FERMILAB Technical Division	**Vacuum Vessel Engineering Note For the NML Cryomodule 1 (CM1)**	**Vessel No. IND-113 Rev. No. --**

Vacuum Vessel Engineering Note
For the
NML Cryomodule 1 (CM1)

Authors: M. Wong	Date: 30 June 2010

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Vacuum Vessel Engineering Note
(per Fermilab ES&H Manual Chapter 5033)

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Reviewed by	[signature]	Date	7/1/10	Div/Sec	PDD/MD
Div/Sec Head	[signature]	Date	7/23/10	Div/Sec	TD

1. Identification and Verification of Compliance

Fill in the Fermilab Engineering Conformance Label information below:

This vessel conforms to Fermilab ES&H Manual Chapter 5033

Vessel Title	New Muon Lab – Type 3+ Cryomodule 1 (NML-CM1)
Vessel Number	IND-113
Vessel Drawing Number	4904.280-ME-459303, 4904.280-ME-459304
Internal MAWP	14.7 psig
External MAWP	14.7 psid
Working Temperature Range	20 °F 100 °F
Design/Manufacturer	Design: DESY/FNAL; Manufacturer: E.Zanon
Date of Manufacture	January, 2007
Acceptance Date	July, 2007

Director's signature (or designee) if vessel is for manned area and requires an exception to the provisions of this chapter.

Amendment No.	Reviewed by:	Date:

Laboratory location code	FIMS #700 (Muon Beam Enclosure at NML)
Laboratory property number	---
Purpose of vessel	Provide insulating vacuum for the 1.3-GHz SCRF dressed cavities

List all pertinent drawings

Drawing No.	Location of Original
4904.280-ME-459303	Fermilab I-DEAS TDM Library
4904.280-ME-459304	Fermilab I-DEAS TDM Library

2. Design Verification

See design calculations in the Note's Appendix A.

3. System Venting Verification

Can this vessel be pressurized either internally or externally? [ ] Yes [X] No

If "Yes", to what pressure? _____________

Manufacturer	**Relief**	**Pressure Setting**	**Flow Rate**	**Size**
Fermilab	Parallel plate relief	<0.5-psig	See Table 9	4.3"

P&ID number 5520.000-ME-442391 (Figure 5 in Appendix A)

4. Operating Procedure Section

Is an operating procedure necessary for the safe operation of this vessel?

[ ] Yes [X] No *(If "Yes", it must be appended)*

Is a testing procedure necessary for the safe acceptance testing (acceptance testing) of this vessel?

[ ] Yes [X] No

If "Yes", the written procedure must be approved by the division head prior to testing and supplied with this Engineering Note.

5. Welding Information

Is the vessel code-stamped? [ ] Yes [X] No

If "No," append WPS, PQR, and WPQ.

6. Exceptional, Existing, Used and Non-Manned Area Vessels

Is this vessel or any part thereof in the above categories? [ ]Yes [X] No

If "Yes" follow the Engineering Note requirements for documentation and append to note.

Appendix A – Design Note

Description and Identification

As part of an agreement between FNAL and DESY, a cryomodule "kit" was put together jointly by DESY and INFN-Milano and shipped to FNAL in July, 2007. The kit included the vacuum vessel and cold mass assemblies, as well as eight individual 1.3-GHz dressed cavities. The cryomodule was assembled at Fermilab by FNAL personnel assisted by DESY personnel. This cryomodule was named Cryomodule #1, or CM1. Now completed, CM1 resides at its final location at the Beam Enclosure in the New Muon Lab in preparation for the commissioning of that facility.

The purpose of the vacuum vessel is to house the sub-assemblies and provide insulating vacuum to the cold mass and the superconducting RF (SCRF) cavities within. The cold mass is cooled to less than 2°K with liquid helium. Thermal shields cooled to 80°K with liquid nitrogen also sit within the vacuum vessel. The vessel is a longitudinal welded pipe. There are openings along the vessel that provide feedthroughs for the RF power couplers, the magnet current leads, and instrumentation.

This engineering note shows that the vacuum vessel for CM1 conforms to FESHM 5033 - "Vacuum Vessel Safety." [1] Since the vacuum vessel houses the insulating vacuum for the SCRF cavities, its external differential MAWP is 14.7-psid [1.0-bar]. The vacuum vessel is designed to the pressures and temperatures and temperatures shown in Table 1:

Table 1 – Design and Operating Pressures and Temperatures

	Design	Operating
External pressure (psid) [bar]	14.7 [1.0]	14.7 [1.0]
Internal pressure (psig) [bar]	14.7 [2.0]	1.5E-10 [1E-9]
Minimum temperature (°F) [°C]	20 [-7]	77 [25]
Maximum temperature (°F) [°C]	100 [38]	77 [25]

Table 2 lists all drawings pertinent to the engineering note. The original drawings are electronically located in the Fermilab TDM Library in the I-DEAS CAD software. Figures 1 and 2 show the two sheets of the engineering drawing of the vacuum vessel (4904.280-ME-459303, 4904.280-ME-459304). Hard copies of the drawings are available, and electronic versions of the drawings are available online at the FERMI I-DEAS Team (RELEASED) Drawing Database. The web address for this database is:

http://www-admscad.fnal.gov/MSDMain/cgi-bin/TP_FERMIifind-web.pl

A PDF file of the drawings is also included online in the CM1 folder of the ILC Document Management System:

http://ilc-dms.fnal.gov/Workgroups/CryomoduleDocumentation/CM1folder/VacVessel/

Table 2 – Engineering Drawings for the Vacuum Vessel of CM1

Drawing No.	Rev.	Title
459303	-	Vessel Weldment Assembly, Sheet 1
459304	-	Vessel Weldment Assembly, Sheet 2
459305	-	Pick Point Weldment
459306	-	Vessel Support Weldment
459307	-	Flange D OD 350
459308	-	Flange DN 63 DF
459309	-	Flange - Instrumentation
459310	-	Flange - K1, K3
459311	-	Flange MC Port
459312	-	Flange Bellows Sliding
459313	-	Flange Fixed Upstream
459314	-	Flange Fixed Downstream
459315	-	Gusset Welded Outrigger
459316	-	Pad Weld Lower
459317	-	Pad Weld Upper
459318	-	Plate MC Mount
459319	-	Plate Mount Gusset
459320	-	Plate Mount Support
459321	-	Piping Support Plate
459322	-	Plate Welded Outrigger
459323	-	Port Middle Coldmass
459324	-	Port End Coldmass
459325	-	Rib - Flange Side
459326	-	Stiffening Rib
459327	-	Ring Flange Stop
459328	-	Vessel Shell
459329	-	MC Bracket Weldment - LH
459330	-	MC Bracket Weldment - RH
459331	-	Flange Weld Ring
459070	-	Flange G 150 OD
106391	-	Vacuum Relief Valve – Complete Assembly
458097	-	ILCTA Cryomodule 1 and Feedbox

As detailed in the drawings, the following materials are selected for the vacuum vessel:

- The shell wall and stiffening rings: ASTM A516 Grade 60
- The nozzles walls: AISI 304L (equivalent to ASTM A240 Type 304L)

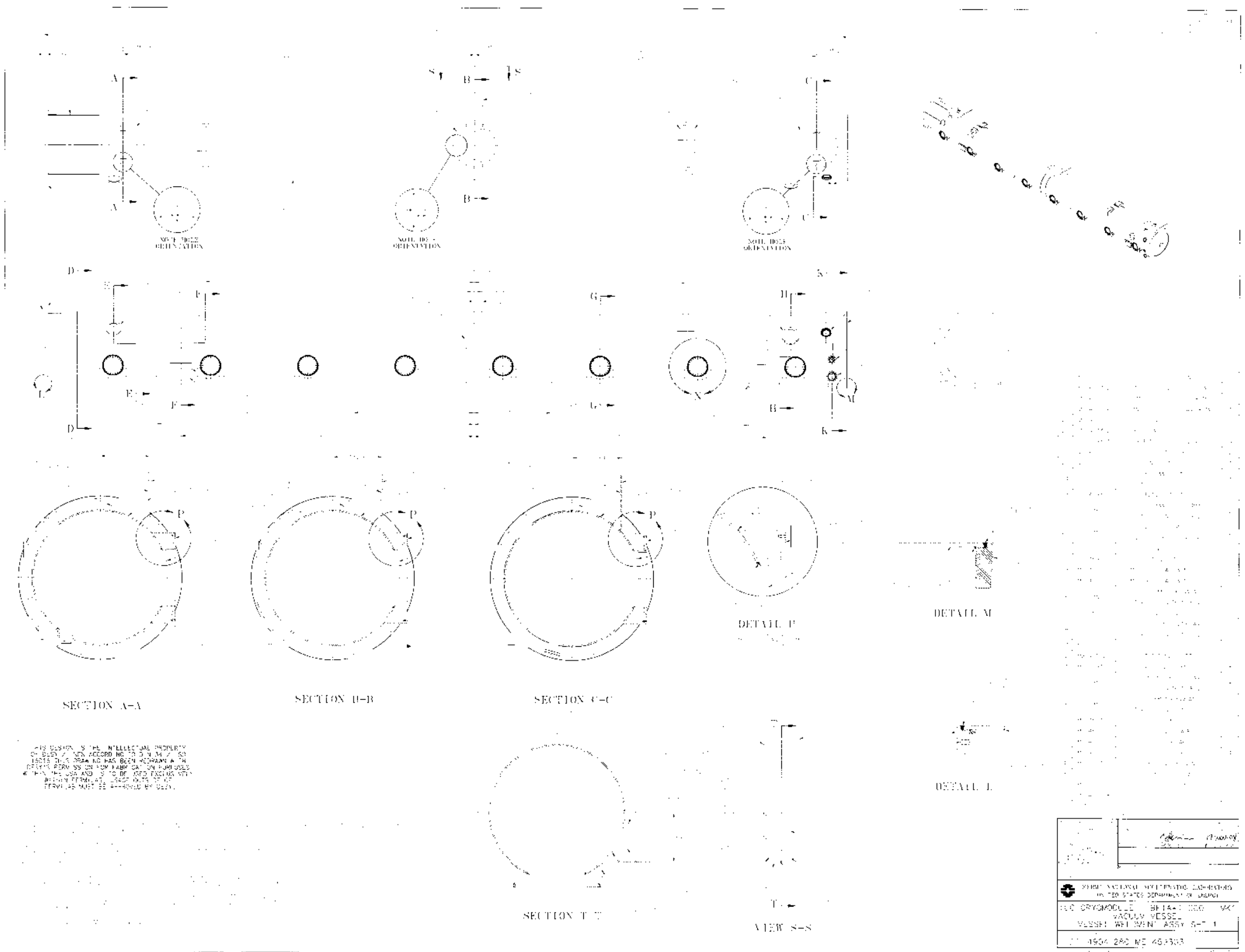

Figure 1 – 1.3-GHz CM1 Vacuum Vessel Drawing 4904.280-ME-459303

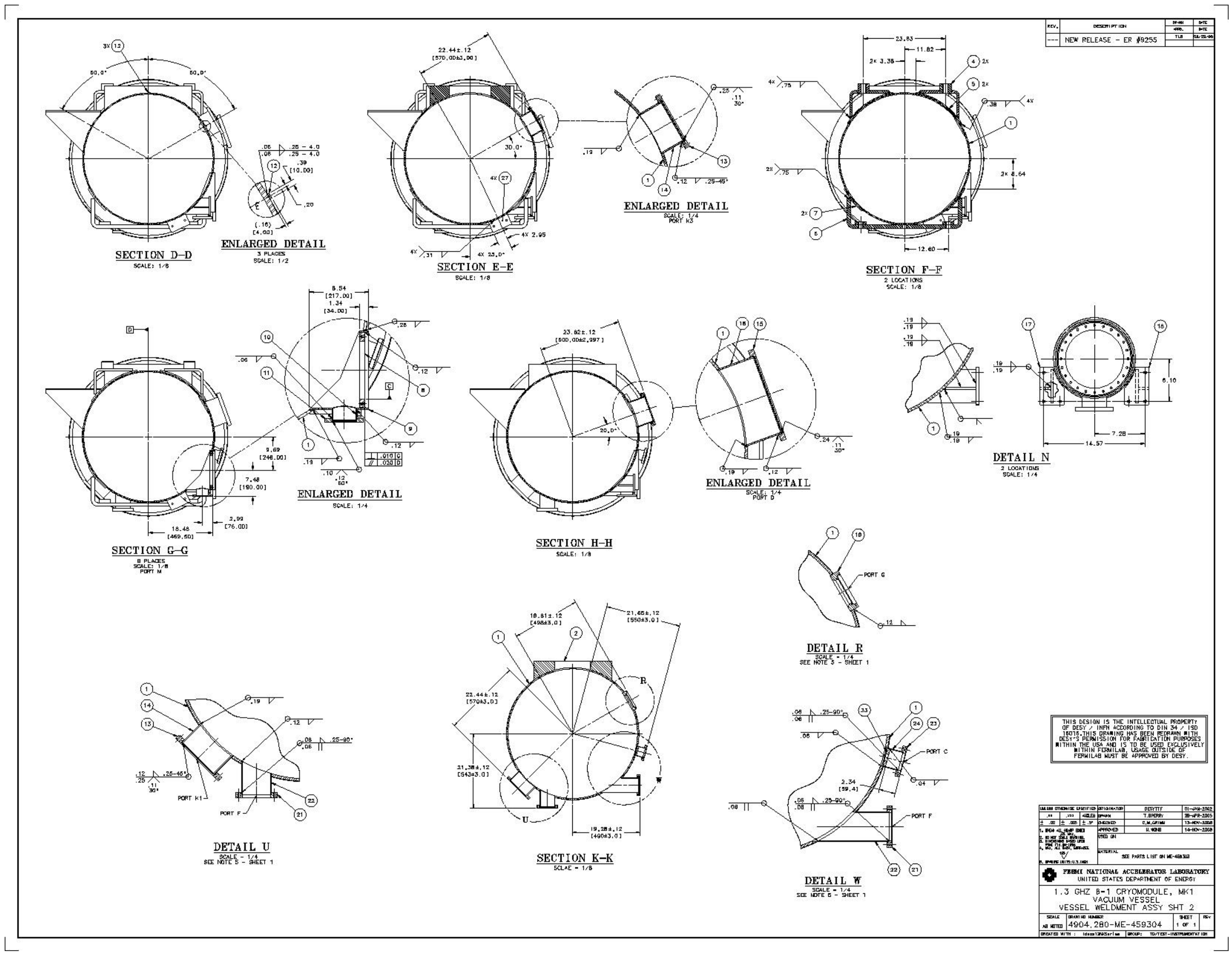

Figure 2 – 1.3-GHz CM1 Vacuum Vessel Drawing 5520-ME-459304

Design Verification

The design of the vacuum vessel follows the applicable rules of the ASME Boiler and Pressure Vessel Code (the Code) Section VIII, Division 1 [2] as listed in FESHM 5033 – "Vacuum Vessel Safety."

Calculation for the Vacuum Vessel Cylindrical Shell Thickness (UG-28, UG-27)

External Pressure:

Calculate the maximum allowed external working pressure following UG-28. The minimum required thickness takes into account the support of the stiffening rings. Note that the actual vessel shell thickness t = 0.375-inch,

$Do := 38.0$ inch (outer diameter of shell)

$t := 0.261$ inch (minimum required thickness of shell for external pressure of 14.5-psia)

$\frac{Do}{t} = 145.594$ Since this ratio is greater than 10, follow UG-28(c)(1)

$L := 235.7$ inch (length of stiffened shell)

$\frac{L}{Do} = 6.203$

$E := 29 \cdot 10^6$ psi (modulus of elasticity for SA-516 Gr 60 carbon steel)

From Table G in Sec II, Subpart 3 to determine Factor A

$A = 1.108 \cdot 10^{-4}$ (Factor A, from Table G of Sec. II, Subpart 3)

$$P\_ext := \frac{2 \cdot A \cdot E}{3 \cdot \left(\frac{Do}{t}\right)}$$

$P\_ext = 14.709$ psi (maximum allowable working external pressure for given t)

A wall thickness of t = 0.261-inch results in a maximum allowable working external pressure of P_ext = 14.7-psia , which is greater than the external pressure that the vacuum vessel will see. *Since the actual wall thickness is 0.375-inch, the vessel design is adequate for the working external pressure.*

Internal pressure

Calculate the minimum required thickness of the vacuum vessel for an internal pressure of 15-psig, following UG-27.

$P\_int := 29.0$ psia (internal design pressure)

$t\_actual := 0.375$ inch (actual wall thickness)

$Do = 38$ inch (outer diameter)

$$R := \frac{Do}{2} - t\_actual$$

$R = 18.625$ inch (inner radius of shell)

$S := 17100$ psi (maximum allowable stress value for SA-516, Gr 60, from Table 1A of Sec II, Part D)

$E\_weld := 0.70$ (weld joint efficiency for a double butt weld that is not radiographed)

$$t\_circum := \frac{P\_int \cdot R}{S \cdot E\_weld - 0.6 \cdot P\_int}$$

$t\_circum = 0.045$ inch (minimum thickness that allows a circumferential stress to equal S)

$$t\_long := \frac{P\_int \cdot R}{2 \cdot S \cdot E\_weld + 0.4 \cdot P\_int}$$

$t\_long = 0.023$ inch (minimum thickness that allows a longitudinal stress to equal S)

$$t\_internal := \begin{vmatrix} t\_circum \ \text{ if } \ t\_circum > t\_long \\ t\_long \ \text{ otherwise} \end{vmatrix}$$

$t\_internal = 0.045$ inch (minimum required wall thickness)

Since the actual vessel thickness of 0.375-inch is greater than the minimum required thickness of 0.045-inch, the thickness is adequate for the vessel to withstand an internal pressure of 29.0-psia (2.0-bar).

Stiffening Rings for Cylindrical Shells under External Pressure (UG-29)

Following the Code, the moment of inertia of the stiffening ring is calculated. It is confirmed that the available moment of inertia is greater than the required moment of inertia. Figure 3 shows the area that is considered.

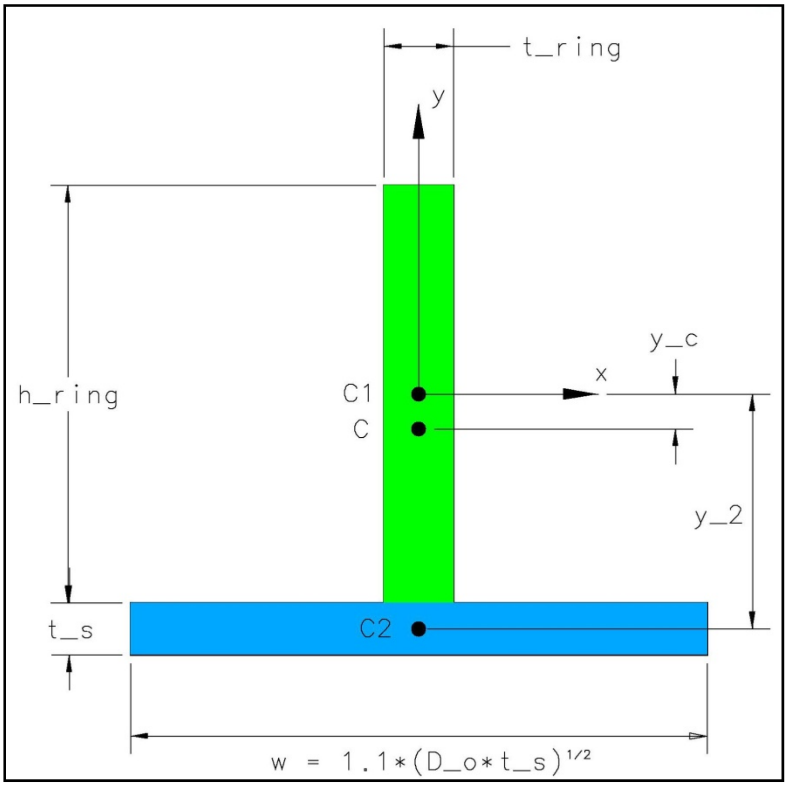

Figure 3 – Cross-Sectional Areas of Stiffening Ring and Shell Sector

The available moment of inertia in the stiffening ring is

$$I\_1 := \frac{t\_ring \cdot h\_ring^3}{12}$$

Where I_1 = available moment of inertia in the stiffening ring (in^4)
t_ring = stiffening ring thickness (inch)
h_ring = stiffening ring height (inch)

The required moment of inertia for the stiffening ring (from UG-29) alone is

$$I\_s := \frac{\left[D\_o^2 \cdot L\_s \cdot \left(t + \frac{A\_s}{L\_s}\right) \cdot A\right]}{14}$$

Where I_s = required moment of inertia for the stiffening ring (in^4)

D_o = outer diameter of the shell (inch)

L_s = one-half of the distance from the centerline of the stiffening ring to the next line of support, plus one-half of the distance from the centerline of the stiffening ring to the next line of support on the other side of the stiffening ring (inch)

t = minimum required shell thickness for shell at external pressure of 14.5-psia (1.0-bar) (inch)

$A\_s = A\_1$ = cross-sectional area of the stiffening ring (in^2)

A = factor determined from Table CS-2 of Subpart 3 of Section II, Part D of the Code for the stiffening ring that is made of SA-516, Gr60 (unitless)

Table 3 lists the values for the calculation of the required and available moments of inertia of the stiffening ring.

Table 3 – Values for Moment of Inertia Calculation

t_ring	0.5-inch
h_ring	3.0-inch
A_s = A_1	1.5-in^2
D_o	38-inch
L_s	122.4-inch
t	0.26-inch
A	$1.05*10^{-4}$
I_1	1.125-in^4
I_s	0.459-in^4

As specified in UG-29 Step 8, *the required moment of inertia is less than the available moment of inertia for the ring (I_s < I_1), so the ring design is adequate.*

Attachment of Stiffening Rings (UG-30)

The stiffening ring is welded to the vacuum vessel shell with a continuous weld. The strength of the weld is calculated by comparing the actual load to the allowable load. The actual load (P_weld) on the weld is a combination of the radial pressure load between the stiffeners, the weld shear flow due to the radial load through the stiffener, and the external design load carried by the stiffener. The weld shear flow is calculated by taking into account the load on the combined ring-shell cross section. The allowable load (P_allow) for the weld is calculated based on the weld size and material strength.

The actual load on the weld is a combination of the radial pressure load (P*L_s) and the weld shear flow (VQ_x/I_s):

$$P\_actual := \sqrt{P \cdot L\_s^2 + F\_external^2 + \left(\frac{V \cdot |Q\_x|}{I'}\right)^2}$$

where

$$V := 0.01 \cdot P \cdot L\_s \cdot D\_o$$

And

$$Q\_x := y\_1 \cdot A\_1 + y\_2 \cdot A\_2$$

Where P_actual = actual load on the attachment weld (lbf/in)
P = external pressure on vessel (psi)
F_external = external design load carried by the stiffener (lbf/in)
V = radial shear load (lbf)
Q_x = first moment of inertia for ring/shell shape (in^3)

L_s, D_o, y_1, y_2, A_1, A_2, and I` are defined in calculations for Stiffening Rings (UG-29)

The allowable load on a continuous attachment weld is calculated:

$$P\_allow := 0.55 \cdot leg \cdot Sv$$

Where P_allow = allowable load on the attachment weld (lbf)
leg = weld size (inch)
Sv = allowable stress for material (psi) – both the vessel and stiffening ring are made of ASTM A 516 Grade 60 (H II DIN 17155)

Table 4 lists the values that result in comparing the actual and allowable loads on the attachment weld.

Table 4 – Values for Attachment Weld Strength

P	14.5-psia
V	675-lbf
Q_x	-2.63-in^3
F_external	0-lbf/in
Radial pressure load (P*L_s)	1.8E3-lbf/in
Weld shear flow (VQ_x/I_s)	502-lbf/in
P_actual	685-lbf/in
leg	0.19-inch
Sv	17100-psi
P_allow	1787-lbf/in

The actual design load P_actual = 685-lbf/in is less than the allowable load P_allow = 1787-lbf/in for the attachment weld. *So the continuous fillet weld with size of 0.19-inch is acceptable.*

Formed Heads with Pressure on Concave Side (UG-32)

The vacuum vessel does not include formed heads, so this paragraph is not applicable.

Formed Heads with Pressure on Convex Side (UG-33)

The vacuum vessel does not include formed heads, so this paragraph is not applicable.

Unstayed Flat Heads on Covers (UG-34)

The vacuum vessel does not include flat heads, so this paragraph is not applicable.

Calculations and Analysis for the Vessel Shell Openings (UG-37)

In the vacuum vessel are a number of openings that are various sizes. Table 5 summarizes the port labels and their dimensions, which are taken from drawings 4904.280-ME-459303 and 4904.280-ME-459304 (Figures 1-2).

Table 5 – Dimensions of Openings in the Vacuum Vessel Shell

Geometric Parameters	Ports N, O, P	Coupler Port (M)	Port C	Port D	Port F-horiz	Port F-vert	Port G	Ports K1-K3
d - inner diameter of opening (inch)	15.5	10.9	2.6	7.2	4.1	4.1	3.9	6.2
tn - actual nozzle wall thickness (inch)	4.843	0.197	0.197	0.453	0.079	0.079	0.591	0.197
L_nozzle - nozzle length (inch)	1.870	4.123	1.960	4.011	4.850	2.240	0.610	3.200

The size and reinforcement of each opening must follow the specifications according to the Code. For external pressure, the required area of reinforcement (A_{req_ext}) for all openings follows UG-37(d)

$$A_{req\_ext} = 0.5*[d*t_{r\_ext}*F + 2*t_n*t_{r\_ext}*F*(1-f_{r1})]$$

Where A_{req_ext} = required area of reinforcement for external pressure (in^2)
d = inner diameter of opening (in)
t_{r_ext} = required thickness of vacuum vessel shell for external pressure = 0.26-in.
t_n = nozzle wall thickness (in.)
F = correction factor = 1.0
S_v = maximum allowable stress for vessel material (SA-516, Gr 60) = 17.1-ksi
S_n = maximum allowable stress for nozzle material (304L) = 16.7-ksi
f_{r1} = strength reduction factor = S_n/S_v = 0.98

Other parameters that are used in the calculations for reinforcement calculations are:

t = 0.375-in. actual wall thickness of vessel shell
E1 = 1 weld joint efficiency for a nozzle that does not pass through a weld

Table 6 lists the required wall thickness of the nozzle. The wall thickness has to be thick enough to withstand the design external pressure of 14.5-psia.

Table 6 – Nozzle Wall Thickness for External Pressure of at Least 14.7-psi

Nozzle Wall Thick. External Pressure	Ports N, O, P	Coupler Port (M)	Port C	Port D	Port F-horiz	Port F-vert	Port G	Ports K1-K3
trn - required nozzle wall thickness (inch)	0.022	0.023	0.008	0.019	0.014	0.011	0.006	0.015
A	0.0007	0.0004	0.0003	0.0003	0.0002	0.0003	0.0006	0.0003
B	7835	5345	4463	4896	3334	4509	7643	4737
Pa - external pressure allowed (psi)	14.8	15.0	18.3	17.1	15.2	16.2	15.5	15.3

For all nozzles, the actual nozzle wall thickness is less than the required nozzle wall thickness (tn < trn).

Table 7 shows the available and required areas of reinforcement for each nozzle for external pressure.

Table 7 – Available and Required Areas of Reinforcement for External Pressure

Area of Reinforcement for External Pressure	Ports N, O, P	Coupler Port (M)	Port C	Port D	Port F-horiz	Port F-vert	Port G	Ports K1-K3
A1 (in2)	1.7	1.2	0.3	0.8	0.5	0.5	0.4	0.7
A2 (in2)	8.8	0.2	0.1	0.8	0.0	0.0	1.1	0.2
A3 (in2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A41, A42, A43 (in2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A_avail - total available area of reinforcement (in2)	10.6	1.5	0.4	1.6	0.5	0.5	1.5	0.9
A_req_ext - required area of reinforcement for external pressure (in2)	2.1	1.4	0.3	0.9	0.5	0.5	0.5	0.8

For all nozzles at the external design pressure of 14.5-psia (1.0-bar), the total available area of reinforcement is at least equal to or greater than the required area of reinforcement (A_avail ≥ A_req_ext), showing that the nozzle design follows the Code.

The required areas (A_{req_int}) of reinforcement for all openings are calculated for internal pressure following UG-37(c):

$$A_{req\_int} = d*t_{r\_int}*F + 2*t_n*t_{r\_int}*F*(1-f_{r1})$$

Where A_{req_int} = required area of reinforcement for internal pressure (in^2)
t_{r_int} = required thickness of vacuum vessel shell for internal pressure = 0.045-in.

Table 8 lists the areas of reinforcement, both available and required, for all ports for an internal pressure of 29.0-psia (2.0-bar).

Table 8 – Available and Required Areas of Reinforcement for Internal Pressure

Area of Reinforcement for Internal Pressure	Ports N, O, P	Coupler Port (M)	Port C	Port D	Port F-horiz	Port F-vert	Port G	Ports K1-K3
trn - required nozzle wall thickness (inch)	2.E-07	2E-07	2E-08	1E-07	6E-08	6E-08	6E-08	1E-07
A1 (in2)	5.0	1.2	0.3	0.8	0.5	0.5	0.6	0.7
A2 (in2)	8.9	0.2	0.1	0.8	0.0	0.0	1.1	0.2
A3 (in2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A41, A42, A43 (in2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A_avail - total available area of reinforcement (in2)	13.9	1.5	0.4	1.7	0.5	0.5	1.7	0.9
A_req_ext - required area of reinforcement for external pressure (in2)	0.7	0.5	0.1	0.3	0.2	0.2	0.2	0.3

For all nozzles at the internal design pressure of 29.0-psia (2.0-bar), the total available area of reinforcement is at least equal to or greater than the required area of reinforcement (A_avail ≥ A_req_ext), showing that the nozzle design follows the Code.

Flued Openings in Shells and Formed Heads (UG-38)

No flued openings exist in the shell of the vacuum vessel, so this paragraph does not apply.

Reinforcement Required for Openings in Flat Heads (UG-39)

This paragraph does not apply to the vacuum vessel.

Limits of Reinforcement (UG-40)

Calculations in this document show that the openings are adequately reinforced with additional reinforcement or attachment. So this paragraph does not apply.

Strength of Reinforcement (UG-41)

Calculations in this document show that the openings are adequately reinforced with additional reinforcement or attachment. So this paragraph does not apply.

Reinforcement of Multiple Openings (UG-42)

Calculations in this document show that the openings are adequately reinforced with additional reinforcement or attachment. So this paragraph does not apply.

Jacketed Vessels (Appendix 9)

The vacuum vessel is not a jacketed vessel as defined in Appendix 9.

Vessels of Noncircular Cross Section (Appendix 13)

This appendix is not applicable to the vacuum vessel.

The Permissible Out of Roundness of the Vessel Cylindrical Shell (UG-80)

Calculate the permissible out-of-roundness of the vessel's cylindrical shell, following UG-80.

Internal Pressure:

Given:
D_i = 37.25 in. Inner diameter of the vessel shell

The difference between the maximum diameter and the minimum diameter of the vessel shell at any cross section shall not exceed 1% of the nominal inner diameter:

$$0.01 \times D_i = 0.373 \text{ in} \geq D_{i\_max} - D_{i\_min}$$

(per section UG-80 (a)(1) of ASME VIII, Div.1)

The exception occurs at a cross section through or near an opening. Here, the permissible difference shall not exceed 2% of the nominal inner diameter:

$$0.02 \quad 0.02 \times D_i = 0.746 \text{ in} \geq D_{i\_max} - D_{i\_min}$$

(per section UG-80 (a)(2) of ASME VIII, Div.1)

External Pressure:

In addition to the out-of-roundness limitations prescribed for Internal Pressure, the shell shall meet the follow requirements at any cross section. The deviation from true circular form is calculated.

Given:

Do = 38 inch (vessel outer diameter)

t_actual = 0.375 inch (actual vessel wall thickness)

L = 235.7 inch (unstiffened length of vessel)

$$\frac{Do}{t\_actual} = 101.333$$

$$\frac{L}{Do} = 6.203$$

$$e := 0.6 \cdot t\_actual$$

$e = 0.225$ inch (maximum permissible deviation on radius, Fig. UG-80.1)

System Relief Verification

The 1.3-GHz CM1 assembly will be a component of the NML cryomodule testing facility. When installed at NML, the cryomodule's insulating vacuum becomes part of the insulating vacuum of the larger system, which includes the feed cap, the end cap, and the feedbox. CM1 has a FNAL standard 4-inch parallel plate relief (flow orifice 4.33-inch diameter, 14.75-in^2 area). The part number is 1620-MC-145615 (Figure 4). Figure 5 shows the P&ID of the system where CM1 sits.

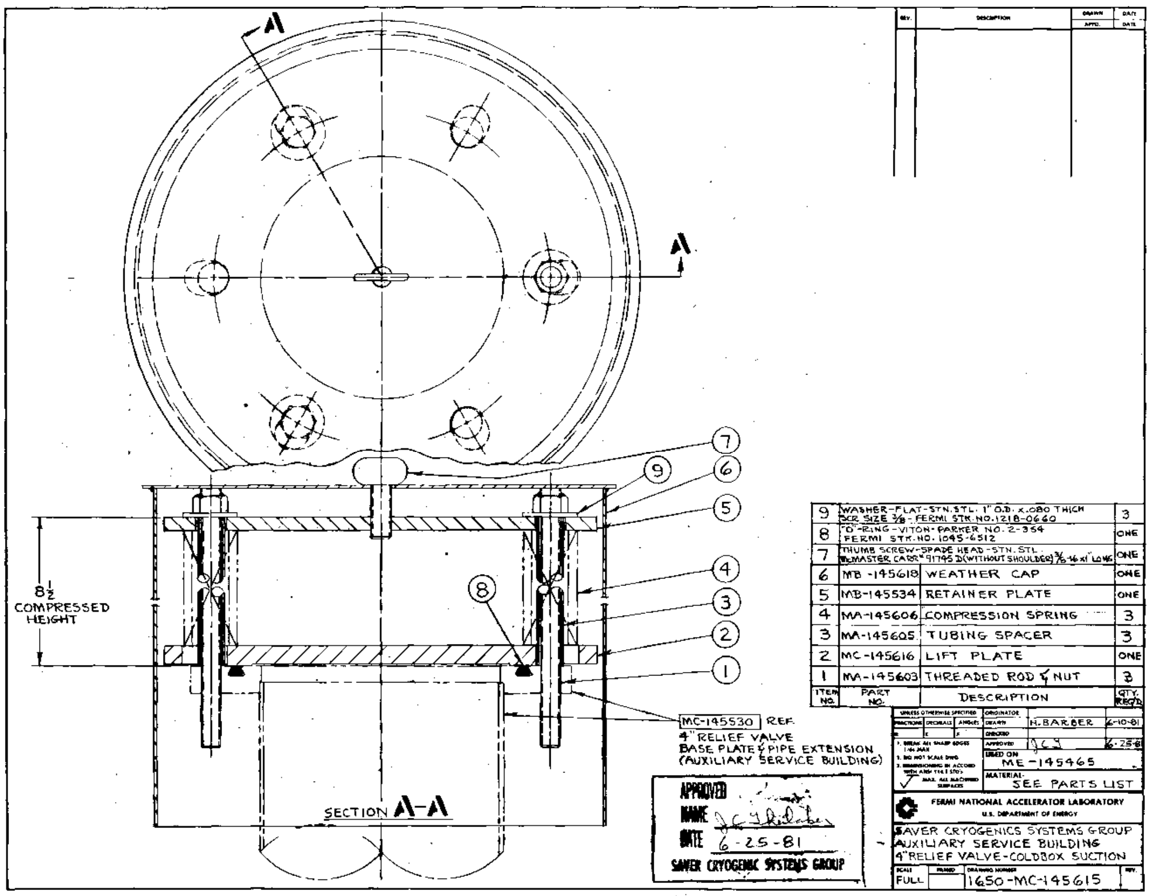

Figure 4 – Parallel Plate Relief Device (drawing 1620-MC-145615)

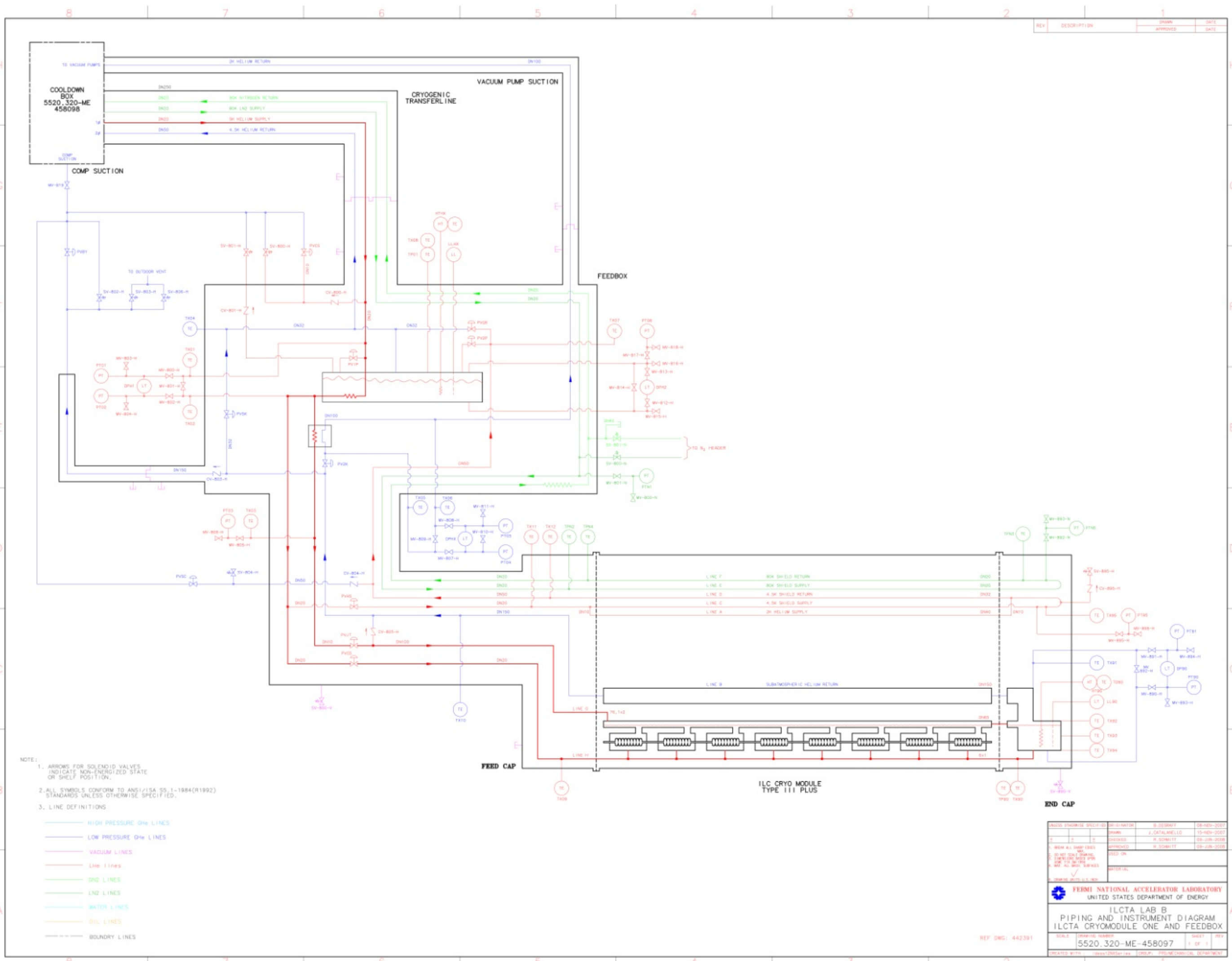

Figure 4 – P&ID of NML System where CM1 is Located (Drawing 5520.000-ME-458097)

Table 9 summarizes the mass flow rate through ruptures in the both lines and compares the flow capacity of the relief device for each cryogen. A single 4-inch relief device is adequately sized for cryogen flow in the event of a rupture in the line.

Table 9 – Comparing Maximum Mass Flow Rates of Cryogens through a Ruptured Line to the Flow Capacity of the Vacuum Relief Device

	Required	Available
Helium	80 g/sec	800 g/sec
Nitrogen	1318 g/sec	2018 g/sec
Discharge area - CGA	4.2 in^2	14.7 in^2

Requirements for the Relief Device

Discharge Area Based on CGA S-1.3-2008, Section 5.4

According to CGA S-1.3-2008, Section 5.4 – Jacket relief device: [6]

“The total discharge area of vacuum jacket relief devices on a container shall be at least 0.00024 in^2/lb of water capacity of the container.”

The total volume of the vacuum vessel is calculated:

$$V = \frac{\pi}{4} D_i L \frac{1}{12^3}$$

Where
V = total volume of the vaccum vessel (ft^3)
D_i = inner diameter of vessel = 37.25 inch
L = vessel length = 448.23 inch

$$V = \frac{\pi}{4}(37.25)(448.23)\frac{1}{12^3} = 282.7\ ft^3$$

The water capacity is then calculated:

$$W_c = V\left(62.4\frac{lb}{ft^3}\right) = 17639\ lb\ of\ water\ capacity$$

The total required discharge area that is based on water capacity is:

$$Area_{req} = 0.00024\frac{in^2}{lb\ of\ water\ capacity}\ W_c = 4.2\ in^2$$

The available area is 14.75-in2, so the relief device is adequate.

Required Helium and Nitrogen Flow Rates

Let us examine the scenario of a rupture in a cryogen line, which disrupts the insulating vacuum. Failure of the helium and the nitrogen lines are both examined. In the worst case scenario, a rupture can result from a crack in a weld or a stainless-to-aluminum transition. Some assumptions are made for the venting calculations:

- For a rupture in the line, assume that the hole diameter equals the diameter of the pipe. This leads to a maximum flow rate for a conservative analysis.
- At the rupture, assume that the cryogen is saturated liquid.
- By the time that the cryogen reaches a vacuum relief device, assume that the cryogen reaches a temperature of 150-K.
- Assume that the maximum cryogen pressure at the vacuum relief equals 0.5-psig.

The maximum helium mass flow rate is 80-g/sec [3]. This is the combined supply from the two refrigerators at NML.

The maximum nitrogen mass flow rate is 1318-g/sec (2.9-lbm/sec) [4]. The nitrogen is supplied from a dewar whose maximum allowed working pressure is 100-psig.

Flow Capacity of Relief Device

The venting calculations show that the vacuum relief devices have the capacity to relieve the flow of a cryogen in the event of a rupture of an internal line in the CM1 vacuum vessel. The mass flow rate of a gas that is required to go through the parallel plate relief is calculated using the formulas from API 520 [5] for sonic flow. For nitrogen, flow is sonic, so the equation used to calculate the mass flow rate through the relief is:

$$W = AK_D CP\sqrt{\frac{M}{TZ}}$$

where

$$Z = \frac{PM}{\rho RT}$$

Table 10 defines the variables and lists the mass flow rate for both helium and nitrogen at the parallel plate relief valve at 150°K.

Table 10 – Mass Flow Rate through Parallel Plate Relief Valve

		Helium	Nitrogen	
P	set pressure plus overpressure allowance	15.2	15.2	psia
K_D	coefficient of discharge	0.62	0.62	
C	gas flow constant for sonic flow	377	356	
d	internal diameter of relief device	4.334	4.334	in
A	flow area	14.75	14.75	in^2
M	molecular weight	4	28	
T	absolute temperature at inlet	270	270	R
Z	compressibility factor	1.014576	0.994669	
ρ	density at flow conditions	0.0207	0.1478	lbm/ft3
R	ideal gas constant	1544	1544	lbf/(lbm-R)
W	mass flow rate	6333.6	15981.3	lb/hr
		799.7	2017.8	g/sec

For both nitrogen and helium, the capacity of a vacuum relief device is adequate for either cryogen that leaks from a rupture line.

Operating Procedures

For safe operation of the CM1 vacuum vessel, operating procedures are not required.

Welding Information

E. Zanon, the manufacturer of the vacuum vessel, provided a data book that accompanied the vessel. This document includes material certifications, welding specifications, inspection results, and quality control documents on the vessel assembly. An electronic copy of the document is located online in the CM1 folder of the ILC Document Management System:

http://ilc-dms.fnal.gov/Workgroups/CryomoduleDocumentation/CM1folder/VacVessel/

References

1. ES&H Manual Chapter 5033, Fermilab.
2. ASME Boiler & Pressure Vessel Code 2007.
3. A. Klebaner, email 18 August 2008.
4. B. Sanders, “NML High Bay ODH Analysis,” 14 March 2007.
5. American Petroleum Institute, “Sizing, Selection, and Installation of Pressure-relieving Devices in Refineries, Part I - Sizing and Selection,” API 520, 8th edition, 2008.
6. Compressed Gas Association, “Pressure Relief Device Standards Part 3 – Stationary Storage containers for Compressed Gases,” CGA S-1.3-2008, 8th Edition.