GEM Noble Liquid Calorimeter Inner Barrel Cryostat Design Concept

Kim Barnstable
Mark Lajczok
Bob Humphreys
Martin Marietta Science System

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Abstract:

The noble liquid calorimeter, an integral part of the overall GEM Calorimeter (Figure 1-1), includes barrel and endcap subsystems. The cryostats in both of these subsystems consist of an inner liquid vessel and an outer vacuum vessel. The barrel calorimeter contains liquid krypton (LKr) while the endcap calorimeter contains liquid argon (LAr). Both vessels provide the structural support for the EM and Hadronic modules. The vacuum vessel provides vacuum conditions around the liquid vessel to reduce heat loss through conduction and provides space for a multi-layer insulation to reduce radiation losses. The design concept for the barrel cryostat is discussed in this report and the endcap cryostat is discussed in GEM TN-93-314.

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1.0 INTRODUCTION

The noble liquid calorimeter, an integral part of the overall GEM calorimeter (Figure 1-1), includes barrel and endcap subsystems. The cryostats in both of these subsystems consist of an inner liquid vessel and an outer vacuum vessel. The barrel calorimeter contains liquid krypton (LKr) while the endcap calorimeter contains liquid argon (LAr). Both vessels provide the structural support for the EM and Hadronic modules. The vacuum vessel provides vacuum conditions around the liquid vessel to reduce heat loss through conduction and provides space for a multi-layer insulation to reduce radiation losses. The design concept for the barrel cryostat is discussed in this report and the endcap cryostat is discussed in TN-93-314.

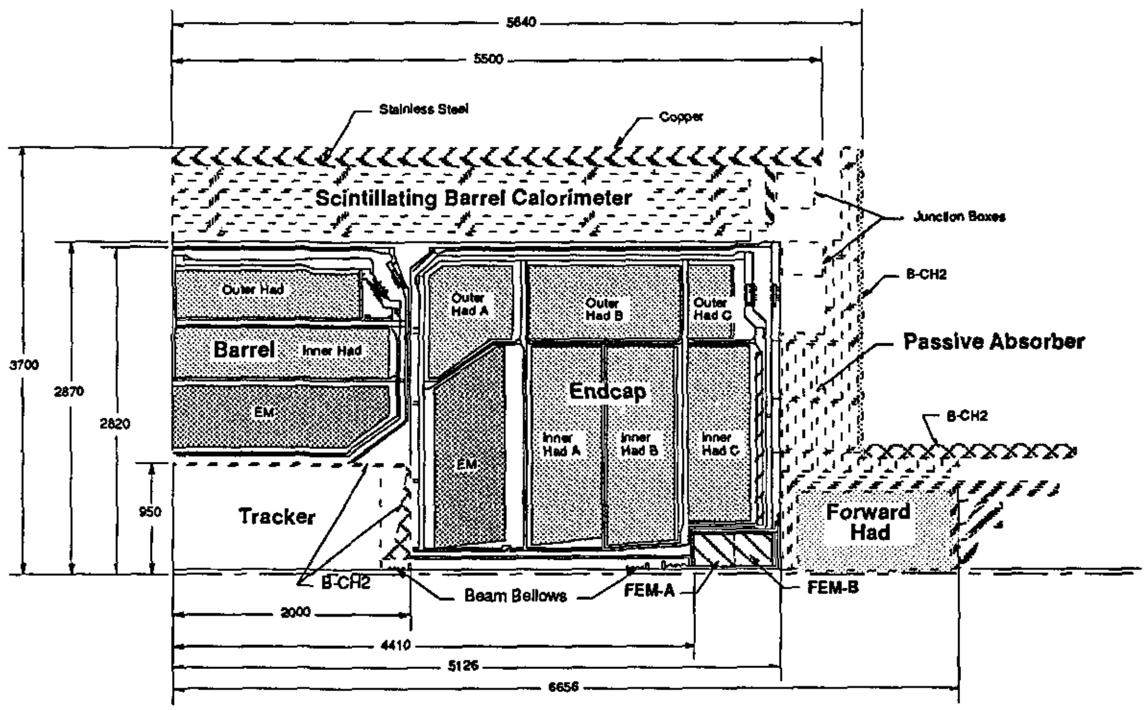

Figure 1-1 GEM Calorimeter Design Concept

2.0 DESIGN REQUIREMENTS

Throughout the conceptual design process consideration has been given to module support, internal vessel stiffness (stays and washers), feedthroughs and cabling orientation, internal cooling circuits, liquid supply systems and the overall thermal effects within the cryostat.

2.1 ASME Code

The liquid and vacuum vessels will be designed to Section VIII, Division 2 ASME code rules and the liquid vessel will be a stamped vessel. The key requirements from the ASME code include the following:

1) Weld joint category (AD-400) and service restriction (AD-155)
2) Base material (Section IX QW-403 and QW-422) and filler material selection (Section IX QW-404 and QW-432).
3) Vessel wall thicknesses (Section VIII, Division 2, Article D-3)
4) Reinforcement of vessel openings (Section VIII, Division 2, Article D-5)
5) Flange thickness (Section VIII, Division 2, Appendix 3)

2.2 Pressure

The liquid vessel must be designed to withstand pressures resulting from the liquid head, ullage pressures, and additional pressure to provide the safety factors required by the ASME code. The barrel liquid krypton vessel design pressure (internal) is .38 MPa (55 psid) at the bottom of the vessel and was derived as follows:

.10 MPa (15 psid)	due to vacuum
.16 MPa (23 psid)	head
.07 MPa (10 psid)	operating over pressure
.05 MPa (7 psid)	relief valve actuation pressure
.38 MPa (55 psid)	

The barrel vacuum vessel is sized to an external operating pressure of 15 psid. The requirements of Section VIII, Division 2 impose restrictive rules to govern design, material selection and non-destructive testing which results in the overall safety factor for the cryostat design.

2.3 Deflection

The vessel wall thicknesses were determined by the deflection, stress and stability requirements. The deflections were limited to 10 mm in all cases and the resultant wall thicknesses were calculated in accordance with Section VIII, Division 2, Articles AD-310, AD-340, and AD-360.

The vacuum vessel wall thickness is determined by atmospheric pressure only and thermal bumpers provide structural integrity through contact with the liquid krypton vessel to minimize excessive dead material within the calorimeter. As a result, the vacuum vessel is not a true pressure vessel per ASME requirements and although constructed to the intent of the ASME requirements, will not be a code stamped vessel. Section 3.2.2. discusses the vessel wall sizing in greater detail. The minimum deflections used for analysis purposes are based primarily on the clearance requirements within the cryostat and as such are not a direct ASME requirement.

2.4 Loads

The liquid vessel is designed to support the weight of the modules with an internal pressure of 0.38 MPa (55 psid). The mass information is given below and in Section 3.1. The approximate mass of these modules in liquid krypton (LKr) is as follows:

EM Modules - 63.5 Mg

Inner Hadronic Modules - 162 Mg

Outer Hadronic Modules - 174 Mg

The vacuum vessel is designed to meet ASME buckling allowables. Section 3.2.2 defines the vessel wall thicknesses as required by ASME code.

2.5 Thermal

The thermal requirements apply to the liquid vessel only. Since the vacuum vessel is isolated from the liquid vessel by insulation it is basically at ambient temperature. The cryostat must provide for the dissipation of heat generated by the electrical components within the ionizing medium and minimize heat loss through conduction and radiation in a manner that assures the following:

a) No localized boiling of the ionization medium,

b) Uniform ionization medium temperature of 120°K, and

c) No more than 1.0% density variation within the ionization medium.

In addition to providing the proper internal thermal environment, the cryostat must withstand the thermal cooldown process without detrimental effects.

3.0 DESIGN CONCEPT

3.1 Overall Size and Mass

The barrel calorimeter is 5640 mm in diameter, 3940 mm in length, and has a mass of approximately 465 Mg. (Fig. 3.1-1) To accommodate the 65,500 electronic channels from the preamps on the barrel EM and Hadronic modules, 40 penetrations in each end of the barrel calorimeter are provided for feedthrough ports. The external radius of the vacuum vessel is limited by the interface with the Scintillating Barrel Calorimeter and the inner radius provides clearance for the Central Tracker installation. The 50 mm minimum space between the vacuum vessel and the liquid vessel on the outside diameter was selected to accommodate the electronics and internal cooling circuits associated with the outer hadronic modules and the liquid vessel outer shell cooling requirements.

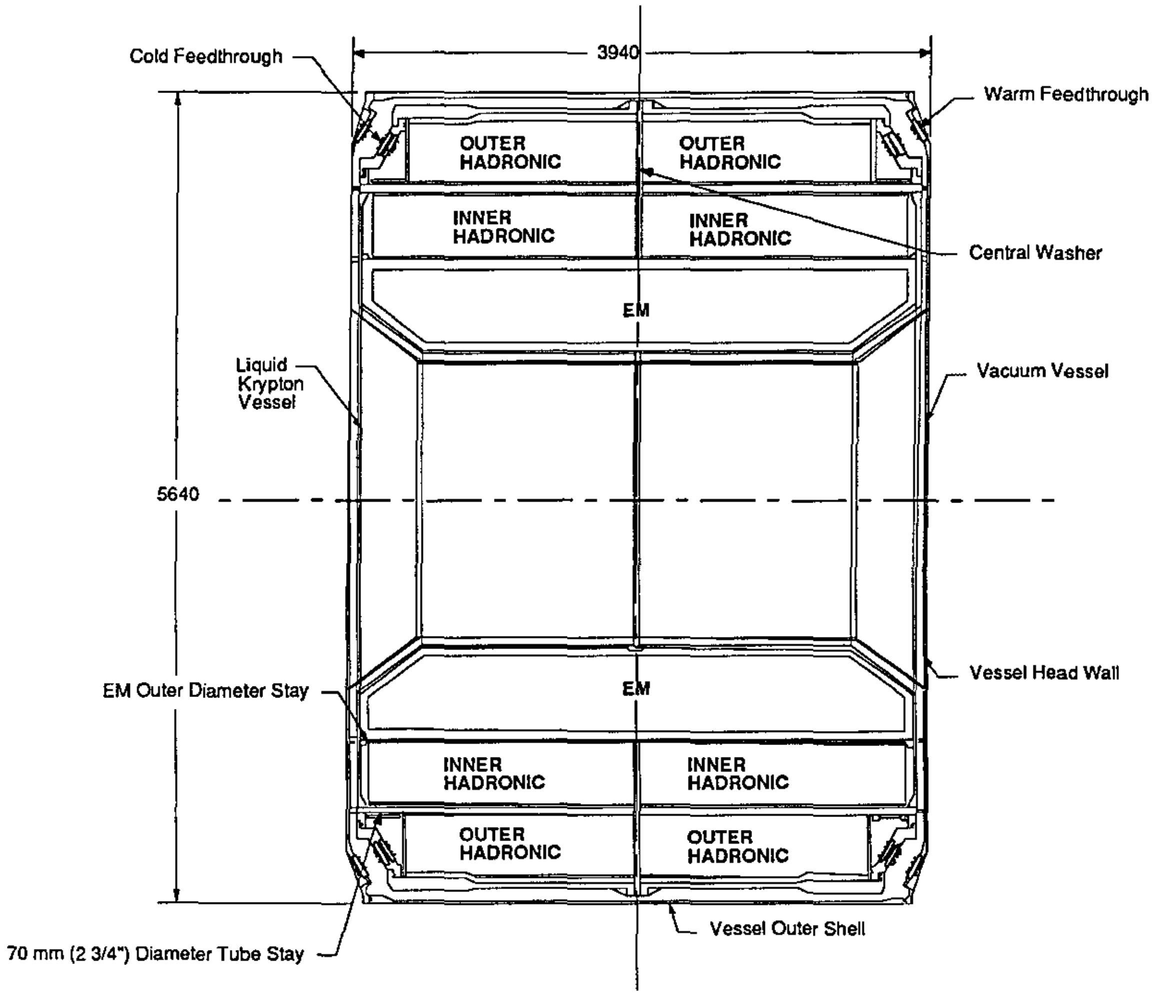

Figure 3.1-1 Key Barrel Cryostat Characteristics

3.2 Structural Design

Both the liquid and vacuum vessels include a series of bolted flanges which are welded using seal welds during assembly. The seal welds limit the heat affected zone during welding. By providing flanged joints with o-ring seals, incremental acceptance testing can be performed and compliance verified during fabrication. The o-ring seals are not used for the final operational configuration.

To accommodate the assembly sequence, the individual EM modules (TN-93-320) and Hadronic modules (TN-93-311) provide their own structural integrity at the 9° module assembly level. However, the liquid krypton vessel must be able to transfer the loads due to the weight of the modules to the support stanchions. For both the EM and Hadronic modules the primary load path within the cryostat is through the central washer and the vessel head walls (Fig. 3.1-1). This configuration allows access for the radial installation of the hadronic modules and axial installation of the EM modules. The central washer and the head walls of the liquid krypton vessel provide restraint in the "Z" direction (parallel to the beamline) for the hadronic modules by engaging a radial keyway (TN-93-311) on the heads and the central washer (Fig. 3.2-1).

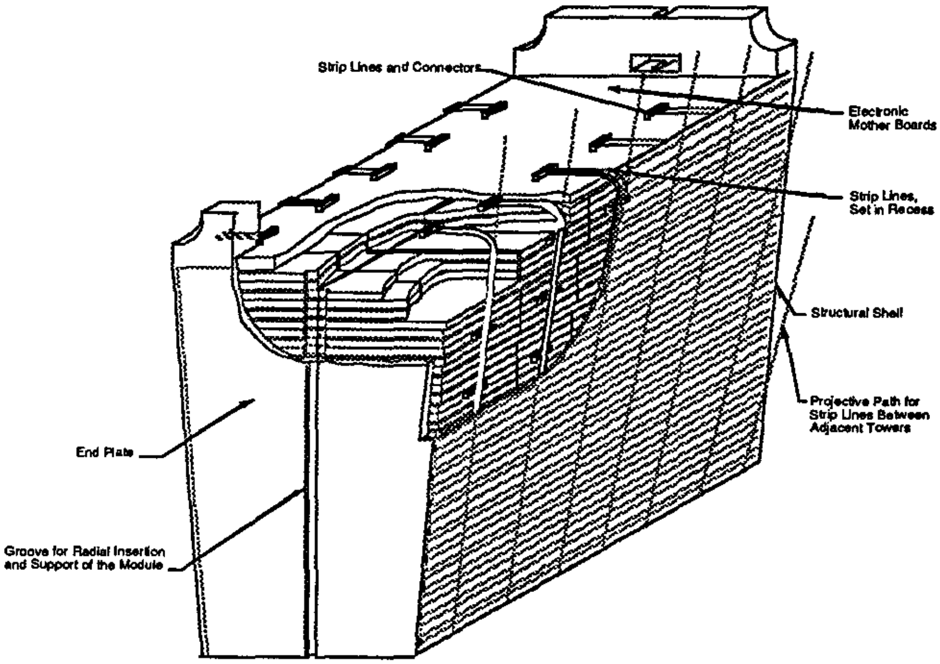

Figure 3.2-1 Hadronic Module Structure

Figure 3.2-2 shows the various liquid and vacuum vessel subassemblies that constitute the cryostat. Assembly requires a structural weld to attach the various subassembly components and flanges. Additional structural welds are used to attach the two halves of the liquid vessel inside diameter section (Fig. 3.2-2a) and the two halves of the vacuum vessel inside diameter sections (Fig. 3.2-2g). The remaining joints are bolted.

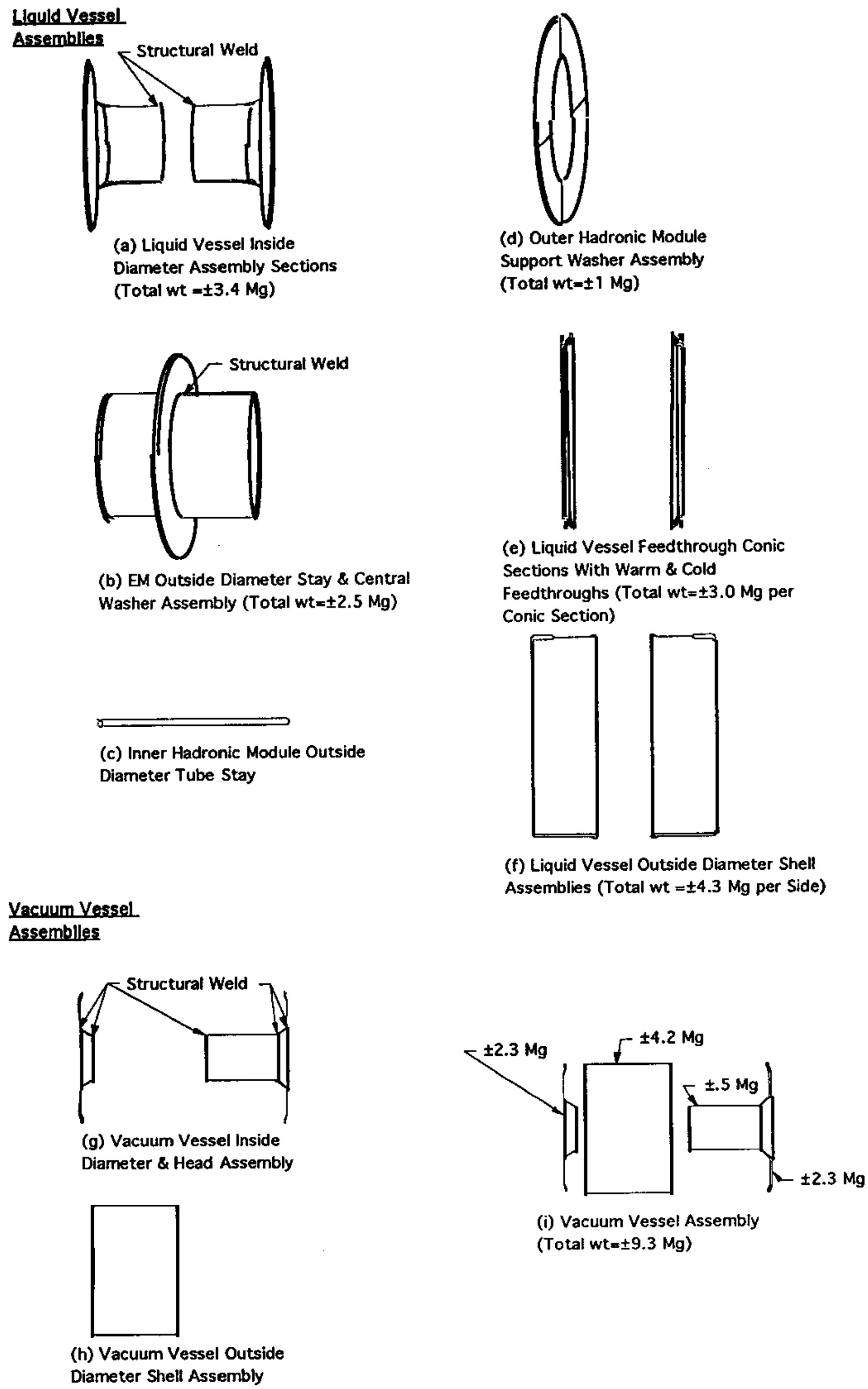

Figure 3.2-2 Major Cryostat Components

Both the liquid krypton and vacuum vessels incorporate flanged joints in their design for ease of assembly. The bolts react axial loads and a keyed surface within the flange design accommodates shear loads. All bolted joints contain heli-coil type inserts and the bolts will be stainless steel per specification number SA-193, Grade B8MNA/316N, Class 1A consisting of Cr-Ni-Mo-N per Section VIII, Division 2. This configuration allows integral proof testing of the vessels prior to assembling the entire barrel calorimeter and requires a seal plate to be welded over the bolts and joints after assembly (Fig. 3.2-3). This sealing process utilizes a partial penetration weld which requires much less heat input than that required for a full penetration welded vessel. Therefore, the heat input and potential damage to electronics can be minimized with this technique.

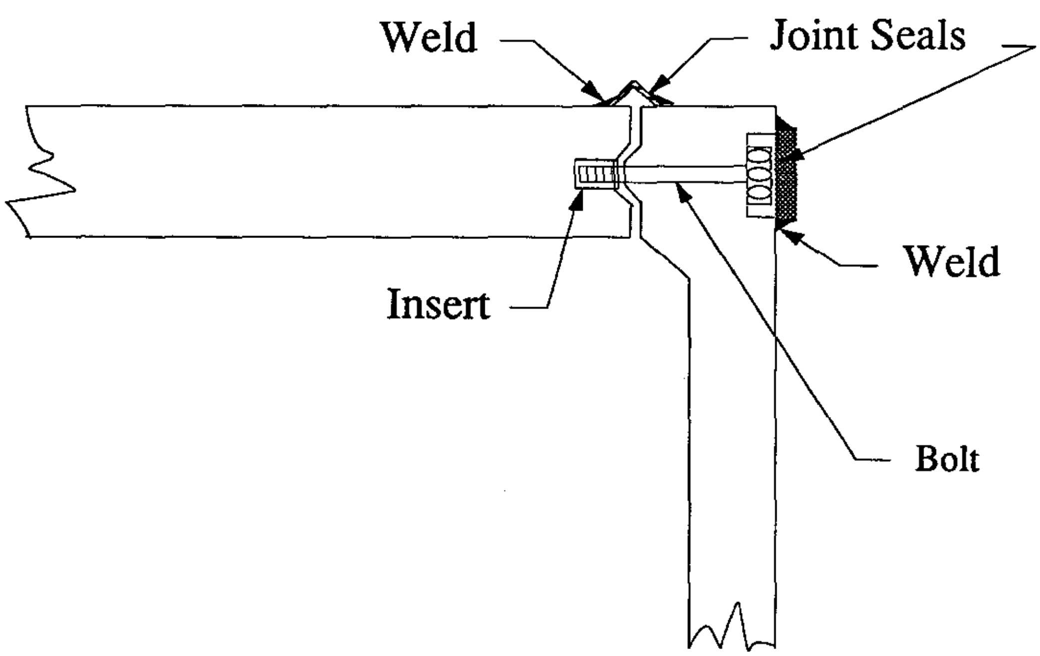

Figure 3.2-3 Joint Seal Details

The liquid vessel is designed for fluid pressure loads, thermal loads and module support loads. A cylindrical stay located between the EM modules and the inner Hadronic modules, and a series of 70 mm (2 3/4 ") diameter tube stays, located radially outward from the inner Hadronic modules, provide structural continuity between the heads, resulting in a thinner head wall (Fig. 3.2-4). The cylindrical stay between the EM and inner Hadronic modules is penetrated for liquid krypton communication and for cables and cooling piping.

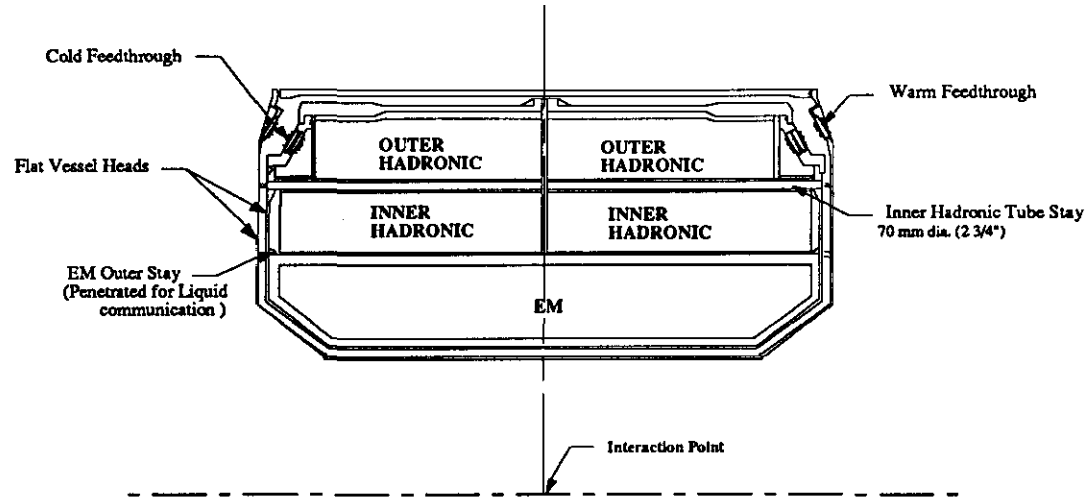

Figure 3.2-4 Barrel Cryostat Components

The heads of the barrel and endcap are flat (rather than conical or elliptical) to minimize the distance between them. This results in the least impact to hermeticity in this transition area.

3.2.1 Material and Allowables

The overall manufacturability and transportability of the cryostat were considered during the conceptual design phase. The choice of 5083 aluminum is a direct result of these considerations. The 5000 series aluminum has a high machinability rating so the speed and ease of machining make it an attractive material for the construction of the cryostat. The weldability, absorption length and radiation length of 5083 aluminum make it a better choice than stainless steel or titanium for the cylindrical shells of the cryostat which are buckling critical. Conversely, the added stiffness and decreased absorption length of titanium make it a better choice for the vessel heads which are bending critical. However, the expense and difficulty involved with welding and sealing bi-metallic joints make the combination of aluminum and titanium less attractive. Therefore, 5083 aluminum is the chosen material throughout the vessels within the barrel cryostat.

ASME Section IX, Welding and Brazing (QW-420) assigns P- Numbers to the base weld materials by grouping similiar characteristics of the base material metals. These characteristics consist of composition, weldability, and mechanical properties. The specification number SB-209 for the 5083 vessels has a P-Number of 25. The specification number SB-241 for the 5454 inner Hadronic module outside diameter stay has a P-Number of 22. The filler material for welding P-Number 25 to P-Number 25 and P-Number 25 to P-Number 22 is ER5356 as specified by SFA-5.10 per ASME Section II, Part C and Section IX, QW-404 and QW-432.2. Some combinations of P-Numbers such as P-Number 22 and P-Number 25 may require additional Weld Procedure Specification (WPS) and Procedure Qualification Records (PQR).

The cryostat is constructed of an aluminum alloy having a nominal composition of Mg-Mn-Cr. The Code specifies SB-209, alloy designation 5083. For welded construction, the stress intensity values (S_m) for this material shall be based on 0 temper. The stress intensities allowed by Section VIII, Division 2, Table ANF-1.1 are shown in Table 3.2.1-1 for metal temperature not exceeding 100°F.

Table 3.2.1-2 shows various loading conditions and compares the absorption and radiation lengths associated with the use of aluminum, stainless steel, or titanium for the cryostat shells, heads, or washers.

The liquid and vacuum vessel shells are stress and buckling stability critical. Table 3.2.1-2 shows that from an absorption length and stress standpoint, titanium would be the best material selection. However, for radiation length aluminum is the best material choice for the shells. Shell stability is best suited for stainless steel but the associated absorption and radiation lengths are optium when using aluminum.

The liquid vessel and vacuum vessel heads are sized by bending and deflection. Table 3.2.1-2 demonstrates that titanium is the preferred choice for bending and stainless steel is the preferred choice for deflection reasons. However, aluminum is the optium material choice for absorption and radiation lengths for both the bending and deflection cases.

The washers within the liquid vessel are stability critical and Table 3.2.1-2 shows that stability is best when using stainless steel. The absorption and radiation lengths are optimum with aluminum washers.

The use of stainless steel or titanium is favorable for most load cases and arguments could be made for using these materials for the vacuum vessel. However, Table 3.2.1-2 shows that using stainless steel or titanium for the vacuum vessel shell results in an absorption length that is greater than that of aluminum by a factor 1.70 to 2.07. In addition, stainless steel or titanium results in a radiation length that is greater than that of aluminum by a factor of 3.65 to 4.45. The vessel heads for either the liquid or vacuum vessel show aluminum as the best choice from the absorption and radiation length standpoints. If titanium or stainless steel was used for the shell design, the aluminum heads would require a bi-metallic flange joint to be used at the shell and head interface. In addition, the inner diameter of the cryostat would need to be aluminum in order to mimimize the associated radiation length. Using two materials in the cryostat design requires careful consideration of the coefficient of thermal expansion for both materials to ensure proper sealing and structural integrity at these bi-metallic joints.

The liquid vessel requires aluminum for the washer and head design and, rather than considering the use of different shell materials and a bi-metallic joint for this pressure vessel, the best overall choice is aluminum.

Table 3.2.1-1 Allowable Stress Intensity for SB-209 (0 temper)

Alloy	Thickness mm(in)	S_m MPa (ksi)
5083	1.3 - 38.1 (0.051 - 1.5)	82.8 (12.0)
5083	38.125 - 76.2) (1.501 - 3.0)	85.5 (11.4)
5083	76.225 - 127 (3.001 - 5.0)	73.8 (10.7)

Table 3.2.1-2 Cryostat Material Performance Based on ASME Section VIII, Division 2 (Referenced to Aluminum)

	Cryostat Performance Ratio		
Feature	Aluminum 5083 SB-209	Steel 304L SA-240	Titanium Grade 3
Material Properties			
ρ (g/cm^2)	2.70	7.92	4.54
λ(cm)	39.407	16.654	27.511
X_o(cm)	8.893	1.747	3.562
S_m(10^3 psi @ 100°F) *	12	16.7	21.7
E (10^6 psi @ 70°F)	10.3	28.3	15.5
Shells			
t/t_{Al}(Stress: $S_m^{1.0}$)	1	0.72	0.55
$(t/t_{Al})(\lambda_{Al}/\lambda)$	1	1.70	0.79
$(t/t_{Al})(X_{oAl}/X_o)$	1	3.66	1.38
t/t_{Al}(External Pressure / Stability: $E^{1/3}$)	1	0.72	0.87
$(t/t_{Al})(\lambda_{Al}/\lambda)$	1	1.70	2.07
$(t/t_{Al})(X_{oAl}/X_o)$	1	3.65	4.45
Heads			
t/t_{Al}(Bending: $S_m^{1/2}$)	1	0.85	0.74
$(t/t_{Al})(\lambda_{Al}/\lambda)$	1	2.01	1.76
$(t/t_{Al})(X_{oAl}/X_o)$	1	4.32	3.79
t/t_{Al}(Deflection: $E^{1/3}$)	1	0.72	0.87
$(t/t_{Al})(\lambda_{Al}/\lambda)$	1	1.70	2.07
$(t/t_{Al})(X_{oAl}/X_o)$	1	3.65	4.45
Washers			
t/t_{Al}(Radial Compression / Stability: $E^{1/2}$)	1	0.60	0.82
$(t/t_{Al})(\lambda_{Al}/\lambda)$	1	1.43	1.93
$(t/t_{Al})(X_{oAl}/X_o)$	1	3.07	4.15

* ASME Section VIII, Division 2, Membrane Stress Intensity

3.2.2 Vessel Component Sizing

An 18 deg finite element model of the barrel cryostat was constructed (Fig. 3.2.2-1). Because of the structural and loading symmetry only half the length of the barrel cryostat was modeled using linear thin shell elements. The 70.0 mm outer diameter tube stays located on the outside diameter of the inner Hadronic models were modeled as a smeared structure using shell elements with Poisson's Ratio in the hoop direction set to zero. Bolted joints were modeled by joining only the translational degrees-of-freedom of the mating shells. Thermal bumpers, discussed in Section 3.2.2.3, were modeled using node-to-node gap elements. For analysis purposes, the thermal bumpers and bolted joint locations have been identified in Figure 3.2.2-2. In addition, identification numbers have been given to the liquid and vacuum vessel walls and to the thermal bumpers.

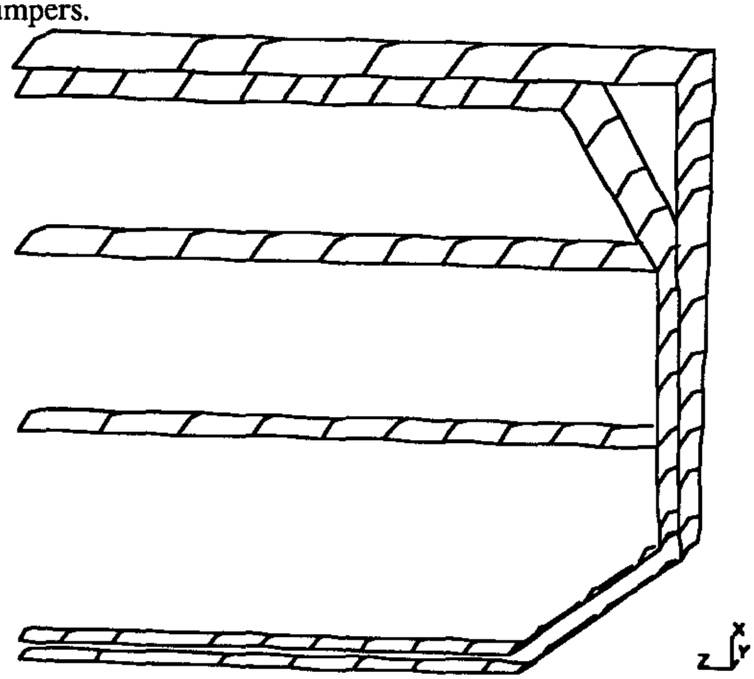

Figure 3.2.2-1 Finite Element Model of Barrel Cryostat

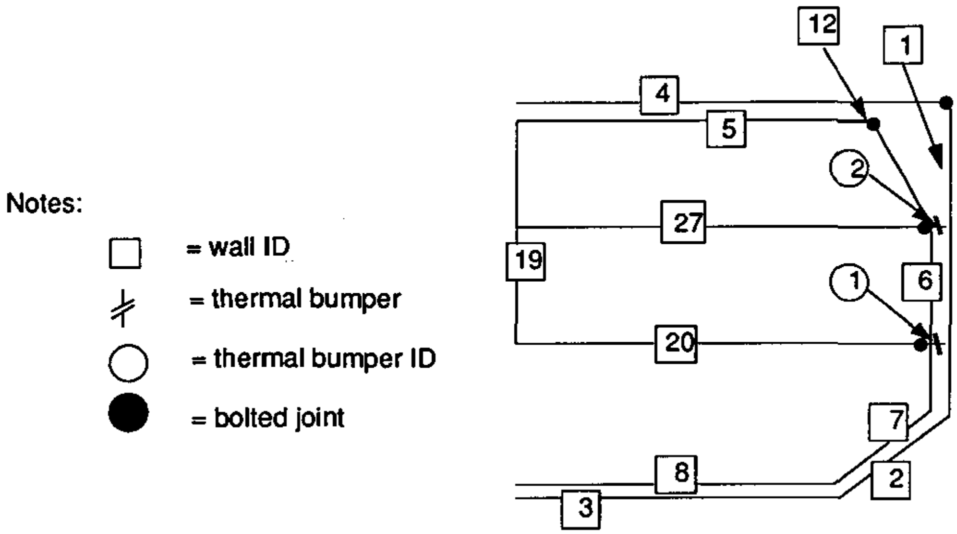

Figure 3.2.2-2 Barrel Cryostat Vessel Wall Components

During assembly, installation and operation, the calorimeter is subject to various loading conditions which must be analyzed to determine their effects on component sizing. These loading conditions are listed below:

1. Assembly
   - weight of the EM and Hadron Modules
2. Operation Condition 1
   - vacuum in liquid and vacuum vessel, atmospheric conditions external to vacuum vessel
3. Operation Condition 2
   - liquid vessel filled with LKr, vacuum in vacuum vessel and atmospheric conditions external to vacuum vessel
4. Fault Condition
   - liquid vessel filled with LKr, vacuum vessel subject to 0.07 MPa (10 psid) over pressure

Currently, finite element analysis has been performed for only Operation Condition 2. However, the wet weight of the EM and Hadronic modules was applied to the stanchion location (wall ID = 12) as a uniform pressure of 1.24 MPa (180 psid). This pressure was based on assuming a uniform pressure existing at the "belly strap" (Section 3.2.3) due to the weight of the modules. Even though the "belly strap" is applied over 135.2° it is applied to the finite element model over the full circumference. The load path taken by the dead weight of the Hadronic and EM Modules was not considered at this time.

The wall thicknesses were determined based on stress, deflection and stability requirements. The deflections were limited to 10 mm. The stress requirements were in accordance with Appendix 4, Article 4-1 of ASME Section VIII, Division 2. The minimum required wall thicknesses of the cylindrical and conical shells under external pressure and axial compression were calculated in accordance with ASME Section VIII, Division 2, Articles AD-310, AD-340 and AD-360. The results of these calculations are shown in Table 3.2.2-1.

Table 3.2.2-1 Minimum Vessel Wall Thickness Based On ASME Buckling Allowables

WALL ID	THICKNESS mm	PRESSURE [1] MPa (psid)	TYPE OF BUCKLING [2]
2	11	0.07(10)	H
3	11	0.07(10)	H
4	23	0.1 (14.7)	H
5	23	0.1 (14.7)	H
7	22	0.38 (55)	H
8	22	0.38 (55)	H
12	89	1.24 (180)	H
20	5	0.1 (14.7)	A

Notes: 1. 0.07 MPa(10 psid) over pressure
2. A = AXIAL , H = HOOP

In addition to the ASME minimum wall criteria, a lower limit of 10 mm was set on all wall thicknesses. The stress allowances and stability requirements as defined in ASME Section VIII, Division 2 were used in determining the vessel wall thicknesses. However, the vessel walls sized by stress or deflection were determined by finite element analysis (Table 3.2.2-2 and Table 3.2.2-3). It should be noted that all wall thicknesses are derived from the stress and deflection requirements and the ASME stability requirements do not drive the wall thicknesses.

Table 3.2.2-2 Minimum Vessel Wall Thickness Based On Finite Element Analysis

WALL ID	THICKNESS mm
1	12
6	23
20	10

The deflections and stresses for the vessel heads are presented in Table 3.2.2-3. The deformation of the barrel cryostat subject to internal and vacuum pressures is illustrated in Figure 3.2.2-3.

Table 3.2.2-3 Deflections and Stresses of Vessel Heads

WALL ID	BEAM LINE DEFLECTION mm		STRESS INTENSITY MPa (ksi)	
	Analysis	Allowable	Analysis	Allowable
1	7.4	10	105 (15.2)	124 (18.0)
6	4.3	10	29.7 (4.3)	124 (18.0)

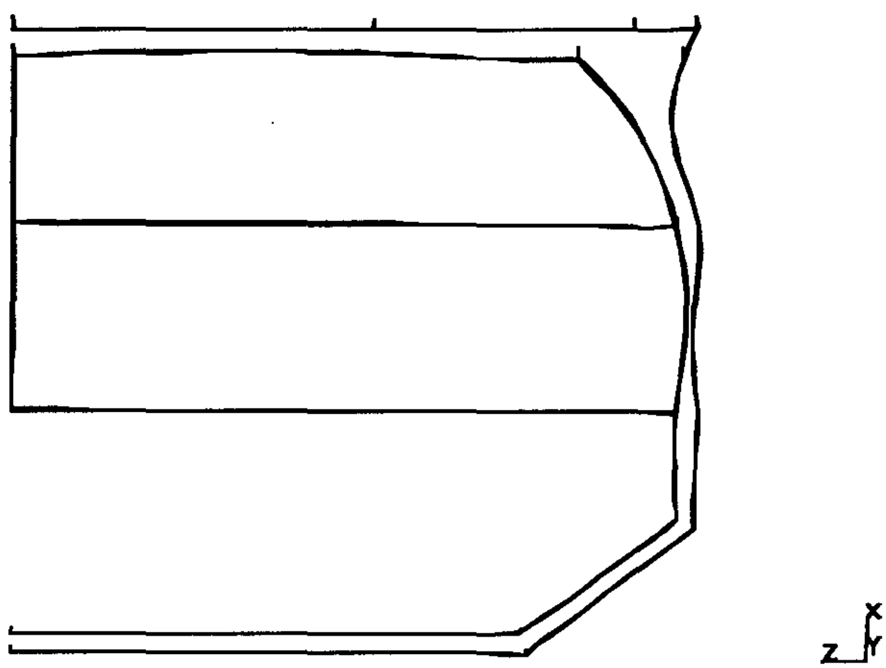

Figure 3.2.2-3 Deformed Finite Element Model of Barrel Cryostat

The bolt loads carried by the joints are presented in Table 3.2.2-4. These loads do not include the effects of heel-toe action.

Table 3.2.2-4 Vessel Bolted Joint Loads

WALL ID	LOAD kN(kips)	WALL ID	LOAD kN (kips)
4	405(91)	12	792(178)
20	1864 (419)	27	1214 (273)

3.2.2.1 Central Washer Sizing

Since the central washer (wall ID = 19) carries approximately the same magnitude of load as the aft endcap washer (TN-93-314), it is also sized for stability due to the compressive loads generated from the weight of the modules being transferred to the stanchion. It was assumed that the compressive loads were applied as a uniform radial pressure along the outer radius of the washer. From Reference 1, the allowable compressive stress is given for a circular plate under uniform compression on the outer edge with the outer edge clamped and the inner edge free. Since the compressive loads are reacted by the stanchion support which is applied only over 135.2° (Fig. 3.2.2.1-1) and the inner edge of the washer is welded to a cylindrical shell, the assumption of a uniform compressive load has an inherent knockdown factor built into the calculation of the wall thickness. The critical buckling stress, σ, is given by:

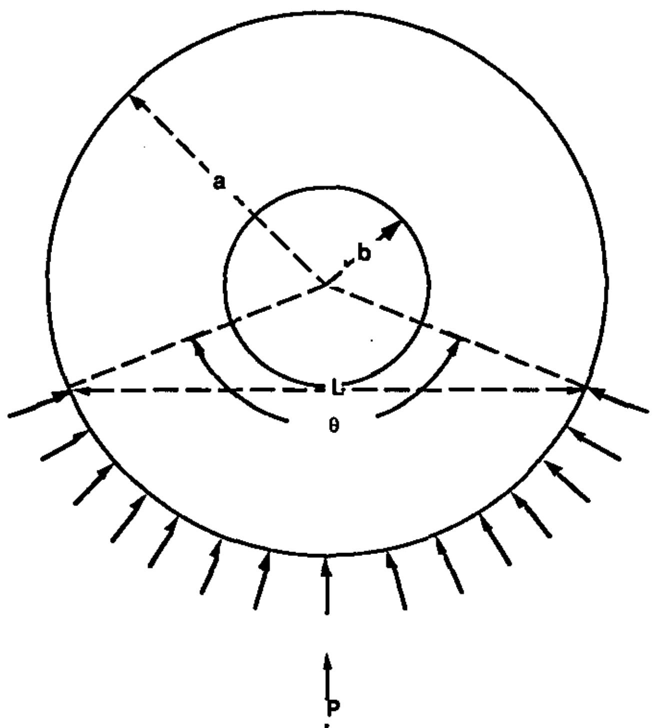

Figure 3.2.2.1-1 Geometry and Loading For Central Washer Sizing

$$\sigma = K \frac{E}{1 - \nu^2} \left(\frac{t}{a}\right)^2$$

where

K depends on $\left(\frac{b}{a}\right)$

given

$E = 71018$ MPa (10.3×10^6psi)

$\theta = 135°$

$\nu = 0.32$

a = 2749 mm (108.23 in)

b = 199.9 mm (7.87 in)

(b/a) = 0.073

for case 12b (fixed)

K = 1.17

The Stanchion stress, σ_s, is given by:

$$\sigma_s = \frac{P}{2 \sin\left(\frac{\theta}{2}\right) a\, t}$$

where

P = stanchion load = 2285 kN (513.7 kips)

θ = support angle =135.2°

By equating the critical stress to the stanchion stress we obtain the required thickness for the washer: t= 34 mm(1.34 in)

3.2.2.2 Hadronic Modules Stay Sizing

Forty tubular stays (wall ID = 27) are located on the outside diameter of the inner Hadronic modules. They are continuous members which pass through the central washer. They are assumed to be fixed at the heads and pinned at the central washer. They are seamless tube made of a aluminum alloy having a nominal composition of Mg-Mn-Cr. The Code specifies SB-241, alloy designation 5454 with 0 temper. The inside diameter is fixed at 12.7 mm. The outside diameter is determined in accordance with the stability requirements of the AISC, ASD, Ninth Edition. The stability condition arises as a result of vacuum pressure (0.1 MPa). The stays are treated as a fixed/pinned beam having an effective length factor, K, equal to 0.8 as given in Table C-C2.1 of the code. The allowable stress, F_a ,is given by Equations (E2-1) and (E2-2) of the code as follows:

$$F_a = \frac{\left[1 - \frac{(Kl/r)^2}{2\,C_c^2}\right] F_y}{\frac{5}{3} + \frac{3\,(Kl/r)}{8\,C_c} - \frac{(Kl/r)^3}{8\,C_c^3}} \qquad \text{(E2-1)}$$

where

$$C_c = \sqrt{\frac{2\,\pi^2\,E}{F_y}}$$

when Kl/r exceeds C_c, the allowable stress is:

$$F_a = \frac{12\,\pi^2\,E}{23\,(Kl/r)^2} \qquad \text{(E2-2)}$$

where

E = modulus of Elasticity = 71018 MPa (10.3×10^6 psi)
F_y = yield strength = 82.7 MPa (12 ksi)
K = 0.8
l = length of stay from head to washer=1886 mm (74.25 in)
r = radius of gyration = $\sqrt{I/A}$
I = area moment of inertia of tube = $\frac{\pi}{4}\left[r_0^4 - r_i^4\right]$
A = cross sectional area of tube = $\pi\left[r_0^2 - r_i^2\right]$
r_0 = outside radius of tube to be determined
r_i = inside radius of tube = 6.35 mm (0.25 in)

The required outside radius is calculated by equating the allowable stress to the compressive stress. The allowable stress is calculated using Eq. (E2-1) based on the stated criteria and the compressive stress is based upon vacuum conditions within the liquid vessel.

$$F_c = f_s / A$$

where

f_s = force acting on each stay = 22.4 kN (5030 lbs)

This results in a required outside radius of 34.9 mm (1.375 in).

3.2.2.3 Thermal Bumper Sizing

Currently, only the loads transferred through the thermal bumpers as a result of internal pressure and vacuum have been calculated (Table 3.2.2.3-1). Bumper locations are shown in Figure 3.2.2-2.

Table 3.2.2.3-1 Thermal Bumper Compressive Loads

BUMPER ID	FORCE kN (kips)
1	488 (109.7)
2	972 (218.6)

3.2.3 Stanchions

The support stanchion concept is similar to that in the D-Zero design. The barrel is supported using four thermal contraction support stanchions. The stanchion consists of a series of parallel plates, that are oriented perpendicular to the interaction point of the barrel so that the vessels will shrink with respect to the interaction point of the barrel calorimeter. A "belly strap" spans from the stanchion on one side of the barrel to the stanchion on the other side to help distribute the load more uniformly and avoid point loading the vessel walls. The vertical parallel plates provide a strong column to carry the weight load of the cryostat but also allows thermal flexibility.

3.2.4 EM Module Support

The 9° EM modules are assembled into a 360° cylinder and are held together using tensioning bands on the inner and outer diameters. The primary load path for the EM modules is through the central washer and the head at each end of the barrel liquid krypton vessel. Further study of the deflections and associated loads due to assembling the Hadronic modules will determine if the EM modules can be radially supported only at each head. In either case the EM modules will be restrained in the "Z" direction at the central washer. Reference TN-93-320 for further details on the EM module structural details.

3.2.5 Hadronic Module Support

The 9° Hadronic modules are supported radially on key ways to lock them in place in the phi direction and are directly bolted to the central washer to provide "Z" restraint. The keyway on the head portion of the vessel locates the phi position of the modules but allows motion in the "Z" direction. This flexibility in the "Z" direction allows for the difference in the coefficients of thermal expansion between the vessel and the module during cool down (TN-93-311).

3.2.6 Future Structural Analysis

So far the overall barrel cryostat component sizing has been based on operation loads. Further analysis is in progress to determine component sizing based on the assembly loads.

Detailed local stress analysis will be performed to determine the dimensions of bolted and welded joints and fastener sizes. Analysis will also be performed to size the stanchions and thermal bumpers.

3.3 Thermal Design

3.3.1 Thermal Expansion and Contraction

During the cool down process the design must accommodate the relative coefficients of thermal expansion within the cryostat. The use of 5083 aluminum throughout the majority of the vessel allows the expansion and contraction of the vessels to be predictable. However, the use of lead, brass, stainless steel and G10 in the construction of the EM and Hadronic modules requires proper engineering design to eliminate the thermal expansion concerns. Table 3.3.1-1 shows the comparison of the warm and cold stackup dimensions in the radial direction for the barrel cryostat.

Table 3.3.1-1 Cold and Ambient Cryostat Locations

	Cold (120°K)		Ambient (293°K)	
Barrel calorimeter	Depth, mm	Radius mm	Depth, mm	Radius mm
Cryostat Inner Radius	950	950.00	950	950.00
Cryostat Vessels				
Vacuum wall	11	961.00	11	961.00
Vacuum Space	50	1011.00	53.44	1014.44
Krypton Wall	22	1033.00	22.07	1036.51
Stay	10	1680.40	10.03	1686.11
Stay	25.4	2189.41	25.5	2196.85
Cryostat Vessels				
Krypton Vessel	35	2709.60	35.12	2718.81
Flange	48	2757.60	48.16	2766.97
Vacuum space	39.4	2797.00	30.03	2797.00
Vacuum Vessel	23	2820.00	23	2820.00
Note : Ambient dimensions based on % Δ L/L = 0.34(Reference 2)				

The support technique for the Hadronic modules account for thermal expansion by bolting one end of the module to the central washer and allowing the other end to expand and contract without compromising the structural integrity of the vessel.

The EM modules are also accommodated by limiting their contact area with the aluminum cryostat and by controlling the G10 lay-up orientation of the components to cause them to expand and contract like the aluminum cryostat.

3.3.2 Internal Cooling Circuits

An internal liquid argon cooling system will be used to efficiently remove the heat output due to the preamps on the EM and Hadronic modules. Additional cooling lines provide a heat intercept at the stanchion supports and the feedthrough locations on the cryostat. This cooling system consists of a series of supply and return networks and provisions are made for these lines to penetrate the vessel shell and heads. The individual cooling loops are supplied with cold liquid argon through a manifold system on the heads and the "warm" liquid argon is returned to a separate manifold system on the heads. Reference TN-93-316 for a detailed description of the internal cooling system.

3.3.3 Support Stanchions

The support stanchions also require thermal design to prevent a thermal short due to a heat leak between the ambient support and the liquid krypton vessel. This is prevented by incorporating a thermal intercept at the interface of the stanchion and the liquid krypton vessel. One method of creating this heat intercept is to use a thermal siphoning system. Such a system would supply liquid cryogen from the bottom of the liquid vessel to the top of the support stanchion. The liquid head pressure in the vessel will transmit the fluid to the heat intercept area. The resultant heat transfer is then within acceptable limits.

3.3.4 Insulation

The ambient vacuum vessel wall is isolated from the cold liquid Krypton vessel by multi-layer insulation (MLI). For cryogenic applications, MLI provides low thermal conductivity and reduces heat transfer due to radiation. It also provides the best performance of all insulations. MLI is very lightweight and more stable than most other insulation options. Some concerns with MLI are that it is difficult to fit onto complex shapes and its performance is dependent upon maintaining adequate vacuum. The solution to this concern is to use care when closing out the MLI wrap so the internal cold wall layers do not create a thermal short to the outer warm layers. The vacuum system design will insure the 1 x E-4 Torr required for adequate MLI performance.

3.3.5 Feedthroughs

Two feedthrough designs are currently under consideration. Both designs require one feedthrough in the liquid krypton vessel wall (cold feedthrough) and one in the vacuum vessel wall (warm feedthrough).

One option consists of a continuous stripline cable from the inside of the liquid krypton vessel to the junction box located at the outer end of the endcap calorimeter. The gas tight stripline cables are encased in epoxy resin and a gas tight seal is created. One connection is required on the liquid side of the cold feedthrough.

The second option is the more conventional feedthrough used in the Mark II and SLD detector designs. This configuration consists of a connector cast in ceramic and requires connection of the stripline cables on each side of the cold feedthrough and on each side of the warm feedthrough.

Heat loss will be one criteria used in selecting the preferred feedthrough design. Both designs will incorporate a thermal length of cable in the vacuum space to reduce heat loss.

3.4 Safety Design Features

The safety of the cryostat design is achieved primarily by designing the liquid krypton vessel to the ASME Section VIII Division 2 requirements. Additional safety is achieved by including the previously mentioned burst discs on the vacuum vessel.

3.4.1 Liquid Vessel Leaks or Rupture

Building and testing prototypes of potential leak areas such as the feedthroughs and cooling pipe penetrations help reduce the risk of future leaks. This should be a part of the research and development phase of the cryostat design. However, in the event of excessive leaks or a rupture the liquid can be off-loaded through drain ports in the bottom of each end of the cryostat to an insulated storage reservoir so boiloff can be minimized and the cryogen can be preserved for reuse.

3.4.2 Loss of Vacuum

Degraded or total loss of vacuum eliminates the insulating capability of the cryostat and can cause the cryogen to boil. Therefore, the vacuum must be carefully monitored and maintained. Upon loss of vacuum the power supply to all preamps will be terminated to reduce boiloff. The cryogen will have to be off-loaded as in the case of a liquid vessel leak or rupture.

3.5 Interfaces

Interfaces external to the barrel cryostat consist of the vacuum ports, the liquid supply and drain ports, the scintillating barrel calorimeter and the central tracker.

3.5.1 Vacuum

The cryostat interfaces with the vacuum system through a vacuum port located in the top of the barrel cryostat on one side of the central washer (Fig. 3.5.1-1).

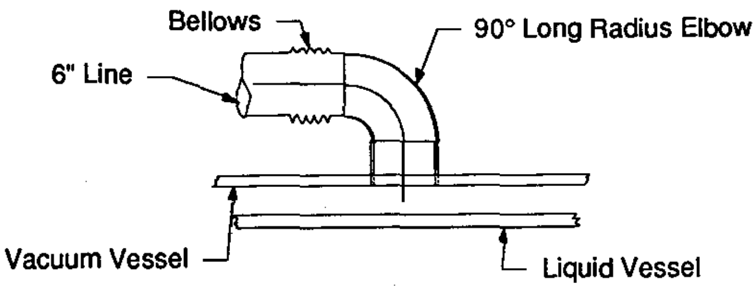

Figure 3.5.1-1 Barrel Cryostat Vacuum Port

3.5.2 Liquid Supply and Drain Ports

The cryostat liquid krypton supply is located opposite the vacuum port on the top of the barrel cryostat (Fig. 3.5.2-1). The liquid supply line is enclosed in a vacuum jacket throughout its length to reduce thermal losses. As previously discussed, the bottom of the barrel cryostat has drain ports to off-load the liquid krypton.

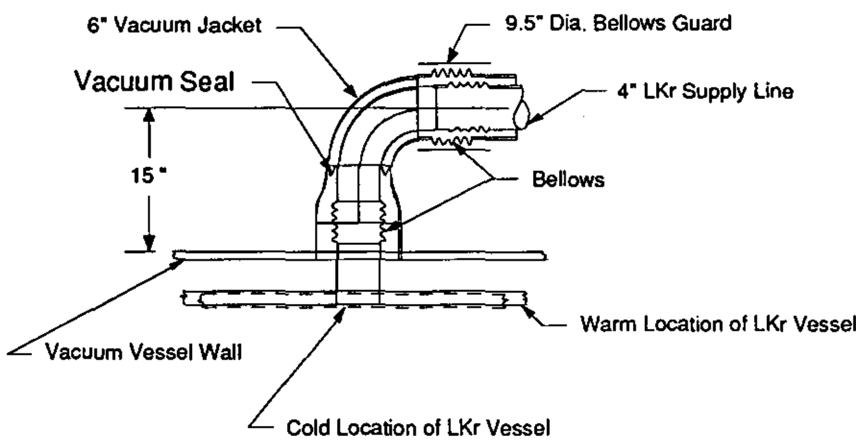

Figure 3.5.2-1 Cryostat Liquid Supply Line

3.5.3 Scintillating Barrel Calorimeter

Another interface external to the barrel cryostat is the scintillating barrel calorimeter. The weight of the barrel calorimeter is carried through the support stanchions and is transferred to a support beam that spreads the load more uniformly into the scintillating barrel calorimeter. Additional interfaces with the scintillating barrel calorimeter include those associated with the routing of piping and electronics between the barrel cryostat outside diameter and the scintillating barrel calorimeter inside diameter. Figure 3.5.3-1 shows the barrel cryostat external interfaces.

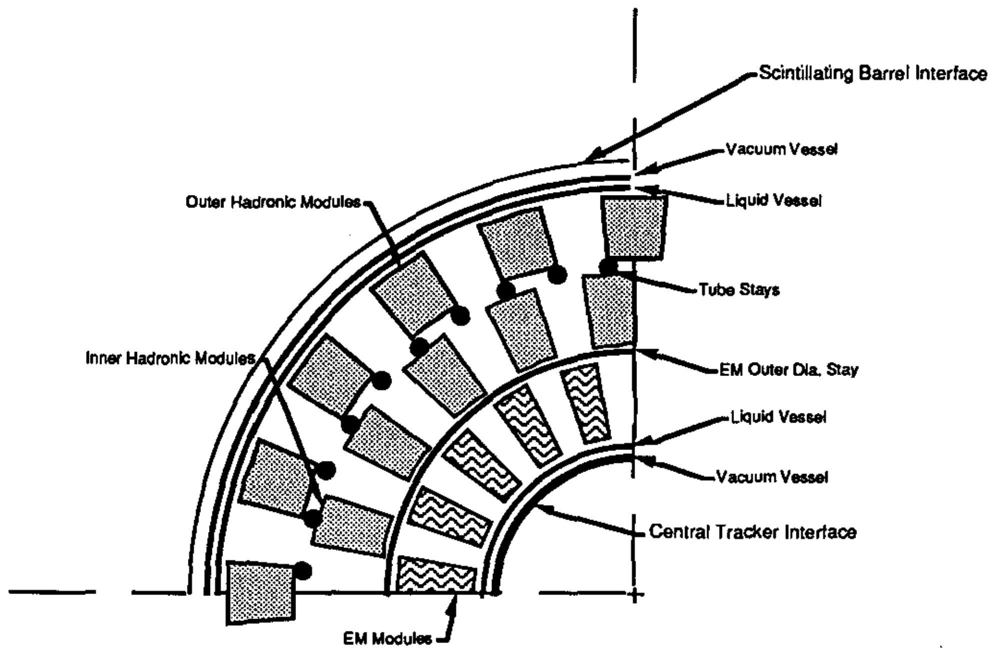

Figure 3.5.3-1 Barrel Cryostat External Interfaces (Endview 1/4 Section)

3.5.4 Central Tracker

Tracker access is a primary concern, so the individual stability of the barrel and endcap cryostats must be such that the endcap can be separated from the barrel cryostat thus allowing access to service the tracker. The barrel cryostat also provides the support for the Tracker.

The barrel calorimeter minimum inside diameter is a controlled interface dimension to ensure proper installation and removal of the central tracker and its cabling and piping. A flange is incorporated into the barrel vacuum vessel inside diameter to support neutron absorbers, connectors, and piping associated with the tracker. The gap between the barrel and endcap calorimeter also reserves space for routing of tracker piping and electronics. The Tracker interface is shown on Figure 3.5.3-1.

4.0 FABRICATION AND ASSEMBLY

The fabrication of the barrel cryostat involves handling large diameter cylinders and flanges throughout the welding and all other processes. After stress relieving, the subsequent final machining is performed. Proof tests will be performed at various intervals throughout the fabrication process. The bolted flanges in the liquid and vacuum vessels will include o-ring grooves to be used in lieu of welding so the final assembly can be pressure tested before shipment and the vacuum vessel can be vacuum acceptance tested.

During the assembly sequence the internal cooling loops are positioned and mounted near the preamps on the modules and the cooling tube penetrations through the vessel heads are completed and attached to the cooling manifolds for the supply and return. This can be leak tested at various stages of the assembly process.

All flanges are bolted together and all bolts and joints are sealed. The bolt and the shear boss within the flange design carry the loads so the seals see no loads.

After completion of the assemblies, final cryogenic tests and vacuum tests are performed on the vessels. Reference TN-93-309 for more specific details on the fabrication and assembly of the barrel cryostat.

Major components of the cryostat are fabricated at offsite locations, shipped to the SSCL, and integrated into the calorimeter during the assembly process. As a result, the cryostat becomes an entity only upon completion of the Inner Barrel assembly. The Inner Barrel cryostat includes approximately 8 major components. Components to be fabricated and assembled at offsite locations have been chosen to facilitate assembly and minimize the need for specialized equipment at the SSCL. However, several pieces of specialized handling equipment will be required in the assembly operations. A detailed description of the assembly process for the cryostat is contained in TN-93-309, Inner Barrel Calorimetry Assembly Concept.

5.0 REFERENCES

1.0 Warren C. Young, Roark's Formulas for Stress & Strain, Table 35, case 12b, Sixth Edition, McGraw-Hill Book Company, 1989.

2.0 LNG material & fluids, prepared by Cryogenics Division Institute for Basic Standards, National Bureau of Standards, Boulder, CO 80302, Douglas Mann, General Editor, First Edition 1977.

3.0 ASME Boiler and Pressure Vessel Code
Section II, Material Specifications Part C
Welding Rods, Electrodes, and Filler Metals

4.0 ASME Boiler and Pressure Vessel Code
Section VIII, Division 2
Alternative Rules

5.0 ASME Boiler and Pressure Vessel Code
Section IX, Welding and Brazing Qualifications