Fermi National Accelerator Laboratory

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Mechanical Safety Subcommittee Guideline for Design of Thin Windows for Vacuum Vessels

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by: Jeffrey L. Western

1. INTRODUCTION

This guideline specifies the usage of thin windows for vacuum vessels in terms of their design and application at Fermilab.

2. SCOPE

2.1 This guideline is to be applied to vacuum vessels when the pressure differential across the window is less than or equal to fifteen (15) psid.

$$dP \leq 15 \text{ psid} \qquad \text{(equation 2.1)}$$

2.2 This guideline will encompass thin windows consisting of circular, square and rectangular geometries.

2.3 This guideline shall fall under the scope of the "Fermilab Safety Manual", Vacuum Pressure Vessel Safety (5033).

2.4 Excluded from this guideline is windows for LH_2 targets which are included under "Guidelines for the Design, Fabrication, Testing, Installation and Operation of LH_2 Targets".

3. GENERAL GUIDELINES

3.1 A thin window is a diaphragm plate where the deflection is greater than 1/2 of the thickness. From Article 10.11, page 457 "Formulas for Stress and Strain" Sixth Edition.

$$y > t/2 \qquad \text{(equation 3.1)}$$

3.2 The allowable stress for thin windows shall be the most stringent of the following:

$$S = 0.5 F_u \quad \textbf{(equation 3.2a)}$$

or

$$S = 0.9 F_y \quad \textbf{(equation 3.2b)}$$

3.2.1 Where:

S = allowable stress (psi)
F_u = ultimate tensile strength (psi)
F_y = yield strength or stress to produce 5% elongation (psi)

3.3 Thin windows shall not be exposed to cyclic loading greater than 1000 load cycles. Negative load cycling is not allowed unless design and testing verifies performance.

3.4 The mounting flange shall have an edge radius to prevent the window from tearing.

3.5 Material documentation: Vendor material certification/ verification shall be included in window documentation.

3.6 Multi-layer mylar window: Mylar windows with a thickness greater than 0.010" shall have that thickness built up from multiple layers of mylar, with no single layer more than 0.010" thick.

4. GUIDELINES FOR FLEXIBLE MATERIAL WINDOWS

4.1 Flexible material circular windows such as mylar/kapton and titanium/stainless steel less than 0.003" **(t < 0.003")**. Design condition: held not fixed.

4.1.1 The allowable stress for circular windows shall be greater than the following: Derived from Equations 1 and 2, page 477, case number 4, page 478 "Formulas for Stress and Strain" Sixth Edition.

$$S > 0.423\,(Eq^2a^2/t^2)^{1/3} \qquad \text{(equation 4.1a)}$$

and the deflection is:

$$y = 0.662\,a\,(qa/Et)^{1/3} \qquad \text{(equation 4.1b)}$$

4.1.2 Where:

- **t** = thickness of window (inch)
- **a** = radius of window measured at O-ring on flange (inch)
- **q** = uniform pressure on window (psid)
- **S** = allowable stress (psi)
- **E** = Young's modulus of window material (psi)
- **y** = window deflection (inch)

4.2 Flexible material rectangular windows such as mylar/kapton and titanium/stainless steel less than 0.003" **(t < 0.003")**. Design condition: held not fixed.

4.2.1 The allowable stress for rectangular windows shall be greater than the following: From Brookhaven National Laboratory "Occupational Health and Safety Guide", Section 1.4.2, appendix B.

$$S > K_1\,(E\,(qa/t)^2)^{1/3} \qquad \text{(equation 4.2a)}$$

and the deflection is:

$$y = K_2\,(qa^4/Et)^{1/3} \qquad \text{(equation 4.2b)}$$

4.2.2 Where:

- **t** = thickness of window (inch)
- K_1 = stress constant based on ratio a/b (see table below)
- K_2 = deflection constant based on ratio a/b (see table below)
- **a** = short side of rectangular window measured at O-ring (inch)

b = long side of rectangular window measured at O-ring (inch)
q = uniform pressure on window (psid)
S = allowable stress (psi)
E = Young's modulus of window material (psi)
y = window deflection (inch)

4.2.3 Constant table for values of K for rectangular windows:

b/a	K_1	K_2
1.0	0.271	0.320
1.1	0.292	0.331
1.2	0.306	0.339
1.3	0.316	0.344
1.4	0.323	0.348
1.5	0.329	0.351
1.6	0.332	0.353
1.7	0.336	0.355
1.8	0.338	0.356
1.9	0.340	0.357
2.0	0.340	0.357
3.0	0.346	0.360
> 3.0	0.346	0.360

Note: K_1 values for maximum stress at center of window.

5. GUIDELINES FOR RIGID MATERIAL WINDOWS

5.1 Rigid material circular windows such as titanium and stainless steel greater than 0.003" **(t > 0.003")**. Design condition: held and fixed.

5.1.1 The allowable stress for circular windows shall be greater than the stress obtained by solving by trial and error equation 5.1b for deflection and then substitute into 5.1a. See equations 1 and 2, page 477, case number 3, page 478 "Formulas for Stress and Strain" Sixth Edition.

$$S > E(t/a)^2[K_3(y/t) + K_4(y/t)^2] \qquad \text{(equation 5.1a)}$$

and the deflection can be calculated from:

$$qa^4/Et^2 = K_1(y/t) + K_2(y/t)^3 \qquad \text{(equation 5.1b)}$$

5.1.2 Where:

t = thickness of window (inch)
a = radius of window measured at O-ring on flange (inch)
q = uniform pressure on window (psid)
S = allowable stress (psi)
E = Young's modulus of window material (psi)
y = window deflection (inch)
K_1 = $5.33/(1-\nu^2)$
K_2 = $2.6/(1-\nu^2)$
K_3 = $2.0/(1-\nu)$
K_4 = 0.976
ν = poisson's ratio

Note: K values for maximum stress at center of window.

5.2 Rigid material rectangular windows such as titanium and stainless steel greater than 0.003" **(t > 0.003")**. Design condition: held and fixed.

5.2.1 The allowable stress for rectangular windows shall be greater than the stress obtained by solving by trial and error equation 5.2b for deflection and then substitute into 5.2a. From Brookhaven National Laboratory "Occupational Health and Safety Guide", Section 1.4.2, appendix C.

$$S > E(t/a)^2[K_3(y/t) + K_4(y/t)^2] \qquad \text{(equation 5.2a)}$$

and the deflection can be calculated from:

$$qa^4/Et^2 = K_1(y/t) + K_2(y/t)^3 \qquad \text{(equation 5.2b)}$$

5.2.2 Where:

t = thickness of window (inch)
K_1 = stress constant based on ratio a/b (see table below)
K_2 = deflection constant based on ratio a/b (see table below)
a = short side of rectangular window measured at O-ring (inch)
b = long side of rectangular window measured at O-ring (inch)
q = uniform pressure on window (psid)
S = allowable stress (psi)
E = Young's modulus of window material (psi)
y = window deflection (inch)

5.2.3 Constant table for values of K for rectangular windows:

b/a	**K_1**	**K_2**	**K_3**	**K_4**
1.0	72.5	30.5	22.3	2.7
1.1	60.9	27.6	21.3	2.7
1.2	53.2	25.7	20.4	2.7
1.3	47.9	24.6	19.7	2.7
1.4	44.3	23.7	19.3	2.7
1.5	41.5	23.1	18.9	2.7
1.6	39.8	22.7	18.7	2.7
1.8	37.5	22.2	18.3	2.7
2.0	36.1	22.0	18.0	2.7
> 2.0	35.2	21.4	17.6	2.7

Note: K_3 and K_4 values for maximum stress at the midpoint of the long edge of window.

6. RESPONSIBILITY / DOCUMENTATION

The responsibility and documentation for thin windows shall follow the "Fermilab Safety Manual", Vacuum Pressure Vessel Safety (5033).

APPENDIX A

EXAMPLE 1: Circular flexible window

Circular 3" diameter by 0.005" thickness Mylar window under vacuum.

t	=	0.005": thickness of window (inch)
a	=	1.5": radius of window measured at O-ring on flange (inch)
q	=	14.7 psi: uniform pressure on window (psid)
S	=	$0.5\ F_u$ = 0.5 x 25,000 psi = 12,500 psi or $0.9\ F_y$ = 0.9 x 15,000 psi = 13,500 psi: allowable stress (psi)
E	=	500,000 psi: Young's modulus of window material (psi)
y	=	window deflection (inch) <= to be calculated

From TM-1380 Page 2, Section 4.1, Circular window with edge held but not fixed.

$$S > 0.423\ (Eq^2a^2/\ t^2)^{1/3} \qquad \textbf{(equation 4.1a)}$$

$$12{,}500\ \text{psi} > 0.423\ [(500{,}000)(14.7)^2(1.5)^2/\ 0.005^2]^{1/3}$$

$$12{,}500\ \text{psi} > \underline{9{,}029\ \text{psi}} \Rightarrow \text{Adequate}$$

and the deflection is:

$$y = 0.662\ a\ (qa/Et)^{1/3} \qquad \textbf{(equation 4.1b)}$$

$$y = 0.662\ (1.5)\ [(14.7)(1.5)/(500{,}000)(0.005)]^{1/3}$$

$$y = \underline{0.205\ \text{inch}} \Leftarrow \text{Deflection}$$

and:

$$y > t/2 \qquad \textbf{(equation 3.1)}$$

$$0.205'' > 0.005''/2$$

$$0.205'' > 0.0025'' \Rightarrow \text{Adequate}$$

APPENDIX A

EXAMPLE 2: Square flexible window

Square 3" by 0.009" thickness Kapton window under vacuum.

t	=	0.009": thickness of window (inch)
a	=	3.0": short side of rectangular window measured at O-ring (inch)
b	=	3.0": long side of rectangular window measured at O-ring (inch)
q	=	14.7 psi: uniform pressure on window (psid)
S	=	$0.5\ F_u$ = 0.5 x 25,000 psi = 12,500 psi or $0.9\ F_y$ = 0.9 x 12,500 psi = <u>11,250 psi</u>: allowable stress (psi)
E	=	400,000 psi: Young's modulus of window material (psi)
y	=	window deflection (inch) <= to be calculated

From TM-1380 Page 3, Section 4.2, Rectangular window with edge held but not fixed.

from table 4.2.3: for b/a = 3.0/3.0 = 1 ==> $K_1 = 0.271$ & $K_2 = 0.320$

$$S > K_1\ [E(qa/t)^2]^{1/3} \qquad \textbf{(equation 4.2a)}$$

$$11{,}250\ \text{psi} > 0.271\ [(400{,}000)(14.7)^2(3.0)^2/(0.009)^2]^{1/3}$$

11,250 psi > <u>5760 psi</u> => Adequate

and the deflection is:

$$y = K_2\ (qa^4/Et)^{1/3} \qquad \textbf{(equation 4.2b)}$$

$$y = 0.320\ [(14.7)(3.0)^4/(400{,}000)(0.009)]^{1/3}$$

y = <u>0.221 inch</u> <= Deflection

and: $y > t/2$ **(equation 3.1)**

0.221" > 0.009"/2

0.221" > 0.0045" => Adequate

APPENDIX A

EXAMPLE 3: Circular rigid window

Circular 6" diameter by 0.005" thickness stainless steel (work hardened 302 S.S.) window under vacuum.

t	=	0.005": thickness of window (inch)
a	=	3.0": radius of window measured at O-ring on flange (inch)
q	=	14.7 psi: uniform pressure on window (psid)
S	=	$0.5\ F_u$ = 0.5 x 250,000 psi = 125,000 psi or $0.9\ F_y$ = 0.9 x 150,000 psi = 135,000 psi: allowable stress (psi)
E	=	30E6 psi: Young's modulus of window material (psi)
v	=	0.3 : poisson's ratio
y	=	window deflection (inch) <= to be calculated

From TM-1380 Page 4, Section 5.1, Circular window with edge held and fixed.

from section 5.1.2: for $v = 0.3 \Rightarrow K_1 = 5.86,\ K_2 = 2.86,\ K_3 = 2.86,\ K_4 = .976$

deflection is: $qa^4/Et^4 = K_1(y/t) + K_2(y/t)^3$ **(equation 5.1b)**

$$14.7(3.0)^4/30E6(.005)^4 = 5.86\ (y/.005) + 2.86\ (y/.005)^3$$

y = 0.14 inch <= Deflection......solved by trial and error

where: y > t/2 **(equation 3.1)**

0.14" > 0.005"/2

0.14" > 0.0025" => Adequate

stress is: $S > E(t/a)^2[K_3(y/t) + K_4(y/t)^2]$ **(equation 5.1a)**

$$125{,}000\ \text{psi} > (30E6)(.005/3.0)^2[2.86(.14/.005) + 0.976(.14/.005)^2]$$

125,000 psi > 38,817 psi => Adequate

APPENDIX A

EXAMPLE 4: Rectangular rigid window

Rectangular 6" x 9" by 0.006" thickness titanium (6AL-4V) window under vacuum.

t	=	0.006": thickness of window (inch)
a	=	6.0": short side of rectangular window measured at O-ring (inch)
b	=	9.0": long side of rectangular window measured at O-ring (inch)
q	=	14.7 psi: uniform pressure on window (psid)
S	=	$0.5\ F_u$ = 0.5 x 130,000 psi = 65,000 psi or $0.9\ F_y$ = 0.9 x 120,000 psi = 108,000 psi: allowable stress (psi)
E	=	16E6 psi: Young's modulus of window material (psi)
v	=	0.3 : poisson's ratio
y	=	window deflection (inch) <= to be calculated

From TM-1380 Page 5, Section 5.2, Rectangular window with edge held and fixed.

from table 5.2.3: for b/a = 1.5 => $K_1 = 41.5$, $K_2 = 23.1$, $K_3 = 18.9$, $K_4 = 2.7$

deflection is: $qa^4/Et^4 = K_1(y/t) + K_2(y/t)^3$ **(equation 5.2b)**

$$14.7(6.0)^4/16E6(.006)^4 = 41.5\ (y/.006) + 23.1\ (y/.006)^3$$

y = 0.21 inch <= Deflection......solved by trial and error

where: y > t/2 **(equation 3.1)**

0.21" > 0.006"/2

0.21" > 0.003" => Adequate

stress is: $S > E(t/a)^2[K_3(y/t) + K_4(y/t)^2]$ **(equation 5.2a)**

$$65{,}000\ \text{psi} > (16E6)(.006/6.0)^2[18.9(.21/.006) + 2.7(.21/.006)^2]$$

65,000 psi > 63,504 psi => Adequate

November1992

Practical Guidelines and Parameters for Thin Windows Used on Vacuum Vessels.

Addendum to FERMILAB-TM-1380

Extracted in part from Brookhaven National Laboratory Occupational Health and safety Guide (Glass and Plastic Window Design for Pressure Vessels 1.4.2 , Feb.,1980)

1. Parameters The following distance relationships should be observed, see figure 1, 2 & 3

(a) The distance from the bolt hole to O-ring groove (B) shall be at least 2/3 of the bolt diameter.

(b) The distance from the O-ring groove to the window opening (A) should be at least 1/8" plus the edge radius.

(c) The window opening edge radius should be a minimum of 15 times the window thickness although 25 is preferred.

(d) For rectangular window mounts, the corner radius shall be a minimum of 0.15 of the shortest span of the window opening, see figure 3.

2. Guidelines

(a) Clamping surfaces should be flat to within 0.0015"/foot.

(b) The clamping bolts shall be designed to exert a clamping force that is a minimum of 3 times the force applied to the window.

(c) The clamping ring must be rigid enough to maintain adequate clamping force between bolts.

(d) Flat washers shall be used under the bolt heads to prevent galling and to ensure the application of the proper torque value.

(e) All bolt holes, in the window, shall be punched with a sharp edged punch. Deburr all holes after punching, do not burn the holes. Normal clearance hole practice should be applied.

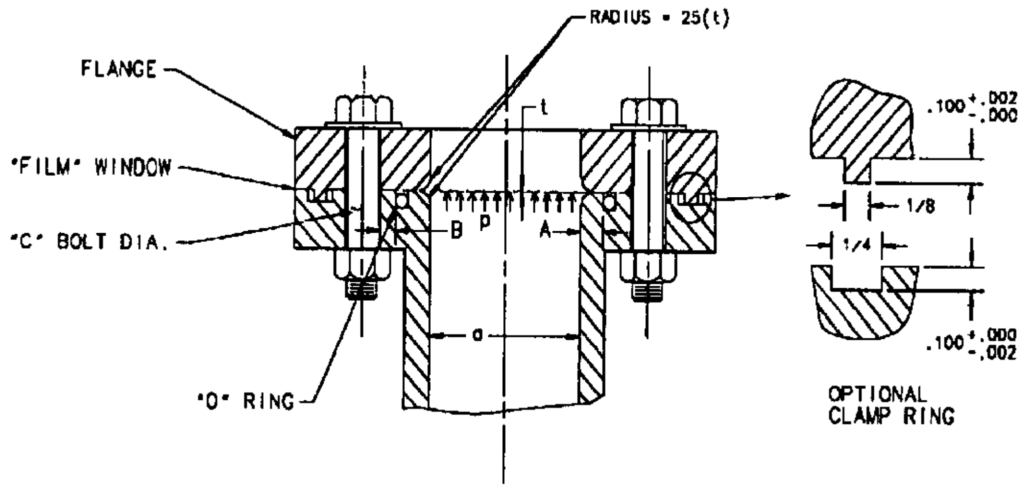
(f) All surfaces shall be 64 micro-inches or better and free of burrs and sharp edges.

3. Plastics windows with "fixed and held mounts. (Figure 2)

(a) The clamping ring and vessel wall must be rigid enough to prevent <u>any</u> local deflections that would permit angular rotation of the window edges.

(b) The window must have significant flexural stiffness. See notes 1 & 2 of figure 2.

WINDOW MOUNT
HELD BUT NOT FIXED



NOTES:

1-CLAMP RING (OPTIONAL) PROVIDES ADDED HOLDING FOR THIN WINDOWS (MAX. THKNESS .042")

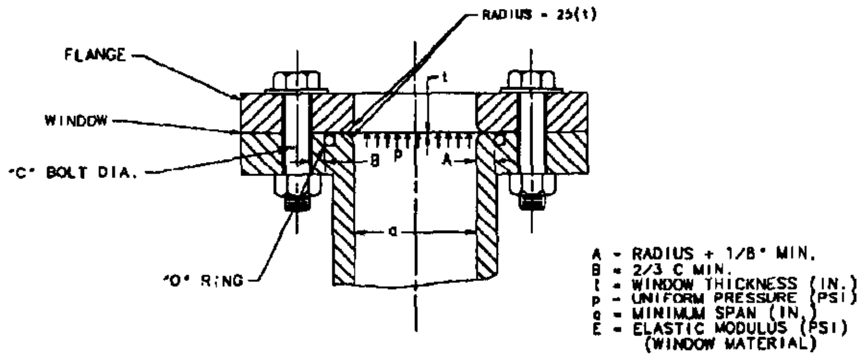
2-WINDOW MOUNT IS CLASSED "HELD BUT NOT FIXED" ONLY IF $p/E(a/t)^4 \geq 500$

3-THIS MOUNT CANNOT BE USED FOR WINDOWS MADE OF BRITTLE MATERIAL SUCH AS GLASS, QUARTZ OR METHYL METHACRYLATE

A = RADIUS + 1/8" MIN.
B = 2/3 C MIN.
t = WINDOW THICKNESS (IN.)
p = UNIFORM PRESSURE (PSI)
a = MINIMUM SPAN (IN.)
E = ELASTIC MODULUS (PSI) (WINDOW MATERIAL)

FIG. 1

WINDOW MOUNT
(HELD AND FIXED)



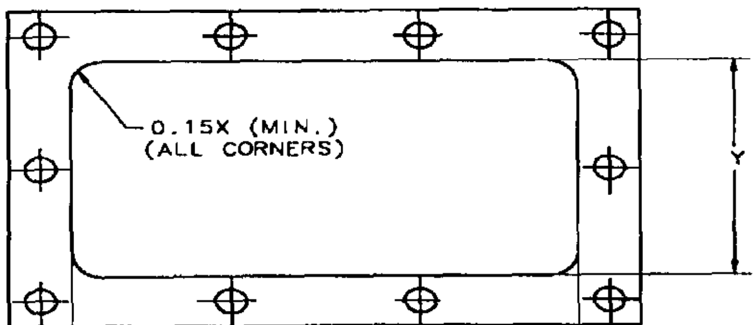
NOTES:

1-WINDOW MOUNT IS CLASSED "HELD AND FIXED" ONLY IF $p/E(a/t)^4 < 500$ AND THE STRESS AT THE EDGES IS BELOW THE YIELD POINT OF THE WINDOW MATERIAL.

2-WINDOW MOUNT IS CLASSED "HELD BUT NOT FIXED" IF EITHER OR BOTH CONDITIONS IN NOTE 1 ARE EXCEEDED.

FIG. 2

FLANGE FOR RECTANGULAR FILM WINDOWS



NOTES:
1-WHERE "X" IS SMALLER OR EQUAL TO "Y"
2-ALL OTHER DIMENSIONS, REFER TO FIG. 1 & 2

FIG. 3