TN-67-2
January 1967
H. Clay

THIN METAL WINDOWS

Introduction

This report is the result of a thin window study and testing program conducted at SLAC to produce thin beam port windows with the following characteristics:

1. Ability to withstand continuous long-term vacuum loading.
2. Capability of withstanding the maximum irradiation of the primary beam.
3. High reliability relative to the safety of personnel and associated instrumentation, and minimum failure down-time.

As a result of this program, all primary and secondary beam port windows now in use at SLAC have the characteristics described herein.

The above conditions, taken separately or collectively, dictate the use of metal windows as opposed to mylar; therefore, this study is primarily concerned with the characteristics of thin metal windows.

Mylar windows have been carefully studied by others in laboratories similar to SLAC, and also at SLAC. However, because of their unpredictable failure characteristics, it is my opinion and the opinion of RAD that such windows should be avoided. At SLAC, mylar windows are considered hazardous and are therefore given special consideration on a window-by-window basis. Therefore, rather than discussing mylar windows here, we have listed several good references applicable to the design of mylar windows at the end of this report.

Empirical Equations for Calculating the Bursting Pressure of Thin Windows

Summarized below are the results obtained by testing circular windows with a material thickness variation of 2 to 10 mils.

The empirical formulae described herein are satisfied by the following conditions:

1. maximum material thickness ten mils (stock)
2. windows are formed by test load from an initially flat circular membrane of uniform thickness
3. no slippage can occur at the boundary (fixed edges)
4. window always breaks at the unsupported center

Nomenclature

a = radius (inches

D = diameter (inches)

σ = tensile stress at initial condition of material (i.e., initial hardness)

P = pressure (psi)

t = thickness (mils)

x = D/D_o where D_o = 4 inch diameter.

Empirical Formulae

A. For Aluminum 5052-0 at room temperature

P_{max} = (Bursting pressure) for $x > 2$

(1) $$P_{max} = 13.8\,t - \left[75 + 63\,(1 - e^{-0.2(x-2)})\right]\left[0.057t + 0.0042\,t^2\right]$$

For $1 \leq x \leq 2$

(2) $$P_{max} = 13.8\,t - 75\,(x-1)\,\left[0.0575t + 0.00425t^2\right]$$

For $0 \leq x < 1$

(3) $$P_{max} = 13.8\left(\frac{4}{D}\right)t$$

$$= 55.2\left(\frac{t}{D}\right)$$

B. For Aluminum Material Other Than 5052-0. Maximum Pressure = P''_{max} .

(4) $$P''_{max} = \left(\frac{\sigma\ \text{initial condition}}{\sigma\ \text{5052-0}}\right)_{T.S.} P_{max}$$

C. For Stainless Steel. Maximum Pressure = P'''_{max} .

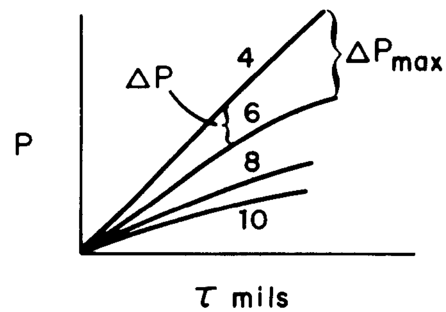
(5) $$P'''_{max} \cong \frac{\%\ \text{Elongation s. st.}}{\%\ \text{Elongation Alum. 5520-0}} \times \frac{E_{s.st.}}{E_{Alum.}} \times P_{max}$$

$$= \frac{50}{25} \times \frac{28}{10}\ P_{max}$$

$$= 5.6\ P_{max}$$

Discussion

The results of this testing are shown on Figs. 1 and 2. From these results it was possible to generate the above equations in the following way:



From the curves on Figs. 1 and 2 we see that

$$\frac{\Delta P}{\Delta P_{max}} = \left[0.575 \left(\frac{t}{t_{max}} \right) + 0.425 \left(\frac{t}{t_{max}} \right)^2 \right]$$

is a universal equation for $D \geq 0, \quad t \leq 10$ where

$$\frac{\Delta P}{\Delta P_{max}} = \frac{P_{4''\text{Dia.}} - P}{\left(P_{4''\text{Dia.}\,max} - P_{max} \right)}_{\substack{t=10\text{ mil.} \\ =t\ max.}}$$

Then

$$\Delta P = \Delta P_{max} \left[0.057t + 0.0042\, t^2 \right] \quad (t_{max} = 10 \text{ mils})$$

To find a relationship between ΔP_{max} and D, a plot of ΔP_{max} vs $\frac{D}{4}$ was made (see Fig. 3), from which the following equations were obtained:

for $1 \leq x \leq 2$

$$\Delta P_{max} = 75(x-1)$$

for $x > 2$

$$\Delta P_{max} = 75 + 63(1-e^{-0.2(x-2)})$$

Thus

$$P_o - P = \Delta P_{max}\left[0.057t + 0.0042t^2\right]$$

$$P = P_o - \Delta P_{max}\left[0.057t + 0.0042t^2\right]$$

P_o is taken as the pressure for a 4-inch-diameter window vs t. Figure 1 yields $P_o = 13.8t$. Then

$$P = 13.8t - \Delta P_{max}\left[0.057t + 0.0042t^2\right]$$

To find P for $0 \leq x \leq 1$ it was assumed that a linear relation would hold for P vs t for all windows with $D \leq 4$. It was further assumed that such a relationship is

$$P = P_{4Dia.} \times \frac{4}{D}$$

$$= 13.8 \frac{4}{D} t$$

$$= 55.2 \frac{t}{D}$$

If this is a true relationship, then it is expected that

$$\frac{\Delta P}{\Delta P_{max}} = \left[0.57\left(\frac{t}{t_{max}}\right) + 0.42\left(\frac{t}{t_{max}}\right)^2\right]$$

As expected, the values predicted by $P = 55.2 \frac{t}{D}$ do indeed satisfy the relation

$$\frac{\Delta P}{\Delta P_{max}} = \frac{\Delta P}{\Delta P_{max}}(t)$$

Equations 5 and 6 were also assumed and tested in comparison with some in-house testing and data listed in referenced reports. The predictions were in good agreements with the data on hand.

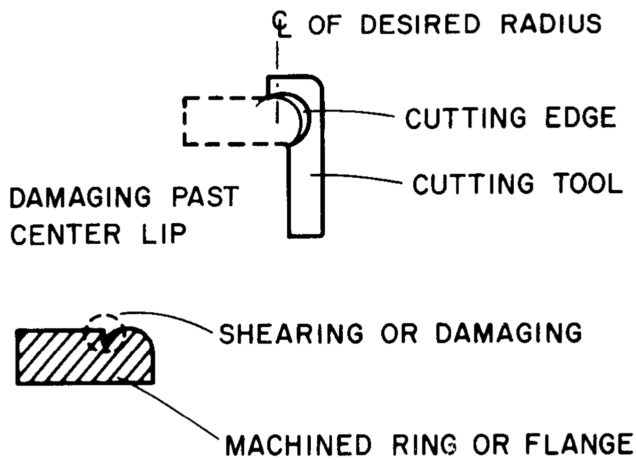
Aluminum Windows

Aluminum windows will not fail under normal operating loads except by corrosion, and even then such failures are usually indicated by relatively slow rising pressure. Irradiation is not a problem at room temperature and for all practical purposes can be discounted even for prolonged continuous radiation at LH_2 temperature. Heat transfer and dependability are additional factors which favor aluminum.

The disadvantage of aluminum is its atomic number relative to that of mylar. However, in my opinion it is far better to have a thinner aluminum window with, say, half the bursting strength of a new mylar window than to try to cope with the changing properties of mylar under static conditions.

Radius vs Window Thickness

The radius around which a thin window must pull should not be less than twice the material thickness, or say 1/32 inch,in order to assure a smooth baring surface. The primary reason that thin windows break at the radius is due to the machining of such radii. Each tool for this operation is usually hand-made, and invariably the tools have a cupping effect which is transferred to the machined part, as shown below:



Radii cut like the one above are not readily noticeable and are relatively effective (depending primarily on the window thickness). The thicker the material, the more damaging effects such radii have. For example, in our testing program, I have had 4, 6, 8, and 10-inch-diameter window frames with radii of this sort (1/16" and 1/8" radii nominal) which have not affected the performance of windows less than 6 mils in thickness and at the same time cause all thicker windows to break at the edge. To remedy this problem one need only remove such burrs after machining, to obtain, say, a 16 finish or better.

SLAC Thin Window Design

SLAC windows are described by the attached drawings

PS 410 - 001 - 02

MA 410 - 001 - 02

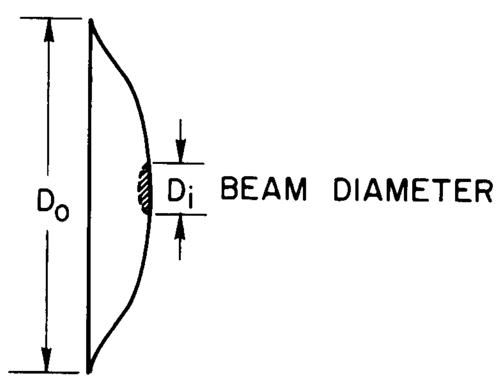
MA 410 - 001 - 08

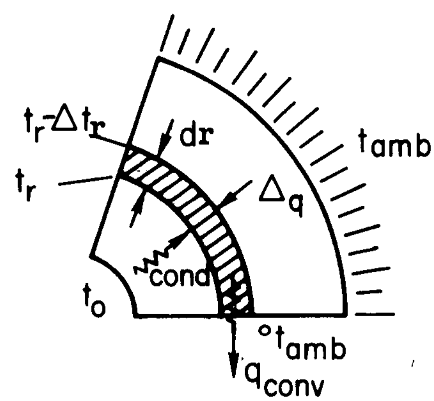
The basic design can be used with any type of vacuum flange, without modification of flange or window design.

Thin Window Heating Problem

Assumptions:

1. The window is equivalent to fin of inner diameter Di; where Di is the beam diameter.
2. There are no radiation heat losses.
3. The primary mode of heat-transfer is by natural convection from one side only.





$$q_{cond.} = \frac{KA(r)}{dr}\left[t_r - (t_r - dt_r)\right]$$

$$= \frac{KA(r)}{dr}\, dt_r$$

$$dq = d\left[\frac{KA(r)\, dt_r}{dr}\right]$$

$$dq_{cond.} \cong hdA\,(t_r - t_a)$$

$$\rho = t_r - t_a$$

$$\underline{d\rho} = dt_r$$

$$d\left[A(r)\,\frac{d\rho}{dr}\right] = \frac{hdA}{K}\,\rho$$

$$A(r) = 2\pi r\delta$$

$$A \cong 2\pi r\, dr \Rightarrow \text{one side of fin only}$$

$$d\left[\frac{rd\rho}{dr}\right] = \frac{hrdr\rho}{K\delta}$$

$$\frac{1}{r}\,\frac{d}{dr}\left[\frac{rd\rho}{dr}\right] = \frac{h}{K\delta}\,\rho$$

$$\frac{d^2\rho}{dr^2} + \frac{1}{r}\,\frac{d\rho}{dr} - \frac{h}{K\delta}\,\rho = 0$$

ρ = excess over surrounding fluid temp. boundary conditions

at $r = r_1$, $\rho = \rho_1$

at $r = r_o$, $\frac{d\rho}{dr} = 0$

Biot Modulus is 1/2 maximum since the fin has one side only.

$$\beta = \beta'/2 = \frac{h}{K\delta}$$

The solution for the above equation is in the form of a Bessel function:

$$Q = 2\pi r_i \delta K \sqrt{\beta}\rho_1 \frac{\left[I_1(r_o\sqrt{\beta})K_1(r_1\sqrt{\beta}) - K_1(r_o\sqrt{\beta})I_1(r_1\sqrt{\beta})\right]}{\left[I_1(r_o\sqrt{\beta})K_o(r_1\sqrt{\beta}) + K_1(r_o\sqrt{\beta})I_o(r_1\sqrt{\beta})\right]}$$

Example: What is the expected ΔT for a $30\text{-}\mu$ A beam passing through a .005-inch aluminum window.

For a .005-inch thick aluminum window,

D_o = 4 inches diameter

$$K = \frac{\text{Btu}}{\text{hr - ft}^2\ {}^o\text{F/ft}}$$

δ = .005/12 amb T = 70^oF

Beam area 1 cm^2

$$h = \frac{\text{Btu}}{\text{hr ft}^2\ {}^o\text{F/ft}}$$

$$\beta = \frac{h}{K\delta}$$

Trial and error method must be used since

$$h = f(\Delta t) = f(\rho)$$

Then for $\Delta t = 10^o$F, for air and natural convection h = .54

$$\beta = 10.9 \qquad \sqrt{\beta} = 3.302$$

$r_1 = .564 \text{ cm} = .018 \text{ ft.}$, $r_o = .33 \text{ ft.}$

$r_1\sqrt{\beta} = .059$	$r_o\sqrt{\beta} = 1.1$
$I_1 = .04$	$I_1 = 1.33$
$K_1 = 16.6$	$K_1 = .51$
$I_o = 1.0$	
$K_o = 5.5$	

$$Q = .55 \text{ Btu/hr} = 1.88 \text{ watts}$$

Let $Q = I_{amps}\ \rho_{density}\ \delta\text{ cm}\quad 1.8 \times 10^6$ = beam heat input

$$\rho \sim \text{g/cc} \ ; \ 1.8 \sim \frac{\text{watts}}{\text{g/cm}^2} \ ; \ \rho_{density} = 2.7 \text{ g/cc}$$

for alum.

Then $I = 30.2\,\mu A$ Beam Current for approximately 10^{o}F temperature difference across window face.

ACKNOWLEDGMENT

Acknowledgment is extended to RAD for its efforts in generating and funding this project, and in particular R. Vetterlein and J. Harris.

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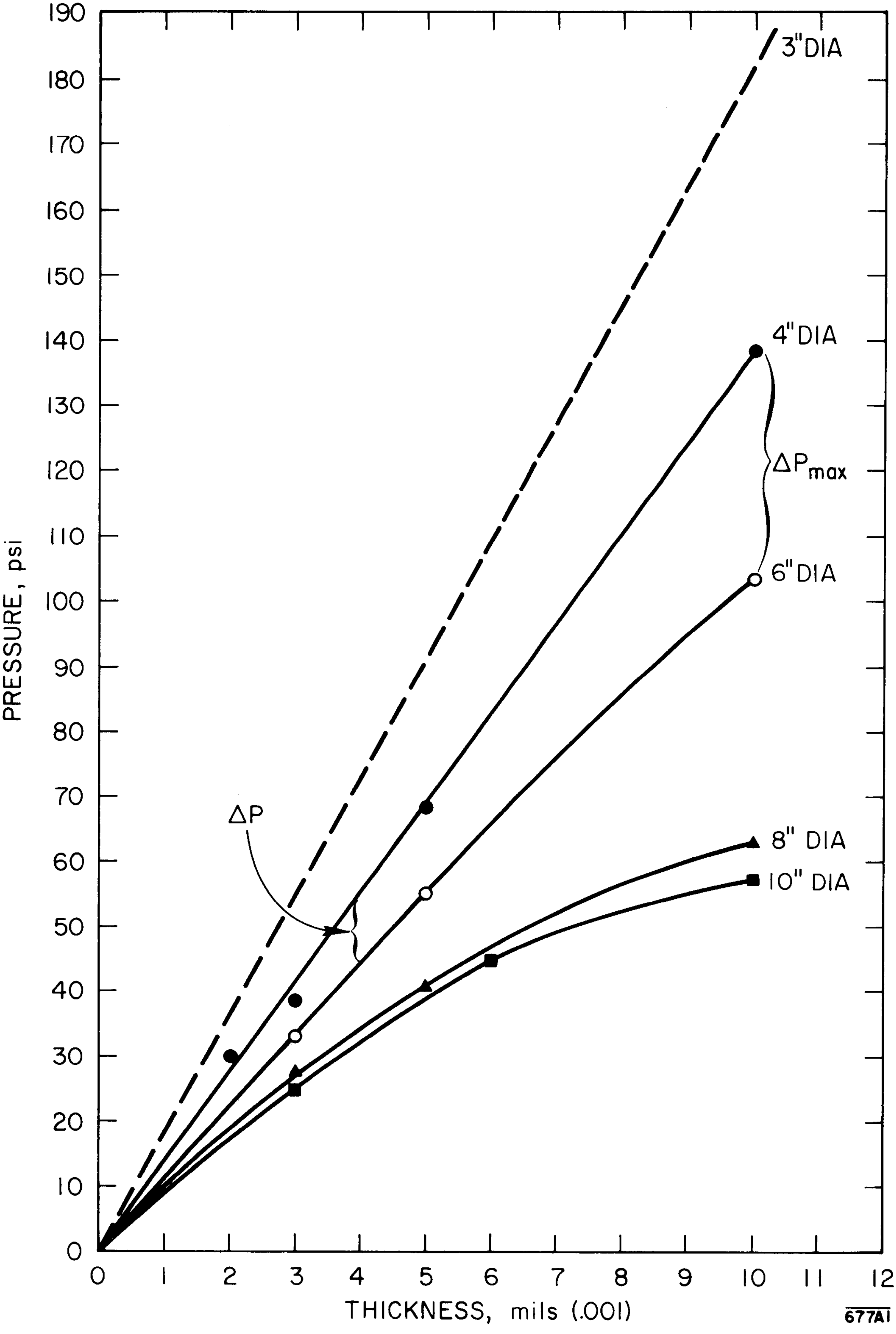
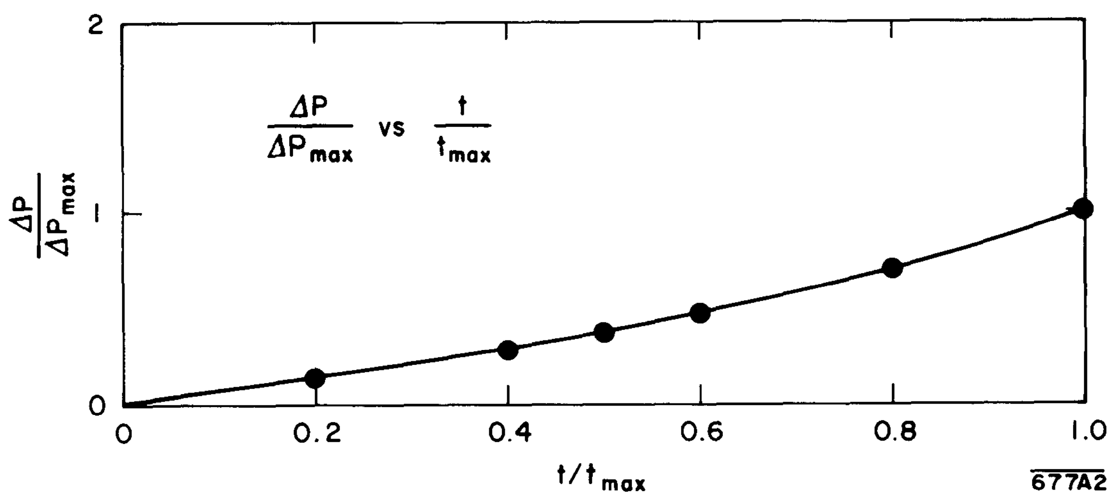


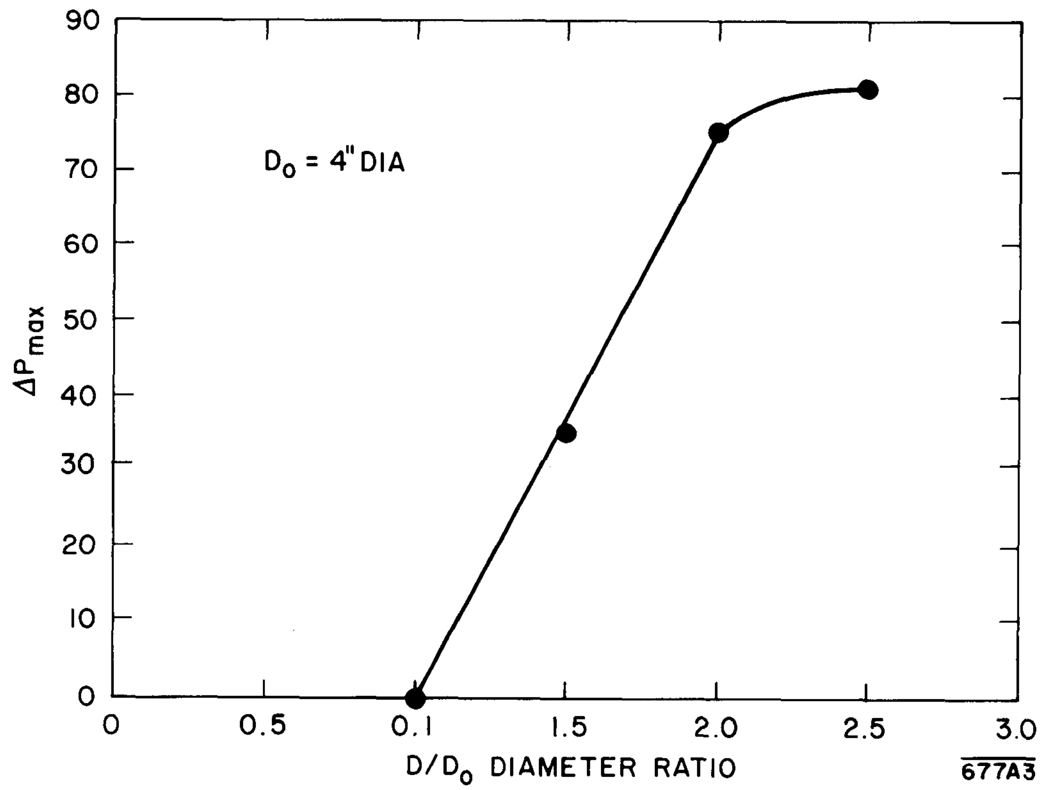
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
PRESSURE, psi
3" DIA
4" DIA
ΔP max
6" DIA
ΔP
8" DIA
10" DIA
0
1
2
3
4
5
6
7
8
9
10
11
12
THICKNESS, mils (.001)
677A1

FIG. 1



$\frac{\Delta P}{\Delta P_{max}}$ vs $\frac{t}{t_{max}}$
$\frac{\Delta P}{\Delta P_{max}}$
2
1
0
0
0.2
0.4
0.6
0.8
1.0
t/t_{max}
677A2

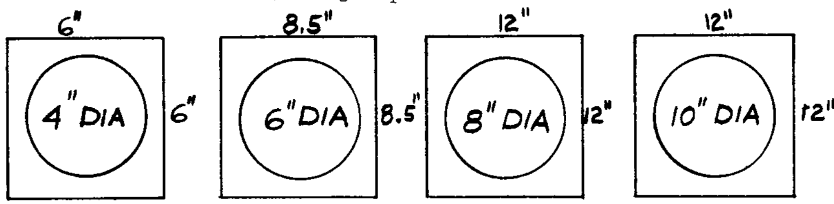
FIG. 2



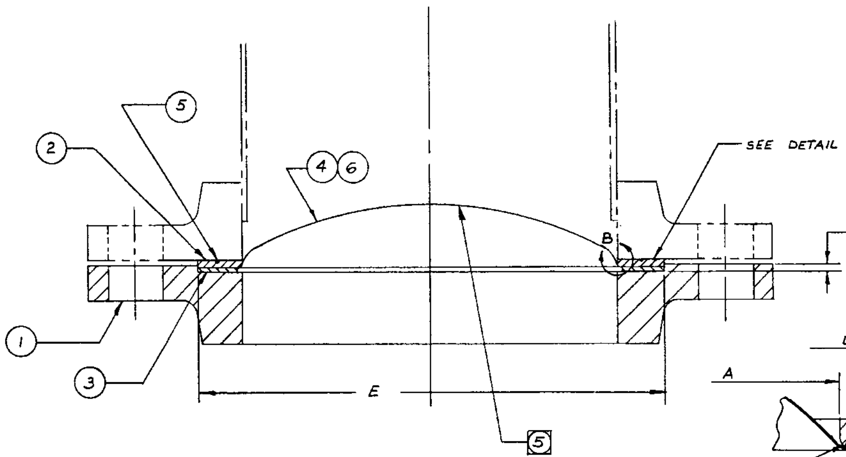
90
80
70
60
50
40
30
20
10
0
ΔP_{max}
D_o = 4" DIA
0
0.5
0.1
1.5
2.0
2.5
3.0
D/D_o DIAMETER RATIO
677A3

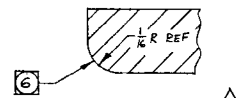
FIG. 3

Sq. in/Part: 4" Window - 48 Sq. In.
6" Window - 90.5 Sq. In.
8" Window - 192 Sq. In.
10" Window - 138 Sq. In.

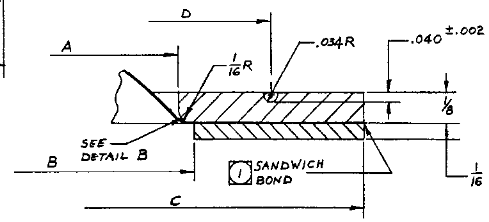


1. Vapor degrease for 5 minutes.
2. Apply 3 to 4 coats of microshield stopoff to area not to be plated, allowing 30 minutes between coats and at least one hour drying time after final coat. Air dry only.
3. Soak clean for one minute in NS-35 alkaline cleaner at 140°F.
4. Tap water rinse.
5. Dip in 30% nitric and 4 oz/gal ammonium bifluoride for 20 seconds at room temperature.
6. Tap water rinse.
7. Immerse for 25 seconds in Alstan No. 75.
8. Transfer without rinsing to bronze bath with current on.(CD22ASF):
   - 4" Window. . . . . . 7.3 Amps for 6 minutes
   - 6" Window. . . . . .13.8 Amps for 6 minutes
   - 8" Window. . . . . .29.3 Amps for 6 minutes
   - 10" Window. . . . . .21 Amps for 6 minutes
9. Tap water rinse.
10. Dip in 3% HCL.
11. Tap water rinse.
12. Distilled water rinse.
13. Plate in pyrophosphate copper.(CD30ASF) .0005":
   - 4" Window. . . . . . 10 Amps for 18 minutes
   - 6" Window. . . . . . 18.9 Amps for 18 minutes
   - 8" Window. . . . . . 40 Amps for 18 minutes
   - 10" Window. . . . . . 28.7 Amps for 18 minutes
14. Tap water rinse.
15. Distilled water rinse.
16. Dry.
17. Apply 3 coats of microshield stopoff to copper for approximately 1/4" on edge of circle.
18. Brush with alkaline cleaner.
19. Tap water rinse.
20. Cyanide dip.
21. Tap water rinse.
22. Dip in 629 acid for 30 seconds.
23. Tap water rinse.
24. Distilled water rinse.
25. Plate in tin-lead bath (CD30ASF).0002" - .0003":
   - 4" Window. . . . . . . 10 Amps for 4 minutes
   - 6" Window. . . . . . . 18.9 Amps for 4 minutes
   - 8" Window. . . . . . . 40 Amps for 4 minutes
   - 10" Window. . . . . . . 28.7 Amps for 4 minutes
26. Tap water rinse.
27. Distilled water rinse.
28. Methanol rinse.
29. Dry in warm oven at 150°F.
30. Remove stopoff in acetone using 3 rinses.

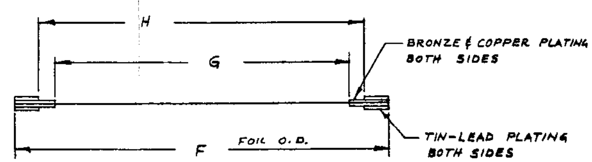




DETAIL B 5A



DETAIL A



SCHEMATIC OF BRONZE, COPPER & TIN-LEAD PLATING OF ALUMINUM FOIL.

1. ALUMINUM FOIL: BRONZE, COPPER AND TIN-LEAD PLATE ALUMINUM FOIL PER SLAC SPEC NO. PS-410-001-02.
   MAKE PLATING DIMENSIONS PER ABOVE SCHEMATIC.
   TIN-LEAD PLATE OUTSIDE EDGES AND 3/8 WIDE BORDER FROM RIM ON MATING SURFACES OF WINDOW FRAME AND BACK-UP FRAME (ITEMS 2 & 3).
   THEN SOFT SOLDER ITEMS 2, 3 AND 4 AS SHOWN ON DETAIL A.
2. MYLAR FOIL: SAND BLAST 3/4 WIDE BORDER ON BOTH SIDES OF FOIL RIM, WITH DENTAL SAND BLASTER, AND THEN BOND ITEM 2, 3 AND 4 WITH EPOXY, AS SHOWN ON DETAIL A.
   COMPOSITION OF EPOXY, BY WEIGHT, 65% EPON 828 AND 35% VERSAMIT 125. CURE AT 150°F FOR ONE HOUR.
3. GASKET MATERIAL SHALL BE LEAD, MADE FROM 15 AMP FUSE WIRE (.068 DIA).
4. LADISH COMPANY, CUDAHY, WISCONSIN OR UNIVERSITY SLAC APPROVED EQUAL.
5. (3B) MARK ON FACE OF WINDOW FOLLOWING INFORMATION, IN INK: WINDOW NOM. SIZE, MATERIAL, THICKNESS AND DATE MADE.
6. (5B) REMOVE ALL SHARP BRAKES OR EDGES ON 1/16 RADIUS AND TRANSITION AREA BETWEEN FLAT SURFACE AND RADIUS. FINISH 32√ FOR SAME AREA.

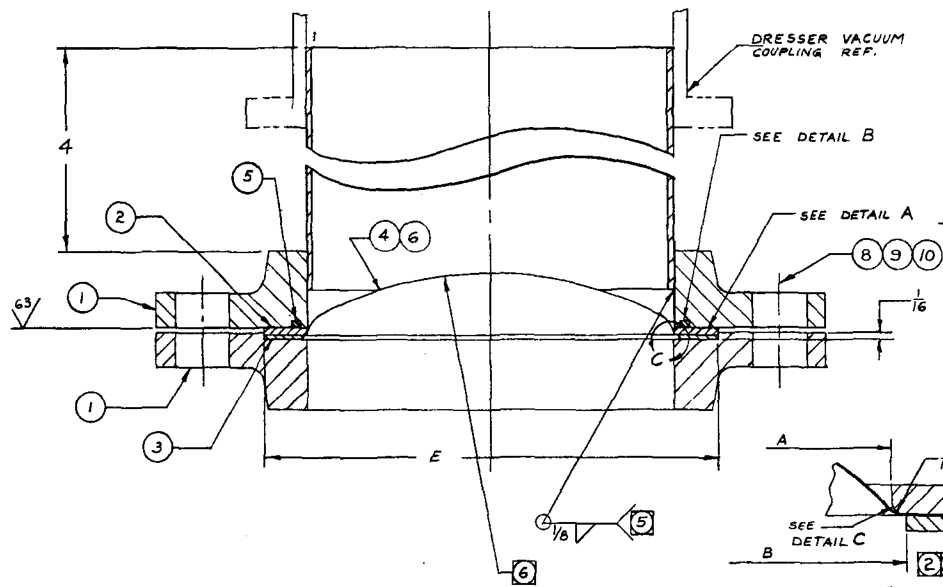
3A

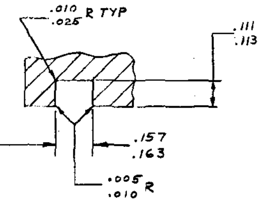
PART NUMBER	WINDOW NOM SIZE	DIAMETER A	B	C	D	E	F	G	H
SA-410-001-17	6	6 1/16	6 3/16	7 1/2	7	7 9/16	7 17/32	6 1/4	6 3/4
SA-410-001-18	10	10 1/16	10 3/16	11 1/2	11 1/8	11 9/16	11 17/32	10 1/4	10 3/4
SA-410-001-19	8	8 1/16	8 3/16	9 1/2	9	9 9/16	9 17/32	8 1/4	8 3/4
SA-410-001-20	9	9 1/16	9 3/16	10 1/2	10	10 9/16	10 17/32	9 1/4	9 3/4
SA-410-001-60 (7)	12	12 1/16	12 3/16	13 1/2	13	13 9/16	13 17/32	12 1/4	12 3/4 (6)

410-001-02

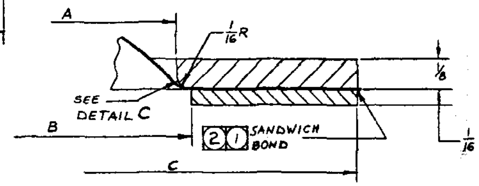
NOTE	ITEM NO.	PREFIX	BASE	SUFFIX	TITLE OR DESCRIPTION	QTY.
2	6				WINDOW FOIL, MYLAR	1
3	5				GASKET RING	1
1	4	PS	410-001	02	WINDOW FOIL, ALUMINUM	1
	3				FRAME, BACK-UP, COPPEP	1
	2				FRAME, WINDOW, COPPER	1
4	1				FLANGE, TUBE OD OR PIPE, LIGHT TYPE FORGED AL, ASA 125 lb, #12411 OR 12013	1

STOCK OR PART NO. — DO NOT SCALE DRAWING — NEXT ASSEMBLY:

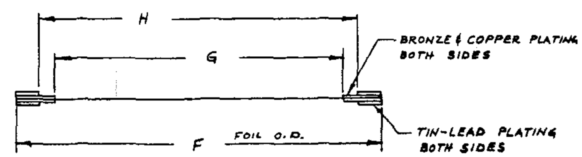




DETAIL B



DETAIL A



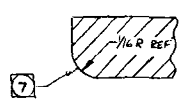
SCHEMATIC OF BRONZE, COPPER & TIN-LEAD PLATING OF ALUMINUM FOIL.

1. ALUMINUM FOIL: BRONZE, COPPER AND TIN-LEAD PLATE ALUMINUM FOIL PER SLAC SPEC NO. PS-410-001-02.
   MAKE PLATING DIMENSIONS PER ABOVE SCHEMATIC.
   TIN-LEAD PLATE OUTSIDE EDGES AND 3/8 WIDE BORDER FROM RIM ON MATING SURFACES OF WINDOW FRAME AND BACK-UP FRAME (ITEMS 2 & 3).
   THEN SOFT SOLDER ITEMS 2, 3 AND 4 AS SHOWN ON DETAIL A.
2. MYLAR FOIL: SAND BLAST 3/4 WIDE BORDER ON BOTH SIDES OF FOIL RIM, WITH DENTAL SAND BLASTER, AND THEN BOND ITEM 2, 3 AND 4 WITH EPOXY, AS SHOWN ON DETAIL A.
   COMPOSITION OF EPOXY, BY WEIGHT, 65% EPON 828 AND 35% VERSAMIT 125. CURE AT 150°F FOR ONE HOUR.
3. PARKER SEAL COMPANY, CULVER CITY, CALIFORNIA, OR UNIVERSITY SLAC APPROVED EQUAL.
4. LADISH COMPANY, CUDAHY, WISCONSIN OR UNIVERSITY SLAC APPROVED EQUAL.
5. INERT GAS ARC WELDING OF ALUMINUM, USING 5356 OR 4043 ELECTRODE. MAKE WELD VACUUM TIGHT.
6. MARK ON FACE OF WINDOW FOLLOWING INFORMATION, IN INK: WINDOW NOM. SIZE, MATERIAL, THICKNESS AND DATE MADE.
7. (2B) REMOVE ALL SHARP BRAKES OR EDGES ON 1/16 RADIUS AND TRANSITION AREA BETWEEN FLAT SURFACE AND RADIUS. FINISH 32 FOR SAME AREA.

PART NUMBER	WINDOW NOM SIZE	DIAMETER A	B	C	D	E	F	G	H	ITEM 5 ID X OD X WIDTH	ITEM 7 OD X WALL
SA-410-001-48	6	6 1/16	6 3/16	7 1/2	6.300/6.250	7 9/16	7 17/32	6 1/4	6 3/4	6 1/4 X 6 1/2 X 1/8	6 X .125
SA-410-001-49	10	10 1/16	10 3/16	11 1/2	10.550/10.500	11 9/16	11 17/32	10 1/4	10 3/4	10 1/2 X 10 3/4 X 1/8	10 X .250
SA-410-001-50	8	8 1/16	8 3/16	9 1/2	8.300/8.250	9 9/16	9 17/32	8 1/4	8 3/4	8 1/4 x 8 1/2 X 1/8	8 X .125
SA-410-001-51	9	9 1/16	9 3/16	10 1/2	9.300/9.250	10 9/16	10 17/32	9 1/4	9 3/4	9 1/4 X 9 1/2 X 1/8	9 X .250

410-001-08

NOTE	ITEM NO.	PREFIX	BASE	SUFFIX	TITLE OR DESCRIPTION	QTY.
	10				WASHER, FLAT, SST 304 OR 316, 3/4 DIA	16
	9				NUT, HEX, SST 304 OR 316, 3/4-10UNC-2B	8
	8				SCREW, HEX, HEAD SST 304 OR 316 3/4-10UNC-2A X 2	8
	7				TUBE, AL 6061-T6, 4 1/2 LG	1
2	6				WINDOW FOIL, MYLAR	1
3	5				O-RING SEAL, VITON A	1
1	4	PS	410-001	02	WINDOW FOIL, ALUMINUM	1
	3				FRAME, BACK-UP, COPPEP	1
	2				FRAME, WINDOW, COPPER	1
4	1				FLANGE, TUBE OD OR PIPE, LIGHT TYPE, FORGED AL, ASA 125 lb, #1241 OR 1201B	2



DETAIL C (2A)

SEE DWG MA-410-001-02 FOR END STATION A AND K-BEAM WINDOWS.