Title
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Publication Date
1978-09-01

To be presented at the 1978 Applied
Superconductivity Conference, Pittsburgh,
PA, September 25 - 28, 1978

LBL-8162

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September 1978

Prepared for the Division of High Energy and Nuclear Physics
of the U. S. Department of Energy under
Contract W-7405-ENG-48

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ABSTRACT

The ESCAR magnet cooling system has been successfully demonstrated. This two-phase helium cooling system includes a CTI-Sulzer gas-bearing turbine refrigerator with two-stage compression by oil-lubricated screw compressors, 120 m of 5-cm-diameter vacuum-insulated transfer line and twelve series-connected magnet cryostats with weirs for liquid level control. The refrigeration plant provides up to 1900 W of refrigeration at 4.5 K with a mass flow of 113 g/s. Heat load within the transfer line has been measured at 0.25 W/m in sub-system testing. Cool-down times to 4.5 K for the 12 warm-iron magnets with a cold mass of 2500 kg have been about 12 hours. The magnet cryostats separate liquid by gravitational extraction and fill in sequence at a rate of up to 400 ℓ/hr. A heater in the transfer line allows adjustment of the inlet coolant quality (ratio of gas to liquid) to the cryostats; flow instabilities were not present and could not be induced. Pressure levels in the cold bore, beam orbit space were below 10^{-10} torr.

Severe pressure transients, incurred as a result of magnet transitions, have been safely handled both in terms of refrigerator response and cryostat pressure relief. Large gas loads at the compressor suction following magnet transition have not caused overloading or interruption of the refrigeration plant output. An electrical arc punctured the helium vessel and allowed liquid helium to flow into the vacuum space. This was handled by the relief system with no additional damage.

INTRODUCTION

Some of the experience gained from the operation of two quadrants of the ESCAR superconducting dipole magnets, helium refrigeration system, and simplified refrigeration distribution system is reported here. For these operations, six dipole magnets were assembled in each of two adjacent quadrants. Within a quadrant all of the magnet cryostats are series-connected (for refrigerant flow), and for these tests the quadrants were series-connected. Provisions for quadrant bypass and refrigerant subcooling that have been previously described were not included (see Ref. 1 and 2).

The objectives of these tests, in addition to magnet system performance, were to determine the fluid mechanics of the pool-boiling cryostats and the interaction of the magnet and refrigeration systems.

SYSTEM DESCRIPTION

A flow schematic for the two-quadrant subsystem is shown in Fig. 1. Cold two-phase helium is circulated from the refrigeration plant to the quadrants and back. Room-temperature helium gas that has given up its refrigeration to the current leads is returned to compressor suction.

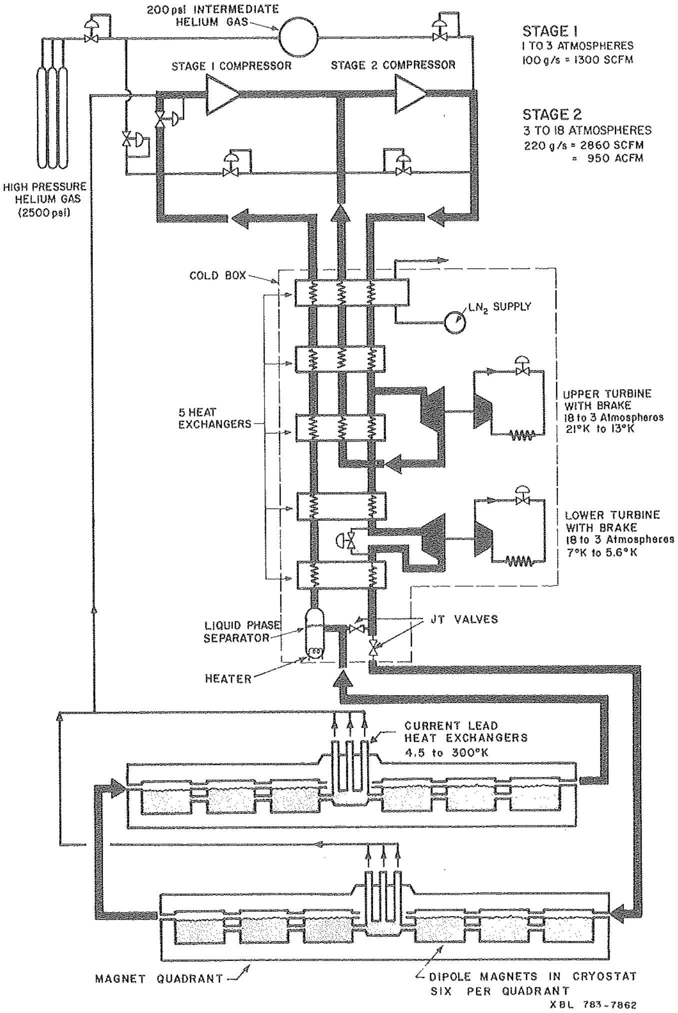

Fig. 1. Refrigerator and two-quadrant subsystem.

Refrigerator System

The helium refrigerator consists of three major components: the cold box, the compressors, and the controls. Capacity of the plant was based on cooling requirements of a complete accelerator ring of 56 magnets plus cyropanels. Fermilab had initiated a refrigerator purchase for a 1500 W turn-key system, and LBL joined in the contract for a cold box only. This was good economics and established a low price of $395,000 for one cold box. Total contract value was $1,070,000.

The system specifications included:

I. Performance

   a. 1450 W at 4.5 K plus 3 g/s liquefaction rate. (LBL Specification)

   b. 360 ℓ/hr as a liquefier.

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*This work was supported by the Division of High Energy and Nuclear Physics of the Department of Energy.

c. 950 W plus 1.7 g/s at 4.5 K plus 1250 W at 21 K. (Fermilab)

II. All expansion and compression to be done with rotary equipment.

III. Complete control by a single operator from a remote location.

IV. Minimum operating costs for electrical power, LN feed, maintenance, and manpower.

The cold box is a Helix Corp. CTI-Sulzer 1500 W unit which includes six Trane brazed-aluminum heat exchangers and two Sulzer gas-bearing expander turbines. All valve control and bayonet penetrations to the 8 ft diameter x 15 ft high vacuum insulated box are located in the top plate. Delivery to LBL was made in June 1977, and acceptance tests were completed October 1977 with maximum loads up to 1900 W. Operations proceeded through the winter and spring of 1977-78.

The Sullair Corp. oil-injected screw compressors were purchased directly by LBL. Subsequent development of oil removal and determination of performance and efficiency with helium was done at LBL. Measured efficiencies are about as predicted, 75 to 85% volumetric and 65 to 75% isentropic. Total installed power is 230 HP (first stage) and 920 HP (second stage) for a total of 1150 HP (with an added potential of about 90 HP using interstage cooling). Displacement is 1710 CFM at 3550 RPM for both machines. Operation of the first stage is 1 to 3 atm compression at 113 g/s and second stage is 3 to 18 atm at 250 g/s with helium gas.

Capella D (mineral base) oil was used during most of the early testing. We now use UCON-LB-170X, a synthetic polyalkyl glycol. Heat transfer and output are better, with less foaming. We believe oil separation is also improved. The compressors were delivered in September 1976, and now have been operated for over 500 hours.

Oil content in the process stream past the aftercooler (before the first coalescer) is 30 $\mathrm{PPM_W}$. The flow moves on through a 0.9 m dia. x 2.5 m long column consisting of 5 cm of compressed fiberglass, 120 cm of charcoal, 60 cm of zeolite, and then through a 3-micron final filter to the cold box. Estimated bed life is in excess of 8000 hours. Future plans include installation of on-line monitoring using fluorescence, photo ionization or laser scatter.

Compressor control is all local and manual. Cold box controls are converted to electrical signals at the coldbox and brought out through an umbilical cable to the control room. Main control is by a Texas Instrument 5 TI micro processor which is still in the rework and debugging stage. Some lessons learned so far are that solid-state devices as well as input/output modules can fail in an unsafe mode. Revisions are in process to correct these problems.

Magnet Cryostats

The magnets are cooled by pool boiling in series-connected cryostats. The cryostats are filled by a gravitational separation of liquid from the coolant stream. The axes of the magnet and cryostat are displaced vertically so as to minimize the liquid volume and maximize the flow cross-section above the magnet. The large flow cross-section results in a low velocity, which enhances the liquid-vapor separation. Liquid level is controlled by the vertical location of the transfer line. When the liquid level reaches the level of the transfer line, which is slightly above the top of the magnet, no further collection of liquid can occur. One end of the horizontal magnet cryostat is shown in Fig. 2. Except for the circumferential location of the supports, the two ends are mirror images. Going from inside to outside, we encounter in order: (1) a stainless steel barrier separating the ultra-high vacuum from liquid helium; (2) an epoxy-fiberglass tube; (3) the coil; (4) the aluminum structural-ring system, which resists the tendency of the coil to go out-of-round under the influence of the Lorentz body forces; (5) the main helium reservoir; (6) the stainless steel outer wall of the helium vessel; (7) the insulating vacuum; (8) the liquid-nitrogen-cooled radiation shield; (9) multi-layer insulation, limiting heat radiation to the nitrogen shield; (10) the stainless steel wall of the vacuum vessel, and, finally, the laminated iron yoke.

The coil weight, and magnetic forces due to its possible eccentricity with respect to the iron, are transmitted first to the fiberglass tube, then to the end extensions of the stainless steel bore tube, and finally to the end plate of the helium vessel.

The helium vessel is supported from the vacuum vessel by a system of seven epoxy-fiberglass (NEMA G-10) compression struts. The room-temperature ends of the struts seat into adjusting screws that also serve as strain-gage load cells. At assembly, the struts are adjusted, using the strain indication, to achieve the desired pre-load. When the magnet is first turned on, the struts are readjusted so that the change in force, upon application of the magnetic field, is reduced to a tolerable level, ensuring centering of the coil within the iron.

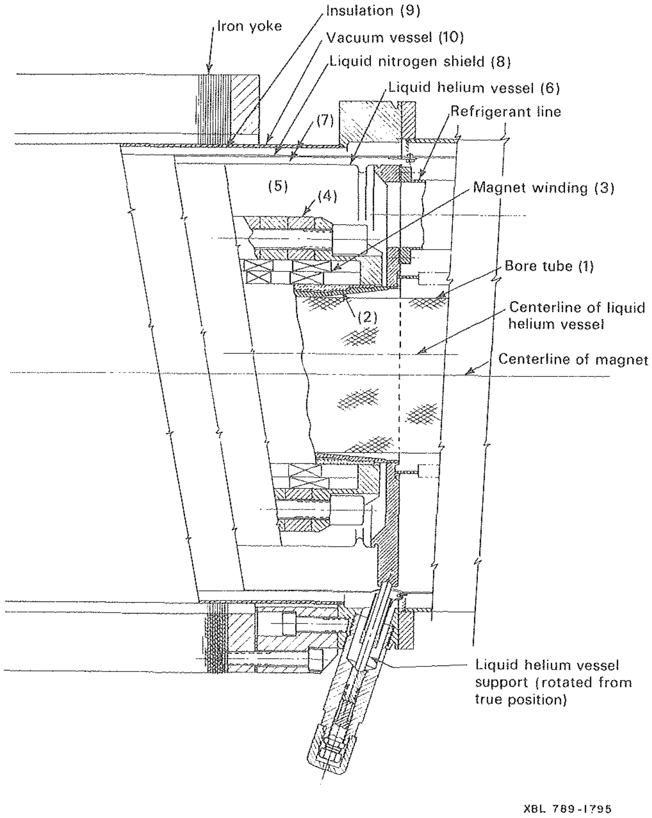

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Fig. 2. Magnet cryostat cross section.

The helium vessels are joined near the top by a 2-1/2-inch diameter tube that carries the two-phase helium. A second smaller tube on the horizontal midplane connects each adjacent helium vessel to a junction box where all of the electrical connections are made. The flanged connections between the tubes and the vessels, and the cover plate for the junction box, are secured with screws and sealed with epoxy-versamid adhesive. The nitrogen-cooled shield and the multilayer insulation are carried through the intermagnet region. The vacuum vessel in this region is split on the horizontal centerline, and is screwed and glued together and to the adjacent magnet vacuum vessels. At the midpoint of a six-magnet quadrant, a much larger vacuum tank contains the high-current and instrumentation lead feed-throughs, and provides a connection to the vacuum pumps. The assembly of magnets is seen in Fig. 3.

Helium Transfer Lines

The same line size is used for both the cold helium supply and cold return. The helium conduit is a 2 inch OD x 0.035 in. wall, type 304 stainless steel tube that is insulated with 40 layers of aluminized (one side), perforated and crinkled mylar and centered within a 3.5 in. OD (3 in., schedule 5) aluminum vacuum jacket. The inner tube is supported within the vacuum jacket by 1/4-inch-diameter fiberglass pins, 120 degrees apart, which extend radially from a fiberglass collar on the inner tube, through the insulation, and bear on the inside of the vacuum jacket. The transfer line was prefabricated in 20-foot lengths, which were later joined in the field. Each 20-foot module had the pin supports located near each end and at the center. The prefabricated elements were joined in the field by welding the inner line, wrapping the weld area with aluminized mylar (which is interleaved with the adjacent laminates), and coupling the vacuum-jacket segments with a larger diameter collar that seals to the outer surface of each with an O-ring. Differential expansion between the inner and outer lines is accommodated by thin-walled bellows on the inner line. Bends are made in the inner line with a bend radius equal to the tube diameter, whereas on the outer line a mitered flange joint is used (Fig. 4). Approximately 400 ft. of transfer line was installed: 200 ft. supply and 200 ft. cold return. The vacuum space is compartmented by a barrier in the jacket at approximately the midpoint of both the supply and the return. Ports for pump-down and pressure relief were provided at several locations along each of the isolated vacuum jacket segments.

Prior to fabrication of the transfer line, heat rate measurements were made with two liquid-helium-filled transfer-line test models. These were of full diameter but of reduced length; one 10 ft. long, the other, 20 ft. The 10-foot model was tested both with and without inner line supports which allowed an assessment of the support contribution to the total heat input. A heat leak of 0.1 W was observed for a single three-pin support and 0.2 W/m for the unsupported line. The inner line in the longer test model was supported at three points along the 20-ft. horizontal section at one location on the approximately one foot vertical section. This second test model corresponded in length and supported spacings to the prefabricated modules envisioned for the prototype ESCAR line and also incorporated an insulated elbow so that its performance should be representative of the final configuration. The measured heat rate to this line was approximately 1/4 W/m.

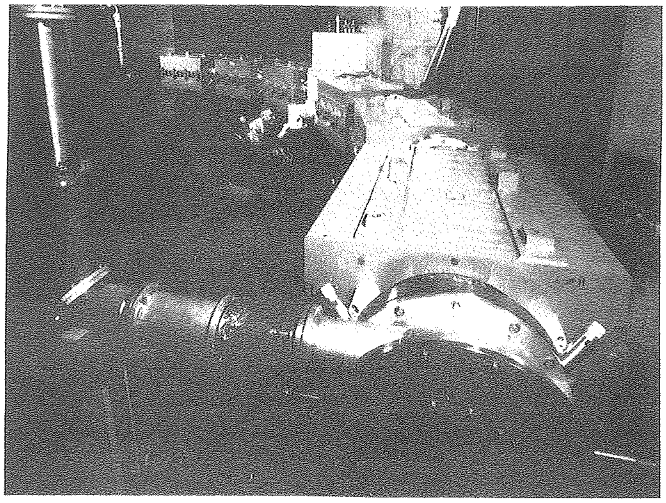

Fig. 3. Quadrant assembly.

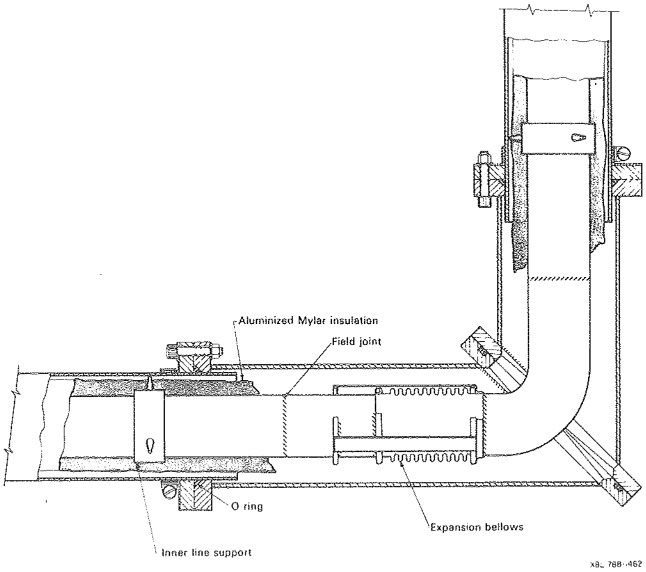

Fig. 4. Transfer line assembly.

Pressure Relief

Helium Space. The pressure relief system has been sized to accomodate a quench of a string of six dipole magnets with total absorption of the stored energy in the helium coolant and a simultaneous rupture of the vacuum space surrounding the magnet cryostats. Under these conditions, energy is transferred to the helium both from the magnets and from the containing vessels. Consideration of the maximum possible heat-transfer rates from these surfaces leads to a vent rate requirement to avoid over-pressurization. For the ESCAR design a vent area of 19 cm^2 at each dipole quadrant was computed as necessary to maintain the pressure below 4 atm. absolute. A large cyrogenic relief valve, which is sent to open at 44 psig, and which has approximately one half of the above area, is provided at each quadrant. Additionally, a 20 cm^2 burst disk (minimum rupture = 50 psi) is also provided at each quadrant.

Transfer Line Vacuum Space. Combination pump out and pressure relief valves are provided at each end and the center of each isolated transfer line vacuum jacket segment. The relief capacity of these valves is not large, and further, they may be susceptible to plugging with fragments of the aluminized Mylar insulation. Therefore, additional 1-inch relief valves were provided. The insulation adjacent to each was restrained with bridal-veil netting in an attempt to preclude plugging of the valve in the event of a catastrophic rupture of the inner line. Additional pressure relief is provided by the slip joint construction of the vacuum jacket. A large positive pressure that was not otherwise relieved would simply result in a separation of the vacuum jacket segments.

Cryostat Vacuum Space. Positive pressures in the cryostat insulating space are relieved by a 2000-cm^2 spring-loaded access cover.

System Operation

The operation of the refrigerator with the 12-magnet heat load went smoothly. There are many benefits in having a large capacity available for rapid cooldown, as well as overcoming excessive heat loads in the research equipment due to vacuum and thermal leaks. Time schedules and manpower loads can be improved.

Refrigerator performance during acceptance tests demonstrated capacity of about 1900 W, and during magnet filling, liquefaction rates of up to 400 ℓ/hr were obtained. The rapid-cooldown heat exchanger makes it possible to cool the cold box in a few hours.

Most of our operations after cooldown and filling were run at reduced compressor capacity, with about a 500 kW power input. The screw compressor is very flexible in operation and can be run over a wide range of capacity. The turbine system, however, is designed to run very near its' maximum load; therefore, most of our operations were conducted with 600 to 900 W on the internal heater. At times only the upper turbine was used.

The operations were conducted for periods of as long as two weeks for one or two shifts per day. The system was shut down at midnight, and restarted at 7:00 a.m. This mode of operation demonstrates a remarkable flexibility for a helium refrigerator plant, as usually all trapped impurities migrate to the cold end in a few hours of outage and plug the system, requiring complete warm-up and purge.

Prior to cooldown from ambient temperature, the complete helium circuit would initially be purged and dried with an ice filter to a dew point of -60°C or less. Cooldown rates were initially between limited to 50 K/hr and the temperature difference the coolant stream and upstream magnet was limited to 50 K. These limits were later relaxed with no apparent ill effects. The initial cooldown of a single quadrant from ambient temperature was accomplished in 13.5 hours. This time was later reduced to 6.6 hours (275 K initially) and to 12 hours for the cooldown of two quadrants (2500 kg cold mass). Initial temperature differences between magnets tended to decrease as cooldown progressed and were virtually zero below 30 K. The magnets generally transitioned to the superconducting state (9.5 K) almost simultaneously. Once the magnets were full, gas make-up was closed off and heater power was brought on (say 400 to 800 W) to keep the suction pressure at the desired value. Fill time for the 205-liter volume (one quadrant) was typically 30 to 40 minutes except on two occasions when only one expander turbine was operating at which time the fill time was approximately doubled. The magnets filled in sequence beginning with the upstream magnet. Very little liquid collection occurred until the adjacent upstream magnet had reached the spillover point (approximately at the midplane) which demonstrates that the cryostats are effective liquid/vapor separators.

As part of these tests, the magnets were powered and caused to undergo normal transitions repeatedly, a process called "training". Power was applied to magnets either singly or in groups of three. Transitions caused the deposit of as much as 270 kilojoules of heat into the liquid helium surrounding one magnet, causing evolution of gas, pressure increase, and loss of liquid helium in the affected magnets' cryostat. On a typical transition, the pressure at the refrigerator suction increased about 2 psi and recovered in about one minute. The affected magnet lost about 5ℓ of liquid and regained it in about two minutes. After a pause of 5 to 6 minutes the current was increased until the next transition occurred, usually at a greater current.

The largest pressure rise experienced in the helium system occurred when an external power supply malfunction caused arcing which punctured the helium pressure vessel, causing a large transfer of liquid into the insulating vacuum space. The pressure rise on the refrigerator return went to an estimated 30 psi, yet the turbines and compressors stayed on until manually shut-down.

The heat rate to one dipole quadrant (inferred from boil off measurements) was found to vary from about 105 to 15 W as the liquid level fell from 94 to 26% in a time period of 75 minutes (current leads not cooled).

Vacuum levels in the cold-bore beam orbit space (indicated by a nude hot filament ion gage, which contributes about 10 W to the refrigeration load) were below 10^{-10} torr.

Pressure in the insulation space surrounding the magnet cryostats fluctuated in response to individual leaks (that were subsequently found and repaired). Pressures as high as 10^{-2} torr were tolerated, with a doubling of the heat leak to the cryostats.

During normal operation the pressure drop between the centers of the two quadrants has been found to be between 2 to 4 inches of water. This low pressure drop, which is about as predicted, is necessary to maintain a low saturation temperature to maximize the magnetic field strength.

An electrically heated vaporizer was incorporated in the transfer line, ahead of the second dipole quadrant, to simulate the fluid dynamics within a magnet located at the downstream end of a series-connected string of magnets. Power input was sufficient that dry-out conditions in the coolant stream could be approached even with full refrigerator flow. No flow instabilities or liquid level oscillations occurred as a result of coolant quality changes. With large power inputs to the heater, a migration of liquid occurred from the upstream magnet cryostats so that the liquid level increased from magnet to magnet in the downstream direction. We believe that the migration was through the lead conduits which connect to the magnet cryostats below the liquid level. Further, this effect appears to be in compliance with the pressure gradient that exists as a result of velocity head losses at the entrance to each magnet cryostat. Stable liquid-level depressions as large as 9 cm have been observed in the upstream magnet.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution of others to this work. Namely, M. Green, W. Pope, and J. Tanabe for their contributions to the refrigeration system design, R. Wolgast for the vacuum system design, and G. Newell and R. Nemetz to the test operations.

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