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

Laura Salamacha, D. Gundo, G. M. Mulenburg, and J. E. Greenleaf

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# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary</td>
<td>1</td>
</tr>
<tr>
<td>Vacuum Chamber: Main Plate and Plexiglass Top</td>
<td>3</td>
</tr>
<tr>
<td>Plexiglass Stress Analysis</td>
<td>4</td>
</tr>
<tr>
<td>HEXEL Board Specifications</td>
<td>5</td>
</tr>
<tr>
<td>HEXEL Bending Moment</td>
<td>6</td>
</tr>
<tr>
<td>Bending Moment Calculation</td>
<td>7</td>
</tr>
<tr>
<td>Support Beams Moment of Inertia</td>
<td>12</td>
</tr>
<tr>
<td>Crush Stress on HEXEL Board at Support Beams</td>
<td>13</td>
</tr>
<tr>
<td>HEXEL Board Bending Stress: End Section</td>
<td>14</td>
</tr>
<tr>
<td>HEXEL Board Stress Analysis: C-Channel Centered</td>
<td>15</td>
</tr>
<tr>
<td>HEXEL Board Bending Stress Analysis: Summary</td>
<td>16</td>
</tr>
<tr>
<td>LBNP Pressure Regulation System</td>
<td>17</td>
</tr>
</tbody>
</table>
Lower Body Negative Pressure Chamber: Design and Specifications for Tilt-Table Mounting

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:


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/in². A semi-cylindrical Plexiglass top (chamber) is attached to the main plate; the pressure within the chamber will be about 10 lb/in² during operation. The stresses incurred by the main plate with this partial vacuum were calculated. All linear dimensions are in inches.
LBNP Tilt Table

Vacuum Chamber

End plate + main plate thickness
0.250 aluminum
0.50 composite thick

*Plexiglas top
Approx 1.0" thick
*(or approx. 0.50 in thick with supports)

Optional aluminum supports (Approx. 1.0 thick by 0.50 wide to fit on outside)

Attach wet-suit material here

Main plate
Approx. 0.50 thick
high stiffness composite
(Like nylon 6 with carbon fiber)

All dimensions in inches

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

\[ W_c = KE \left( \frac{t}{D} \right)^3 \text{ psi} \]

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

\[ \frac{\text{length}}{\text{radius}} = \frac{60 \text{ in}}{14 \text{ in}} = 4.3 \quad \frac{\text{diam}}{\text{thickness}} = \frac{24,125 \text{ in}}{1 \text{ in}} = 24,125 \]

When \( K = 8.0 \)

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

**Case 1:**
\[ W_c = 273 \text{ psi} \quad W_c = 115 \text{ psi for } t = 0.75 \text{ in} \]

**CASE 2:**
For radial external pressure with fixed edges

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

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

**Case 2:**
\[ W_c = 324 \text{ psi} \quad W_c = 137 \text{ psi for } t = 0.75 \text{ in} \]

Margin of safety is large for working pressure differentials near 5 lb/in².
LBNP Tilt Table

HEXEL Board Specifications

Top view

Blue Hexcel Board

1/2 2024 T35 edging

24 1/8

2024 T3511

74 1/2

Side view

11/2

5052 Aluminum

13 3/32

14 9/32

Honeycomb material

1.0

0.020

Side view closeup

All dimensions in inches

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.
LBNP Tilt Table

HEXEL Bending Moment

---

Supported edge

Unsupported edge

---

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

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

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

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

All dimensions in inches
Bending Moment Calculation

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

Pressure force (resultant) - acts in center of plate
\[ F_p = (4.7 \text{ lb/in}^2) (26 \text{ in}) (24.125 \text{ in}) = 2948 \text{ lb} \]

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.

\[ \Sigma M_{xx} = F_{end} \cdot d_{end} + (F_{side} \cdot d_{side}) \text{ 2 sides} \]
LBNP Tilt Table

The loading of the supports can be found from the total load.
\[
F_{\text{total}} = 2948 \text{ lb} \\
I_{\text{load}} = 2 \cdot 26 + 24.125 = 76.125 \text{ in}
\]
for 1/2 of the pressurized section

Distribution bad = \( \frac{F_{\text{total}}}{I_{\text{load}}} = \frac{2948 \text{ lb}}{76.125 \text{ in}} \)

38.7 lb/in along perimeter (assuming equal load distribution)

From the moment equation on the previous page:
\[
\Sigma M_{xx} = F_{\text{end}} \cdot d_{\text{end}} + (F_{\text{side}} \cdot d_{\text{side}})^2
\]
where \( F_{\text{side}} = (\text{dist.} \cdot \text{load}) (d_{\text{side}}) \)
\[
= (38.7 \text{ lb/in}) (24.125 \text{ in}) (26 \text{ in}) + (38.7 \text{ lb/in}) (26 \text{ in}) (13 \text{ in}) (2)
\]
\[
\Sigma M_{xx} = 50469 \text{ lb/in}
\]

The center of moment (CM) measured from the "cut" edge is
\[
CM = \frac{\Sigma M_{xx}}{F_p} = \frac{50469 \text{ lb/in}}{2948 \text{ in}}
\]
CM = 17.12 in

Free-body diagram:

\[
\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \therefore F_p = F_R = 2948 \text{ lb}
\]
\[
\Sigma M = F_p \cdot d_p - F_R \cdot d_R
\]
\[
= (2948 \text{ lb}) (17.12 \text{ in}) - (2948 \text{ lb}) (13 \text{ in})
\]
\[
\Sigma M = 12145 \text{ lb/in}
\]

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

![Diagram of a rectangular board with dimensions and annotations]

Cutting the board lengthwise this time:

\[ \text{All dimensions in inches} \]

\[ F_p = P.A. \]
\[ = (4.7 \text{ lb/in}^2) (52 \text{ in}) (12.0625 \text{ in}) \]
\[ F_p = 2948 \text{ lb} \text{ as found previously} \]

Find location of reaction force (F,R):  

\[ \Sigma M_y = F_{end} d_{end} + F_{side} d_{side} \]

\[ d_{end} = \frac{12.0625}{2} = 6.03125 \text{ in} \]
\[ d_{side} = 12.0625 \text{ in} \]

Find distributed load

\[ \text{dist. load} = \frac{F_p}{l_{supported}} \]
\[ = \frac{(2948 \text{ lb})}{(12.0625 + 52) \text{ in}} = 46.02 \text{ lb/in along perimeter} \]

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

\[ F_{\text{end}} = (\text{dist. load}) (l_{\text{end}}) = (46.02 \text{ lb/in}) (12.0625 \text{ in}) = 555 \text{ lb} \]
\[ F_{\text{side}} = (\text{dist. load}) (l_{\text{side}}) = (46.02 \text{ lb/in}) (52 \text{ in}) \]

Substituting:

\[ \Sigma M_{yy} = F_{\text{end}} d_{\text{end}} + F_{\text{side}} d_{\text{side}} \]
\[ = (555 \text{ lb/in}) (6.03125 \text{ in}) + (2393 \text{ lb}) (12.0625 \text{ in}) \]

\[ \Sigma M_{yy} = 32213 \text{ lb/in} \]

to find the center of moment (CM)

\[ \text{CM} = \frac{\Sigma M_{yy}}{F_p} = \frac{32213 \text{ lb/in}}{2948 \text{ in}} \]

\[ \text{CM} = 10.93 \text{ in} \]

Free-body diagram:

\[ \Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \therefore F_p = F_R = 2948 \text{ lb} \]
\[ \Sigma M = F_R \cdot d_R - F_P \cdot d_P \]
\[ = (2948 \text{ lb}) (10.93 \text{ in}) - (2948 \text{ lb}) (6.03125 \text{ in}) \]

\[ \Sigma M = 14433 \text{ lb/in} \]

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**

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

\[ l_{\text{load}} = 24.1250 + 2 (14.5938) = 53.3 \text{ in} \]

\[ \text{Dist. load} = \frac{1655 \text{ lb}}{533 \text{ in}} = 31.05 \text{ lb/in} \]

\[ \Sigma M_{xx} = (31.05 \text{ lb/in}) (24.1250 \text{ in}) (14.5938 \text{ in}) + (31.05 \text{ lb/in}) (14.5938)^2 \]

\[ = 17543 \text{ lb/in} \]

\[ CM = \frac{\Sigma M_{xx}}{F_P} = \frac{17543 \text{ lb/in}}{1655 \text{ lb}} = 10.60 \text{ in} \]

\[ FR = F_P = 1655 \text{ lb} \]

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

\[ M = 5466 \text{ lb/in} \]

**Configuration B – centered section**

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

\[ l_{\text{load}} = 14.5938 \text{ in} \]

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

\[ \Sigma M_{xx} = 4990.1 \text{ lb/in} \]

\[ M = \Sigma M_{xx} = 4990.1 \text{ lb/in} \]

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

All dimensions in inches.
Support Beams Moment of Inertia

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

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

\[ I = 0.0398 \text{ in}^4 \]

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

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

\[ \frac{I}{C} = 0.00758 \text{ in}^3 \]

Material: 2024 T3511 Aluminum

Use lower values:

\[ F = 54 = Su \]

\[ 37 = Sy \]

\[ E = 10.8 \times 10^3 \text{ ksi} \]

\[ 29 = \text{Shear w} \]
LBNP Tilt Table

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)
= 749.1 lb

Total channel contact area = (channel length) • (channel width)
= (24.125 in) (1.50 in)
= 36.2 in²

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

\[ \sigma_c = \frac{749.1 \text{ lb}}{36.2 \text{ in}^2} = 20.7 \text{ lb/in}^2 \]

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

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

Configuration B

Total load on C-Channel = (56.7 lb/in) (24.125 in)
= 1368 lb

Total channel contact area = 36.2 in² (shown above)

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

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**

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<th></th>
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</thead>
<tbody>
<tr>
<td>HEXEL upper skin</td>
<td>1</td>
<td>24.125</td>
<td>0.02</td>
<td>0.4825</td>
<td>0.01</td>
<td>0.00483</td>
<td>0.00005</td>
<td>1.6083E-05</td>
</tr>
<tr>
<td>HEXEL lower skin</td>
<td>1</td>
<td>24.125</td>
<td>0.02</td>
<td>0.4825</td>
<td>0.99</td>
<td>0.47768</td>
<td>0.47290</td>
<td>1.6083E-05</td>
</tr>
</tbody>
</table>

\[
\Sigma A = 0.9650 \quad \Sigma (A*y) = 0.4825 \quad \Sigma (A*y^2) = 0.4729 \quad \Sigma lo = 3.2167E-05
\]

\[
Y(I) = \Sigma(A*y)/\Sigma A = 0.5000 \text{ in}
\]

\[
I(n) = \Sigma lo + \Sigma(A*y^2) - \Sigma A*Y(I)^2 = 0.2317 \text{ in}^4
\]

\[
\text{Stress Max. } = \frac{M*Y(I)}{I(n)} \quad M = 5465 \text{ lb/in} \quad (\text{from previous calculations})
\]

\[
\text{Stress Max. } = 11.79 \text{ ksi}
\]

**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

<table>
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</thead>
<tbody>
<tr>
<td>HEXEL upper skin</td>
<td>1</td>
<td>14.5938</td>
<td>0.02</td>
<td>0.2919</td>
<td>1.874</td>
<td>0.5497</td>
<td>1.02503</td>
<td>9.7292E-06</td>
</tr>
<tr>
<td>HEXEL lower skin</td>
<td>1</td>
<td>14.5938</td>
<td>0.02</td>
<td>0.2919</td>
<td>0.876</td>
<td>0.25568</td>
<td>0.22398</td>
<td>9.7292E-06</td>
</tr>
<tr>
<td>Channel B sections</td>
<td>1</td>
<td>1.5</td>
<td>0.125</td>
<td>0.0938</td>
<td>0.375</td>
<td>0.3516</td>
<td>0.01318</td>
<td>0.00024</td>
</tr>
<tr>
<td>Channel C Sections</td>
<td>2</td>
<td>0.125</td>
<td>0.75</td>
<td>0.0938</td>
<td>0.375</td>
<td>0.3516</td>
<td>0.01318</td>
<td>0.00439</td>
</tr>
</tbody>
</table>

ΣA = 0.9588  
Σ(A*y) = 1.0253  
Σ(A*y²) = 1.3992  
Σ lo = 0.0091

\[ Y(I) = \frac{\Sigma(A*y)}{\Sigma A} = 1.0694 \text{ in} \]

\[ I(n) = \Sigma lo + \frac{\Sigma(A*y²)}{\Sigma A Y(I)^2} = 0.3117 \text{ in}^4 \]

Stress Max. = \[ \frac{M*Y(I)}{I(n)} \]  
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

<table>
<thead>
<tr>
<th></th>
<th>Configuration A</th>
<th>Configuration B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Moment</td>
<td>5465 lb/in</td>
<td>4990 lb/in</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>0.2317 in(^4)</td>
<td>0.3117 in(^4)</td>
</tr>
<tr>
<td>Distance to Neutral Axis</td>
<td>0.500 in</td>
<td>1.0694 in</td>
</tr>
<tr>
<td>Max. Calculated Stress</td>
<td>11.79 ksi</td>
<td>17.12 ksi</td>
</tr>
<tr>
<td>Max. Allowable Stress</td>
<td>28.0 ksi</td>
<td>28.0 ksi</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>2.37 S.F.</td>
<td>1.64 S.F.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Configuration A</th>
<th>Configuration B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Stress</td>
<td>20.7 psi</td>
<td>37.8 psi</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>16 S.F.</td>
<td>8.7 S.F.</td>
</tr>
</tbody>
</table>

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

![Diagram](image)
**ABSTRACT (Maximum 200 words)**

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/in². A semi-cylindrical Plexiglass top (chamber) is attached to the main plate; the pressure within the chamber will be about 10 lb/in² during operation. The stresses incurred by the main plate with this partial vacuum were calculated. All linear dimensions are in inches.