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Abstract

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RECONFIGURATION OF A B&W/SSC/LINDE LIQUEFIER TO MEET SLAC-BaBar DETECTOR MAGNET REQUIREMENTS

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ABSTRACT

A partly finished helium refrigeration and liquefaction plant, originally designed and intended for use on the SSC quadrupole magnet testing program, has been successfully adapted for use with the SLAC/BaBar Detector Magnet. Via judicious reconfiguration, the plant's intended role was considerably modified to satisfy SLAC's projected physics program.

INTRODUCTION

A helium liquefier/refrigerator was needed to meet the projected requirements of the Stanford Linear Accelerator Center (SLAC) physics program. Following a detailed cost and plant availability analysis, it was decided that the effective solution was to procure and reconfigure one of two plants which had been under construction by Linde Kryotechnik AG, for Babcock & Wilcox (B&W), a contractor for the Superconducting Super Collider (SSC) quadrupole magnets, Kelley [1]. Both plants, which were approximately 60% complete at the demise of the SSC, were made available to SLAC by the Department of Energy (DOE).

The plants, as configured by B&W, exceeded the immediate refrigeration and liquefaction requirements necessary for the superconducting solenoid magnet coil of the BaBar Particle Physics Detector, a key element of the physics program. B&W requirements included mass flows of up to 150 g/s, temperatures as low as 3.3 K, 20K shield capacity, low temperature subcoolers and liquid helium pumps. SLAC's requirements, i.e. to provide refrigeration and liquid helium, via a 60 meter long transfer line, for the thermo-siphon cooling system of the BaBar coil, were more modest. Although SLAC had 200 g/s of interconnected compressor capacity (one 100 g/s and two 50 g/s oil lubricated Sullair screw compressors), 100 g/s would be required, on occasion, for an existing liquefier system. Therefore, SLAC wished to optimize the B&W/SSC plant for 100 g/s supply.

Judicious deployment and configuration of heat exchangers has met these goals. Other design changes provide for the future incorporation of two beam line superconducting quadrupole magnets (Q1) at the detector interaction point.

ORIGINAL SPECIFICATION

Two modified Linde Kryotechnik AG, TCF 200 cold boxes, were ordered from the Lotepro Corporation to meet the diverse cryogenic requirements of the SSC quadrupole magnet testing program. Each cold box was designed to provide 800 W of refrigeration with 5.2 g/s of liquefaction at less than 4.5 K, 150 g/s at 3.3 K and 2-20 g/s at 20 K for magnet shields. Each contained a TGL-22 upper stage and a TGL-32 lower stage turbine expander. Other refinements included high and low temperature subcoolers and a 150 g/s at 4.5 K Barber Nichols variable speed centrifugal pump. The plants would be fully automatic including regeneration of the 80 K cold box adsorbers, which would have to cope with the impurities introduced during a projected 2.5 magnet/week continuous test program.

COLD BOX STATUS

When SLAC took possession of the plants, the valve boxes were fabricated, the turbine housings were installed, all valve bodies and transfer line bayonets were tack welded in place, a few interconnecting pipings were tack welded in place and the heat exchanger trains were fabricated but not interconnected nor installed, as shown in Figures 1 & 2. All parts with the exception of the cold box vessels, which were outside in a storage yard, had hibernated for over two years in a warehouse at Linde's Schalchen factory in Germany. The condition of all components was good. The availability of a complete set of spare parts allowed for valve resizing as and where required.

Figure 1 Cold box/valve box with components

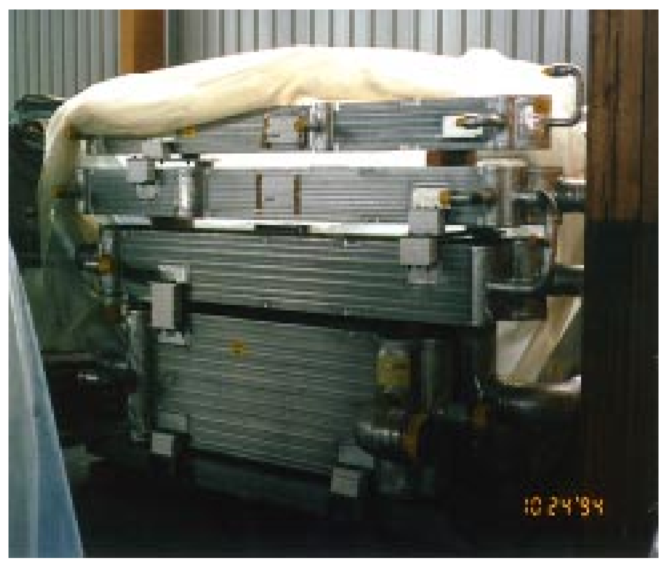

Figure 2 Heat Exchanger Train

SLAC REQUIREMENTS and SPECIFICATION

The immediate projected cryogenic requirements of the SLAC physics program, centered on cool down and normal operation (thermo-siphon) of the superconducting magnet coil of the BaBar detector, Fabbricatore [2]. Ansaldo, Italy was supplying the coil. From the perspective of capacity and of course cost, these requirements could probably have been met by a modest plant providing 50 l/h and 100 watts of refrigeration at 4.5 K. However, assuming that two superconducting quadrupole focusing magnets (Q1), would probably be incorporated in future detector/beam line upgrades, and that SLAC would be required to supply LHe in 2,000 liter dewars for small ancillary experiments, the procurement of a larger plant was justified. The quadrupole magnets could be supplied from the cold box/valve box. Helium trailers/dewars could be filled from the plants 4,000 liter LHe storage dewar. As the shield requirements of the BaBar solenoid magnet were unclear at this stage, provision could also be made for the extraction of cold gas (~ 30 K) from the Joule-Thompson (JT) stream between the turbine 1 & 2 heat exchangers. Although implemented, this provision was not utilized and the shield is helium vapor cooled, like the current leads, using boil off from the magnet reservoir to maintain a shield outlet temperature of ~50 K.

The plant was designed to meet all SLAC requirements (operational modes) using the existing cold box/valve box components, where possible, and compressors. Calculated (specified) values are summarized in Table 1. The plant was optimized for case 3. Figure 3, is a schematic of the cold box process. Figure 6, is a photograph of the installed plant showing LHe storage dewar, adsorber regeneration skid and transfer lines.

Case #	Helium Flow Rate (g/s)	Supply Pressure (bar)	LN_2 Precooling (g/s)	Liquefaction g/s (l/h)	Refrigeration at 4.4 K (watts)
1	100	16.5	none	0	615
2	88	16.5	none	4.2 (121)	0
3	100	16.5	none	3.95 (114)	180
4	Deleted				
5	100	16.5	31.0	9.1 (262)	0
6	135	16.5	48.0	14.0 (404)	0
7	100	16.5	13.0	0	725
8	150	16.5	4.0	0	1040
9	100	16.5	none	2.3 (66)	400
10	150	16.5	41.0	11.0 (317)	450
11	100	16.5	18.0	4.7 (135)	360

Table 1 Calculated liquefaction/refrigeration parameters for SLAC operating modes

EXPANSION TURBINES

The B&W/SSC plants were intended for operation with a mass flow of 150 g/s and LN_2 precooling. The main SLAC operating modes required 100 g/s without LN_2 precooling. Fortunately, the size of the existing expansion turbines, SLAC's operating mode changes (lower mass flow, no LN_2) compensated each other. Only minor changes in the nozzle/impeller configuration were necessary, but the turbine frame size could remain the same.

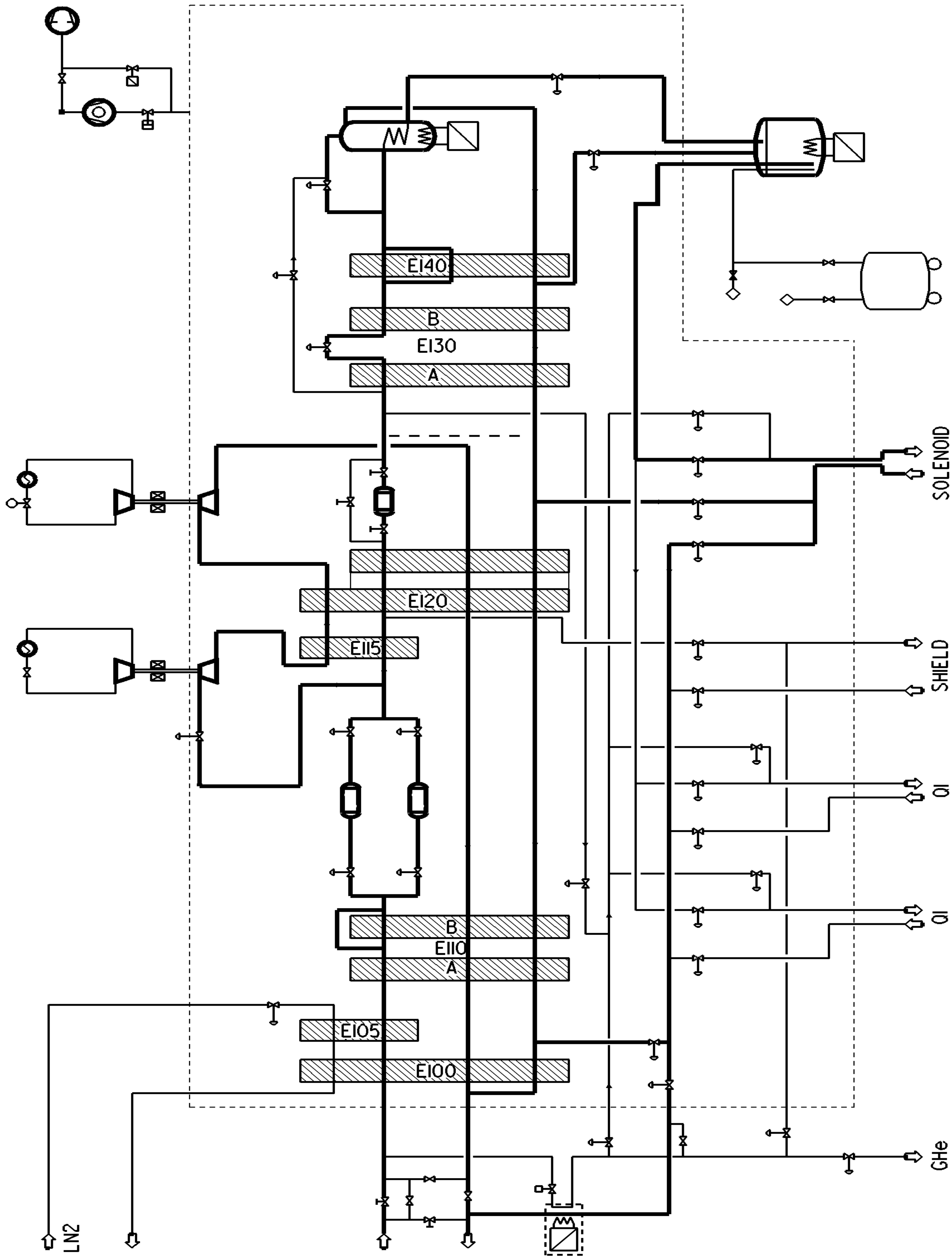

Figure 3 Schematic of the SLAC configured cold box process.

HEAT EXCHANGERS

Initially it was believed that downrating from 150 g/s to 100 g/s would not present heat exchanger problems. However, when getting into the details, two aspects demanded modification in the flow distribution and hardware. Since the B&W/SSC system was intended to operate with LN_2 precooling only, the two 80 K guard adsorbers in the high pressure stream were placed directly downstream of the LN_2 evaporator. Operation without LN_2 precooling, as foreseen for most of SLAC operation, would result in temperatures in this portion of the heat exchangers varying between 120 and 180 K, depending on operating mode. Such an environment is not suitable for guard adsorbers. Flow input to these had to be relocated just upstream of the point where the high pressure turbine stream splits off from the Joule-Thomson (JT) stream. Unfortunately, in the original design this split off point was located in the middle of a plate fin heat exchanger block, which of course had already been manufactured. The solution was to deactivate a part of this heat exchanger block such that the split off was outside of the block. To maintain the same temperature level for turbine and JT heat exchanger streams, a new small "tube in tube" exchanger was added to replace the deactivated part of the original block. As configured for SLAC requirements, exchanger E110B was too small for the high pressure flow stream so part of this flow was bypassed around the exchanger.

A specialty of this type of Linde refrigerator is the horizontal installation of the plate fin heat exchangers. To avoid poor distribution, a certain minimum flow pressure drop is mandatory in the heat exchanger core, especially in the coldest exchangers where the gas is denser. After downrating the plant, this minimum pressure drop condition could not be guaranteed in all of the foreseen operating modes. The solution was to take a surplus small subcooling exchanger from one of the B&W/SSC plants and add it in series to the cold end of the JT exchanger. This elevated the temperature level in the original JT exchanger, resulting in smaller density differences between warm and cold end and a larger pressure drop. The performance results of the acceptance tests proved the validity of the modifications.

TRANSFER LINE BAYONETS

The B&W/SSC cold box/valve box configuration did not have sufficient transfer line ports to fulfill SLAC magnet and LHe storage dewar supply/return requirements. Also, the existing female bayonets were not compatible with SLAC transfer lines. To meet offline commissioning and online operational requirements, SLAC had elected to connect the BaBar Detector and Q1 magnets via flexible, coaxial, return gas shielded, vacuum insulated lines, as successfully employed on numerous magnets at CERN and the SLD/SCFF quadrupole magnets at SLAC, Blessing, H. [3,4]. The distance between the cold box and the magnets is 60 meters. Three cryogen paths were also required between the valve box and the 4,000 L LHe supply dewar, i.e., LHe supply to the dewar and LHe supply/cold gas return from the dewar.

For inter magnet connection, existing valve box bayonets were removed and replaced by SLAC supplied coaxial transfer line bayonets. To reduce the number of transfer lines/bayonets required and save space on the dewar neck, SLAC designed a vacuum insulated triaxial transfer line and supplied the accompanying female bayonet, Figure 1. This bayonet was mounted in place of the centrifugal pump. The HDPE seals between cryogen paths are similar in design and conception to the coaxial transfer line seals. This triax line, four meters between the vertical axis, replaced the three lines requisite for dewar LHe supply and return and cold gas return. Figure 4, illustrates the bayonet design.

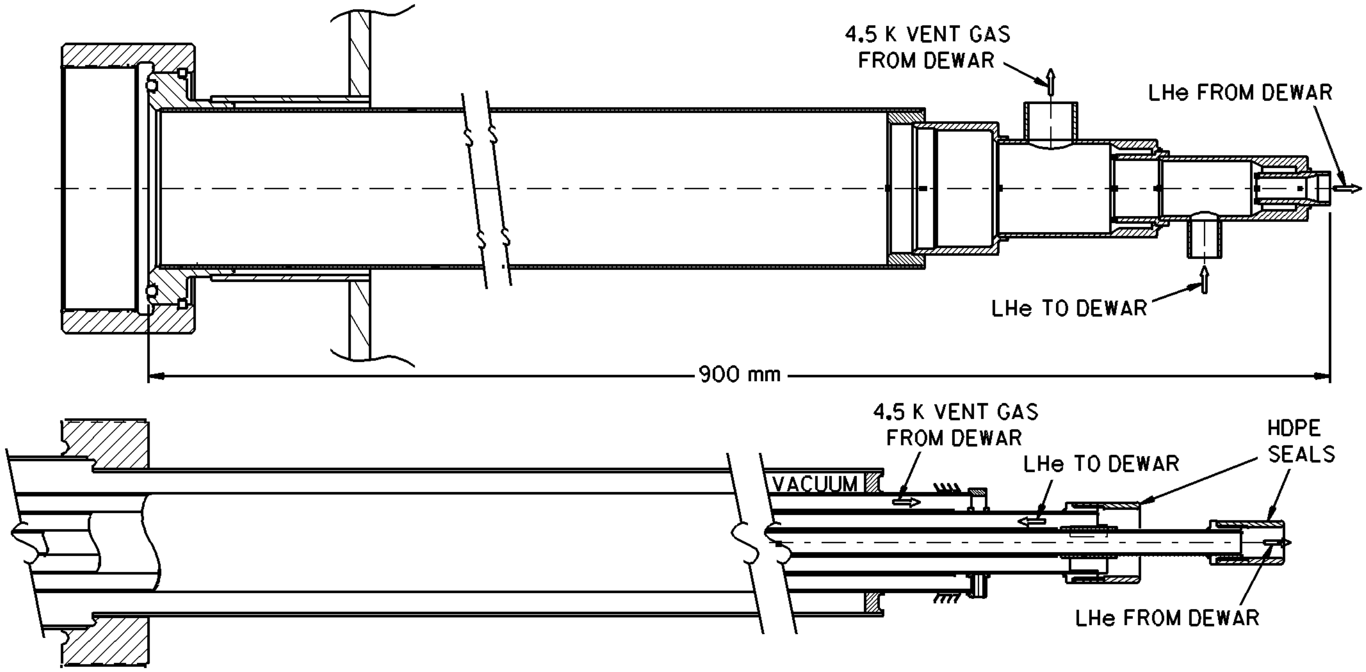

Figure 4 Cold box and triaxial transfer line bayonets.

PROCESS CONTROL

SLAC's goal from the outset was to procure a fully automatic plant in order to minimize operator monitoring and intervention. Based on the recommendations and experience of other laboratories and companies, SLAC decided on a stand alone PLC system. SLAC also required a fully automatic liquefier control system that could interface with the Ansaldo solenoid control system and the BaBar Detector VME/EPICS control system. Remote monitoring, but not control, from any Internet connected PC was mandatory to reduce operational costs. The chosen control system was required to be industrially robust, well supported, easily modifiable, expandable, reasonably fast and relatively inexpensive. An Allen Bradley SLC 500 PLC system with a National Instruments BridgeView Graphical User Interface (GUI) satisfied all requirements. Linde supplied the necessary process logic. SLAC contracted Descon Engineering of California, a company experienced in supplying PLC systems for cryogenic plants, to supply the control.

The Allen Bradley PLC SLC 500/4 programmed with AB RSLogix ladder logic software system was selected because it is good compromise between cost and speed and it has an excellent reputation. BridgeView was chosen since it was the only package at the time, which provided Internet capability with a PLC. In addition, BridgeView is essentially a superset of LabView and is used throughout SLAC. BridgeView includes historical trend plotting, data archiving, and device drivers for the AB SLC 500.

The BaBar liquefier SLC 500 control system is a sixty slot system with 121 active analog and 107 active digital channels of I/O. Silicon diode temperature sensors are conditioned through external transmitters.   A second remote single SLC 500 rack is used for compressor control. A dual Pentium II 266 MHz PC is used for BridgeView display, and another single Pentium II PC is used to display and modify the RSLogix in real time, which has proven to be very useful for diagnostics and commissioning. Liquefier compressors are controlled by a second remote SLC 500 in a single rack. PCs and PLCs are connected via Allen Bradley's Data Highway Plus network. The entire control system is run on UPS power. Turbine expanders and the internal dewar heater have additional hardwired interlock protection.

SLC 500 / RSLogix operations and commissioning has been excellent. A complete cycle takes approximately 40 msec. BridgeView, a new product, is slower but acceptable, and it continues to improve. The BridgeView Internet capability has proven to be extremely valuable for remote monitoring.

We are currently in the process of changing the VME based solenoid magnet's control system to a SLC 500/BridgeView system, which will result in a single unified control system with solenoid Internet and BaBar EPICS monitoring.

COMMISSIONING AND PERFORMANCE TESTS

Due primarily to care and attention during installation and set up procedures, coupled with sound process logic, plant commissioning, including simulated cool down of the BaBar solenoid, went very smoothly and was basically completed within four weeks. Most of this time was devoted to optimizing process control parameters and acceptance tests. Simulated cool down and normal operation of the BaBar magnet were performed using a test cryostat incorporating appropriate valves and heaters.

Due to severe time constraints, only case 3 and case 10 of the calculated performance values were fully tested as these are indicative of the minimum and maximum parameters. The results are summarized in Table 2.

Case #		Helium Flow Rate (g/s)	Supply Pressure (bar)	LN_2 Precooling (g/s)	Liquefaction g/s (l/h)	Refrigeration at 4.4 K (watts)
3	Calculated:	100	16.5	none	3.95 (114)	180
3	Measured:	101	16.2	none	3.3 (96)	182
10	Calculated:	150	16.5	41.0	11.0 (317)	450
10	Measured:	153	15.8	< 40	11.5 (331)	450

Table 2 Summary of measured versus calculated liquefaction/refrigeration parameters.

Liquefaction was measured by maintaining a constant LHe level in the dewar while measuring the resultant ambient temperature gas mass flow. Case 3 performance is less than calculated and is possibly due to underestimation of the heat leak to the extended 4.5 K pipings in the cold box, or to the fact that optimum operating conditions for this mode were not found during the test. Another non-specified test performed with 100 g/s @ 16.4 bar (no refrigeration), resulted in 4.6 g/s of liquefaction with a slightly rising dewar level, suggesting the latter. Case 10 performance comfortably exceeds the calculated value. It is interesting to note that the heat loads of the BaBar solenoid cryogenic system, ~50 watts @ 4.7 K, are almost met using one compressor delivering 54 g/s @ 16 bar. The operating pressures of the helium supply dewar and the BaBar magnet reservoir were 1.5 bar and 1.3 bar respectively.

SUMMARY

The reconfiguration of a B&W cold box has been a success. The plant and its control system meet all design and operational goals including the controlled cool down and operation of the BaBar solenoid magnet. Operational experience, while limited to ~5 months, has been positive and apart from minor interventions, trouble free.

Figure 6 The completed cold box installed at SLAC.

ACKNOWLEDGEMENTS

We are greatly indebted to J.P. Kelley, formerly of B&W, who was instrumental in the original cold box conception, design and configuration, for his help and encouragement both in the procurement and reconfiguration. He claims this only stems from a vested interest in seeing some fruits from his original labors. Thanks go to Lutz Dekker of Linde Kryotechnik, for process logic and his guidance during commissioning. We also thank A. Candia and W. Kaminskas (SLAC Cryogenics Group) for their invaluable help and participation from procurement through installation and commissioning. It is now their prerogative in life to oversee the operation and maintenance. Thanks also go to G. Kraft (SLAC Mechanical Design) for procurement and design aid, including the innumerable drawings he patiently produced during the interminable changes. Special thanks go to C. Titcomb (Descon Engineering), whose excellent knowledge and experience of PLC systems and cryogenic processes, helped produce a system that more than satisfied all requirements of logical and safe process control.

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