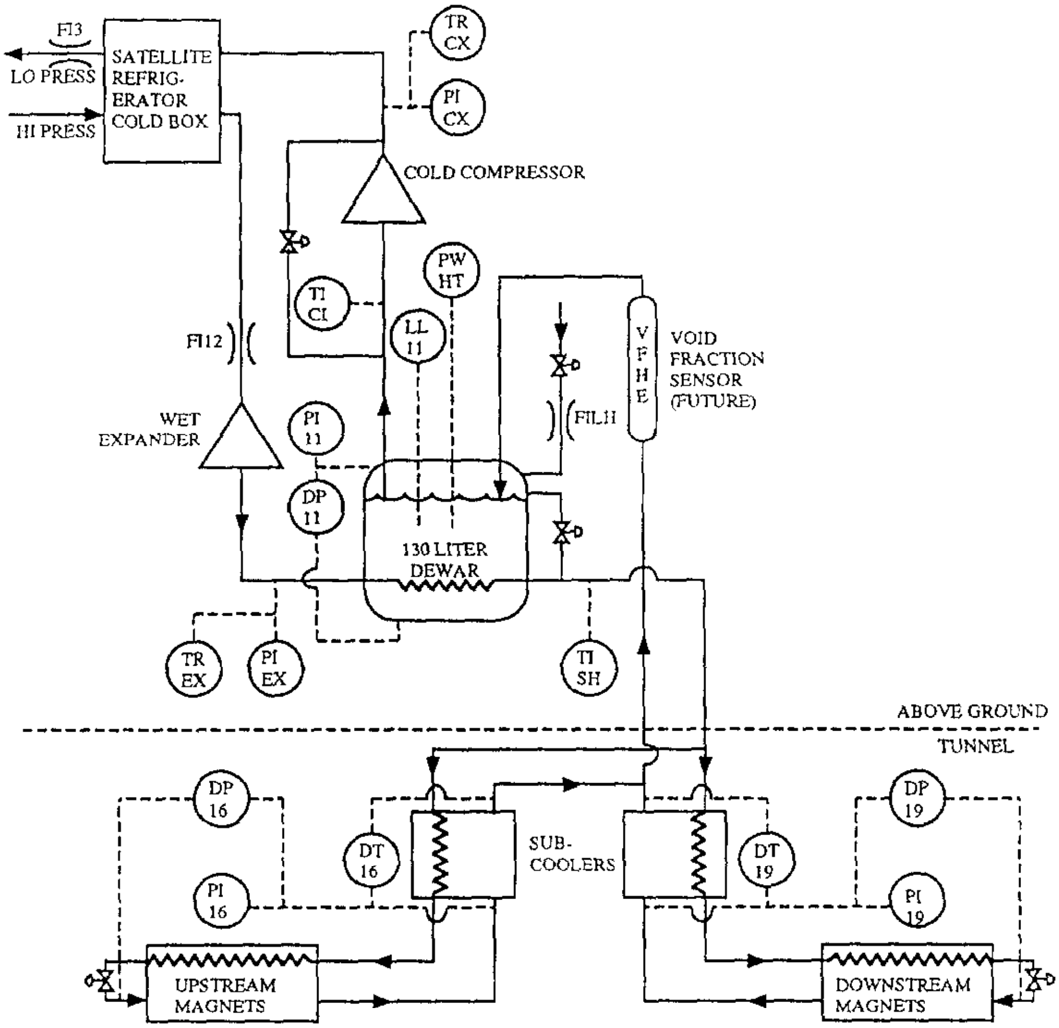

Figure 3. New or modified cryogenic instrumentation.

CONCLUSION

The Tevatron Low Temperature Upgrade has led to a major control system modification including a new distributed control system, new motor controllers and significant changes to the refrigeration instrumentation. This new controls' package will allow the Tevatron operators the ability to monitor and control the new TeV equipment in a very precise manner. Expanded software and hardware will allow for any future changes to the cryogenic system while maintaining the present reliability.

Additions such as the circular buffer hardware will provide engineers with an on-line tool for analyzing dynamic problems, and provide insight to some interesting cryogenic questions.

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