NASA Technical Memorandum 110372

NASA-TM-110372
19960008026

Lower Body Negative Pressure Chamber: Design and Specifications for Tilt-Table Mounting

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Moffett Field, California 94035-1000

Contents

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LAURA SALAMACHA, D. GUNDO, G. M. MULENBURG, AND J. E. GREENLEAF

Ames Research Center

Summary

The tendency to faint (syncope) is increased when a person moves from a horizontal or sitting position to a standing position. Most people have appropriate compensatory physiological responses that maintain systemic blood pressure to inhibit fainting. About 10 percent of the population are "fainters"; i.e., they have low fainting tolerance (less than 3 min standing) due to hereditary (genetic) predisposition. Illness and neurological abnormalities will also induce early fainting. In normal healthy people, exposure to prolonged bed rest or spaceflight deconditioning can result in early fainting when they assume the upright posture after rest or landing, respectively. Some endurance-trained runners and other athletes appear to have significantly reduced syncopal tolerance.

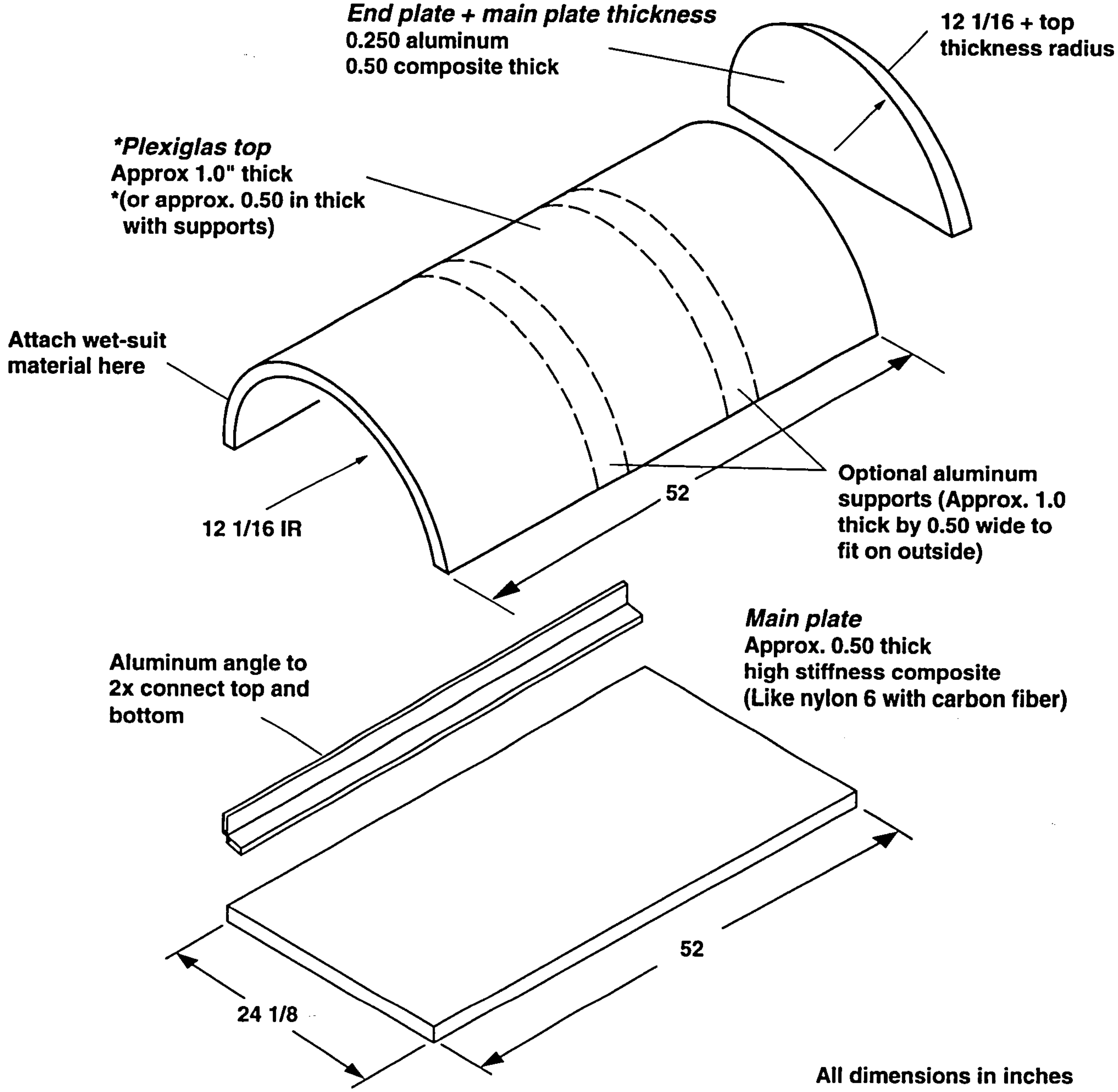
In spite of extensive research over the past 100 years, the mechanism (cause) of fainting is unknown. One problem encountered with the conduct of human research studies is difficulty in reproducing and attenuating the sequence of physiological responses leading up to the fainting episode. Current testing procedures include prolonged standing, hanging, or standing on a foot-plate on a tilting table; i.e., head-up tilt (HUT), total body acceleration in the +Gz (head-to-foot) direction, and exposure of the lower body to reduced atmospheric pressure induced within an air-tight chamber surrounding the waist and lower limbs; i.e., lower body negative pressure (LBNP). However, each of these stress procedures has disadvantages, one being difficulty in controlling the rate of the onset of pre-syncopal physiological responses such as lower blood pressure and cardiac output, and higher heart rate, peripheral vascular resistance, and vasoactive hormone responses.

Use of LBNP and HUT simultaneously should allow for greater control of the pre-syncopal response parameters. This combination has been used by at least two research groups:

1. Newberry, P. D., A. W. Hatch, and J. M. MacDonald. Cardio-respiratory events preceding syncope induced by a combination of lower body negative pressure and head-up tilt. Aerospace Med. 41:373-378, 1970.
2. El-Bedawi, K. M., and R. Hainsworth. Combined head-up tilt and lower body suction: a test of orthostatic tolerance. Clin. Auton. Res. 4:41-47, 1994.

Specifications for a lower body negative pressure chamber for mounting on a tilting table are presented. The main plate is made from HEXEL honeycomb board 1.0 inch thick. The plate, supported at three edges, will be subjected to a uniform pressure differential of –4.7 lb/in^2. A semi-cylindrical Plexiglass top (chamber) is attached to the main plate; the pressure within the chamber will be about 10 lb/in^2 during operation. The stresses incurred by the main plate with this partial vacuum were calculated. All linear dimensions are in inches.

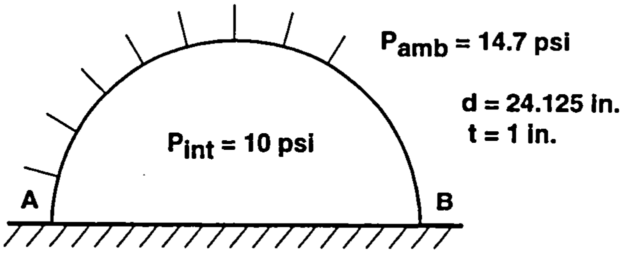
Vacuum Chamber



All dimensions in inches

Keep weight to a minimum (max 180 lbs.)
Keep large plate deflections under 3/8 in

Plexiglas Stress Analysis



Base-assume inflexible, rigid surface

- The calculation of forces of reaction at points A & B

There is an equal pressure differential across the hemi-cylindrical surface of the tube material.

Collapsing pressure of the cylinder is

$W_C = KE\left(\frac{t}{D}\right)^3$ psi where;

K = a constant
E = elastic modules = 480,000 psi
t = thickness of material
D = diameter of cylinder

CASE 1:

For radial external pressure with simply supported edges

$$\frac{\text{length}}{\text{radius}} - \frac{60\text{ in}}{14\text{ in}} = 4.3 \qquad \frac{\text{diam}}{\text{thickness}} = \frac{24.125}{1\text{ in}} = 24.125$$

When $K = 8.0$

$$W_C = (8.0)\,(480{,}000\text{ psi})\left(\frac{1\text{ in}}{24{,}125\text{ in}}\right)^3$$

$\underline{\underline{W_C = 273\text{ psi}}}$ $\underline{\underline{W_C = 115\text{ psi for } t = 0.75\text{ in}}}$

CASE 2:

For radial external pressure with fixed edges

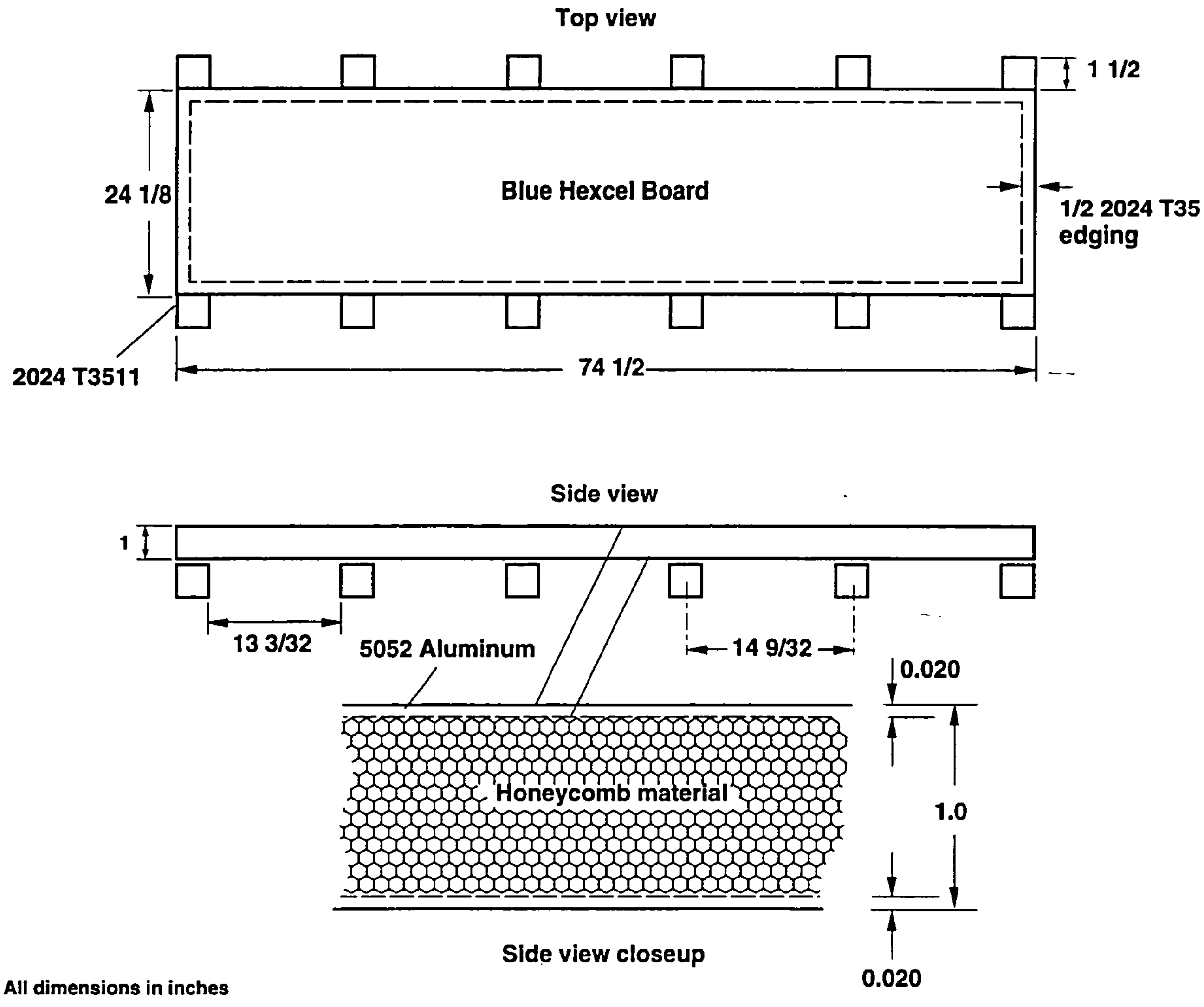
$$\frac{\text{length}}{\text{radius}} = 4.3, \quad \frac{D}{T} = 28, \text{ from above } K = 9.5$$

$$W_C = (9.5)\,(480{,}000\text{ psi})\left(\frac{1\text{ in}}{24{,}125\text{ in}}\right)^3$$

$\underline{\underline{W_C = 324\text{ psi}}}$ $\underline{\underline{W_C = 137\text{ psi for } t = 0.75\text{ in}}}$

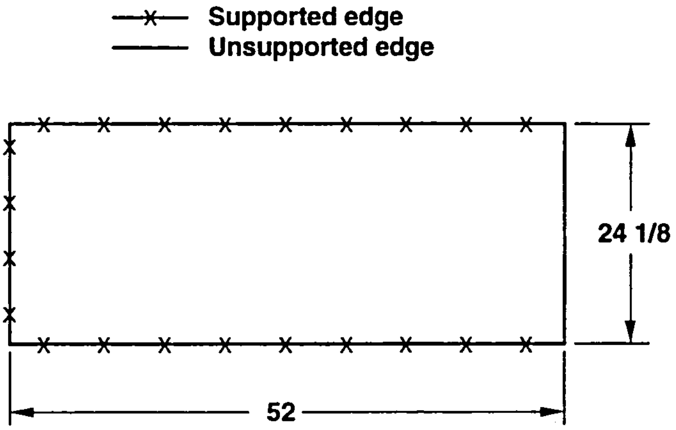
$\Longrightarrow$ Margin of safety is large for working pressure differentials near 5 lb/in^2.

HEXEL Board Specifications

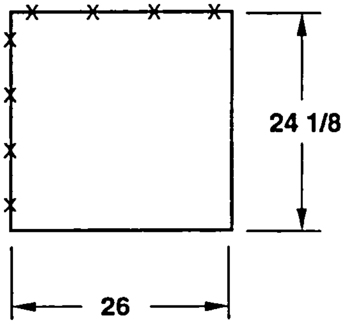


Note: For bending stress calculations the honeycombed center of the Hexcel board was ignored and the cross section used for analysis assumed a hollow center section.

HEXEL Bending Moment



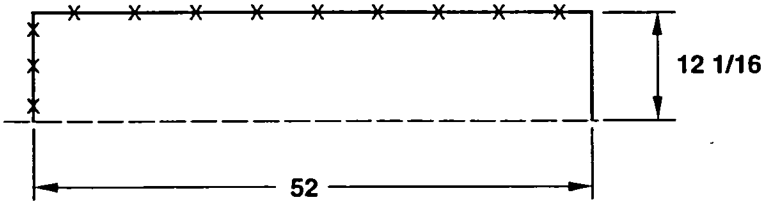
(1)



distributed load = 42.75 lb/in
(on supported edges)

$\Sigma M_{\text{bending}}$ = 12145 lb/in

(2)

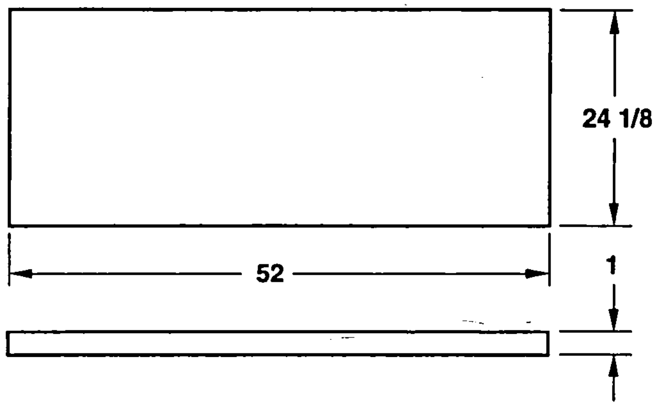


distributed load = 51.82 lb/in
(on supported edges)

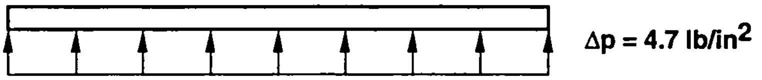
$\Sigma M_{\text{bending}}$ = 14433 lb/in

All dimensions in inches

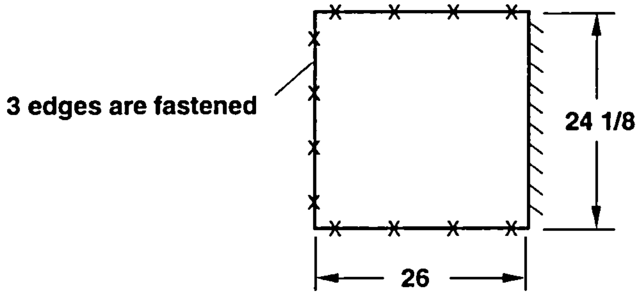
Bending Moment Calculation



Loading



Looking at half of the board in order to calculate the bending moment:



Pressure force (resultant) – acts in center of plate

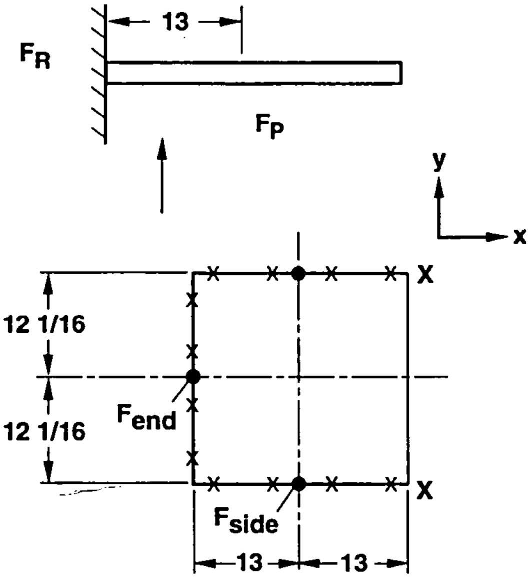
$F_P = (4.7\ \text{lb/in}^2)\ (26\ \text{in})\ (24.125\ \text{in}) = \underline{\underline{2948\ \text{lb}}}$

There must be a downward force, F_R, to balance F_P.

The point of action of this force F_R is weighted by the three supports.

By symmetry the weighted center will be on the midline in the y direction.

$\Sigma M_{xx} = F_{end} \cdot d_{end} + (F_{side} \cdot d_{side})$ 2 sides



The loading of the supports can be found from the total load.

$$\left.\begin{aligned} F_{total} &= 2948 \text{ lb} \\ l_{load} &= 2 \bullet 26 + 24.125 = 76.125 \text{ in} \end{aligned}\right\rangle \text{ for 1/2 of the pressurized section}$$

$$\text{Distribution bad} = \frac{F_{total}}{l_{load}} = \frac{2948 \text{ lb}}{76.125 \text{ in}} \quad \begin{array}{l}\text{38.7 lb/in along perimeter} \\ \text{(assuming equal load distribution)}\end{array}$$

From the moment equation on the previous page:

$$\Sigma M_{xx} = F_{end} \bullet d_{end} + (F_{side} \bullet d_{side})\, 2 \qquad \text{where } F_{side} = (\text{dist.} \bullet \text{load})\,(d_{side})$$

$$= (38.7 \text{ lb/in})\,(24.125 \text{ in})\,(26 \text{ in}) + (38.7 \text{ lb/in})\,(26 \text{ in})\,(13 \text{ in})\,(2)$$

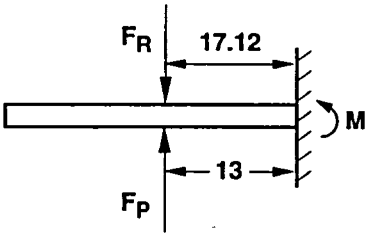
$$\underline{\Sigma M_{xx} = 50469 \text{ lb/in}}$$

The center of moment (CM) measured from from the "cut" edge is

$$CM = \frac{\Sigma M_{xx}}{F_P} = \frac{50469 \text{ lb/in}}{2948 \text{ in}}$$

$$CM = 17.12 \text{ in}$$

Free-body diagram:



All dimensions in inches.

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \therefore \qquad F_P = F_R = 2948 \text{ lb}$$

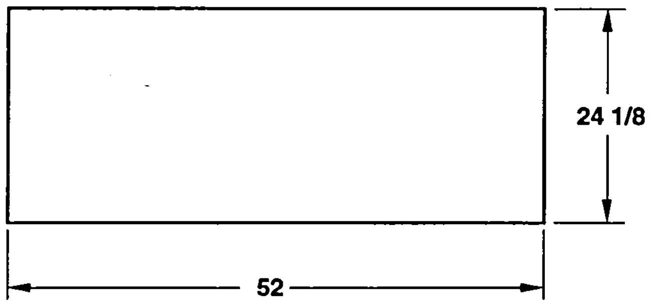
$$\Sigma M = F_P \bullet d_P - F_R \bullet d_R$$

$$= (2948 \text{ lb})\,(17.12 \text{ in}) - (2948 \text{ lb})\,(13 \text{ in})$$

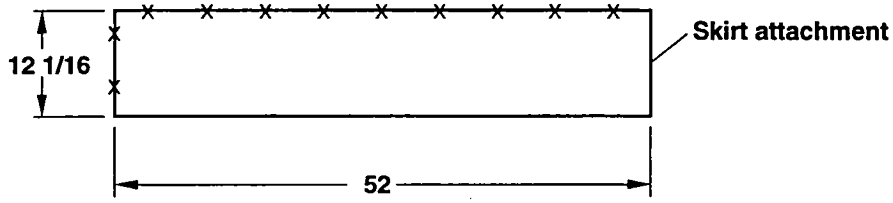
$$\underline{\underline{\Sigma M = 12145 \text{ lb/in}}}$$

Next, it was decided to look at the board from another perspective: cutting it longitudinally

LBNP Tilt Table



cutting the board lengthwise this time:



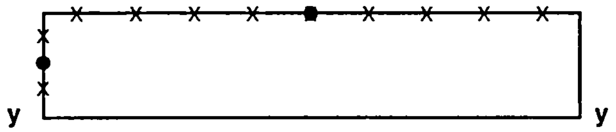
All dimensions in inches

F_P = P.A.

= (4.7 lb/in^2) (52 in) (12.0625 in)

F_P = 2948 lb as found previously

find location of reaction force (F_R):



$$\Sigma M_{yy} = F_{end}\, d_{end} + F_{side}\, d_{side} \qquad \text{dist from y-y to force} \begin{cases} d_{end} = \dfrac{12.0625}{2} = 6.03125 \text{ in} \\ d_{side} = 12.0625 \text{ in} \end{cases}$$

find distributed load

$$\text{dist. load} = \frac{F_P}{l_{\text{supported}}}$$

$$= \frac{(2948 \text{ lb})}{(12.0625 + 52) \text{ in}} = 46.02 \text{ lb/in along perimeter}$$

(Again assuming equal load distribution along sides/end.)

$$F_{end} = (\text{dist. load})(l_{end}) = (46.02\ \text{lb/in})(12.0625\ \text{in})$$

$$= 555\ \text{lb}$$

$$F_{side} = (\text{dist. load})(l_{side}) = (46.02\ \text{lb/in})(52\ \text{in})$$

Substituting:

$$\Sigma M_{yy} = F_{end}\ d_{end} + F_{side}\ d_{side}$$

$$= (555\ \text{lb/in})(6.03125\ \text{in}) + (2393\ \text{lb})(12.0625\ \text{in})$$

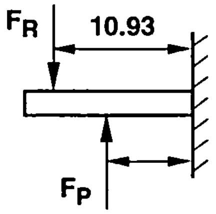
$$\underline{\Sigma M_{yy} = 32213\ \text{lb/in}}$$

to find the center of moment (CM)

$$CM = \frac{\Sigma M_{yy}}{F_P} = \frac{32213\ \text{lb/in}}{2948\ \text{in}}$$

$$CM = 10.93\ \text{in}$$

Free-body diagram:



All dimensions in inches.

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \therefore \qquad F_P = F_R = 2948\ \text{lb}$$

$$\Sigma M = F_R \bullet d_R - F_P \bullet d_P$$

$$= (2948\ \text{lb})(10.93\ \text{in}) - (2948\ \text{lb})(6.03125\ \text{in})$$

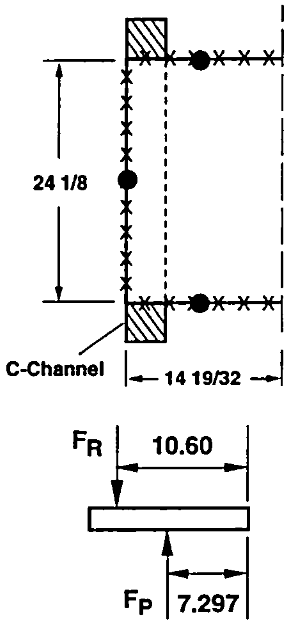
$$\underline{\underline{\Sigma M = 14433\ \text{lb/in}}}$$

At this point, channels were added to the design to provide stability to the board. The subsequent analyses were on the channels and subsections of the board.

Considering a smaller section:

BENDING MOMENT – 14 in sections

Configuration A – end section



$F_P = (4.7\ \text{lb/in}^2)\,(14.5938\ \text{in})\,(24.1250\ \text{in}) = 1655\ \text{lb}$

$l_{\text{load}} = 24.1250 + 2\,(14.5938) = 53.3\ \text{in}$

$\text{Dist. load} = \dfrac{1655\ \text{lb}}{533\ \text{in}} = 31.05\ \text{lb/in}$

$\Sigma M_{XX} = (31.05\ \text{lb/in})\,(24.1250\ \text{in})\,(14.5938\ \text{in}) + (31.05\ \text{lb/in})\,(14.5938)^2$

$= 17543\ \text{lb/in}$

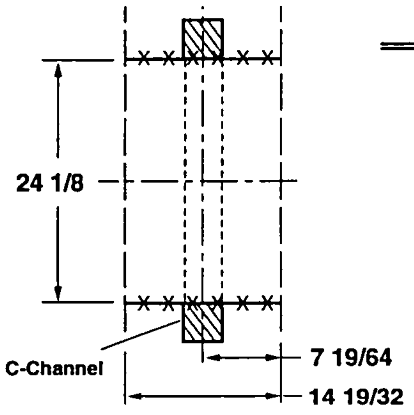
$CM = \dfrac{\Sigma M_{XX}}{F_P} = \dfrac{17543\ \text{lb/in}}{1655\ \text{lb}} = 10.60\ \text{in}$

$FR = F_P = 1655\ \text{lb}$

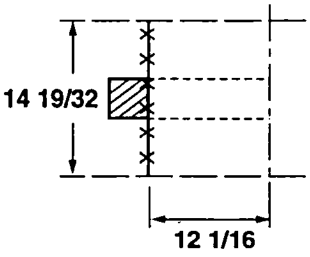
$M = F_R\,d_R - F_P\,d_P = (3.30\ \text{in})\,(1655\ \text{lb})$

$M = 5466\ \text{lb/in}$

Configuration B – centered section



⟹ Looking at half of this section and turning it 90°:



by same method: $F_P = 827.4\ \text{lb}$

$l_{\text{load}} = 14.5938\ \text{in}$

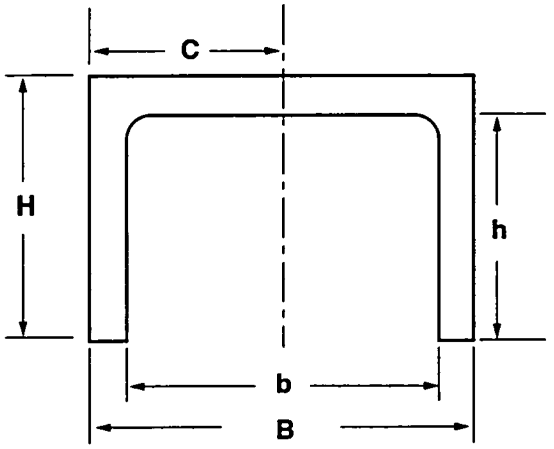
$\text{Dist. load} = 56.7\ \text{lb/in}$

$\Sigma M_{XX} = 4990.1\ \text{lb/in}$

$M = \Sigma M_{XX} = 4990.1\ \text{lb/in}$

All dimensions in inches.

Support Beams Moment of Inertia



Dimensions

H = 0.875 in
h = 0.750 in
C = 0.750 in
B = 1.50 in
b = 1.25 in

$$I = \frac{BH^3 - bh^3}{12}$$

$$= \frac{(1.5\text{ in})\,(0.875\text{ in})^3 - (1.25\text{ in})\,(0.750\text{ in})^3}{12}$$

$$\underline{\underline{I = 0.0398\text{ in}^4}}$$

$$\frac{I}{C} = \frac{BH^3 - bh^3}{6H}$$

$$= \frac{(1.5\text{ in})\,(0.875\text{ in})^3 - (1.25\text{ in})\,(0.750\text{ in})^3}{6\,(0.875\text{ in})}$$

$$\underline{\underline{\frac{I}{C} = 0.00758\text{ in}^3}}$$

Material	2024	T3511	Aluminum
F	Use lower values	54 = Su	
		37 = Sy	E = 10.8 × 10³ ksi
		29 = Shear w	

Crush Stress on HEXEL Board at Support Beams

Configuration A – end section

Total load on C-Channel = (distributed load) • (length of channel)

= (31.05 lb/in) (24.125 in)

= $\underline{749.1 \text{ lb}}$

Total channel contact area = (channel length) • (channel width)

= (24.125 in) (1.50 in)

= $\underline{36.2 \text{ in}^2}$

Assuming the load is evenly distributed and compressive at the supports:

$$\sigma_c = \frac{\text{total load}}{\text{contact area}} = \frac{749.1 \text{ lb}}{36.2 \text{ in}^2} = 20.7 \text{ lb/in}^2$$

$$\sigma_u = 330 \text{ lb/in}^2 \text{ for Hexcel board in flat compression}$$

$$\text{safety factor} = \frac{330 \text{ lb/in}^2}{20.7 \text{ lb/in}^2} = \underline{\underline{16.0}}$$

Configuration B

Total load on C-Channel = (56.7 lb/in) (24.125 in)

= 1368 lb

Total channel contact area = 36.2 in^2 (shown above)

$$\text{compressive stress} = \frac{1368 \text{ lb}}{36.2 \text{ in}^2} = 37.8 \text{ lb/in}^2$$

$$\text{safety factor} = \frac{330 \text{ lb/in}^2}{37.8 \text{ lb/in}^2} = 8.7$$

HEXEL Board Bending Stress: End Section

Moment of Inertia – Stress Analysis
HEXEL Board – 14.5 in. sub-section (End Section)
Configuration A

Item	Number of Items	Width [in]	Height [in]	Area (A) [in^2]	dist. CG to x-x	static mom.	moment @ x-x	neutral mom.
					y [in]	(A*y) [in^3]	(A*y^2) [in^4]	(lo = w*$h^{3/12}$) (in^4)
HEXEL upper skin	1	24.125	0.02	0.4825	0.01	0.00483	0.00005	1.6083E-05
HEXEL lower skin	1	24.125	0.02	0.4825	0.99	0.47768	0.47290	1.6083E-05

ΣA =	Σ(A*y)=	Σ(A*y^2) =	Σ lo =
0.9650	0.4825	0.4729	3.2167E-05

Y(l) = Σ(A*y)/ΣA = 0.5000 in

I(n) = Σlo + Σ(A*y2) – ΣA*Y $(I)^2$ = 0.2317 in^4

Stress Max. = M*Y(I)/I(n)

M = 5465 lb/in (from previous calculations)

Stress Max. = 11.79 ksi

Max. allowable = 28 ksi
Safety Factor = 2.37

HEXEL Board Stress Analysis: C-Channel Centered

Moment of Inertia – Stress Analysis
HEXEL Board – 14.5 in. sub-section (Center to Center)
Configuration B

Item	Number of Items	Width [in]	Height [in]	Area (A) [in^2]	dist. CG to x-x y [in]	static mom. (A*y) [in^3]	moment @ x-x (A*y^2) [in^4]	neutral mom. (lo = w*h^3/12) (in^4)
HEXEL upper skin	1	14.5938	0.02	0.2919	1.874	0.5497	1.02503	9.7292E-06
HEXEL lower skin	1	14.5938	0.02	0.2919	0.876	0.25568	0.22398	9.7292E-06
Channel B sections	1	1.5	0.125	0.1875	0.8125	0.15234	0.12378	0.00024
Channel C Sections	2	0.125	0.75	0.0938	0.375	0.3516	0.01318	0.00439

ΣA =	$\Sigma(A*y)$=	$\Sigma(A*y^2)$ =	Σ lo =
0.9588	1.0253	1.3992	0.0091

$Y(I) = \Sigma(A*y)/\Sigma A$ = 1.0694 in

$I(n) = \Sigma lo + \Sigma(A*y^2) - /\Sigma A*Y\ (I)^2$ = 0.3117 in^4

Stress Max. = M*Y(I)/I(n)

M = 4990 lb/in (from previous calculations)

Stress Max. = 17.12 ksi

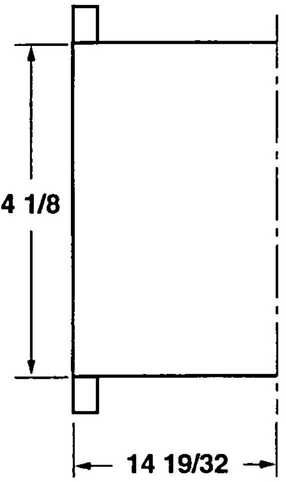
Max. allowable = 28 ksi
Safety Factor = 1.64

HEXEL Board Bending Stress Analysis Summary

	Configuration A	Configuration B
Bending Moment	5465 lb/in	4990 lb/in
Moment of Inertia	0.2317 in^4	0.3117 in^4
Distance to Neutral Axis	0.500 in	1.0694 in
Max. Calculated Stress	11.79 ksi	17.12 ksi
Max. Allowable Stress	28.0 ksi	28.0 ksi
Safety Factor	2.37 S.F.	1.64 S.F.
Compressive Stress	20.7 psi	37.8 psi
Safety Factor	16 S.F.	8.7 S.F.

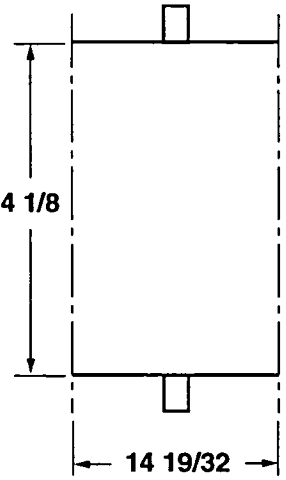
Note: The calculated safety factors for the bending moment are artificially low due to the absence of the aluminum honeycomb in the stress calculations.

Configuration A



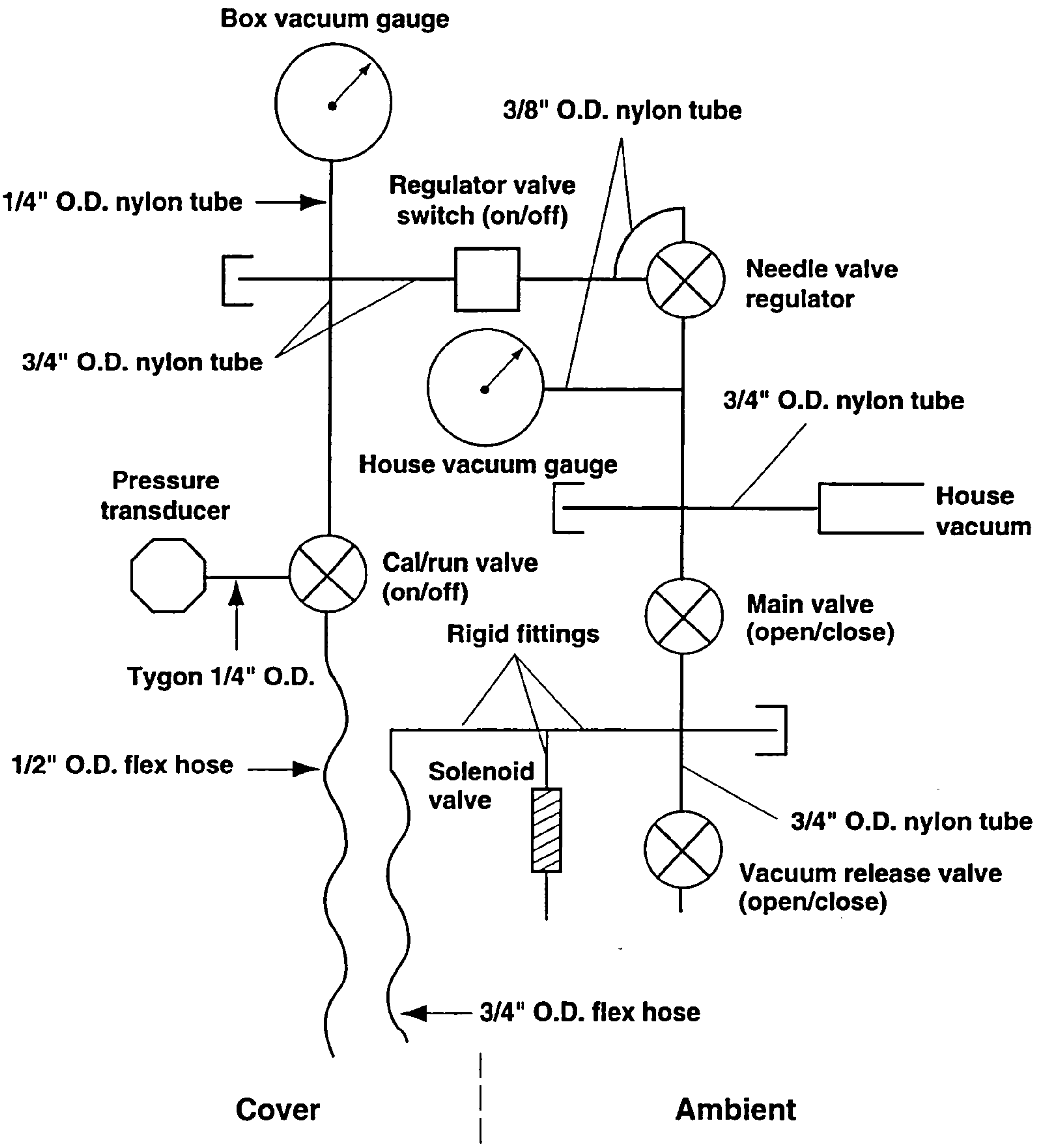
C-Channel on end of span

Configuration B



C-Channel on center of span

LBNP Pressure Regulation System



REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE November 1995	3. REPORT TYPE AND DATES COVERED Technical Memorandum

4. TITLE AND SUBTITLE Lower Body Negative Pressure Chamber: Design and Specifications for Tilt-Table Mounting	5. FUNDING NUMBERS 199-18-12-07
6. AUTHOR(S) Laura Salamacha, D. Gundo, G. M. Mulenburg, and J. E. Greenleaf	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Ames Research Center Moffett Field, CA 94035-1000	8. PERFORMING ORGANIZATION REPORT NUMBER A-960221
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-110372

11. SUPPLEMENTARY NOTES

Point of Contact: J. E. Greenleaf, Ames Research Center, MS 239-11, Moffett Field, CA 94035-1000
(415) 604-6604

12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified — Unlimited Subject Category 52	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS LBNP, Tilting, Humans	15. NUMBER OF PAGES 20
	16. PRICE CODE A03

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT