GEM TN-93-314

GEM Noble Liquid Calorimeter Endcap Cryostat Design Concept

Kim Barnstable
Mark Lajczok
Bob Humphreys
Martin Marietta Science System

April 30, 1993

Abstract:

The noble liquid calorimeter is an integral part of the overall GEM calorimeter (Figure 1-1) and includes both endcap and barrel subsystems. The cryostats in both of these subsystems consist of an inner liquid vessel and an outer vacuum vessel. The endcap calorimeter contains liquid argon (LAr) while the barrel calorimeter contains liquid krypton (LKr). Both vessels provide the structural support for the EM and Hadronic sections within the cryostat. The vacuum vessel that surrounds the liquid vessel provides the vacuum environment required to reduce heat loss through conduction and provides space for a multi-layer insulation to reduce radiation losses. The design concept for the endcap cryostat is discussed in this report and the barrel cryostat is discussed in GEM TN-93-313.

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1.0 INTRODUCTION

The noble liquid calorimeter is an integral part of the overall GEM calorimeter (Figure 1-1) and includes both endcap and barrel subsystems. The cryostats in both of these subsystems consist of an inner liquid vessel and an outer vacuum vessel. The endcap calorimeter contains liquid argon (LAr) while the barrel calorimeter contains liquid krypton (LKr). Both vessels provide the structural support for the EM and Hadronic sections within the cryostat. The vacuum vessel that surrounds the liquid vessel provides the vacuum environment required to reduce heat loss through conduction and provides space for a multi-layer insulation to reduce radiation losses. The design concept for the endcap cryostat is discussed in this report and the barrel cryostat is discussed in TN-93-313.

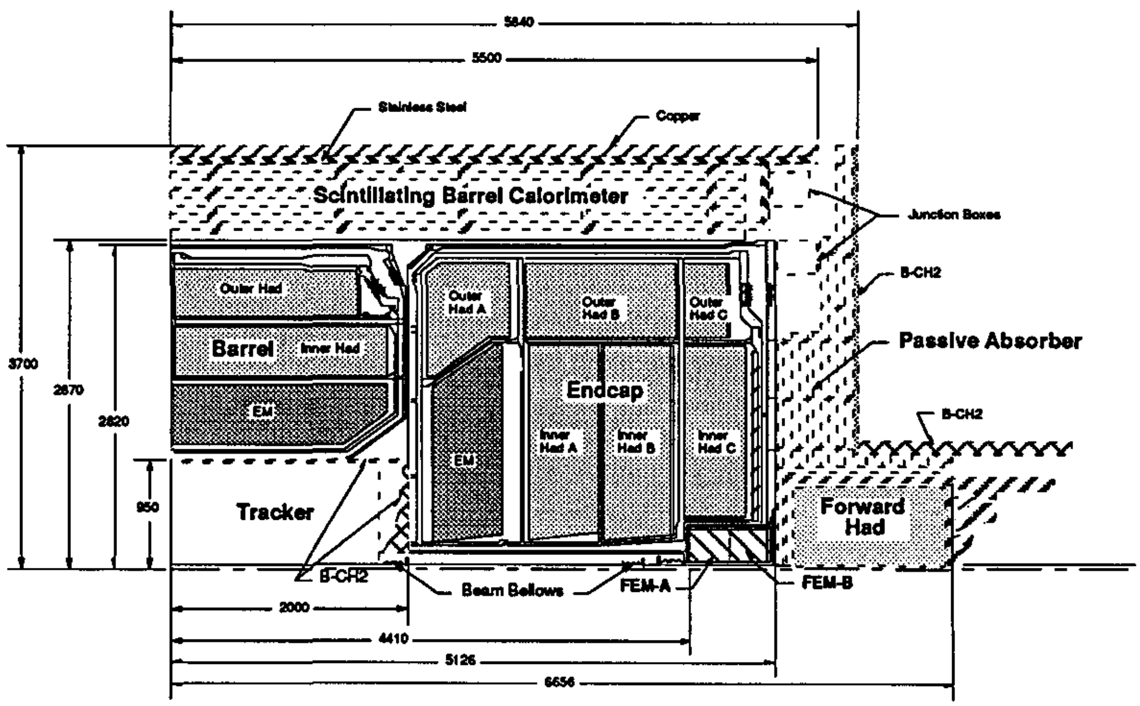

Figure 1-1 GEM Calorimeter Design Concept

2.0 DESIGN REQUIREMENTS

Throughout the conceptual design process consideration has been given to module support, internal vessel stiffness as provided by 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 and ullage pressures with additional pressure allowances to provide the safety factors required by the ASME code. The endcap liquid argon vessel design pressure (internal) is .31 MPa (45 psid) at the bottom of the vessel and was derived as follows:

.10 MPa (15 psid)	due to vacuum
.09 MPa (13 psid)	head
.07 MPa (10 psid)	operating over pressure
.05 MPa (7 psid)	relief valve actuation pressure
.31 MPa (45 psid)	

The vacuum vessel of the endcap calorimeter is sized to an external operating pressure of .10 MPa (15 psid). The requirements of Section VIII, Division 2 impose restrictive rules to govern design, material selection and non-destructive testing. By following these rules an overall safety factor is achieved for the cryostat design.

2.3 Deflection

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

The stress and deflection requirements determine the wall thickness for the vacuum vessel. Thermal bumpers provide structural integrity through contact with the liquid argon vessel so that the excessive dead material within the calorimeter can be minimized. 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. Vessel wall sizing is discussed in greater detail in Section 3.2.2. 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 including the EM structure and Hadronic modules has a total weight per endcap of 389 Mg. It is designed to support the weight of the modules and for an internal pressure of 0.31 MPa (45 psid). The approximate mass of the EM structure, Hadronic modules and Forward EM in liquid argon (LAr) is as follows:

EM Structure - 23 Mg
Inner Hadronic Module A - 48.5 Mg
Inner Hadronic Module B - 48.5 Mg
Inner Hadronic Module C - 41 Mg
Outer Hadronic Module A - 57 Mg
Outer Hadronic Module B - 86 Mg
Outer Hadronic Module C - 24 Mg
FEM A & B - 2 Mg

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

2.5 Thermal

The thermal requirements apply only to the liquid vessel. The vacuum vessel is isolated from the liquid vessel by a high vacuum and multi-layer insulation so that it is basically at ambient temperature. The heat generated by the electrical components located in the ionizing medium must be dissipated and the cryostat design must 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 approximately 87°K, and
c) No more than 1.0% density variation within the ionization medium.

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

3.0 DESIGN CONCEPT

3.1 Overall Size and Mass

The endcap calorimeter is approximately 5640 mm in diameter, 3126 mm in length, and weighs 389 Mg (Fig. 3.1-1). Approximately 30,000 electronic channels from the preamps on the endcap EM and Hadronic sections, require 40 penetrations in the outer head wall of the liquid and vacuum vessel in the form of electronic 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 with the beamline and its vacuum jacket. There is a 50 mm minimum gap between the vacuum vessel and the liquid vessel on the outside diameter to accommodate the electronics and internal cooling circuits associated with the outer hadronic modules and the liquid vessel outer shell cooling requirements.

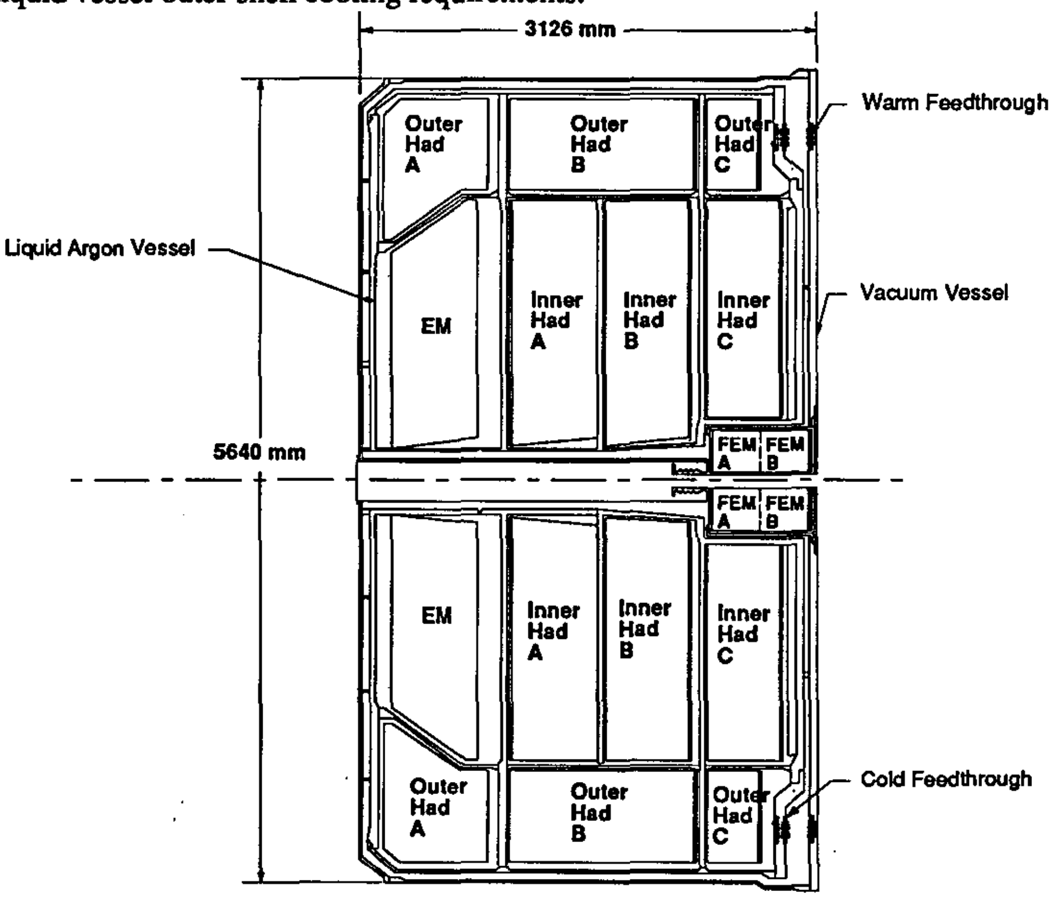

Figure 3.1-1 Key Endcap Cryostat Characteristics

3.2 Structural Design

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

Due to the assembly sequence, the Endcap EM Calorimeter Structure (TN-93-321) and Hadronic modules (TN-93-312) provide their own structural integrity at the EM structure and Hadronic 9° and 18° module assembly levels. However, the liquid argon vessel must be able to transfer the loads due to the weight of these structures to the support stanchions. For both the EM structure and the Hadronic modules, the primary load path within the cryostat is through the structural washers and the vessel head walls (Figure 3.1-1). This configuration allows access for the radial installation of the hadronic modules and axial installation of the EM structure structure. The Hadronic modules are restrained in the phi direction by a keyway mounted on the structural washer that engages a radial groove in each end of the module (Figure 3.2-1). Further details on the Hadronic module support are discussed in Section 3.2.5. The Endcap EM Calorimeter Structure is currently under study and will be discussed in detail in TN-93-321. This structure will be inserted axially and may use the outer structural stay on its outer diameter for support and installation purposes.

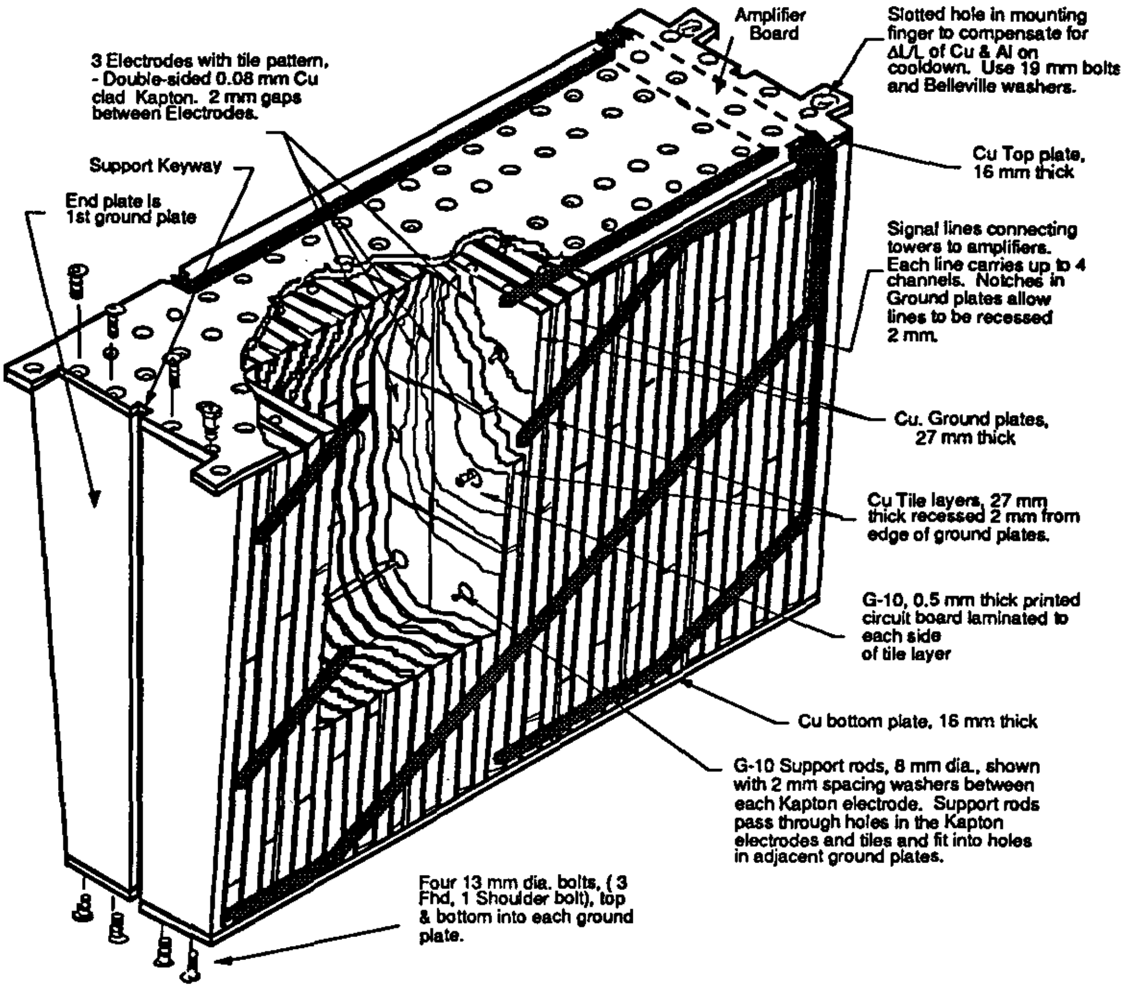

Figure 3.2-1 Hadronic Module Structure

The various liquid and vacuum vessel subassemblies that constitute the cryostat are shown in Figure 3.2-2. Assembly requires a structural weld to attach the various subassembly components and flanges. An additional structural weld is required to attach the liquid vessel front head plate assembly to the liquid vessel assembly (Fig. 3.2-2 c). Also, the vacuum vessel requires a weld at final assembly to attach the vacuum vessel inner head to the outer shell assembly (Fig. 3.2-2 h).

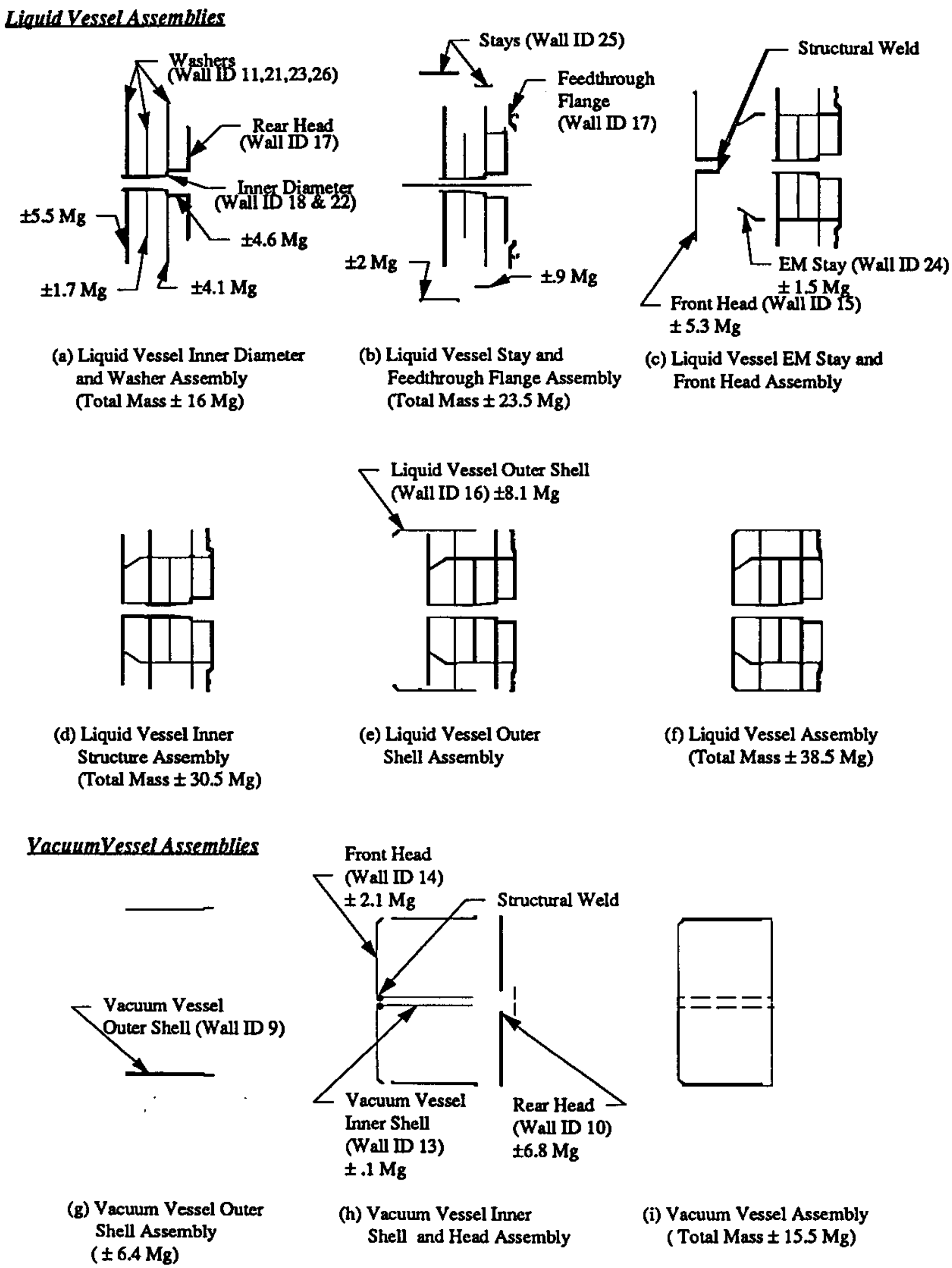

Figure 3.2-2 Major Cryostat Subassemblies

Both the liquid argon and vacuum vessels will incorporate a flanged joint concept in their design for ease of assembly. The bolts will react axial loads and a keyed surface within the flange design will accommodate shear loads. All bolted joints will 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 endcap 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.

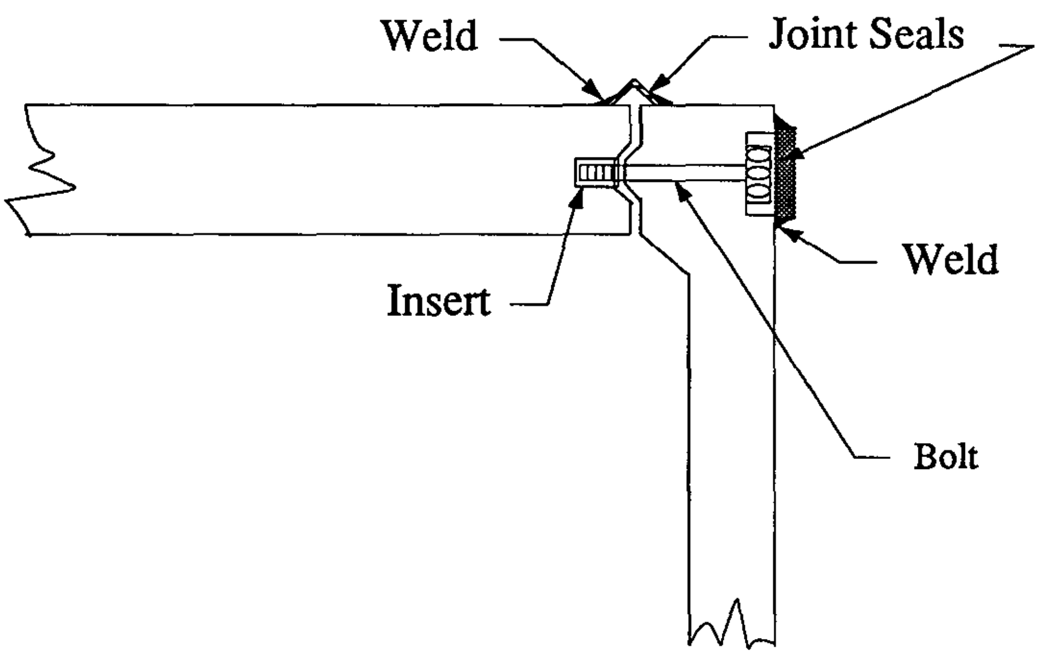

Figure 3.2-3 Joint Seal Details

The liquid vessel is designed for fluid pressure loads, thermal loads and module support loads. A cylindrical stay located between the EM structure and Outer Hadronic module A, and a series of extruded stay segments on the outside diameter of the Inner Hadronic modules A, B and C provide structural continuity between the heads, in order to minimize the head wall thickness. All stays are penetrated for liquid argon communication and for cables and cooling piping (Fig. 3.2-4).

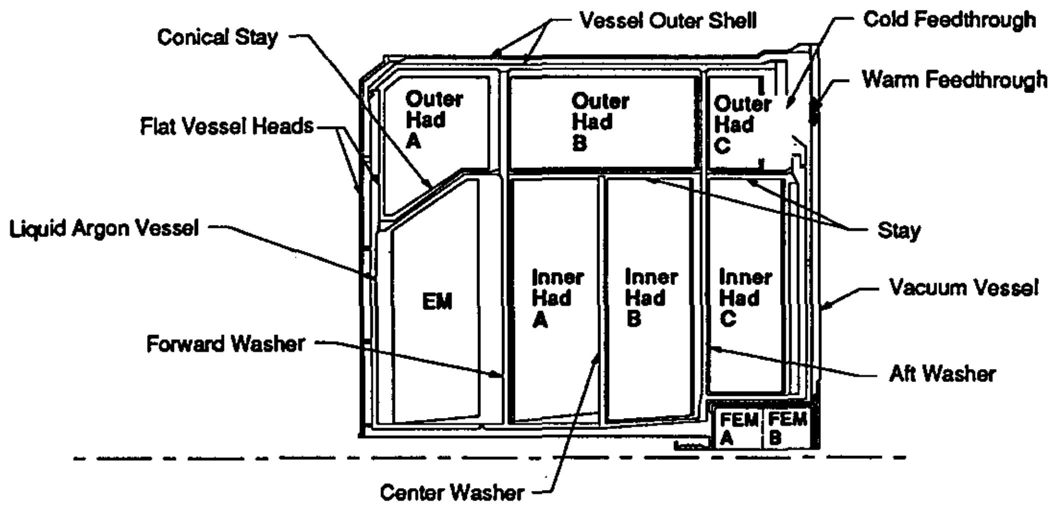

Figure 3.2-4 Endcap Cryostat Components

The heads of the endcap and barrel 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 cylindrical shells of the cryostat are buckling critical. The weldability and absorption and radiation lengths of 5083 aluminum make it a better option than stainless steel or titanium. Conversely, since the vessel heads are bending critical, they would prefer the added stiffness and decreased absorption length of titanium. 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. These numbers are assigned by the comparable 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 filler material for welding P-Number 25 to P-Number 25 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 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 in accordance with 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 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/cm²)	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 using linear thin shell elements was constructed of the endcap cryostat (Figure 3.2.2-1). 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. 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. The liquid vessel is joined axially (z direction) to the vacuum vessel at the two support stanchion locations. The stanchions are located at the interface between the washers (wall ID 21 & wall ID 26) and the outer liquid vessel wall (wall ID 16). Rigid body restraint in the z direction is provided at the interface between the rear vacuum vessel head (wall ID 10) and the outer vacuum vessel wall (wall ID 9).

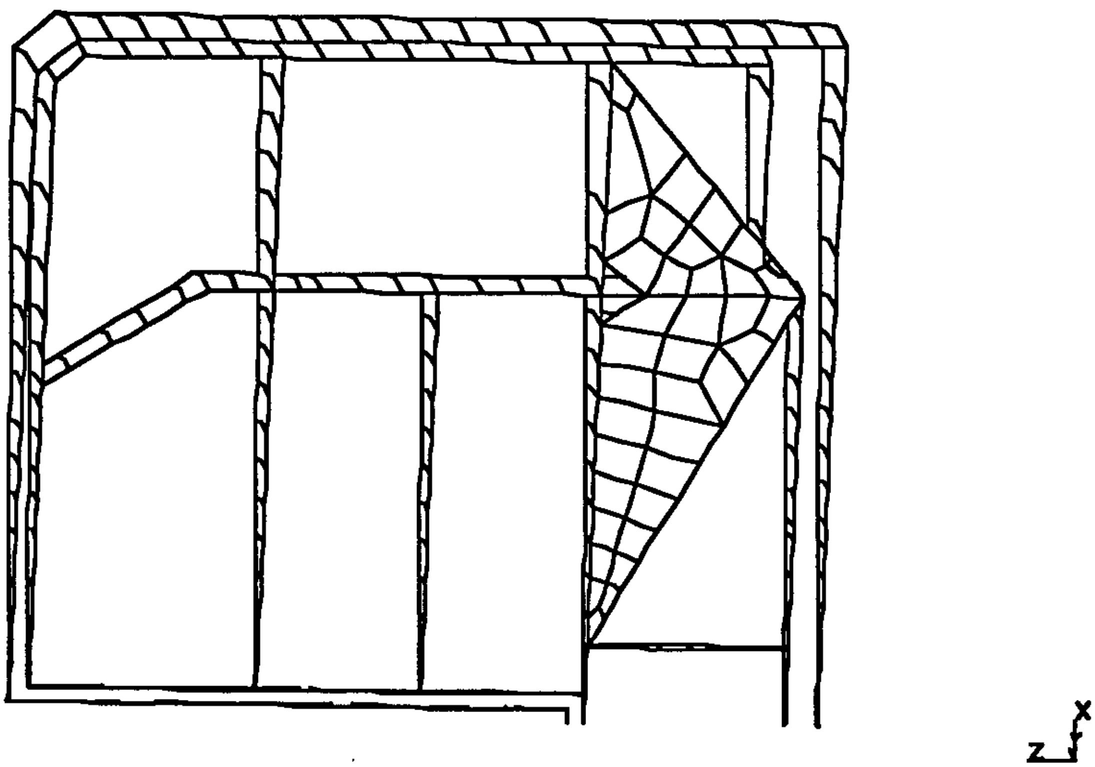

Figure 3.2.2-1 Finite Element Model of Endcap Cryostat

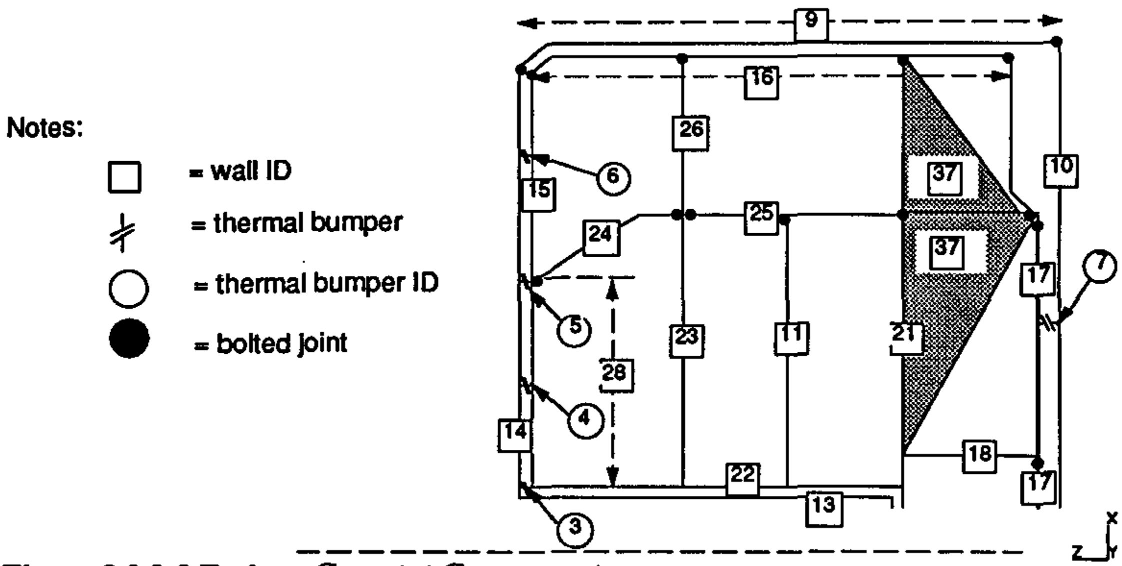

Figure 3.2.2-2 Endcap Cryostat Components

During assembly, installation and operation, the endcap cryostat 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 barrel calorimeter and vacuum vessel, atmospheric conditions external to vacuum vessel
3. Operation Condition 2
   - endcap calorimeter filled with LAr, vacuum in vacuum vessel and atmospheric conditions external to vacuum vessel
4. Fault Condition
   - endcap calorimeter filled with LAr, 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 locations, which are positioned on the outer cryostat shell (wall ID = 16) 10 mm on either side of the forward (wall ID = 26) and aft washer (wall ID = 21), 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 modules and EM structure 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 ASME Section VIII, Division 2, Appendix 4, Article 4-1. The minimum required wall thicknesses of the cylindrical and conical shells under external pressure and axial compression were calculated in accordance with Articles AD-310, AD-340 and AD-360 of ASME Section VIII, Division 2. 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 MPa (psid)	TYPE OF BUCKLING [1]
9	21	0.1 (14.7)	H
16	20	0.1 (14.7)	H
22	7	0.31 (45)	H
24	7	0.1 (14.7)	A
25	7	0.1 (14.7)	A
27	4	0.1 (14.7)	A
28	5	0.1 (14.7)	A

notes: 1. 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 stability requirements and stress allowables as defined by ASME Section VIII, division 2 were used to determine the vessel wall thicknesses. 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 the vessel wall thicknesses are determined based on stress and deflection requirements. ASME stability requirements do not drive any wall thicknesses.

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

WALL ID	THICKNESS mm
9	22
10	75
11	25
13	10
14	13
15	50
16	28
17	50
18	35
24	22
25	22
28	29
37	34

The deflections and stresses for the vessel heads and other high stress regions are presented in Table 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
14	4.8	10	115.9 (16.8)	124 (18.0)
15	5.0	10	52.4 (7.6)	124 (18.0)
17	4.3	10	43.4 (6.3)	124 (18.0)
22	1.0	10	151.7 (22.0)[1]	248 (36.0)
28	5.2	10	127.6 (18.5)[1] 75. 17 (10.9)[2]	248 (36.0) 124 (18.0)
37	1.9	10	81.4 (11.8)[3]	82.8 (12.0)

Notes: 1. discontinuity stress which occurs at intersection of of two vessel walls
2. stress located near center of head
3. membrane stress

The deformation of the endcap cryostat subject to internal and vacuum pressure is shown in Figure 3.2.2-3.

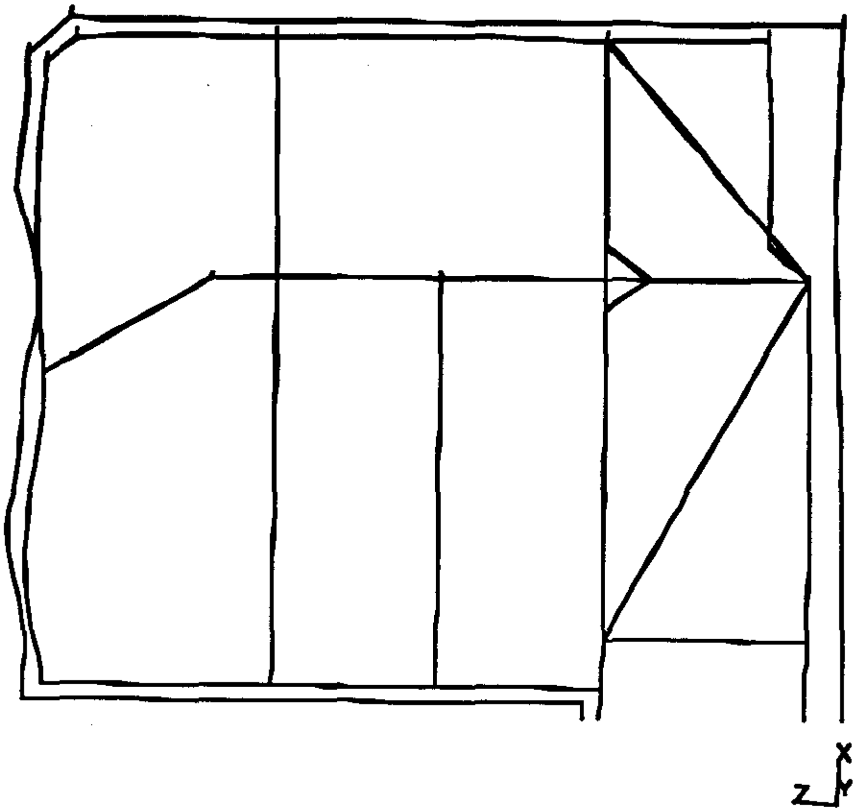

Figure 3.2.2-3 Deformed Finite Element Model of Endcap Cryostat

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 MN (kips)	WALL ID	LOAD MN (kips)
9 (front)	0.33 (75)	9 (back)	1.04 (234)
16 (front)		16 (back)	
24 (front)	2.64 (594)	24 (back)	3.33 (748)
25 (front)	2.64 (594)	25 (back)	3.33 (748)

3.2.2.1 Liquid Vessel Washer Sizing

The upper forward washer (wall ID = 26) is bolted to the outer liquid vessel wall (wall ID=16). It has a lateral support (z direction) from the cylindrical stay (wall ID=24 & 25) and is welded to the inner liquid wall (wall ID=22). It was conservatively sized for stability due to stanchion load based on being pinned at the outer liquid vessel wall (wall ID=16) and free at the inner liquid wall (wall ID=22). It was assumed that the stanchion load was applied as a uniform radial pressure. From Reference 1, the allowable compressive stress is given for a circular plate under uniform compression on the outer edge with the outer edge pinned and the inner edge free. Since the stanchion support is applied only over 135.2° (Fig. 3.2.2.1-1). The critical buckling stress, s , is given by:

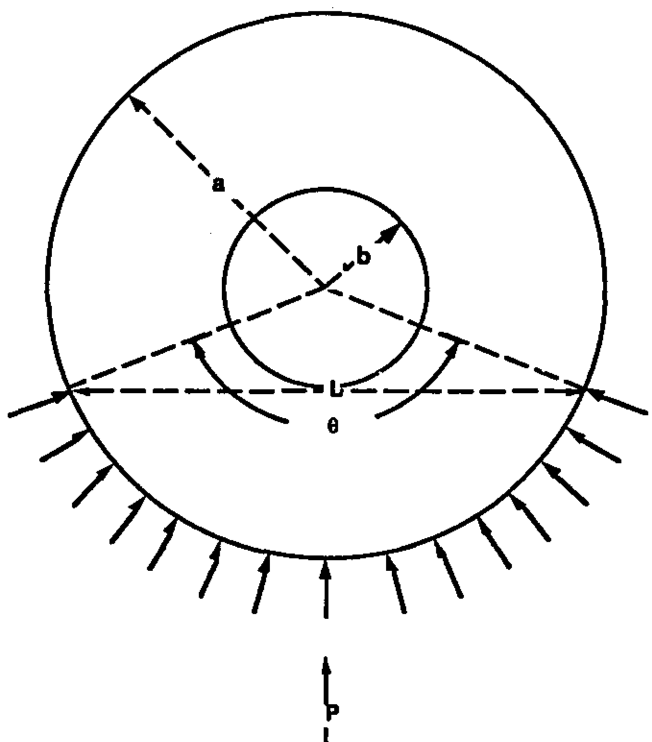

Figure 3.2.2.1-1 Geometry and Loading For Washer Sizing

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

where

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

given

E = 71018 MPa (10.3 x 10^6psi)
q = 135 °
n = 0.32
a = 2749 mm (108.23 in)
b = 199.9 mm (7.87 in)

(b/a) = 0.073

for case 12b (pinned)

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 = 2.29 MN (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= 51 mm(2.0 in)

The lower forward washer (wall ID=23) can be considered as being pinned at the cylindrical stay (wall ID=24 & 25) and welded (fixed) at the liquid vessel inner wall (wall ID=22). For conservatism the lower forward washer was assumed to be free at the inner wall. From Reference 1, the allowable compressive stress is given for a circular plate under uniform compression on the outer edge with the outer edge pinned and the inner edge free. The critical buckling stress, σ , is given by:

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

where

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

given

E = 71018 MPa (10.3 x 10^6psi)
q = 135 °
n = 0.32
a = 1813.8 mm (71.41 in)
b = 199.9 mm (7.87 in)

(b/a) = 0.11

for case 12b (pinned)

K = 0.33

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 = 2.29 MN (513.7 kips)

θ = support angle = 135.2°

c= radius to stanchion support = 2749 mm (108.23 in)

By equating the critical stress to the stanchion stress we obtain the required thickness for the washer: t= 39 mm(1.52 in)

The central washer (wall ID = 11) is mainly provided for attachment of the Hadron Modules. For Operation Condition 2 it is not subject to much compressive stress. Until the remaining load cases are investigated it was conservatively sized to be 25 mm in thickness.

The aft washer (wall ID=21) is bolted to the outer liquid vessel (wall ID=16) and is welded to the inner liquid wall (wall ID=22 & 18). It's lateral support is provided by the rib stiffeners (wall ID=37). Even though the rib stiffeners provide considerable restraint against buckling, the wall thickness is based on assuming that the washer is welded to the outer liquid vessel (wall ID=16) and free at the inner radius (wall ID =22). This results in the aft washer having the same wall thickness as the outer forward washer which is t= 51 mm(2.0 in).

3.2.2.2 Liquid Vessel Rib Stiffener Sizing

Twenty rib stiffeners (wall ID = 37) are attached to the aft washer (wall ID=21) and the cylindrical stay (wall ID=25). They act as shear stiffeners whose primary function is to minimize the axial motion of the inner cylindrical shell (wall ID=18). Finite element structural analysis was performed to determine the deflections of the endcap calorimeter without the rib stiffeners. The deformation of the endcap calorimeter subject to internal and vacuum pressure is shown in Figure 3.2.2.2-1. The axial deflection of the endcap calorimeter without the rib stiffeners (34.8 mm) is about 6 times that of the endcap cryostat with rib stiffeners. From this it can be concluded that the rib stiffeners are required.

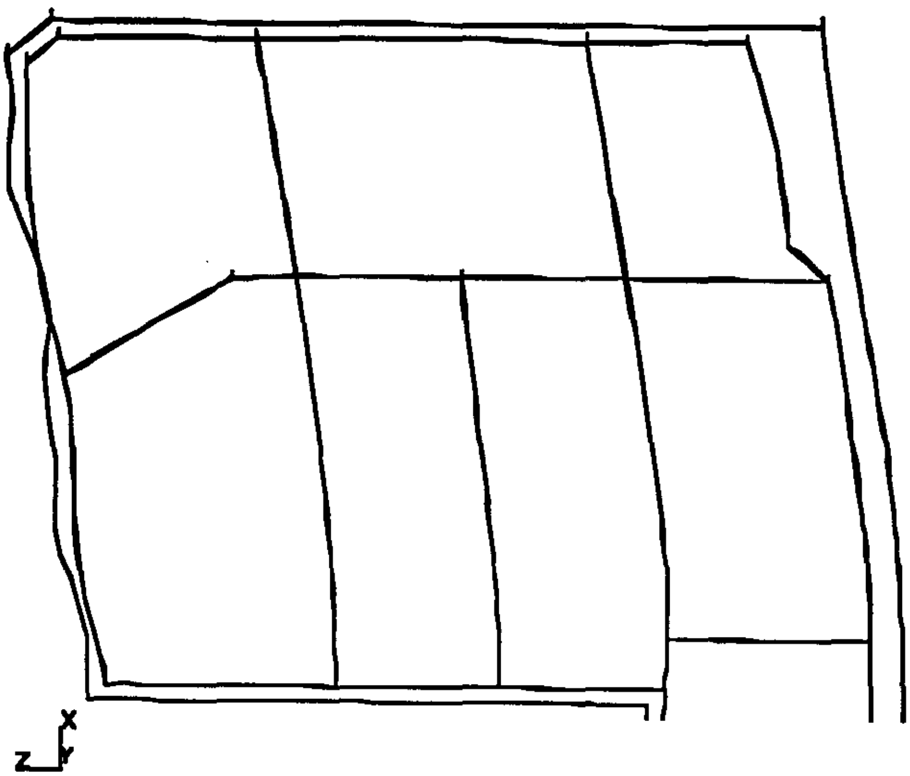

Figure 3.2.2.2-1 Deformed Finite Element Model of Endcap Cryostat (w/o Rib Stiffeners)

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 and are presented in 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 MN (kips)
3	0.06 (13.3)
4	0.33 (74.8)
5	0.58 (132.0)
6	1.01 (227.6)
7	1.49 (335.2)

3.2.3 Stanchions

The support stanchion concept is similar to that in the D-Zero design (Fig. 3.2.3-1). The endcap 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 so that the vessels will shrink with respect to the interaction point of the calorimeter. Further analysis will be performed on the stanchion design and although the modules and cryostat loads are transmitted through the forward and aft washers, a "belly strap" concept may prove effective. A "belly strap" could span 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 within the stanchion design provide a strong column to carry the weight load of the cryostat but also allows thermal flexibility.

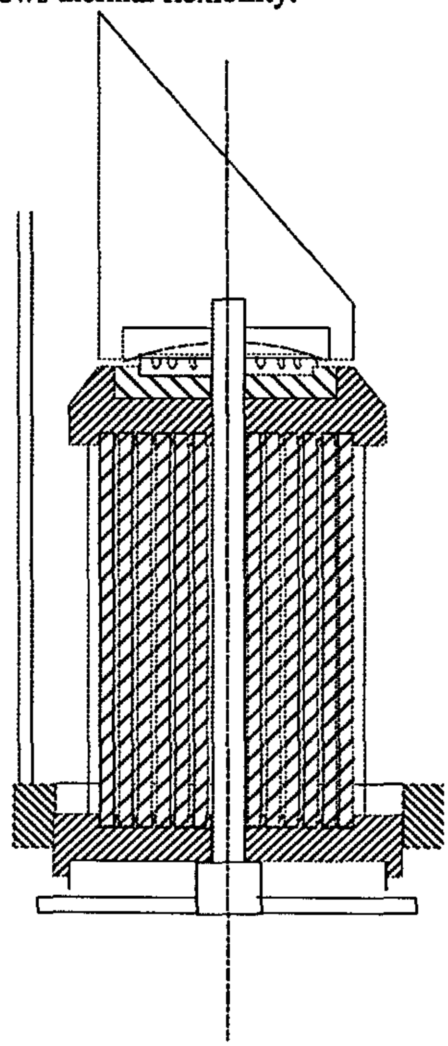

Figure 3.2.3-1 Support Stanchion Concept

3.2.4 EM Support

The EM structure represents a 360° cylinder which can be supported within the conical stay around its outer diameter. The primary load path for the EM structure is through the structural washer at the forward end of the liquid argon vessel. Reference TN-93-321 for further details on the EM module structural details.

3.2.5 Hadronic Module Support

The 9° Outer Hadronic modules and 18° Inner Hadronic modules are supported radially on keyways in the structural washers that lock them in place in the phi direction. The outermost radius of the modules are then directly bolted on one end to the structural washers to provide restraint in the "Z" direction (parallel to the beamline). The opposite end of the module is also bolted or pinned for radial support but is allowed to move in the "Z" direction independent of the vessel structure to allow for the thermal expansion of the module. A detailed description of the Endcap Hadronic module design is presented in TN-93-312.

3.2.6 Future Structural Analysis

So far the overall endcap 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

The endcap cryostat design must accommodate the relative coefficients of thermal expansion during the cooldown process. 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 copper, lead, brass, stainless steel and G10 in the construction of the EM and Hadronic modules requires proper engineering design to eliminate the relative thermal expansion concerns. Table 3.3.1-1 shows the comparison of the warm and cold stackup dimensions in the axial direction for the endcap cryostat.

Table 3.3.1-1 Cold and Ambient Cryostat Locations

Endcap Calorimeter	Depth, mm	Cold (87°K) "Z" Location mm	Ambient (293°K) "Z" Location mm
Front Face Vacuum Vessel		2000.00	2000.00
Cryostat Vessels			
Vacuum wall	13	2013.00	2013.00
Vacuum Space	57	2070.00	2077.87
Argon Wall	29	2099.00	2106.98
Forward Washer	39	2997.00	3008.39
Center Washer	25	3657.70	3671.60
Aft Washer	34	4352.30	4368.84
Cryostat Vessels			
Argon Vessel	50	5026.00	5045.10
Vacuum space	50	5076.00	5076.00
Vacuum Vessel	50	5126.00	5126.00
Note: Ambient dimensions based on % ΔL/L =0.38 (Reference 2)			

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

The EM structure is also accommodated by limiting the contact area with the aluminum cryostat and by controlling the G10 layup orientation of the components to cause them to expand and contract like the aluminum cryostat.

3.3.2 Internal Cooling Circuits

An internal liquid nitrogen 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 nitrogen through a manifold system on the heads and the "warm" liquid nitrogen 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 argon vessel. This is prevented by incorporating a thermal intercept at the interface of the stanchion and the liquid argon 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 argon vessel by multilayer insulation (MLI). MLI provides low thermal conductivity and reduces heat transfer due to radiation. MLI also provides the best performance of all insulations used in cryogenic systems. 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 1 x E-4 Torr required for adequate MLI performance is provided by the vacuum system design.

3.3.5 Feedthroughs

Two feedthrough designs are currently under consideration. Both designs require a feedthrough in the liquid argon 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 argon 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. This option requires one connection 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 of the 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 argon 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 minimal 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 and 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 endcap cryostat consist of the vacuum ports, the liquid supply and drain ports, the scintillating barrel calorimeter, the forward hadronic calorimeter, and the beampipe. Although these interfaces are identified, detailed interface control documents must be developed to monitor the impact of any design revisions on the adjacent interfacing components.

3.5.1 Vacuum Ports

The vacuum system for the endcap cryostat penetrates the aft head wall (Fig. 3.5.1-1).

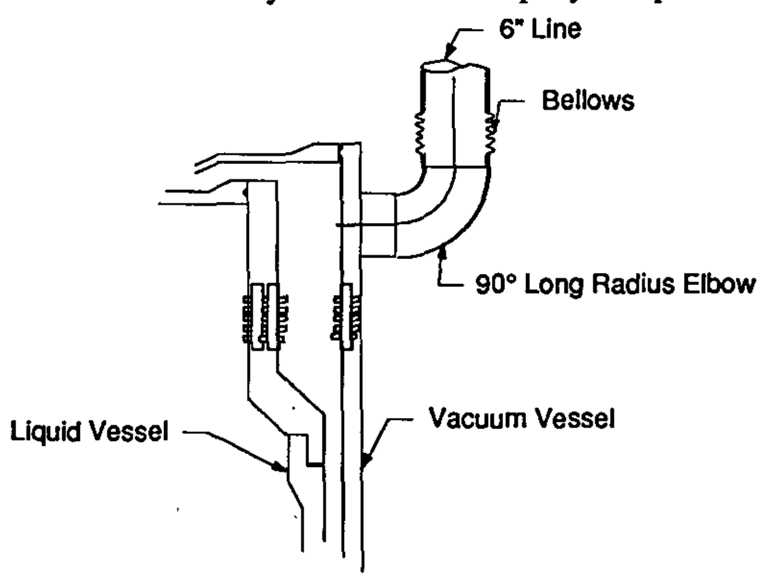

Figure 3.5.1-1 Endcap Cryostat Vacuum Port

3.5.2 Liquid Supply and Drain Ports

The cryostat liquid argon supply is located on the top of the endcap cryostat near Outer Hadronic Module C (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 in Section 3.4.1, the bottom of the endcap cryostat has drain ports to off-load the liquid argon.

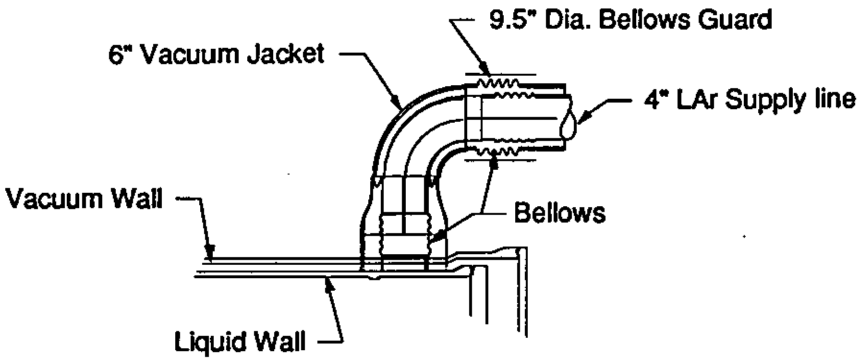

Figure 3.5.2-1 Cryostat Liquid Supply Line

3.5.3 Scintillating Barrel Calorimeter

Another interface external to the endcap cryostat is the scintillating barrel calorimeter. The weight of the endcap 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 endcap cryostat outside diameter and the scintillating barrel calorimeter inside diameter. Figure 3.5.3-1 shows the endcap cryostat external interfaces.

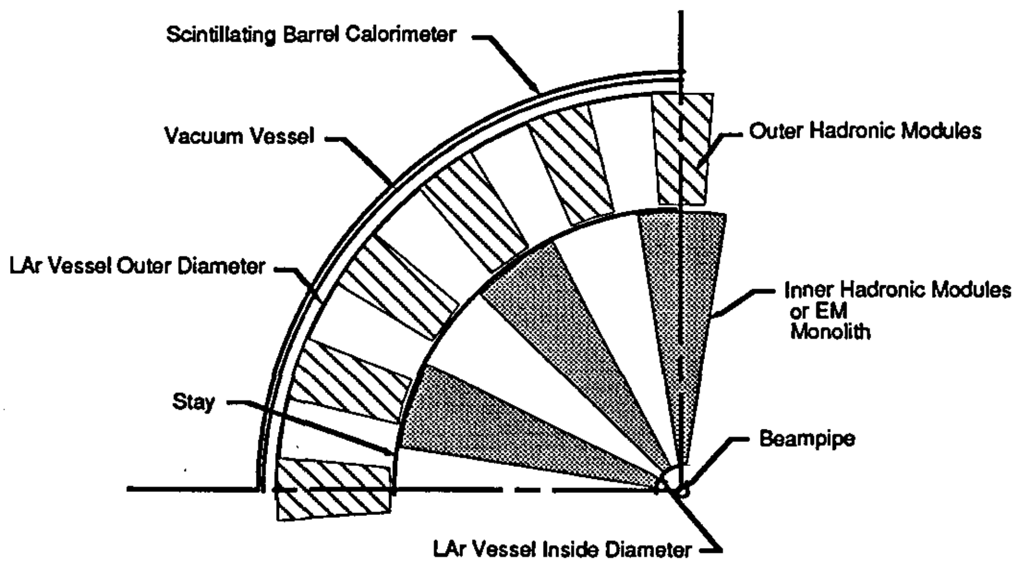

Figure 3.5.3-1 Endcap Cryostat External Interfaces (Endview 1/4 Section)

3.5.4 Forward Hadronic Calorimeter and Passive Absorber

The Forward Hadronic calorimeter interferes with the back of the endcap calorimeter (that face furthest away from the interaction point). This Forward Hadronic calorimeter is mounted in a cylindrical flange that bolts to the Passive Absorber structure. The Passive Absorber consists of a series of washers built into a cylindrical structure. The Passive Absorber and Forward Hadronic calorimeter assembly is then attached to the Scintillating Barrel calorimeter on its outside diameter. The Scintillating Barrel calorimeter supports the majority of the Forward Hadronic and Passive Absorber assemblies but additional bolting through the Passive Absorber and into the vacuum vessel head on the back face of the endcap calorimeter may be required.

3.5.4 Beamline

The beampipe is an 80 mm diameter through pipe that runs axially through the noble liquid calorimeter centerline. This diameter includes the outer vacuum jacket on the beampipe. The endcap calorimeter provides clearance on its inside diameter for the beampipe but has bellows that interface with the beampipe outside diameter. These bellows allow alignment of the beampipe within the calorimeter and provide the vacuum seal for the endcap vacuum vessel that surrounds the liquid argon vessel.

4.0 FABRICATION AND ASSEMBLY

The fabrication of the endcap 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-93-310 for more specific details on the fabrication and assembly of the endcap cryostat.

Major components of the endcap 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 endcap assembly. The endcap cryostat includes approximately 14 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-93-310, Endcap Calorimetry Assembly Concept.

5.0 REFERENCES

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

2.0 LNG material & fluids, prepared by Cryogenics Division Insitute 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