NuMI Beam Line
Beryllium Vacuum Window

FESHM Chapter 5033.1
Engineering Note

J. Misek 8/4/2004

EXHIBIT A

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

Vacuum Window Number: Numi MB-422562

Identification and Verification of Compliance:

Prepared by	Joel Misek JM	Date	8/3/04	Div/Sec	Accelerator
Reviewed by	Bob Wands RW 9/10	Date	8/5/04	Div/Sec	PPD
Div/Sec Head	Roger L. Dixon	Date	8-9-04	Div/Sec	AD

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-422562
8875.114-MC-422641
8875.114-MB-422640

Drawing No.	Location of Originals
MB-422562	A0 AD Mechanical Support Drafting
MC-422641	A0 AD Mechanical Support Drafting
MB-422640	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 ***See Drg. MB-422562***

   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 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.

   Window poses no personnel safety hazard after exposure to beam. 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.

Appendix "A"

Engineering Note

Design Loads & Other Considerations:

This window is designed to satisfy manned area requirements namely a safety factor greater than 2 even though the window will be shielded from access when the NuMI Target Hall is fully operational.

Calculations for vacuum loading give edge stresses of 32,000 psi and center stresses of 20,700 psi. The material used for this window has a characteristic ultimate tensile stress value of 65,000 psi as stated by Brush Wellman representative (See Appendix "F"). This gives a safety factor of 2.02 at the edge and 3.13 at the center.

Beam exposure is an additional concern for this window. Windows of this material, thickness, and diameter have been tested at AP0 as part of testing for the NuMI target. These tests demonstrated that no damage to the window was observed at the integrated energy deposition rates that the NuMI beam will generate.

Testing of a representative window shows that failure occurs at the outer edge and not at the center where the beam heating may reduce ultimate stress levels.

Given the location, a "beam on" failure does not pose a personnel safety issue. The beryllium contamination issue and equipment damage issue is discussed in the attached note (See Appendix "E") where a backup window of titanium is used to stop any possible air burst down the beam tube which could spread beryllium contamination or damage profile monitor foils.

Calculations:

Even though the windows have an initial deflection from flat, the following calculations will provide a "worst case" check on the stresses developed in the window.

"Formulas for stress and strain" by Roark is used to calculate the stresses in the beryllium window. A flat plate calculation is made utilizing case 10a.

Bending Stress = $6M/t^2$
where $M_{center} = qa^2(1+v)/16$ & $M_{edge} = qa^2/8$

$q = 14.7$ psi (vacuum)
a = outer radius = 1.125/2 = .5625 in.
v = Poisson's ratio = 0.1
t = thickness = .010 in.

Appendix "A"

$M_{center} = 14.7(.5625)^2(1+.1)/16 = .262$
$M_{edge} = 14.7(.5625)^2/8 = .581$

Bending stress @ center = $6(.262)/(.010)^2 = 15{,}720$ psi
Bending stress @ edge = $6(.581)/(.010)^2 = 34{,}860$ psi

Check deflection to see if less than 1/2 thickness (if not, use diaphragm equations)
Deflection = $y = qa^4/64D$
where $D = Et^3/12(1-v^2)$
$E = 42{,}000{,}000$ psi

$D = 42{,}000{,}000(.010)^3/12(1-.1^2) = 42(1)/12(.99) = 3.54$

$y = 14.7(.5625)^4/64(3.54) = .0065$ in.

Since the deflection is larger than 1/2 the plate thickness, the use of the Roark diaphragm plate equations is justified.

The equations are:

$qa^4/Et^4 = K_1(y/t) + K_2(y/t)^2$

Stress = $E(t/a)^2[K_3(y/t) + K_4(y/t)^2]$

The first equation is solved for deflection y and this is substituted into the stress equation.

$K_1 = 5.33/(1-v^2) = 5.384$ and $K_2 = 2.6/(1-v^2) = 2.626$

Solving for y = .00564 in.

With the deflection known, the stresses can now be calculated:

Stress = combined flexure and diaphragm = $E(t/a)^2[K_3(y/t) + K_4(y/t)^2]$

K_3 at center = $2/(1-v) = 2/.9 = 2.22$
K_3 at edge = $4/(1-v^2) = 4/(1-.01) = 4/.99 = 4.04$

K_4 at center = .976
K_4 at edge = .476

Stress at center = $42x10^6(.01/.5625)^2[2.22(.00564/.01) + .976(.00564/.01)^2]$
= 20,750 psi

Stress at edge = $42x10^6(.01/.5625)^2[4.04(.00564/.01) + .476(.00564/.01)^2]$
= 32,230 psi

Appendix "A"

Additional calculations were made for different pressures for possible use during hydrostatic testing. The results are:

Loading	Deflection	Stress
30 psi	.0093 in.	55,340 psi
60 psi	.0136 in.	84,540 psi
120 psi	.0192 in.	126,220 psi

Testing:

A hydrostatic test to failure was made on a window taken from the production order of six units. See Appendix "C".

The window failed at a pressure of 160 psig. The deflection was measured to see how well it matched the theoretical calculations. The actual window had an initial deformation of the window of approximately .020". This deformation comes from the brazing operation of the manufacturing process. Typically the dishing or performing of a window reduces the stresses for a given load. This is consistent with the failure being higher than calculated and the deflection per load being approximately half of the flat disc calculations. The failure of the window at the outer edge at the braze interface is consistent with the calculated higher stresses at the edge.

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. Testing 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 a 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 NuMI Target Hall. The calculations, testing and backup window have demonstrates that the hazards associated with this window are minimal.

APPENDIX "B"

OMLEY INDUSTRIES, INC.

150 CORPORATE WAY
GRANTS PASS, OR 97526

TELEPHONE (800) 541-3355
FAX (800) 717-3355
E-mail: info@omley.com

CERTIFICATE OF COMPLIANCE

Customer: Fermilab

Date: 5/25/2004

Customer PO #: 556804

Assembly Name/Part #: #875.114-MB-422562, Beryllium Window

Quantity: 6

Omley SO #: 44804

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:

Omley Inspection Report # 19158

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"

<u>Hydrostatic Pressure Test</u>

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.

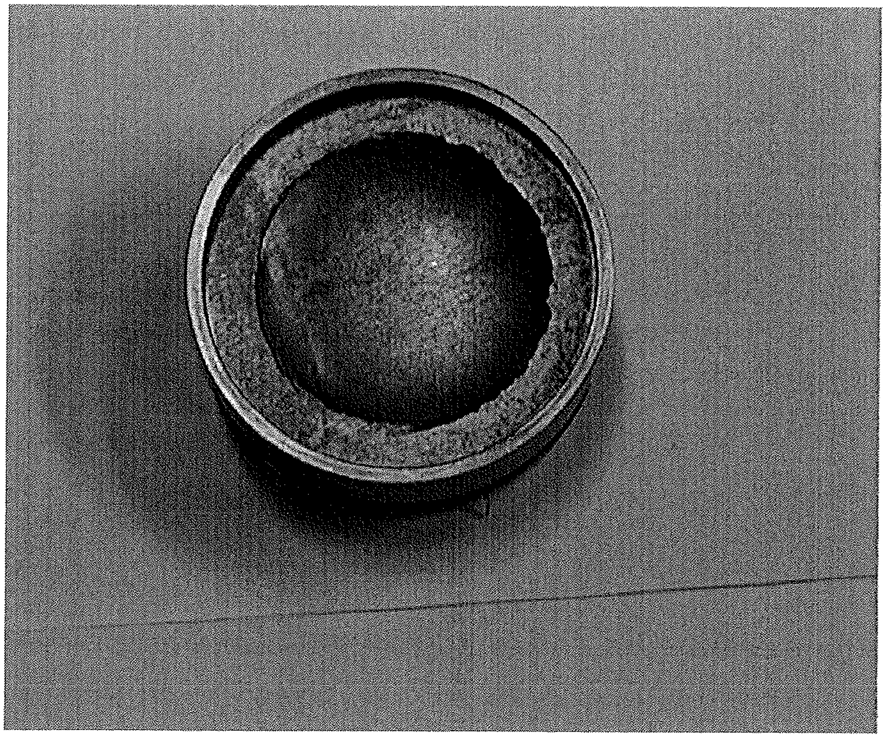
<u>Pressure</u>	<u>Deflection</u>
0	Initial deformation as received from vendor = .020"
10	.002
15	.0025
20	.003
30	.005
let up to 0	.002
30	.005
40	.0065
50	.008
60	.095
70	.0105
80	.012
Let up to 0	.006
100	.0125
120	.015
140	.017
160	.020
165 Failed	

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 Drg. # 8875.114-MB-422562

Procedure:

1. Measure window position with depth micrometer.
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: .001"

Hazards: Possible fragmented projectiles, beryllium contamination

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

Date: 8/6/04

Name: J. MISEK JM

Appndix "E"

J. Misek
8/3/04

Beryllium containment for the NuMI Beam Line Beryllium/Titanium Window Assembly Drg. # 8875.114-MC-422641

Introduction:

The NuMI beam line Beryllium/Titanium window assembly will be located at the most downstream end of the 1100 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 x 10^{-7} Torr. See Fig 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 .002" thick titanium window to the extent that it could not maintain 1 x 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, these identical windows were 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. With this successful operational history, it is NuMI's plan to use a beryllium window of the same diameter and thickness. The calculated safety factor of the beryllium window is 2.0.

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.

Be/Ti Window Design:

For NuMI, the addition of a separate vacuum section with additional titanium windows 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.

Appndix "E"

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 NuMI Beryllium/Titanium design has a titanium window less than an inch upstream from the beryllium window. This backup titanium window will act as a barrier preventing a burst of air with window fragments from traveling up the beam tube toward the Main Injector. Only the small volume between the windows will travel past the failed window. This volume is less than a cubic inch. The volume between the two windows communicates with the beam tube vacuum through 4 small bleed holes. See Fig. 2

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 .12 cu. ft./min. The closing speed of the isolation valves is 5 sec. giving a total influx of only 16 cu. in. 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 upstream 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 move 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 cu. ft. 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 is located within the NuMI interlocked section and any work in this section would not compromise Main Injector operation. The second section is within the Main Injector interlocks and would require a Main Injector shutdown.

Appndix "E"

The backup titanium window under normal operation does not see loading. From our experiences at the AP 0 Target Hall, the titanium window is expected to see degradation. Inspection of windows that leaked showed no visual holes indicating that the damage 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 window to fail catastrophically. The window does not loose its vacuum load carrying capability but just bleeds up through the hole. Under normal operation, the titanium window does not see a vacuum load and will only see a vacuum load if the beryllium window fails catastrophically. Never the less, the calculated safety factor for this window is greater than 2.

Appndix “E”

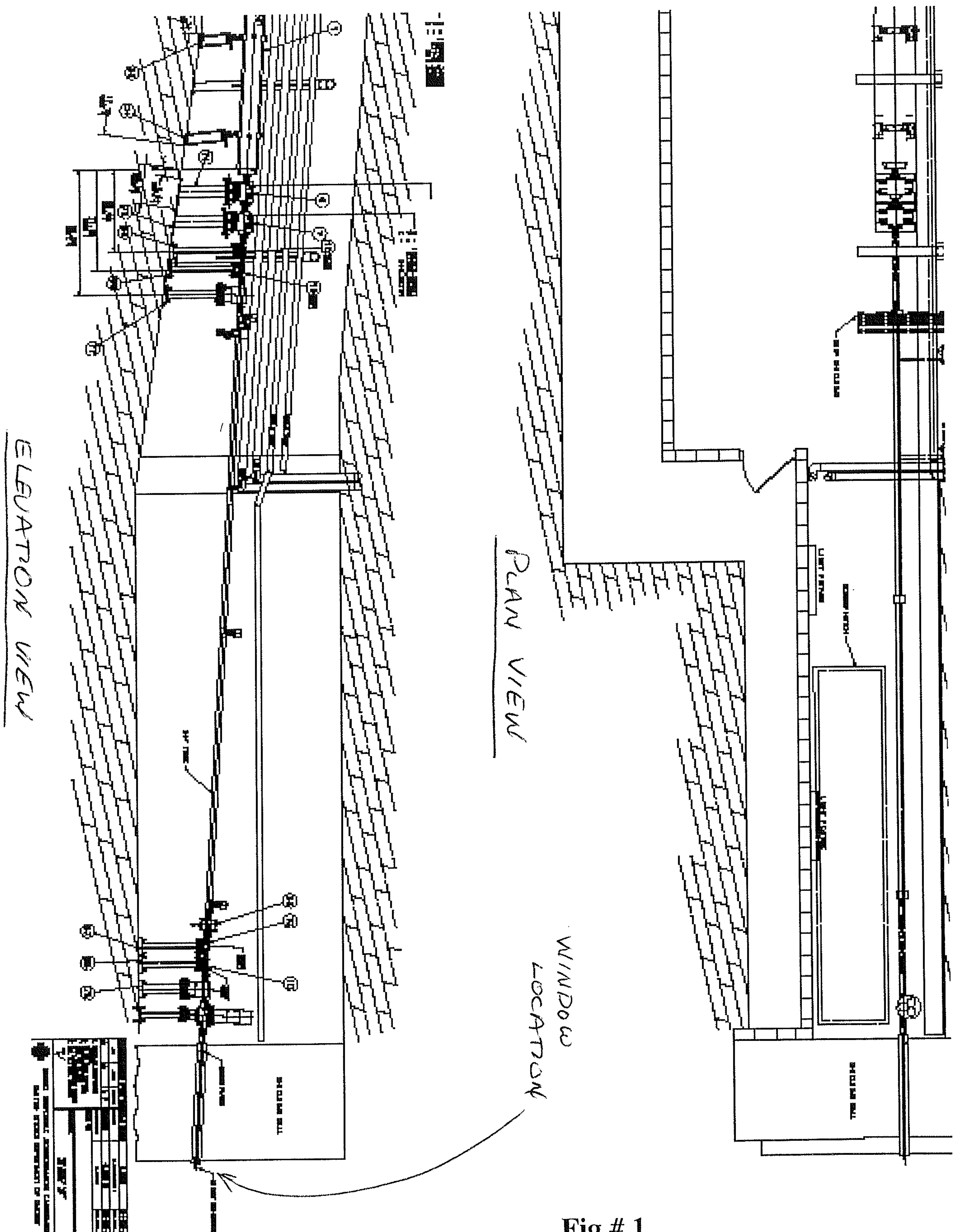


Fig.# 1

Appndix “E”

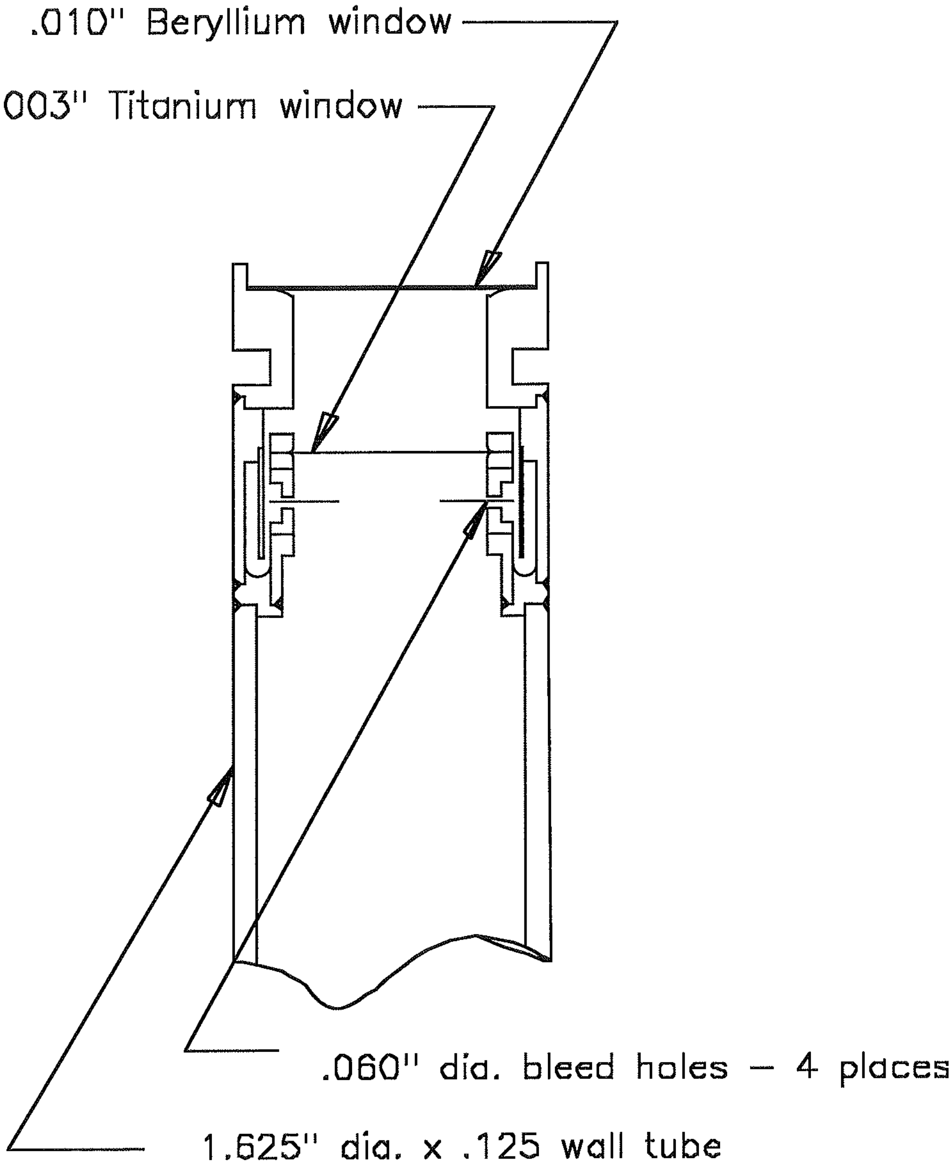


Fig. #2

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

Appendix "E-1"

Vacuum Window Location Hazard Assessment for Be/Ti Window Assembly (Dwg. # 8875.114-MC-422641) Installed in AP-1 Pre-Vault Area

P. G. Hurh
9/22/04

Reviewed by:______________________ Date: 9-27-04
AD ES&H Dept. Head

Reviewed by:______________________ Date: 1 Oct 04
AD P-Bar Dept. Head

I. Introduction

A beamline vacuum window is required at the downstream end of the AP-1 beamline. This beamline delivers proton beam to the AP-0 Target Hall vault for p-bar production. Titanium windows at this location began failing as proton beam intensities increased during the summer of 2001. During October of 2001 a Be (.01" thick) window was installed. In order to limit the impact of possible Be contamination of upstream beamline components upon window failure, a vacuum break (two back-to-back titanium foil windows) were installed about 20 feet upstream of the Be window in a location where beam intensities were much lower (larger spot size).

Due to excessive beam losses at this vacuum break, it is desirable to remove the vacuum break and return the beamline vacuum to a continuous state. In order to still protect against possible Be contamination, a vacuum window assembly identical to the NuMI Beam Line Beryllium Vacuum Window (NuMI MB-422562) will be installed. This window assembly includes a secondary titanium thin foil window less than 1 inch upstream of the terminating Be window. Flow of Be particles and fragments (as well as atmospheric air) into the beamline will be significantly impeded by use of this assembly.

The original engineering note (per FESHM Chapter 5033.1) for the NuMI installation is almost completely applicable to this new installation at AP-1. All design calculations for vacuum loading are identical (safety factor of 2.0 by calculation, safety factor of 10 by failure test). As is the case for NuMI, the AP-1 window assembly is located within a shield wall cavity that is inaccessible when pumped down, thus window failure itself does not pose a personnel safety hazard.

This document will discuss differences between the two installations and re-assess the hazards associated with the new AP-1 installation. In addition, acceptance test documentation of the new AP-1 window assembly will be attached. In order to differentiate between the two installations, window assemblies destined for use in AP-1 will be identified with the prefix "AP-1" instead of "NuMI" in the vacuum window number (i.e. AP-1 MB-422562).

II. Beam Loading

Although it is relatively straightforward to calculate temperature rises due to beam interaction, it is much more difficult to analyze the resulting stress, shocks, and material degradation arising from the sudden energy deposition. In situations like these, empirical results are helpful. Besides operational experience with the previous Be window installation (no failure in almost 3 years) and NuMI target tests at AP-0 with higher intensity beam (no damage observed), there is a similar Be window installed on a stand-alone vacuum chamber (TSEM) just upstream of the p-bar production target. This window sees much smaller spot sizes than at the AP-1 window location (order of magnitude higher peak energy deposition). It has served without failure for over 6 years. Due to experiences with same material, thickness and diameter windows with higher energy deposition rates, beam loading is not expected to damage or degrade the AP-1 window installation.

III. Beryllium Contamination

(Note that this section is primarily taken from the original engineering note's Appendix E. It has been revised for the AP-1 beamline geometry)

For a catastrophic failure of a window, an unimpeded burst would likely travel into the Main Ring Remnant Line before the isolation valves had a chance to close. The possibility of beryllium contamination reaching beyond AP-1 line would exist. Most contamination would be generated by larger pieces fragmenting as they are carried down the beam tube. The new AP-1 Beryllium/Titanium design has a titanium window less than an inch upstream from the beryllium window. This backup titanium window will act as a barrier preventing a burst of air with window fragments from traveling up the beam tube toward the Main Ring Remnant Line. Only the small volume between the windows will travel past the failed window. This volume is less than a cubic inch. The volume between the two windows communicates with the beam tube vacuum through 4 small bleed holes. See Fig. 2 in Appendix E.

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 .12 cu. ft./min. The closing speed of the isolation valves is 5 sec. giving a total influx of only 16 cu. in. 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 500 feet upstream 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 section to be let up to atmosphere. This slow bleed up will have low air velocities and subsequently will not have enough energy to move particulate significantly upstream. In addition the beam tube diameter changes multiple times between 6", 5-1/4" and 3" outer diameters, which will further impede migration of particles.

The AP-3 line also joins into the AP-1 line at a location approximately 75 feet upstream of the window. This beam line is oriented at an angle of about 10 degrees to AP-1 such that particles moving upstream would have to reverse their path by 170 degrees to travel towards the Accumulator ring. Since any particles originating at the window and making it down to this junction would have momentum in the upstream direction, a path reversal is unlikely. In the improbable event that Be contamination does reverse and head down the AP-3 line, there are 2 isolation valves (one 70 feet and one 700 feet upstream of the AP-1/AP-3 junction) that would isolate the contamination from the Accumulator ring.

Thus, the possibility of Be contamination due to a window failure is limited to the AP-1 line and some portion of the AP-3 line. Most likely, with the inclusion of the back-up titanium window, Be contamination, if any, will be local to the first few feet upstream of the window.

The back-up titanium window under normal operation does not see loading. From our experiences at the AP 0 Target Hall, the titanium window is expected to see degradation from interaction with proton beam. Inspection of windows that leaked showed no visual holes indicating that the damage 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 window to fail catastrophically. The window does not lose its vacuum load carrying capability but just bleeds up through the hole. Under normal operation, the titanium window does not see a vacuum load and will only see a vacuum load if the beryllium window fails catastrophically. Never the less, the calculated safety factor for this window is greater than 2.

IV. Acceptance Testing

Acceptance testing documentation is attached to this Appendix.

Appendix "E-1"

Acceptance Test

For beryllium window Dwg. # 8875.114-MB-422562
(Vacuum window serial number: AP-1 MB-422562-1)

Procedure:

1. Measure window position with depth micrometer. .1305"
2. Install aluminum window cover.
3. Pump down unit with leak detector.
4. Remove window cover and measure deflection. Record below. .132"

Deflection under vacuum load: 0.0015"

Hazards: Possible fragmented projectiles, beryllium contamination

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

Date: 9-23-04

Name: P. Hurd [signature]