CHAPTER 4

MAGNET CRYOSTAT

4.1 General

The magnet cryostat consists of four major components: the vacuum vessel, the liquid nitrogen cooled radiation shield, the cold mass support system with liquid nitrogen cooled intercepts, and the helium cooling tube on the outer support cylinder of the superconducting coil. The superconducting coil and outer support cylinder have been described in Chapter 2. The instrumentation required in the cryostat for operation of the system is described in Chapter 9. The cryostat is shown in Figure 4.1.

4.2 Vacuum Vessel

The vacuum vessel consists of inner and outer coaxial shells with flat annular bulkheads welded to each end. The superconducting buses from the coil and the cryogen pipes from the outer support cylinder and the radiation shields leave the vacuum vessel through the service chimney nozzle welded into the bulkhead at one end (the "south" end) of the cryostat. The vacuum vessel is fabricated of 5083-0 aluminum and the major dimensions are listed in Table 4.1. The shells are designed according to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 so that they fulfill the requirements of the Fermilab Environment/Safety/Health Manual, Section 5033 [1]. The cryostat is designed for full internal vacuum and for an internal relieving pressure of 0.044 MPa (6.4 psig). The bulkhead is sufficiently stiff to support the loads from the cold mass support members and the loads from the brackets which fasten the cryostat to the existing CC of the DØ detector.

4.3 Cold Mass Support System

The magnet cold mass — the superconducting coil and outer support cylinder — weighs 1.46 metric tons (3200 lbm). The cold mass support system consists of axial members which locate the coil axially and support it against axial thermal, decentering and seismic forces, and nearly tangential members which locate the coil radially and provide radial support against thermal, gravitational, seismic, and decentering forces. The support members connect the outer support cylinder of the coil to the flat annular bulkheads of the vacuum vessel. Figures 4.2 throughout 4.4 show details of the support members. Six axial members are provided at the service chimney end of the magnet, and 6 radial members at each end of the coil.

All cold mass support members have thermal intercepts which operate near 87 K and the radial supports have a thermal intercept below 10 K. Axial and radial contraction of the coil support cylinder is accommodated by spherical bearings on both ends of each support member.

Each axial member has a design load capacity of 16870 N (3765 lbf) in tension and 3160 N (706 lbf) in compression and each radial member has a design load capacity of 39590 N (8836 lbf) in tension. The radial members are designed to support no load in compression. These design loads accommodate a safety factor of 4 in tension or compression using the 300K properties of the Inconel 718 from which they are made.

ANSYS [2] analysis was made of the magnet outer support cylinder and cold mass support system to illustrate the manner in which loadings from e.g. accelerations of the cold mass during shipping, then cooldown, and finally and magnetic hoop stress on the support cylinder, change the loadings on the support members. For example, when the system is at room temperature the axial members support an acceleration of 6 g in tension, but only 1 g in compression (i.e. directed toward the chimney end). The radial members support lateral accelerations in excess of 4 g. To ensure that the axial members are not loaded excessively in compression during shipping temporary shipping restraints can be utilized.

When the system is cooled the axial contraction of the cold mass increases the loads in the radial members opposite the chimney end since the axial members tend to fix the cold mass at the chimney end. The addition of magnetic hoop stress in the coil when it is energized increases the loads in the radial members at the top and bottom of the coil. These loads then decrease the accelerations that may be added to the cold mass so that when the magnet is cold and energized the limiting radial acceleration it can tolerate is 2g downward; the limiting axial acceleration remains 1 g toward the chimney end.

Conservative estimates of the decentering forces of 1.4×10^4 N in the axial direction and 4.4×10^4 N in the radial direction are made. These forces stem from generously overestimating the imprecision which which the magnet will be centered in the toroid steel — 20 cm in the axial case and 40 cm in the radial case — or equivalently, by assuming that for a conservative decentering of e.g. 1 cm, the estimates of the decentering force constants as calculated are multiplied by a factor of 20 and 40 for the axial and radial cases respectively to ensure conservatism. These grossly overestimated decentering loads correspond to 0.98 g axial and 0.31 g radial loadings.

Finally, although Fermilab is in a Class 0 seismic zone, the requirements for a Class 1 seismic zone, a lateral acceleration of slightly less than 0.08 g, are imposed for conservatism. The seismic loads are easily accommodated by the radial members, and they only slightly overload the axial members when added to the decentering loads. Evidently a small re-optimization of the design of the axial members would erase this slight overload. The loading design values are shown in Table 4.2

The magnet cryostat is attached to the central calorimeter by support brackets which carry the weight of the cryostat and the tracking devices which will be attached to it. The brackets at the service chimney end constrain axial motion of the cryostat and the brackets at the opposite end allow axial motion.

4.4 Alignment of the Coil

The magnet must be installed in the detector and aligned to the TeVatron so that after it is energized it does not destructively perturb the orbits of the particle beams stored in the TeVatron. The cold-mass support system must preserve this initial alignment through subsequent thermal and energization cycles.

The silicon and scintillator fiber tracking elements must be installed in the magnet bore and aligned to specified points on the vacuum vessel so that the full resolution of the tracking system is achieved as designed. Again, it is necessary for the coil to remain stably positioned throughout thermal and magnetic cycling so the initial orientation of the tracking system with respect to the magnetic field is not degraded.

If after the magnet is cooled and energized the locations of the ends of the coil within the cryostat with respect to fiducials marked on the outer vacuum vessel are specified and maintained to ± 5 mm (in any radial direction), then the angular uncertainty in the direction of the field axis does not exceed ≈ 4 mrad. In appendix F we show that this tolerance is sufficient to preserve necessary alignment of the magnet both for machine requirements and for tracking requirements. It is likely that the tracking system may eventually be incorporated into the trigger for the detector. This eventuality may further constrain the alignment precision in order that minimal ϕ-dependence be introduced into trigger thresholds. This additional precision, if any, has not been estimated.

It is instructive to note that the field axis of the CDF magnet was found to be misaligned by $\approx 1.52 \pm 0.07$ milliradians with respect to the axis of the field mapping device [3] which was in turn aligned to the magnet using fiducials marked on the vacuum vessel by the manufacturer of the coil. This measured misalignment can be interpreted as characterizing the accuracy to which the manufacturer predicted the final location of the energized coil within the cryostat. Since the magnet is 5 meters long, this angular misalignment indicates that a radial tolerance of approximately $\pm$ 4 mm was achieved for this magnet.

4.5 Coil Thermal Design and Cool Down Characteristics

Heat from the coil and outer support cylinder is absorbed by 4.6 K two-phase helium flowing through a tube welded to the outer support cylinder. The steady-state heat load on the coil and support cylinder comes from the thermal radiation from the radiation shields, Joule heating in the conductor joints in the coil, and conduction through the cold mass support members. Additional heat is generated by eddy current heating in the support cylinder and coil while charging, discharging, or quenching the coil.

Figure 4.5 shows the tubing layout on the support cylinder and indicates the location of the radial and axial supports. The support cylinder cooling tube is 15 mm (0.59 in) ID with a minimum wall thickness of 1.5 mm (0.056 in) and made of extruded 6061-T6 aluminum with a maximum allowable working pressure of 9.3 MPa (1350 psid). This pressure rating is based on an ANSI/ASME B31.3-1990 allowable stress of 55 MPa (8 ksi). The tubing is routed longitudinally on the outer support cylinder with 18 straight sections spaced approximately 210 mm apart. The tubing and support brackets are welded to the support cylinder in order to insure good thermal contact.

The cooling tubes are laid out so that they pass near the support brackets. The tube spacing was determined using a 2-D finite element model. Cool-down and steady-state flow calculations were used to determine the tube diameter. The maximum temperature in the coil was determined with 3-D finite element models concentrating on the temperature profiles near the support brackets. The estimated steady-state thermal heat loads are given in Table 4.3; ohmic heating in the conductor joints is negligible.

To reduce the heat load on the coil, both the coil and the radiation shields are coated with aluminum tape (e.g. 3M No. 425 [4]). Experience shows that there is uncertainty in radiation heat load calculations therefore the radiation heat load to the helium surface listed in Table 4.3 includes a factor of 10 increase from the calculated value. Since conduction along the support struts is well understood no contingency has been added to the conduction values in Table 4.3. The charging rate used for the transient calculation is 12 A/s (see Chapter 11).

To lower the coil temperature near the radial supports most of the heat load from the radial supports is intercepted by connecting high purity aluminum shorting straps from the end of the supports directly to the nearby helium cooling tube. To ensure good thermal contact between the support cylinder and the end flanges of the support cylinder an indium gasket is inserted before bolting on each flange. Finite element analyses indicates that the maximum coil temperature is near the axial support blocks (see Figures 4.6 and 4.7). This maximum temperature is 4.9 K for steady current and 5.1 K while charging at 12 A/s. The steady current maximum coil temperature away from the supports is within 0.1 K of the cooling tube wall temperature of 4.7 K.

The steady-state flow of the helium through the control dewar, service chimney, and magnet cryostat has been modeled assuming a homogeneous two-phase flow regime as detailed by Barron [5]. In the calculations the heat fluxes to the tubing are applied with contingencies added where appropriate. Tube lengths, diameters, restrictions, and elevation changes have been taken into account for pressure drop and fluid flow frictional heating effects. Figure 4.8 shows the exit quality of the helium as a function of helium flow rate. The temperature of the helium for the flow rates shown in Figure 4.8 is about 4.6 K. A helium flow rate of 5 grams per second is sufficient to ensure proper cooling of all components during steady state operation of the solenoid.

The cool down time for the cold mass is illustrated in Figure 4.9. To obtain this cool down curve the solenoid is cooled in two stages. During the first stage helium from the refrigerator compressor is cooled in a helium to liquid nitrogen heat exchanger (see Chapter 13) and sent to the cooling coil on the solenoid. The rate of cooldown is regulated by controlling the temperature and mass flow rate of the gas. The desired maximum cooldown rate is 2 K/hr with a maximum temperature difference between the coil and incoming helium of 100K. Cool-down constraints are determined by analyzing the thermal stresses in the cold mass caused by differential contraction of the support cylinder and the coil.

When the coil reaches 90K the second stage of cooling begins. Liquid helium from the storage dewar of the refrigerator is passed through the cooling tube. During this stage of cooldown there are no temperature constraints imposed.

During a quench the temperature of the coil will increase (see Chapter 11) which will result in rapid pressurization of the helium in the cooling tube. The resulting peak pressure in the supercritical helium in the tubing is based on the maximum quench heating rate and on the placement of relief valves which are provided on both the supply and return tubing in the control dewar. The maximum quench heating rate is that corresponding to a fast discharge using the protection resistor which generates maximum heating in the support cylinder. For a conservative estimate of the peak pressure the helium in the tubing on the support cylinder is modeled to be the same temperature as the support cylinder. Table 4.4 gives some of the results of this calculation.

Quench recovery is accomplished as in stage two of the cool down. The recovery time is limited by the pressure drop through the support cylinder tubing. The time required to cool down the cold mass to its operating temperature is 36 minutes (see Figure 4.10); this cooldown will require about 580 liters from the liquid helium storage dewar.

4.6 Loss of Vacuum

If there is a loss of vacuum in the cryostat the pressure in the helium cooling tube will rise due to the increased heat load caused by the freezing of air on the cold mass. A heat flux of 12 W/cm^2 on the cooling tube will cause a peak pressure in the tube of about 130% of the MAWP of the tubing. ANSI B31.3 allows 133% MAWP for single occurrences of less than 10 hours duration and multiple occurrences of less than 100 hours per year total duration. Calculations indicate that the finite thermal diffusivity of the cold mass will lead to a slower response of the support cylinder and coil to the heat flux than through the helium tube. This means that the helium in the cooling tube will pressurize and relieve before significant heat is transferred from the support cylinder to the cooling tube. This heat will arrive at the cooling tube after the most of the helium inventory of the tube is vented.

Figure 6.3 of NBS Monograph 111 [6] indicates that the maximum heat flux for air condensation on a bare vessel is 6.6 W/cm^2. Thus a complete failure of the vacuum jacket will not lead to rupture of the helium cooling tube.

It can be noted that if the entire cold mass surface is allowed to participate in heating the helium in the cooling tube (by assuming instantaneous heat transfer from the entire cold mass to the helium tube) then the freezing of 500 g/s of air will produce a heat load of 260 kW in the tube, sufficient to raise the helium pressure to 120% MAWP of the tubing. For this severely non-physical approximation, an orifice with a diameter of 59 mm in the vacuum vessel would be sufficiently large to provide this amount of air. Such a penetration would come from a very severe accident to say the least.

The rupturing of a nitrogen line in the vacuum space likewise does not threaten the helium cooling tube. To generate 260 kW heating in helium cooling tube a flow rate of more than 19500 g/s of liquid nitrogen is required. A complete rupture of a nitrogen line cannot provide more than about 80 g/s flowrate given the length of the nitrogen lines from the supply dewar and the maximum operating pressure of the dewar.

4.7 Liquid Nitrogen Cooled Shields and Intercepts

Figure 4.11 shows the nitrogen cooling tube layout. The heat load from the radiation shields and cold mass support intercepts is absorbed by two-phase nitrogen flowing through tubes welded to the radiation shields and intercepts. There are two independently controlled cooling tube circuits. One circuit is used to cool the shields and the other the cold mass support intercepts. Flow conditions in the nitrogen circuits were modeled using the Lockhart-Martinelli correlation for two-phase flow.

The radiation shields are fabricated from 1.6 mm (0.063 in) thick 1100 aluminum and are supported off the vacuum jackets. The end shield heat loads are picked up by direct contact to the outer shield tubing. The steady-state heat load is the sum of the thermal radiation heating from the vacuum jacket and the conduction heating through the fasteners which connect the shield to the vacuum jacket. To reduce the thermal radiation from the vacuum jacket, multilayer insulation (MLI) 18 mm (0.71 in) thick at a density of 10 layers/cm (25 layers/in) is placed between the shield and vacuum jacket. At each cold mass support a thin sheet of aluminum shields the higher temperature of the support from radiating to the coil package.

In order to prevent eddy current heating in the shields each is split longitudinally and rejoined by a G-10 plate which provides a current break in the shield. The heat loads to the nitrogen system are listed in Table 4.3. The radiation heat loads listed have been inflated by a factor of 5 over what is conventionally measured for the apparent thermal conduction of multilayer insulation to accommodate imperfections in installation, etc.

The cooling tube for the shield is 9.5 mm (0.375 in) OD with a minimum wall thickness of 1.25 mm (0.049 in), and is made of extruded 6061-T6 aluminum so that the maximum allowable working pressure is 14.4 MPa (2100 psid). This rating is based on an ANSI/ASME B31.3-1990 allowable stress of 55 MPa (8 ksi) for 6061-T6. The tubing is routed longitudinally on the shield with 12 equally spaced straight sections and welded to it to ensure good thermal contact.

The calculated maximum shield temperature is 84 K. Thermal contraction of the shield is accommodated by enlarging the support holes where it is fastened to the vacuum shells and allowing the longitudinal eddy current break gap to widen. The G-10 plate that is used to bridge the gap is pinned to both sides of the gap with slotted holes to allow relative motion; its presence also prevents thermal radiation from penetrating the gap.

The cold mass support intercept cooling tube is welded to the Inconel cold mass support members therefore it is made of 304L stainless steel with a maximum allowable working pressure of 24.0 MPa (3480 psid). This pressure rating is based on an ANSI/ASME B31.3-1990 allowable stress of 92 MPa (13.36 ksi) for 304L (welded). The calculated maximum temperature at the intercepts is 87 K.

4.8 Radial Clearances and Tolerances

Figure 4.12 shows the warm radial dimensions of the cryostat. The radial clearances between the nitrogen and helium cooled surfaces are such that they provide adequate clearances when the cold mass is cold as well as when it is warm. These clearances include allowances for the worst-case build up of tolerances, and always exceed 7 mm (0.28 in), since the thermal motion of the cold mass generated by the cooldown of the support members is estimated to be less than 0.3 mm.

The radial tolerances on all shells must not exceed about 0.5%. For the outer vacuum shell, the tolerance is taken to be +0 mm/-3.18 mm (0.125 in) on the radius. For the inner vacuum shell, the tolerance is taken to be +3.18 mm (0.125 in)/-0 mm on the radius. These expressions ensure that the finished vessel does not encroach on the spaces allowed for the tracking systems that are to be mounted inside and outside the vacuum vessel. The radial tolerance on the cold mass is also taken to be 0.5%.

4.9 Assembling the Coil and Cryostat

After the cooling tubing is welded to the radiation shields and the eddy current breaks are installed, MLI blankets are applied to the vacuum shell side of each shield. Then the shields are attached to the vacuum shells with fasteners designed for this purpose.

The finished coil and support cylinder is placed with its axis vertical and current buses upright and the axial supports are attached to it. The inner and outer vacuum shells are then slid down over the coil so that the upper end of the coil is exposed. The radial support members at the service chimney end are attached to the coil support cylinder and the end radiation shield and MLI are installed. The outer bulkhead is put in place and the cryogen lines and current buses are routed through the service chimney nozzle. The warm ends of the cold mass support members are attached to the bulkhead. Measurements are made of the cold mass and bulkhead locations so the survey markers which characterize the geometry and position of the cold mass can be transferred to the outside of the cryostat. Then the inner and outer vacuum shells are lifted vertically into place and welded to the bulkhead. The assembly is then lifted and the radial support members and end radiation shield installed on the lower end. Instrumentation leads are connected to connectors in the outer end bulkhead and the bulkhead is welded to the vacuum shells after making the necessary measurements to transfer the survey marks on the cold mass to the outside of the bulkhead.

References

[1] Fermilab ES&H Section 5033 requires large vacuum vessels to be designed following the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2 but they need not be code stamped. If the vessel is so designed for full internal vacuum (0.103 MPa or 15 psid) and relieved at less than one atmosphere internal pressure differential it will satisfy Section 5033.

[2] Swanson Analysis Systems, Inc., PO Box 65, Houston, PA 15342

[3] C. Newman-Holmes, *et.al.*, "Measurement of the Magnetic Field of the CDF Magnet", Nuclear Instruments and Methods in Physics Research **A274**, 443-451, 1989.

[4] Minnesota Mining and Manufacturing, Minneapolis, Minn.

[5] R. Barron,"Cryogenic Systems", McGraw-Hill, Inc.

[6] Kropschot,R.H., Birmingham,B.W., and Mann,D.B., Technology of Liquid Helium, NBS Monograph 111, October 1968, p. 270

TABLE 4.1: Dimensions of the Magnet Cryostat	
Length	273 cm (107.48 in)
Outer Radius	707.3 mm (27.85 in)
Inner Radius	532.8 mm (20.98 in)
Thickness of Outer Shell	7.94 mm (0.313 in)
Thickness of Inner Shell	6.35 mm (0.250 in)
Thickness of End Bulkheads	20 mm (0.79 in)

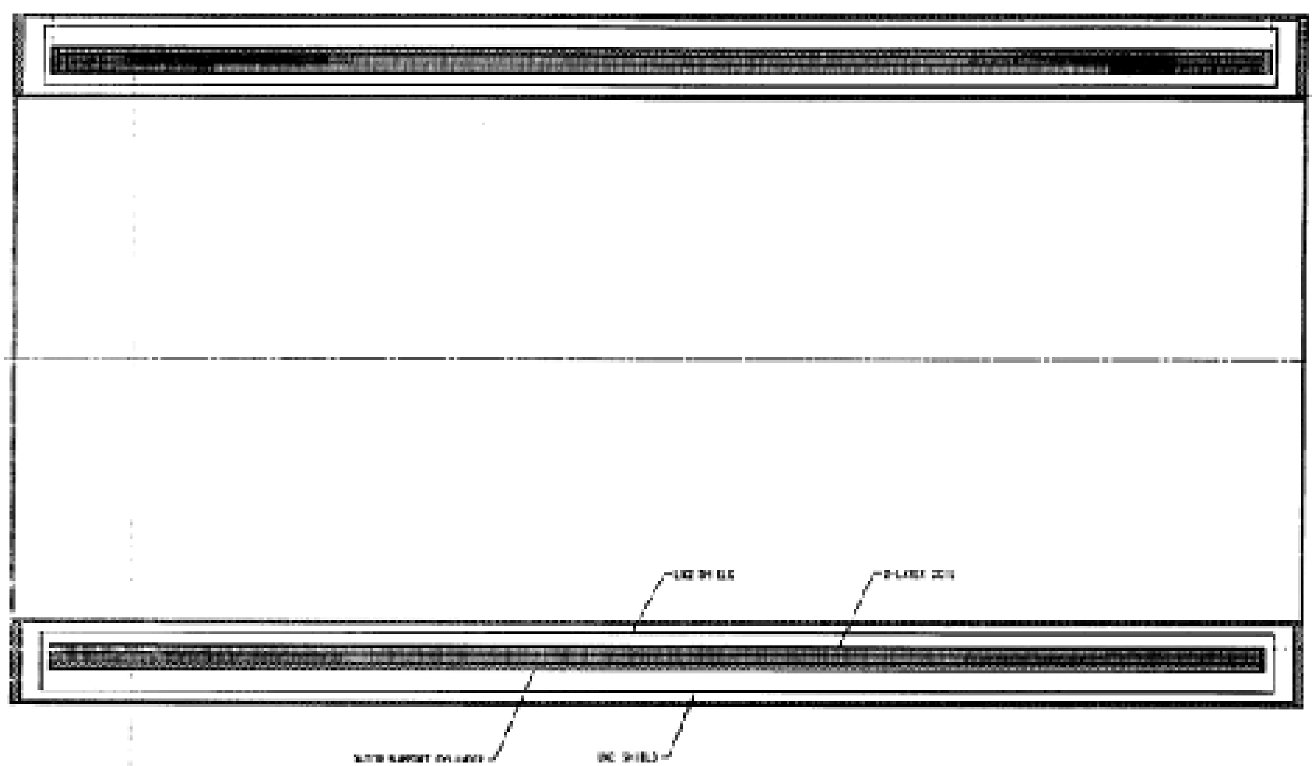
TABLE 4.2: Loading the Cold Mass Support System

Condition	Radial Loading Acceleration	Axial Loading Acceleration
Shipping	4 g	6 g
Coil at 4.7 K	2 g	1 g

TABLE 4.3: Steady State Thermal Loads

Component	300 K to 80 K (Watts)	80 K to 4 K (Watts)
Radiation	130	9.3
Conduction:		
Shield Standoffs	12	
6 Axial Supports	6.6	0.5
12 Radial Supports	16.7	2.7
Eddy Currents (Charging)	0	20

TABLE 4.4: Quench Temperature and Pressure	
Max Temp after Quench	42 K (47 K omitting helium)
Peak Pressure during Quench:	
Two Way Relieving	3.6 MPa (520 psia)
One Way Relieving	1.7 MPa (250 psia)
Required Tube Thickness:	
One Way Relieving	0.52 mm (0.021 in)
Two Way Relieving	0.24 mm (0.010 in)



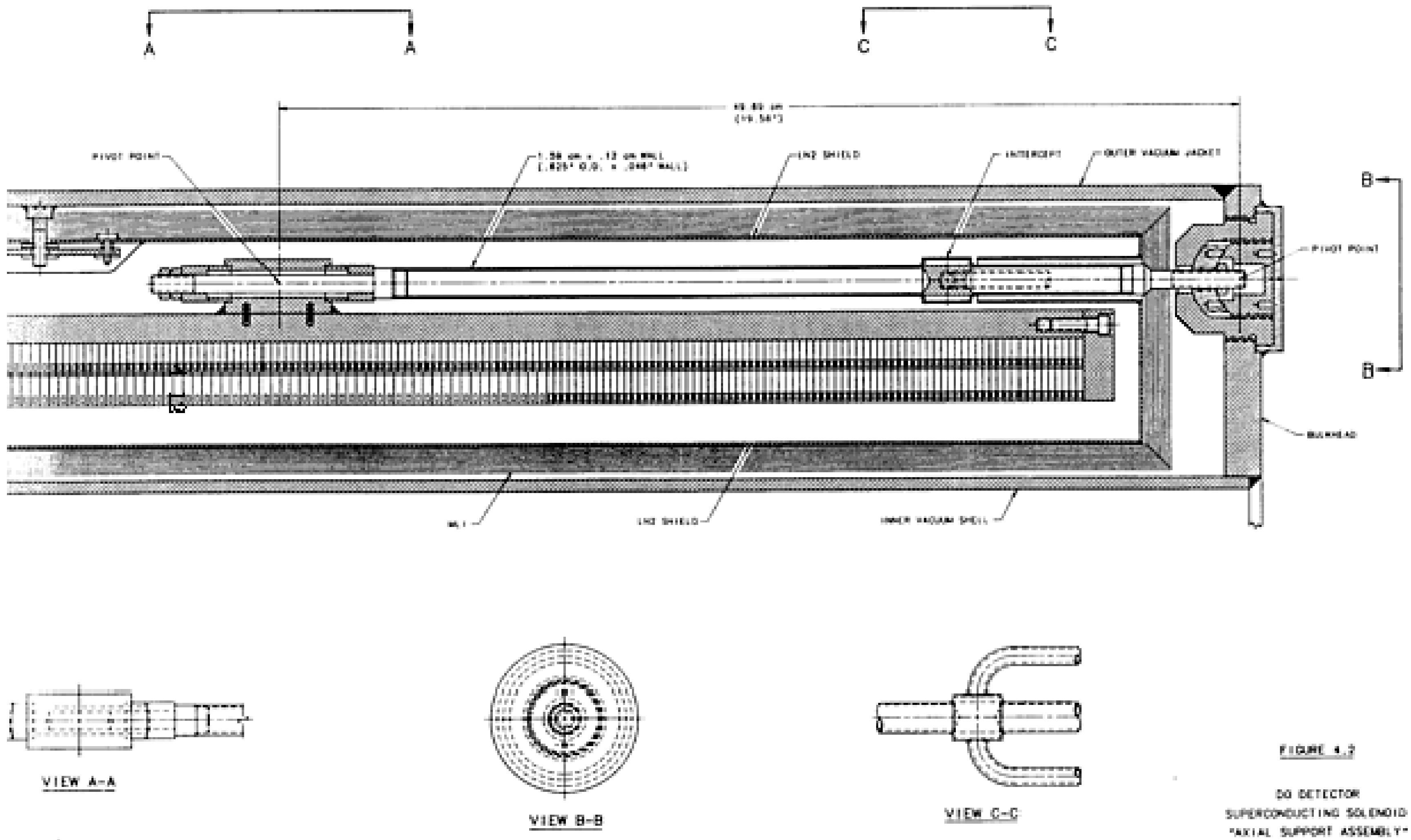


FIGURE 4.2

D0 DETECTOR
SUPERCONDUCTING SOLENOID
"AXIAL SUPPORT ASSEMBLY"

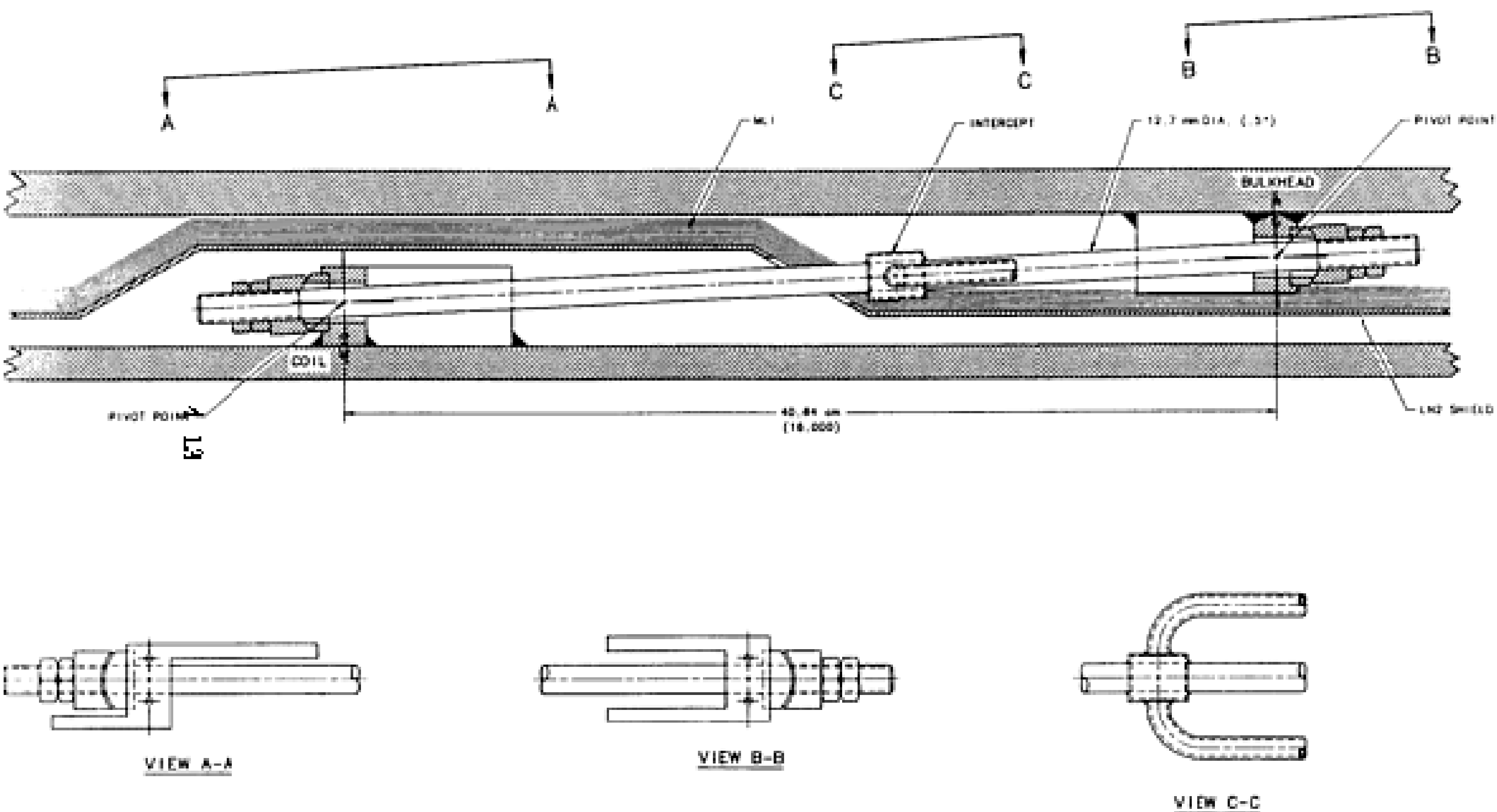


FIGURE 4.3

D0 DETECTOR
SUPERCONDUCTING S
"RADIAL" SUPPORT #

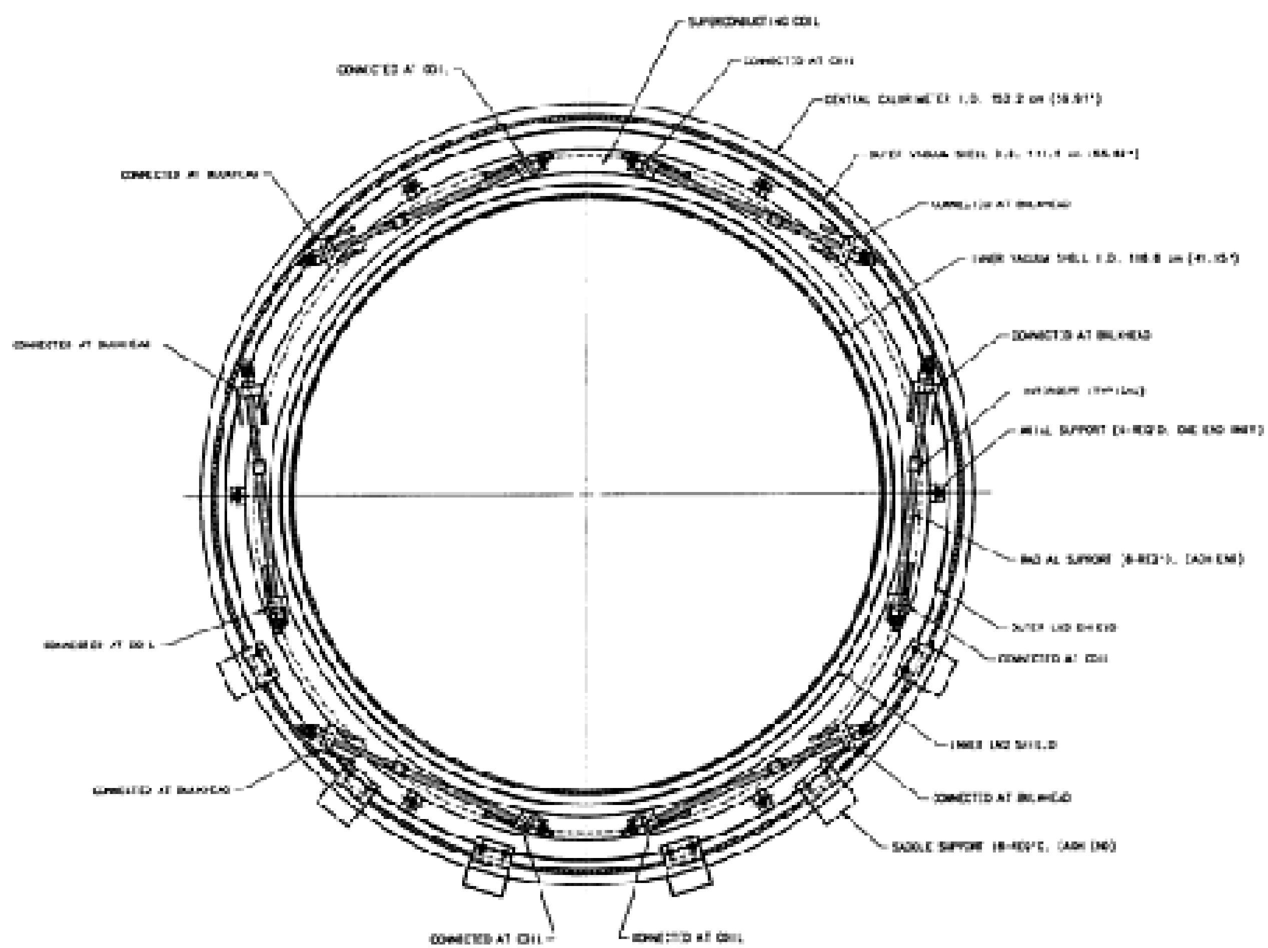


FIGURE 4.4

D0 DETECTOR
SUPERCONDUCTING SOLENOID
CRYOSTAT/COIL END VIEW

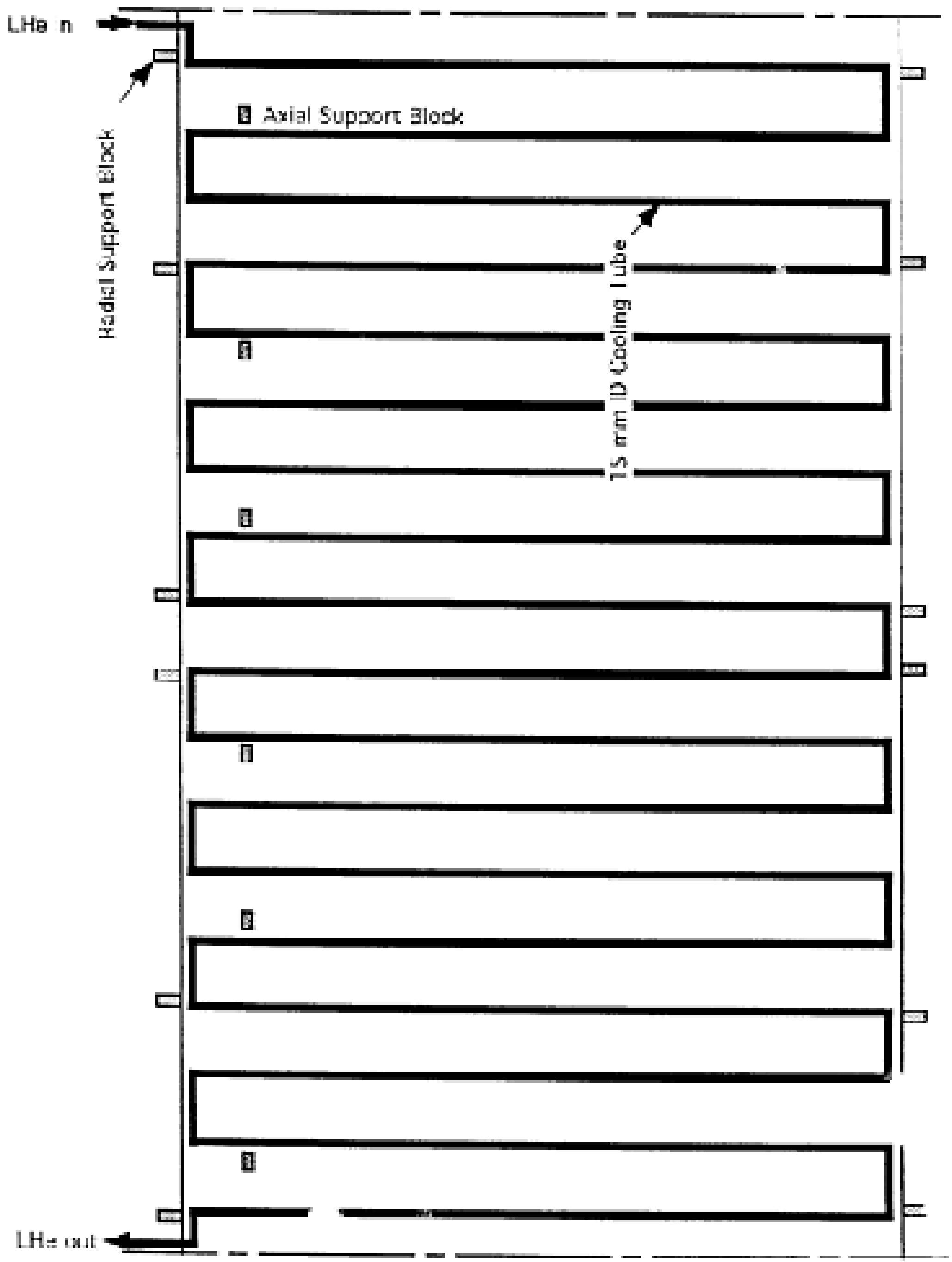


Figure 4.5 Routing of liquid helium cooling tube on the support cylinder.

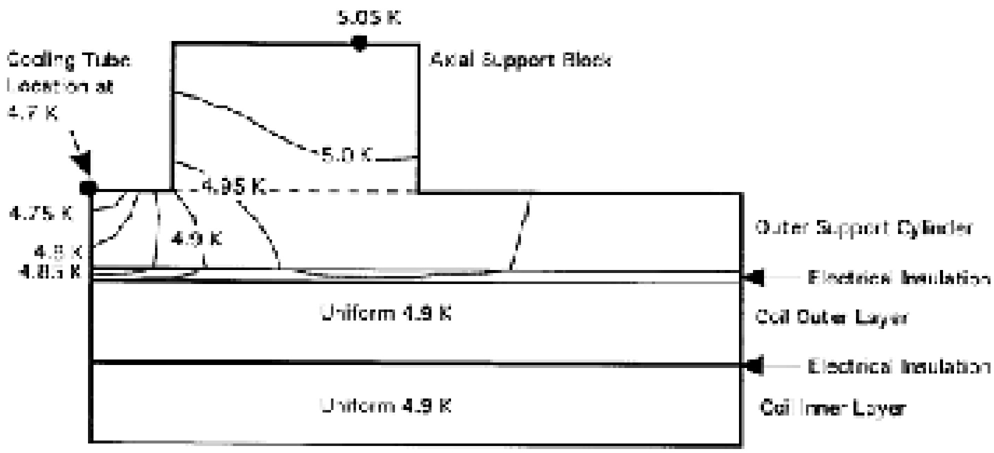


Figure 4.6 Temperature profile near an axial support.

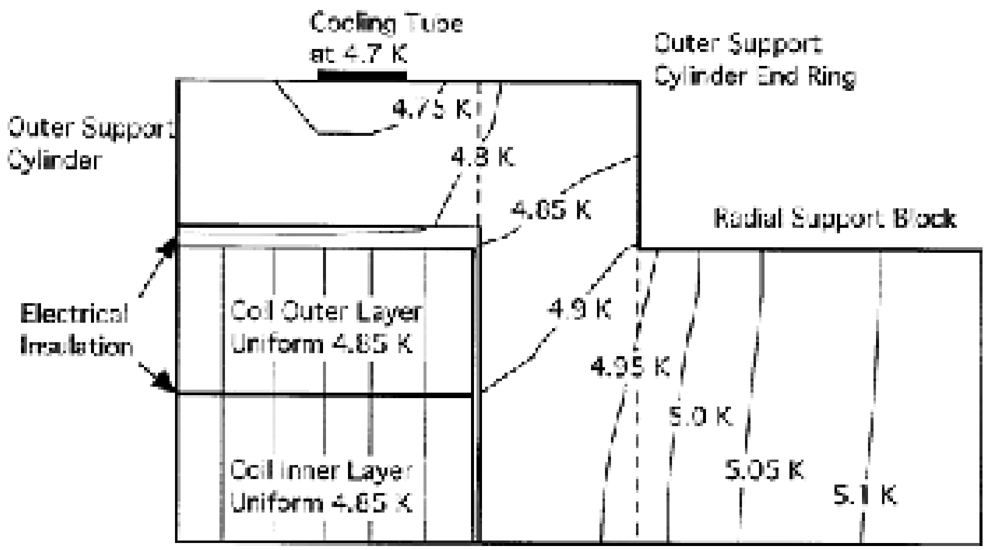


Figure 4.7 Temperature profile near a radial support.

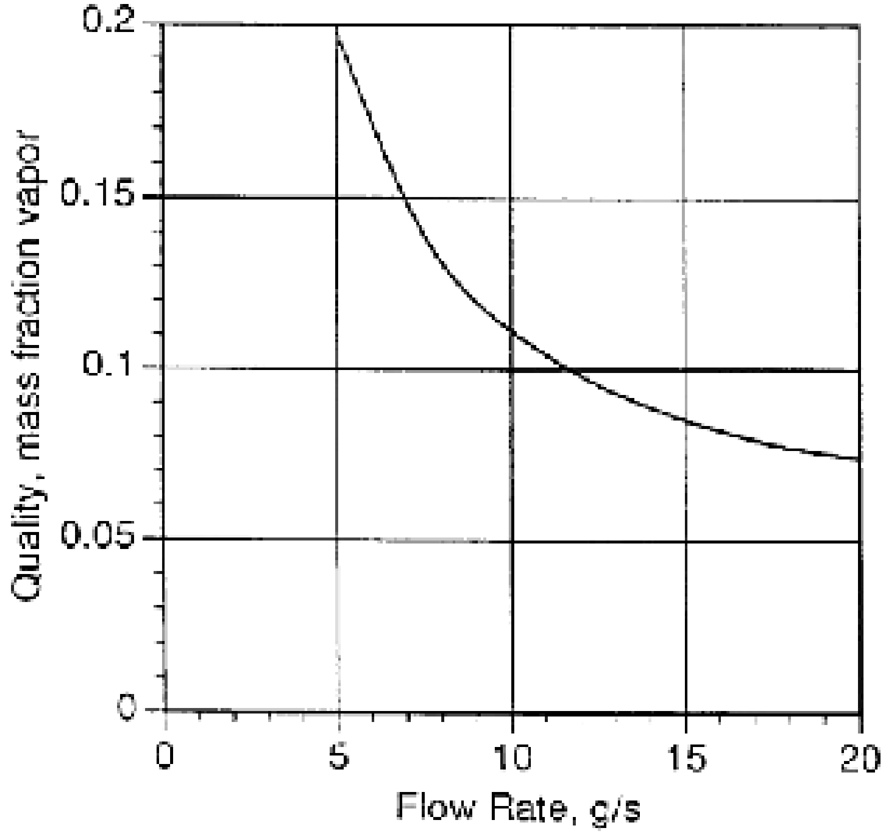


Figure 4.8 Quality of helium leaving the cryostat as a function of mass flow rate of the helium.

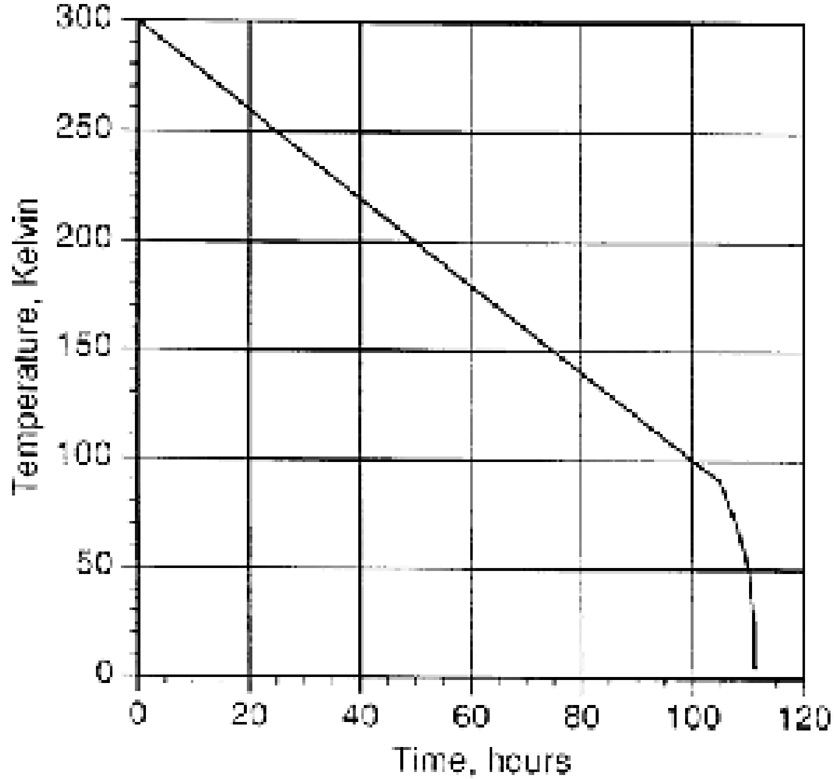


Figure 4.9 Cool down curve for the solenoid cold mass: Coil temperature versus time from beginning of cool down.

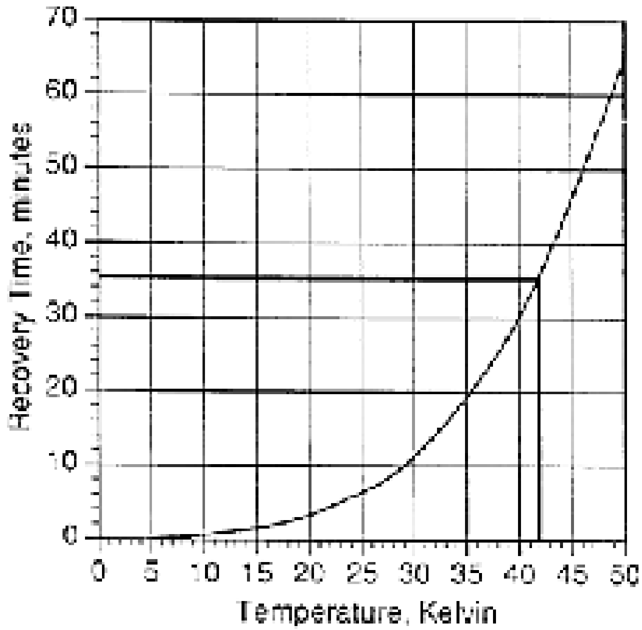


Figure 4.10 Time for coil to reach 4.6 K from an elevated coil temperature.

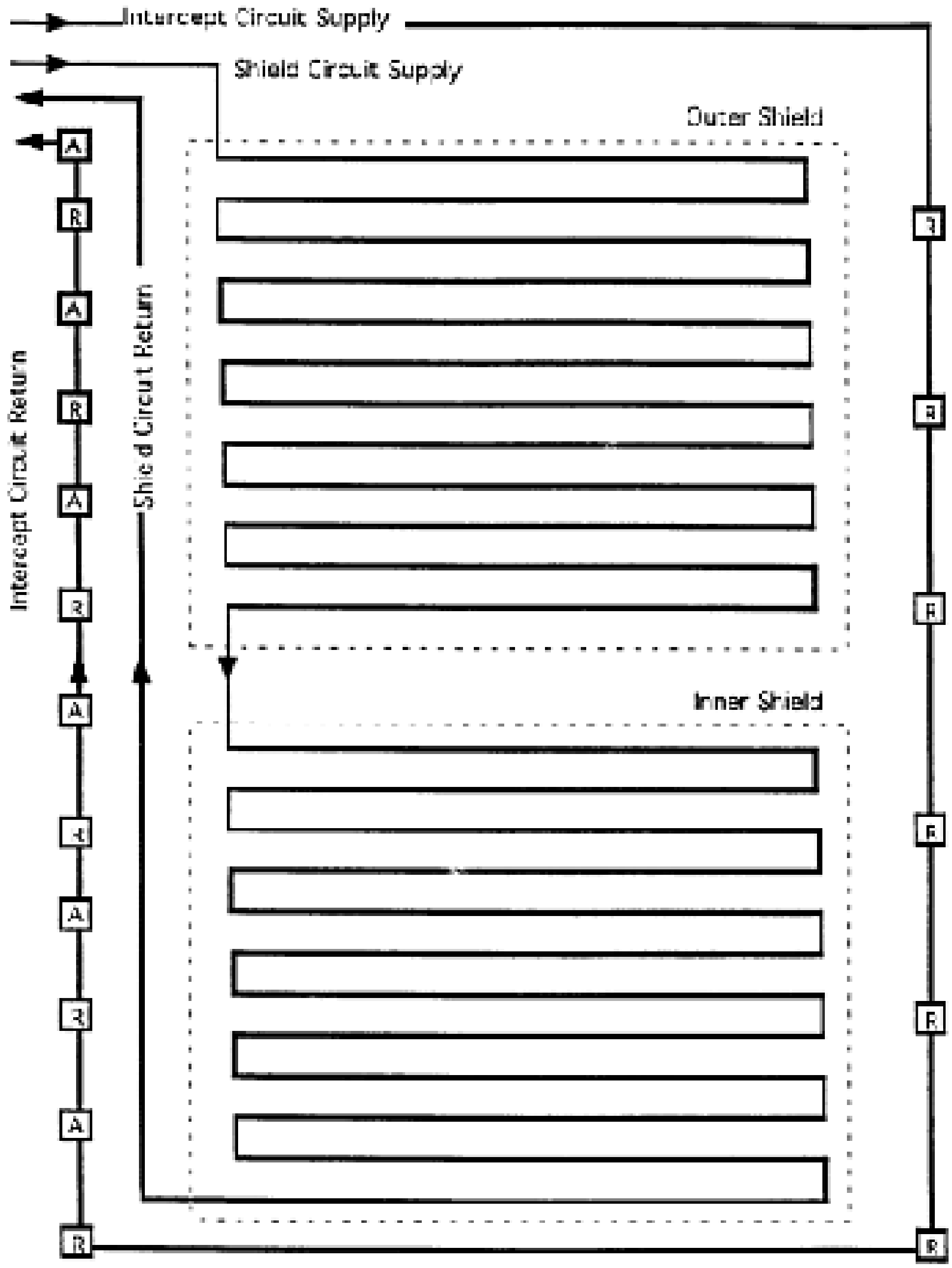


Figure 4.11 Routing of liquid nitrogen cooling tube.

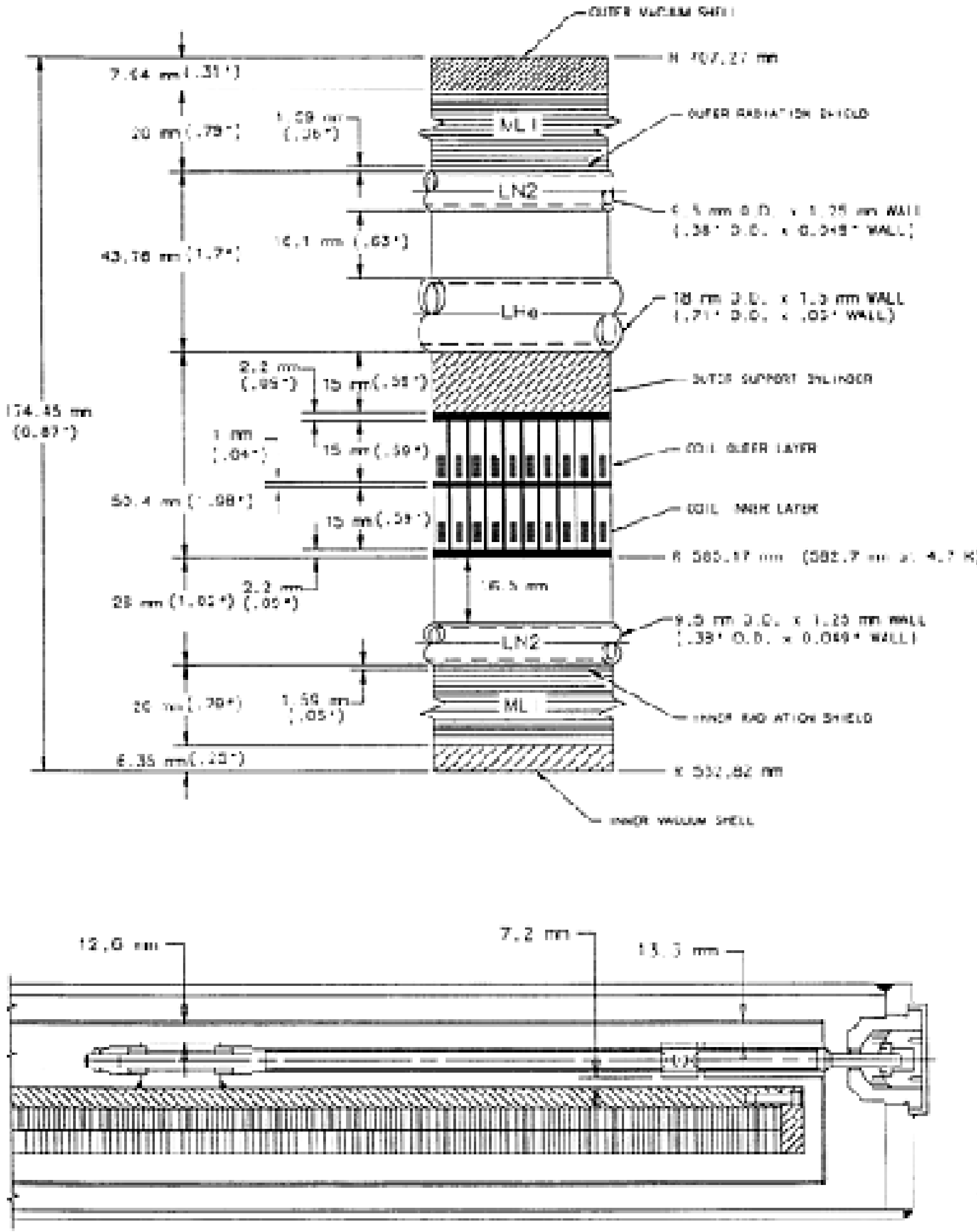


Figure 4.12 Cross sections of the cryostat showing radial dimensions and clearances. All dimensions are with the cold mass at room temperature.