APPENDIX 2.10.1

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APPENDIX 2.10.1

NUHOMS®-MP197 CASK BODY STRUCTURAL ANALYSIS

2.10.1.1 Introduction

This appendix presents the structural analyses of the NUHOMS®-MP197 cask body including the cylindrical shell assembly and bottom assembly, the lid, the local stresses at the trunnion / cask body interface, and the shear key block/cask body interface. The specific methods, models and assumptions used to analyze the cask body for the various individual loading conditions specified in 10CFR71.71 [1] and 10CFR71.73 [2] are described. Stress results are reported at selected locations for each load case. Maximum stresses from this appendix are evaluated in Sections 2.6 and 2.7 of Chapter Two where the load combinations outlined in Regulatory Guide 7.8 [3] are performed and the results evaluated against the ASME Code [4] and Regulatory Guide 7.6 [5] design criteria described in Section 2.1.2.

The NUHOMS®-MP197 cask body structural analyses generally use static or quasistatic linear elastic methods. The stresses and deformations due to the applied loads are generally determined using the ANSYS [6] computer program.

The detailed calculations for the lid bolts are presented in Appendix 2.10.2. Stress evaluations for the lifting and tie-down devices are described in Section 2.5 of Chapter 2.

The analysis methods described in this appendix and used to evaluate the cask body for the loading conditions are:

- ANSYS Analysis - Axisymmetric and Asymmetric Loads

2.10.1.2 ANSYS Analysis

Geometry Description

The containment vessel is the primary containment boundary of the packaging. Key dimensions of the containment vessel are shown in Figure 2.10.1-1. The shell, or cask body cylinder assembly, is an open ended (at the top) cylindrical unit with an integral closed bottom end. This assembly consists of concentric inner shell (SA-240 Gr. XM 19) and an outer shell (SA-240 Gr. 316) welded to a massive closure flange (SA-240 Gr. XM 19) at the lid end and a flat stainless steel plate (SA-240 Gr. XM 19) at the bottom end. The annulus between the shells is filled with lead shielding. The lead is poured into the annulus in a molten state using a carefully controlled procedure. The lid is bolted to the cylindrical shell by 48-1 1/2 in. diameter high strength bolts and sealed with two O-rings. A detailed physical description of the containment vessel is provided in Chapter One. Appendix 1.3 of Chapter One contains reference drawings of the NUHOMS®-MP197 cask which are the source of dimensions and other information used to develop analysis models.

ANSYS Cask Finite Element Models

NUHOMS®-MP197 Cask, Lid & Ram Cover Closure FEM Construction:

Two separate FEMs were constructed. The first, is a 2-dimensional, axisymmetric representation of the cask, which is constructed with plane elements. The second model is a 180°, 3-dimensional "brick" element representation. Due to the cyclic symmetry of the NUHOMS®-MP197, all nodes in the FEM are rotated into a cylindrical coordinate system, with an origin at the cask axis of rotation (i.e. global Cartesian X = Y = Z = 0.0). To effectively model the cask wall & lid interaction, node-to-node contact elements are utilized. The lead/cask wall interaction is modeled with surface-to-surface contact elements. A total of 2050 elements and 2250 nodes comprise the NUHOMS®-MP197 2D FEM, while a total of 38075 elements and 9575 nodes comprise the NUHOMS®-MP197 3D FEM. The finite element models are shown in Figures 2.10.1-2 and 2.10.1-3.

NUHOMS®-MP197 Bolt & FEM Representation:

The NUHOMS-MP197 180° FEM includes 24 lid bolts & 12 ram cover plate bolts utilizing a series of link elements as shown in the following figures. The bolt modeling methodology is intended to transfer the compressive force generated between the lid and cask flange. A similar methodology is adapted for the 2D model, where the total lid & ram closure bolt loads are simulated with single link elements (with the full 360° preload). It's noted that the methodology does not account for any bending stiffness, or shear strength of the bolts. The Stress on the lid bolts are calculated in Appendix 2.10.2, based on NUREG-6007.

The 2D FEM includes the modeling the lid and ram cover closure bolts, which are simulated using a series of LINK1 elements. To effectively model the lead, cask walls and lid interactions, point-to-point CONTACT 12 elements are used in the radial and axial orientations.

Bolt Head: 8 - Link1 elements connect the bolt head to the lid and are used to simulate the axial stiffness of the actual bolt head. Bolt head stiffness is calculated based on the area, elastic modulus & length [K_b = No. Bolts×($AE/(L\times n)$)], where n = the total number of link elements representing the bolt head.

Bolt Shank: A single Link1 element connects to the bolt head elements, and is used to simulate the axial prestrain of the actual 1.450" Dia. Bolt shank. Bolt shank prestrain is calculated based on [ε = No. of Bolts×(σ/E)].

The 3D FEM includes the modeling of 24 lid bolts, which are simulated using a series of LINK8 elements as shown on Figure 2.10.1-4. To effectively model the cask wall & lid interaction, point-to-point CONTACT 52 elements are used in the radial and axial orientations as shown in Figure 2.10.1-4. The contact interaction between the lead and cask walls is modeled using surface-to-surface CONTACT 171/173 elements.

Bolt Head: Several Link8 elements (arranged in a "spider" configuration) are used to connect the bolt head to the lid counterbore, and are used to simulate the axial stiffness of the actual bolt head. Bolt head stiffness is calculated based on the area, elastic modulus, length & number of elements ($K_b = AE/L \times n$). Note, no thread element prestrain is considered, since the bolt shank accounts for the entire bolt prestrain.

Bolt Shank: A single Link8 element is used to connect the bolt head and thread elements, and is used to simulate the axial prestrain of the actual 1.450" diameter bolt shank. Bolt shank prestrain is calculated based on ($\varepsilon = \sigma/E$), where σ is the bolt prestress (87ksi and 25ksi for lid and ram cover plate respectively).

Bolt Threads: A series of Link8 elements (arranged in a "spider" configuration) are used to connect the shank to the cask wall. No thread element prestrain is considered, since the bolt shank accounts for the entire bolt prestrain. Stiffness of the threads is assumed to be 100 times that of the shank.

Weak Spring Element Methodology:

To help aid in convergence, "key option" in ANSYS is used, which models a "weak" spring element across each pair of nodes comprising a contact52 element. The option is used for the tension capabilities developed in order to "hold" the cask wall and lid together, and thus prevent rigid body motion. ANSYS ensures the elements do not transfer a substantial amount of tensile load between the cask wall and lid by assigning an axial stiffness equal to 1×10^{-6} times the assigned normal contact stiffness (KN).

Boundary Conditions:

For the various loading cases analyzed (42), 7 separate sets of boundary conditions are required, see Table below. The BC sets are used to prevent rigid body motion and are assigned based on the specific loading configuration. In each of the BC sets, displacement constraints are fixed such that no displacement is permitted in the prescribed direction. All 3D boundary condition sets have the symmetry plane fixed in the hoop direction.

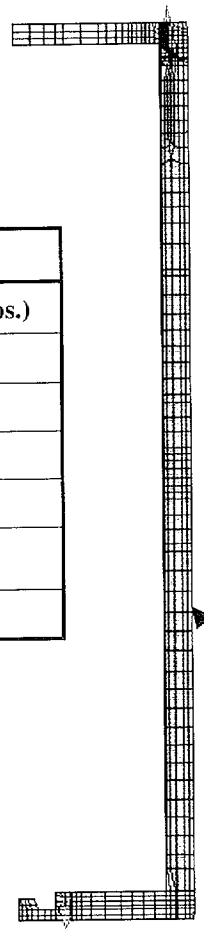
Listing of Various Boundary Conditions Applied

BC Description	Figure
2D-End Drop on Lid	Figure 2.10.1-5a
2D-End Drop on Bottom	Figure 2.10.1-5b
3D-Transport & 1G Gravity Loading	Figure 2.10.1-5c
3D-Side Drop	Figure 2.10.1-5d
3D-End Drop on Lid & Lid End Corner Drop	Figure 2.10.1-5e
3D-End Drop on Bottom & Bottom End Corner Drop	Figure 2.10.1-5f
3D-3G Lift	Figure 2.10.1-5g

2D-Finite Element Model Assumed Weights:

To accurately model the correct NUHOMS®-MP197 component weights, the material densities were scaled and adjusted based on assumed and actual FEM weights. This was accomplished by multiplying the ratio of actual component weight (tabulated below) over the model "component" weight.

NUHOMS®-MP197 Cask	
Component	**Weight (kips.)**
Cask	144.42
Lid	5.61
Internals	88.39
Front Impact Limiter	13.78
Rear Impact Limiter w/Thermal Shield	14.09
Total	266.29



The mass of the internals, and impact limiters are *not* included in the FEM. This mass is accounted for in the applied loading

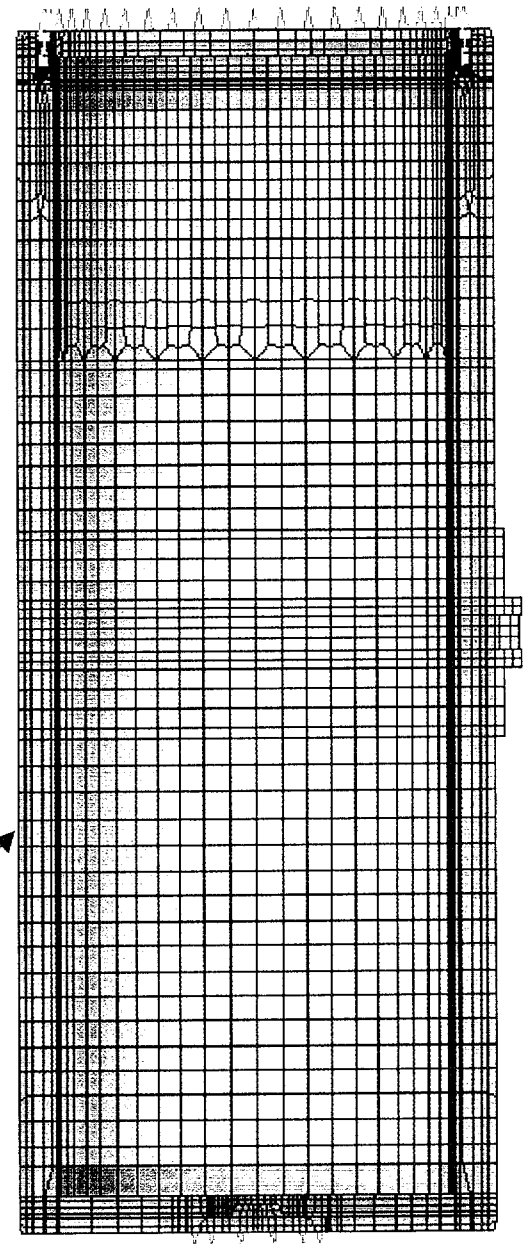
The mass of the neutron shield is accounted for at the outer wall elements and is "smeared" into the density as appropriate.

Note: 266.29 kips is conservatively used for structural analysis (including weight of trunnions), actual weight during transportation is 265.1 kips (trunnions will be removed and replaced with trunnion replacement plugs)

3D-Finite Element Model Assumed Weights

To accurately model the correct NUHOMS®-MP197 component weights, the material densities were scaled and adjusted based on assumed and actual FEM weights. This was accomplished by multiplying the ratio of actual component weight (tabulated below) over the model "component" weight.

NUHOMS®-MP197 Cask	
Component	**Weight (kips.)**
Cask Body	144.42
Lid	5.61
Internals	88.39
Front Impact Limiter	13.78
Rear Impact Limiter w/Thermal Shield	14.09
Total	266.29



The mass of the internals, and impact limiters are *not* included in the 3D FEM. This mass is accounted for in the applied loading

The mass of the neutron shield is accounted for at the outer wall elements and is "smeared" into the density as appropriate.

Note: 266.29 kips is conservatively used for Structural analysis (including weight of trunnions), actual weight during transportation is 265.1 kips (trunnions will be removed and replaced with trunnion replacement plugs)

Loading

The loading conditions analyzed simulate the normal conditions of transport and hypothetical accident conditions specified in 10CFR71. The 22 individual load cases for the NUHOMS®-MP197 containment vessel are described in this section.

NUHOMS®-MP197 22 Individual Load Cases		
Load Case	Loading Condition	FEM Model
1	Bolt preload (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	2D & 3D
2	Internal pressure loading (50 psig) (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
3	External pressure loading (25 psig) (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
4	External pressure loading (immersion) (290 psig) (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
5	Hot environment condition thermal stresses (100°F ambient) (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
6	Cold environment condition thermal stresses (-20°F ambient) (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
7	Cold environment condition thermal stresses (-40°F uniform) (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
8	Fire accident thermal stresses (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
9	3G lifting (3G up, cask at vertical orientation and held at two top trunnion locations)	3D
10	Rail car shock loads (4.7G all directions (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
11	Rail car vibration loads (0.37G vertical, 0.19G lateral, and 0.19G longitudinal. (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
12	1G loading (Cask in horizontal orientation and held at bearing block in the longitudinal direction, supported by two saddles and held by tie down straps)	3D
13	1-foot end drop on lid end (30G)	2D
14	1-foot end drop on bottom end (30G)	2D
15	1-foot side drop (30G)	3D
16	30-foot end drop on lid end (75G)	2D
17	30-foot end drop on bottom end (75G)	2D
18	30-foot side drop (75G)	3D
19	30-foot CG over corner drop on lid end (45G Axial, 16G Transverse)	3D
20	30-foot CG over corner drop on bottom end (45G Axial, 16G Transverse)	3D
21	30-foot oblique impact on lid end (35G Axial, 60G Normal, 198G Rotational)	3D
22	30-foot oblique impact on bottom end (35G Axial, 60G Normal, 196G Rotational)	3D

Method of Load Applies to the Cask Body

Pressures applied in the axial direction are calculated based on load divided by area pressure calculation. For example, to calculate the pressure applied due to internal loading on the inner bottom cask surface due to 1-foot End Drop on Lid End, divide the total load applied by the cross-sectional area. See Section 2.10.1.2.1 for example numerical calculation.

Pressures applied in the radial direction were based on cosine distributed pressure functions. These pressure distributions simulate the internal cask contents applying pressure to the inner cask wall, or the contact between the impact limiter and the outer surface of the cask. The pressure distribution is assumed to be in the longitudinal direction over a specified length and vary with a cosine distribution around the circumference of the cask. For the impact conditions, the angle of contact is dependent upon the amount of crush occurring in the impact limiter. Two separate cosine distributed pressure functions have been utilized. Cosine distributed cosine pressure loading and Cosine × Hyperbolic Cosine distributed cosine pressure loading, see Section 2.10.1.2.2 for detailed information.

1. Bolt Preload and Lid Seating Pressure

The axial prestress of 87 & 25 ksi at the lid bolt & ram cover plate bolt shanks are simulated by specifying an initial strain to the link elements representing the bolts. The required initial strain value was determined by first calculating the initial strain required to produce an axial stress of 87.0 ksi (i.e. $\varepsilon = \sigma/E = 87.0\times10^3/26.7\times10^6 = 0.003258$). Then, an initial "dummy" analysis with the hand calculated strain was conducted, and the resulting bolt prestress determined. Since, a portion of the assigned strain becomes strain in the clamped parts, the backed out prestress from the initial analysis does not produce the desired 87.0 ksi. The initial value was then updated by multiplying the link element real constant by the ratio of (desired prestress / initial analysis prestress). A second dummy analysis was conducted to verify the desired 87.0 ksi bolt prestress.

The bolt preload case is calculated by both 2D and 3D models and the results are listed in Table 2.10.1-4. Since the modeling methodologies of the 2D and 3D differ with respect to the lid modeling. A discussion of these differences and how they effect the load combinations are presented in Section 2.10.1.6.

2. Internal Pressure Loading

An internal pressure of 50 psig is applied to the cavity surface as shown in Figure 2.10.1-6. The pressure is applied up to the lid seal inner radius.

3-4. External Pressure Loading

An external pressure of 25 psig (case 3) & 290 psig (case4) is applied to the outer surface of the cask body as shown in Figure 2.10.1-7. The pressure is applied up to the lid seal outer radius.

5. Thermal Stress for Hot Environment Condition at 100°F Ambient Temperature

The normal condition of transport thermal analysis of the cask body is described in Chapter 3. The thermal model is used to obtain the steady state metal temperatures in the cask body for the normal condition which includes a 100° F daily averaged ambient air temperature, maximum decay heat, and maximum solar heat loading. These temperatures are then used as ANSYS input for the thermal stress analysis.

6. Thermal Stresses for Cold Environment Condition at -20°F Ambient Temperature

The minimum ambient temperature thermal analysis of the cask body is described in Chapter 3. The thermal model is used to obtain the steady state metal temperatures in the cask body for the minimum condition which includes a -20° F daily averaged ambient air temperature, minimum decay heat, and minimum solar heat loading. These temperatures are then used as ANSYS input for the thermal stress analysis.

7. Thermal Stresses for Cold Test at -40°F Ambient Temperature

A uniform temperature of -40°F is input on the structural model, which simulates a constant cask temperature of –40°F.

8. Thermal Accident Condition

An ANSYS transient thermal analysis of the cask for the 0.5-hour thermal accident is reported in Chapter 3. The initial condition is steady state at 100°F ambient conditions with maximum decay heating. The initial steady state condition is followed by a 0.5-hour severe thermal transient, which is then followed by a cool-down period. The maximum thermal gradient load step is used as input to the cask model for thermal stress analysis.

9. 3G Lifting

The cask is oriented vertically and held by the 2 top trunnions. Applying a 3G vertical acceleration to the finite element model simulates the inertial loading. Figure 2.10.1-8 illustrates the loading condition. Since the internals are not included in the model, their loading effects are simulated by a distributed pressure ($P_i = 71.2$ psi) acting on the inside bottom surface of the cask cavity.

10. Rail Car Shock Loading

For rail car shock loading, the cask is oriented horizontally and secured to the transport skid at the bearing block in the longitudinal direction, supported at two saddles and held by tie down straps. The peak inertia (acceleration) values used are based on NUREG 766510 [8]:

Rail Car Shock

Vertical	4.7 G
Longitudinal	4.7 G
Lateral	4.7 G

The forces acting in this case are listed below and illustrated in Figure 2.10.1-9.

A. Cask / Lid Inertial loads:

- A longitudinal 4.7G acceleration (applied in the axial direction)
- The resultant of the vertical & lateral accelerations (applied in the vertical direction) and calculated at $(4.7^2 + 4.7^2)^{1/2} = 6.65G$

B. Axial Pressure Due to Rear Impact Limiter:

A pressure due to the weight of the rear impact limiter (P_{ra} = 12.5 psi) is applied axially at the outer bottom surface:

C. Pressure Due to Internals:

An axial pressure from the internals is applied on the inside surface of the lid (P_{ia} = 114.4 psi). A radial pressure (P_{iv} = 61.9 psi) acting on the lower half of the inner cask surface due to the weight of internals is represented as a cosine varying pressure around the lower radial portion (0° to 75° range) of the cavity.

D. Radial Pressures Due to Impact Limiters:

In addition, radial pressure due to the front impact limiter weight (P_{fr} = 67.2 psi) is applied along the contacting surfaces of the limiter and the lid/cask wall. The pressure follows a cosine variation and is applied from (105° to 180°).

A radial pressure due to the rear impact limiter weight (P_{rr} = 74.2 psi) is also applied along the contacting surfaces of the limiter and the cask wall. Similar to the front impact limiter, the cosine varying pressure is applied from (105° to 180°).

E. Reaction Pressure

To simulate the reaction pressure at the skid bands, pressures applied by the rear and front transport skid saddle and tiedown strap reactions (P_{spr} = 592.9 psi and P_{spf} = 2829.8 psi) on the lower longitudinal half of the outer cask body during impact. These pressures are assumed to vary in a cosine distribution around the bottom half of the outer surfaces (0° to 75°) and are calculated just as the internal pressures are. However, the total force applied in the equation is based on the total reaction loads required to support equilibrium. That is, a dummy analysis was first executed by applying all necessary loading except the reaction pressures. The model was then constrained radially at the transport skid support saddle (at 0°) and solved. The "vertical" reactions calculated by ANSYS were then used as input to the cosine distributed pressure loading. All additional loading was reapplied and the model solved.

11. Rail Car Vibration Loading

For rail car vibration loading, the cask is oriented horizontally and secured to the transport skid at the bearing block in the longitudinal direction, supported at two saddles and held by tie down straps. The peak inertia (acceleration) values used are based on NUREG 766510 [8]:

Rail Car Vibration

Vertical	0.37 G
Longitudinal	0.19 G
Lateral	0.19 G

The forces acting in this case are listed below and illustrated in Figure 2.10.1-9.

A. Cask / Lid Inertial loads:

- A longitudinal 0.19G acceleration (applied in the axial direction)
- The resultant of the vertical & lateral accelerations (applied in the vertical direction) and calculated at $(0.19^2 + 0.37^2)^{1/2} = 0.416G$

B. Axial Pressure Due to Rear Impact Limiter:

A pressure due to the weight of the rear impact limiter (P_{ra} = 0.52 psi) is applied axially at the outer bottom surface:

C. Pressure Due to Internals:

An axial pressure from the internals is applied on the inside surface of the lid (P_{ia} = 4.62 psi). A radial pressure (P_{iv}= 3.88 psi) acting on the lower half of the inner cask surface due to the weight of internals is represented as a cosine varying pressure around the lower radial portion (0° to 75° range) of the cavity.

D. Radial Pressures Due to Impact Limiters:

In addition, radial pressure due to the front impact limiter weight (P_{fr} = 4.21 psi) is applied along the contacting surfaces of the limiter and the lid/cask wall. The pressure follows a cosine variation and is applied from (105° to 180°).

A radial pressure due to the rear impact limiter weight (P_{rr} = 4.65 psi) is also applied along the contacting surfaces of the limiter and the cask wall. Similar to the front impact limiter, the cosine varying pressure is applied from (105° to 180°).

E. Reaction Pressure:

To simulate the reaction pressure at the skid bands, pressures are applied by the rear and front transport skid saddle and tiedown strap reactions (P_{spr} = 62.7 psi and P_{spf} = 151.5 psi) on the lower longitudinal half of the outer cask body during impact. These pressures are assumed to vary in a cosine distribution around the bottom half of the outer surfaces (0° to 75°) and are calculated just as the internal pressures are. However, the total force applied in the equation is based on the total reaction loads required to support equilibrium. That is, a dummy analysis was first executed by applying all necessary loading except the reaction pressures. The model was then constrained radially at the transport skid support saddle (at 0°) and solved. The "vertical" reactions calculated by ANSYS were then used as input to the cosine distributed pressure loading. All additional loading was reapplied.

12. <u>1G Loading (Cask in Horizontal Position)</u>

For the 1G loading, the cask is oriented horizontally and secured radially to the transport skid support saddle. For the inertial loading, a vertical acceleration of 1G is applied in the global X direction. Figure 2.10.1-10 illustrates the loading condition. A brief explanation of the applied loading is presented below:

A. Pressure due to Internals:

Radial pressure (P_{iv} = 9.32 psi) acting on the lower half of the inner cask surface due to the weight of internals is represented as a cosine varying pressure applied around the lower radial portion (0° to 75° range) of the cavity.

B. Pressure due to Front Impact Limiter:

In addition, radial pressure due to the front impact limiter weight (P_{fr} = 10.1 psi) is applied along the contacting surfaces of the limiter and the lid/cask wall. The pressure follows a cosine distribution and is applied from the vertical (Y=180°) to (Y=105°).

C. Pressure due to Rear Impact Limiter:

A radial pressure due to the rear impact limiter weight (P_{rr} = 11.2 psi) is also applied along the contacting surfaces of the limiter and the cask wall. Similar to the front impact limiter, the pressure follows a cosine distribution and is applied from the vertical (Y=180°) to (Y=105°).

D. Reaction Pressure

To simulate the reaction pressure at the skid bands, pressures are applied by the rear and front saddle reactions (P_{rr} = 400.07 psi and P_{rf} = 373.3 psi) on the lower longitudinal half of the outer cask body during impact. These pressures are assumed to vary in a cosine distribution around the bottom half of the outer surfaces (0° to 75°) and are calculated just as the internal pressures are. However, the total force applied in the equation is based on the total reaction loads required to support equilibrium. That is, a dummy analysis was first executed by applying all necessary loading except the reaction pressures. The model was then constrained radially at the transport skid support saddle (at 0°) and solved. The "vertical" reactions calculated by ANSYS were then used as input to the cosine distributed pressure loading. All additional loading was reapplied.

13. <u>1-Foot End Drop on Lid (Front Impact Limiter)</u>

The dynamic analysis described in Appendix 2.10.8 determined the inertial load on the NUHOMS®-MP197 packaging for a 1-foot end drop onto an unyielding surface, and calculated a maximum axial deceleration of 10G. However, 30G is conservative used for stress analysis of the cask. Since the payload and the impact limiters are not included in the FEM, their loading effects are simulated as distributed pressures applied to the cask at the appropriate locations. The contacting impact limiter force on the cask is applied as the reaction pressure on the lid required to balance the inertial forces of the system. Thus, the cask body is in equilibrium under the applied forces. The system of forces on the cask body is presented in Figure 2.10.1-11. The following loads are applied to the FEM:

A. Cask / Lid Inertial loads:

30G vertical acceleration to the finite element model simulates the cask/lid inertial loading.

B. Pressure Due to Internals:

An axial pressure due to internals (P_i = 730.2 psi) is applied at the inner lid surface.

C. Pressure Due to Rear Impact Limiter:

An axial pressure due to the rear impact limiter (P_{ra} = 82.9 psi) is applied at the cask bottom including the chamfer.

D. Reaction Pressures

The axial reaction pressure due to cask body and rear impact limiter (P_{rlo} = 6,784 psi) is applied at the outer area of the lid (i.e. it is assumed the entire inertial load flows down the cask wall only, and is reacted out at the outer lid surface only). An axial reaction pressure due to internals and middle lid portion (P_{rlm} = 771.2 psi) is applied at the mid-area of the lid.

14. <u>1-Foot End Drop on Bottom (Rear Impact Limiter)</u>

An analysis similar to that of the 1-foot drop on the lid is performed for the 1-foot drop on the bottom. The same inertial forces (30G) are used for the bottom (rear) impact case as for the front impact case. A similar methodology used for the lid drop is applied for this case. A brief explanation of the applied loading is presented below.

A. Cask / Lid Inertial loads:

A 30G vertical acceleration to the finite element model simulates the inertial loading.

B. Pressure Due to Internals:

An axial pressure due to internals (P_i = 781.9 psi) is applied at the inner base surface.

C. Pressure Due to Front Impact Limiter:

An axial pressure due to the front impact limiter (P_{fa} = 83.5 psi) is applied at the outer lid surfaces based on the projected area.

D. Reaction Pressures:

The axial reaction pressure due to cask body and front impact limiter (P_{rbo} = 3,148 psi) is applied at the outer area of the base. The entire inertial load flows down the cask wall, and is reacted out at the projected chamfer area only. An axial reaction pressure due to internals and middle base portion (P_{rbm} = 761.7 psi) is applied at the mid area of the lid.

The system of forces on the cask body is presented in Figure 2.10.1-12.

15. 1-Foot Side Drop

The dynamic analysis described in Appendix 2.10.8 determined the inertial load on the NUHOMS®-MP197 packaging for a 1-foot side drop onto an unyielding surface and resulted in a maximum transverse deceleration of 24G. However, 30G is conservatively used for stress analysis of the cask. Since the payload & impact limiters are not included in the FEM, their loading effects are simulated as distributed pressures applied on the cask at the appropriate locations. The contacting impact limiter forces on the cask & lid are applied as reaction pressures required to balance the inertial forces of the system. Thus, the cask is in equilibrium under the applied forces. During the side drop, the pressure at the inner surface due to internals and the reaction pressure on the outer side from the impact limiters are assumed to vary as cosine functions over 180°. The system of forces acting on the cask is presented in Figure 2.10.1-13. The loads acting in this case are:

A. Cask Body Inertia

Applying 30G vertical acceleration to the finite element model in the transverse direction simulates inertial loading.

B. Pressure Due to Internals

Radial pressure (P_{iv} = 279.6 psi) acting on the lower half of the inner cask surface due to the weight of internals is represented as a cosine varying pressure applied from 0 to 75 degrees on the lower radial portion of the cavity wall.

C. Impact Reaction Pressures:

P_{rr} (2,888 psi) and P_{fr} (2,568 psi) are the pressures applied by the rear and front impact limiter reactions on the lower longitudinal half of the outer cask body during impact. These pressures are assumed to vary in a cosine distribution around the bottom half of the outer surfaces (0° to 180°) and are calculated just as the internal pressures are. However, the total force applied in the equation is based on the total reaction loads required to support equilibrium. That is, a dummy analysis was first executed by applying all necessary loading except the reaction pressures. The model was then constrained radially at the impact limiters (at 0°) and solved. The "vertical" reactions calculated by ANSYS were then used as input to the cosine distributed pressure loading. All additional loading was reapplied.

16. 30-Foot End Drop on Lid (Front Impact Limiter)

The dynamic analysis described in Appendix 2.10.8 determined the inertial load on the NUHOMS®-MP197 packaging for a 30-foot end drop onto an unyielding surface, and resulted in a maximum axial deceleration of 50G. However, 75G is conservatively used for stress analysis of the cask. The loading applied for this case is identical to that applied for the 1-foot lid drop case except that the pressures applied are scaled based on the increased acceleration.

17. 30-Foot End Drop on Bottom (Rear Impact Limiter)

The loading applied for this case is identical to that applied for the 1-foot bottom drop case except that the pressures applied are scaled based on the increased acceleration.

18. 30-Foot Side Drop

The dynamic analysis described in Appendix 2.10.8 determined the inertial load on the NUHOMS®-MP197 packaging for a 30-foot side drop onto an unyielding surface, and resulted in a maximum radial deceleration of 60G. However, 75G is conservatively used for stress analysis of the cask. The loading applied for this case is identical to that applied for the 1-foot side drop case except that the pressures applied are scaled based on the increased acceleration.

19. 30-foot CG Over the Corner Drop on Lid End

For CG over corner, the cask is inclined at approximately 60° from the horizontal. All the applied loads and reaction forces are transformed into axial and normal components. The axial pressure components due to the internals, bottom impact limiter and impact reaction are assumed uniformly distributed. All radial pressure components (i.e. pressure due to internals, rear impact limiter and impact reactions) are assumed to have cosine variation over a determined arc length. The system of forces acting on the cask is presented in Figure 2.10.1-14.

The forces acting in this case are:

A. Cask Body Inertia

The component accelerations (45G axial & 16G Radial) are applied as translational inertial loads in the axial and radial directions respectively. In addition, a rotational acceleration of 32G is applied at the vessel CG to counteract the out-of-balance caused by the component's acceleration resultant, which is not normal to the horizontal. That is, the component translational accelerations applied have been conservatively rounded, which results in a slight resultant moment (out-of-balance) when the solution is executed. This moment is counteracted by the applied angular acceleration (torque) and the model returned to static equilibrium.

B. Pressure Due to Internals:

Radial pressure (P_{ir} = 199.1 psi) acting on the inner cask wall due to the weight of internals is represented as a cosine varying pressure applied along the contact surface between the internals (197" total contact length assumed) and the inner cask wall (105° to 180°). In addition, an axial pressure (P_{ia} = 1095.2 psi) due to the weight of the internals is applied to the cask inner lid surface.

C. Pressure Due to Rear Impact Limiter:

The inertia load of the nonstriking impact limiter is also applied to the cask in two mutually perpendicular directions. The axial component (P_{ra} = 123.1 psi) is applied as a uniform pressure over the outside surface at the interface with the impact limiter on the bottom end. The radial component (P_{rr} = 178.5 psi) is applied as a cosine varying pressure along the contact surface (23.25" total contact length assumed) between the rear limiter and the outer cask wall from (0° to 75°).

D. Reaction Pressures Due to Front Impact Limiter

The reaction pressure of the striking impact limiter is also applied to the cask in two mutually perpendicular directions. The axial component (P_{fa} = 4,692 psi) is applied as a uniform pressure over ½ the lid surface area. The radial component pressure (P_{fr} = 4,264 psi) follows the cosine distribution around the radial crush footprint from 90° to 180° on the cask, and is applied along the contact surface (25" total contact length assumed) between the front limiter and the outer cask wall.

The loading applied is summarized in the table below.

Load Description	Loading Formulae	Symbol on Figure
Pressure applied in radial direction due to weight of internals	Cosine Dist. over 75deg	Pir
Pressure applied in axial direction due to weight of internals	P/A	Pia
Pressure applied in axial direction due to weight of rear impact limiters	P/A	Pra
Pressure applied in radial direction due to weight or rear impact limiters	Cosine Dist. over 75deg	Prr
Radial reaction pressures due to front impact limiter	Cosine Dist. over 90deg	Pfr
Axial reaction pressures due to front impact limiter	P/A	Pfa

20. <u>30-foot CG Over the Corner Drop on Bottom End</u>

For this corner drop, the cask is again inclined at approximately 60° from the horizontal. The applied loads are transformed into axial and normal components, and are applied using the same methodology adopted for the CG over corner lid drop. All radial pressure components (i.e. pressure due to internals, front impact limiter and impact reactions) are assumed to have cosine variation over a determined arc length. The system of forces acting on the cask is presented in Figure 2.10.1-15.

A brief explanation of the applied loading is presented below:

A. Cask Body Inertia

The component accelerations (i.e. 45G axial & 16G Radial) are applied as translational inertial loads in the axial and radial directions respectively. In addition, a rotational acceleration of 32G is applied at the vessel CG to counter act the out-of-balance and return the model to static equilibrium.

B. Pressure Due to Internals:

Radial pressure (P_{ir} = 199.1 psi) acting on the inner cask wall due to the weight of internals is represented as a cosine varying pressure applied along the contact surface between the internals (197" total contact length assumed) and the inner cask wall (0° to 75°). In addition, an axial pressure (P_{ia} = 1,180 psi) due to the weight of the internals is applied to the cask inner bottom surface.

C. Pressure Due to Front Impact Limiter:

The inertia load of the nonstriking impact limiter is also applied to the cask in two mutually perpendicular directions. The axial component (P_{fa} = 128.0 psi) is applied as a uniform pressure over the outside surface at the interface with the impact limiter on the front end. The radial component (P_{fr} = 162.1 psi) is applied as a cosine varying pressure along the contact surface (25" total contact length assumed) between the front limiter and the outer cask wall from (105° to 180°).

D. Reaction Pressures Due to Rear Impact Limiter

The reaction pressure of the striking impact limiter is also applied to the cask in two mutually perpendicular directions. The axial component (P_{ra} = 4,450 psi) is applied as a uniform pressure over ½ the bottom surface area. The radial component pressure (P_{rr} = 2,878 psi) follows the cosine distribution around the radial crush footprint from 0° to 90° on the cask, and is applied along the contact surface (23.25" total contact length assumed) between the rear limiter and the outer cask wall.

The loading applied is summarized in the table below.

30 Foot CG Over the Corner Drop on Bottom End		
Load Description	Loading Formulae/Appendix	Symbol on Figure
Pressure applied in radial direction due to weight of internals	Cosine Dist. over 75deg	Pir
Pressure applied in axial direction due to weight of internals	P/A	Pia
Axial pressures due to front impact limiter	P/A	Pfa
Radial pressures due to front impact limiter	Cosine Dist. over 75deg	Pfr
Radial reaction pressures due to rear impact limiter	Cosine Dist. over 90deg	Prr
Axial reaction pressures due to rear impact limiter	P/A	Pra

21. <u>30-Foot Oblique Impact on Lid End</u>

For oblique lid impact, the cask is inclined at 20° from the horizontal. All applied loads and reaction forces are transformed into axial and normal components respectively. The axial pressure components due to the internals, bottom impact limiter and impact reaction are assumed uniformly distributed. All radial pressure components (i.e. pressure due to internals & rear impact limiter) are assumed to have cosine variation over a 90° determined arc length. In addition, the radial pressures due to the internals are input as a linear distribution based on the axial location of the element with maximum values applied toward the crush end. The reaction pressures are applied using a cos×cosh distribution over the 90° arc length (based on the 180° model), see Appendix D. The system of forces acting on the cask is presented in Figure 2.10.1-16.

A brief explanation of the applied loading is presented below:

A. Cask Body Inertia

The component accelerations (i.e. 35G axial & 60G radial) are applied as translational inertial loads in the axial and radial directions respectively. In addition, a rotational acceleration of 198G is applied at the vessel CG to counter act the out-of-balance forces due to the induced torque (i.e. the perpendicularly offset CG from the impact location) and return the model to static equilibrium.

B. Pressure Due to Internals:

Radial pressure (Pir = 1,165 psi) acting on the impact side of the inner cask wall due to the weight of internals is represented as a cosine varying pressure around the upper radial portion (105° to 180° range) of the cavity. The pressure also varies linearly as a function of axial position with respect to the overall applied length (197" total length assumed). In addition, an axial pressure (P_{ia} = 851.9 psi) due to the weight of the internals is applied to the cask inner lid surface.

C. Pressure Due to Rear Impact Limiter:

The inertia load of the nonstriking impact limiter is also applied to the cask in two mutually perpendicular directions. The axial component (P_{ra} = 95.7 psi) is applied as a uniform pressure over the outside bottom cask surface at the interface with the rear impact limiter. The radial component (P_{rr} = 669.5 psi) is applied as a cosine varying pressure along the contact surface (25" total contact length assumed) between the rear limiter and the outer cask wall from (0° to 75°).

D. Reaction Pressures Due to Front Impact Limiter

The axial component (P_{fa} = 1,778 psi) is applied as a uniform pressure over the entire outer lid surface area. The radial component pressure follows a cos×cosh distribution around the radial crush footprint from 90° to 180° on the cask.

The loading applied is summarized in the table below.

Load Description	Loading Formulae	Symbol on Figure
Pressure applied in radial direction due to weight of internals	Cosine Dist. over 75deg	Pir
Pressure applied in axial direction due to weight of internals	P/A	Pia
Pressure applied in axial direction due to weight of rear impact limiters	P/A	Pra
Pressure applied in radial direction due to weight or rear impact limiters	Cosine Dist. over 75deg	Prr
Radial reaction pressures due to front impact limiter	Cos*cosh dist. Over 90deg	Pfr
Axial reaction pressures due to front impact limiter	P/A	Pfa

22. 30-foot Oblique Impact on Bottom End

For oblique bottom impact, the cask is inclined at 20° from the horizontal. The loading applied is similar to the oblique lid drop with applied loads and reaction forces transformed into axial and normal components respectively. The axial pressure components due to the internals, front impact limiter and impact reaction are assumed uniformly distributed. All radial pressure components (i.e. pressure due to internals & front impact limiter) are assumed to have cosine variation over a 90° determined arc length. In addition, the radial pressures due to the internals are input as a linear distribution based on the axial location of the element, with maximum values applied toward the crush end. The reaction pressures are applied using a cos×cosh distribution over the 90° arc length (based on the 180° model) (see Section 2.10.1.2.2). The system of forces acting on the cask is presented in Figure 2.10.1-17.

A brief explanation of the applied loading is presented below:

A. Cask Body Inertia

The component accelerations (i.e. 35G axial and 60G radial) are applied as translational inertial loads in the axial and radial directions respectively. In addition, a rotational acceleration of 196G is applied at the vessel CG to counter act the out-of-balance forces due to the induced torque (i.e. the perpendicularly offset CG from the impact location) and return the model to static equilibrium.

B. Pressure Due to Internals:

Radial pressure (P_{ir} = 1,153 psi) acting on the impact side of the inner cask wall due to the weight of internals is represented as a cosine varying pressure around the upper radial portion (105° to 180° range) of the cavity. The pressure also varies linearly as a function of axial position with respect to the overall applied length (197" total length assumed). The axial component of pressure (P_{ia} = 917.6 psi) due to the weight of the internals is applied to the cask inner lid surface.

C. Pressure Due to Front Impact Limiter:

The inertia load of the nonstriking impact limiter is also applied to the cask in two mutually perpendicular directions. The axial component (P_{fa} = 97.0 psi) is applied as a uniform pressure over the outside lid/cask surface at the interface with the impact limiter. The radial component (P_{fr} = 605.9 psi) is applied as a cosine varying pressure along the contact surface (25" total contact length assumed) between the front limiter and the outer cask wall from (0° to 75°).

D. Reaction Pressures Due to Rear Impact Limiter

The axial component (P_{ra} = 1,689 psi) is applied as a uniform pressure over the entire outer bottom surface area. The radial component pressure follows a cos×cosh distribution around the radial crush footprint from 90° to 180° on the cask, and is applied along the contact surface (25" total contact length assumed) between the rear limiter and the outer cask wall.

The loading applied is summarized in the table below.

30 Foot Oblique Impact on Bottom End		
Load Description	**Loading Formulae**	**Symbol on Figure**
Pressure applied in radial direction due to weight of internals	Cosine Dist. over 75deg	Pir
Pressure applied in axial direction due to weight of internals	P/A	Pia
Axial pressures due to front impact limiter	P/A	Pfa
Radial pressures due to front impact limiter	Cosine Dist. over 75deg	Pfr
Radial reaction pressures due to rear impact limiter	Cos*cosh dist. Over 90deg	Prr
Axial reaction pressures due to rear impact limiter	P/A	Pra

2.10.1.2.1 Evenly distributed pressure over contact area of cask for impact load in axial direction

Pressures applied in the axial direction are calculated based on load divided by area pressure calculation. For example, to calculate the pressure applied due to internal loading on the inner bottom cask surface due to 1-foot End Drop on Lid End, divide the total load applied by the cross-sectional area.

$$P_i = P_{total} / A$$

$$P_i = W_i \times G_{axial} / (\pi \times r^2)$$

$$P_i = 88{,}390 \times 30 / (\pi \times 34^2)$$

$$P_i = 730.2 \text{ psi}$$

2.10.1.2.2 Cosine Distributed Pressure Functions:

A. <u>Cosine Distributed Pressure Loading:</u>

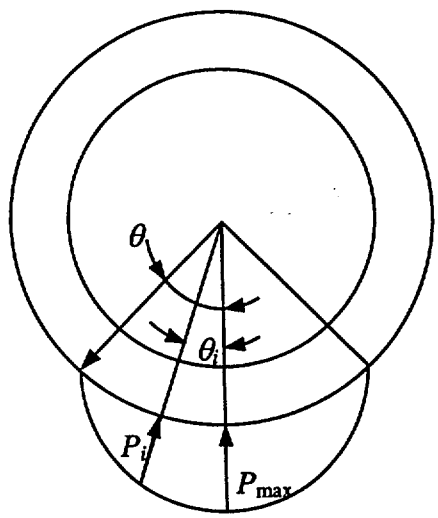
The circumferential cosine pressure distribution over a half angle, θ, is calculated as follows:

$$P_i = P_{max} \cos(\pi\theta_i / 2\theta)$$

Where:

P_i = Pressure load at angle θ_i.
P_{max} = Peak pressure load, at point of impact.
θ_i = Angle corresponding to point of interest.

The circumferential pressure distribution is illustrated in following Sketch.



The peak pressure load, P_{max}, is determined by setting the integral of the vertical pressure components, Q_i, equal to the total transverse impact load, F_t, as follows:

$$F_t = \int_{-\theta}^{\theta} Q_i LRd\theta_i = \int_{-\theta}^{\theta} P_i \cos(\theta_i) LRd\theta_i = \int_{-\theta}^{\theta} P_{max} \cos\left(\frac{\pi\theta_i}{2\theta}\right)\cos(\theta_i) LRd\theta_i$$

$$= \frac{P_{max} LR}{2} \int_{-\theta}^{\theta} \left[\cos\left(\frac{\pi\theta_i}{2\theta} + \theta_i\right) + \cos\left(\frac{\pi\theta_i}{2\theta} - \theta_i\right)\right] d\theta_i$$

$$= P_{max} LR \left[\frac{\sin\left(\frac{\pi}{2} + \theta\right)}{\left(\frac{\pi}{2\theta}\right) + 1} + \frac{\sin\left(\frac{\pi}{2} - \theta\right)}{\left(\frac{\pi}{2\theta}\right) - 1}\right]$$

Rearranging terms gives the peak pressure, P_{max}, as follows:

$$P_{max} = \frac{F_t}{LR}\left[\frac{\sin\left(\frac{\pi}{2} + \theta\right)}{\left(\frac{\pi}{2\theta}\right) + 1} + \frac{\sin\left(\frac{\pi}{2} - \theta\right)}{\left(\frac{\pi}{2\theta}\right) - 1}\right]^{-1}$$

Therefore, the pressure at any circumferential location is given by:

$$Pi = \frac{F_t}{LR}\left[\frac{\sin\left(\frac{\pi}{2} + \theta\right)}{\left(\frac{\pi}{2\theta}\right) + 1} + \frac{\sin\left(\frac{\pi}{2} - \theta\right)}{\left(\frac{\pi}{2\theta}\right) - 1}\right]^{-1} \cos\left(\frac{\pi\theta_i}{2\theta}\right)$$

$$F_t = G \times W$$

Where, W is the weight of internals or impact limiter, G is the acceleration in the transverse direction. Therefore,

$$Pi = G\frac{W}{LR}\left[\frac{\sin\left(\frac{\pi}{2} + \theta\right)}{\left(\frac{\pi}{2\theta}\right) + 1} + \frac{\sin\left(\frac{\pi}{2} - \theta\right)}{\left(\frac{\pi}{2\theta}\right) - 1}\right]^{-1} \cos\left(\frac{\pi\theta_i}{2\theta}\right)$$

For example, to calculate the maximum internal pressure applied for the 1ft Side Drop condition;

$$Pi = G\frac{F}{LR}\frac{1}{\dfrac{\sin\left(\frac{\pi}{2}+\theta\right)}{\frac{\pi}{2\theta}+1}+\dfrac{\sin\left(\frac{\pi}{2}-\theta\right)}{\frac{\pi}{2\theta}-1}}\times\cos\left(\frac{\pi\theta i}{2\theta}\right)$$

Where:
G = Acceleration
θ = Angle of application
$\theta(i)$= Circumferential angle pressure is applied
F = Weight of internals
L = Length pressure is applied

$$\text{Pi} = 30\frac{88{,}390}{197.0\times34.0}\frac{1}{\dfrac{\sin(90+75)}{\left(\frac{180}{2\times75}\right)+1}+\dfrac{\sin(90-75)}{\left(\frac{180}{2\times75}\right)-1}}\times\cos\left(\frac{180\times0}{2\times75}\right)$$

Pi = 280.2psi

B. Cosine × Hyperbolic Cosine Distributed Pressure Loading:

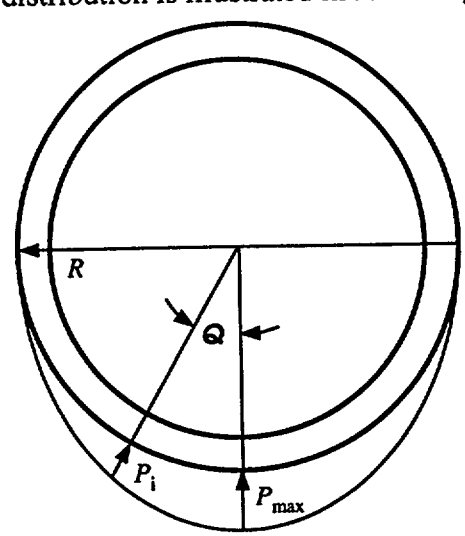
The circumferential cos×cosh pressure distribution over an angle of 90° is calculated as follows:

$$P_i = P_{max}\cos(x)\times\cosh(x)$$

Where:

P_i = Pressure load at angle θ_i.
P_{max} = Peak pressure load, at point of impact.
x = Angle corresponding to point of interest.

The circumferential pressure distribution is illustrated in following Illustration.



The peak pressure load, P_{max}, is determined by setting the integral of the vertical pressure components, Q_i, equal to the total transverse impact load, F_t, as follows:

$$F_t = \int_{-\theta}^{\theta} Q_i LRd\theta_i = \int_{-\theta}^{\theta} P_i \cos(\theta_i) LRd\theta_i = \int_{-\theta}^{\theta} P_{max} \cos(\theta)\cosh(\theta) \times \cos(\theta) LRd\theta$$

Evaluating the integral from $\pi/2$ to $-\pi/2$, then rearranging terms gives the peak pressure, P_{max}, as follows:

$$= P_{max} LR \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos^2(\theta)\cosh(\theta) d\theta$$

$$= P_{max} LR \left[\frac{1}{2}\sinh(\theta) + \frac{1}{10}\left(\sinh(\theta)\cos(2\theta) + 2\cosh(\theta)\sin(2\theta)\right) \right]_{\frac{-\pi}{2}}^{\frac{\pi}{2}}$$

$$P_{max} = \frac{F_t}{LR}(0.543)$$

Therefore, the pressure at any circumferential location is given by:

$$Pi = \frac{F_t \times 0.543}{LR}\cos(\theta)$$

$$Where\ F_t = G \times W$$

Where, W is the weight of internals or impact limiter, G is the acceleration in the transverse direction.

2.10.1.3 ANSYS Analysis Results and Reporting Methodology

Due to the nonlinearities associated with contact elements, it is not possible to run the 22 separate load cases and then combine the results by superposition. Rather, it's necessary to run each of the individual load case or combined load case independently and post process the results separately. A total of 43 separate loading conditions (individual and combined load cases) are executed based on combinations of the previous discusses 22 individual load cases and are grouped into three categories:

A. Individual load conditions: These analyses (runs 1-12) are based on 12 of the 22 individual load cases (see Table 2.10.1-1). Some of the stress results from these runs are used for the fatigue analysis.

B. Load combinations for normal condition of transport: These analyses (runs 13-26) are based on combinations of the 22 individual load cases. See Table 2.10.1-2.

C. Load combinations for accident condition of transport: These analyses (runs 27-42) are also based on combinations of the 22 individual load cases, but simulate accident conditions of transport. See Table 2.10.1-3.

Detailed stresses and displacements in the ANSYS model of the NUHOMS®-MP197 are obtained for each of the 42 load cases listed in the Tables 2.10.1-1, -2, and –3. Boundary conditions used for these runs are shown in Figures 2.10.1-5a to 5g. To simplify results interpretation, the analysis results are post processed with tabulated stresses ($S_{stress\ intensity}$) created at 35 assigned locations on the transport cask structure shown in Figure 2.10.1-19. These locations give an overall global state of stress within the structure during various loading conditions. It should be noted that, for the axisymmetric load analyses, the stress is constant around the cask at every location. For asymmetric load analyses with significant differences in stress magnitudes on the extreme opposite sides of the cask, the stresses at locations on different sides of the cask (impact side and side away from impact) are reported.

The locations selected as shown in Figure 2.10.1-19 are key points that, when carefully studied, indicate the global stress state of the entire structure. However, the maximum stress may occur at a different location for each load case.

Stress intensities at nodal locations on the inner and outer surfaces of the cask body components for the load cases analyzed in Table 2.10.1-1are reported in Tables 2.10.1-4 through 2.10.1-15. For load cases such as 3G lifting, railcar shock, and railcar vibration, the stresses at the trunnion and transport skid bearing block locations are not considered accurate due to the limitations of the finite element mesh. As a result, the local stresses at the trunnion/transport skid bearing block locations are calculated from the "Bijlaard" analysis as described in the Section 2.5 of this SAR. There are no specific limits for individual stress components. Some of the stress results from these runs are used for the fatigue analysis as described in Sections 2.6.

Stress intensities at nodal locations on the inner and outer surfaces of the cask body component for the normal condition load combinations are list in tables 2.10.1-13 to 2.10.1-26. These stress intensities are determined for each location, classified, and compared with the design criteria of Section 2.1.2 in Section 2.6.

Stress intensities at nodal locations on the inner and outer surfaces of the cask body component for the accident condition load combinations are listed in tables 2.10.1-27 to 2.10.1-42. These stress intensities are determined for each location, classified and compared with the design criteria of Section 2.1.2 in Section 2.7.

2.10.1.4 Tie-Down Load

For the tie-down loading, the cask is oriented horizontally and secured to the transport skid at the bearing block in the longitudinal direction, supported at two saddles and held by tie down straps. The peak inertia (acceleration) values used are:

Rail Car Vibration

Vertical	2 G
Longitudinal	10 G
Lateral	5 G

The forces acting in this case are listed below and illustrated in Figure 2.10.1-18.

A. Cask / Lid Inertial loads:

- A longitudinal 10G acceleration (applied in the axial direction)
- The resultant of the vertical & lateral accelerations (applied in the lateral direction) and calculated at $(2^2 + 5^2)^{1/2} = 5.3G$

B. Axial Pressure Due to Rear Impact Limiter:

A pressure due to the weight of the rear impact limiter ($P_{ra} = 0.51$ psi) is applied axially at the outer bottom surface:

C. Pressure Due to Internals:

An axial pressure from the internals is applied on the inside surface of the lid ($P_{ia} = 243.4$ psi). A radial pressure ($P_{iv} = 63.2$ psi) acting on the lower half of the inner cask surface due to the weight of internals is represented as a cosine varying pressure around the lower radial portion (0° to 75° range) of the cavity.

D. Radial Pressures Due to Impact Limiters:

In addition, radial pressure due to the front impact limiter weight (P_{fr} = 67.5 psi) is applied along the contacting surfaces of the limiter and the lid/cask wall. The pressure follows a cosine variation and is applied from (105° to 180°).

A radial pressure due to the rear impact limiter weight (P_{rr} = 69.0 psi) is also applied along the contacting surfaces of the limiter and the cask wall. Similar to the front impact limiter, the cosine varying pressure is applied from (105° to 180°).

E. Reaction Pressure

To simulate the reaction pressure at the skid bands, pressures applied by the rear and front transport skid saddle and tiedown strap reactions (P_{spr} = 1047.7 psi and P_{spf} = 3820.7 psi) on the lower longitudinal half of the outer cask body during impact. These pressures are assumed to vary in a cosine distribution around the bottom half of the outer surfaces (0° to 75°) and are calculated just as the internal pressures are. However, the total force applied in the equation is based on the total reaction loads required to support equilibrium. That is, a dummy analysis was first executed by applying all necessary loading except the reaction pressures. The model was then constrained radially at the transport skid support saddle (at 0°) and solved. The "vertical" reactions calculated by ANSYS were then used as input to the cosine distributed pressure loading. All additional loading was reapplied.

Results

The tie-down analysis stress results are presented in Table 2.10.1-46. All the calculated stresses are less than the yield stresses of the component materials.

2.10.1.5 Fabrication Stress Calculation

Introduction

The objective of this calculation is to evaluate fabrication stresses in NUHOMS®-MP197 cask due to lead pouring and the subsequent cool down to room temperature. The differential contraction induced stresses are also evaluated for both normal and hypothetical accident condition load cases.

The NUHOMS®-MP197 cask containment boundary is defined as the cask body inner shell (both cylinder and head), the closure flange and lid. The subject of this analysis is the cylindrical portion of the inner shell. The length of this cylinder is 193.5 in., the inside diameter is 68.00 in. and the thickness is 1.25 in. The cylinder is welded to and supported by the closure flange at the lid end and by the bottom plate at its closed end. The cylindrical region around the inner containment cylinder, within the outer shell, is filled with lead.

The inner containment cylinder is subjected to various loads during fabrication and operation. The stresses in the cylinder have been conservatively evaluated and are shown to be acceptable.

Loading

The inner containment cylinder is subjected to various loads during cask fabrication and operation. The first significant loading during the fabrication process is an external pressurization of the cylinder produced by the hydrostatic head of molten lead created during the pouring process. The column of the molten lead is less than 193.5 in. long. This head causes a maximum hydrostatic pressure of 193.5 in. $\times$ 0.410 lb/in^3 or 79.34 psi on the cylinder. The hoop stress in the cylinder is $p \times R_o/t$ or 79.34 $\times$ 35.25 / 1.25 which equals –2,237 psi. It is shown in Section 2.10.5.5.3 of Appendix 2.10.5 that this stress is well below any cylinder buckling limit.

The next significant loading on the cylinder occurs during cooldown to room temperature after freezing of the molten lead. The assembly of concentric steel-lead-steel cylinders is stress free and void free at the lead freezing temperature (620° F).

This state occurs since the frozen lead had little strength at this temperature and molten lead is added continuously to fill voids that occur as the lead freezes. When the composite steel-lead-steel assembly begins to cool, the lead shrinks radially against the inner steel cylinder (but away from the outer cylinder). This occurs since the thermal contraction of the lead is higher than that of the steel cylinders.

The loads generated by the differential contraction are minimized by cooling the lead very slowly. This allows time for the lead to creep so that residual fabrication stresses relax. The cool down rate is limited by an approved procedure so that the total time for cool down is approximately one week.

During Normal of Transport and Hypothetical Accident Conditions, the inner cylinder is subjected to additional loads caused by thermal expansion. The thermal stresses generated by temperature gradients in the cask are small relative to the thermal stresses generated by the difference in the thermal expansion of the lead and the stainless steel shells.

The analysis below computes the thermal stresses generated by both lead cool down and differential expansion during normal and accident temperature changes.

Fabrication Stresses

As shown before, the inner containment cylinder is subjected to a relatively mild hoop compressive stress during the lead pouring operation due to the hydrostatic head of 79.34 psi. The hoop stress in the cylinder at that time is –2,237 psi.

During cool down from the lead freezing temperature of 620° F to room temperature, the lead shrinks more than the inner containment cylinder. The differential expansion is equal to:

$$\Delta R_{Lead\text{-}Steel} = R\,\Delta\alpha\,\Delta T$$

$$\Delta R = (35.25 \text{ in.})\,(17.88 - 9.84)10^{-6}\ {}^{\circ}\text{F}^{-1}\ (620\text{-}70)\ {}^{\circ}\text{F}$$

$$\Delta R = 0.1559 \text{ in.}$$

Therefore the lead cylinder, if it were free, would shrink 0.1559 in. radially more than the inner containment cylinder. If all of this differential contraction is accommodated in lead, the lead strain equals:

$$\varepsilon_{lead} = \Delta R/R = 0.1559/35.25 = 0.00442 \text{ in/in.}$$

This is 0.44% strain in the lead. If the lead remained a linear elastic material, the residual stress in lead would be equal to:

$$\sigma_{lead} = E_{lead} \times \varepsilon_{lead}$$
$$= (2.49 \times 10^{6})\ (0.00442) = 11{,}000 \text{ psi}$$

If the lead cylinder remained elastic at this stress level, significant loads with corresponding high stresses and strains would be applied to the inner containment cylinder. However, the lead is actually quite soft, and the stress level in the lead remains low because of its inelastic behavior. Figure 2.10.1-20 shows typical short-time and low-strain-rate lead stress vs. strain curves for various temperatures obtained by Tietz [9]. Note that the lead stress corresponding to 0.44% strain is of the order of 450 psi for essentially pure lead, even for very rapid straining (curve A strain rate produces 0.44% strain in less than 6 seconds -- $.0044 \times 60/.05 = 5.28$ second).

Additional insight to the possible magnitude of lead stresses for slow loading rates can be obtained from the stress relaxation and creep data (also by Tietz) in Figures 2.10.1-21 and 22. From Figure 2.10.1-21, it can be seen that 0.5% strain rapidly applied (at strain rate of 0.05 in/in per minute) at 100° F produces a stress of about 500 psi which relaxes to 300 psi in 100 hrs., 290 psi in 168 hrs. (one week), and continues to relax. Also note from Figure 2.10.1-22 that indicates a constant stress of 280 psi in the lead for a strain of 0.5% in about 200 hrs. at 100° F.

This data indicates that lead stress will not exceed about 300 psi if the cool down is accomplished slowly (about 1 week). The interface pressure between the lead cylinder and inner containment cylinder required to exert an average hoop stress of 300 psi in lead can be readily determined:

$$P_{interface} = \sigma_{lead} \times t_{lead} / R_{interface}$$

$$= 300 \text{ psi} \times 3.25 \text{ in.} / 35.25 \text{ in.} = 27.7 \text{ psi}$$

The hoop stress in the inner containment cylinder is then:

$$\sigma_{\theta} \text{ inner cylinder} = p_{interface} \times \mathrm{R}_{\mathrm{interface}} / t_{cylinder}$$
$$= -27.7 \text{ psi} \times 35.25 \text{ in.}/1.25 \text{ in} = -781 \text{ psi}$$

This stress is small and will become negligible with increasing time. It may also be noted that the hydrostatic head stress will become zero when lead is frozen.

Normal Condition of Transport

As described above, the annulus between the inner containment cylinder and outer shell is filled with lead that has frozen in the annulus, completely filling it at a temperature of about 620° F. The lead contracts more than the volume of the annulus decreases during cool down after the lead pour. Finally, lead creep occurs with time under stress so that the lead cylinder exerts only negligible residual loading on the inner containment cylinder in the "as fabricated" condition.

When the cask body assembly temperature increases to 302° F, as expected during the hot environment normal condition of transport from Chapter 3, the lead cylinder expands away from the inner containment cylinder, but its volume increase will not fill the annulus between the shells. Therefore, differential expansion induced loads on the inner cylinder only occur for the cases where temperature is below room temperature. Consequently, residual fabrication stresses will decrease further during the hot (100° F ambient) normal condition of transport.

If the cask body assembly is subjected to the –40° F cold environment, the lead cylinder will shrink radially more than the inner containment cylinder. The differential expansion is equal to:

$$\Delta R_{Lead\text{-}Steel} = R\,\Delta\alpha\,\Delta T$$

$$\Delta R = (35.25 \text{ in.})\,(15.55 - 8.5)\times10^{-6}\ {}^\circ\text{F}^{-1}\,(70 + 40)\ {}^\circ\text{F}$$

$$\Delta R = 0.02734 \text{ in.}$$

Therefore the lead cylinder, if it were free, would shrink 0.02734 in. radially more than the inner containment cylinder. If all of this differential contraction is accommodated in lead, the lead strain equals:

$$\varepsilon_{lead} = \Delta R / R = 0.02734/35.25 = 0.00078 \text{ in/in.}$$

This is 0.078% strain in the lead. If the lead remains a linear elastic material, the residual stress in lead would be roughly (2.49×10^6) (0.00078) or 1,942 psi. Figure 2.10.1-20 shows that the lead stress will not exceed 300 psi at strain level of 0.078%, and the stress in the inner containment cylinder will be less than –800 psi, even if the strain is rapidly applied. This stress is small and will become negligible with increasing time.

Hypothetical Accident Condition of Transport

As described above, the annulus between the inner containment cylinder and outer shell is filled with lead that has frozen in the annulus, completely filling it at a temperature of about 620° F. The lead contracts more than the volume of the annulus during cool down after the lead pour. Finally, lead creep occurs with time under stress so that the lead cylinder exerts only negligible residual loading on the inner containment cylinder in the "as fabricated" condition.

When the cask body assembly temperature increases to 535° F, as expected during the thermal accident condition, the lead cylinder expands away from the inner containment cylinder, but its volume increase will not fill the annulus between the shells. The fabrication residual stresses will, therefore, decrease during the hypothetical thermal accident condition.

Conclusion

From the results of analyses, it is concluded that the cask fabrication stresses due to the molten lead pouring process and the subsequent freezing to room temperature are small. The differential contraction induced stresses, during –40° F normal condition, are negligible. Furthermore, the fabrication stresses remaining in the cask components at the time the cask will be used for transportation will be insignificant.

2.10.1.6 Bolt Preload Discussion

Discussion:

The modeling methodologies of the 2D and 3D differ with respect to the lid. The 2D axisymmetric model assumes a solid lid (i.e. with no counterbores modeled), where as the 3D FEM explicitly models the counterbores (as shown in Figure 1). As a result, the local stiffness off the lid, and thus it's response to that loading changes.

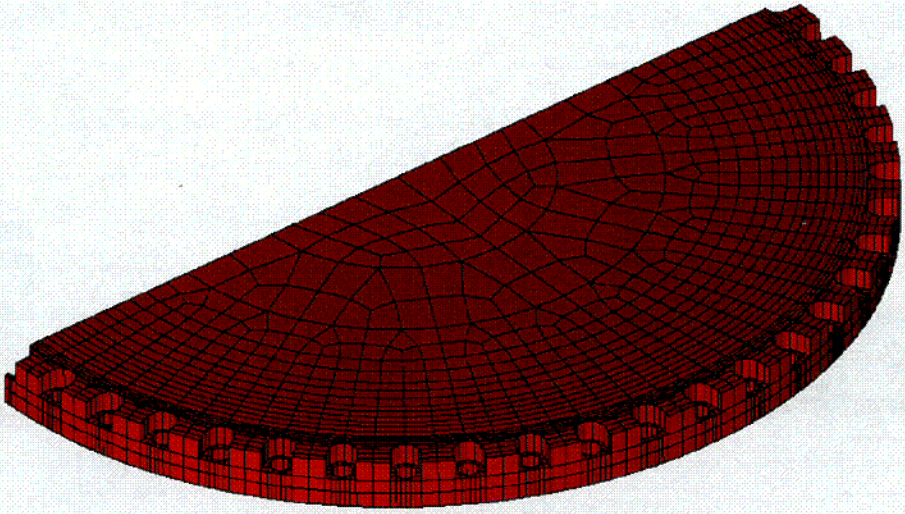


Figure 1: 3D FEM Lid Illustration

Typically, a bolted lid experiences bending stress along the outer surfaces, where the bending stress is greatest. This is clearly visible when viewing a bending stress plot from the FEM results.

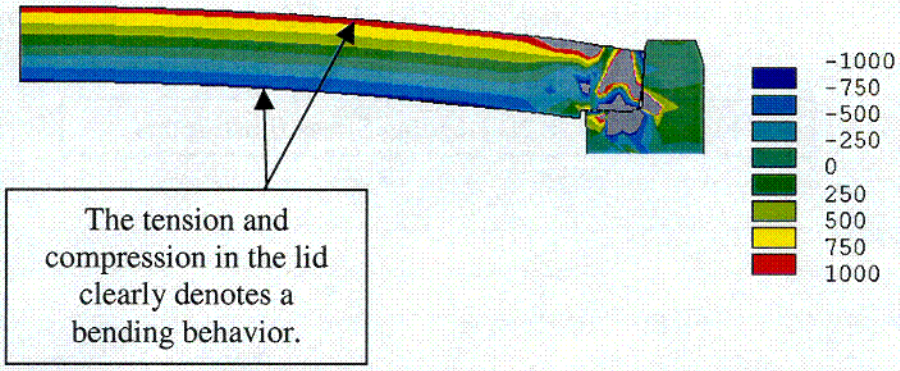


Figure 2: 2D FEM Bending Illustration

C01

Because the 2D FEM assumes an axisymmetric structure, the local stiffness of the lid (at the bolt region) is higher then in the 3D FEM. As such, the sliding behavior of the contact surfaces between the lid and upper cask wall is different in the 2D & 3D models. The less stiff 3D model tends to slide more due to the additional compression of the outer lid surface (at the bolts). This additional sliding creates a larger moment due to the larger perpendicular distance that the bolt load induces in the lid/cask wall. The larger moment produces larger bending stresses.

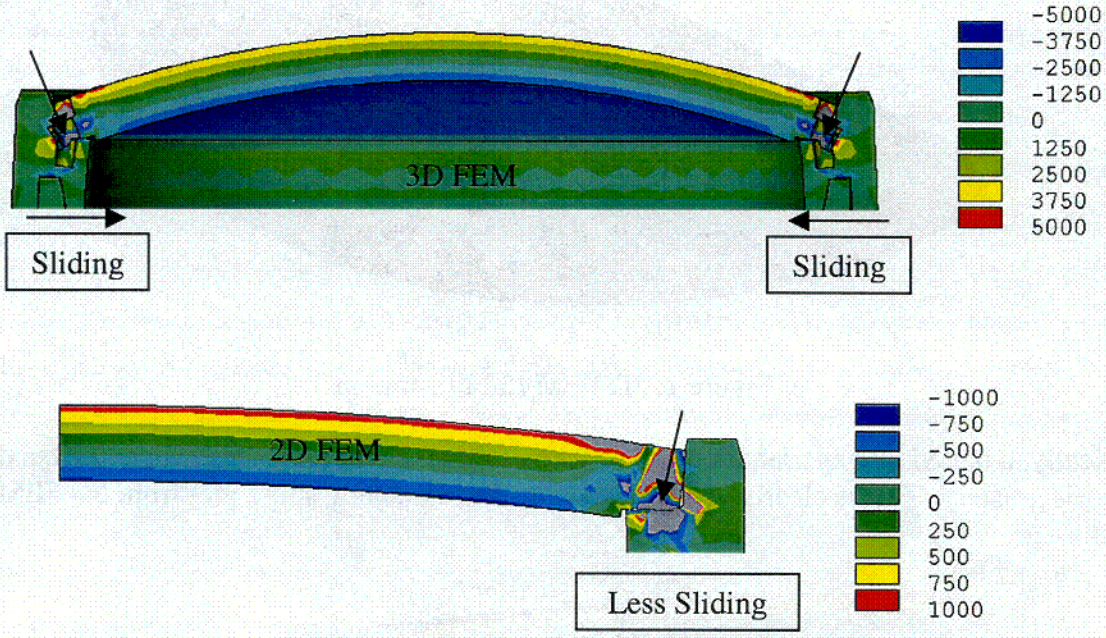


Figure 3: 3D & 2D Bending Stress Illustrations

C02

As a result, the stress intensity fields in the 2D & 3D models will differ for the bolt preload conditions (Tables 2.10.1-4). In the local lid region, the 3D stress intensity reported is approximately 4ksi, whereas the 2D model reports ~1ksi.

Furthermore, tabulated stress results for various loading cases with little or no inertial loading (i.e. railcar shock, railcar vibration, 1g gravity loading, 3g lifting, etc.) using 3D model may report stress results that when compared seem inexplicable. For example, the rail car vibration (0.416g, resultant of vertical & lateral acceleration) load stresses in lid and lid-flange region (Locations 1 to 15 of Table 2.10.1-11) and in the bottom ram closure region (locations 34 and 35 of Table 2.10.1-11) are almost same as for the bolt-preload stresses. The reason being that the preload stresses are hardly overcome by the vibratory load stresses, thus resulting in any significant increase in the stresses. In the case of rail car shock (6.65g, resultant of vertical & lateral acceleration) load, the preload stresses are exceeded. Therefore, the extra vibratory and shock stresses result only after overcoming the preload stresses, and the shock/vibration stress ratio (≈ 3) is different than the shock/vibration load ratio (≈ 16) in the regions effected by the bolt preloads.

In order to check the validity of the finite element model response, some simple closed-form calculations are conducted. While these simple results are unlikely to duplicate the complex geometry of and loading conditions of the model, they can be used to verify the stresses in simple areas away from discontinuities.

Section 2.10.1.7 verifies the stress results from the 2D finite element model due to the 1-foot end drop on lid end load case.

2.10.1.7 Verification of Computer Stress Results due to 1-Foot End Drop on Lid End

The two-dimensional model Bolt Preload Stresses and Bolt Preload plus 1-Foot End Drop on Lid Stresses at locations 1 and 2 (center of lid), and 16, 17, 18 and 19 (cask wall) are compared with hand-calculated stresses. These locations are defined in Figure 2.10.1-19, and are selected because they are located away from geometric discontinuities.

The end drop on lid loading is shown in Figure 2.10.1-11.

P_i = 730.2 psi (axial pressure due to internals)
P_{rlm} = 768.4 psi (axial reaction pressure due to internals and lid)
P_{rlo} = 4,592.9 psi (axial reaction pressure due to cask body and rear impact limiter)

Stresses at the Lid Center

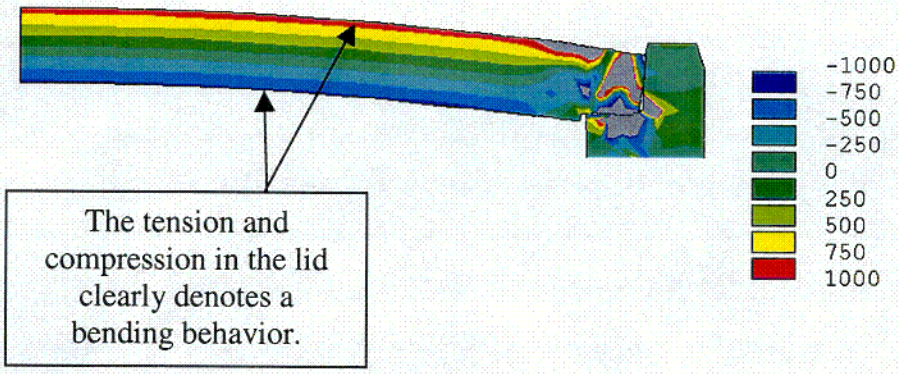
The stresses computed by the 2-dimensional model at locations 1 and 2 are:

a) Bolt Preload Stresses:

At Location 1, S_x = - 840 psi S_y = -13 psi S_z = -837 psi S.I. = 829 psi

At Location 2, S_x = 875 psi S_y = 18 psi S_z = 872 psi S.I. = 861 psi

The deformed lid shape due to bolt prelod is shown below. Typically, a bolted lid experiences bending stress (S_x) along the outer surfaces, where the bending stress is greatest. This is clearly visible when viewing a bending stress plot from the FEM results.

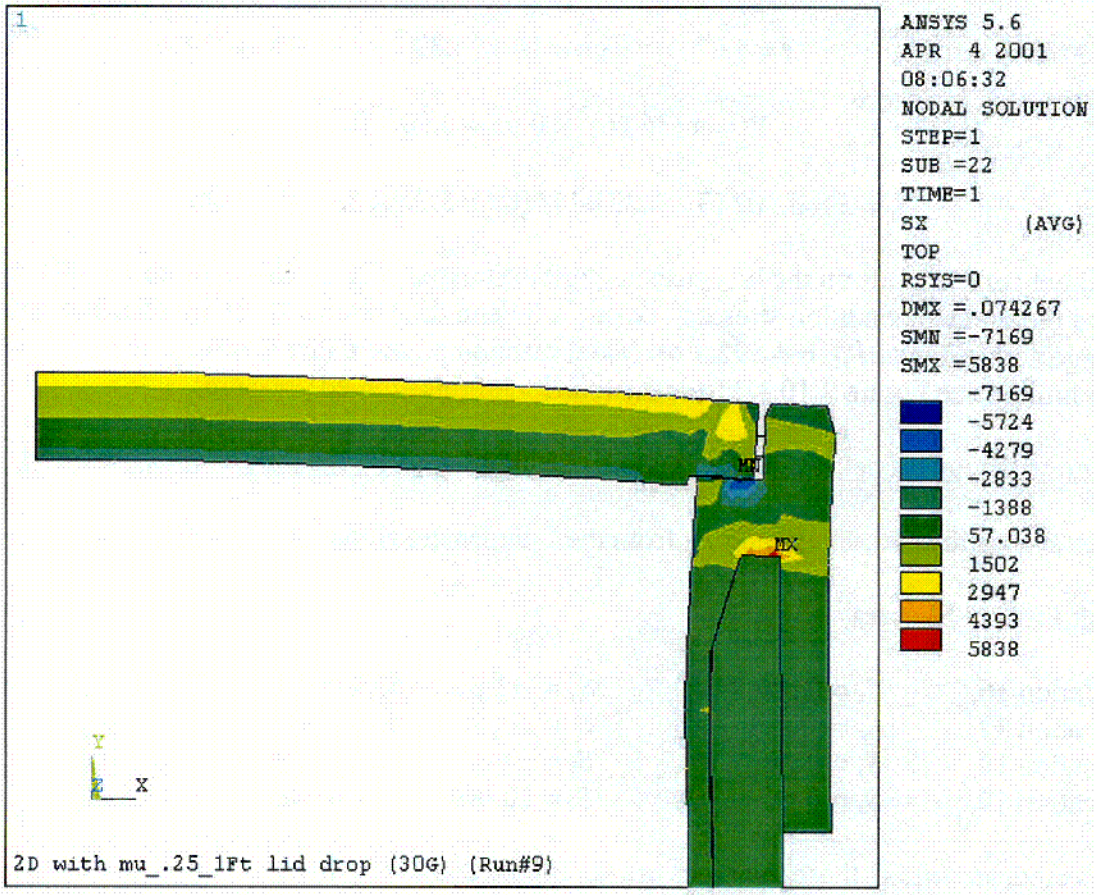


b) Bolt Preload plus Lid End Drop Stresses (30g) :

At Location 1, S_x = - 1956 psi S_y = -767 psi S_z = -1949 psi $S.I.$ = 1200 psi

At Location 2, S_x = 2095 psi S_y = -721 psi S_z = 2086 psi $S.I.$ = 2823 psi

The deformed lid shape and stress distribution due to preload plus lid end drop loads is shown below. This shape is similar to the preload case. The uniform bending stress at lid top and bottom surfaces shows that this stress distribution results also from the bending moment at the bolted-lid location.



Hand – Calculations for Lid stresses due End Drop Pressure:

It is observed that the lid is deformed in similar shape due to bolt preload and preload plus end drop loadings. The stress intensities at the lid center are also similar for the two loadings. Ordinarily, it is expected that the stresses at the lid center will be much higher during the lid end drop. However, the calculations given below show that the lid stresses at center are hardly effected by the direct loads during the end drop.

Pressure P_i , due to internals = 730.2 psi (Outward)
Pressure P_{rlm}, reaction due to internals & lid = 768.4 psi (Inward)

Pressure P, due to lid inertia for 30g = $(A \times t \times \text{density} \times 30) / A$
$= (4.5 \times 0.29 \times 30) = 39.15$ psi (Outward)

C04

Net pressure on the central lid region = 730.2 + 39.15 – 768.4 = 0.95 psi (Outward)

Stresses due to this net outward pressure are calculated by treating the lid as a circular flat plate with edges supported and uniform load over the surface (from Roark, Ref. 10, Table 10, Case 1):

At Center, Max. $S_r = 3W(3m+1)/(8\pi m t^2)$

$a = 72.31/2 = 36.16"$ $t = 4.5"$ $m = 1/\nu = 3.33$ $w = 0.95$ psi

$$W = \pi (36.16)^2 \times 0.95 = 3{,}902 \text{ lb.}$$

$$S_r = 3 \times 3{,}902\,(3 \times 3.33 + 1) / (8\pi \times 3.33 \times 4.5^2) = 76 \text{ psi}$$

Thus direct central loads on the lid cause negligible stresses. The small increase in lid stresses (beyond the preload condition stresses), during a lid end drop results from the edge moment from lid-flange action due to P_{rlo} = 4,592.9 psi (axial reaction pressure due to cask body and rear impact limiter, see Figure 2.10.1-11 for the location of this applied pressure).

<u>The 2-dimensional model stresses at locations 16,17,18 and 19 (see Figure 2.10.1-19) are:</u>

Stresses at locations 16, 17, 18 and 19 from the 2-dimensional model result files are:

a) Bolt Preload Stresses:

At Location 16,	S_x = 0 psi	S_y = -11 psi	S_z = -8 psi	$S.I.$ = 11 psi
At Location 17,	S_x = -1 psi	S_y = -9 psi	S_z = -7 psi	$S.I.$ = 8 psi
At Location 18,	S_x = 0 psi	S_y = 5 psi	S_z = -1 psi	$S.I.$ = 6 psi
At Location 19,	S_x = 0 psi	S_y = 10 psi	S_z = 0 psi	$S.I.$ = 10 psi

As expected, stresses at these locations are negligible due to lid-flange end moment on the cask.

b) Bolt Preload + lid end drop Stresses:

At Location 16,	S_x = -9 psi	S_y = -2879 psi	S_z = -1219 psi	$S.I.$ = 2870 psi
At Location 17,	S_x = -42 psi	S_y = -3095 psi	S_z = -1238 psi	$S.I.$ = 3054 psi
At Location 18,	S_x = -90 psi	S_y = -3391 psi	S_z = 1615 psi	$S.I.$ = 5006 psi
At Location 19,	S_x = 6 psi	S_y = -3281 psi	S_z = 1545 psi	$S.I.$ = 4826psi

As expected, the axial stress component (S_y) is the dominant stress component and is used for verification by hand calculation.

Average Stress in the Section = - 1/4 (2,879 + 3,095 + 3,391 + 3,281) = -3,162 psi.

c) Hand – Calculated Stresses due Lid End Drop :

Axial Compressive Stress is calculated in the section containing locations 16, 17, 18 and 19 due to a 30g load. The effective weight of this section (y = 165.5" from the outer surface of the cask bottom) is calculated as follow:

Rear impact limiter and thermal shield	= 14,090 lb.
Bottom End	= 9,954 lb.
Body, Inner Layer 15260 × (165.5 – 6.5)/193.5	= 12,539 lb.
Body, Outer Layer 35,037 × (165.5 – 6.5)/193.5	= 28,790 lb.
Outer Shell 2,472 × (165.5 – 24)/158.5	= 2,207 lb.
Resin 9,975 × (140.5)/157.5	= 8,900 lb.
Aluminum Boxes 2,021 × (140.5)/157.5	= 1,805 lb.
Total Weight	= 78,285 lb.

Gamma Shield Lead Weight = 59,739 × 159/193.5 = 49,088 lb.
Weight transferred to cask body by friction = 0.25 × 49,088 = 12,272 lb.

Total downward weight on section = 78,285 + 12,272 = 90,557 lb.

Section Area of inner and outer cylinders = $\pi/4\ (70.5^2 - 68.0^2) + \pi/4\ (82.0^2 - 77.0^2)$
= 271.94 + 624.39 = 896.33 in^2

Compressive Axial Stress, S_y = - 90,557 × 30g / 896.33 = - 3,030 psi (≈ -3,162 psi calculated from computer).

This stress is quite close (about 4% off) to the computer calculated stress.

Conclusion

There is a good correlation between the computer and hand-calculated stresses at the selected locations for 1-foot lid end drop.

2.10.1.8 References

1. 10CFR 71.71, Normal Conditions of Transport.

2. 10CFR 71.73, Hypothetical Accident Conditions.

3. Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping casks for Radioactive Material".

4. ASME Code Section III, Subsection NC and Appendices, 1998, including 1999 Addendum.

5. Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels".

6. ANSYS Users Manual, Rev. 5.6, 1998.

7. WRC Bulletin 107, March 1979, "Local Stresses in Spherical and Cylindrical Shells Due to External Loadings".

8. NUREG 766510, "Shock and Vibration Environments for Large Shipping Containers on Rail Cars and Trucks".

9. T.E. Tietz,"Mechanical Properties of High Purity Lead and a 0.058 Percent Copper-Lead Alloy", Presented at the Sixty Second Annual Meeting of the ASTM Society, June 1959, ASTM 59, 1052.

10. Roark, Raymond J., "Formulas for Stress and Strain", Fourth Edition, McGraw-Hill Book Company.

Table 2.10.1-1
Individual Load Conditions

Run No.	Applicable Individual Loads	Load Used in Run	Stress Result Tables
1	Bolt preload	-	2.10.1-4
2	Internal pressure	50 psig	2.10.1-5
3	External pressure	25 psig	2.10.1-6
4	Thermal stresses at hot environment	-	2.10.1-7
5	Thermal stresses at –20° F cold environment	-	2.10.1-8
6	3G lifting	3G	2.10.1-9
7	Rail Car Shock loads	4.7G – all directions	2.10.1-10
8	Rail car vibration loads	0.37G – vertical 0.19G –lateral 0.19G – longitudinal	2.10.1-11
9	1 foot end drop on lid end	30 G	2.10.1-12
10	1 foot end drop on bottom end	30 G	2.10.1-13
11	1 foot side drop	30 G	2.10.1-14
12	1G gravity loading	1 G	2.10.1-15

Table 2.10.1-2
Summary of Load Combinations for Normal Condition of Transport

Run No.	Load Combination	Applicable Individual Loads Applied in the ANSYS Model									
		Bolt Pre-load	Gravity 1g	Int. Pres.	Ext. Pres.	Thermal Hot	Thermal Cold	Thermal -40°F Uniform	Rail Car Vib.	Rail Car shock	Stress Result Table
13	Hot Environment (100° F amb.)	x	x	x		x					2.10.1-16
14	Cold Environment (-40° F amb.)	x	x		x			x			2.10.1-17
15	Increased External Pressure	x	x		x		x				2.10.1-18
16	Min. External Pressure	x	x	x		x					2.10.1-19
17	Rail Car Vibration	x		x		x			x		2.10.1-20
18		x			x		x		x		2.10.1-21
19	Rail Car Shock	x		x		x				x	2.10.1-22
20		x			x		x			x	2.10.1-23

Run No.	Load Combination	Applicable Individual Loads Applied in the ANSYS Model								
		Bolt Pre-load	Internal Pres. (50 psi)	External Pres. (25 psi)	Thermal Hot	Thermal Cold	Lid End Drop	Bottom End Drop	Side drop	Stress Result Table
21	1 Ft End Drop on Lid End	x	x		x		x			2.10.1-24
22		x		x		x	x			2.10.1-25
23	1 Ft End Drop on Bottom End	x	x		x			x		2.10.1-26
24		x		x		x		x		2.10.1-27
25	1 Ft Side Drop	x	x		x				x	2.10.1-28
26		x		x		x			X	2.10.1-29

Table 2.10.1-3
Summary of Load Combinations for Accident Condition of Transport

Run No.	Load Combination	Applicable Individual Loads Applied in the ANSYS Model								
		Bolt Pre-Load	Int. Pres. (50 psi)	Ext. Pres. (25 psi)	Thermal Hot	Thermal Cold	Lid End Drop	Bot. End Drop	Side Drop	Stress Result Table
27	30 Ft. End Drop on Bottom End	x	x		x			x		2.10.1-30
28		x		X		x		x		2.10.1-31
29	30 Ft. End Drop on Lid End	x	x		x		x			2.10.1-32
30		x		X		x	x			2.10.1-33
31	30 Ft. Side Drop	x	x		x				x	2.10.1-34
32		x		X		x			x	2.10.1-35

Run No.	Load Combination	Applicable Individual Loads Applied in the ANSYS Model								
		Bolt Pre-Load	Int. Pres. (50 psi)	Ext. Pres. (25 psi)	Thermal Hot	Thermal Cold	Corner Drop Lid End	Corner Drop Bot End	Oblique Drop Lid End	Stress Result Table
33	30 Ft. CG Over Corner Drop on Bottom End	x	x		x			x		2.10.1-36
34		x		x		x		x		2.10.1-37
35	30 Ft. CG Over Corner Drop on Lid End	x	x		x		x			2.10.1-38
36		x		x		x	x			2.10.1-39
37	30 Ft. 20° Oblique Impact on Lid End	x	x		x				x	2.10.1-40
38		x		x		x			x	2.10.1-41

Table 2.10.1-3
Summary of Load Combinations for Accident Condition of Transport (continued)

Run No.	Load Combination	Applicable Individual Loads Applied in the ANSYS Model							
		Bolt Pre-load	Int. Pres. (50 psi)	Ext. Pres. (25 psi)	Thermal Hot	Thermal Cold	Oblique Drop Lid End	Oblique Drop Bottom End	Stress Result Table
39	30 Ft. 20° Oblique Impact on Bottom End	x	x		x			x	2.10.1-42
40		x		x		x		x	2.10.1-43

Run No.	Load Combination	Applicable Individual Loads Applied in the ANSYS Model								
		Bolt Pre-load	Int. Pres. (50 psi)	Ext. Pres. (25 psi)	Thermal Hot	Thermal Cold	Immersion Ext. Pres. (290 psi)	Fire	Oblique Drop Bottom End	Stress Result Table
41	Immersion (290 psi)	x				x	x			2.10.1-44
42	Fire Accident	x	x					x		2.10.1-45

Table 2.10.1-4
Bolt Preload

Component	location	Max Stress Intensity $P_m + P_b$ (ksi) (2D Model)	Max Stress Intensity $P_m + P_b$ (ksi) (3D Model)
Lid	1	0.83	3.68
	2	0.86	3.58
	3	0.78	3.29
	4	1.91	4.89
Upper Cask Wall	5	4.31	7.01
	6	0.46	1.25
	7	0.82	3.11
	8	0.62	3.07
	9	0.45	0.83
	10	0.36	1.26
	11	0.98	1.77
	12	0.39	1.91
	13	0.32	1.34
	14	0.30	1.14
	15	0.25	1.07
Upper Trunnion	16	0.01	0.20
	17	0.01	0.20
	18	0.01	0.14
	19	0.01	0.08
Mid Cask Wall	20	0.01	0.15
	21	0.01	0.15
	22	0.01	0.05
	23	0.01	0.05
Lower Trunnion	24	0.01	0.14
	25	0.01	0.14
	26	0.01	0.07
	27	0.01	0.07
Lower Cask wall	28	0.01	0.07
	29	0.02	0.20
	30	0.02	0.15
	31	0.01	0.04
Base	32	0.01	0.04
	33	0.02	0.07
	34	0.24	0.41
	35	0.22	0.40

Table 2.10.1-5
Internal Pressure (50 psi.) only

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	3.20	46.70
	2	3.40	46.70
	3	1.82	46.70
	4	1.97	46.70
Upper Cask Wall	5	4.94	31.40
	6	0.46	31.40
	7	0.84	31.40
	8	0.65	31.40
	9	0.54	31.40
	10	0.51	31.40
	11	0.90	31.40
	12	0.56	31.40
	13	0.43	31.40
	14	0.37	31.40
	15	0.32	31.40
Upper Trunnion	16	0.58	31.40
	17	0.54	31.40
	18	0.41	20.00
	19	0.37	20.00
Mid Cask Wall	20	0.57	31.40
	21	0.53	31.40
	22	0.43	20.00
	23	0.38	20.00
Lower Trunnion	24	0.63	31.40
	25	0.59	31.40
	26	0.42	20.00
	27	0.37	20.00
Lower Cask wall	28	1.25	31.40
	29	0.45	31.40
	30	0.71	31.40
	31	0.49	31.40
Base	32	0.94	31.40
	33	0.85	31.40
	34	1.25	31.40
	35	1.37	31.40

Table 2.10.1-6
External Pressure (25 psi.) only

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	0.35	46.70
	2	0.41	46.70
	3	0.44	46.70
	4	2.37	46.70
Upper Cask Wall	5	4.03	31.40
	6	0.55	31.40
	7	1.30	31.40
	8	1.01	31.40
	9	0.62	31.40
	10	0.56	31.40
	11	1.06	31.40
	12	0.54	31.40
	13	0.31	31.40
	14	0.41	31.40
	15	0.27	31.40
Upper Trunnion	16	0.30	31.40
	17	0.28	31.40
	18	0.22	20.00
	19	0.19	20.00
Mid Cask Wall	20	0.28	31.40
	21	0.26	31.40
	22	0.22	20.00
	23	0.20	20.00
Lower Trunnion	24	0.30	31.40
	25	0.28	31.40
	26	0.22	20.00
	27	0.19	20.00
Lower Cask wall	28	0.50	31.40
	29	0.19	31.40
	30	0.31	31.40
	31	0.21	31.40
Base	32	0.46	31.40
	33	0.30	31.40
	34	0.28	31.40
	35	0.57	31.40

Table 2.10.1-7
Thermal Stresses at hot Environment (100° F)

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	2.38	46.70
	2	2.75	46.70
	3	2.31	46.70
	4	3.67	46.70
Upper Cask Wall	5	5.04	31.40
	6	3.22	31.40
	7	6.39	31.40
	8	6.95	31.40
	9	15.63	31.40
	10	5.50	31.40
	11	4.28	31.40
	12	8.54	31.40
	13	7.83	31.40
	14	3.55	31.40
	15	3.40	31.40
Upper Trunnion	16	8.81	31.40
	17	8.03	31.40
	18	6.27	20.00
	19	7.86	20.00
Mid Cask Wall	20	17.19	31.40
	21	14.84	31.40
	22	9.19	20.00
	23	13.26	20.00
Lower Trunnion	24	11.43	31.40
	25	10.01	31.40
	26	7.09	20.00
	27	9.62	20.00
Lower Cask wall	28	6.64	31.40
	29	7.52	31.40
	30	6.74	31.40
	31	3.17	31.40
Base	32	2.99	31.40
	33	2.76	31.40
	34	2.60	31.40
	35	2.97	31.40

Table 2.10.1-8
Thermal Stresses at Cold Environment (-20° F)

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	2.13	46.70
	2	2.53	46.70
	3	2.08	46.70
	4	3.43	46.70
Upper Cask Wall	5	4.54	31.40
	6	3.21	31.40
	7	0.59	31.40
	8	3.51	31.40
	9	9.35	31.40
	10	1.96	31.40
	11	3.45	31.40
	12	2.92	31.40
	13	7.18	31.40
	14	5.79	31.40
	15	0.99	31.40
Upper Trunnion	16	5.72	31.40
	17	5.12	31.40
	18	4.19	20.00
	19	6.33	20.00
Mid Cask Wall	20	14.04	31.40
	21	11.89	31.40
	22	7.09	20.00
	23	11.78	20.00
Lower Trunnion	24	8.10	31.40
	25	6.84	31.40
	26	5.08	20.00
	27	8.23	20.00
Lower Cask wall	28	4.11	31.40
	29	6.72	31.40
	30	6.14	31.40
	31	2.16	31.40
Base	32	1.82	31.40
	33	2.31	31.40
	34	2.12	31.40
	35	2.31	31.40

Table 2.10.1-9
3*g* Lifting

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	0.12	46.70
	2	0.04	46.70
	3	0.55	46.70
	4	1.87	46.70
Upper Cask Wall	5	4.06	31.40
	6	0.74	31.40
	7	1.57	31.40
	8	1.84	31.40
	9	1.68	31.40
	10	0.79	31.40
	11	0.83	31.40
	12	0.92	31.40
	13	1.42	31.40
	14	1.20	31.40
	15	0.59	31.40
Upper Trunnion	16	0.57	31.40
	17	0.58	31.40
	18	0.13	20.00
	19	0.14	20.00
Mid Cask Wall	20	0.54	31.40
	21	0.54	31.40
	22	0.66	20.00
	23	0.66	20.00
Lower Trunnion	24	0.45	31.40
	25	0.45	31.40
	26	0.54	20.00
	27	0.53	20.00
Lower Cask wall	28	2.61	31.40
	29	1.65	31.40
	30	2.07	31.40
	31	1.00	31.40
Base	32	1.31	31.40
	33	1.31	31.40
	34	2.01	31.40
	35	2.09	31.40

Table 2.10.1-10
Rail Car Shock Loads

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	12.71	12.67	12.54	46.70
	2	12.26	12.16	12.19	46.70
	3	7.12	6.97	7.03	46.70
	4	7.46	9.23	7.66	46.70
Upper Cask Wall	5	7.94	5.75	6.83	31.40
	6	1.74	0.84	1.17	31.40
	7	3.63	3.61	2.00	31.40
	8	3.56	1.95	3.24	31.40
	9	2.27	4.96	0.72	31.40
	10	0.93	0.92	0.91	31.40
	11	2.27	2.07	1.67	31.40
	12	2.63	2.82	0.94	31.40
	13	2.45	1.98	2.25	31.40
	14	2.78	3.57	0.92	31.40
	15	0.78	2.04	0.54	31.40
Upper Trunnion	16	6.23	3.64	0.56	31.40
	17	2.02	3.58	1.78	31.40
	18	7.20	5.76	2.29	20.00
	19	1.11	5.76	1.95	20.00
Mid Cask Wall	20	5.67	5.00	2.52	31.40
	21	2.67	3.75	2.44	31.40
	22	3.54	6.28	3.66	20.00
	23	2.81	5.31	3.12	20.00
Lower Trunnion	24	2.72	1.73	1.00	31.40
	25	1.09	1.69	1.32	31.40
	26	6.62	2.68	2.04	20.00
	27	3.61	2.79	1.67	20.00
Lower Cask wall	28	3.54	1.50	2.37	31.40
	29	3.90	1.25	2.19	31.40
	30	4.95	1.94	2.19	31.40
	31	2.09	1.29	1.00	31.40
Base	32	2.15	1.21	1.71	31.40
	33	1.17	0.81	1.42	31.40
	34	0.73	0.53	0.87	31.40
	35	0.66	0.67	0.52	31.40

Table 2.10.1-11
Rail Car Vibration Loads

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	4.05	4.03	4.00	46.70
	2	3.91	3.89	3.88	46.70
	3	3.43	3.42	3.43	46.70
	4	4.89	4.89	4.89	46.70
Upper Cask Wall	5	7.06	6.69	7.00	31.40
	6	1.24	1.20	1.24	31.40
	7	3.05	2.98	3.04	31.40
	8	3.17	2.80	3.15	31.40
	9	1.00	0.59	0.90	31.40
	10	1.28	1.21	1.28	31.40
	11	1.78	1.71	1.74	31.40
	12	2.01	1.83	1.92	31.40
	13	1.46	1.27	1.38	31.40
	14	1.30	0.92	1.18	31.40
	15	1.02	1.10	1.01	31.40
Upper Trunnion	16	0.40	0.22	0.15	31.40
	17	0.33	0.16	0.21	31.40
	18	0.40	0.37	0.12	20.00
	19	0.09	0.38	0.09	20.00
Mid Cask Wall	20	0.42	0.24	0.27	31.40
	21	0.31	0.12	0.29	31.40
	22	0.28	0.41	0.21	20.00
	23	0.17	0.35	0.16	20.00
Lower Trunnion	24	0.32	0.14	0.18	31.40
	25	0.20	0.13	0.20	31.40
	26	0.34	0.23	0.10	20.00
	27	0.12	0.24	0.08	20.00
Lower Cask wall	28	0.19	0.16	0.15	31.40
	29	0.08	0.31	0.08	31.40
	30	0.13	0.28	0.03	31.40
	31	0.08	0.11	0.06	31.40
Base	32	0.13	0.08	0.12	31.40
	33	0.07	0.08	0.09	31.40
	34	0.43	0.37	0.43	31.40
	35	0.37	0.35	0.38	31.40

Table 2.10.1-12
1 Foot End Drop on Lid End

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	1.20	46.70
	2	2.82	46.70
	3	1.14	46.70
	4	3.83	46.70
Upper Cask Wall	5	7.34	31.40
	6	5.99	31.40
	7	3.32	31.40
	8	2.07	31.40
	9	2.18	31.40
	10	8.64	31.40
	11	5.93	31.40
	12	1.71	31.40
	13	6.22	31.40
	14	3.28	31.40
	15	5.36	31.40
Upper Trunnion	16	2.87	31.40
	17	3.05	31.40
	18	5.01	20.00
	19	4.83	20.00
Mid Cask Wall	20	2.31	31.40
	21	2.31	31.40
	22	2.59	20.00
	23	2.55	20.00
Lower Trunnion	24	1.73	31.40
	25	1.71	31.40
	26	1.20	20.00
	27	1.18	20.00
Lower Cask wall	28	4.08	31.40
	29	2.13	31.40
	30	2.76	31.40
	31	1.46	31.40
Base	32	2.04	31.40
	33	1.56	31.40
	34	0.50	31.40
	35	3.55	31.40

Table 2.10.1-13
1 Foot End Drop on Bottom End

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	3.30	46.70
	2	3.51	46.70
	3	1.68	46.70
	4	4.04	46.70
Upper Cask Wall	5	3.45	31.40
	6	0.62	31.40
	7	4.23	31.40
	8	2.25	31.40
	9	2.96	31.40
	10	1.89	31.40
	11	1.14	31.40
	12	2.95	31.40
	13	1.84	31.40
	14	1.90	31.40
	15	1.15	31.40
Upper Trunnion	16	2.07	31.40
	17	2.05	31.40
	18	1.08	20.00
	19	1.04	20.00
Mid Cask Wall	20	2.71	31.40
	21	2.70	31.40
	22	2.45	20.00
	23	2.42	20.00
Lower Trunnion	24	3.30	31.40
	25	3.39	31.40
	26	4.61	20.00
	27	4.44	20.00
Lower Cask wall	28	4.74	31.40
	29	2.55	31.40
	30	6.35	31.40
	31	4.14	31.40
Base	32	1.55	31.40
	33	0.71	31.40
	34	2.74	31.40
	35	4.66	31.40

Table 2.10.1-14
1 Foot Side Drop

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	8.27	7.93	46.70
	2	7.86	7.64	46.70
	3	12.36	2.57	46.70
	4	5.57	6.06	46.70
Upper Cask Wall	5	13.38	6.71	31.40
	6	8.56	3.10	31.40
	7	11.55	9.18	31.40
	8	10.17	4.74	31.40
	9	13.17	8.97	31.40
	10	12.76	4.95	31.40
	11	4.96	5.46	31.40
	12	19.15	8.58	31.40
	13	14.88	6.98	31.40
	14	24.16	8.08	31.40
	15	19.73	7.46	31.40
Upper Trunnion	16	4.69	8.99	31.40
	17	7.54	9.88	31.40
	18	2.61	7.13	20.00
	19	7.55	8.59	20.00
Mid Cask Wall	20	9.67	4.40	31.40
	21	11.53	3.88	31.40
	22	7.39	6.22	20.00
	23	10.90	5.13	20.00
Lower Trunnion	24	3.81	8.54	31.40
	25	7.15	9.21	31.40
	26	2.22	7.96	20.00
	27	8.11	8.83	20.00
Lower Cask wall	28	14.50	8.90	31.40
	29	12.88	6.59	31.40
	30	21.22	8.41	31.40
	31	16.99	5.63	31.40
Base	32	10.82	3.01	31.40
	33	3.70	3.67	31.40
	34	6.02	2.36	31.40
	35	2.95	2.70	31.40

Table 2.10.1-15
1*g* Gravity Loading

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	3.81	3.79	46.70
	2	3.58	3.57	46.70
	3	3.31	3.29	46.70
	4	4.89	4.88	46.70
Upper Cask Wall	5	7.16	6.68	31.40
	6	1.30	1.20	31.40
	7	3.26	3.03	31.40
	8	3.49	2.70	31.40
	9	1.39	0.48	31.40
	10	1.38	1.20	31.40
	11	1.84	1.71	31.40
	12	2.21	1.84	31.40
	13	1.67	1.24	31.40
	14	1.65	0.81	31.40
	15	1.00	1.15	31.40
Upper Trunnion	16	0.77	0.35	31.40
	17	0.40	0.30	31.40
	18	0.99	0.66	20.00
	19	0.24	0.66	20.00
Mid Cask Wall	20	0.88	0.52	31.40
	21	0.65	0.33	31.40
	22	0.92	0.87	20.00
	23	0.59	0.68	20.00
Lower Trunnion	24	0.78	0.33	31.40
	25	0.38	0.32	31.40
	26	0.85	0.60	20.00
	27	0.24	0.60	20.00
Lower Cask wall	28	0.46	0.48	31.40
	29	0.27	0.60	31.40
	30	0.42	0.63	31.40
	31	0.20	0.26	31.40
Base	32	0.31	0.26	31.40
	33	0.13	0.20	31.40
	34	0.48	0.39	31.40
	35	0.42	0.38	31.40

Table 2.10.1-16
1g Side Loading, Hot Environment (100° F Ambient)

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	5.71	5.70	46.70
	2	9.31	9.30	46.70
	3	3.42	3.58	46.70
	4	7.88	8.29	46.70
Upper Cask Wall	5	5.36	5.31	31.40
	6	3.60	3.60	31.40
	7	9.62	9.85	31.40
	8	6.46	6.50	31.40
	9	9.57	10.17	31.40
	10	3.11	2.92	31.40
	11	4.66	4.89	31.40
	12	4.70	5.45	31.40
	13	4.48	4.90	31.40
	14	1.81	2.14	31.40
	15	7.08	7.25	31.40
Upper Trunnion	16	7.16	8.04	31.40
	17	7.14	6.90	31.40
	18	6.72	5.90	20.00
	19	7.88	8.42	20.00
Mid Cask Wall	20	12.88	14.66	31.40
	21	13.67	12.20	31.40
	22	6.79	8.01	20.00
	23	10.56	13.33	20.00
Lower Trunnion	24	9.21	10.02	31.40
	25	8.44	8.32	31.40
	26	7.25	6.40	20.00
	27	9.61	10.06	20.00
Lower Cask wall	28	5.74	6.22	31.40
	29	6.73	7.54	31.40
	30	7.86	8.55	31.40
	31	2.29	2.22	31.40
Base	32	2.44	2.70	31.40
	33	3.23	3.73	31.40
	34	3.95	3.50	31.40
	35	3.56	3.74	31.40

Table 2.10.1-17
1*g* Side Loading, Cold Environment (-40° F Ambient)

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	1.33	1.31	46.70
	2	2.92	2.91	46.70
	3	2.02	2.04	46.70
	4	5.73	5.67	46.70
Upper Cask Wall	5	7.89	7.66	31.40
	6	0.16	0.23	31.40
	7	2.93	3.16	31.40
	8	3.70	4.53	31.40
	9	7.08	7.97	31.40
	10	1.19	1.36	31.40
	11	2.42	2.50	31.40
	12	3.54	3.96	31.40
	13	6.69	7.43	31.40
	14	4.14	4.91	31.40
	15	2.63	2.67	31.40
Upper Trunnion	16	6.24	5.97	31.40
	17	5.88	5.73	31.40
	18	3.63	3.54	20.00
	19	5.41	6.01	20.00
Mid Cask Wall	20	10.87	12.27	31.40
	21	10.65	9.89	31.40
	22	4.35	5.22	20.00
	23	9.30	11.31	20.00
Lower Trunnion	24	7.04	7.70	31.40
	25	6.11	6.10	31.40
	26	4.12	3.54	20.00
	27	7.61	7.86	20.00
Lower Cask wall	28	3.69	4.11	31.40
	29	7.13	7.91	31.40
	30	6.00	6.68	31.40
	31	2.30	2.04	31.40
Base	32	1.93	1.83	31.40
	33	2.46	2.51	31.40
	34	1.81	1.71	31.40
	35	1.93	1.86	31.40

Table 2.10.1-18
1*g* Side Loading, Increased External Pressure (25 psig.)

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	1.15	1.13	46.70
	2	2.95	2.93	46.70
	3	1.78	1.83	46.70
	4	5.69	5.76	46.70
Upper Cask Wall	5	7.35	7.00	31.40
	6	0.44	0.48	31.40
	7	3.55	3.59	31.40
	8	2.60	3.18	31.40
	9	7.12	7.94	31.40
	10	1.44	1.53	31.40
	11	2.34	2.44	31.40
	12	3.24	3.86	31.40
	13	6.04	6.69	31.40
	14	3.70	4.15	31.40
	15	3.32	3.41	31.40
Upper Trunnion	16	5.91	5.91	31.40
	17	5.72	5.54	31.40
	18	4.05	3.72	20.00
	19	5.73	6.35	20.00
Mid Cask Wall	20	11.26	12.68	31.40
	21	11.10	10.28	31.40
	22	4.56	5.50	20.00
	23	9.45	11.49	20.00
Lower Trunnion	24	7.31	7.98	31.40
	25	6.38	6.35	31.40
	26	4.44	3.85	20.00
	27	7.86	8.09	20.00
Lower Cask wall	28	3.79	4.18	31.40
	29	6.78	7.58	31.40
	30	6.06	6.70	31.40
	31	2.33	2.15	31.40
Base	32	1.99	1.86	31.40
	33	2.44	2.48	31.40
	34	1.80	1.69	31.40
	35	1.92	1.85	31.40

Table 2.10.1-19
1g Side Loading, Reduced External Pressure (50 psig.)

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	5.71	5.70	46.70
	2	9.31	9.30	46.70
	3	3.42	3.58	46.70
	4	7.88	8.29	46.70
Upper Cask Wall	5	5.36	5.31	31.40
	6	3.60	3.60	31.40
	7	9.62	9.85	31.40
	8	6.46	6.50	31.40
	9	9.57	10.17	31.40
	10	3.11	2.92	31.40
	11	4.66	4.89	31.40
	12	4.70	5.45	31.40
	13	4.48	4.90	31.40
	14	1.81	2.14	31.40
	15	7.08	7.25	31.40
Upper Trunnion	16	7.16	8.04	31.40
	17	7.14	6.90	31.40
	18	6.72	5.90	20.00
	19	7.88	8.42	20.00
Mid Cask Wall	20	12.88	14.66	31.40
	21	13.67	12.20	31.40
	22	6.79	8.01	20.00
	23	10.56	13.33	20.00
Lower Trunnion	24	9.21	10.02	31.40
	25	8.44	8.32	31.40
	26	7.25	6.40	20.00
	27	9.61	10.06	20.00
Lower Cask wall	28	5.74	6.22	31.40
	29	6.73	7.54	31.40
	30	7.86	8.55	31.40
	31	2.29	2.22	31.40
Base	32	2.44	2.70	31.40
	33	3.23	3.73	31.40
	34	3.95	3.50	31.40
	35	3.56	3.74	31.40

Table 2.10.1-20
Rail Car Vibration Loads, Internal pressure, Hot Environment

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	6.02	6.01	5.94	46.70
	2	9.67	9.65	9.58	46.70
	3	3.63	3.73	3.65	46.70
	4	8.15	8.39	8.18	46.70
Upper Cask Wall	5	5.40	5.27	5.40	31.40
	6	3.62	3.56	3.65	31.40
	7	9.64	9.71	9.60	31.40
	8	6.50	6.43	6.49	31.40
	9	9.77	10.15	9.90	31.40
	10	3.15	2.91	3.23	31.40
	11	4.73	4.80	4.79	31.40
	12	4.91	5.33	5.01	31.40
	13	4.62	4.89	4.77	31.40
	14	1.93	2.15	2.00	31.40
	15	7.12	7.17	7.04	31.40
Upper Trunnion	16	7.40	7.90	7.53	31.40
	17	7.17	6.93	7.09	31.40
	18	6.49	6.05	6.38	20.00
	19	7.93	8.29	7.92	20.00
Mid Cask Wall	20	13.13	14.38	14.00	31.40
	21	13.72	12.25	12.33	31.40
	22	6.39	8.24	8.55	20.00
	23	10.64	13.07	12.68	20.00
Lower Trunnion	24	9.38	9.84	9.60	31.40
	25	8.54	8.38	8.59	31.40
	26	7.11	6.58	6.97	20.00
	27	9.53	9.83	9.53	20.00
Lower Cask wall	28	5.86	6.09	5.95	31.40
	29	6.89	7.38	7.17	31.40
	30	8.01	8.36	8.00	31.40
	31	2.24	2.26	2.37	31.40
Base	32	2.50	2.64	2.57	31.40
	33	3.24	3.68	3.54	31.40
	34	3.89	3.49	3.59	31.40
	35	3.54	3.73	3.80	31.40

Table 2.10.1-21
Rail Car Vibration Loads, External pressure, Cold Environment

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	1.43	1.41	1.40	46.70
	2	3.29	3.27	3.26	46.70
	3	1.92	1.98	1.94	46.70
	4	5.72	5.75	5.72	46.70
Upper Cask Wall	5	7.30	7.03	7.28	31.40
	6	0.48	0.45	0.52	31.40
	7	3.49	3.47	3.48	31.40
	8	2.78	3.16	2.84	31.40
	9	7.38	7.91	7.45	31.40
	10	1.51	1.52	1.57	31.40
	11	2.36	2.41	2.30	31.40
	12	3.39	3.78	3.49	31.40
	13	6.20	6.63	6.27	31.40
	14	3.86	4.14	3.90	31.40
	15	3.32	3.35	3.27	31.40
Upper Trunnion	16	5.80	5.79	5.62	31.40
	17	5.64	5.57	5.73	31.40
	18	3.83	3.67	3.68	20.00
	19	5.78	6.21	5.83	20.00
Mid Cask Wall	20	11.49	12.47	11.86	31.40
	21	11.16	10.31	10.39	31.40
	22	4.24	5.67	6.11	20.00
	23	9.52	11.30	10.72	20.00
Lower Trunnion	24	7.36	7.80	7.39	31.40
	25	6.55	6.42	6.67	31.40
	26	4.48	4.04	4.58	20.00
	27	7.68	7.87	7.40	20.00
Lower Cask wall	28	3.87	4.11	3.94	31.40
	29	6.84	7.42	6.92	31.40
	30	6.12	6.57	6.11	31.40
	31	2.30	2.21	2.41	31.40
Base	32	1.99	1.82	1.82	31.40
	33	2.44	2.43	2.34	31.40
	34	1.76	1.68	1.77	31.40
	35	1.90	1.84	1.91	31.40

Table 2.10.1-22
Rail Car Shock Loads, Internal pressure, Hot Environment

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	15.77	15.77	15.59	46.70
	2	18.27	18.31	18.11	46.70
	3	7.88	8.72	7.89	46.70
	4	10.90	14.09	11.31	46.70
Upper Cask Wall	5	5.34	5.93	4.80	31.40
	6	1.77	2.42	3.10	31.40
	7	6.27	9.37	6.68	31.40
	8	4.88	5.80	5.72	31.40
	9	9.45	13.98	9.96	31.40
	10	3.03	3.79	3.74	31.40
	11	2.29	4.91	3.61	31.40
	12	1.96	7.93	3.68	31.40
	13	3.43	6.76	4.95	31.40
	14	3.18	4.60	2.71	31.40
	15	5.28	7.64	5.24	31.40
Upper Trunnion	16	7.54	10.62	6.12	31.40
	17	6.57	6.07	7.74	31.40
	18	9.62	6.25	7.60	20.00
	19	7.33	12.09	6.09	20.00
Mid Cask Wall	20	9.17	17.94	11.44	31.40
	21	12.67	11.64	12.85	31.40
	22	8.64	6.22	10.36	20.00
	23	8.00	16.51	9.96	20.00
Lower Trunnion	24	6.69	10.91	8.61	31.40
	25	8.56	7.86	9.08	31.40
	26	9.89	5.61	7.77	20.00
	27	8.32	11.42	8.13	20.00
Lower Cask wall	28	4.17	6.91	5.63	31.40
	29	4.41	8.27	6.24	31.40
	30	5.51	9.35	6.54	31.40
	31	3.57	2.38	2.88	31.40
Base	32	2.33	2.83	2.68	31.40
	33	2.51	3.65	2.82	31.40
	34	3.31	2.76	3.39	31.40
	35	3.35	3.03	3.59	31.40

Table 2.10.1-23
Rail Car Shock Loads, External pressure, Cold Environment

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	10.23	10.20	10.09	46.70
	2	11.38	11.31	11.33	46.70
	3	5.75	5.86	5.66	46.70
	4	7.26	9.39	7.48	46.70
Upper Cask Wall	5	8.19	6.65	7.25	31.40
	6	1.19	0.41	0.55	31.40
	7	1.07	5.83	1.70	31.40
	8	2.71	6.53	3.22	31.40
	9	7.10	12.55	7.78	31.40
	10	1.23	2.72	2.22	31.40
	11	1.75	2.92	1.70	31.40
	12	1.34	6.37	2.86	31.40
	13	4.89	8.75	5.44	31.40
	14	3.91	7.96	4.51	31.40
	15	1.99	3.98	2.86	31.40
Upper Trunnion	16	8.22	8.33	4.77	31.40
	17	6.17	4.51	5.72	31.40
	18	7.44	5.36	4.75	20.00
	19	5.42	10.46	4.36	20.00
Mid Cask Wall	20	9.04	16.01	9.26	31.40
	21	10.12	9.97	10.69	31.40
	22	6.51	5.05	7.71	20.00
	23	7.31	14.73	8.08	20.00
Lower Trunnion	24	6.81	8.94	6.45	31.40
	25	6.49	6.13	7.09	31.40
	26	7.18	3.98	5.34	20.00
	27	6.48	9.77	6.09	20.00
Lower Cask wall	28	2.95	4.62	3.52	31.40
	29	4.20	8.59	5.31	31.40
	30	3.49	7.41	4.50	31.40
	31	3.42	2.00	3.07	31.40
Base	32	2.66	1.95	2.76	31.40
	33	2.64	2.38	2.77	31.40
	34	1.44	0.96	1.51	31.40
	35	1.40	1.09	1.64	31.40

Table 2.10.1-24
1 Foot End Drop on Lid End, Internal Pressure, Hot Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	5.00	46.70
	2	6.84	46.70
	3	3.33	46.70
	4	5.35	46.70
Upper Cask Wall	5	10.49	31.40
	6	8.11	31.40
	7	6.74	31.40
	8	4.04	31.40
	9	13.15	31.40
	10	13.51	31.40
	11	7.58	31.40
	12	8.28	31.40
	13	13.81	31.40
	14	2.99	31.40
	15	5.47	31.40
Upper Trunnion	16	8.12	31.40
	17	7.53	31.40
	18	7.65	20.00
	19	8.25	20.00
Mid Cask Wall	20	16.63	31.40
	21	14.32	31.40
	22	9.67	20.00
	23	13.68	20.00
Lower Trunnion	24	10.95	31.40
	25	9.55	31.40
	26	7.62	20.00
	27	10.08	20.00
Lower Cask wall	28	5.80	31.40
	29	6.36	31.40
	30	5.45	31.40
	31	4.18	31.40
Base	32	3.77	31.40
	33	2.69	31.40
	34	1.09	31.40
	35	1.55	31.40

Table 2.10.1-25
1 Foot End Drop on Lid End, External Pressure, Cold Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	1.27	46.70
	2	3.10	46.70
	3	2.32	46.70
	4	5.69	46.70
Upper Cask Wall	5	10.19	31.40
	6	7.70	31.40
	7	2.39	31.40
	8	7.07	31.40
	9	7.41	31.40
	10	10.04	31.40
	11	8.17	31.40
	12	4.24	31.40
	13	15.03	31.40
	14	2.31	31.40
	15	5.39	31.40
Upper Trunnion	16	8.51	31.40
	17	8.64	31.40
	18	5.18	20.00
	19	6.13	20.00
Mid Cask Wall	20	14.34	31.40
	21	12.17	31.40
	22	6.81	20.00
	23	11.54	20.00
Lower Trunnion	24	8.73	31.40
	25	7.46	31.40
	26	4.92	20.00
	27	8.09	20.00
Lower Cask wall	28	5.00	31.40
	29	6.31	31.40
	30	3.30	31.40
	31	3.45	31.40
Base	32	3.46	31.40
	33	2.84	31.40
	34	0.82	31.40
	35	1.34	31.40

Table 2.10.1-26
1 Foot End Drop on Bottom End, Internal Pressure, Hot Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	0.13	46.70
	2	1.06	46.70
	3	1.40	46.70
	4	4.61	46.70
Upper Cask Wall	5	4.34	31.40
	6	2.90	31.40
	7	8.34	31.40
	8	7.87	31.40
	9	14.09	31.40
	10	4.61	31.40
	11	3.87	31.40
	12	6.22	31.40
	13	8.03	31.40
	14	3.29	31.40
	15	4.01	31.40
Upper Trunnion	16	8.32	31.40
	17	7.53	31.40
	18	6.81	20.00
	19	8.35	20.00
Mid Cask Wall	20	16.69	31.40
	21	14.38	31.40
	22	9.75	20.00
	23	13.76	20.00
Lower Trunnion	24	10.92	31.40
	25	9.59	31.40
	26	8.25	20.00
	27	10.12	20.00
Lower Cask wall	28	6.28	31.40
	29	9.11	31.40
	30	4.02	31.40
	31	4.76	31.40
Base	32	1.48	31.40
	33	2.77	31.40
	34	2.40	31.40
	35	2.67	31.40

Table 2.10.1-27
1 Foot End Drop on Bottom End, External Pressure, Cold Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	3.21	46.70
	2	2.56	46.70
	3	1.72	46.70
	4	5.45	46.70
Upper Cask Wall	5	3.82	31.40
	6	1.90	31.40
	7	4.27	31.40
	8	1.98	31.40
	9	5.01	31.40
	10	1.15	31.40
	11	2.45	31.40
	12	3.30	31.40
	13	7.25	31.40
	14	3.25	31.40
	15	1.72	31.40
Upper Trunnion	16	6.92	31.40
	17	6.83	31.40
	18	4.01	20.00
	19	6.20	20.00
Mid Cask Wall	20	14.48	31.40
	21	12.29	31.40
	22	6.96	20.00
	23	11.66	20.00
Lower Trunnion	24	10.67	31.40
	25	9.78	31.40
	26	5.86	20.00
	27	8.08	20.00
Lower Cask wall	28	7.07	31.40
	29	10.06	31.40
	30	2.11	31.40
	31	2.93	31.40
Base	32	1.45	31.40
	33	3.01	31.40
	34	3.23	31.40
	35	3.48	31.40

Table 2.10.1-28
1 Foot Side Drop, Hot Environment, Internal Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	10.10	9.79	46.70
	2	12.59	12.39	46.70
	3	11.40	4.03	46.70
	4	7.38	11.22	46.70
Upper Cask Wall	5	9.52	9.07	31.40
	6	12.16	4.92	31.40
	7	13.57	19.92	31.40
	8	14.37	12.55	31.40
	9	21.97	16.09	31.40
	10	15.01	6.43	31.40
	11	8.02	10.07	31.40
	12	23.94	15.70	31.40
	13	21.53	8.60	31.40
	14	27.06	8.94	31.40
	15	19.15	14.76	31.40
Upper Trunnion	16	4.02	11.23	31.40
	17	5.09	11.55	31.40
	18	9.56	9.24	20.00
	19	13.45	11.00	20.00
Mid Cask Wall	20	14.16	10.52	31.40
	21	14.67	12.48	31.40
	22	7.48	10.99	20.00
	23	18.41	9.61	20.00
Lower Trunnion	24	6.20	11.13	31.40
	25	5.72	11.28	31.40
	26	9.13	10.19	20.00
	27	16.24	12.04	20.00
Lower Cask wall	28	20.05	12.74	31.40
	29	19.49	11.08	31.40
	30	26.07	12.90	31.40
	31	15.51	6.38	31.40
Base	32	12.70	4.96	31.40
	33	6.01	3.69	31.40
	34	6.18	5.56	31.40
	35	5.72	5.76	31.40

Table 2.10.1-29
1 Foot Side Drop, Cold Environment, External Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	6.48	6.13	46.70
	2	7.76	7.56	46.70
	3	11.97	2.16	46.70
	4	7.15	7.46	46.70
Upper Cask Wall	5	12.96	7.66	31.40
	6	9.36	2.27	31.40
	7	12.99	12.85	31.40
	8	13.64	5.81	31.40
	9	18.39	14.37	31.40
	10	13.27	5.04	31.40
	11	5.63	6.59	31.40
	12	20.41	12.23	31.40
	13	19.75	8.17	31.40
	14	27.99	10.32	31.40
	15	19.67	9.44	31.40
Upper Trunnion	16	1.76	9.86	31.40
	17	2.10	10.58	31.40
	18	6.15	7.43	20.00
	19	12.62	9.14	20.00
Mid Cask Wall	20	11.70	9.23	31.40
	21	11.49	10.46	31.40
	22	7.40	8.44	20.00
	23	18.43	7.65	20.00
Lower Trunnion	24	4.05	10.17	31.40
	25	2.48	10.43	31.40
	26	6.41	8.44	20.00
	27	14.58	10.77	20.00
Lower Cask wall	28	16.16	10.14	31.40
	29	17.61	10.52	31.40
	30	25.45	12.65	31.40
	31	15.99	6.45	31.40
Base	32	12.68	4.19	31.40
	33	6.10	3.57	31.40
	34	5.60	3.81	31.40
	35	4.36	4.00	31.40

Table 2.10.1-30
30 Foot End Drop on Bottom End, Internal Pressure, Hot Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	7.17	98.00
	2	6.20	98.00
	3	3.80	98.00
	4	7.43	98.00
Upper Cask Wall	5	2.14	65.94
	6	1.74	65.94
	7	13.79	65.94
	8	10.80	65.94
	9	10.46	65.94
	10	3.85	65.94
	11	2.33	65.94
	12	3.93	65.94
	13	8.38	65.94
	14	3.78	65.94
	15	5.48	65.94
Upper Trunnion	16	8.62	65.94
	17	8.41	65.94
	18	6.95	48.00
	19	8.47	48.00
Mid Cask Wall	20	16.81	65.94
	21	14.60	65.94
	22	12.49	48.00
	23	13.83	48.00
Lower Trunnion	24	16.82	65.94
	25	16.19	65.94
	26	14.54	48.00
	27	14.27	48.00
Lower Cask wall	28	13.06	65.94
	29	15.67	65.94
	30	12.59	65.94
	31	10.04	65.94
Base	32	1.78	65.94
	33	3.95	65.94
	34	7.35	65.94
	35	8.36	65.94

Table 2.10.1-31
30 Foot End Drop on Bottom End, External Pressure, Cold Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	10.41	98.00
	2	9.45	98.00
	3	5.34	98.00
	4	9.08	98.00
Upper Cask Wall	5	4.45	65.94
	6	1.07	65.94
	7	9.04	65.94
	8	2.58	65.94
	9	2.01	65.94
	10	3.09	65.94
	11	3.12	65.94
	12	7.04	65.94
	13	8.06	65.94
	14	1.52	65.94
	15	2.89	65.94
Upper Trunnion	16	9.89	65.94
	17	9.95	65.94
	18	4.13	48.00
	19	6.30	48.00
Mid Cask Wall	20	17.20	65.94
	21	15.25	65.94
	22	10.18	48.00
	23	11.72	48.00
Lower Trunnion	24	17.82	65.94
	25	17.32	65.94
	26	12.22	48.00
	27	11.96	48.00
Lower Cask wall	28	15.92	65.94
	29	16.74	65.94
	30	11.18	65.94
	31	8.73	65.94
Base	32	2.50	65.94
	33	4.27	65.94
	34	7.54	65.94
	35	10.06	65.94

Table 2.10.1-32
30 Foot End Drop on Lid End, Internal Pressure, Hot Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	5.56	98.00
	2	9.56	98.00
	3	4.17	98.00
	4	8.21	98.00
Upper Cask Wall	5	19.91	65.94
	6	16.69	65.94
	7	9.66	65.94
	8	6.43	65.94
	9	10.17	65.94
	10	25.81	65.94
	11	15.78	65.94
	12	8.47	65.94
	13	25.61	65.94
	14	6.76	65.94
	15	13.42	65.94
Upper Trunnion	16	13.59	65.94
	17	13.92	65.94
	18	14.40	48.00
	19	14.66	48.00
Mid Cask Wall	20	16.56	65.94
	21	14.30	65.94
	22	12.79	48.00
	23	13.57	48.00
Lower Trunnion	24	11.23	65.94
	25	9.83	65.94
	26	7.72	48.00
	27	10.16	48.00
Lower Cask wall	28	7.31	65.94
	29	5.77	65.94
	30	4.83	65.94
	31	6.35	65.94
Base	32	5.99	65.94
	33	3.47	65.94
	34	1.07	65.94
	35	3.65	65.94

Table 2.10.1-33
30 Foot End Drop on Lid End, External Pressure, Cold Environment

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	2.08	98.00
	2	6.08	98.00
	3	3.42	98.00
	4	8.64	98.00
Upper Cask Wall	5	20.39	65.94
	6	16.45	65.94
	7	5.77	65.94
	8	13.05	65.94
	9	6.89	65.94
	10	23.97	65.94
	11	16.59	65.94
	12	7.14	65.94
	13	27.97	65.94
	14	3.26	65.94
	15	14.78	65.94
Upper Trunnion	16	15.34	65.94
	17	15.47	65.94
	18	11.43	48.00
	19	12.19	48.00
Mid Cask Wall	20	15.40	65.94
	21	13.44	65.94
	22	11.03	48.00
	23	11.53	48.00
Lower Trunnion	24	10.58	65.94
	25	9.71	65.94
	26	5.09	48.00
	27	8.12	48.00
Lower Cask wall	28	8.95	65.94
	29	6.77	65.94
	30	2.59	65.94
	31	5.04	65.94
Base	32	6.04	65.94
	33	4.59	65.94
	34	1.14	65.94
	35	6.98	65.94

Table 2.10.1-34
30 Foot Side Drop, Hot Environment, Internal Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	13.73	13.35	98.00
	2	15.83	15.68	98.00
	3	18.38	4.73	98.00
	4	9.30	11.94	98.00
Upper Cask Wall	5	15.01	16.44	65.94
	6	30.89	7.84	65.94
	7	42.10	31.92	65.94
	8	38.24	20.30	65.94
	9	49.24	21.53	65.94
	10	33.75	13.45	65.94
	11	20.15	14.91	65.94
	12	55.77	25.89	65.94
	13	46.55	19.14	65.94
	14	68.093*	16.92	65.94
	15	44.99	21.42	65.94
Upper Trunnion	16	8.58	23.97	65.94
	17	15.83	23.87	65.94
	18	10.77	23.93	48.00
	19	29.26	24.21	48.00
Mid Cask Wall	20	30.23	10.04	65.94
	21	27.00	17.04	65.94
	22	17.35	21.07	48.00
	23	36.06	6.91	48.00
Lower Trunnion	24	9.91	23.33	65.94
	25	16.58	23.74	65.94
	26	9.21	25.53	48.00
	27	31.36	24.89	48.00
Lower Cask wall	28	47.42	20.31	65.94
	29	40.57	16.91	65.94
	30	63.19	20.80	65.94
	31	40.78	19.26	65.94
Base	32	26.87	8.60	65.94
	33	9.90	8.17	65.94
	34	11.25	8.62	65.94
	35	9.00	8.90	65.94

*Linearized stress intensities Sm=47.80ksi, Sm+b=68.09ksi, are under the 65.94 & 94.2ksi

Table 2.10.1-35
30 Foot Side Drop, Cold Environment, External Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	10.92	10.43	98.00
	2	12.76	12.84	98.00
	3	19.28	2.90	98.00
	4	8.27	8.27	98.00
Upper Cask Wall	5	14.48	11.15	65.94
	6	27.94	6.05	65.94
	7	41.19	22.88	65.94
	8	37.36	12.85	65.94
	9	45.37	19.92	65.94
	10	32.80	12.99	65.94
	11	16.83	11.13	65.94
	12	51.70	20.95	65.94
	13	44.35	16.40	65.94
	14	69.156*	18.98	65.94
	15	46.42	18.44	65.94
Upper Trunnion	16	5.72	24.24	65.94
	17	14.89	23.91	65.94
	18	10.00	22.91	48.00
	19	28.91	23.39	48.00
Mid Cask Wall	20	27.67	10.68	65.94
	21	23.49	15.84	65.94
	22	17.93	19.54	48.00
	23	35.83	6.16	48.00
Lower Trunnion	24	6.36	23.41	65.94
	25	15.55	23.23	65.94
	26	8.24	24.53	48.00
	27	30.82	24.21	48.00
Lower Cask wall	28	43.86	17.10	65.94
	29	38.91	16.35	65.94
	30	62.54	20.26	65.94
	31	41.39	19.23	65.94
Base	32	26.11	7.81	65.94
	33	9.88	8.55	65.94
	34	11.08	7.07	65.94
	35	7.71	7.38	65.94

* Linearized stress intensities Sm=47.60ksi, Sm+b=69.16ksi, are under the 65.94 & 94.2ksi

Table 2.10.1-36

30 Foot CG Over Corner Drop on Bottom End, Hot Environment, Internal Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	8.93	8.37	98.00
	2	8.75	6.47	98.00
	3	3.97	3.54	98.00
	4	5.98	6.45	98.00
Upper Cask Wall	5	9.36	5.40	65.94
	6	4.35	4.38	65.94
	7	12.23	12.98	65.94
	8	5.47	7.64	65.94
	9	8.75	5.92	65.94
	10	2.94	2.79	65.94
	11	6.30	5.07	65.94
	12	7.42	6.65	65.94
	13	5.11	3.73	65.94
	14	1.88	2.85	65.94
	15	8.22	7.01	65.94
Upper Trunnion	16	7.77	8.43	65.94
	17	6.87	9.31	65.94
	18	6.19	7.88	48.00
	19	10.99	6.64	48.00
Mid Cask Wall	20	14.30	15.25	65.94
	21	11.90	15.21	65.94
	22	8.55	12.28	48.00
	23	15.29	11.28	48.00
Lower Trunnion	24	24.83	20.38	65.94
	25	21.11	19.15	65.94
	26	17.87	13.76	48.00
	27	16.12	13.11	48.00
Lower Cask wall	28	51.50	29.83	65.94
	29	14.95	19.30	65.94
	30	25.95	15.12	65.94
	31	9.72	17.98	65.94
Base	32	24.09	27.67	65.94
	33	23.67	22.89	65.94
	34	36.90	20.19	65.94
	35	59.45	39.23	65.94

Table 2.10.1-37
30 Foot CG Over Corner Drop on Bottom End, Cold Environment, External Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	9.78	9.26	98.00
	2	13.31	10.53	98.00
	3	2.95	3.62	98.00
	4	6.67	8.58	98.00
Upper Cask Wall	5	15.44	8.68	65.94
	6	0.73	0.78	65.94
	7	6.08	8.41	65.94
	8	2.95	1.88	65.94
	9	5.49	2.03	65.94
	10	1.70	2.89	65.94
	11	4.08	2.70	65.94
	12	6.23	6.35	65.94
	13	8.00	6.52	65.94
	14	3.02	1.77	65.94
	15	3.70	3.20	65.94
Upper Trunnion	16	8.12	9.15	65.94
	17	7.23	10.01	65.94
	18	3.39	5.08	48.00
	19	8.61	4.57	48.00
Mid Cask Wall	20	14.85	15.05	65.94
	21	12.25	14.68	65.94
	22	6.52	10.38	48.00
	23	13.95	9.52	48.00
Lower Trunnion	24	25.67	20.36	65.94
	25	22.02	19.12	65.94
	26	15.68	12.39	48.00
	27	13.99	11.83	48.00
Lower Cask wall	28	51.89	30.74	65.94
	29	17.26	20.17	65.94
	30	28.14	15.46	65.94
	31	10.38	17.69	65.94
Base	32	25.10	28.04	65.94
	33	24.77	23.50	65.94
	34	36.71	20.24	65.94
	35	61.84	41.72	65.94

Table 2.10.1-38
30 Foot CG Over Corner Drop on Lid End, Hot Environment, Internal Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	*101.63	61.64	98.00
	2	*107.80	65.82	98.00
	3	36.13	35.84	98.00
	4	47.89	40.17	98.00
Upper Cask Wall	5	14.93	25.22	65.94
	6	17.09	3.97	65.94
	7	48.08	36.36	65.94
	8	21.25	20.35	65.94
	9	27.38	20.70	65.94
	10	17.75	12.04	65.94
	11	17.00	10.64	65.94
	12	27.88	25.87	65.94
	13	21.33	23.14	65.94
	14	4.48	17.34	65.94
	15	8.66	16.32	65.94
Upper Trunnion	16	20.99	19.38	65.94
	17	20.22	19.91	65.94
	18	12.99	12.55	48.00
	19	15.06	12.95	48.00
Mid Cask Wall	20	15.17	15.13	65.94
	21	9.99	15.22	65.94
	22	7.76	12.93	48.00
	23	17.69	10.81	48.00
Lower Trunnion	24	9.97	8.97	65.94
	25	6.55	9.24	65.94
	26	6.58	8.23	48.00
	27	12.70	8.17	48.00
Lower Cask wall	28	4.87	7.14	65.94
	29	7.24	4.61	65.94
	30	6.54	3.95	65.94
	31	4.10	5.07	65.94
Base	32	1.48	3.39	65.94
	33	2.03	3.03	65.94
	34	1.36	1.09	65.94
	35	1.15	1.66	65.94

* Linearized stress intensities Sm=9.36ksi, Sm+b=107.8ksi, are under the 98.0 & 140.0ksi

Table 2.10.1-39
30 Foot CG Over Corner Drop on Lid End, Cold Environment, External Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	95.93	54.27	98.00
	2	*105.97	63.41	98.00
	3	30.94	33.43	98.00
	4	49.04	40.26	98.00
Upper Cask Wall	5	16.69	28.66	65.94
	6	13.87	5.35	65.94
	7	46.39	33.77	65.94
	8	18.91	18.05	65.94
	9	34.41	24.80	65.94
	10	20.96	15.50	65.94
	11	15.03	11.85	65.94
	12	28.32	27.89	65.94
	13	23.19	25.30	65.94
	14	5.24	16.85	65.94
	15	9.63	14.99	65.94
Upper Trunnion	16	21.70	19.59	65.94
	17	20.84	19.93	65.94
	18	10.79	10.68	48.00
	19	12.70	11.16	48.00
Mid Cask Wall	20	14.04	15.34	65.94
	21	11.09	15.05	65.94
	22	5.81	10.63	48.00
	23	15.60	9.11	48.00
Lower Trunnion	24	8.54	9.65	65.94
	25	6.73	9.64	65.94
	26	4.11	5.61	48.00
	27	10.69	6.32	48.00
Lower Cask wall	28	5.40	8.05	65.94
	29	7.93	5.43	65.94
	30	4.45	2.01	65.94
	31	3.44	4.69	65.94
Base	32	1.51	3.87	65.94
	33	2.30	3.47	65.94
	34	1.77	1.17	65.94
	35	3.32	3.73	65.94

Table 2.10.1-40

30 Foot 20° Oblique Drop on Lid End, Hot Environment, Internal Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	35.48	32.44	98.00
	2	46.41	46.48	98.00
	3	15.92	13.08	98.00
	4	21.10	22.47	98.00
Upper Cask Wall	5	50.91	20.89	65.94
	6	58.88	9.51	65.94
	7	57.27	32.44	65.94
	8	47.41	31.24	65.94
	9	50.49	15.79	65.94
	10	51.97	21.68	65.94
	11	46.70	17.20	65.94
	12	54.48	31.28	65.94
	13	47.67	30.18	65.94
	14	*69.31	19.65	65.94
	15	41.60	29.68	65.94
Upper Trunnion	16	2.43	35.25	65.94
	17	18.33	32.67	65.94
	18	10.45	33.55	48.00
	19	37.14	30.66	48.00
Mid Cask Wall	20	25.82	14.13	65.94
	21	17.03	19.66	65.94
	22	21.85	22.45	48.00
	23	36.90	10.64	48.00
Lower Trunnion	24	13.84	11.94	65.94
	25	7.34	15.01	65.94
	26	9.13	14.21	48.00
	27	16.19	11.35	48.00
Lower Cask wall	28	10.97	7.45	65.94
	29	12.81	5.34	65.94
	30	13.17	5.27	65.94
	31	2.43	8.25	65.94
Base	32	4.50	4.29	65.94
	33	2.69	4.09	65.94
	34	0.70	1.23	65.94
	35	1.51	1.54	65.94

* Linearized stress intensities Sm=55.19ksi, Sm+b=69.31ksi, are under the 65.94 & 94.2ksi

Table 2.10.1-41
30 Foot 20° Oblique Drop on Lid End, Cold Environment, External Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	35.10	31.78	98.00
	2	49.55	49.54	98.00
	3	19.96	14.17	98.00
	4	22.55	24.68	98.00
Upper Cask Wall	5	43.72	16.48	65.94
	6	53.40	7.64	65.94
	7	51.40	26.81	65.94
	8	46.27	27.17	65.94
	9	48.35	12.29	65.94
	10	49.57	20.73	65.94
	11	40.19	12.32	65.94
	12	51.52	18.54	65.94
	13	45.37	35.72	65.94
	14	*71.84	32.44	65.94
	15	41.30	29.09	65.94
Upper Trunnion	16	4.57	29.83	65.94
	17	20.65	30.25	65.94
	18	9.72	32.59	48.00
	19	35.97	28.91	48.00
Mid Cask Wall	20	23.11	8.23	65.94
	21	15.87	5.20	65.94
	22	21.16	4.62	48.00
	23	37.18	8.16	48.00
Lower Trunnion	24	12.19	14.60	65.94
	25	4.58	19.45	65.94
	26	10.03	21.35	48.00
	27	16.16	9.50	48.00
Lower Cask wall	28	8.60	11.75	65.94
	29	14.16	14.85	65.94
	30	14.09	13.05	65.94
	31	3.50	10.69	65.94
Base	32	3.96	5.23	65.94
	33	2.13	4.68	65.94
	34	0.41	0.38	65.94
	35	2.19	1.28	65.94

* Linearized stress intensities Sm=54.95ksi, Sm+b=71.84ksi, are under the 65.94 & 94.2ksi

Table 2.10.1-42

30 Foot 20° Oblique Drop on Bottom End, Hot Environment, Internal Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	3.13	5.22	98.00
	2	2.27	2.48	98.00
	3	1.52	2.56	98.00
	4	10.21	6.38	98.00
Upper Cask Wall	5	9.04	5.76	65.94
	6	7.77	4.94	65.94
	7	16.29	12.36	65.94
	8	9.67	9.32	65.94
	9	18.75	5.57	65.94
	10	6.23	4.77	65.94
	11	10.82	5.28	65.94
	12	12.87	6.95	65.94
	13	9.83	6.64	65.94
	14	8.20	5.48	65.94
	15	10.31	8.26	65.94
Upper Trunnion	16	12.38	11.74	65.94
	17	3.39	15.78	65.94
	18	10.69	14.16	48.00
	19	16.54	10.54	48.00
Mid Cask Wall	20	27.13	14.62	65.94
	21	17.23	21.49	65.94
	22	21.78	24.13	48.00
	23	37.59	10.42	48.00
Lower Trunnion	24	5.23	31.99	65.94
	25	16.16	30.20	65.94
	26	11.20	33.46	48.00
	27	39.06	30.53	48.00
Lower Cask wall	28	35.97	27.26	65.94
	29	37.11	29.77	65.94
	30	59.47	15.44	65.94
	31	34.02	32.20	65.94
Base	32	24.31	11.05	65.94
	33	22.88	20.05	65.94
	34	6.86	5.92	65.94
	35	23.09	28.59	65.94

Table 2.10.1-43
30 Foot 20° Oblique Drop on Bottom End, Cold Environment, External Pressure

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	6.91	12.68	98.00
	2	5.95	10.28	98.00
	3	1.57	15.70	98.00
	4	6.75	12.23	98.00
Upper Cask Wall	5	7.90	5.96	65.94
	6	2.97	6.10	65.94
	7	10.55	4.05	65.94
	8	9.58	5.67	65.94
	9	18.84	8.08	65.94
	10	5.36	32.24	65.94
	11	6.20	16.77	65.94
	12	10.69	29.58	65.94
	13	14.33	28.37	65.94
	14	13.98	30.17	65.94
	15	6.74	32.65	65.94
Upper Trunnion	16	10.68	29.75	65.94
	17	1.66	31.91	65.94
	18	12.97	9.49	48.00
	19	16.12	22.86	48.00
Mid Cask Wall	20	24.69	21.49	65.94
	21	16.95	15.46	65.94
	22	20.84	6.62	48.00
	23	37.90	8.30	48.00
Lower Trunnion	24	2.96	20.95	65.94
	25	17.72	11.24	65.94
	26	10.40	4.41	48.00
	27	37.33	8.17	48.00
Lower Cask wall	28	34.05	4.35	65.94
	29	35.37	8.27	65.94
	30	59.14	1.83	65.94
	31	35.04	2.96	65.94
Base	32	23.32	2.92	65.94
	33	24.10	4.84	65.94
	34	6.77	31.28	65.94
	35	25.75	6.12	65.94

Table 2.10.1-44
Immersion, Cold Environment, 290psi External Pressure

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	12.23	98.00
	2	12.47	98.00
	3	5.35	98.00
	4	9.18	98.00
Upper Cask Wall	5	4.22	65.94
	6	0.36	65.94
	7	8.15	65.94
	8	3.46	65.94
	9	2.01	65.94
	10	3.13	65.94
	11	2.27	65.94
	12	4.61	65.94
	13	5.26	65.94
	14	0.82	65.94
	15	3.17	65.94
Upper Trunnion	16	9.40	65.94
	17	8.60	65.94
	18	2.28	48.00
	19	3.99	48.00
Mid Cask Wall	20	17.81	65.94
	21	15.36	65.94
	22	4.54	48.00
	23	9.57	48.00
Lower Trunnion	24	11.96	65.94
	25	10.47	65.94
	26	2.31	48.00
	27	5.78	48.00
Lower Cask wall	28	6.63	65.94
	29	5.11	65.94
	30	1.07	65.94
	31	4.89	65.94
Base	32	6.56	65.94
	33	4.04	65.94
	34	1.00	65.94
	35	5.91	65.94

Table 2.10.1-45
Fire Accident

Component	location	Max Stress Intensity $P_m + P_b$ (ksi)	Allowable Membrane Stress Intensity (ksi)
Lid	1	0.46	98.00
	2	0.09	98.00
	3	3.73	98.00
	4	2.82	98.00
Upper Cask Wall	5	12.06	65.94
	6	8.72	65.94
	7	5.94	65.94
	8	23.71	65.94
	9	6.21	65.94
	10	4.95	65.94
	11	8.42	65.94
	12	8.18	65.94
	13	20.32	65.94
	14	11.94	65.94
	15	16.68	65.94
Upper Trunnion	16	16.48	65.94
	17	13.56	65.94
	18	20.09	48.00
	19	23.33	48.00
Mid Cask Wall	20	15.74	65.94
	21	13.89	65.94
	22	17.38	48.00
	23	20.78	48.00
Lower Trunnion	24	15.86	65.94
	25	13.83	65.94
	26	18.99	48.00
	27	20.89	48.00
Lower Cask wall	28	9.46	65.94
	29	17.69	65.94
	30	10.16	65.94
	31	15.28	65.94
Base	32	4.92	65.94
	33	6.16	65.94
	34	0.79	65.94
	35	5.31	65.94

Table 2.10.1-46
Tie Down Loading

Component	Location	Max Stress Intensity $P_m + P_b$ (ksi) At Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 90° from Contact Side	Max Stress Intensity $P_m + P_b$ (ksi) 180° from Contact Side	Allowable Membrane Stress Intensity (ksi)
Lid	1	22.97	22.95	22.70	101.80
	2	22.17	21.99	22.02	101.80
	3	11.92	12.14	11.83	101.80
	4	11.86	15.02	12.02	101.80
Upper Cask Wall	5	8.35	6.13	7.14	43.30
	6	2.30	1.06	1.06	43.30
	7	3.30	5.98	1.92	43.30
	8	2.28	4.62	2.34	43.30
	9	1.86	9.12	0.69	43.30
	10	0.93	2.07	0.60	43.30
	11	2.92	2.30	1.56	43.30
	12	2.71	4.93	2.33	43.30
	13	1.88	4.00	2.62	43.30
	14	2.10	6.90	0.92	43.30
	15	0.78	2.20	1.08	43.30
Upper Trunnion	16	8.08	5.32	1.21	43.30
	17	2.73	4.87	2.96	43.30
	18	8.52	8.84	3.85	23.40
	19	2.19	8.31	2.79	23.40
Mid Cask Wall	20	7.93	9.16	4.82	43.30
	21	4.33	6.77	4.42	43.30
	22	7.01	10.74	7.47	23.40
	23	5.44	9.44	6.00	23.40
Lower Trunnion	24	3.10	3.37	3.60	43.30
	25	3.24	2.92	2.45	43.30
	26	10.32	4.64	5.93	23.40
	27	7.62	4.36	3.27	23.40
Lower Cask wall	28	6.07	2.52	5.61	43.30
	29	8.04	1.67	4.89	43.30
	30	9.29	2.91	5.73	43.30
	31	3.65	1.72	2.11	43.30
Base	32	3.75	2.10	3.54	43.30
	33	2.14	1.53	2.45	43.30
	34	1.00	0.96	1.27	43.30
	35	1.78	1.76	1.56	43.30

FIGURE WITHHELD AS SENSITIVE UNCLASSIFIED INFORMATION

Figure 2.10.1-1: NUHOMS - MP197 Key Dimensions

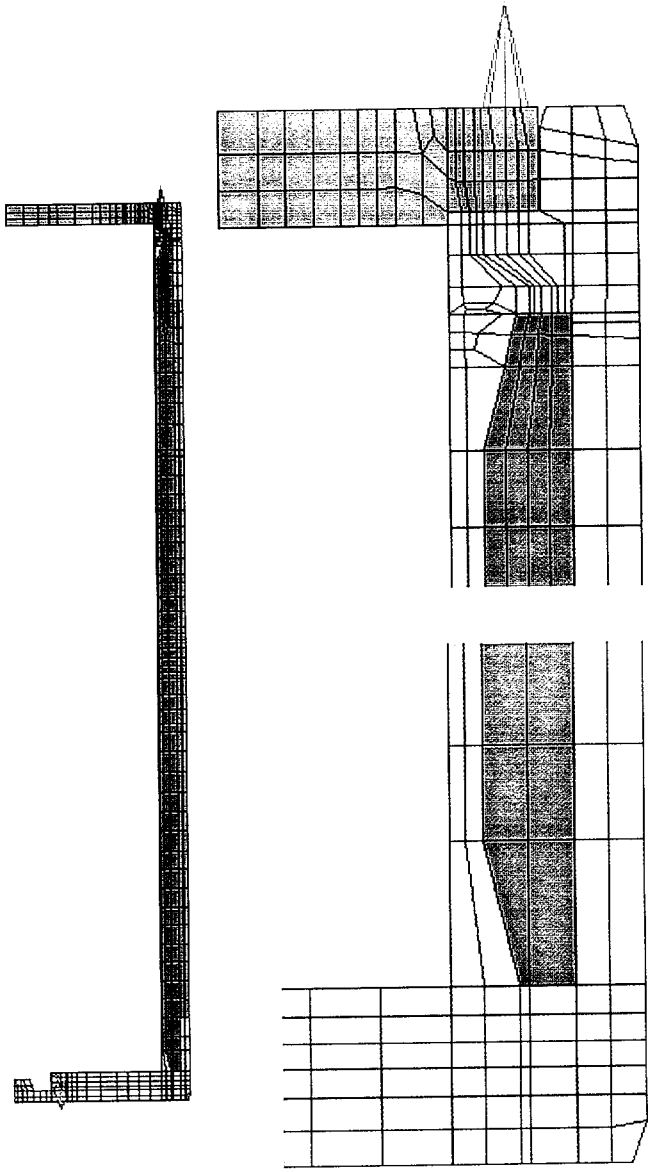


Figure 2.10.1-2: NUHOMS – MP197 Cask 2D Finite Element Model

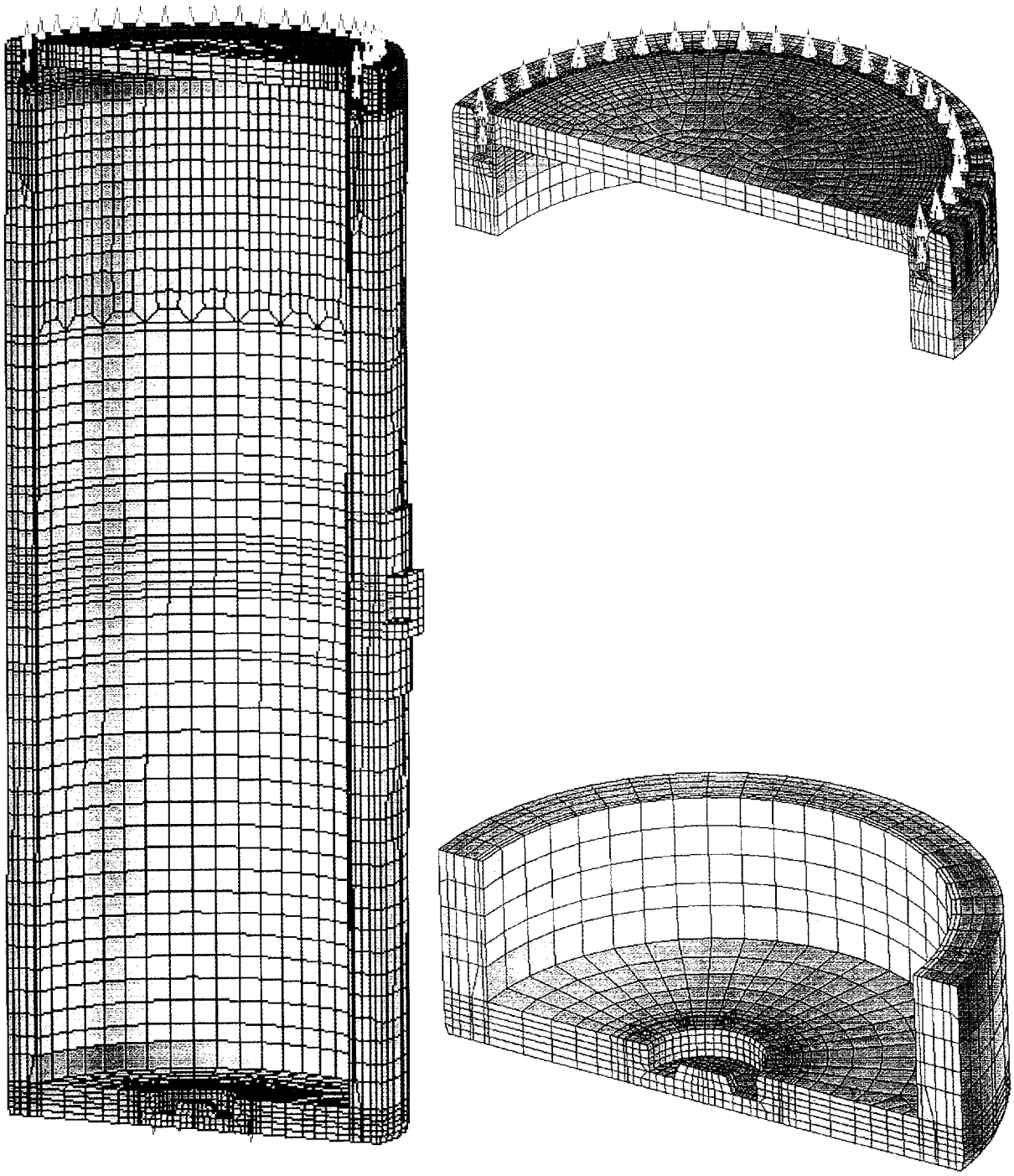


Figure 2.10.1-3: NUHOMS – MP197 Cask
3D Finite Element Model

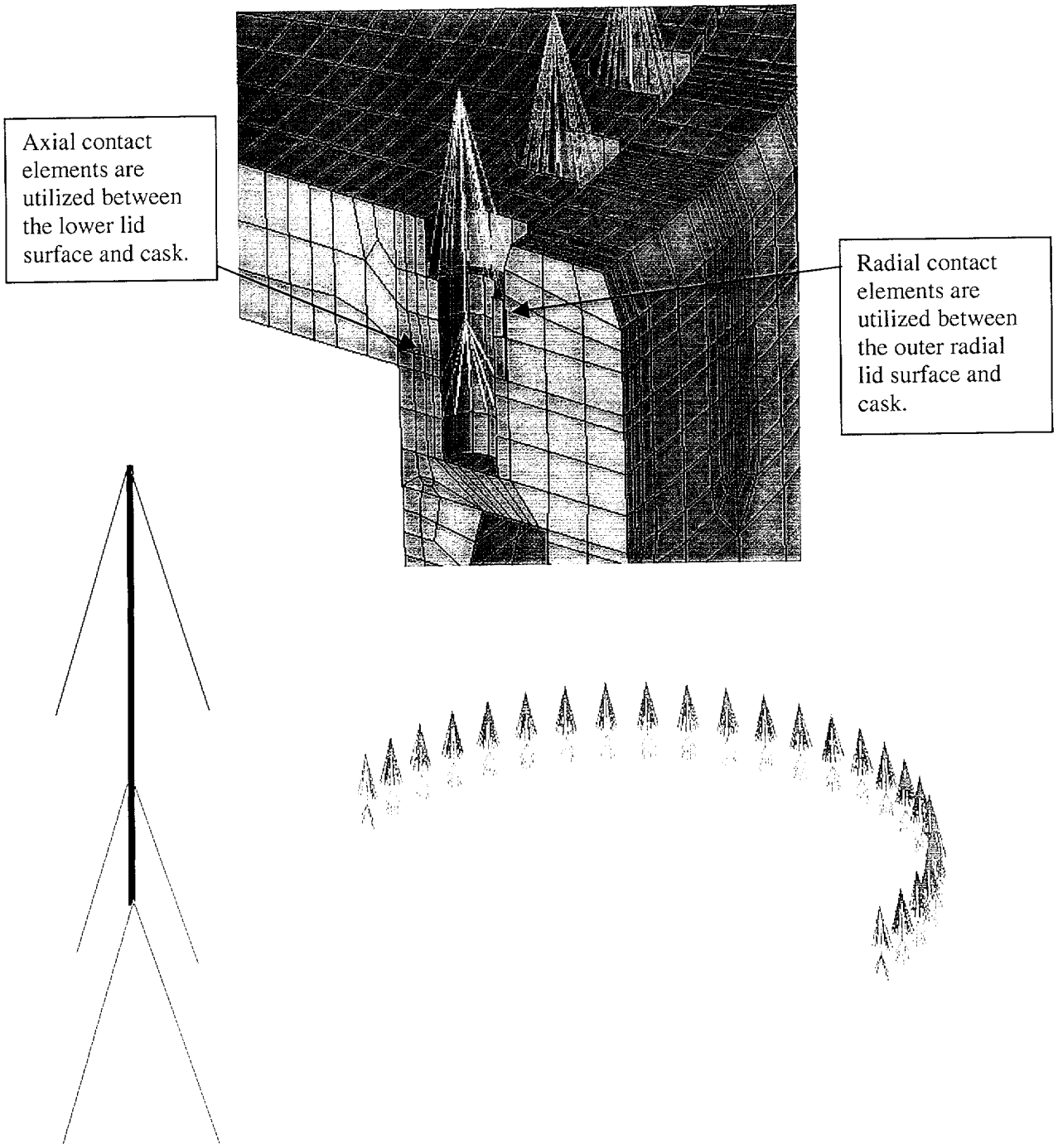


Figure 2.10.1-4: NUHOMS – MP197 Cask Bolt Representation

Figure 2.10.1-5a: 2D Lid End Drop - Boundary Condition

Figure 2.10.1-5b: 2D Bottom End Drop - Boundary Condition

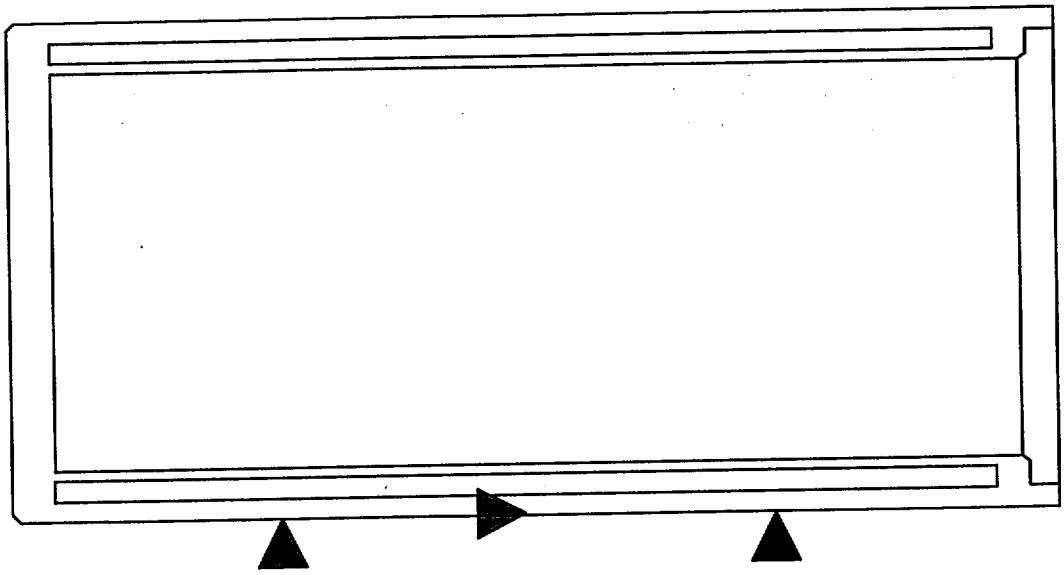


Figure 2.10.1-5c: 3D Transport Boundary Condition

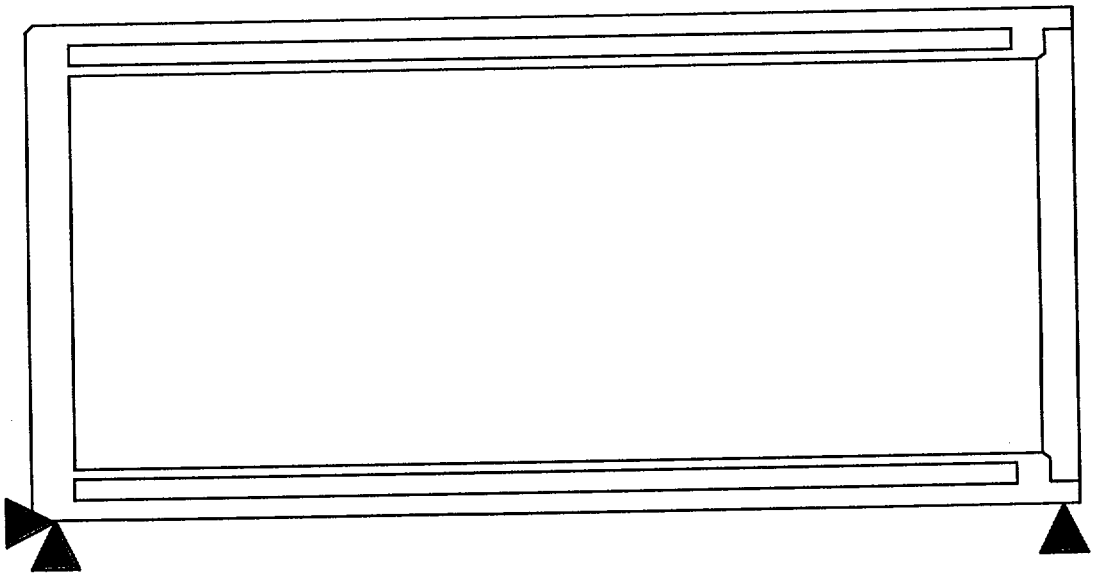


Figure 2.10.1-5d: 3D Side Drop Boundary Condition

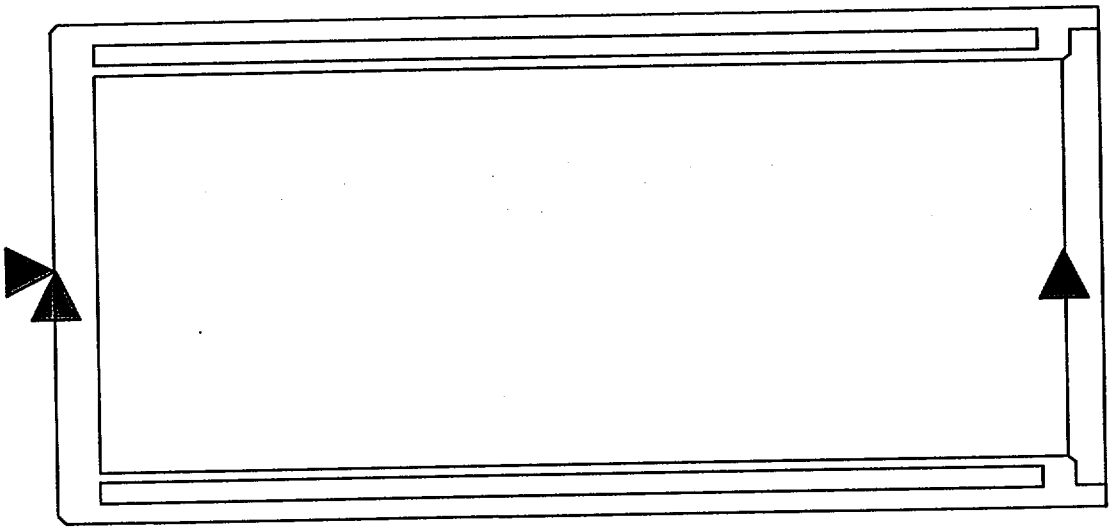


Figure 2.10.1-5e: 3D Lid End and Lid Corner Drop Boundary Condition

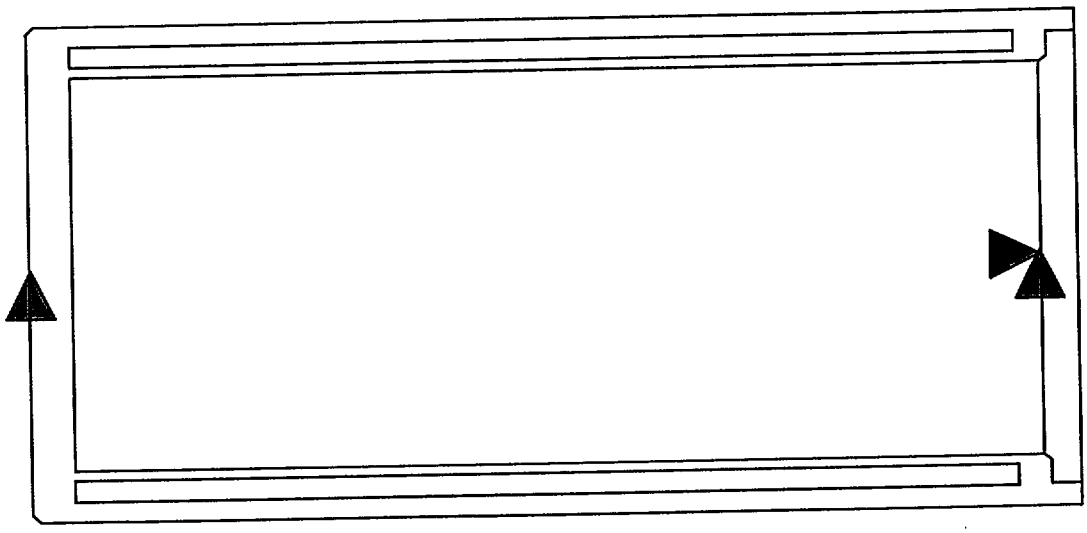


Figure 2.10.1-5f: 3D Bottom End - Bottom Corner Drop Boundary Condition

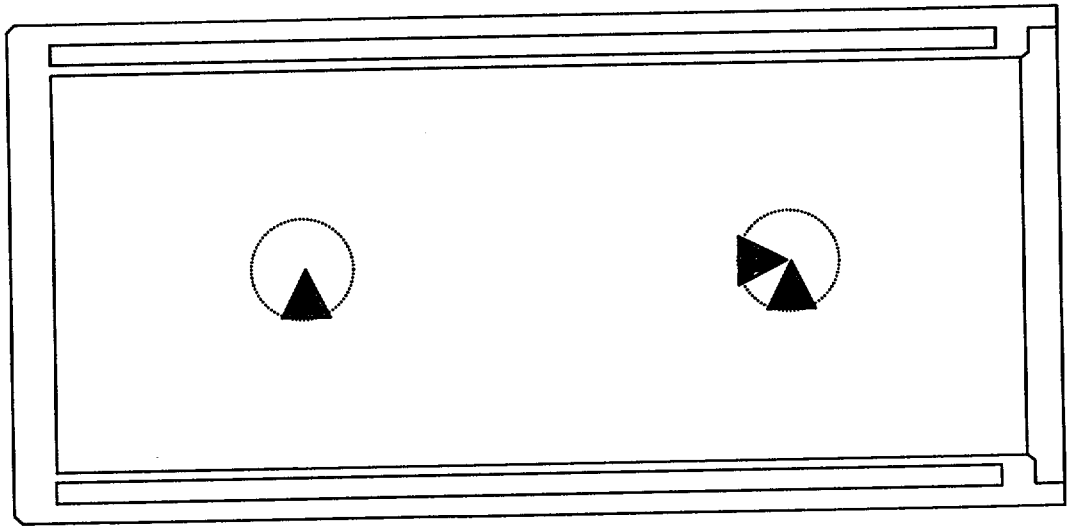


Figure 2.10.1-5g: 3D 3-G Lift Boundary Condition

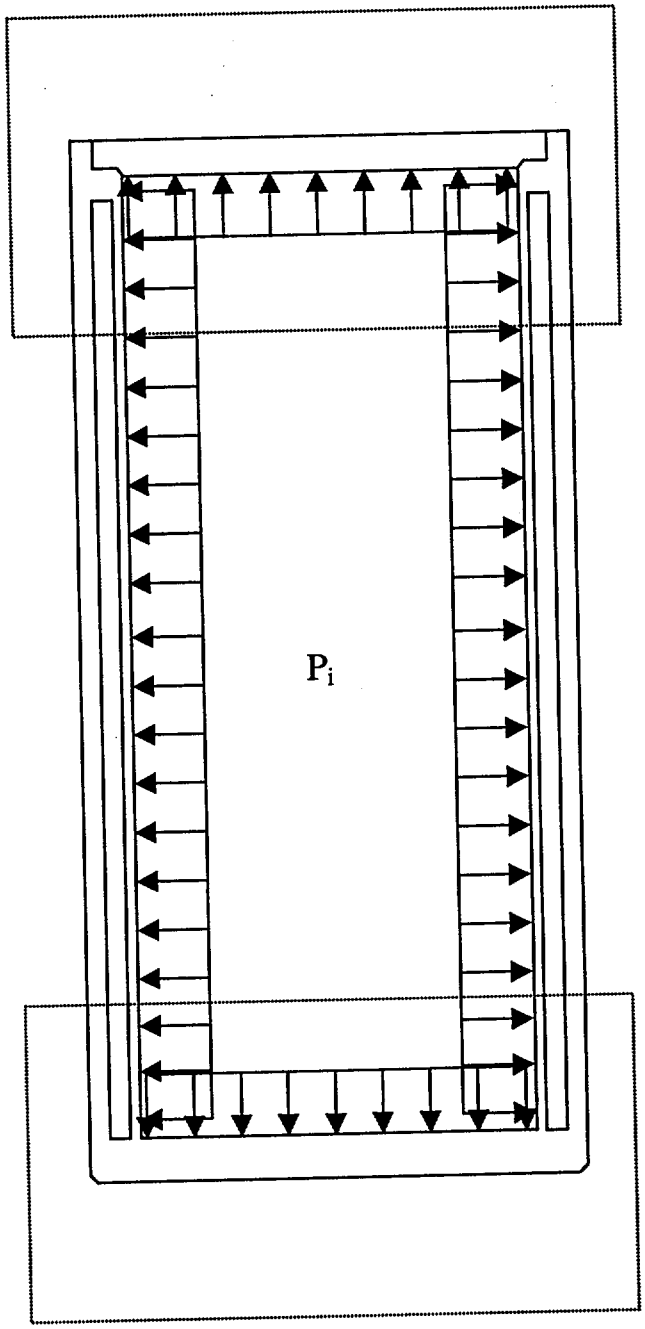


Figure 2.10.1-6: Internal Pressure Loading

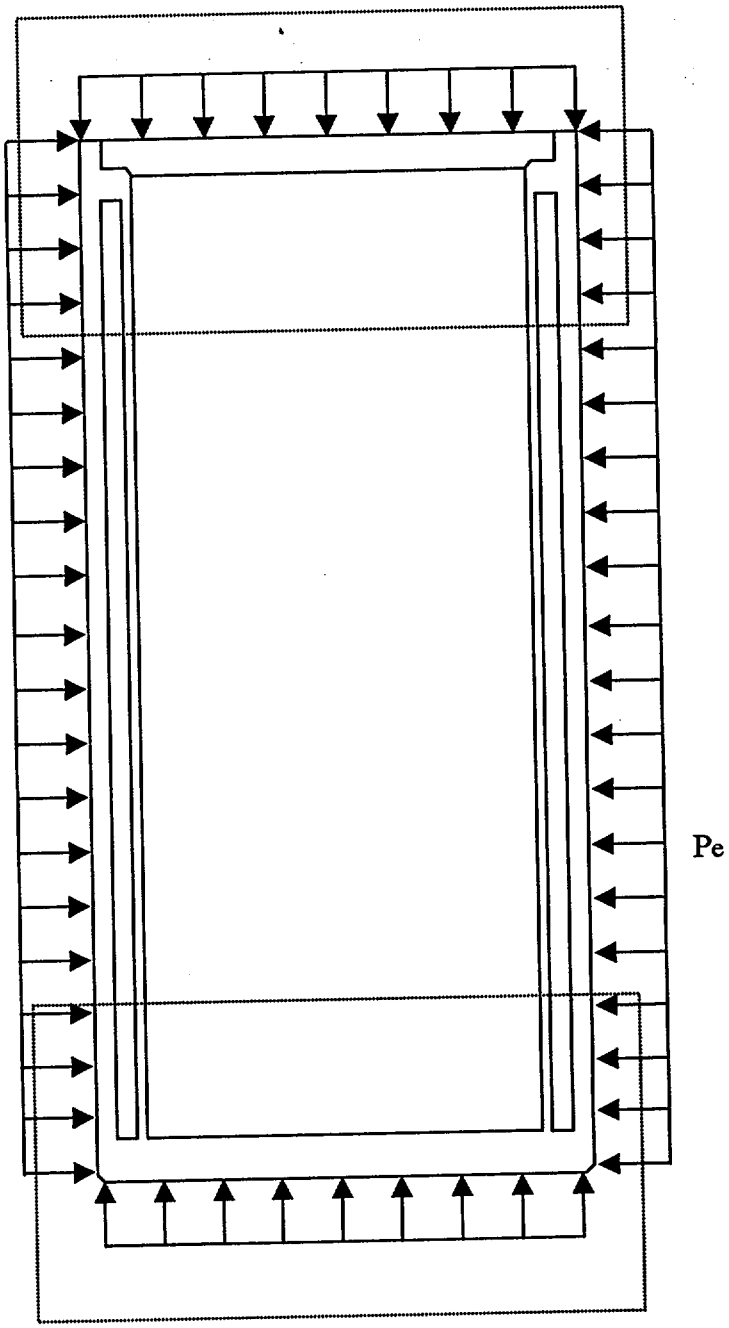


Figure 2.10.1-7: External Pressure Loading

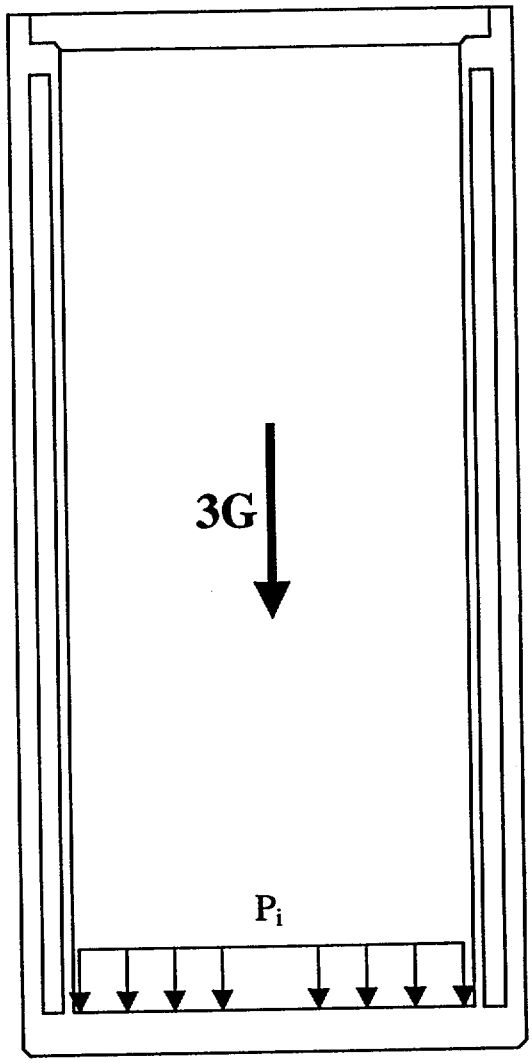


Figure 2.10.1-8: 3G Lift Loading

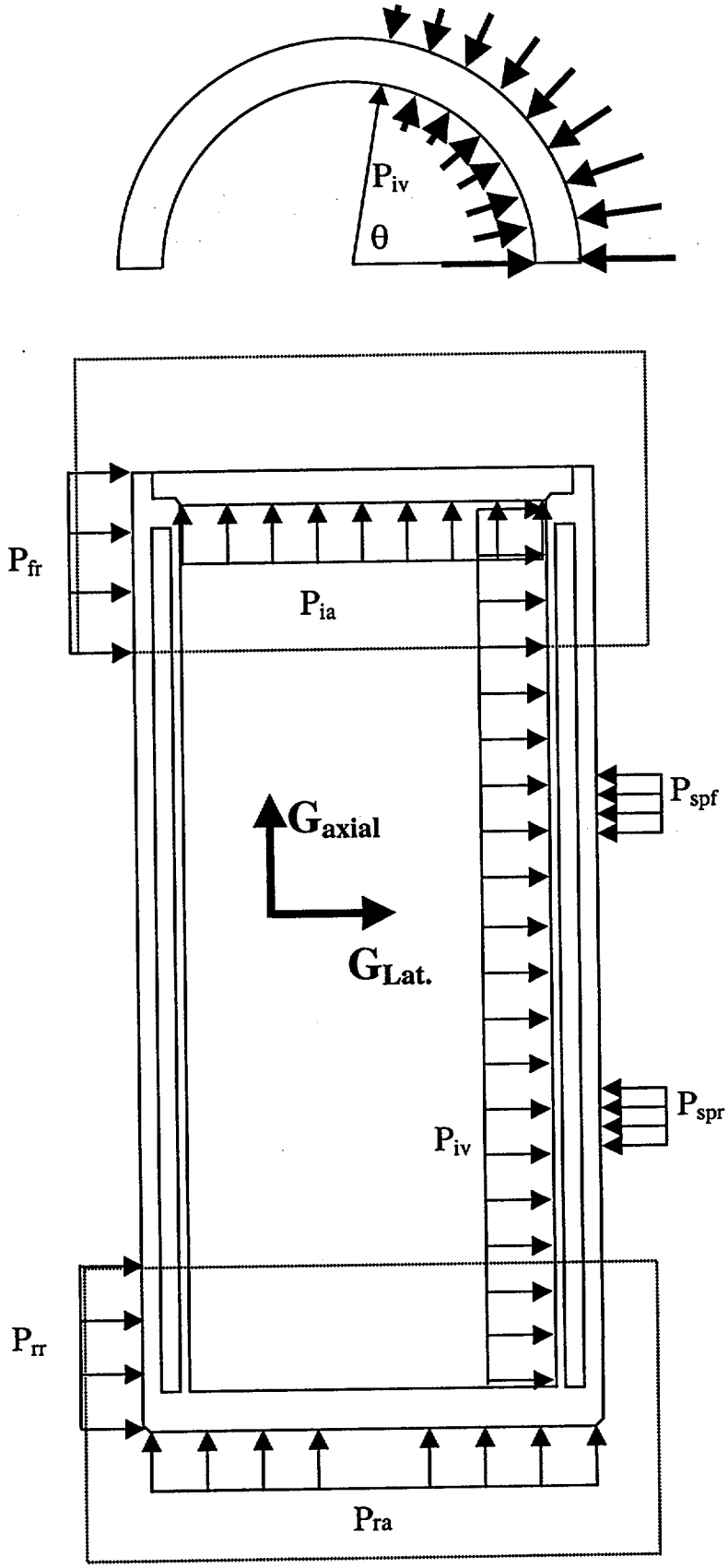


Figure 2.10.1-9: Rail Car Transport Loading

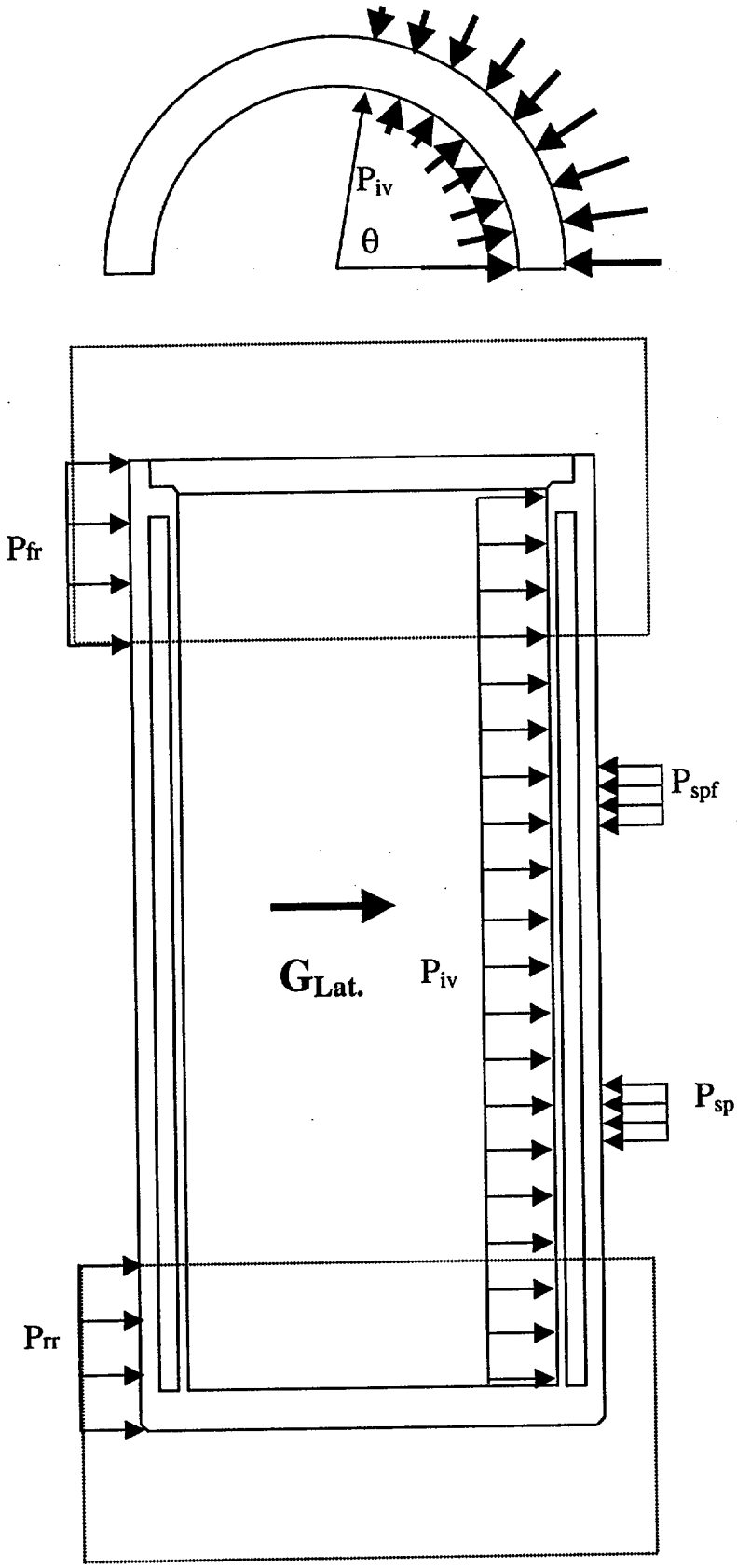


Figure 2.10.1-10: 1G Loading

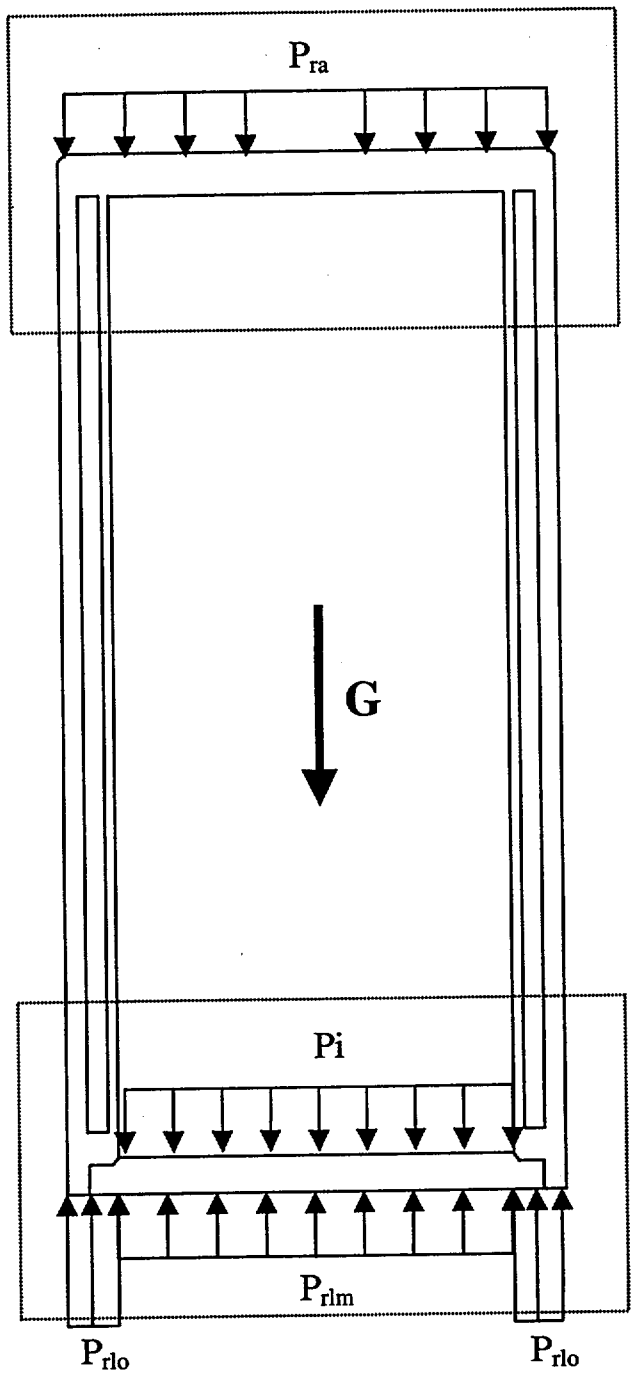


Figure 2.10.1-11: End Drop on Lid Loading

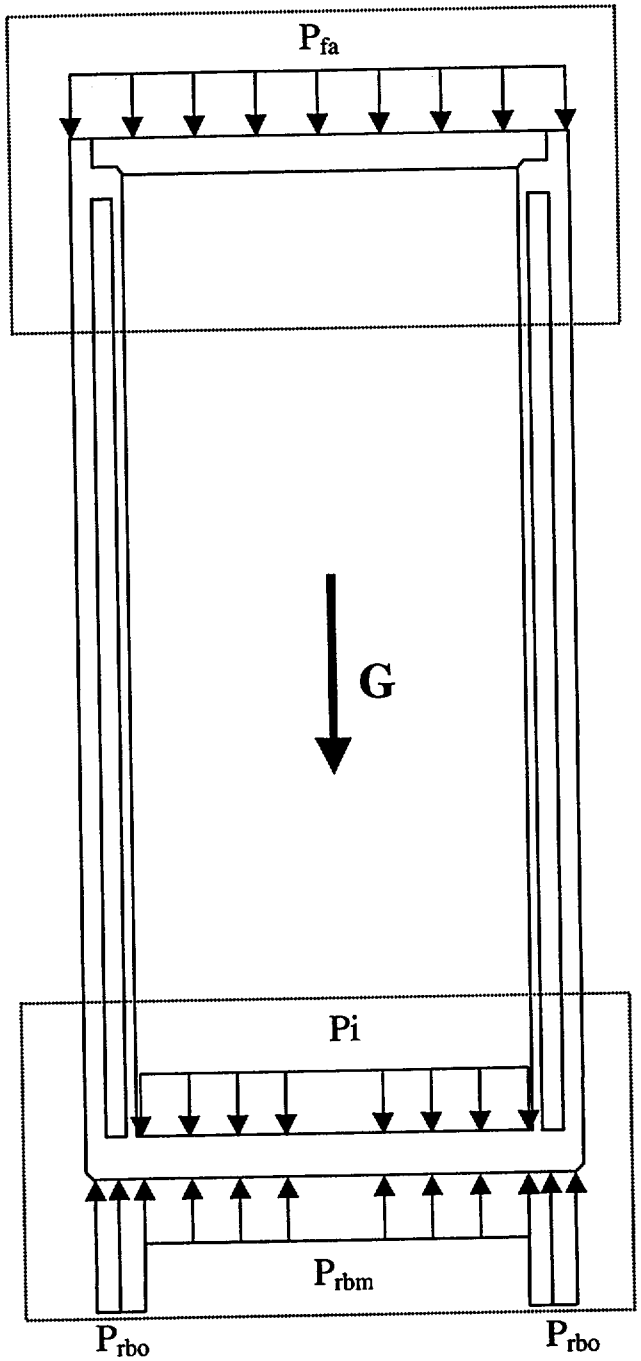


Figure 2.10.1-12: End Drop on Base Loading

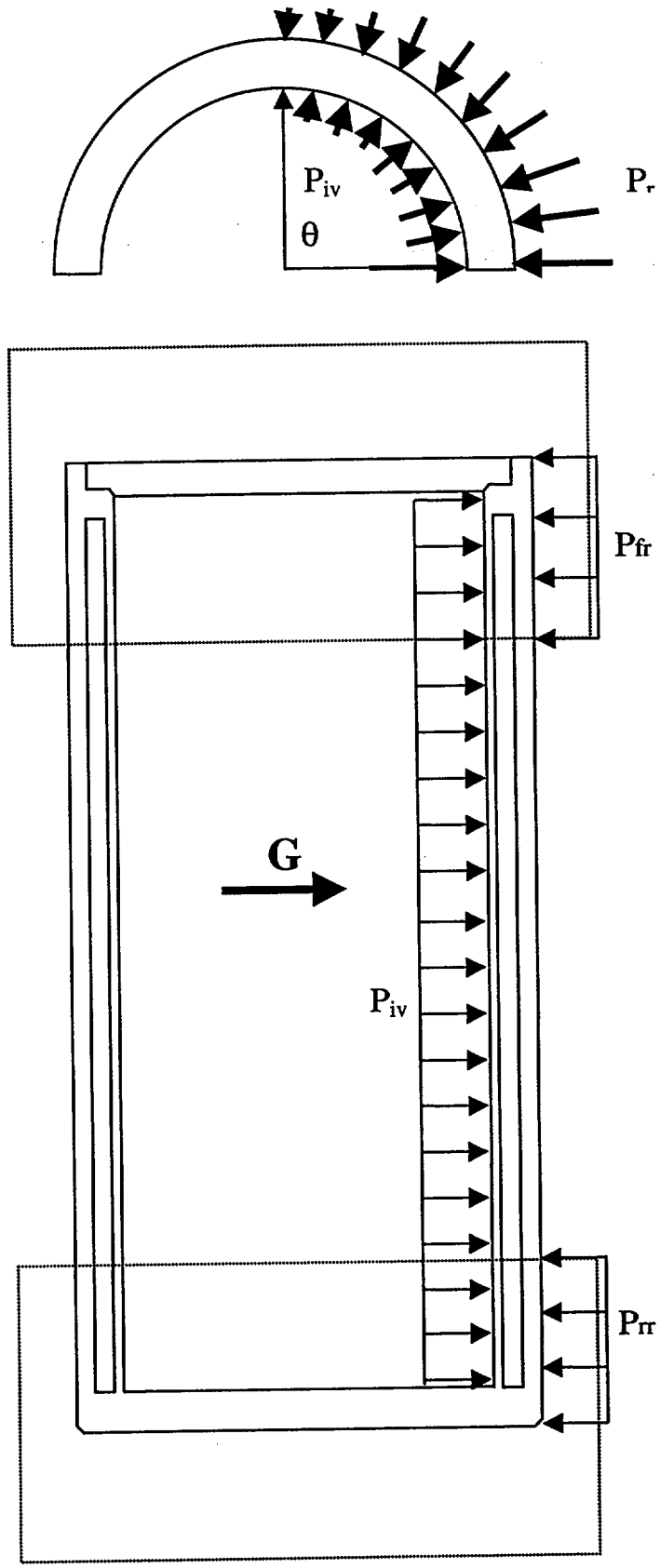


Figure 2.10.1-13: Side Drop Loading

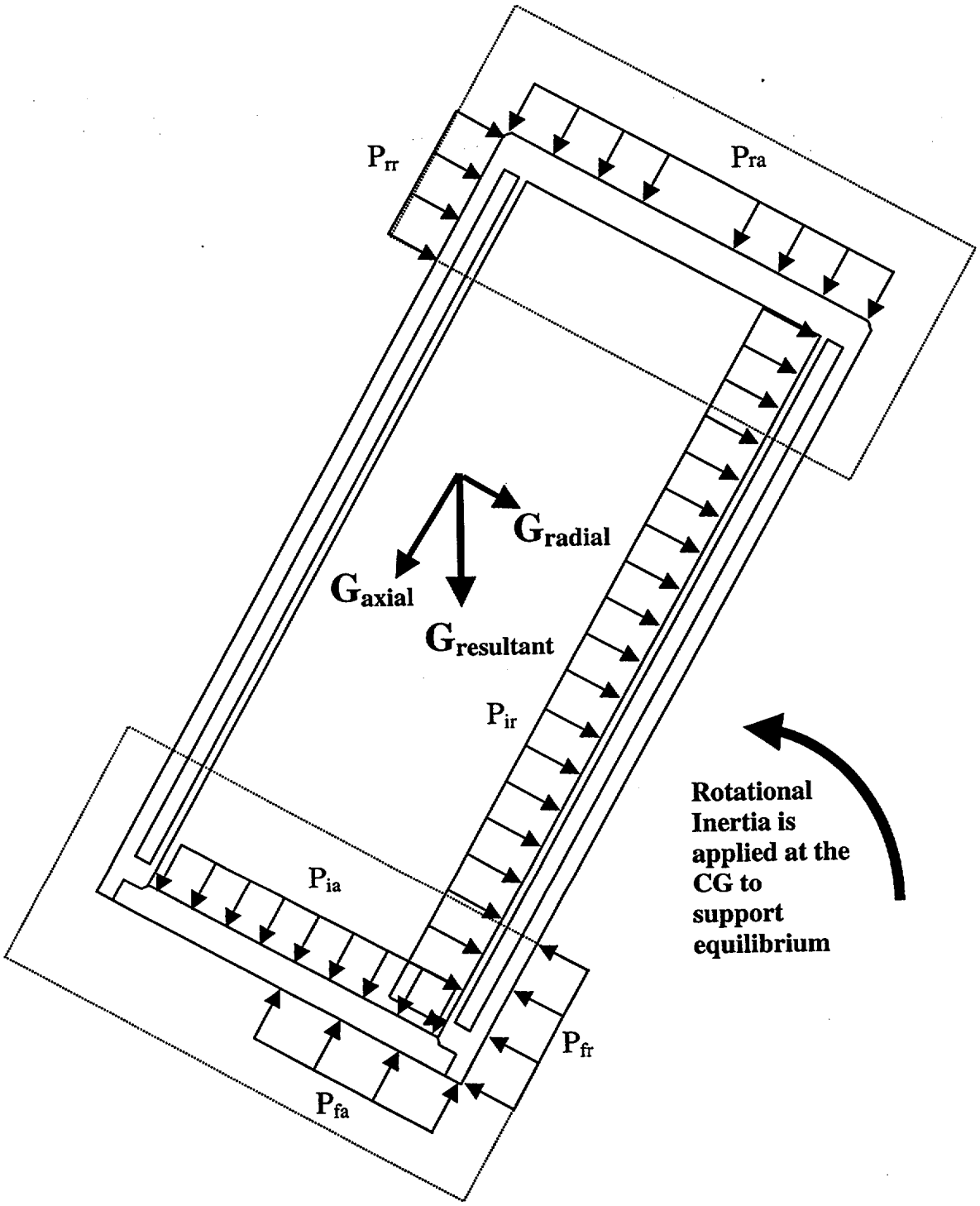


Figure 2.10.1-14: 30 Foot CG Over Corner Drop on Lid End Loading

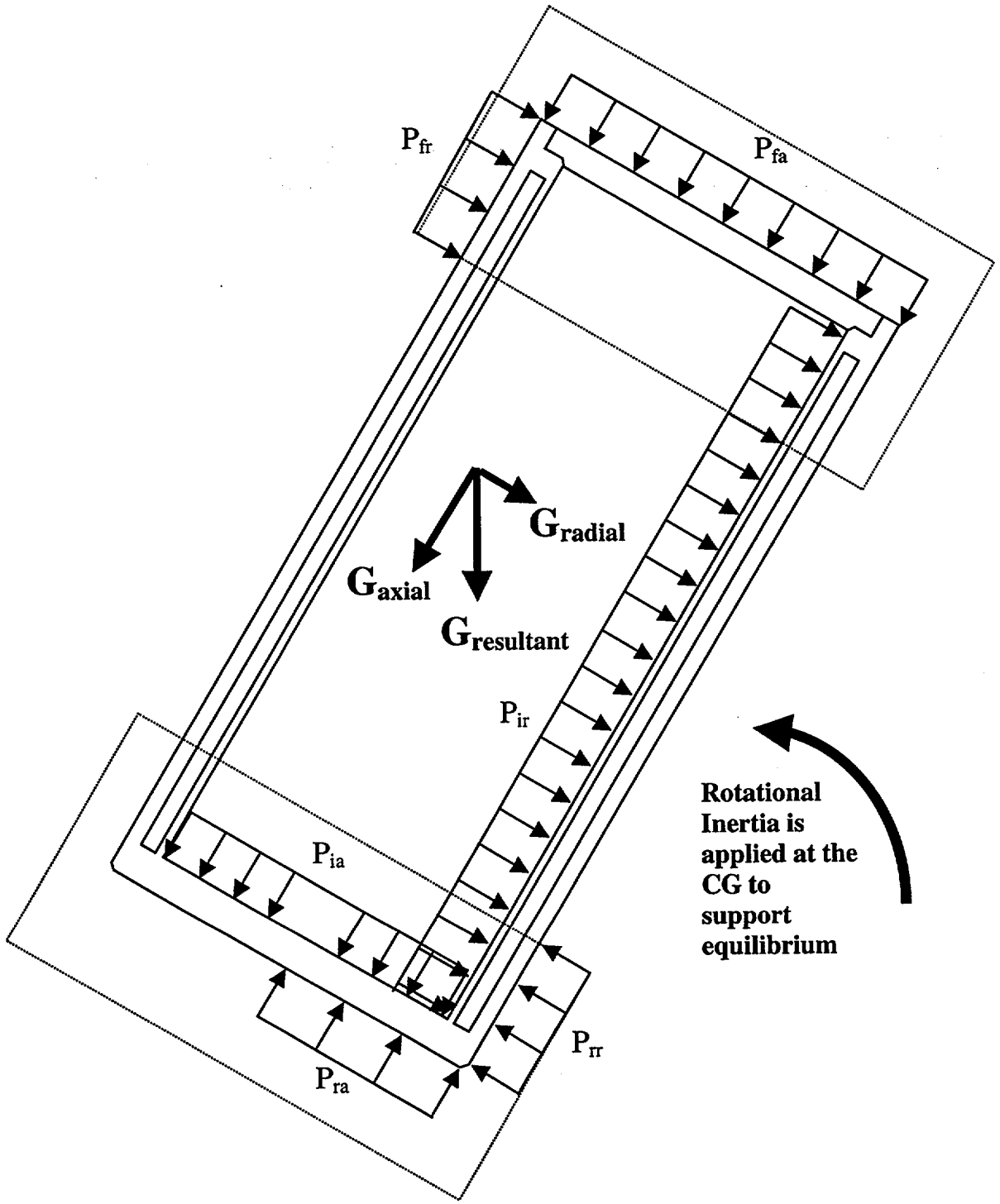


Figure 2.10.1-15: 30 Foot CG Over Corner Drop on Bottom End Loading

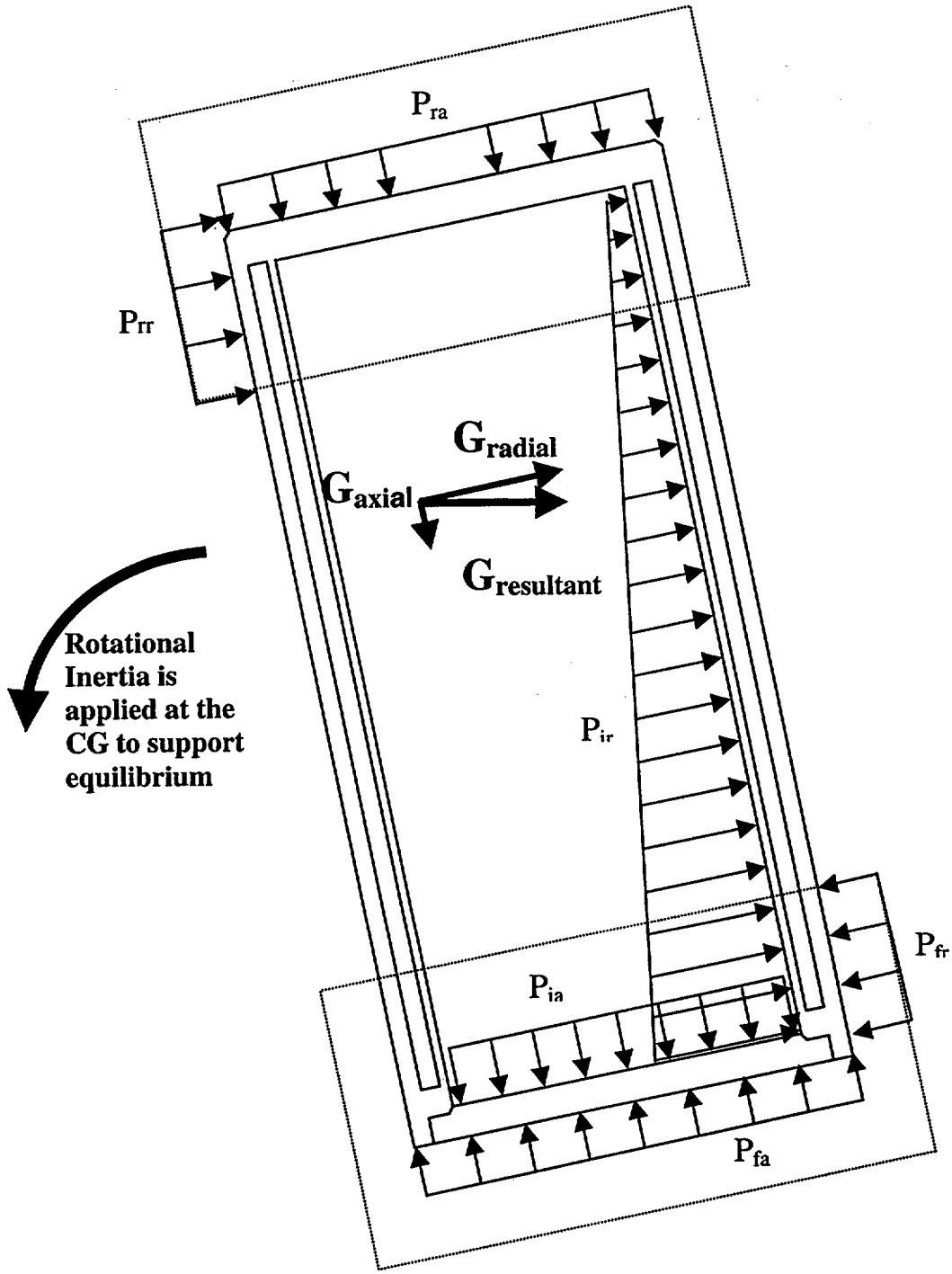


Figure 2.10.1-16: 30 Foot Oblique Impact on Lid End Loading

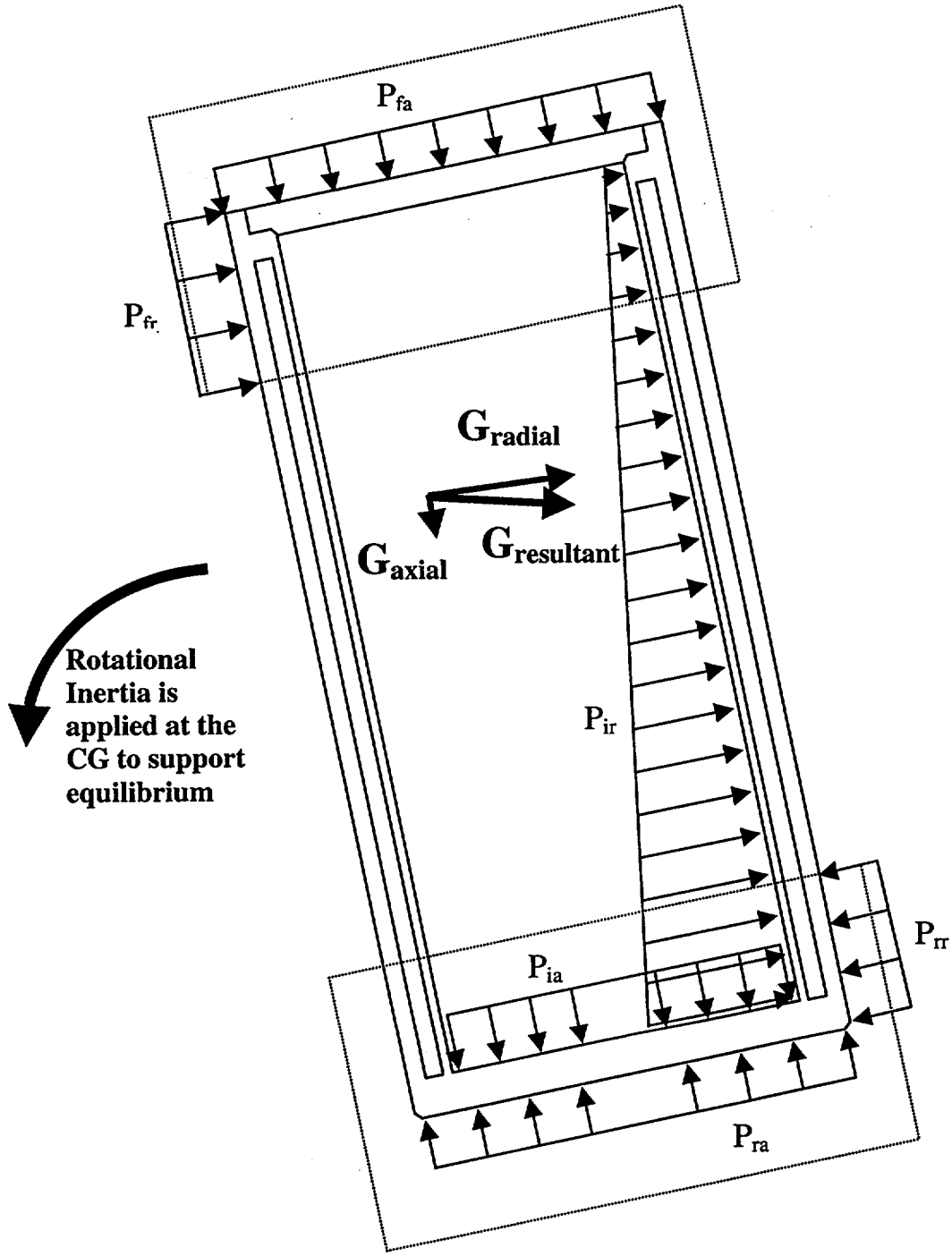


Figure 2.10.1-17: 30 Foot Oblique Impact on Bottom End Loading

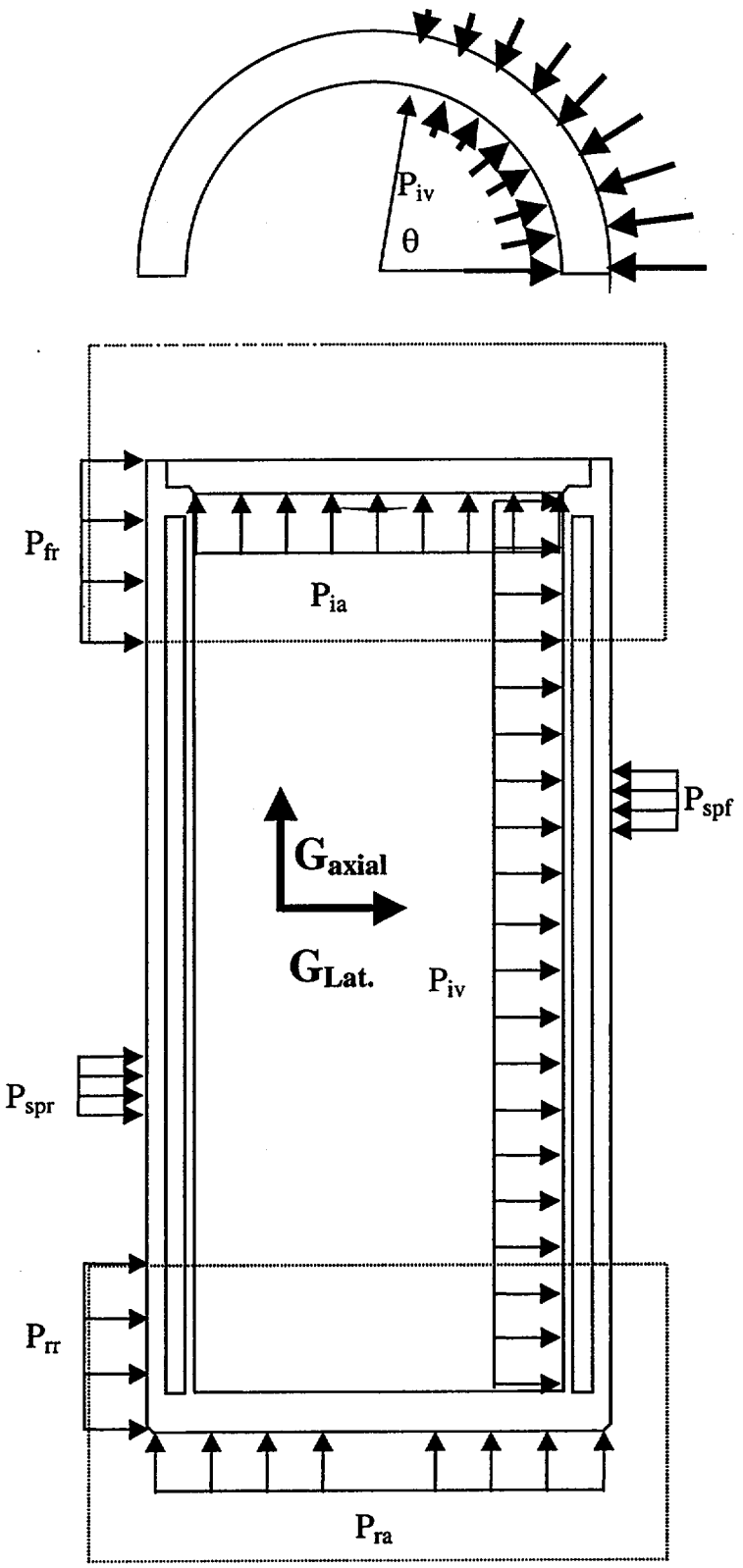


Figure 2.10.1-18: Tie-Down Loading

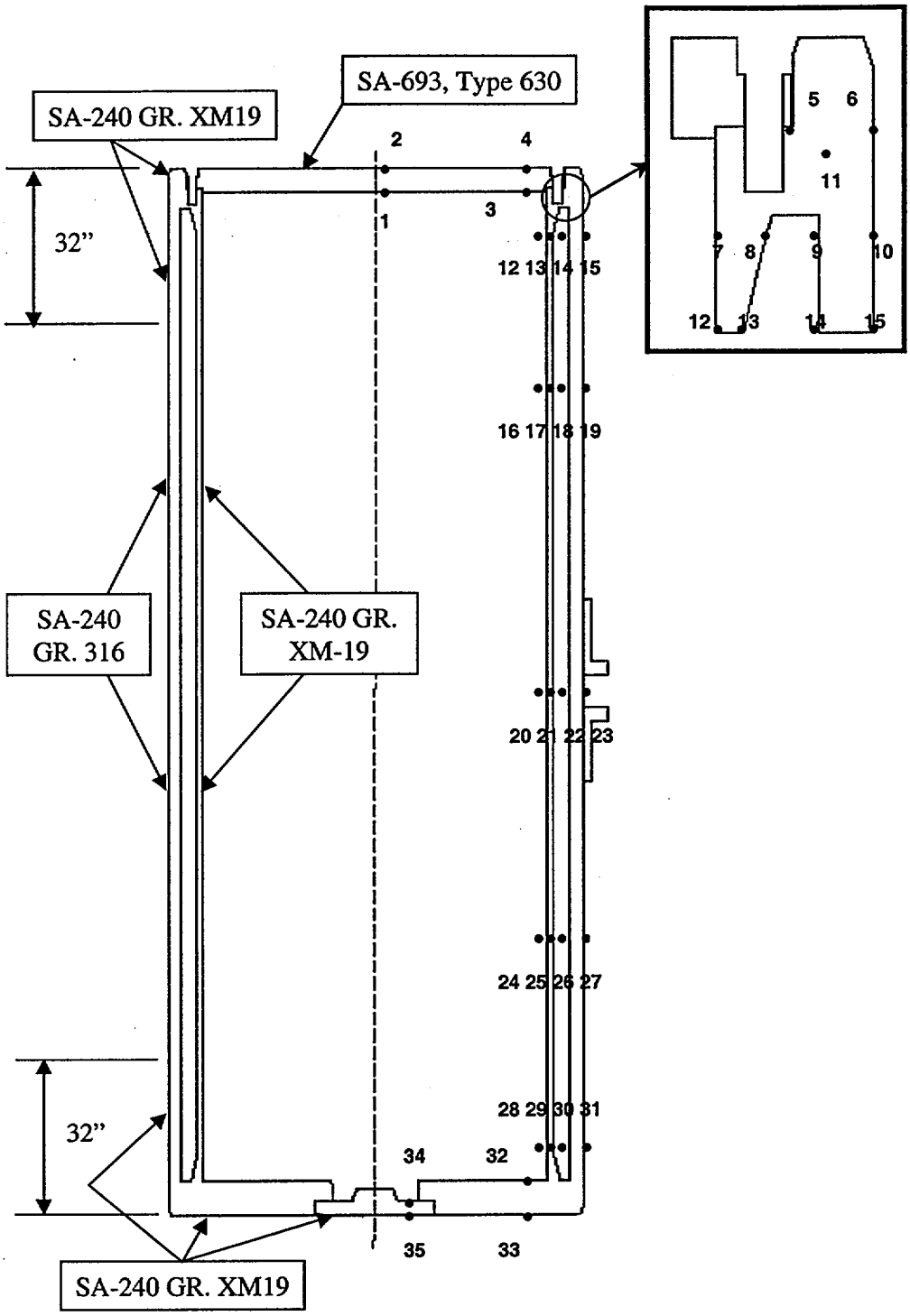
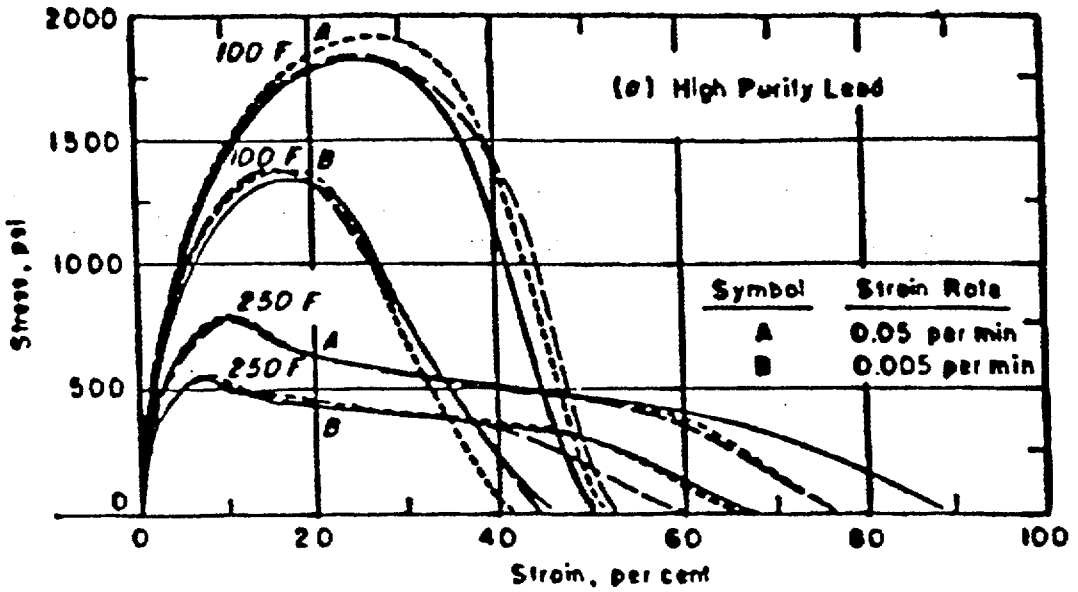
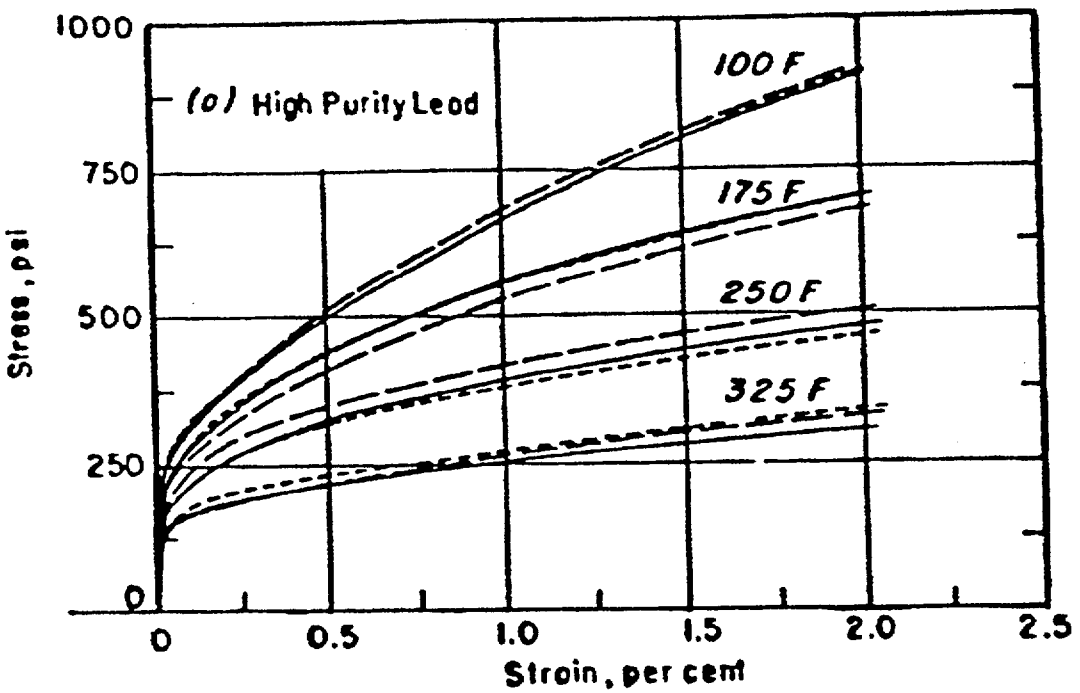


Figure 2.10.1-19:Standard Stress Report Locations



—Effect of Strain Rate on the Tensile Stress-Strain Curves at 100 and 250 F.



—Tensile Stress-Strain Curves to 2 per cent Strain at a Strain Rate of 0.005 per min.

Figure 2.10.1-20
Typical Stress-Strain Curve for Pure Lead

Figure 2.10.1-21

Stress Relaxation versus Time at Constant Strain Values of 0.2%, 0.5%, 1.0%, and 2.0% for Pure Lead

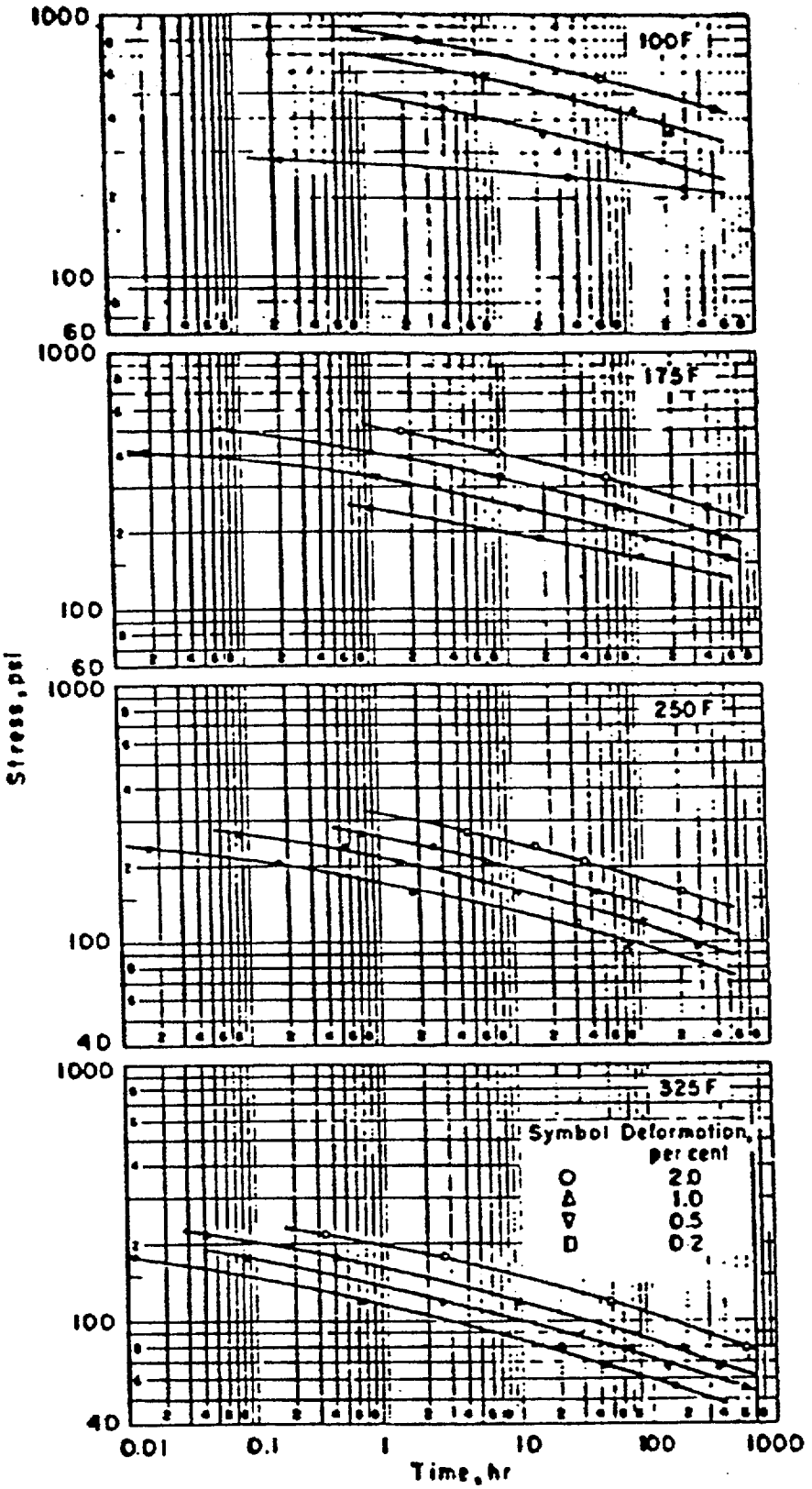
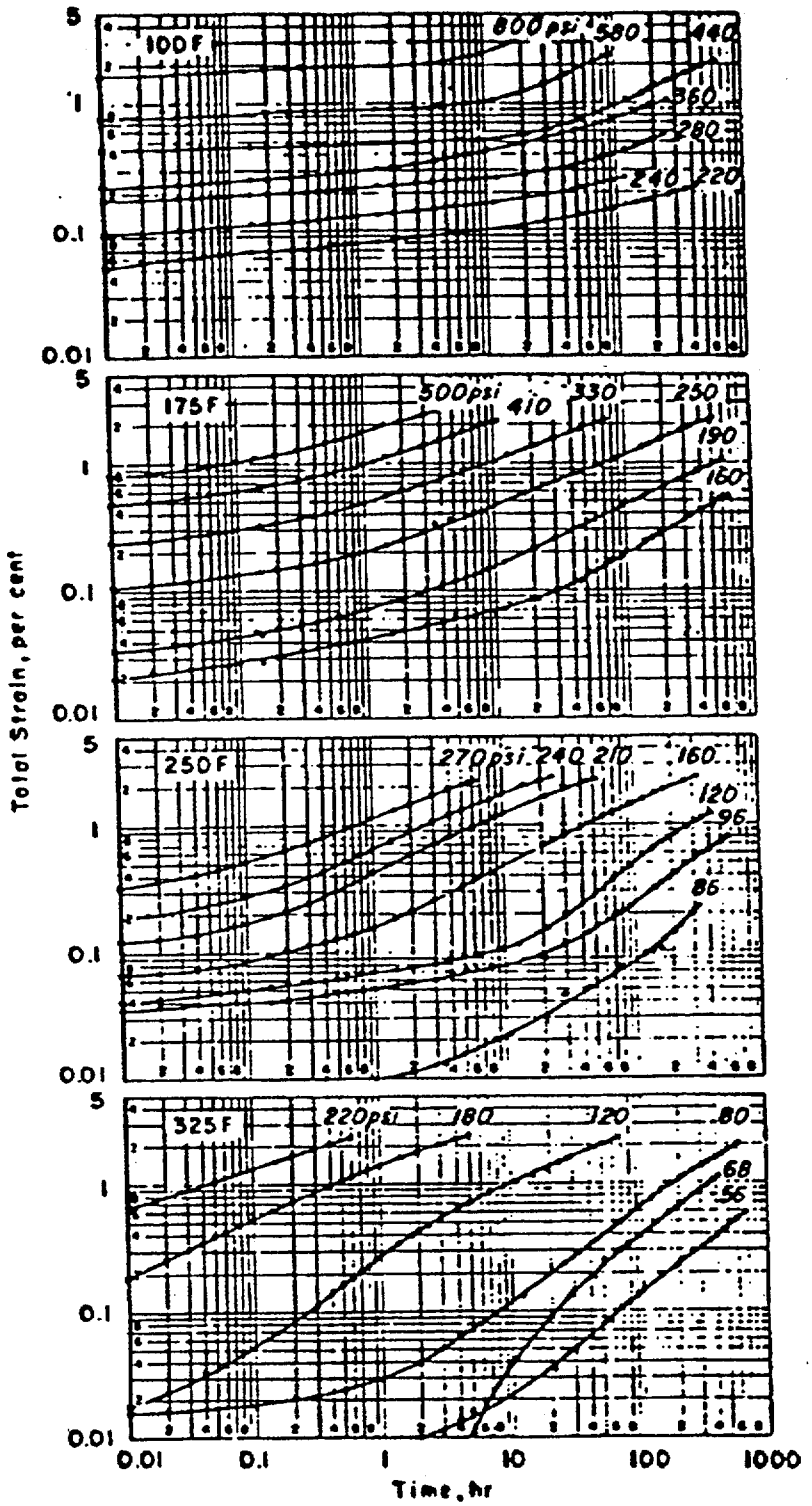


Figure 2.10.1-22

Total Strain versus Creep Time for Pure Lead

TIETZ ON PROPERTIES OF LEAD AT ELEVATED TEMPERATURES



—Total Strain *versus* Creep Time for High-Purity Lead.