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W.W. Craddock, A. Angelov, P. L. Anthony, R. Badger, M. Berndt,
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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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W.W. Craddock, [1] A. Angelov, [1] P. L. Anthony,[1] R. Badger, [1] M. Berndt, [1]
W. Burgess,[1] A. Candia,[1] G. Oxoby,[1] C. Titcomb[2]

[1]SLAC, Stanford, CA 94309, USA
[2]Descon Engineering, Walnut Creek, CA 94596 USA

ABSTRACT

The BaBar 27 MJ superconducting solenoid and 1000 W helium liquefier at the Stanford Linear Accelerator Center (SLAC) have been operating with high reliability since October 1998. The control system consists of two Allen Bradley SLC 500/4 PLC controllers and two Windows NT PCs running BridgeView as the Graphical User Interface (GUI) all connected via a common Data Highway Plus network. A third 500/4 PLC and PC have been recently added to the network, integrating control of a second compressor system that is used with another helium liquefier. Separate hardwired protection systems for both the solenoid and liquefier are provided. All GUI screens are viewable over the Web. Operating, upgrading and commissioning experience of this control system is discussed. Control system hardware, software technical performance, and instrumentation and wiring issues are detailed. Operator interaction issues are also included.

INTRODUCTION

A 27 MJ, 5000 A, superconducting thin solenoid [1,2] cooled by a 1000 W helium liquefier [3,4] is part of the PEPII/BaBar Detector, SLAC's primary experiment. The BaBar solenoid, helium liquefier, and compressors are controlled by an Allen Bradley (AB) SLC 500/4 PLC based system. BridgeView (BV), a National Instruments product, running on Windows NT PCs serves as the Graphical User Interface (GUI) that is viewable but not controllable over the Web. All PLCs and PCs are connected via a local Allen Bradley Data Highway Plus network. Separate hardwired circuits protect the liquefier and solenoid.

HISTORY

A Linde model TCF 200 helium liquefier originally intended for the SSC quadrupole program was completed to SLAC's requirements. No control system work had begun when SLAC obtained ownership of the liquefier. Linde provided the logic diagrams, PID control loop diagrams and on site help during commissioning for their liquefier. Allen-Bradley PLC hardware with Rockwell Automation software was selected for the control system based on reputation and its ability to communicate with BaBar EPICS [5].

The SLC 500/4 PLC model was chosen based on cost and acceptable performance. A more powerful and expensive Allen-Bradley PLC 5 processor family was initially considered. However, the SLC 500/4 has proven to be more than adequate for our needs. The Central Helium (compressor) Facility (CHF) is located ~ 400 meters from the liquefier. Since an inadequate number of existing cables ran between the two locations, a second SLC 500/04 unit was added at the CHF as a communication node. All the logic was to reside on the main PLC unit with only I/O connections to be on the CHF PLC. Since then, all compressor control and monitoring for BaBar has been moved or will be moved to the CHF PLC 2. A CTI 4000 helium liquefier that was used for the SLAC's, now deactivated, SLD experiment (Final Focus Quadrupoles) was moved to accommodate the E158 experiment and other fixed target experiments. An additional SLC 500/04 PLC unit (PLC 3) was installed in the CHF for control and monitoring of this compressor system. Although PLC 2 is more than adequate to handle all CHF control and monitoring, the additional PLC permits any hardware, software or rewiring modifications to the CTI 4000 system without jeopardizing BaBar operations. TABLE 1 lists the modules and I/O signals in the three PLC systems. Two 400 HP Sullair compressors or one 800 HP Sullair compressor can be valved into either of the two liquefier/compressor systems.

BridgeView is essentially LabView with the added ability to communicate with PLCs. BridgeView was chosen since it was the only package at the time that provided Internet capability with a PLC, and SLAC has a large number of LabView users. BridgeView includes historical trend plotting, data archiving, and alarm panels. Significant problems were initially encountered because of bugs in the first release version 1.0. Only minor problems are now encountered with our current version 2.1.1.

As part of the BaBar collaboration, INFN designed the solenoid and was responsible for its procurement. Ansaldo completed magnet design details and manufactured the solenoid. Ansaldo provided a magnet control system very similar to the ones they built for the Zeus solenoid at DESY and for other superconducting magnet systems. The VME based system used an OS-9 operating system. It was written in C and had individual Siemens PID controllers. It was felt that using Ansaldo's existing control program was the fastest route to testing the magnet in Italy and then commissioning it at SLAC. Six months after commissioning the INFN/Ansaldo solenoid, the VME/Siemens PID controller portion was replaced with AB hardware and a dedicated PC with BridgeView.

Converting the programming logic from C code into Rockwell Software RSLogix ladder logic was relatively easy. It was imperative that this change be made to simplify long-term operations and maintenance and to provide for online program modifications without having to turn off the solenoid. Ansaldo's hardwired interlocks, fast data acquisition, and slow scanner data acquisition hardware were all retained.

TABLE 1. PLC configuration and current I/O channel count

MODULE	PLC 1 Modules	PLC 1 Channels	PLC 2 Modules	PLC 2 Channels	PLC 3 Modules	PLC 3 Channels
Analog Input 4 ch & 8 ch	3 & 0	5	17 & 0	68	0 & 1	3
RTD and resistance 4 ch	1	0	8	27	0	0
Analog Output 4 ch	1	3	11	35	1	3
Digital Input 16 ch	1	6	6	86	0	0
Digital Output 16 ch	1	15	3	14	1	0
TC & mV 8 ch	1	3	0	0	1	0

Descon Engineering in Walnut Creek, CA assembled the PLC controls system, converted Linde and Ansaldo logic into ladder logic, and completed a large portion of the initial BV programming. This was a fast and cost effective way to proceed since we had no previous PLC controls experience.

LIQUEFIER/MAGNET CONTROL SYSTEMS

The BaBar liquefier and magnet are controlled with a single Allen Bradley, sixty slot, SLC500/04 (PLC 1) system programmed with RSLogix version 4.1.0 ladder logic. The SLC 500/04 direct address limit of 30 slots is extended to sixty by using AB 1747-ASB Remote I/O Adapter Modules and 1747-SN Scanner Modules. Four Windows NT PCs are located in the liquefier control room. PC 1 and PC 2 are dedicated to the BV magnet and liquefier/compressor displays. PC 3 is dedicated to online RsLogix modifications, and direct PLC liquefier/magnet monitoring and control. A fourth PC is used for occasional local magnet power supply control and monitoring via SLAC's "X Windows accelerator" Control Program (SCP). Another PC in the CHF is dedicated to the CTI 4000/compressor system BV and RsLogix control. The CTI 4000 liquefier is controlled locally by BridgeView and DAQ boards on a Windows NT PC. All PCs with the exception of the CTI 4000 PC and all SLC 500 PLCs are linked by Allen Bradley's hardware and software Data Highway Plus (DH+) network. Each PC is connected to the DH+ network by an AB 1784-KTX communication card and Rockwell Software RSLinx version 1.73 device driver.

The original VME magnet control system used an HP 34401A multimeter and an HP 3852A data acquisition scanner module to record 80 analog signals. This hardware was preserved in the new control system with the signals monitored by the magnet BV system through a GPIB interface. BridgeView controls the data acquisition process of the two HP units via the same GPIB bus. BridgeView commands open and close scanner channels and select multimeter settings. Strain gage values are measured as a four-wire resistance with fixed current by the multimeter. Care must be taken to ensure that BV GPIB multimeter commands select the correct resistance range so that the carbon glass resistors (CGR) are not heat damaged. BridgeView on PC 1 transforms the cryogenic linear temperature sensor (CLTS), strain gage and CGR thermometers values from the multimeter into engineering units. CLTS conversion is two part piecewise linear fit, and strain gauge conversion is linear with a cubic polynomial temperature correction. Chebychev polynomial curve fits are required for the CGRs. Substantially more effort was required for BV programming of sensor conditioning and GPIB control than was required to convert the magnet control logic in C to ladder logic. Several signals used for cryogenic control or critical monitoring were switched to a more reliable PLC input. The SLC 500 control system now consists of 100 direct digital I/O and 130 analog I/O channels in addition to the 80 analog signals from the slow scanner into the PC 1 BridgeView system. FIG 1 is a block diagram of the entire control system.

LakeShore 231 transmitters linearize the four wire Si diodes. 16 Ω resistors are added in series with the 100 Ω (3-wire) platinum RTDs to extend the 73 K lower range of the RTD input modules at five channels. Almost all PLC analog inputs are 4-20 mA. All AOs, DOs and 24 VDC power have easily removable fuses. This has proven to be a key feature when valve position must be guaranteed. All DOs are buffered with relays. All RsLogix PID controllers have limiting ramp rates and set point ramp rates.

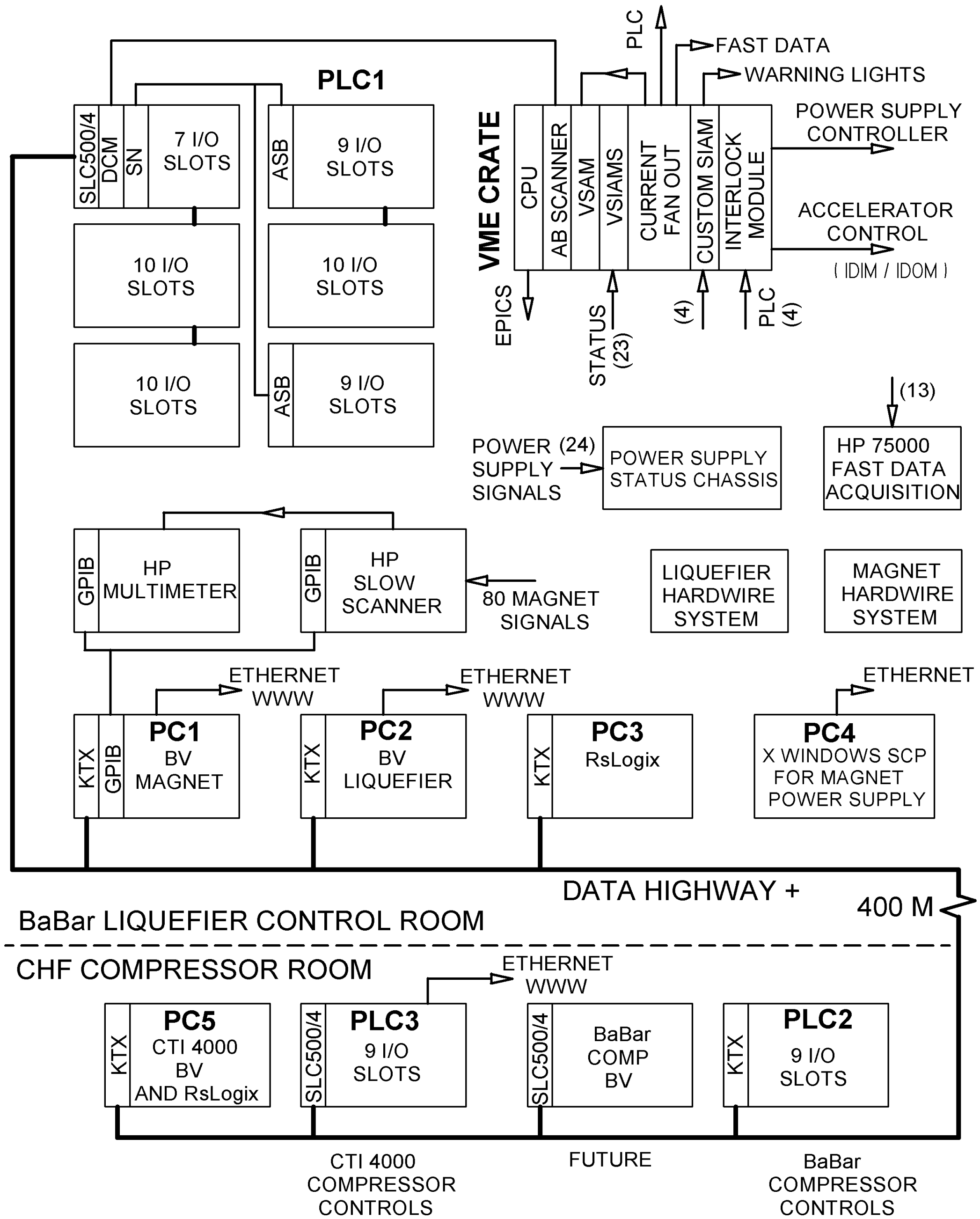

FIGURE 1. Control system layout

An invaluable diagnostic and operational aid was making all BridgeView display screens, including alarm panels and historical trend viewing, available on the WWW. System experts can monitor performance from off site locations greatly reducing on-site engineering manpower requirements. All BV liquefier and magnet display pages can be found at: http://cryocon2.slac.stanford.edu:8080. A second important operational tool is an automatic dialer system, triggered by BV alarm panels and two standalone Betalarm panels, that sequentially pages four system experts. Alarms can be acknowledged and the auto dialer system stopped by telephoning and pressing the reset code.

The liquefier adsorber regeneration equipment is controlled manually by toggle switches operating solenoid valves. External dewar pressure required for LHe transfer through a 60 meter Kabelmetal transfer line is set with a variac.

EPICS INTERFACE, VME CRATE AND POWER SUPPLY CONTROL

The Liquefier/Solenoid/Power Supply Control System is required to exchange information with the BaBar collaboration Detector Control System (DCS). BaBar uses EPICS (Experimental Physics and Industrial Control Software) on VME CPU boards running the VxWorks real-time operating system for its DCS. Information exchanged between BaBar and the Liquefier/Solenoid control systems via EPICS Channel Access includes: liquefier and solenoid hardware interlock status, solenoid and bucking coil power supply status, solenoid and bucking coil current levels, solenoid dump resistor status, UPS status, and detector door and end plug closure status. A BaBar standard VME crate (21 slot, 6U, Motorola based CPU) with BaBar standard Summary and Interlock and Alarm (SIAM) modules, and a VME Smart Analog Monitor (VSAM) module, provide the interface between this control system and the BaBar DCS. The VME crate has a power supply current level, fan out module, and a custom SIAM that directly activates magnet warning lights. In addition, there is a module that sends PLC power supply commands to the power supply and to SLAC accelerator controls. These PLC commands are stop magnet ramp, ramp down and open dump breaker.

Communication between this crate and SLC 500/4 system is implemented using an Allen-Bradley 6008-SV1R Scanner module in the VME crate and an AB Direct Communication Module, 1747 DCM, in the PLC 1 rack. Information is passed between the control systems using the 8 input/output registers of the 1747 DCM. The programming for this data transfer has not been completed.

A SLAC power supply controller is connected to the PEP II control system via BITBUS for solenoid control. Operator interface is through the X Windows SLAC Control Program (SCP) screens or BaBar EPICS screens. Some power supply interlocks and signals are sent to the power supply controller chassis and some are sent directly to the power supply. An AB SLC 500 PLC provides the I/O for the direct power supply signals and provides the logic for the interlocks. This PLC system has two digital input, two digital output and two TTL digital output modules.

HARDWIRED PROTECTION SYSTEM

The magnet control system has ten hardwired interlocks that will open the dump breaker and initiate a fast discharge when tripped. The quench detection modules and hardwired interlock modules are original Ansaldo custom modules with some upgrades and rework at SLAC. The liquefier has five hardwired interlocks that will close the turbine inlet valve or turn off the internal dewar heater. All hardwired interlocks are duplicated as software interlocks at lower thresholds. The magnet software interlocks have a ramp down threshold and a lower stop magnet ramp up threshold. TABLE 2 lists the interlocks. Quench detector 1 compares voltage imbalance across both halves of the coil, while quench detector 2 includes the superconducting bus bars from coil to bottom of current leads. Hardwired turbine overspeed comes directly out of the Jaquet speed transmitter units. Liquefier turbine and internal dewar overtemp hardwired interlocks come from the relay output of M-System model AS, isolated DC alarm modules. Voltage across the two sensor wires at the RTD module is the input to the alarm modules. A LakeShore 2 mA constant current source replaced the RTD module scanning internal current source.

TABLE 2. Hardwired and software interlocks

MAGNET HW INTERLOCKS	MAGNET SOFTWARE INTELOCKS	LIQUEFIER
Quench detectors ready	Magnet over current	Turbine 1 speed
Quench detector 1	Magnet strain gage summary	Turbine 2 speed
Quench detector 2	Three magnet temperatures summary	Turbine 1 temperature
+ Current lead voltage	+ Current lead voltage	Turbine 2 temperature
- Current lead voltage	- Current lead voltage	Internal dewar temp.
+ Superconducting bus bar voltage	+ Current lead temperature	
- Superconducting bus bar voltage	- Current lead temperature	
LHe Reservoir Level	LHe Reservoir Level	
Vacuum Level	Vacuum Level	
Panic Button	LHe inlet temperature supply > 6 K	
Magnet ΔT O.K. (future)		

INSTRUMENTATION AND MISCELLANEOUS CONTROLS

TABLE 3 is a list of PLC 1 instrumentation, not including: redundant or unused sensors and standard standalone modules such as Leybold vacuum controllers, water bath heaters and video cameras. Four 150 watt cartridge heaters mounted in the connecting bus bar of each of the two current leads eliminate condensation and icing. Standalone temperature controllers provide 48 VAC power on a time proportional basis via a zero crossover circuit, reducing noise. Dual 330 K Klixon temperature switches on each bus bar ensure over-temperature protection. Lead temperatures are monitored, but not protected, by the PLC system with alarms at 280 K and 300 K.

TABLE 3. Sensors and instruments for PLC 1

Transducer Type	Manufacturer/Model	#	Location	Input	Comments
Pressure	KPSI / Model 27	25	Liquefier and 1 at magnet	PLC	1 failed
Pressure	Valcom	3	Magnet	PLC	
Platinum RTD	Lakeshore PT-103	24	Liquefier and 1 on magnet shield outlet	PLC	
Strain Gauge	Micro Measurement WK -06-250-BG-350	28	Solenoid support rods	GPIB	7 have failed T. compensated
Silicon Diodes	Lake Shore DT-470/231 transmit.	20	Liquefier, 2 in solenoid reservoir, 1 in 4000 l dewar	PLC	1 failed: at connector
Cryogenic Linear Temp. Sensors	Micro Measurement CLTS -2B	33	Solenoid cylinder, shield, support rods and reservoir	30 GPIB 3 PLC/	1 has failed (3 RTD inputs)
LHe level probe	AMI/ Model 135	2	Solenoid and 4000 l dewar	PLC	
LHe ΔP level measurement	Rosemount	2	Liquefier internal dewar and 4000 liter dewar	PLC	
Carbon Glass	Lakeshore/CGR1200	9	Solenoid	GPIB	2 have failed
Zero Flux Current Transductor	Dyna Power ZFCT	2	Solenoid and power supply	PLC	
Thermocouple	Omega Micro Mega 77553 controller	2	Solenoid current leads	PLC	Heater control and thermometer
He Flow Rate Meters	Sierra Instruments Model 600 & Bronkhorst	2 2	Solenoid shield and liquefier Current leads	PLC	Insertion probe type; Rotor type
Axial Positioner	linear potentiometer	6	Solenoid	By hand	1 has failed
Turbine Speed	Jaquet/FT 1400	2	Liquefier	PLC	

TABLE 4. PC size and performance

UNIT	Processor/Memory	CPU usage	Memory used	BV Tags	BV Panels
PC 1 (magnet BridgeView)	199 MHz Pentium 3/196 MB	~ 25%	145 MB	180	6
PC 2 (liquefier BridgeView)	266 MHz Dual Pentium 3 /196 MB	~ 20%	165 MB	545	11
PC 3 (RSLogix)	397 MHz Pentium 3 /261 MB	~2%	75 MB	N/A	N/A
PC 5 (CTI 4000 compressor BV and RsLogix)	266 MHz Pentium 3 / 328 MB	~10%	140	111	6

TABLE 5. RsLogix program size and SLC 500/04 performance

PLC Processor	PLC 1 BaBar Liquefier and Solenoid	PLC 2 BaBar Compressor System	PLC 3 CTI 4000 Compressor System
SLC 500/04 Memory	64 K	64 K	32 K
Instruction Words used	9729	690	503
Lines of ladder logic	1484	123	89
Number of PID Loops	25	0	2
Data Base Tag Names	98	1487	260
Data Table Words Used	1255	2826	2582
Program Avg. Scan Time (ms)	50	1	1
Program Max. Scan Time (ms)	60	1	2

CONTROL SYSTEM PROGRAM SIZE AND PERFORMANCE

RSLogix scan time is approximately 50 msec. However, BV response time on both PC 1 and PC 2 is in the two to ten second range. This long response time is acceptable because any necessary quick reaction is performed by the logic in one of the PLCs. BridgeView is slow because all display panels must be running concurrently so that they can be displayed on the Web. Solutions, however, may be possible. PC 3 is more powerful than normally required, but it was sized to serve as the back up PC for either the liquefier or magnet BridgeView displays. One can clearly see from TABLES 4 and 5 that the PLCs have plenty of capacity while BV performance could be improved with faster and more powerful PCs. BridgeView on PC 2 stores ~65 MG/month of historical Citadel Data Base information.

OPERATIONAL EXPERIENCE, SYSTEM RELIABILITY AND UPGRADES

The BaBar solenoid/liquefier/compressor system has been relatively trouble free for more than three years. Our most frequent magnet downtimes are now caused by loss of site water, air, and power. Vacuum system mechanical failures, sensor failures and local valve I/P converter malfunctions are the second most frequent category of downtimes. The BaBar cryogenic control system is on an uninterruptible power supply (UPS), so critical control and monitoring is always maintained. An additional battery guarantees that the solenoid dump breaker can open in the event of power loss. Typically the liquefier and magnet now operate for many weeks at a time without operator intervention. The three Sullair screw compressors are twelve to twenty five years old. The only failures during their lifetime have been very infrequent compressor seals, motor bearings and plugged water heat exchangers problems. If compressor maintenance is required, the CTI 4000 system compressors are switched to the higher priority BaBar system.

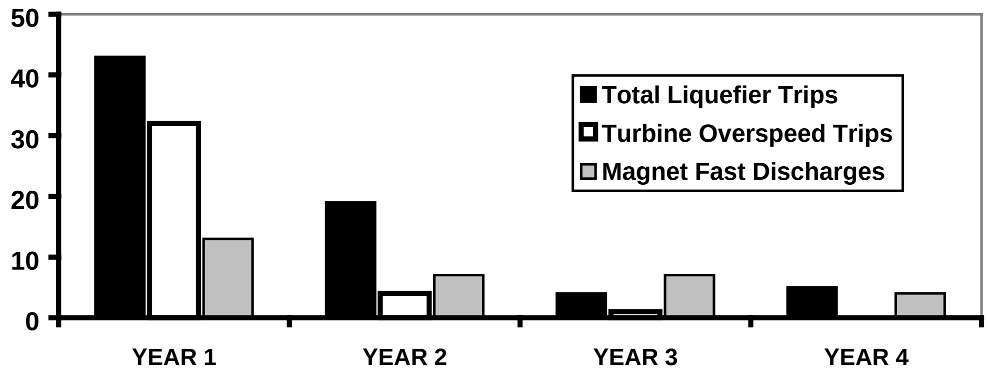

FIGURE 2. Unintentional BaBar Liquefier Shutdowns and Solenoid Fast Discharges. Years represent years of service. The solenoid has 4 fast discharges 3 months into its fourth year of operation. Total liquefier trips are turbine over speed trips plus other plant fault conditions causing turbine trips.

The PLC systems have been remarkably robust since the start of liquefier operations in August 1997. With the exception of several RTD input module failures, solved with revision B modules during liquefier commissioning, no PLC module in any of the three PLC systems has ever had to be replaced. PLC 1 has faulted on about three occasions, shutting down the liquefier and magnet and requiring a reboot. No shutdowns have occurred due to problems with the Data Highway Plus network. After commissioning we have experienced no shutdowns of liquefier or magnet caused by mistakes in online PLC program modifications. However, big changes to ladder logic are usually made during extended BaBar shutdowns to minimize risk and to use faster offline programming. Small changes to BridgeView are also routinely made with the magnet /liquefier operating without incident. Remarkably, there have been approximately only five unplanned shutdowns from an operator pushing a wrong display or physical button.

Turbine trips and magnet fast discharges were commonplace during commissioning and early operations of the PLC system as graphically displayed in FIG 2. Most of the early turbine trips were caused by rapid depressurization of the 4000 liter LHe storage dewar increasing suction line pressure and over-speeding the turbines. Changes in logic and the addition of a back pressure regulator to the dewar have solved this problem. The control system is now tuned so that fast discharges leave the liquefier virtually unperturbed, and LHe continues to be delivered to the now 35K magnet, cooling it back down without operator intervention.

Finally, it has been proven that commenting on the smooth operations on late Friday afternoon virtually ensures shutdown from utility loss or other mechanical failure.

Operator Experience and Training

Nine experienced cryogenic technicians are available on site to operate the BaBar liquefier/compressor/magnet system for most but not all of 24 hr/7days per week. They have been trained to operate the system through the BridgeView interface, but they are not qualified or expected to make even minor modifications to the BV or RsLogix controls. All training to date has been sporadic individual training with a system expert. Unfortunately, most of these technicians were fully utilized elsewhere when the controls for the liquefier, compressors and magnet were being installed and commissioned.

Now that the system is running so smoothly, there are very few times during the year when anything more than basic operations can be taught. Operator training is ongoing and one of our highest priorities during BaBar shutdowns.

Upgrades

Several major upgrades are planned during the next extended BaBar shutdown. CHF sensors will be upgraded and switched from a SLAC custom data logger to PLC 2 and PLC 3. BaBar compressor PID loop control will be moved from PLC 1 to PLC 2. A PC dedicated to monitoring PLC 2 will be added in the CHF control room. PLC 3 will be fully commissioned. BridgeView will be replaced with National Instrument's newest version of LabView with its Supervisory and Control Module. RsLinx 1.73 will be upgraded on all PLCs to the substantially revised RSLinx version 2.2. The paging system will be modified to send out pager messages indicating the type of alarm.

CONCLUSIONS AND RECOMMENDATIONS

Hardware cost in a large control system, where long-term reliability is mandatory, is only a small portion of the true cost of the system. One should select high quality sensors and PLC hardware and use good wiring practices. Redundant sensors that can be easily switched into the PLC system should be installed at critical locations. If at all possible, one should choose all software and hardware from one vendor. It will probably be more bug free and there can be no back and forth between vendors to solve problems. Removable fuses for AOs and DOs are invaluable.

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