NuMI Beam Line Beryllium Vacuum Window

FESHM Chapter 5033.1

Engineering Note

Michael McGee

February 5, 2013

EXHIBIT A

Vacuum Window Engineering Note
(per Fermilab ES&H Manual Chapter 5033.1)

Vacuum Window Number: NuMI MB-488722

Identification and Verification of Compliance:

Prepared by	Michael McGee	Date	2/4/2013	Div/Sec	AD/MS
Reviewed by		Date	2-21-13	Div/Sec	A0/MSD
Div/Sec Head		Date		Div/Sec	

Director's signature (or designee) if vacuum window requires an exception to the provisions of this chapter.

Amendment No.	Reviewed by	Date

Vacuum Vessel Title for the vacuum vessel to which the Vacuum Window is attached.

Not attached to a vessel – Beam line window

Vacuum Vessel Number for the vacuum vessel to which the Vacuum Window is attached.

Not attached to a vessel – Beam line window

Vacuum Window Drawing Number (List all pertinent drawings):

8875.114-MB-488722
8875.114-MB-488726

Drawing No.	Location of Originals
8875.114-MB-488722	A0 AD Mechanical Support Drafting
8875.114-MB-488726	A0 AD Mechanical Support Drafting

Laboratory location code	MI-65 NuMI Target Hall
Purpose of vacuum vessel and vacuum window	NuMI beam line window
Internal MAWP	1 psig
External MAWP	15 psia
Working Temperature Range	50 °F 95 °F

1. Design Verification: Provide design calculations in the Note Appendix.
See Appendix "A"

2. Fabrication: Is this vacuum window fabricated in house? [ ] Yes [X] No
If "Yes", Attach the written fabrication procedure in the Note Appendix.

3. Inspection: Attach inspection reports and Travelers in the Note Appendix. Include date(s) of manufacture.
See Appendix "B"

4. Testing: Attach failure and acceptance testing procedure and results in the Note Appendix. Include dates of testing
See Appendix "C" & "D"

5. System Venting Verification:

Is the relieving system of the vacuum vessel to which this vacuum window is attached sufficiently sized such that if the vessel is pressurized, the maximum differential pressure across the window cannot exceed the design differential pressure of the vacuum window?
[X] Yes [ ] No **Beam line vacuum nitrogen let up supply is protected by 1 psig relief valve at every let up station. No calculations are necessary.**
Attach Calculations in the Note Appendix

6. Operating Procedure Section:

Is an operating procedure necessary for the safe operation of this vessel? [ ] Yes [X] No
If "Yes", the operating procedure must be attached to the Note Appendix

7. Hazard Analysis: Is the safety factor on this vacuum window less than 2.0? [ ] Yes [X] No
See Appendix "A"
If "Yes", a hazard analysis must be prepared and attached to the Note Appendix

8. Degradation from Exposure: Will the integrity of the window be compromised over time by exposure to radiation or cyclic stress? [ ] Yes [ ] No **Unknown**
If "Yes", include in the technical appendix any requirements for recording exposure, as well as a change-out schedule.
The window poses no personnel safety hazard after exposure to beam. The window will be in a high radiation area where access will not be available. If window degrades from beam exposure, window will be replaced when adequate vacuum can no longer be maintained. Spare window assembly will be used in this event. Time to failure will be determining factor in evaluating if redesign is necessary. The NuMI beam line window began leaking sometime in 2012. It was determined that beam heating (over $7 x 10^7$ pulses) and corrosion played a key role. The current window was redesigned with a 0.020" preset and the braze alloy encapsulated with a gold barrier layer to prevent atmospheric corrosion. Also, the titanium window used for beryllium containment in case of a catistsphic failure of the beryllium window was moved upstream to prevent further heating due to heat radiation.

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Engineering Note

Design Loads and Other Considerations

The NuMI pre-target primary beam line beryllium window is designed to meet the criteria for safe operation within a manned area under the FESHM 5033.1 requirement for a safety factor greater than 2[1]. The window will be shielded from access during Target Hall operation and thus considered an UNMANNED AREA according to FESHM 5033.1. Nevertheless the design meets the more conservative required SF of 2 for a MANNED AREA.

The original calculations for the "NuMI Beam Line Beryllium Vacuum Window[2]" completed by Joel Misek denote a "worst case" stress condition for this window based on a flat window and "Formulas for Stress and Strain" by Roark[3]. These calculations showed that the flat window marginally met the theoretical safety factor of 2 required by FESHM Chapter 5033.1[1,4]. The new pre-formed window design provides a reduction of stress given the original flat case. The pre-formed geometry will reduce planar stiffness of the window and therefore reduces compressive stresses caused by beam heating. This report considers both the history of past operation and confirms that this window is appropriate for safe use in the NuMI beam line.

Calculation for vacuum loading (only) provide edge stresses of 32,230 psi and center stresses of 20,740 psi (when considering a "flat" window geometry). An improvement to the note involves a rework of the design provided by Omley Industries regarding a pre-formed (0.020" inward deflection). The new design is given in drawing MB-488722 (Appendix "H" Figure H-1).

Calculations

The following calculations provide a "worst case" check of the stresses developed within the window under vacuum loading, assuming that initial window deflection was from flat. These estimates of stresses within the beryllium window are provided by Roark[3]. Case 10a (a circular flat plate with uniform loading over the entire surface)[2] and outlined in "Mechanical Safety Subcommittee Guideline for Design of Thin Windows of Vacuum Vessels[4]." The beryllium properties given in Table 1 reflect information collected from Brush Wellman Inc.[5] and testing completed by Sandia National Laboratory.

Table 1: Properties of pure beryllium as a function of temperature.

Temperature (K)	300	400
Density (kg/m^3)	1,848	1,848
Ultimate Strength (MPa)	448.2*	---
Yield Strength (MPa)	283	---
Modulus of Elasticity (MPa)	296e3	290e3
Poisson's Ratio	0.1	0.1
Fatigue Strength (MPa)	268**	---
Thermal Conductivity (W/m/K)	199	162
Coef. of Thermal Expansion (m/m/K)	1.16e-5	1.25e-5
Specific Heat (J/kg/K))	1,857	2,156

*From Brush Wellman tests performed on 0.25 mm thick PF-60 material (see email in Appendix “F”).
**Based on > 10^7 cycles.

Bending Stress $\sigma = 6(M/t^2)$, where $M_{center} = q(a)^2(1+\nu)/16$ & $M_{edge} = q(a)^2/8$

Given
q (load) = 14.7 psid (vacuum)
a (outer radius) = 1.125”/2 = 0.5625”
ν (Poisson’s ratio) = 0.1
t (thickness) = 0.010”

Solving
$M_{center} = 14.7$ psi $(0.5625”)^2(1+0.1)/16 = 0.321$ lbf
$M_{edge} = 14.7$ psi $(0.5625”)^2/8 = 0.581$ lbf

$\sigma_{center} = 6(0.321 \text{ lbf})/(0.010”)^2 = 19{,}190$ psi [132. 3MPa]
$\sigma_{edge} = 6(0.581 \text{ lbf})/(0.010”)^2 = 34{,}880$ psi [240.5 MPa]

Determine if deflection is less than ½ thickness (if not, use diaphragm equations)

Deflection $y = q(a)^4/(64(D))$, where $D = E(t)^3/(12(1-\nu^2))$

Given $E = 42 \times 10^6$ psi

Solving
D = 42 x 106 psi $(0.010”)^3/(12(1-0.1^2)) = 3.54$ in(lbf)
y = 14.7 psid (0.5625”)4/(64(3.54”(lbf)) = 0.0065”

Since the deflection is larger than half of the plate thickness, the use of the Roark diaphragm plate equations is justified.

The equations are: $q(a)^4/E(t)^4 = K_1(y/t) + K_2(y/t)^2$ (Eqn. 5.1a)[4]

Stress $\sigma = E(t/a)^2[K_3(y/t) + K_4(y/t)^2]$ (Eqn. 5.1b)[4]

Given $K_1 = 5.33/(1-\nu^2)$; $K_2 = 2.6/(1-\nu^2)$ (K-values for maximum stress.)

Solving $K_1 = 5.33/(1-0.1^2)$; $K_2 = 2.6/(1-0.1^2)$ or $K_1 = 5.384$; $K_2 = 2.626$

Solved for y in Eqn. 5.1b by finding the root of $F(y) = K_1(y/t) + K_2(y/t)^2 - q(a)^4/E(t)^4 = 0$

Deflection y = 0.005635”

This result is substituted into the stress equation:

Stress at Edge K3 = 2.0/(1-0.1); K4 = 0.976 or K3 = 2.222; K4 = 0.976

$\sigma_e = 42 \times 10^6$ psi $(0.010”/0.5625”)^2[2.222(0.005635”/0.010”) + 0.976(0.005635”/0.010”))^2]$
= 20,740 psi

Stress at Center K3 = $4.0/(1-0.1^2)$; K4 = 0.476 or K3 = 4.04; K4 = 0.476

$\sigma_c = 42 \times 10^6$ psi $(0.010”/0.5625”)^2[4.04(0.005635”/0.010”) + 0.476(0.005635”/0.010”))^2]$

Additional calculations considered higher pressures for comparison with possible hydrostatic testing results shown in Table 2.

Table 2: Summary of stresses at window edge given extended pressures.

Loading (psid [MPa])	Deflection (in [mm])	Maximum Stress at Edge (psi [MPa])
30 [0.207]	0.0093 [0.236]	55,340 [381.6]
60 [0.414]	0.0136 [0.345]	84,540 [582.9]
120 [0.827]	0.0192 [0.488]	126,220 [870.3]

Testing

In the original note "NuMI Beam Line Beryllium Vacuum Window[2]" by Joel Misek, a hydrostatic test to failure was completed on a beryllium window taken from the original window production order of six units (refer to Appendix "C").

This window failed at a pressure of 160 psi [1.103 MPa]. As the pressure was increased from 15 psi, deflection measurements were made to compare the theoretical to the actual. The actual window had an initial deformation of roughly 0.020" [0.5 mm] as a result from the brazing operation during the manufacturing process. This dishing or performing of a window will typically reduce the stress for a given load.

Finite Element Models

Further finite element (FE) analysis involving steady-state and transient analysis were applied to estimate the effect of thermal strain. First, a steady-state FE analysis was considered using a solid model in Workbench. Second, a transient FE analysis was completed for the flat and preset 0.020" curved beryllium window cases in classical ANSYS.

Steady-state Cases

In each case, a solid model of the upstream (US) pre-target beryllium vacuum window was imported into ANSYS Workbench for steady-state thermal and then structural analysis. Figure 1 provides the sectioned-view of the meshed solid model with outer stainless steel (SS) flanges, beryllium and titanium (Ti) windows.

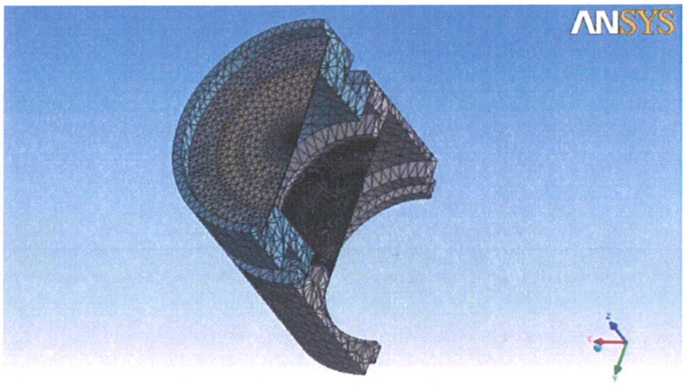

Figure 1: Flanged assembly of FE model with beryllium and Ti windows.

For the thermal model, internal heat generation values were added based on MARS15[6] estimates outlined in Table 3 under average power density and based on beam power of 700 kW (NOvA parameters are shown in Table 4) case. Also, a film coefficient of 2 W/(m^2-°C) was applied at the outer face of the beryllium window. Internally, radiant heat exchange between the beryllium and Ti windows was considered using view factors assumed as 1.0 and emissivity values of 0.18 and 0.19, respectively[7]. In this case, ANSYS Parametric Design Language (APDL) was applied using an ANSYS Radiosity Solution Method via a Command object in Workbench. A temperature of 30.8 °C was defined at the most upstream (US) face of the flange (which would be connected to the beamtube), based on an initial study by Brian Hartsell[8]; "NuMI Vacuum Tube Assembly – Axisymmetric Steady-state ANSYS Modeling." The surrounding environment was assumed to be 24 °C.

Table 3: Summary of MARS15 energy deposition (ED) for 700 kW.

Bin		**Average Power Density (W/mm^3)**		**Instantaneous Power Density (W/mm^3)**
r_1 (cm)	**r_2 (cm)**	**Be***	**Ti**	**Be***
0	0.05	1.8E-01	3.2E-01	4.30E13
0.05	0.10	1.5E-01	2.9E-01	3.81E13
0.10	0.15	1.1E-01	2.1E-01	2.85E13
0.15	0.20	7.4E-02	1.4E-01	1.80E13
0.20	0.25	4.2E-02	7.8E-02	1.03E13
0.25	0.30	2.1E-02	3.8E-02	5.07E12
0.30	0.35	8.6E-03	1.6E-02	2.11E12
0.35	0.40	3.3E-03	6.2E-03	8.25E11
0.40	0.45	1.1E-03	2.0E-03	2.65E11
0.45	0.50	3.5E-04	5.8E-04	7.67E10
> 0.50		2.6E-05	2.3E-05	1.01E10

*Values are within 10% of MARS15 2010 ME estimate from Bryon Lundberg[9].

Table 4: NOvA (700 kW) beam parameters.

Beam Energy	120 GeV/c
Protons per Pulse	4.90 x 10^{13}
Cycle Time, sec	1.33
Beam Sigma, mm (rms) in (x,y) plane	1.3
Pulse Length, sec	1 x 10^{-5}

In the structural model, a pressure of 101,400 Pa (or vacuum loading) was applied to the outer beryllium window surface and the outer window edge. Both, large deflection and stress stiffening options were activated. The most US flange edge of the assembly was held fixed. The steady-state thermal conditions were also applied prior to structural analysis completed in a separate ANSYS run.

Transient Cases

In each transient case, a 2-D IGES file of the pre-target beryllium vacuum window was imported into ANSYS and a solid model was generated. A Solid90 ANSYS element was used for the solid model in terms of the transient thermal and subsequent structural analysis.

FE Model Results

Figures 2(a) and 2(b) gives the steady-state temperature profile under 700 kW beam power (NOvA) conditions for flat and 0.020" preset curved beryllium window geometry, respectively. The equivalent (von Mises) stress for the flat window geometry is provided in Figure 3. A summary of results is given in Table 5.

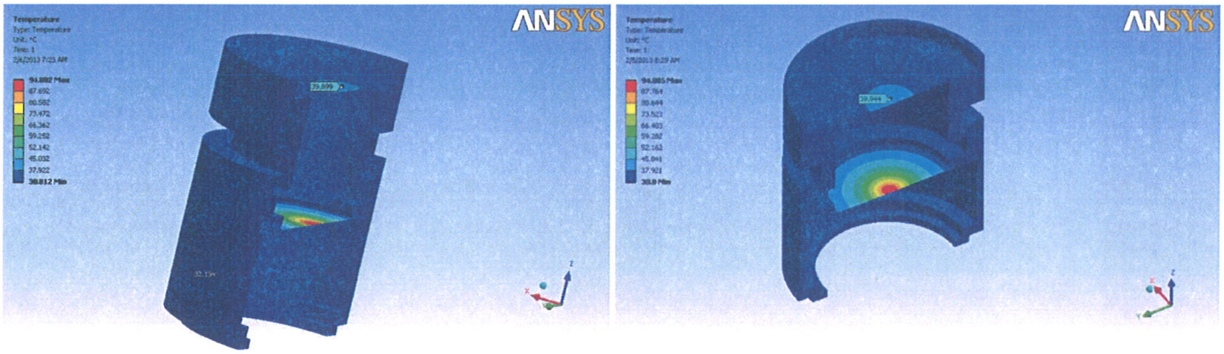

Figure 2(a): Temperature profile of 700 kW flat beryllium window with vacuum and ED. **2(b):** Preset 0.020" curved window T-profile.

Figure 3: Equivalent von Mises stress of 700 kW preset 0.020" curved window with vacuum and ED.

Table 5: Result for steady-state model with vacuum loading, ED and heat radiation.

Window Geometry	P (kW)	T(Be) [^{o}C]	T(Ti) [^{o}C]	Von-Mises σ_e [MPa]	Von-Mises σ_c [MPa]	Allowable σ_a [MPa]	Deflection d_{max} [mm]
Flat	NA	24*	24*	196.9	96.8	224.1	0.091
	700	39.9	94.8	200.2	86.4		0.086
0.020” Curved	NA	24*	24*	119.9	28.9		0.061
	700	39.9	94.9	119.9	29.2		0.061

The steady-state thermal (ED and heat radiation) with structural (vacuum loading) results show that a flat 0.25 mm (0.010”) thick beryllium pre-target window of the NuMI style design does meet the allowable stress at 700 kW beam power as established by Fermilab FESHM Chapter 5033.1. The maximum stress of 200.2 MPa was found at the window edge and the FESHM allowable stress was 224.1 MPa (noted in Joel Misek’s “NuMI Beam Line Beryllium Vacuum Window” Note and outlined in Table 4). Changing the window design to preset 0.020” curved geometry, considering that a maximum equivalent stress of 119.9 MPa would improve the existing Safety Factor of 2 by another factor of 2.

Transient Cases

After 380 seconds of operation using a continuous 10 μsec beam pulse every 1.33 seconds, the beryllium window center temperature rises from 56.5 °C to 66.4 °C. Figure 4(a) shows the temperature profile for the flat beryllium window transient case. Figure 4(b) provides the contour plot of von Mises equivalent stress. Table 6 provides a summary of the transient cases under comparison; flat and 0.020” preset curved window geometry. The values for von Mises stress and maximum deflection closely follow the steady-state result in each case.

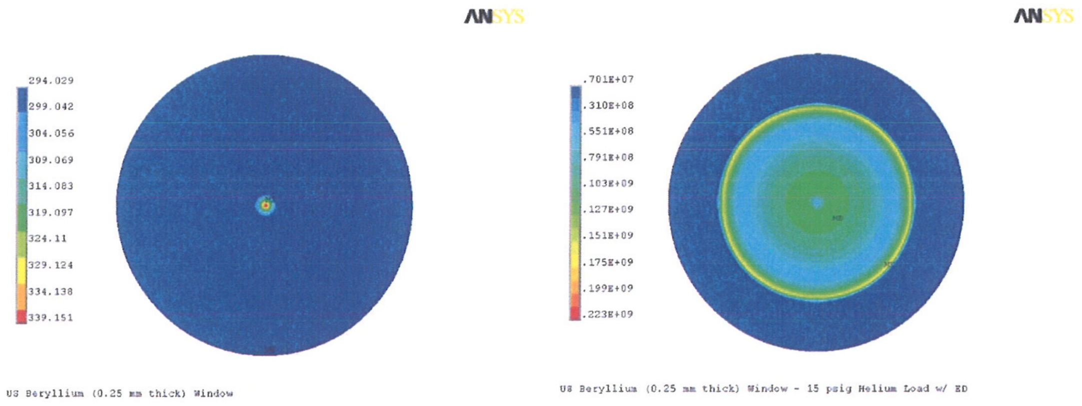

Figure 4(a): Temperature profile of 700 kW flat beryllium window with vacuum and ED. **4(b):** Flat window von Mises equivalent stress.

Table 6: Result for transient model with vacuum loading and 700 kW ED.

Window Geometry	T_a [^{o}C]	T_b [^{o}C]	Von-Mises σ_e [MPa]	Von-Mises σ_c [MPa]	Allowable σ_a [MPa]	Deflection d_{max} [mm]
Flat	56.5	66.4	219	122	224.1	0.150
0.020”Curved	57.9	68.2	141	46.2		0.071

Fatigue Analysis

In the case of beryllium, the fatigue data available is on the order of 10^7 cycles for S-200F in Figure 5. Note that beryllium PF-60 foil is a rolled form of S-200F. Higher fatigue values are not supported and no elevated-temperature fatigue data is available. Considering the limitation of relevant data, a Goodman Diagram Method shown below is applied. The previous pre-target window for NuMI had seen ~7.0 e7 beam pulses[5] before developing a small vacuum leak. This one data point could also indicate the validity of the chosen method.

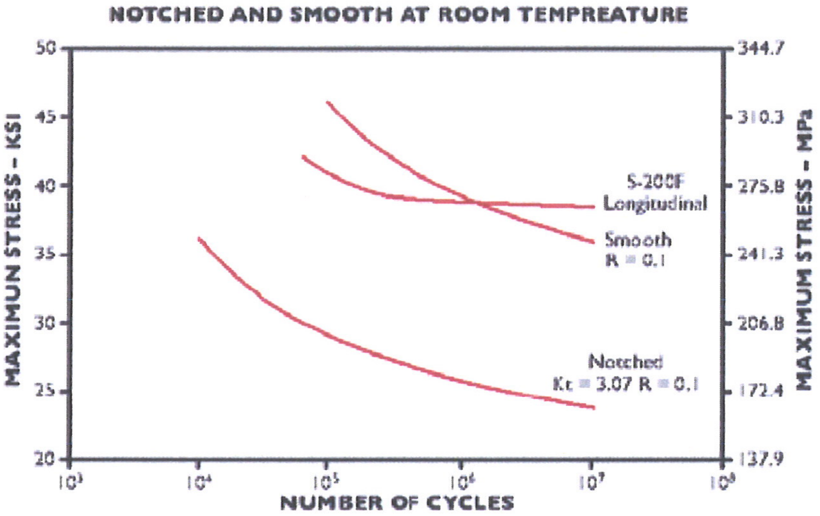

Figure 5: S-N curves for S-200F beryllium sheet[10].

Goodman Diagram and Method

The method described below was developed by Curtis Baffes[11] within “ASTA Beryllium Beam Exit Window.” A single stress reversal ratio “R” (the ratio of the minimums stress within the loading cycle to the maximum) is given within a Goodman Diagram. In order to compare the data found within the graph (shown in Figure 6) to the actual R/σ fatigue loading condition found in the window design, the Goodman Diagram is used to interpolate fatigue strength at values of R.

This method allows for bracketing the window of acceptable fatigue under the area shown in Figure 6 for Goodman values of 10^7 cycles. Another factor in the failure was corrosion. Moist air coupled with ionizing radiation within the target chase creates a highly corrosive environment. One extra precaution involved a braze joint between the window and stainless flange at the interface being encapsulating with gold to prevent corrosion.

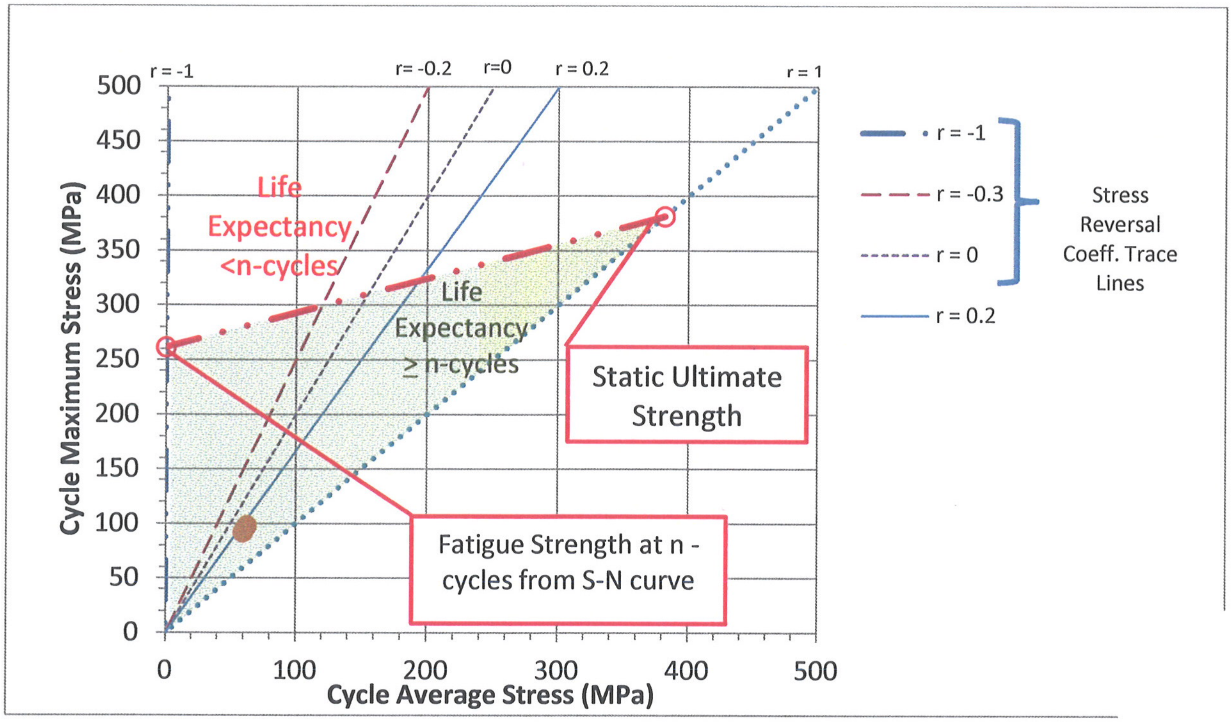

Figure 6: Theoretical bases for simplified Goodman Diagram given fatigue at n-cycles.

Values in terms of radial and hoop stress provided on the graph shown in Figure 6 were taken from the ANSYS transient analysis run within a section cut of the window near the center where relative motion would be the highest over time.

The failure criteria line was established at (r = 0) on the Goodman diagram. The reversal coefficient (r) is defined as the smallest magnitude over the largest magnitude of stress. This coefficient exists between -1 and 1, where a (+) sign relates to tension and a (-) sign to compression.

The worst case stress was found in the compressive sector (left side of Figure 7) along the line (r = -0.2), and also given in Figure 8. This considers that tension is found in the most outer fiber of the window, vacuum-side surface and compression on the most outer pressure-side surface.

As beam heating occurs (during high cycle), the most outer fibers at the window's center which are in tension (while under vacuum) expand and go further into tension. Conversely, the most outer fibers at the outside surface under atmospheric pressure or under compression expand and cause further compression. After a beam pulse, as the window cools (during low cycle) the most outer fibers of the window contract while under tension (on the vacuum-side). The opposite fibers under atmospheric pressure also contract away from their compressive state. Therefore, during the low cycle within the compressive sector, fatigue is the greatest. The fatigue data point acquired from the NuMI run is found just outside of the fatigue envelope along the low cycle (r = -0.2) line in Figure 8.

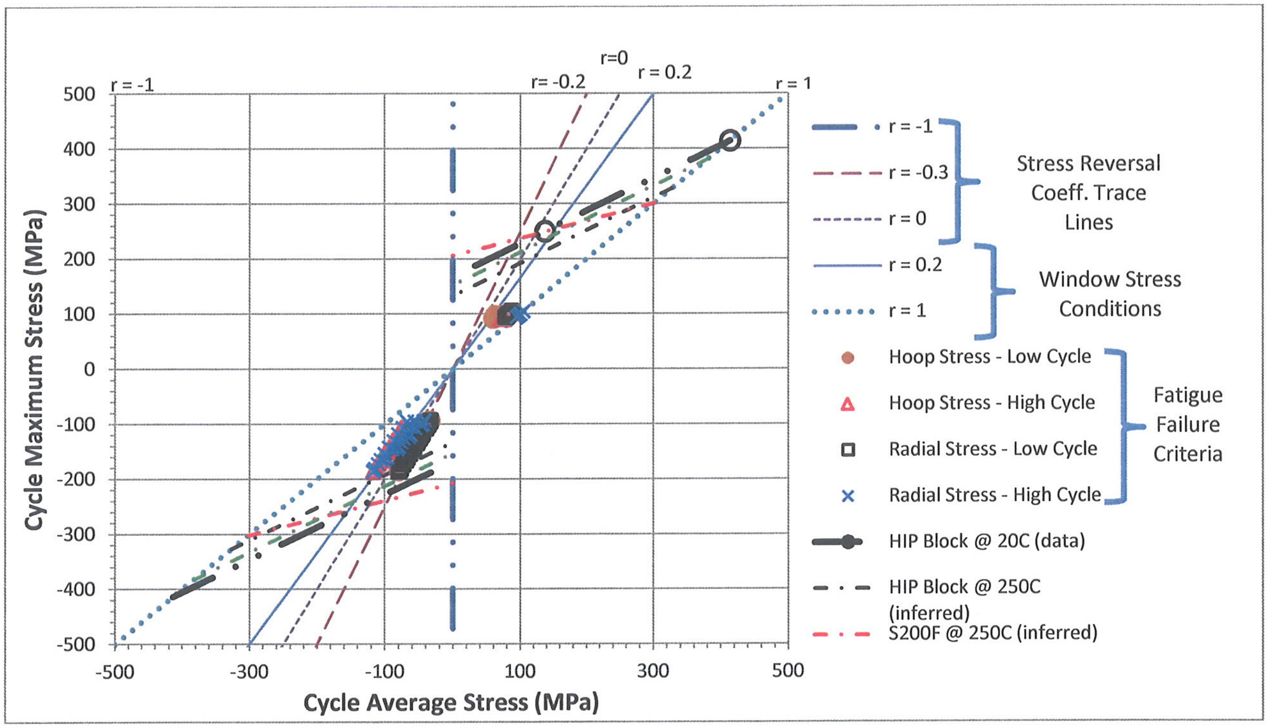

Figure 7: Goodman Method for fatigue at 10^7-cycles.

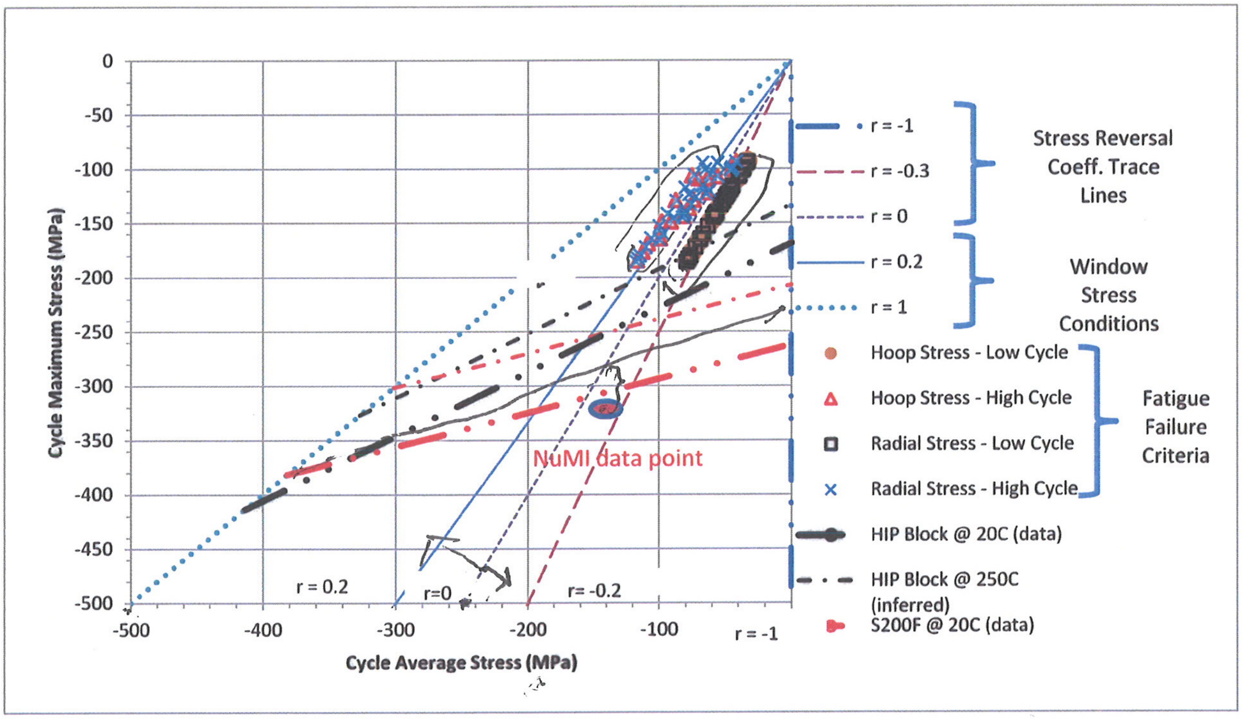

Figure 8: Compressive sector of Goodman Diagram for fatigue at 10^7-cycles.

Conclusion

The NuMI vacuum window assembly is designed with a theoretical safety factor of greater than the 2 required by the FESHM chapter 5033.1. Steady-state and transient ANSYS analysis show a safety factor of roughly 4. Initial testing completed during the NuMI Era shows that the beryllium window actually fails at 160 psi or a factor of 10 over vacuum loading. With a window size of only 1" in diameter, the personnel hazards from failure are relatively small. Appropriate personnel protection will be utilized when leak testing the final assembly prior to installation. The issue of beryllium contamination control has been presented which shows that in the unlikely event of a window failure, the contamination, if any, will be localized within the NuMI vacuum system in the section closest to the Target Hall. The calculations, testing and backup window have demonstrated that the hazards associated with the window are minimal.

References

1. Fermilab, Fermilab ES&H Manual, Chapter 5033.1, "Vacuum Window Safety," http://www-esh.fnal.gov/FESHM/5000/5033.htm.
2. J. Misek, "NuMI Beam Line Beryllium Window," Fermilab Thin Window Engineering Note, Fermilab, August, 2004.
3. W. Young, "Roark's Formulas for Stress & Strain," 6th Edition, pp. 428-477, 1989.
4. J. L. Western, "Mechanical Safety Subcommittee Guideline for Design of Thin Windows for Vacuum Vessels," Fermilab – TM – 1380, March 1993.
5. Brush Wellman Inc., Engineering Materials, "Designing with Beryllium," 17876 St. Claire Ave., Cleveland, Ohio, 44110, 1997.
6. MARS Code System, http://www-ap.fnal.gov/MARS/.
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9. Private communication with Byron Lundberg, Fermilab, September 2009.
10. Materion, "Designing and Fabricating Beryllium," Materion Brush & Beryllium Composites, 2011.
11. C. Baffes, "ASTA Beryllium Beam Exit Window," Beams docdb, September 3, 2010.

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CERTIFICATE OF COMPLIANCE

Customer: Fermilab

Date: 3/14/2013

Customer PO #: 610223

Assembly Name/Part #: #8875.114-MB-488722, Beryllium Window

Quantity: 2

Omley SO #: 48906

Bake-out:

Leak/Pressure Test: Less than 1x10^{-9}cc/sec under a partial pressure of helium for three minutes.
Non-Standard –

Hi-Pot/Electrical Test:

Dimensions:

Other: Sending back the third unused housing.

Omley Inspection Report # 35701
This is to certify that the described parts have been processed as required by the above mentioned purchase order in accordance with the corresponding specifications.

Certified Inspector of Omley Industries, Inc.

Appendix "C"

Hydrostatic Pressure Test

for beryllium window Drg. # 8875.114-MB-422562

Date: 6/21/04 Present: Ralph Ford, Mike Bonkalski, Joel Misek

Test was performed with a hand actuated pump to hydrostatically pressurize the window assembly with water. All air was bled from lines and window volume prior to test. Measurements were made at approximately 15 second intervals.

Deflection of window was measured versus pressure.

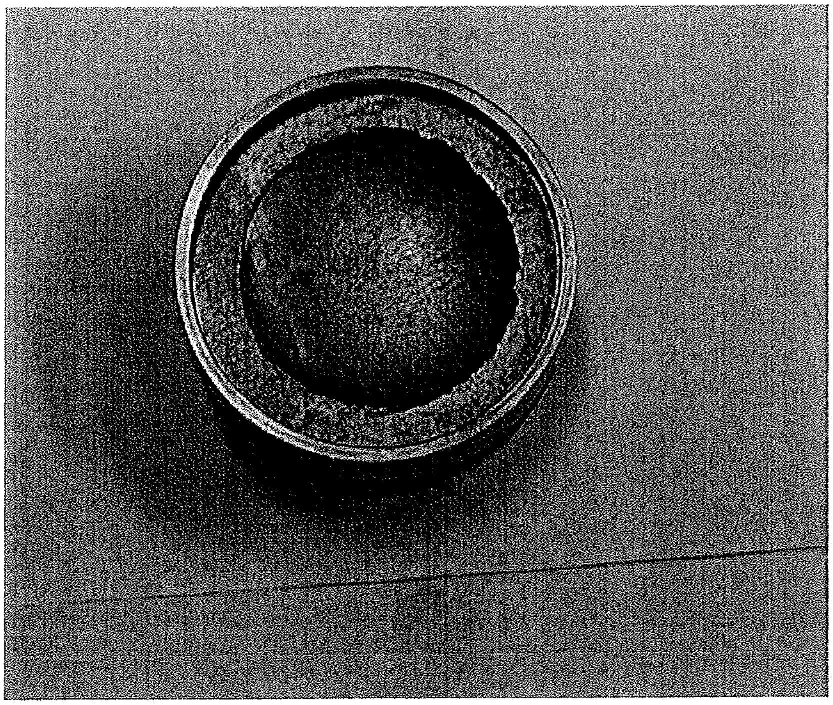
Pressure	Deflection
0	Initial deformation as received from vendor = .020"
10	.002
15	.0025
20	.003
30	.005
let up to 0	.002
30	.005
40	.0065
50	.008
60	.095
70	.0105
80	.012
Let up to 0	.006
100	.0125
120	.015
140	.017
160	.020
165 Failed	

Comments:
The failure was instantaneous. See following photo for view of failure.
The circumferential crack has a radius of .56 in. This is approximately where the relief on the window body begins and the braze joint ends. The beryllium slug was still attached and could not be removed.

Hazards: Possible fragmented projectiles, beryllium contamination

1. All personnel to wear safety glasses
2. Bag window assembly and fixturing for beryllium containment
3. Handle with gloves – by qualified beryllium handler

Appendix “C”



Appendix "D"

Acceptance Test

(For beryllium window drawing 8875.114 MB-488722)

Procedure:

1. Measure window position with depth micrometer.
   Pre-curved Deflection (without vacuum load): 0 (.133)
2. Install aluminum window cover.
3. Pump down unit with leak detector.
4. Remove window cover and measure deflection. Record below.

   Deflection under vacuum load: .002" (.135)

   Helium leak rate: 2.21 x 10^{-11} TORRL/S

Hazards: Possible fragmented projectiles, beryllium contamination.

1. All personnel to wear safety glasses
2. Handle assembly with gloves – by qualified beryllium handler

Date: 3/28/13

Name: Sali Sylejmani

Appendix "E"

Beryllium containment for the NuMI Beam line Beryllium/Titanium Window Assembly

Drawing # 8875.114 MC-488726

Introduction:

(Note that this section is primarily taken from the original "NuMI Beam Line Beryllium Vacuum Window" Engineering Note by Joel Misek. The updates in the current window note are due to changes in the design for ANU (NOvA) and increased understanding of the operation, after running for 9 years.)

The NuMI beam line Beryllium/Titanium window assembly will be located at the most downstream (DS) end of the 1,100 ft. beam line. At this location, after passing through a 7 foot thick shield wall, the beam line vacuum terminates with the window assembly. The beryllium window will need to maintain a vacuum of 1×10^{-7} Torr as shown in NuMI primary beam line layout Figure E-1.

Choices for a window material are limited to titanium or beryllium. The argument for using beryllium stems from the operational experience in the P-bar Source's AP1 beam line where the higher intensities have degraded their 0.002" thick titanium window to the extent that it could not maintain 1×10^{-6} Torr vacuum. This condition developed over the years and with multiple failures, this titanium window was replaced with a beryllium window. After five years of running with this beryllium window, no vacuum failures have taken place. In addition, a similar window was used for the NuMI target tests run at the AP0 Target Hall in 1999 (Ref. NuMI-B-448). The intensities were increased for these tests and the window showed no signs of damage or leaks. Given this successful history NuMI utilized a beryllium window with the same diameter and thickness within the primary vacuum beam line until delivering its final pulse in November 2012. This window received roughly 7×10^{7} pulses of beam.

A major concern in using a beryllium window is the possibility of spreading beryllium contamination up the beam line if a window failed. For the P-bar Source AP1 beam line window, this concern was addressed by isolating the beryllium window with its own independent vacuum section complete with pumps and controls. This also required the addition of titanium windows and an air gap be added to the beam line. The titanium windows were positioned 20 ft. from the beryllium window where beam size is larger and energy deposition/area is at a tolerable level.

Beryllium/Titanium Window Design:

For NuMI, the addition of a separate vacuum section with additional titanium window is not a preferred option. Cost, operational demands, and the issue of increased beam losses if an additional window is installed are the dominant reasons. In this context, a combined beryllium/titanium window assembly is presented which will substantially reduce the possibility of spreading beryllium contamination into the beam line from a ruptured beryllium window.

For a catastrophic failure of a window, an unimpeded burst would likely travel into the Main Injector before the isolation valves had a chance to close. The possibility of beryllium contamination reaching the Main Injector would exist. Most contamination would be generated by larger pieces fragmenting as they are carried down the beam tube. The new NuMI Beryllium/Titanium design has a titanium window 6.678" US preventing a burst of air with window fragments from traveling up the beam tube toward the Main Injector. This backup window will act as a barrier preventing a burst of air with window fragments from traveling up the beam tube towards the Main Injector. Only a small volume between the windows will travel past the failed window. This volume is less than 10 cubic inches. The volume between the two windows communicates with the beam tube vacuum through 4 small bleed holes as shown in Figure E-2 (taken from drawing 8875.114 MC-488726).

To further reduce flow velocities, the bleed holes will have check-valve-flaps installed over the openings so that in the event of a beryllium rupture the flap will close off the flow passage to the majority of the air flow. The measured flow through the 4 bleed holes is approximately 0.12 ft^3/min. The closing speed of the isolation valves is 5 seconds giving a total influx of only 16 in^3 of air. Any small dust size particles will travel with the air bleeding in through the bleed holes. The first isolation gate valve for the vacuum line is approximately 400 feet US of the window. The valves close when ion pumps trip off from high current. The high current is sensed when molecules travel to the first set of pumps. It will take less than a second for the pumps to trip off and start the valves closing. With the first isolation valve closed it will take over 2 hours for this first section to be let up to atmosphere. This slow bleed up will have low air velocities and subsequently will not have enough energy to more particulate up the 15% slope of the beam line.

The NuMI beam line vacuum system is separated into three distinct sections with a total volume of 235 ft^3. The first section extends from the window to the 12 inch diameter tube in the carrier pipe. This section is approximately 400 feet long and contains various magnet, instrumentation and pumping devices. The second section is a 12 inch diameter tube that extends up the carrier pipe for a distance of 220 feet. This section contains only the vacuum pumps and isolation valves located on each end. The third section extends from the 12 inch tube to the isolation valve located immediately downstream of the extraction Lambertson magnets in the Main Injector. This section is approximately 540 feet long and contains various magnet, instrumentation and pumping devices.

It is highly unlikely that beryllium contamination would go beyond the first section. If in that unlikely event, the second section with its large diameter and large volume would offer further resistance to particulate migrating up the pipe. With this section being primarily smooth pipe, identifying beryllium contamination would be straightforward. The first vacuum section would not compromise Main Injector operation. The second section is within the Main Injector interlocks and would require a Main Injector shutdown.

The backup titanium window under normal operation does not see loading. From our experiences at AP0 Target Hall, the titanium window is expected to see degradation. Inspection of windows that leaked showed no visual holes indicating that the damaged to the window is extremely small and would not compromise its mechanical strength. Testing of a similar titanium window has demonstrated that a puncture of the window does not cause the windows to fail catastrophically. Nevertheless, the calculated safety factor for this window is greater than 2.

Appendix "E"

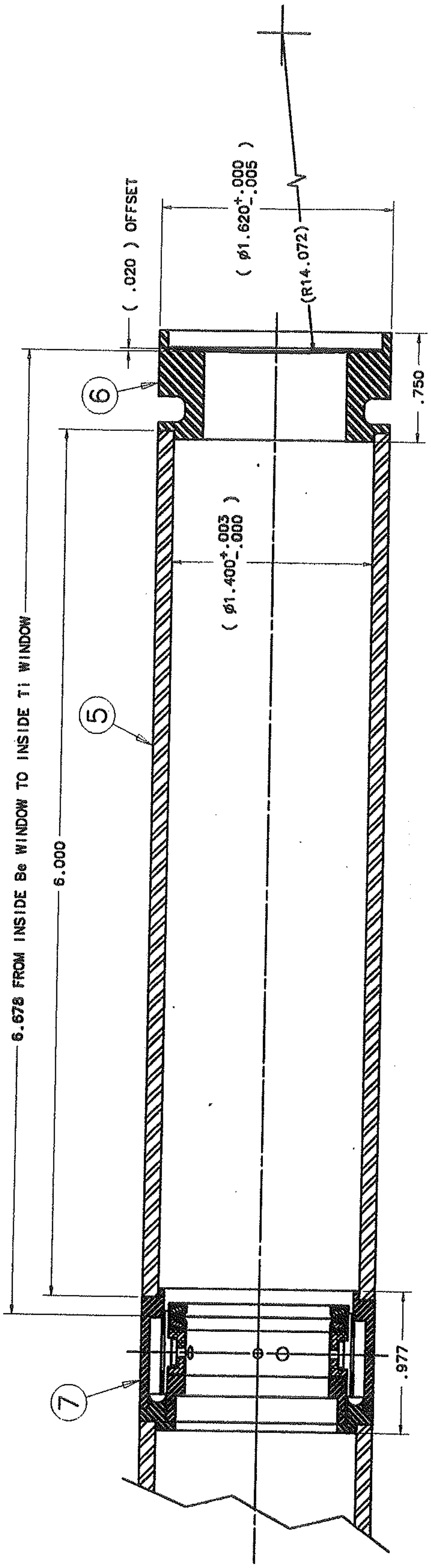


Figure E-2

Appndix “E”

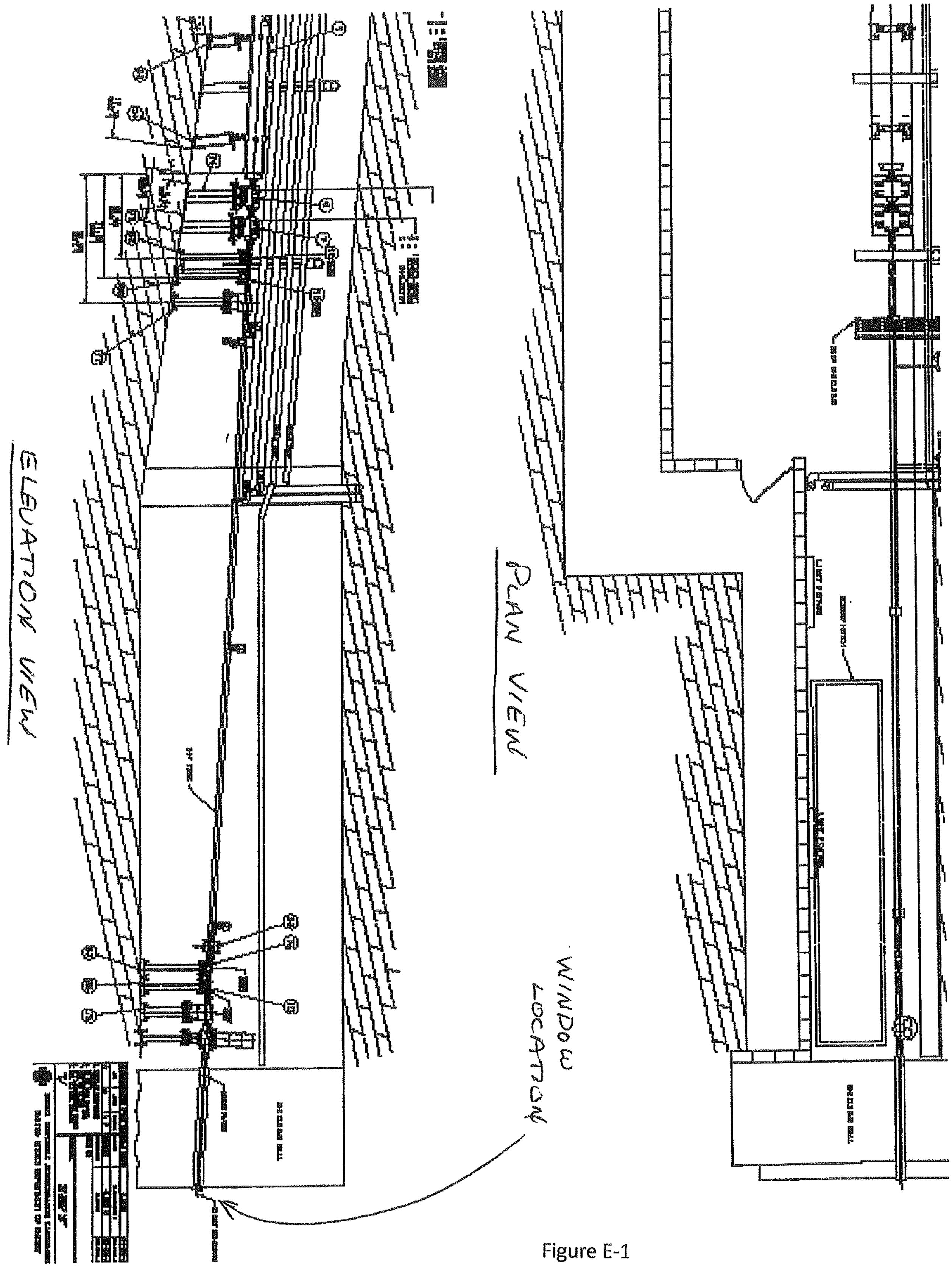


Figure E-1

Appendix "F"

From: Gordon_Simmons@brushwellman.com
Subject: **PF-60 Tensile Data**
Date: May 24, 2004 6:03:23 PM CDT
To: misek@fnal.gov
Cc: Jose_Villanueva@brushwellman.com

Joel,

As we discussed on the telephone earlier, PF-60 material is characterized for chemical, but not mechanical properties. If you need to have beryllium sheet material which is characterized for mechanical properties, SR-200 is the only choice that we offer. However, SR-200 beryllium sheet material is not produced in thicknesses below 0.020".

We have performed a few mechanical tests on 0.010" thick PF-60 material. The results of that testing indicated an ultimate tensile strength of approximately 65 ksi. Please note this testing was performed on only a few pieces of 0.010" thick material and the results may not be representative of all PF-60 beryllium foil.

Feel free to contact me if you have additional questions concerning our products.

Best regards,
Gordon

\- -

Gordon Simmons
Engineering Manager

Brush Wellman Inc.
Electrofusion Products
44036 South Grimmer Blvd.
Fremont, CA 94538

TEL 510-661-9715
FAX 510-623-7600
EMAIL <Gordon_Simmons@BrushWellman.com>
WEBSITE http://www.ElectrofusionProducts.com

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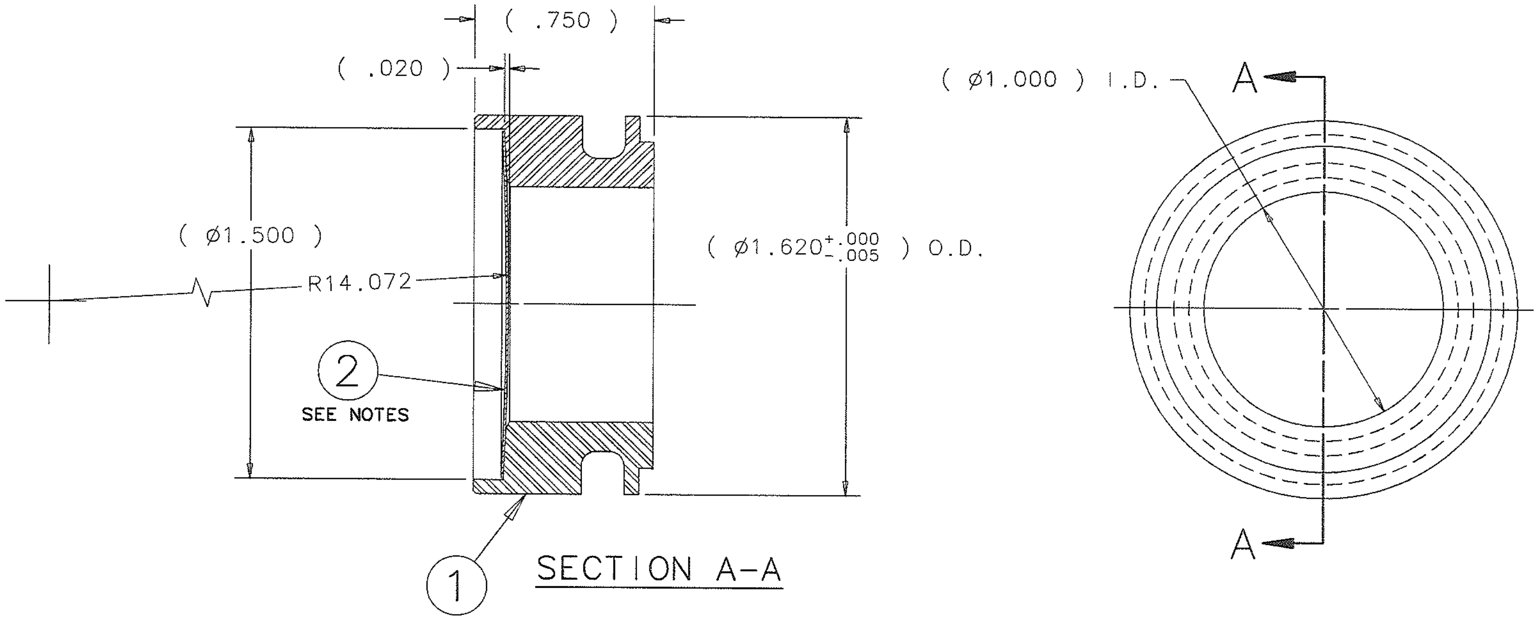
Appendix "G"

Operations

Hazards: Beryllium contamination, damage to window

1. Handle with gloves - by qualified beryllium handlers
2. Keep aluminum protective cap on end of window when exposed
3. Post area at shield wall near window with "Beryllium" signage

REV	DESCRIPTION	DRAWN APPROVED	DATE DATE



NOTES

1. BRAZE MATERIAL COPPER/SILVER/TIN IS ACCEPTABLE
2. BRAZE TO BE VACUUM LEAK TIGHT- NO LEAK DETECTABLE ON MOST SENSITIVE SCALE OF A HELIUM LEAK DETECTOR WITH A MINIMUM SENSITIVITY OF 10E-9 ATM.CC/SEC.
3. BRAZE ALLOY TO BE ENCAPSULATED WITH GOLD BARRIER LAYER TO PREVENT ATMOSPHERIC CORROSION.

ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
2	MB-488724	BE WINDOW	1
1	MB-488723	BE WINDOW HOLDER	1.

PARTS LIST

UNLESS OTHERWISE SPECIFIED

.XX	.XXX	ANGLES
± .015	± .005	±1/2°

1. BREAK ALL SHARP EDGES .015 MAX.
2. DO NOT SCALE DRAWING.
3. DIMENSIONS BASED UPON ASME Y14.5M-1994
4. MAX. ALL MACH. SURFACES 125√
5. DRAWING UNITS: U.S. INCH

ORIGINATOR	K.ANDERSON	02-JAN-2013
DRAWN	G.WAVER	02-JAN-2013
CHECKED	K.ANDERSON	17-JAN-2013
APPROVED	K.ANDERSON	17-JAN-2013

USED ON

MATERIAL
SEE PARTS LIST

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

ANU VACUUM BEAMLINE
.020 OFFSET
BERYLLIUM WINDOW ASSEMBLY

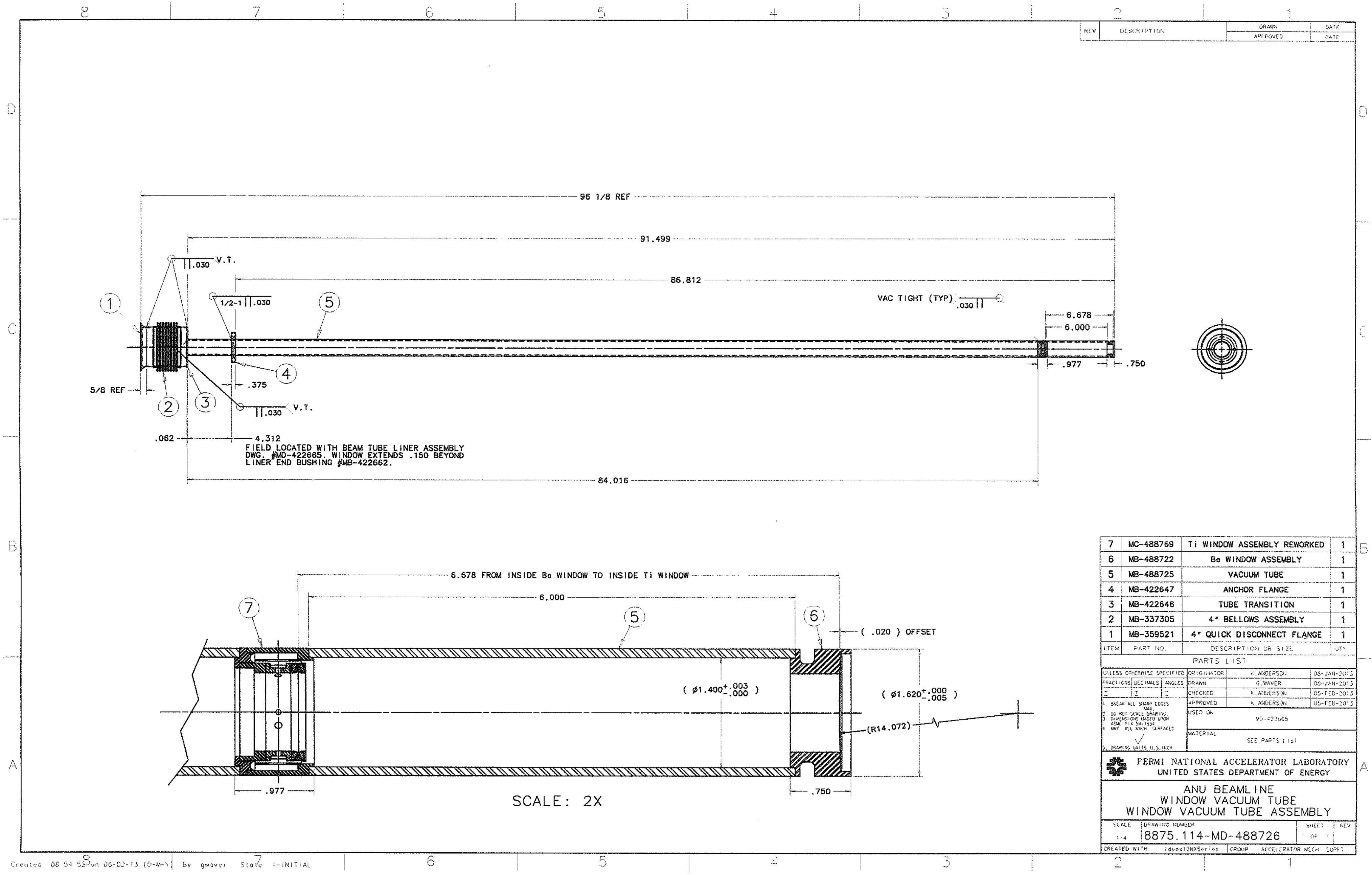
SCALE	DRAWING NUMBER	SHEET	REV
2:1	8875.114-MB-488722	1 OF 1	

CREATED WITH : Ideas12NXSeries GROUP: ACCELERATOR MECH. SUPPT.

Created: 10:18:03 on 17-01-13 (D-M-Y) By: gwaver State: 1-INITIAL

Figure H-1

Appendix "H"



ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
7	MC-488769	Ti WINDOW ASSEMBLY REWORKED	1
6	MB-488722	Be WINDOW ASSEMBLY	1
5	MB-488725	VACUUM TUBE	1
4	MB-422647	ANCHOR FLANGE	1
3	MB-422646	TUBE TRANSITION	1
2	MB-337305	4" BELLOWS ASSEMBLY	1
1	MB-359521	4" QUICK DISCONNECT FLANGE	1

PARTS LIST

ORIGINATOR	R. ANDERSON	08-JAN-2013
DRAWN	G. WAVER	08-JAN-2013
CHECKED	R. ANDERSON	05-FEB-2013
APPROVED	R. ANDERSON	05-FEB-2013

UNLESS OTHERWISE SPECIFIED
FRACTIONS ± DECIMALS ± ANGLES ±
1. BREAK ALL SHARP EDGES MAX.
2. DO NOT SCALE DRAWING.
3. DIMENSIONS BASED UPON ASME Y14.5M-1994
4. MAX. ALL MACH. SURFACES ✓
5. DRAWING UNITS: U.S. INCH

USED ON MD-422665

MATERIAL SEE PARTS LIST

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

ANU BEAMLINE
WINDOW VACUUM TUBE
WINDOW VACUUM TUBE ASSEMBLY

SCALE 1:4 DRAWING NUMBER 8875.114-MD-488726 SHEET 1 OF 1 REV

CREATED WITH Ideas12NXSeries GROUP ACCELERATOR MECH. SUPPT.

Created 08:54:52 on 08-02-13 (D-M-Y) by gwaver State: 1-INITIAL

Figure H-2