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APPENDIX 3A

STRUCTURAL ANALYSIS OF THE TN-68 STORAGE CASK BODY

3A.1 Introduction

This appendix presents the structural analysis of the TN-68 storage cask body which consists of the cask body, the trunnions and the outer shell. Analyses are performed to evaluate the various cask components under the loadings described in Section 2.2.5.

The detailed calculations for the cask body are presented in Section 3A.2 and the lid bolt analysis is reported in Section 3A.3. The calculations for the outer shell are reported in Section 3A.4. The trunnions are analyzed in Chapter 3, Section 3.4.3.

The design criteria used in the analyses of the cask components are in accordance with the ASME Code, Section III, Subsection NB(1). The material properties used are those obtained from the ASME Code, Section II, Part D(2). Key dimensions of the storage cask are shown in Figure 3A.1-1.

3A.2 Cask Body Structural Analysis

3A.2.1 Description

The cask body as shown in Figure 3A.1-1 consists of:

1. A 1 1/2 in thick inner vessel with a welded flat bottom, a flange welded at the top, and a lid bolted to the flange by 48, 1.875 in diameter high strength bolts and sealed with two metallic o-rings. This is the confinement vessel, the primary confinement boundary of the cask.

2. A thick cylindrical vessel with a welded flat bottom surrounding the confinement. This vessel and a steel disk welded to the lid inner surface provide the gamma shielding.

The lid and the flange are carbon steel forgings as are the gamma shielding components. The cask body is designed as a Class 1 component in accordance with the rules of the ASME Code. A static, linear elastic analysis is performed on the cask body so that combinations of loads can be obtained by superposition of individual loads. The stresses and deformations due to the applied loads are generally determined using the ANSYS computer program(3). A 2D ANSYS model was specifically developed for this purpose. Exceptions include the analyses of the local effects at the trunnion and of the lid bolt locations, as well as effects of local loads due to tornado missile impacts.

3A.2.2 ANSYS Cask Model

A two dimensional ANSYS model is used to evaluate the stresses in the cask body due to the individual load cases. The finite elements used in the model are the axisymmetric shell element, SHELL 61, and the axisymmetric harmonic element, PLANE 25. Both of these elements consider axisymmetric and non-axisymmetric loadings.

The cylindrical confinement shell and bottom are modeled using SHELL 61 elements. The remainder of the cask body is modelled with PLANE 25 elements except for the lid bolts which are modelled with the two dimensional elastic beam, BEAM 3. The finite element model of the cask body is shown in Figure 3A.2-1.

Figure 3A.2-2 shows an enlarged view of the bottom corner with the weld joining the gamma shielding flat bottom to cylinder simulated by coupling nodes 236-107 and 280-108.

The weld connecting the gamma shielding cylinder to the confinement flange is simulated by coupling nodes 63-328 and 64-329 as shown in Figure 3A.2-3. The gamma shielding is heated prior to assembly with the confinement shell and flange for ease of installation. During cooldown, a gap may result between the flange and the gamma shield shell. The gap is filled with shim plates made from SA-516, Grade 70 plate. The plates are fit between the gamma shield shell and the flange behind the weld. These shim plates are not modeled. The weld between the gamma shield and the flange is not affected by the shims. Also shown in this figure are the lid bolts connecting the lid to the confinement flange. The connection is simulated by coupling nodes 505, 506 and 507 of the bolts to the corresponding nodes 81, 74, and 67 of the flange; and nodes 501, 502 and 503 of the bolts to the corresponding nodes 438,439, and 440 of the lid. In this manner the threaded portion of the bolt is fixed to the flange while the bolt head is fixed to the top surface of the lid. In order to prevent the lid from moving into the flange, nodes 79 and 395 are also coupled in the axial or Y direction. The enlarged view in Figure 3A.2-4 shows the coupling of nodes 394-383 and 395-384 which simulates the weld connecting the confinement lid to the gamma shielding disk.

The pairs of nodes listed above, with the exception of nodes 79-395, are coupled in the X, Y and Z directions. The coupling of nodes 79-395 is in the Y direction only. Nodes 80-396 and 82-398 are also coupled in Y-direction. These are accomplished using constraint equations. The reactions at these nodes are monitored during the analysis to insure that tensile forces between the flange and the lid are not developed.

Appropriate boundary conditions are applied to prevent rigid body motion and to show that the system of forces applied to the cask in each of the individual load cases is in equilibrium. Generally a node at the center of the vessel bottom is held in all directions and all nodes at the center line are held in the X direction. Node 78 (Figure 3A.2-3) is held in the Z direction to avoid rigid body motion.

3A.2.3 Individual Load Cases

Individual load cases are evaluated to determine the stress contribution due to specific individual loads. Stress results are reported in this Appendix for each individual load. Since the individual load cases are linearly elastic, their results can be ratioed and/or superimposed as required in order to obtain the load combinations characteristic of the particular loading condition.

3A.2.3.1 Normal Conditions

The following individual loads are analyzed using the ANSYS model described in the previous section: (These loads are defined in Chapter 2, section 2.2.5.4.1)

1. Bolt preload and seal seating pressure.
2. Internal pressure loading.
3. External pressure loading.
4. 1 g down with cask standing in a vertical position on the concrete storage pad.
5. 6 g lifting (Cask Vertical) load.
6. Worst normal thermal condition.
7. 1 g lateral and 2 g down bounding loads for tornado wind, flood water, and seismic loads on the cask standing in a vertical position on the concrete pad. The 2 g bounding load includes 1.0 g dead weight and 0.17 g seismic load.

Loadings for Cases 1 through 6 are axisymmetric. In Case 7, Fourier series representation of the nonaxisymmetric loads are required. Each discrete load acting on the cask body is expanded into a Fourier series and is input into ANSYS as a series of load steps. Each load step contains all of the terms from the applied loads having the same mode number. The number of terms in the

Fourier series required to adequately represent a load varies with the type of load (concentrated or distributed) and the degree of accuracy required. In this case, the load applied by the internals to the inside wall of the confinement is assumed to be a distributed load varying sinusoidally in the arc 90° to 270° and acting on the total length of the cavity. Figure 3A.2-5 shows that only a few terms of the series are required to get a satisfactory representation of the load.

Since Case 7 is asymmetric, the resulting stresses are asymmetric. Therefore, in order to properly characterize the stress condition in the cask body, results are obtained at the two worst diametrically opposite locations and reported for the location where they are maxima.

The individual loads are described in the following paragraphs:

1. Bolt Preload and Seal Seating Pressure

   A lid bolt preload corresponding to 35,000 psi (actual lid bolt preload stress is 25,000 psi, however, lid bolt preload corresponding to 35,000 psi is used for all load combinations) direct stress in the bolt shank is simulated by specifying an initial strain in the elements representing the bolts. A portion of this strain becomes elastic preload strain in the bolts, and a portion becomes strain in the clamped parts. The required initial strain value of 0.001309 in/in (in the bolts) was determined by trial and error.

   The selected bolt preload is sufficient to insure a full seating of the metallic seals under a maximum design internal pressure of 100 psig. The metallic seal seating load is 1,399 lb/in/seal(4) or 2,798 lb/in for 2 seals. This load is simulated by applying a pressure of 3,498 psi on an annular ring on both the confinement lid and flange surfaces as shown in Figure 3A.2-6.

2. Internal Pressure Loading

   A conservative design pressure of 100 psig is used as the maximum pressure acting in the confinement vessel cavity as shown in Figure 3A.2-7.

3. External Pressure Loading

   A pressure of 25 psig is used as the maximum external pressure acting on the outer surface of the cask body as shown in Figure 3A.2-8.

4. 1 g Down

   The cask is stored vertically on the concrete storage pad as shown in Figure 3A.2-9, with the following loads acting on it:

   a. A distributed vertical down inertia force of 1 g acting at each finite element in the model. For practical purposes, the resultant of all these forces is shown acting at the C.G. of the cask. Note that the resin, the outer shell and the trunnions are not included in the model. They are accounted for by increasing the density of the gamma shielding.

b. Since the internals are not included in the model, their loading effects are simulated by a distributed pressure acting on the inside bottom surface of the cask cavity.

c. All nodes on the outside bottom surface of the cask are fixed in the axial directions.

5. Lifting: 6 g Vertical Up

The cask is oriented vertically in space held by the 2 top trunnions and subjected to a vertical down load of 6 g, as shown on Figure 3A.2-10.

The inertia force acting on the cask elements and the pressure from the internals on the confinement bottom inner surface are as described in Case 4 multiplied by a factor of 6. The total cask weight (including internals) is replaced by forces applied to the 2 top trunnions so that the system of forces acting on the cask is again in equilibrium. A cask weight of 240,000 lb is used in the calculations. The two trunnion forces F_{TR} are replaced by a total force:

$$F_Y = 6.0 \text{ x } (240{,}000) \text{ x } 1.15 = 1{,}656{,}000 \text{ lb}$$

A 15% additional load is included to cover the dynamic effects of lifting. This force acting in the Y direction on the outer surface node 319 (location 36, Figure 3A.2-12) of the gamma shielding at the trunnion location. Superimposed on this solution are the local trunnion effects at two locations around the circumference which are determined by using the Bijlaard method. The trunnion flange and bolt stresses are determined using hand calculations.

6. Worst Temperature Distribution in the Cask Body

Thermal analyses of the cask under normal and off-normal storage conditions are performed in Chapter 4. An average daily ambient temperature of 100 ^{o}F is considered for the maximum off-normal storage temperature and –20 ^{o}F for the minimum off-normal storage temperature. Normal ambient storage temperatures are bounded by these two maximum and minimum off-normal temperatures. The temperature profiles in the cask, which are calculated from the thermal stress analyses in Chapter 4, are imposed to the ANSYS stress model of Figure 3A.2-1 for calculation of the thermal stresses.

7. 1 g Lateral and 2 g Down Bounding Loads - Cask Standing in a Vertical Orientation on the Pad.

The sinθ and cosθ terms of the Fourier series are used to represent the 1 g lateral load acting at the CG of each finite element model. The lateral load applied by the internals to the inside surface of the confinement is assumed to vary sinusoidally on a 180° arc as shown in Figures 3A.2-5, and the same Fourier representation applies. The 2 g down load is applied simultaneously (as described in item 4, above) with the 1 g lateral load. The cask is held at the bottom and no tilting or sliding is allowed (See Figure 3A.2-11). This load combination is an upper bound loading for tornado wind, flood water, seismic loads, etc. (See Table 2.2-3).

3A.2.3.2 Accident Conditions

This section evaluates the effects of a hypothetical drop or tipover of the cask on the ISFSI storage pad. The following cases are evaluated:

- An 18 inch end drop onto a concrete storage pad. This is the maximum height the cask will be lifted during transport to the storage location.
- A tipover of the cask onto a concrete storage pad.
- Fire Accident

The stability of the TN-68 storage cask in the upright position on the ISFSI concrete storage pad is demonstrated in Section 2.2 of this SAR. The effects of tornado wind and missiles, flood water and earthquakes are also described in Section 2.2. It is shown in this section that the cask will not tip over under the bounding natural phenomena specified.

The storage pad is the hardest concrete surface outside of the containment building. The cask is generally oriented vertically and is never lifted higher than 18 in once it leaves the containment building. Therefore this case is an upper bound drop event since impact onto a softer surface would result in lower cask deceleration and a lower impact force. The 18 in drop and tip over of the cask impact G loads are presented in Appendix D. Postulated end drops at specific sites which exceed 18 inches will be evaluated on a site specific basis to ensure that the g loading on the cask does not exceed 60 g's. If the cask is to be rotated after loading or handled horizontally at a specific site, evaluations shall be performed to verify that the equivalent side drop g loading of 65 g's is not exceeded. For example, if the cask needs to be lifted 3 feet at a specific site, impact limiters could be used to ensure that the end drop g loading does not exceed 60 g's.

The stress analysis results for two hypothetical impact accidents are reported in this section. These are the 60 g bottom end drop onto the storage pad (18 inch drop), and a 65 g side drop which envelops the tip over case. As explained in Chapter 2, these accidents have a very low probability of occurrence, but in view of their potential impact on the environs, a detailed analysis was performed. Thermal stresses caused by a fire accident are also evaluated in this section.

Cask Body Stress Analysis

A conservative 60 g bottom drop onto the concrete pad was analyzed. The ANSYS model in Section 3A.2.2 was used to evaluate the stresses in the cask body due to the drop. The 60 g bottom drop individual load case is simply 60 times the 1g vertical load case described previously.

A 65 g side drop was also analyzed. The applied load is asymmetric and a Fourier series representation of the loading is required. Figure 3A.2-14 shows the degree of approximation obtained when the series is truncated after 13 terms and the foot print of the external impact force is approximated by a rectangular strip along the cask length. The inertia force due to internals is applied as a cosine pressure distribution inside the cask. This pressure is represented by 3 terms of the Fourier series (Figure 3A.2-5). The side impact analysis results, at the selected locations, are reported in Table 3A.2.3-13 through 3A.2.3-16 for a side load of 1 g. Since a linear analysis was performed, the stresses for the 65 g load case will be 65 times the 1g load case results.

3A.2.3.3 Summary of Individual Load Cases

Stress results for these individual loads are reported in Tables 3A.2.3-1 through 3A.2.3-18. Figure 3A.2-12 shows the locations on the cask body, where stress results are reported. These locations are divided into two groups, confinement and non-confinement. Stress intensities at nodal locations on the inner and outer surfaces of each cask body component are reported in these tables.

These results are provided to indicate the relative significance of the individual loads. These point-wise results are combined in Section 3A.2.5 with the results of several hand computations to provide results for the various load combinations which are compared to the design criteria in Chapter 3.

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

- Bolt Preload

  Bolt tensile stress = Strain * Modulus of Elasticity

  $$= .001309 \times 27.8 \text{ E } 10^6 = 36{,}390 \text{ psi}$$

  This is close to the simulated preload of 35,000 psi by the computer run which takes into account the flange and lid stiffnesses.

- Internal Pressure (100 psig)

  Membrane stress intensity in a cylinder = $\frac{P * r_m}{t} + \frac{P}{2}$

  = [(100 * 38.5 / 7.5) + (100/2)] = 513 psi

  Average of stress intensities at locations 11 and 32 (Figure 3A.2-12) from computer output at Tables 3A.2.3-5 and 3A.2.3-6 = ½ (589 + 416) = 503 psi. This is close to the hand-calculated stress intensity.

- Normal Thermal Condition

  Thermal stress in a cylinder = $\frac{E * \alpha * \Delta T}{2(1-\mu)}$

  ΔT between locations 11 and 32 ≅ 210 – 201 = 9°F
  Thermal stress = (28.6E6*6.7E-6*9)/(2*0.7) = 1232 psi

  Average stress intensity at locations 11 and 32 from computer output (Tables 3A.2.3-9 and 3A.2.3-10) = ½ (1220+1699) = 1460 psi. This is close to the hand-calculated intensity.

The above comparison indicates that the finite element response to various simple loads is reasonable.

3A.2.3.4 Fire Accident

The lid and lid bolts reach about 470°F (see Table 4.4-1). Since the lid and lid bolts have the same thermal expansion coefficients, no bolt preload will be lost and a positive (compressive) seal load is maintained during the fire accident conditions.

The maximum temperature in seal region is 470^{o}F (SeeTable 4.4-1) which is lower than the maximum allowable operating temperature of 536^{o}F for the Helicoflex seal.

The basket temperature does not change appreciably while the cask temperature rises during the fire accident (See Table 4.4-1). The gap between the outside diameter of the basket and inside diameter of the cask will slightly increase (See Section 3B.3.4), therefore, no thermal stress will be induced in the basket.

3A.2.4 Additional Cask Body Analyses

Additional analyses of the cask body were performed using classical methods rather than the ANSYS finite element method. These analyses determine the maximum stresses at local points on the body: (a) due to the trunnion reactions (while lifting the cask) and (b) in the locations where tornado missile impact might occur.

3A.2.4.1 Trunnion Local Stresses

The local stresses in the cask body outer gamma shielding at the trunnion locations due to the loadings applied through the trunnions are described in Section 3.4.3. These local effects are not included in the ANSYS stress result tables reported above in Section 3A.2.3. The local stresses must be superimposed on the above stress results for the cases where the inertial lifting loads are reacted at the trunnions. The local stresses are calculated in accordance with the methodology of WRC Bulletin 107(6) which is based on the Bijlaard analysis for local stresses in cylindrical shells due to external loadings.

The maximum membrane and membrane plus bending stress intensities due to a vertical lift (6 G) are 7.3 ksi and 19.8 ksi, respectively. These local stresses are combined with the finite element results from Section 3A.2.3 at the same locations (15,16,35, and 36 of Figure 3A.2-12) and compared with the allowables in Section 3A.2.5.

3A.2.4.2 Tornado Missile Impact

According to NUREG-1536 (Reference 12), the cask systems are not required to survive missile impacts without permanent deformations. The stresses due to tornado missiles are presented in chapter 2 in section 2.2.1.3. It is seen from the summary table that the maximum stress of 32.3 ksi occurs due to missile B (8 inches diameter rigid missile). The maximum wall penetration of 1.13 inches is also caused by missile B. This maximum stress is conservatively added to the highest stress (irrespective of its location) due to combined effect of bolt preload, 1 G down, 25 psi external pressure and thermal loads in Table 3A.2.5-11 which is 13 ksi (at location 23). It may be noted that this stress is almost entirely due to thermal gradient and the stresses due to other loads are negligible. Therefore, the wall thickness reduction due to 1.13 inch penetration will have no significant effect on these stresses.

Thus, the maximum combined stress due to tornado missiles, preload, gravity, external pressure and thermal load = 32.3 + 13 = 45.3 ksi. This stress is less than even the accident membrane allowable of 49 ksi ($0.7S_u$). It is further seen from Table 3.4-6 that stresses due to this load combination are less than reported for stress combinations with tip-over load and therefore are not bounding.

3A.2.4.3 Impact on a Trunnion

This section describes the analysis of the storage cask tipping over and impacting against the ISFSI concrete pad with the cask oriented so that an upper trunnion contacts the pad. The analyses of the trunnions and cask body under Normal conditions (when the trunnions are used to lift the cask) are reported in Section 3.4.3. This analysis is a variation of the Hypothetical Tipping Accident analyzed in 3A.2.3 to consider the particular case of the cask contacting the pad on a trunnion.

The upper trunnion could strike the pad during tipover, but the consequences would be minimal. The contact area between the cask and pad would initially be equal to the projected end area of the trunnion. The trunnion would punch into the pad for a few inches until the neutron shield and then the forged gamma shield strike the concrete pad. At this point the contact area between the cask and pad would be the full side area of the cask (as analyzed in Section 3A.2.3.2).

From Figure 3A.2-15, the projected trunnion area is $(\pi/4)(11.25^2-7.60^2)$ or 54.04 in^2. For a 4,200 psi concrete compressive strength, the impact force on the end of the trunnion would be (54.04)(4,200) = 226,968 lb

The center of the trunnion is 173.25 in above the corner of the cask (the pivot point). The 226,968 lb impact force would apply a torque or moment about the pivot point of (226,968)(173.25) or 39.32×10^6 in- lb. The moment of inertia of the cask about the corner pivot point is $I_p = 8.77 \times 10^6$ lb- in- sec^2. The rotational deceleration that would occur as the trunnion punches into the concrete can be determined from the relationship Torque = I α or α = Torque/I. The rotational deceleration, α, = 39.32×10^6 in-lb/8.77×10^6 lb- in- $sec.^2$ or 4.483 radians/sec^2.

The translational deceleration at any distance (d) from the pivot point is equal to (d) x α. The deceleration at the CG where d = 105.72 in from Figure 2.2-2 is (105.72)(4.483) = 473.9 in/sec^2. This is a deceleration at the CG of 473.9/386 = 1.23g. Therefore, the peak CG deceleration of the cask during initial trunnion impact after tipover is much less than 65 g deceleration conservatively determined in Section 3A.2.3 for full side impact. Therefore the stress analysis cases for the cask body (except for the local gamma shielding stresses due to the trunnion loads) and basket conservatively assuming 65 g deceleration bound those for the 1.26g trunnion impact case.

The trunnion is attached to the gamma shielding of the cask body using a flanged connection with 12-1.5 in diameter high strength bolts. The compressive stress in the trunnion due to the trunnion impact force would be $226{,}968/[(\pi/4)(9.75^2-7.6^2)]$ or 7.8 ksi. The minimum wall thickness of the gamma shielding at the flat machined for the trunnions is 5.09 in. Therefore the shear stress around the plug of gamma shield material behind the 17 inch diameter trunnion flange is $226{,}968/(\pi \times 17.0 \times 5.09)$ or 0.9 ksi. The bearing stress under the flange is $226{,}968/\pi(8.5)^2$ or 1.0 ksi.

The local and discontinuity stresses in the gamma shell are computed using Ref. 8 (shell subjected to radial load P uniformly distributed over small area A).

Area, $A = \pi(8.5)^2 = 227$ in^2
Shell thickness, t = 5.09 in
Shell mean radius, R = 36.25 + 5.09/2 = 38.80 in
P = 226,968 lb

$A/R^2 = 227/38.80^2 = 0.15$

R/t = 38.80/5.09 = 7.62

From Ref. 8, Table XIII, Case 7

$S'_2 (t^2)/P \approx .6$ and $S_2(Rt)/P \approx 2.0$

Where S'_2 is hoop bending stress and
S_2 is hoop membrane stress

$$S'_2 = \frac{.6\ (226{,}968)}{(5.09)^2} = 5{,}256 \text{ psi} = 5.3 \text{ ksi}$$

$$S_2 = \frac{2.0 \times 226{,}968}{38.80 \times 5.09} = 2{,}299 \text{ psi} = 2.3 \text{ ksi}$$

Combined hoop stress, $\sigma_H = 5.3 + 2.3 = 7.6$ ksi
Assuming Conservatively, Longitudinal Stress = Hoop Stress = 7.6 ksi
Shear Stress = 0.9 ksi

Therefore, the maximum Stress Intensity = 8.5 ksi

The allowable stress intensities for non confinement structure in Table 3.1-4 for Level D loads can be used to evaluate these Hypothetical Accident stresses, in the gamma shielding.

S_u and S_m for the SA-266 gamma shielding at 400°F is 70 ksi and 20.6 ksi, respectively. The membrane plus bending allowable, $P_m + P_b$, is the smaller of $3.6S_m$ or S_u, which is 70 ksi. The allowable shear stress is 0.42 S_u or 29.4 ksi.

The 0.9 ksi shear stress is well below the 29.4 ksi shear limit. The maximum combined stress intensity is 8.5 ksi is also well below the allowable of 70 ksi. Therefore tipping of the cask onto a trunnion results in acceptable stresses.

3A.2.5 Evaluation (Load Combinations Vs. Allowables)

The TN-68 cask loading conditions are listed in Section 2.2.5, Table 2.2-4. The individual loads acting on the various cask components due to these loading conditions have been applied to the cask and the resulting stresses are reported in Tables 3A.2.3-1 through Table 3A.2.3-18.

The loading conditions listed in Table 2.2-4 are categorized according to the rules of the ASME Code, Section III, Subsection NB for Class 1 nuclear components. These categories include Normal (Design and Level A) and Hypothetical Accident (Level D) loading conditions. See Tables 2.2-5 through 2.2-7 for these categories. Next, the load combinations are determined based on those loads that can occur simultaneously. The individual loads of each combination are indicated in Tables 2.2-8 and 2.2-9.

The stress intensities for the combined load cases are evaluated using ANSYS postprocessor and hand calculations at the locations indicated in Figure 3A.2-12 and compared to the stress limits associated with each service loading. The normal condition load combinations are summarized in Table 3A.2.5-1. Stresses due to normal condition load combinations are presented in Tables 3A.2.5-2 through 3A.2.5-13. The accident condition load combinations are summarized in Table 3A.2.5-14. Stresses due to accident condition load combinations are presented in Tables 3A.2.5-15 through 3A.2.5-30.

Tables 3A.2.5-1 and 3A.2.5-14 provide matrices of the individual loads and how they are combined to determine the cask body stresses for the specified normal and accident conditions. The thermal stresses are actually secondary stresses that could be evaluated using higher allowables than for primary stresses. They are conservatively added to the primary stresses and the combined stresses are evaluated using primary stress allowables. Finally, for those load combinations that include trunnion reactions, the local stresses at the trunnion locations found by the Bijlaard method are superimposed on the ANSYS combined stresses at the stress reporting locations near the trunnions. In nearly all of the locations selected the stress intensities thus calculated are less than the membrane allowable stress. At the two locations (locations 25, 32, and 34, Figure 3A.2-12) where the maximum combined stress intensities (membrane plus bending) exceed the membrane allowable stress, the stresses are linearized and membrane and bending stresses are separated for comparison with the allowables.

3A.3 Lid Bolt Analyses

3A.3.1 Introduction

The TN-68 cask lid closure arrangement is shown in Figure 3A.3-1. The 5.0 inch thick lid is bolted directly to the end of the confinement vessel flange by 48 high strength alloy steel 1.875 inch diameter bolts. Close fitting alignment pins ensure that the lid is centered in the vessel.

The lid bolt is shown in Figure 3A.3-2. The bolt material is SA-540 Gr. B24 class 1 which has a minimum yield strength of 150 ksi at room temperature.

This section analyzes the ability of the cask closure to maintain a leak tight seal under normal and accident conditions. Also evaluated in this section, are the bolt thread and internal thread stresses. The stress analysis is performed in accordance with NUREG/CR-6007(10).
The following evaluations are documented in this section:

- Lid bolt torque
- Bolt preload
- Gasket seating load
- Pressure load
- Temperature load
- Impact load
- Thread engagement length evaluation
- Bearing stress
- Load combinations for normal and accident conditions
- Bolt stresses and allowables

The following loads are used in the lid bolt analysis:

Cask cavity pressure = 100 psig
Impact loads: bottom end drop = 60 g
Tip over drop = 65 g

The design parameters of the lid closure are summarized in Table 3A.3-1. The lid bolt data and material allowables are presented in Tables 3A.3-2 to 3A.3-4. The following load cases are considered in the analysis. A maximum temperature of 300°F is used in the lid bolt region during normal and accident conditions.

Load Case #1: Preload + Temperature Load (normal condition)
Load Case #2: Pressure Load (Normal Condition)
Load Case #3: Pressure + Gasket Load + Impact Load (accident condition)

3A.3.2 Bolt Load Calculations

Symbols and terminology for this analysis is taken from NUREG/CR-6007 and are reproduced in Table 3A.3-1.

A. Lid Bolt Torque

The desired maximum preload stress in lid bolts is 25,000 psi

For a 1 7/8" – 8UN – 2A bolt,

Tensile Stress Area = 2.414 in^2 (see Table 3A.3-1)

F_a= 25,000 x Stress Area = 25,000 x 2.414 = 60,350 lb

The torque required to achieve this preload is (Ref. 10, Section 4.0):

$Q = K\, D_b\, F_a$ = 0.1 (1.875) (60,350) = 11,315 in- lb = 943 ft- lb

A bolt torque range of 840 to 940 ft-lb has been selected.

Using the minimum torque,

F_a = 840 x 12/(0.1 x 1.875) = 53,760 lb, and
Preload stress = 53,760/2.414= 22,270 psi.

B. Bolt Preload (Ref. 10, Table 4.1)

$F_a = Q/KD_b$ = 11,315/0.1(1.875) = 60,350 lb

Residual torsional moment, M_{tr} = 0.5Q =.5(11,315) = 5,657 in-lb
Residual tensile bolt force, $F_{ar} = F_a$ = 60,350 lb

C. Gasket Seating Load (Seal - Helicoflex HND 229, Aluminum Jacket -Ref 4)

The diameter of inner seal, D_{ls} = 71.3 in
The diameter outer seal, D_{os} = 72.9 in
The force to seat the seals is 1399 lb/in (245 N/mm) (Ref. 4) times the circumference of the seal.

The force required to seat the seals is:

Inner π (71.3) (1399) = 313,370 lb
Outer π (72.9) (1399) = 320,402 lb

Total, F_a = 633,772 lb

Therefore, The gasket seating load is:

$F_a/48 = 633{,}772/48 = 13{,}204$ lb/bolt

D. Pressure Loads (Ref. 10, Table 4.3)

Axial force per bolt due to internal pressure is:

$$F_a = \frac{\pi D_{lg}^2 \ (pli - Pl_o)}{4 N_b}$$

D_{lg} for outer seal (conservative) = 72.9 in

$$F_a = \frac{\pi (72.9)^2 (100 - 0)}{4 (48)} = 8{,}696 \text{ lbs/bolt}$$

Fixed edge closure lid force,

$$F_f = \frac{D_{lb} (Pli - Pl_o)}{4} = \frac{75.88(100)}{4} = 1897 \text{ lb/in}$$

Fixed edge closure lid moment,

$$M_f = \frac{(Pli - Pl_o) D_{\ell b}^2}{32} = \frac{100 \text{ x } (75.88)^2}{32} = 17{,}993 \text{ in-lb/in}$$

Shear bolt force per bolt,

$$F_s = \frac{\pi E_l t_l (Pli - Pl_o) D_{lb}^{\ 2}}{2 N_b E_c t_c (1 - N_{\upsilon l})} = \frac{\pi (27.8 * 10^6)(5.0)(100)(75.88)^2}{2(48)(27.8 * 10^6)(7.5)(0.7)} = 17{,}945 \text{ lbs/bolt}$$

This shear force is taken by the lid shoulder during the tipover accident.

E. Temperature Loads

The lid bolt material is SA-540GR.B24 Cl. 1, 2Ni ¾ Cr 1/3 M_o. This is Group E in the thermal coefficients of expansion tables in Reference 2. The lid is SA-350 Gr. LF3, 3 ½ Ni, which is in Group E also. The flange is also made of SA- 350 Grade LF3. Thus, bolts, lid and flange have same coefficient of thermal expansion (6.78 x 10^6 in/in-^{o}F at 300^0F). Therefore, heating to the maximum isothermal temperature will have no effect on the loads.

F. Impact Loads (Ref. 10, Table 4.5)

Non-Prying tensile bolt force, per bolt (F_a)

$$F_a = \frac{1.34 \text{ Sin (xi) DLF ai (Wl + Wc)}}{N_b} = \frac{1.34 \text{ x Sin (xi) (1.2) ai (89500)}}{48} = 2{,}998.3 \text{ ai Sin (xi) lb/bolt}$$

Shear bolt force

$$F_s = \frac{\text{Cos (xi) ai } W_l}{N_b} = \frac{\text{(12,100) ai Cos (xi)}}{48} = 252.1 \text{ ai Cos (xi)}$$

Shear force is taken by the lid shoulder during accident condition drops.

$$F_s = 0$$

Fixed-edge closure lid force (F_f)

$$F_f = \frac{1.34 \text{ Sin (xi) DLF ai } (W_l + Wc)}{\pi D_{lb}} = \frac{1.34 \text{ Sin (xi) (1.2) ai (89,500)}}{\pi(75.88)}$$

$$= 604 \text{ ai Sin (xi)}$$

Fixed-edge closure lid moment (M_f)

$$M_f = \frac{1.34 \text{ Sin (xi) DLF ai } (W_l + Wc)}{8\pi} = \frac{1.34 \text{ Sin (xi) (1.2) ai (89500)}}{8\pi}$$

$$= 5726 \text{ ai Sin (xi)}$$

Loads for bottom end drop

ai = 60 g

In case of bottom impact, the non-prying and prying bolt forces are zero.

$F_a = 0$ $F_f = 0$ $M_f = 0$

Loads for tipover

Maximum tip over G load = 65

For the lid bolt load calculations, it is assumed that cask is oriented 10^o below horizontal at the end of tipover with 65 g. maximum rigid-body acceleration. This is very conservative since the impacting end of the cask is not expected to indent into the concrete enough to result in a 10° angle.

$F_a = 2998.3\ (65)\ (\sin 10^o) = 33{,}911$ lbs/bolt

$F_f = 614\ (65)\ (\sin 10^o) = 6{,}831$ lbs/in

$M_f = 5726\ (65)\ (\sin 10^o) = 64{,}761$ in-lb/in

The individual lid bolts are summarized in the following table.

LID BOLT INDIVIDUAL LOAD SUMMARY

Load Type	Condition	Non-Prying Tensile Force, F_a (lb)	Torsional Moment, M_t (in-lb)	Prying Force, F_f (lb/in)	Prying Moment, M_f (in-lb/in)
Preload	Residual	60,350	5,657	0	0
Pressure	100 Psig Internal	8,696	0	1,897	17,993
Gasket	Seating Load	13,204	0	0	0
Impact	End Drop (60 G)	0	0	0	0
	Tipover (65 G)	33,911	0	6,831	64,761
Thermal	300^oF	0	0	0	0

3A.3.3 Load Combinations (Ref. 10, Table 4.9)

A summary of normal and accident load combinations is presented in the following table.

LID BOLT NORMAL AND ACCIDENT LOAD COMBINATIONS

Load Case	Combination Description	Non-Prying Tensile Force, F_a (lb)	Torsional Moment, M_t (in-lb)	Prying Force, F_f (lb/in)	Prying Moment, M_f (in-lb/in)
1	Preload + Temp Load (Normal)	60,350	11,315**	0	0
2	Pressure (Normal)	8696	0	1,897	17,993
3	Pressure + Tip over (Accident)	42,607	0	8,728	82,754

** 100% torque is used as M_t in load combination and stress calculations.

The maximum bending bolt moment generated by the applied load is evaluated as follows:

Bending Moment Bolt, M_{bb} (Ref. 10, Table 2.2)

$M_{bb} = (\pi \times D_{lb}/N_b)\ [\ K_b/(K_b + K_l)]\ M_f$

The K_b and K_l are defined in reference 10, Table 2.2, by substituting the values given above,

$K_b = 0.68 \times 10^6$ and $K_l = 11.29 \times 10^6$

Therefore, $M_{bb} = 0.282\ M_f$,

For normal condition, M_f = 17,933 in-lb

Substituting the value given above,

M_{bb} = 5,074 in-lb/bolt

3A.3.4 Bolt Stress Calculations (Ref.10, Table 5.1)

A. Average Tensile Stress

Normal Condition $Sb_a = 1.2732 \dfrac{(60{,}350)}{(1.753)^2} = 25{,}000 \text{ psi} = 25.0 \text{ ksi}$

Accident Condition $Sb_a = 1.2732 \dfrac{(60{,}350)^{**}}{(1.753)^2} = 25{,}000 \text{ psi} = 25.0 \text{ ksi}$

** The bolt preload is calculated to withstand the worst case load combination and to maintain a clamping (compressive) force on the closure joint, both under normal and accident conditions. Based upon the load combination results (see Table on pg. 3A.3-6), it is shown that a positive (compressive) load is maintained on the clamped joint for all load combinations. Therefore, in both normal and accident load cases, the maximum non-prying tensile force of 60,350 lbs from preload + temperature load is used for bolt stress calculations.

B. Bending Stress

$S_{bb} = \dfrac{10.186\ M_{bb}}{(D_{ba})^3}$ $M_{bb} = 5{,}074$ in-lb

$S_{bb} = 10.186\ (5{,}074)/1.753^3 = 9{,}595 \text{ psi} = 9.6 \text{ ksi}$

C. Shear Stress

Average shear stress caused by shear bolt force (Fs)

$S_{BS} = 0$

Maximum shear stress caused by the torsional moment (M_t)

$S_{bt} = \dfrac{5.093\ M_t}{(D_{ba})^3} = 5.093 \dfrac{(11{,}315)}{(1.753)^3} = 10{,}698 \text{ psi} = 10.7 \text{ ksi}$

D. Maximum Stress Intensity Caused By Tension + Shear + Bending + Torsion

$S_{bi} = [(Sb_a + S_{bb})^2 + 4(Sb_s + Sb_t)^2]^{0.5}$

For normal condition;

$S_{bi} = [(25{,}000 + 9{,}595)^2 + 4\ (0 + 10{,}698)]^{0.5} = 40{,}677$ Psi = 40.7 ksi

E. Stress Ratios

$R_t^2 + R_s^2 < 1$

For normal conditions: (Ref. Table 3A.3-3)

$R_t = 25{,}000/92{,}400 = 0.27$, $R_s = 10{,}698/55{,}400 = 0.19$

$R_t^2 + R_s^2 = (0.27)^2 + (0.19)^2 = 0.11 < 1.0$ O.K.

For accident conditions: (Ref. Table 3A.3-4)

$R_t = 25{,}000/115{,}500 = 0.22$

$R_t = 10{,}698/69{,}300 = 0.15$

$R_t^2 + R_s^2 = (0.22)^2 + (0.15)^2 = 0.07 < 1.0$ O.K.

F. Bearing Stress (Under Bolt Head)

Maximum Axial Force = 60,350 lb

Bolt head corresponding to 2 1/4" dia. Bolt is used for 1 7/8" dia. Shank due to higher bearing load in transport. The total bearing area under the 2 1/4" Hex bolt head is 5.54 in^2 The bearing stress is:

Bearing Stress = 60,350/5.54 =10,894 psi = 10.9 ksi

3A.3.5 Results

A summary of the stresses is listed in the following table:

SUMMARY OF STRESSES AND ALLOWABLES

Stress Type	Normal Condition	Accident Condition
Avg. Tensile (ksi) Allowable (ksi)	25.0 92.4	25.0 115.5
Shear (ksi) Allowable (ksi)	10.7 55.4	10.7 69.3
Combined (ksi) Allowable (ksi)	40.7 124.7	(Not Required per Reference 10)
Interaction E.Q. $R_t^2 + R_s^2 < 1$	0.11	0.07
Bearing (ksi) Allowable (ksi) (S_y of lid material)	10.9 33.2	(Not Required per Reference 10)

The calculated bolt stresses are all less than the specified allowable stresses.

3A.3.6 Minimum Engagement Length, L_e For Bolt And Flange (Ref. 11, Page 1149)

$$L_e = \frac{2A_t}{3.146K_{n\max}\left[\frac{1}{2} + .57735n\left(E_{s\min} - K_{n\max}\right)\right]}$$

Bolt: 1 7/8" – 8UN – 2A

Material: SA – 540 GR. B24 Cl.1

Su = 165 ksi Sy = 150 ksi (at room temperature)

Flange Material: SA – 350 GR. LF3

Su = 70 ksi Sy = 37.5 ksi (at room temperature)

A_t: Tensile Stress Area = 2.414 in^2

n: Number Of Threads = 8

$K_{n\ Max}$: Maximum Minor Diameter Of Internal Threads = 1.765 in

$E_{s\ Min}$: Minimum Pitch Diameter Of External Threads = 1.7838 in

$D_{s\ min}$: Minimum Major Dia. Of External Threads = 1.8577”

Substituting the values given above,

$$L_e = \frac{2 \times 2.414}{3.1416 \times 1.765\ [0.5 + .57735 \times 8\ (1.7838 - 1.765)]} = 1.484 \text{ in}$$

$$J = \frac{A_s \text{ x Tensile Strength of External Thread Material}}{A_n \text{ x Tensile Strength of Internal Thread Material}}$$

A_s: Shear Area External Threads = 3.1416 $nL_e\ K_{n\ max}\ [1/2n + .57735\ (E_{s\ min} - K_{n\ max})]$

A_n: Shear Area, Internal Threads = 3.1416 $nL_e\ D_{s\ min}\ [1/2n + .57735(D_{s\ min} - E_{n\ max})]$

A_s = 3.1416 x 8 x 1.484 x 1.765 [1/(2 x 8) + .57735 (1.7838 – 1.765)] = 4.829 in^2

$E_{n\ max}$: Max. Pitch Dia. of Internal Threads = 1.8038”

A_n = 3.1416 x 8 x 1.484 x 1.8577 [1/(2 x 8) + .57735 (1.8577 – 1.8038)] = 6.487 in^2

$$J = \frac{4.829 \times 165.0}{6.487 \times 70.0} = 1.755$$

Therefore, the minimum required engagement length, Q = JL_e = 1.755 x 1.484 = 2.605 in

The actual minimum engagement length = 2.79 in > 2.605 in O.K.

3A.3.7 Conclusions

1. Bolt stresses meet the acceptance criteria of NUREG/CR-6007 "Stress Analysis of Closure Bolts for Shipping Casks".
2. A positive (compressive) load is maintained during normal and accident condition loads as bolt preload is higher than the applied loads.
3. The bolt and flange thread engagement length is acceptable.

3A.4 Outer Shell

This section presents the structural analysis of the outer shell of the TN-68 storage cask. The outer shell consists of a cylindrical shell section and closure plates at each end which connect the cylinder to the cask body. The normal loads acting on the outer shell are due to internal and external pressure and the normal handling operations. Membrane stresses and bending due to the pressure difference and handling loads are determined. These stresses are compared to the allowable stress limits in Section 3.1 to assure that the design criteria are met.

3A.4.1 Description

The outer shell is constructed from low-alloy carbon steel and is welded to the outer surface of the cask body gamma shielding. The cylindrical shell section and the closure plates are 0.75 in thick. Pertinent dimensions are shown in Fig. 3A.4-1 and Drawing 972-70-1.

3A.4.2 Materials Input Data

The outer shell cylindrical section and closure plates are SA 516-GR 70. The material properties are taken from the ASME(2) Code, Section II, Part D. The yield strength of the material is also obtained from the code at a temperature of 300°F.

3A.4.3 Applied Loads

It is assumed that a pressure of 25 psi may be applied to the inside or outside of the outer shell. This bounding assumption envelopes the actual expected pressures described in Section 2.2.5.

The handling loads acting on the outer shell are a result of lifting. The loads applied to the shell as a result of these operations consist of the values given in Section 2.2.5. The weight or inertia g load can include all of the weights of the outer shell, neutron resin shield, and aluminum containers. The most severe Normal Service (Design and Level A) Condition load is assumed 3 g inertia load in the vertical lifting orientation. The shell is also analyzed for 3 g loading when the cask is oriented horizontally to ensure it is not damaged during delivery.

- Cask in the Vertical Orientation
    - Stress due to 25 psi pressure
    - Stress due to 3G inertia load (lifting)

- Cask in the Horizontal Orientation
    - Stress due to 25 psi pressure
    - Stress due to 3G inertia load

3A.4.4 Method of Analysis

ANSYS Model

A finite element model is built for the structural analysis of the outer shell and closure plates. The outer shell and closure plates are modeled with ANSYS Plane 42 elements. The element is used as an axisymmetric element. Double nodes are created at weld locations. The partial penetration welds are simulated by coupling the nodes where weld existed. The basic geometry of the outer shell and weld sizes used for analysis are shown in Figure 3A.4-1. The finite element model is shown in Figures 3A.4-2, -3, and –4.

A. Cask in the Vertical Orientation

- Stresses due to 25 psi Pressure

An external pressure of 25 psi will not induce any load or stress in the outer shell since it is in contact with and supported by the resin filled aluminum containers.

An internal pressure of 25 psi is used as the maximum pressure acting in the inner surface of the outer shell as shown on Figure 3A.4-5. The maximum stress intensity for this load case is 4.5 ksi.

- 3G Down

The weight of the resin and aluminum containers is modeled as an additional pressure on the bottom inner surface as shown on Figure 3A.4-6. The maximum stress intensity for this load case is 9.1 ksi.

B. Cask in the Horizontal Orientation

The stress due to 25 psi internal pressure is same as for the vertical orientation. The stress due to 3G inertia load conservatively assumes that the weight of the outer shell, resin, and aluminum containers is uniformly distributed over the 160 in length and at a 45^o angle only. Therefore, the equivalent pressure applied to the outer shell is:

Weight of outer shell: 11.2 kip
Weight of resin: 13.9 kip
Weight of alum. Containers: 2.5 kip

$$P_{equipment} = (11.2 + 13.9 + 2.5)(3)(1000)(360)/(\pi)(96.5)(160)(45) \approx 14 \text{ psi}$$

The stress results from this 14 psi load is approximately assumed that this pressure is acting like the internal pressure and applied on the full 360^o inner surface of the outer shell. Therefore, the stress due to the this 3G inertia load can be ratioed from the 25 psi internal pressure case and is:

σ = 4,468 (14)/25 = 2,502 psi (2.5 ksi)

C. Maximum Combined Stress Intensities

Based on the above calculations the stress intensities are summarized in the following table:

Loading	Stress Intensities
25 psi Internal Pressure	4.5 ksi
25 psi + 3G Down (Cask in Vertical Orientation)	9.1 ksi
25 psi + 3G Down (Cask in Horizontal Orientation)	7.0 ksi

3A.4.5 Results

The stresses acting on the outer shell and closure plates are also listed in Table 3A.4-1. They are compared with the allowable values in Table 3.4-10.

3A.5 References

1. American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section III, 1995 including 1996 addenda.

2. American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section II, Part D, 1998 including 2000 addenda.

3. ANSYS Engineering Analysis System, Users Manual for ANSYS Revision 6.0, Swanson Analysis Systems, Inc., Houston, PA, 2001.

4. High Performance Sealing, Metal Seals Helicoflex Catalog, Helicoflex Co., Boonton, N.J., ET 507 E 5930.

5. (Deleted)

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

7. (Deleted)

8. Roark, R.J.: "Formulas for Stress & Strain", 4th Edition, McGraw-Hill Book Co.

9. (Deleted)

10. NUREG/CR-6007, “Stress Analysis of Closure Bolts for Shipping Cask.”

11. Machinary Handbook, 21st Ed.

12. NUREG-1536, “Standard Review Plan for Dry Cask Storage Systems,” January 1997.

13. American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section III, 1998 including 2000 addenda.

14. American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section II, Part D, 1998 including 2000 addenda.

TABLE 3A.2.3-1

BOLT PRELOAD (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	1
	2	1
	3	1
	4	1
	5	12
	6	11
INNER SHELL	7	12
	8	12
	9	12
	10	12
	11	12
	12	12
	13	10
	14	13
	15	44
	16	27
	17	13
	18	10

TABLE 3A 2.3-2

BOLT PRELOAD (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19	528
	20	418
LID	21	13
	22	141
OUTER BOTTOM PLATE	23	1
	24	1
	25	16
	26	1
GAMMA SHIELDING CYLINDER	27	3
	28	3
	29	3
	30	3
	31	3
	32	3
	33	5
	34	2
	35	57
	36	43
WELDS	37	1
	38	121
	39	299

TABLE 3A 2.3-3

ONE (1) G DOWN (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	26
	2	21
	3	28
	4	17
	5	90
	6	66
INNER SHELL	7	72
	8	70
	9	61
	10	61
	11	44
	12	44
	13	27
	14	27
	15	20
	16	18
	17	17
	18	8

TABLE 3A.2.3-4

ONE (1) G DOWN (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19	39
	20	10
LID	21	51
	22	84
OUTER BOTTOM PLATE	23	23
	24	25
	25	98
	26	64
GAMMA SHIELDING CYLINDER	27	79
	28	69
	29	63
	30	64
	31	47
	32	46
	33	29
	34	30
	35	23
	36	16
WELDS	37	87
	38	12
	39	96

TABLE 3A.2.3-5

INTERNAL PRESSURE - 100 PSI (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	301
	2	136
	3	239
	4	74
	5	1419
	6	737
INNER SHELL	7	493
	8	456
	9	601
	10	544
	11	589
	12	532
	13	590
	14	535
	15	524
	16	417
	17	638
	18	500

TABLE 3A.2.3-6

INTERNAL PRESSURE - 100 PSI (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19 20	1057 713
LID	21 22	1398 2335
OUTER BOTTOM PLATE	23 24 25 26	1031 1419 2532 738
GAMMA SHIELDING CYLINDER	27 28 29 30 31 32 33 34 35 36	295 296 578 439 565 416 567 421 520 310
WELDS	37 38 39	869 775 2478

TABLE 3A.2.3-7

EXTERNAL PRESSURE - 25 PSI (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	75
	2	45
	3	61
	4	32
	5	345
	6	164
INNER SHELL	7	123
	8	130
	9	151
	10	151
	11	148
	12	148
	13	148
	14	149
	15	128
	16	125
	17	159
	18	141

TABLE 3A.2.3-8

EXTERNAL PRESSURE - 25 PSI (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19	280
	20	172
LID	21	351
	22	584
OUTER BOTTOM PLATE	23	261
	24	357
	25	629
	26	186
GAMMA SHIELDING CYLINDER	27	75
	28	73
	29	146
	30	111
	31	143
	32	105
	33	143
	34	106
	35	131
	36	79
WELDS	37	219
	38	189
	39	620

TABLE 3A.2.3-9

THERMAL STRESS (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)	
		HOT	COLD
INNER BOTTOM PLATE	1	7916	8591
	2	8753	9553
	3	7345	8044
	4	7940	8747
	5	2715	3078
	6	936	878
INNER SHELL	7	911	1080
	8	981	1091
	9	1064	1200
	10	830	973
	11	1080	1220
	12	814	954
	13	1005	1143
	14	888	1030
	15	584	921
	16	1304	1447
	17	754	639
	18	1382	1561

TABLE 3A.2.3-10

THERMAL STRESS (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)	
		HOT	COLD
FLANGE	19 20	806 1150	475 994
LID	21 22	12 269	7 252
OUTER BOTTOM PLATE	23 24 25 26	12715 1106 3806 393	13191 1179 4962 176
GANNA SHIELDING CYLINDER	27 28 29 30 31 32 33 34 35 36	420 999 1061 1198 1388 1738 827 1237 854 657	629 1108 935 1161 1269 1699 719 1209 759 706
WELDS	37 38 39	2090 1142 750	2054 1254 713

TABLE 3A.2.3-11

SIX (6) G ON TRUNNION (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	801
	2	12
	3	704
	4	167
	5	1974
	6	1329
INNER SHELL	7	505
	8	551
	9	431
	10	435
	11	561
	12	562
	13	695
	14	633
	15	815
	16	672
	17	757
	18	942

TABLE 3A.2.3-12

SIX (6) G ON TRUNNION (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19	581
	20	794
LID	21	353
	22	626
OUTER BOTTOM PLATE	23	1931
	24	2465
	25	3712
	26	1223
GAMMA SHIELDING CYLINDER	27	850
	28	590
	29	445
	30	534
	31	607
	32	607
	33	800
	34	676
	35	118
	36	1243
WELDS	37	1215
	38	426
	39	847

TABLE 3A.2.3-13

ONE (1) G SIDE DROP - CONTACT SIDE (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	212
	2	202
	3	243
	4	228
	5	230
	6	363
INNER SHELL	7	487
	8	164
	9	703
	10	297
	11	813
	12	359
	13	687
	14	274
	15	430
	16	169
	17	346
	18	190

TABLE 3A.2.3-14

ONE (1) G SIDE DROP - CONTACT SIDE (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19 20	444 417
LID	21 22	17 17
OUTER BOTTOM PLATE	23 24 25 26	137 69 917 79
GAMMA SHIELDING CYLINDER	27 28 29 30 31 32 33 34 35 36	291 395 490 707 605 829 534 753 301 445
WELDS	37 38 39	322 111 229

TABLE 3A.2.3-15

ONE (1) G SIDE DROP - SIDE OPPOSITE CONTACT (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	102
	2	93
	3	101
	4	88
	5	57
	6	107
INNER SHELL	7	100
	8	48
	9	174
	10	119
	11	252
	12	177
	13	164
	14	108
	15	83
	16	49
	17	72
	18	78

TABLE 3A.2.3-16

ONE (1) G SIDE DROP - SIDE OPPOSITE CONTACT (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19	111
	20	114
LID	21	41
	22	22
OUTER BOTTOM PLATE	23	58
	24	9
	25	245
	26	54
GAMMA SHIELDING CYLINDER	27	68
	28	60
	29	116
	30	170
	31	184
	32	244
	33	141
	34	195
	35	67
	36	71
WELDS	37	82
	38	39
	39	24

TABLE 3A.2.3-17

SEISMIC LOAD - 2 G DOWN + 1G LATERAL (SHELL ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
INNER BOTTOM PLATE	1	652
	2	650
	3	265
	4	265
	5	164
	6	344
INNER SHELL	7	174
	8	157
	9	72
	10	83
	11	26
	12	33
	13	27
	14	39
	15	32
	16	46
	17	65
	18	74

TABLE 3A.2.3-18

SEISMIC LOAD - 2 G DOWN + 1G LATERAL (SOLID ELEMENTS)

LOCATION		NODAL STRESS INTENSITY (PSI)
FLANGE	19	118
	20	97
LID	21	184
	22	203
OUTER BOTTOM PLATE	23	529
	24	543
	25	893
	26	161
GAMMA SHIELDING CYLINDER	27	229
	28	102
	29	109
	30	119
	31	7
	32	109
	33	29
	34	105
	35	36
	36	86
WELDS	37	519
	38	115
	39	248

TABLE 3A.2.5-1

NORMAL CONDITION LOAD COMBINATIONS

INDIVIDUAL LOAD COMBINED LOAD	BOLT PRELOAD	1G DOWN	INTERNAL PRESSURE 100 PSI	EXTERNAL PRESSURE 25 PSI	THERMAL	6G ON TRUNNION	TRUNNION LOCAL STRESS	STRESS TABLE NO.
N1	X	X	X					3A.2.5-2 3A.2.5-3
N2	X	X	X		X			3A.2.5-4 3A.2.5-5
N3	X		X		X	X	X	3A.2.5-6 3A.2.5-7
N4	X	X		X				3A.2.5-8 3A.2.5-9
N5	X	X		X	X			3A.2.5-10 3A.2.5-11
N6	X			X	X	X	X	3A.2.5-12 3A.2.5-13

TABLE 3A.2.5-2

BOLT PRELOAD +100 PSI INTERNAL PRESSURE + 1G DOWN (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	0.3
	2	0.2
	3	0.3
	4	0.1
	5	1.4
	6	0.9
INNER SHELL	7	0.5
	8	0.5
	9	0.6
	10	0.6
	11	0.6
	12	0.6
	13	0.6
	14	0.6
	15	0.6
	16	0.5
	17	0.7
	18	0.5

TABLE 3A.2.5-3

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + 1G DOWN
(SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19 20	0.8 0.8
LID	21 22	1.4 2.4
OUTER BOTTOM PLATE	23 24 25 26	1.1 1.5 2.7 0.8
GAMMA SHIELDING CYLINDER	27 28 29 30 31 32 33 34 35 36	0.3 0.3 0.6 0.5 0.6 0.5 0.6 0.5 0.6 0.4
WELDS	37 38 39	1.0 0.7 2.2

TABLE 3A.2.5-4

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + 1G DOWN + THERMAL (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
INNER BOTTOM PLATE	1	8.2	8.9
	2	8.6	9.4
	3	7.5	8.2
	4	7.9	8.7
	5	1.6	1.7
	6	0.6	0.1
INNER SHELL	7	0.9	0.8
	8	0.9	0.8
	9	0.8	0.9
	10	0.6	0.7
	11	0.9	0.9
	12	0.7	0.7
	13	1.0	0.8
	14	0.9	0.8
	15	0.2	0.4
	16	1.1	1.2
	17	0.9	0.8
	18	1.7	1.7

TABLE 3A.2.5-5

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + 1G DOWN + THERMAL (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
FLANGE	19 20	1.3 1.2	1.1 1.2
LID	21 22	1.4 2.1	1.4 2.1
OUTER BOTTOM PLATE	23 24 25 26	13.7 0.3 6.3 0.9	14.1 0.3 7.4 0.8
GAMMA SHIELD CYLINDER	27 28 29 30 31 32 33 34 35 36	0.5 1.2 0.9 1.5 1.2 1.9 0.6 1.4 0.7 1.0	0.8 1.4 0.8 1.5 1.0 1.9 0.5 1.4 0.7 1.1
WELDS	37 38 39	2.0 1.8 1.4	2.0 1.9 1.4

TABLE 3A.2.5-6

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + THERMAL + 6G UP + TRUNNION LOCAL STRESS
(SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
INNER BOTTOM PLATE	1	9.0	9.7
	2	8.6	9.4
	3	8.2	8.9
	4	8.1	8.9
	5	0.7	0.5
	6	1.3	1.2
INNER SHELL	7	0.3	0.4
	8	0.3	0.4
	9	0.3	0.4
	10	0.1	0.4
	11	0.3	0.3
	12	0.2	0.2
	13	0.3	0.1
	14	0.3	0.1
	15	20.4 (1)	20.4 (3)
	16	20.1 (2)	20.3 (4)
	17	0.8	0.5
	18	0.8	0.7

Note :1. P_m at Location 15 = 12.9 ksi
2. P_m at Location 16 = 12.7 ksi
3. P_m at Location 15 = 13.0 ksi
4. P_m at Location 16 = 12.9 ksi

TABLE 3A.2.5-7

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + THERMAL + 6G UP + TRUNNION LOCAL STRESS (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
FLANGE	19 20	1.3 0.4	0.8 0.4
LID	21 22	1.1 1.6	1.1 1.6
OUTER BOTTOM PLATE	23 24 25 26	15.6 2.8 9.9 2.2	16.1 2.7 11.1 2.0
GAMMA SHIELD CYLINDER	27 28 29 30 31 32 33 34 35 36	0.4 1.3 0.4 2.1 0.5 2.6 0.4 2.1 20.5 (1) 21.1 (2)	0.2 1.6 0.2 2.1 0.4 2.6 0.4 2.1 20.5 (3) 21.2 (4)
WELDS	37 38 39	2.1 1.4 0.7	2.1 1.5 0.7

Note : 1. P_m at Location 35 = 13.1 ksi
2. P_m at Location 36 = 13.7 ksi
3. P_m at Location 35 = 13.1 ksi
4. P_m at Location 36 = 13.7 ksi

TABLE 3A.2.5-8

BOLT PRELOAD + 1G DOWN + 25 PSI EXTERNAL PRESSURE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	0.1
	2	0.1
	3	0.1
	4	0.1
	5	0.5
	6	0.1
INNER SHELL	7	0.2
	8	0.2
	9	0.2
	10	0.2
	11	0.2
	12	0.2
	13	0.2
	14	0.2
	15	0.2
	16	0.1
	17	0.2
	18	0.2

<u>TABLE 3A.2.5-9</u>

BOLT PRELOAD +1G DOWN + 25 PSI EXTERNAL PRESSURE
(SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	0.9
	20	0.5
LID	21	0.4
	22	0.6
OUTER BOTTOM PLATE	23	0.3
	24	0.4
	25	0.6
	26	0.2
GAMMA SHIELDING CYLINDER	27	0.2
	28	0.2
	29	0.2
	30	0.2
	31	0.2
	32	0.2
	33	0.2
	34	0.2
	35	0.2
	36	0.1
WELDS	37	0.2
	38	0.4
	39	1.0

<u>TABLE 3A.2.5-10</u>

BOLT PRELOAD + 1G DOWN + 25 PSI EXTERNAL PRESSURE + THERMAL
(SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
INNER BOTTOM PLATE	1	7.8	8.5
	2	8.8	9.6
	3	7.3	8.0
	4	7.9	8.8
	5	3.2	3.5
	6	1.0	1.0
INNER SHELL	7	1.0	1.2
	8	1.2	1.3
	9	1.2	1.4
	10	1.0	1.1
	11	1.2	1.4
	12	1.0	1.1
	13	1.1	1.3
	14	1.0	1.2
	15	0.7	1.0
	16	1.4	1.5
	17	0.7	0.8
	18	1.5	1.6

TABLE 3A.2.5-11

BOLT PRELOAD +1G DOWN + 25 PSI EXTERNAL PRESSURE + THERMAL (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
FLANGE	19 20	0.2 0.7	0.5 0.5
LID	21 22	0.4 0.8	0.4 0.8
OUTER BOTTOM PLATE	23 24 25 26	12.5 1.4 3.3 0.4	12.9 1.5 4.4 0.3
GAMMA SHIELD CYLINDER	27 28 29 30 31 32 33 34 35 36	0.5 0.9 1.2 1.3 1.5 1.6 0.9 1.2 0.8 0.6	0.8 1.0 1.0 1.2 1.4 1.6 0.8 1.1 0.7 0.7
WELDS	37 38 39	2.2 0.8 1.7	2.1 0.9 1.7

TABLE 3A.2.5-12

BOLT PRELOAD + 25 PSI (EXT. P) + THERMAL + 6G UP + TRUNNION LOCAL STRESS (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
INNER BOTTOM PLATE	1	8.6	9.3
	2	8.8	9.6
	3	7.9	8.6
	4	8.1	8.9
	5	1.1	1.5
	6	0.6	0.3
INNER SHELL	7	0.7	0.8
	8	0.7	0.8
	9	0.8	1.1
	10	0.7	1.0
	11	0.6	0.9
	12	0.5	0.8
	13	0.4	0.8
	14	0.4	0.8
	15	20.3 (1)	20.6(3)
	16	20.5(2)	20.8(4)
	17	0.1	0.3
	18	0.6	0.7

Note :1. P_m at Location 15 = 12.9 ksi
2. P_m at Location 16 = 13.1 ksi
3. P_m at Location 15 = 13.2 ksi
4. P_m at Location 16 = 13.4 ksi

TABLE 3A.2.5-13

BOLT PRELOAD + 25 PSI (EXT. P) + THERMAL + 6G UP + TRUNNION LOCAL STRESS (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)	
		HOT	COLD
FLANGE	19 20	0.7 0.6	0.6 0.5
LID	21 22	0.7 1.3	0.7 1.3
OUTER BOTTOM PLATE	23 24 25 26	14.3 1.0 6.8 1.3	14.8 0.9 8.0 1.1
GAMMA SHIELD CYLINDER	27 28 29 30 31 32 33 34 35 36	0.5 0.9 0.9 1.9 1.2 2.3 0.8 1.8 20.6(1) 21.0(2)	0.3 1.2 0.7 1.8 1.0 2.3 0.7 1.8 20.5(3) 21.0(4)
WELDS	37 38 39	1.8 0.6 2.5	1.8 0.7 2.4

Note : 1. P_m at Location 35 = 13.2 ksi
2. P_m at Location 36 = 13.6 ksi
3. P_m at Location 35 = 13.1 ksi
4. P_m at Location 36 = 13.6 ksi

TABLE 3A.2.5-14

ACCIDENT CONDITION LOAD COMBINATIONS

INDIVIDUAL LOAD / COMBINED LOAD	BOLT PRELOAD	INTERNAL PRESSURE 100 PSI	EXTERNAL PRESSURE 25 PSI	18” BOTTOM END DROP 60G	TIP OVER SIDE DROP 65G	SEISMIC, TORNADO, OR FLOOD 1G LATERAL + 2G DOWN	STRESS TABLE NO.
A1	X	X		X			3A.2.5-15 3A.2.5-16
A2	X		X	X			3A.2.5-17 3A.2.5-18
A3	X	X			X		3A.2.5-19 3A.2.5-20 3A.2.5-21 3A.2.5-22
A4	X		X		X		3A.2.5-23 3A.2.5-24 3A.2.5-25 3A.2.5-26
A5	X	X				X	3A.2.5-27 3A.2.5-28
A6	X		X			X	3A.2.5-29 3A.2.5-30

TABLE 3A.2.5-15

BOLT PRELOAD + 60G DOWN END DROP + 100 PSI INTERNAL PRESSURE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	1.3
	2	1.4
	3	1.5
	4	1.3
	5	4.1
	6	4.8
INNER SHELL	7	4.5
	8	4.4
	9	3.9
	10	3.9
	11	2.9
	12	2.9
	13	1.9
	14	1.9
	15	1.4
	16	1.3
	17	1.1
	18	0.9

TABLE 3A.2.5-16

BOLT PRELOAD + 60 G DOWN END DROP + 100 PSI INTERNAL PRESSURE (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	1.9
	20	0.8
LID	21	1.7
	22	2.6
OUTER BOTTOM PLATE	23	0.4
	24	2.9
	25	8.3
	26	3.4
GAMMA SHIELDING CYLINDER	27	4.7
	28	4.2
	29	4.2
	30	4.1
	31	3.1
	32	3.1
	33	2.1
	34	2.0
	35	1.6
	36	1.2
WELDS	37	6.1
	38	0.5
	39	3.6

TABLE 3A.2.5-17

BOLT PRELOAD + 60G DOWN END DROP + 25 PSI EXTERNAL PRESSURE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	1.7
	2	1.3
	3	1.8
	4	1.1
	5	5.8
	6	3.9
INNER SHELL	7	4.4
	8	4.4
	9	3.8
	10	3.8
	11	2.8
	12	2.8
	13	1.8
	14	1.8
	15	1.2
	16	1.1
	17	1.2
	18	0.6

TABLE 3A.2.5-18

BOLT PRELOAD + 60G DOWN END DROP + 25 PSI EXTERNAL PRESSURE (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19 20	3.2 1.0
LID	21 22	3.4 5.5
OUTER BOTTOM PLATE	23 24 25 26	1.7 1.2 5.4 4.0
GAMMA SHIELDING CYLINDER	27 28 29 30 31 32 33 34 35 36	4.8 4.2 3.9 3.9 2.9 2.9 1.9 1.9 1.5 0.9
WELDS	37 38 39	5.1 1.0 6.7

TABLE 3A.2.5-19

BOLT PRELOAD + TIP OVER (65G) + 100 PSI INTERNAL PRESSURE OPPOSITE CONTACT SIDE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	6.7
	2	6.1
	3	6.5
	4	5.8
	5	4.1
	6	6.2
INNER SHELL	7	7.0
	8	3.6
	9	11.8
	10	8.0
	11	16.6
	12	11.7
	13	11.2
	14	7.3
	15	5.9
	16	3.7
	17	5.2
	18	5.3

TABLE 3A.2.5-20

BOLT PRELOAD + TIP OVER (65g) + 100 PSI INTERNAL PRESSURE OPPOSITE CONTACT SIDE (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	6.8
	20	7.7
LID	21	4.1
	22	2.9
OUTER BOTTOM PLATE	23	3.7
	24	2.0
	25	13.5
	26	2.8
GAMMA SHIELDING CYLINDER	27	4.6
	28	3.7
	29	8.1
	30	10.6
	31	12.6
	32	15.5
	33	9.6
	34	12.3
	35	4.6
	36	4.3
WELDS	37	4.5
	38	1.9
	39	0.7

TABLE 3A.2.5-21

BOLT PRELOAD + TIP OVER (65G) + 100 PSI INTERNAL PRESSURE CONTACT SIDE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	13.8
	2	13.1
	3	15.7
	4	14.8
	5	15.3
	6	22.8
INNER SHELL	7	32.1
	8	11.1
	9	46.3(1)
	10	19.5
	11	53.3(2)
	12	23.5
	13	45.1(3)
	14	18.1
	15	28.4
	16	11.5
	17	23.1
	18	12.5

Note: (1) P_m at location 9 = 31.9 ksi
(2) P_m at location 11 = 37.2 ksi
(3) P_m at location 13 = 31.1 ksi

TABLE 3A.2.5-22

BOLT PRELOAD + TIP OVER (65g) + 100 PSI INTERNAL PRESSURE CONTACT SIDE (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	28.5
	20	27.3
LID	21	1.1
	22	3.4
OUTER BOTTOM PLATE	23	8.9
	24	4.6
	25	57.2(1)
	26	4.7
GAMMA SHIELDING CYLINDER	27	19.3
	28	25.5
	29	32.6
	30	45.6
	31	40.1
	32	53.6(2)
	33	35.5
	34	48.6(3)
	35	20.3
	36	28.6
WELDS	37	20.2
	38	7.0
	39	12.8

Note: (1) P_m at location 25 = 10.6 ksi

(2) P_m at location 32 = 10.8 ksi

(3) P_m at location 34 = 10.0 ksi

TABLE 3A.2.5-23

BOLT PRELOAD + TIP OVER (65G) + 25 PSI EXTERNAL PRESSURE OPPOSITE CONTACT SIDE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	6.7
	2	6.1
	3	6.6
	4	5.7
	5	3.7
	6	7.1
INNER SHELL	7	6.4
	8	3.0
	9	11.3
	10	7.7
	11	16.3
	12	11.4
	13	10.5
	14	7.0
	15	5.3
	16	3.1
	17	4.6
	18	5.0

TABLE 3A.2.5-24

BOLT PRELOAD + TIP OVER (65g) + 25 PSI EXTERNAL PRESSURE OPPOSITE CONTACT SIDE (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	8.0
	20	7.9
LID	21	2.6
	22	1.7
OUTER BOTTOM PLATE	23	3.8
	24	0.5
	25	16.6
	26	3.7
GAMMA SHIELDING CYLINDER	27	4.5
	28	4.0
	29	7.5
	30	11.2
	31	11.9
	32	16.0
	33	9.2
	34	12.8
	35	4.4
	36	4.7
WELDS	37	5.6
	38	2.9
	39	2.5

TABLE 3A.2.5-25

BOLT PRELOAD + TIP OVER (65G) + 25 PSI EXTERNAL PRESSURE CONTACT SIDE (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	13.8
	2	13.1
	3	15.8
	4	14.8
	5	14.8
	6	23.7
INNER SHELL	7	31.4
	8	10.5
	9	45.4
	10	19.2
	11	52.5(1)
	12	23.2
	13	44.4
	14	17.8
	15	27.8
	16	11.0
	17	22.3
	18	12.2

Note: (1) P_m at location 11 = 36.5 ksi

TABLE 3A.2.5-26

BOLT PRELOAD + TIP OVER (65g) + 25 PSI EXTERNAL PRESSURE CONTACT SIDE (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	29.6
	20	27.5
LID	21	1.4
	22	0.9
OUTER BOTTOM PLATE	23	9.0
	24	4.5
	25	60.4(1)
	26	5.4
GAMMA SHIELDING CYLINDER	27	19.0
	28	25.8
	29	31.8
	30	46.1
	31	39.4
	32	54.1(2)
	33	34.7
	34	49.2(3)
	35	19.6
	36	29.0
WELDS	37	21.2
	38	7.5
	39	15.7

Note: (1) At location 25, P_m=10.8 ksi
(2) At location 32, P_m=11.1 ksi
(3) At location 34, P_m=10.5 ksi

TABLE 3A.2.5-27

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + SEISMIC (TORNADO, FLOOD) (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	0.7
	2	0.8
	3	0.3
	4	0.3
	5	1.3
	6	1.1
INNER SHELL	7	0.5
	8	0.5
	9	0.7
	10	0.6
	11	0.6
	12	0.6
	13	0.6
	14	0.6
	15	0.6
	16	0.5
	17	0.7
	18	0.6

<u>TABLE 3A.2.5-28</u>

BOLT PRELOAD + 100 PSI INTERNAL PRESSURE + SEISMIC (TORNADO, FLOOD)
(SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	0.9
	20	0.9
LID	21	1.3
	22	2.3
OUTER BOTTOM PLATE	23	1.2
	24	1.9
	25	3.5
	26	0.6
GAMMA SHIELDING CYLINDER	27	0.4
	28	0.3
	29	0.7
	30	0.6
	31	0.6
	32	0.6
	33	0.6
	34	0.6
	35	0.6
	36	0.5
WELDS	37	1.4
	38	0.8
	39	2.0

TABLE 3A.2.5-29

BOLT PRELOAD + 25 PSI EXTERNAL PRESSURE + SEISMIC (TORNADO, FLOOD) (SHELL ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
INNER BOTTOM PLATE	1	0.7
	2	0.7
	3	0.3
	4	0.3
	5	0.5
	6	0.2
INNER SHELL	7	0.3
	8	0.3
	9	0.2
	10	0.2
	11	0.2
	12	0.2
	13	0.2
	14	0.2
	15	0.2
	16	0.1
	17	0.2
	18	0.2

TABLE 3A.2.5-30

BOLT PRELOAD + 25 PSI EXTERNAL PRESSURE + SEISMIC (TORNADO, FLOOD) (SOLID ELEMENTS)

LOCATION		COMBINED STRESS INTENSITY (KSI)
FLANGE	19	0.9
	20	0.5
LID	21	0.6
	22	0.7
OUTER BOTTOM PLATE	23	0.7
	24	0.6
	25	0.4
	26	0.4
GAMMA SHIELDING CYLINDER	27	0.3
	28	0.2
	29	0.2
	30	0.1
	31	0.2
	32	0.1
	33	0.2
	34	0.1
	35	0.2
	36	0.1
WELDS	37	0.4
	38	0.3
	39	1.2

TABLE 3A.3-1

DESIGN PARAMETERS FOR LID BOLT ANALYSIS

-	D_b	Nominal diameter of closure bolt; 1.875 in
-	K	Nut factor for empirical relation between the applied torque and achieved preload, used 0.1 for neolube
-	Q	Applied torque for the preload (in-lb)
-	D_{lb}	Closure lid dia at bolt circle, 75.88 in
-	D_{lg}	Closure lid dia at the seal (outer) = 72.90 in
-	E_c	Young’s modulus of cask wall material, 28 x 10^6 Psi
-	E_l	Young’s modulus of lid material, 27.8 x 10^6 Psi
-	N_b	Total number of closure bolts, 48
-	N_{ul}	Poisson’s ratio of closure lid, 0.3
-	P_{ei}	Inside pressure of cask, 100 Psig
-	D_{lo}	Closure Lid Dia at outer edge, 79.88 in
-	P_{li}	Pressure inside the closure lid, 100 Psig
-	t_c	Thickness of cask wall, 6.0 + 1.5 = 7.5 in
-	t_l	Thickness of lid, 9.5/5.0 in
-	l_b	Thermal coeff of expansion bolt material, 6.27 x 10^{-6} at R.T., 6.78 x 10^{-6} in/in-^{o}F at 300^{o}F
-	l_c	Thermal coeff of expansion, cask 6.27 x 10^{-6} at R.T., 6.78 x 10^{-6} in/in- ^{o}F at at 300^{o}F
-	l_l	Thermal coeff of expansion, lid 6.27 x 10^{-6} R.T., 6.78 x 10^{-6} in/in ^{o}F at 300 ^{o}F
-	E_b	Young's modulus of bolt material, 27.8 x 10^6 Psi
-	ai	Maximum rigid-body impact acceleration (g) of the cask
-	DLF	Dynamic load factor to account for any difference between the rigid body acceleration and the acceleration of the contents and closure lid = 1.2
-	W_c	weight of contents = 46,920 (fuel) + 30,320(basket)** = 77,240 lb
-	W_ℓ	weight of lid = 12,074 lb, say 12,100 lbs
-	W_c+W_l	77,240 + 12,074 = 89,314 lb, say 89,500 lb
-	xi	Impact angle between the cask axis and target surface
-	S_{yl}	Yield strength of closure lid material
-	S_{ul}	Ultimate strength of closure lid, 70,000 psi
-	S_{yb}	Yield strength of bolt material (see Table 3A.3-3)
-	S_{ub}	Ultimate strength of bolt material (see Table 3A.3-4)
-	Pl_o	Pressure outside the lid
-	L_b	Bolt length between the top and bottom surfaces of closure 5.0 in

** Conservatively using higher basket weight for lid bolt analysis.

TABLE 3A.3-2

BOLT DATA (Ref.10, Table 5.1)

Bolt: 1 7/8"– UN8 – 2A

N: no of threads per inch = 8

p: Pitch = 1/8" = .125 in

$D_{b:}$ Nominal Diameter = 1.875 in

D_{ba}: Bolt diameter for stress calculations = D_b - .9743p = 1.875 - .9743 (.125) = 1.753 in

Stress Area = $\pi/4\ (1.753)^2 = 2.414\ \text{in}^2$

TABLE 3A.3-3

ALLOWABLE STRESSES IN CLOSURE BOLTS FOR NORMAL CONDITIONS

(MATERIAL: SA-540 Gr. B24 CL.1)

Temperature (^{o}F)	Yield Stress (1) (ksi)	Normal Condition Allowables		
		F_{tb} (2,4) (ksi)	F_{vb} (3.4) (ksi)	S.I (5) (ksi)
100	150	100.0	60.0	135.0
200	143.4	95.6	57.4	129.1
300	138.6	92.4	55.4	124.7
400	134.4	89.6	53.8	121.0
500	130.2	86.8	52.1	117.2
600	124.2	82.8	49.7	111.8

Notes:

1. Yield stress values are from ASME Code, Section II, Table Y-1 (Ref.2)
2. Allowable Tensile stress, $F_{tb} = 2/3\ S_y$
3. Allowable shear stress, $F_{vb} = 0.4\ (S_y)$
4. Tension and shear stresses must be combined using the following interaction equation:

$$\frac{(f_{tb})^2}{(F_{tb})^2} + \frac{(f_{vb})^2}{(F_{vb})^2} \leq 1.0$$

5. Stress intensity from combined tensile, shear and residual torsion loads, S.I. $\leq 0.9\ (S_y)$

TABLE 3A.3-4

ALLOWABLE STRESSES IN CLOSURE BOLTS FOR ACCIDENT CONDITIONS

(MATERIAL: SA-540 Gr. B24 Cl.1)

Temperature (^oF)	Yield Stress (1) (ksi)	Accident Condition Allowables		
		$0.6\ S_y$ (3) (ksi)	F_{tb}(2,4) (ksi)	F_{vb} (3,4) (ksi)
100	150.0	90.0	115.5	69.3
200	143.4	86.0	115.5	69.3
300	138.6	83.2	115.5	69.3
400	134.4	80.6	115.5	69.3
500	130.2	78.1	115.5	69.3
600	124.2	74.5	115.5	69.3

Notes:

1. Yield and tensile stress values are from ASME Code, (Ref.2) Table Y-1, Note that Su is 165 KSI at all temperatures of interest.

2. Allowable tensile stress, F_{tb} is the smaller of $0.7\ S_u$ or S_y
   where: $0.7\ S_u = 0.7\ (165) = 115.5$ ksi.

3. Allowable shear stress, F_{vb} is smaller of $0.42\ S_u$ or $0.6\ S_y$,
   where: $0.42\ S_u = 0.42\ (165.) = 69.3$ ksi.

4. Tension and shear stresses must be combined using the following interaction equation:

$$\frac{(f_{tb})^2}{(F_{tb})^2} + \frac{(f_{vb})^2}{(F_{vb})^2} \leq 1.0$$

TABLE 3A.4-1

Stress In Outer Shell and Closure Plates

LOADING	LOCATIONS	STRESS INTENSITIES (ksi)
25 psi internal pressure	Juncture of outer Shell and top plate	4.5
25 psi + 3 G down Cask Vertical	Juncture of outer Shell and top plate	9.1
25 psi + 3G down Cask Horizontal	Outer Shell	7.0

Note: The allowables are listed in Chapter 3, Table 3.4-10

Figure Withheld Under 10 CFR 2.390

FIGURE 3A.1-1
CASK BODY KEY DIMENSIONS

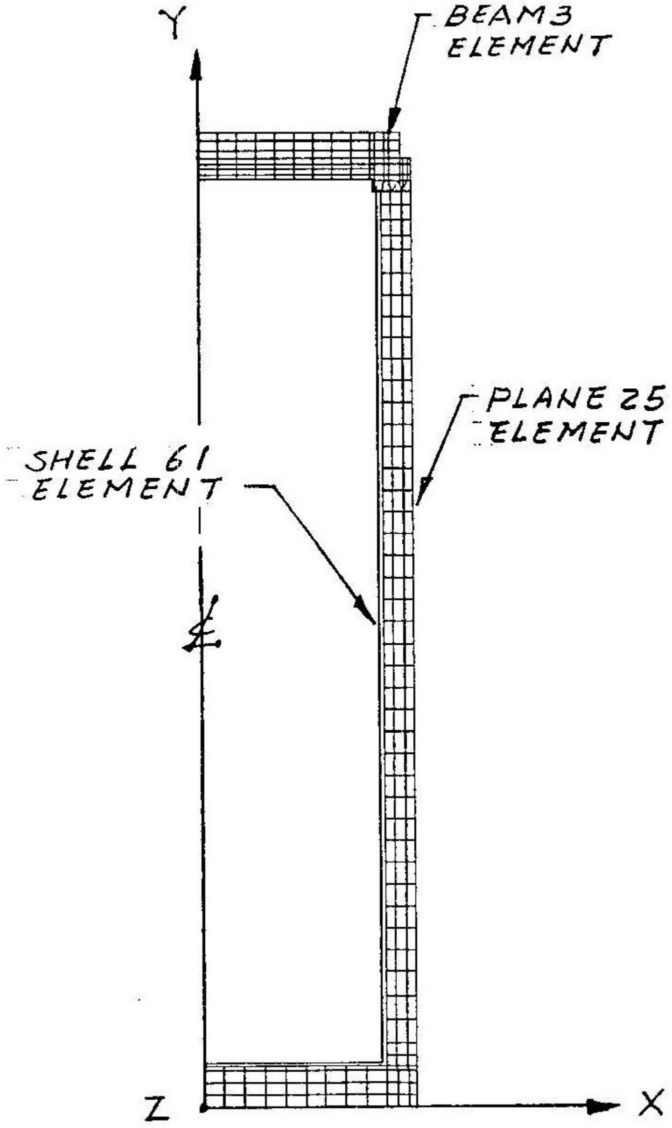
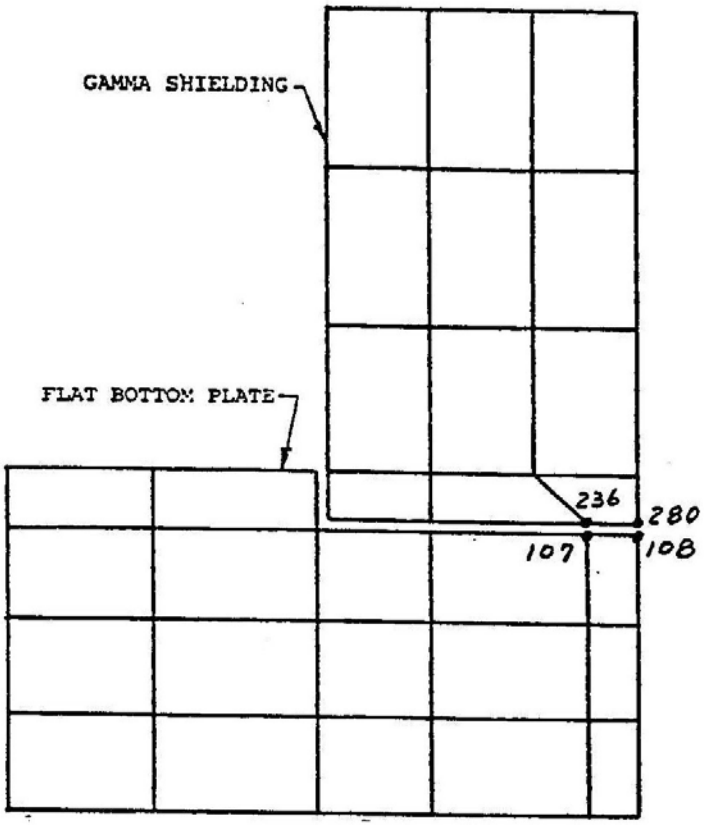
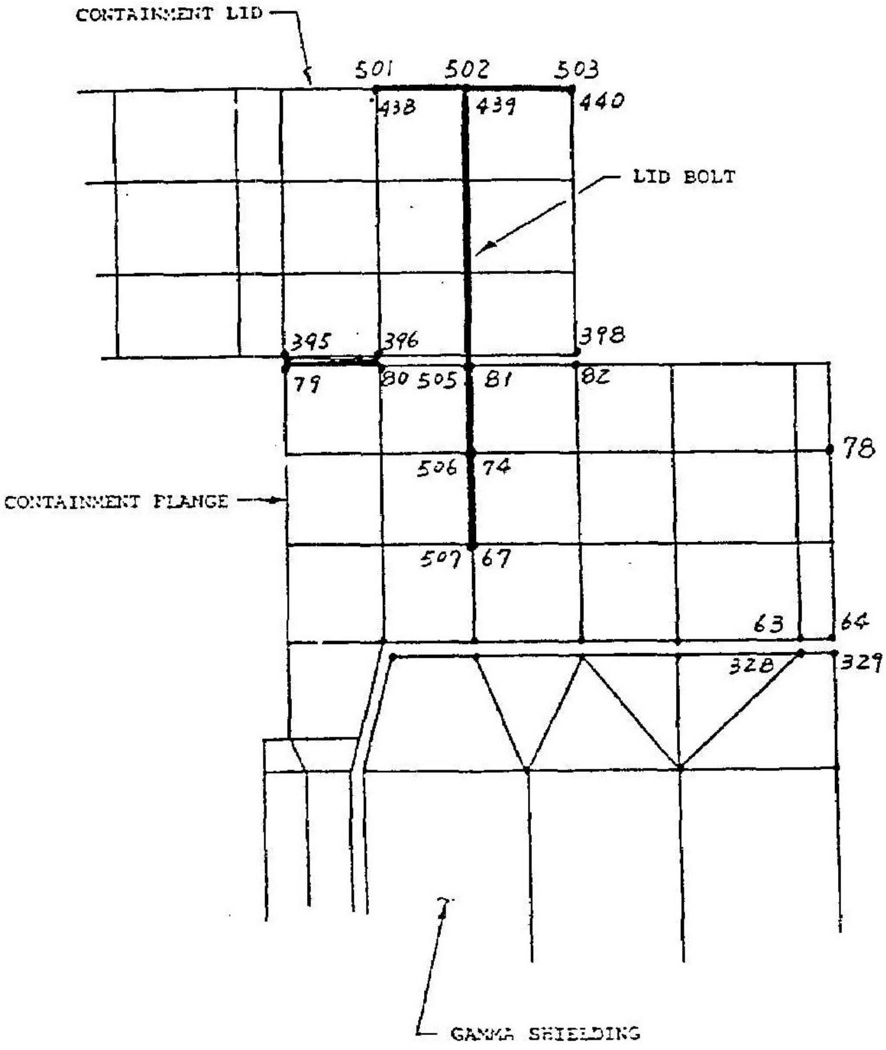


FIGURE 3A.2-1
CASK BODY FINITE
ELEMENT MODEL



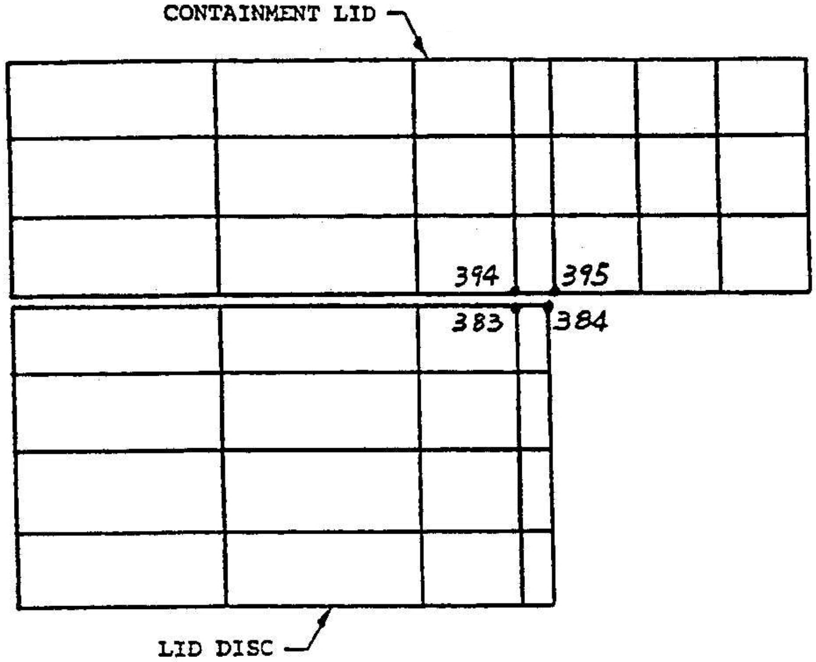
WELD SIMULATION AT JUNCTION OF GAMMA SHIELDING CYLINDRICAL SHELL TO FLAT BOTTOM BY COUPLING NODES 107-236 AND 108-280

FIGURE 3A.2-2
CASK BODY
BOTTOM CORNER



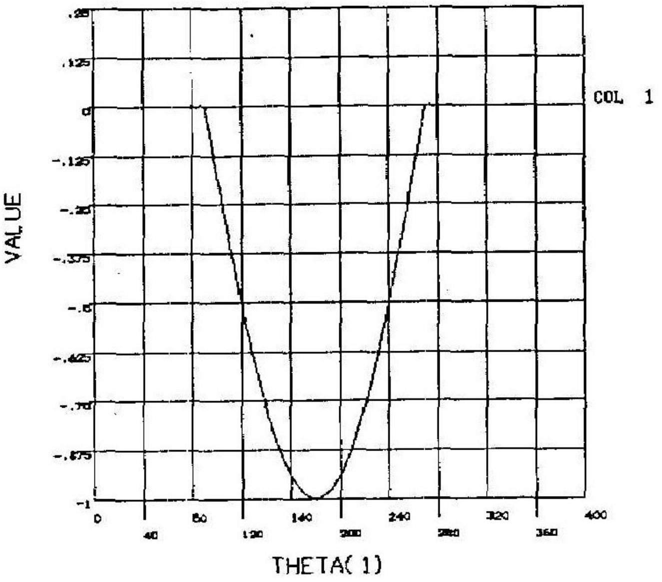
LID BOLTS CONNECTING PRIMARY LID TO CONTAINMENT FLANGE AND WELD ATTACHING GAMMA SHIELDING TO FLANGE

FIGURE 3A.2-3
CASK BODY
TOP CORNER



SIMULATION OF WELD CONNECTING CONTAINMENT LID TO LID DISC BY COUPLING NODES 383-394 AND 384-395

FIGURE 3A.2-4
CASK LID TO SHIELD
PLATE CONNECTION

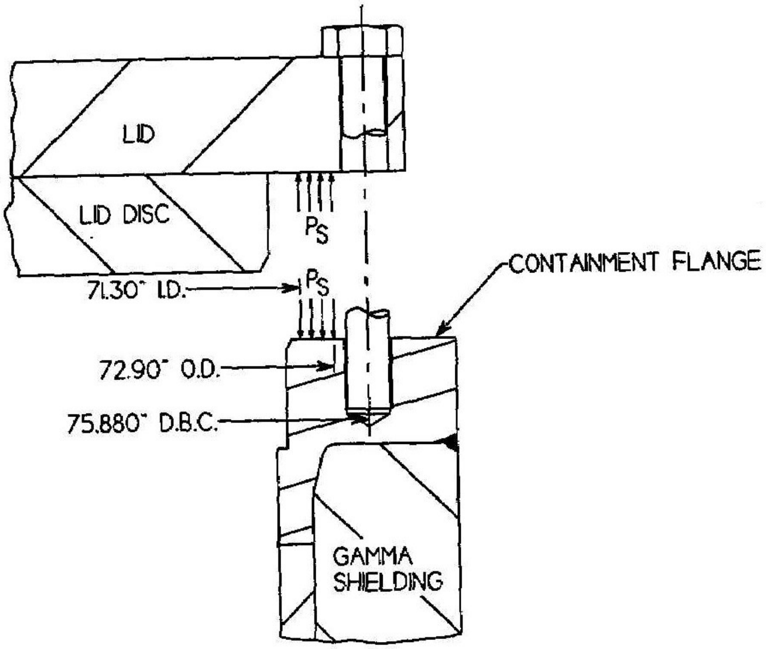


FOURIER COEFFICIENTS

MODE	COEFF	ISYM
0.0000	-0.3182	1.0000
1.0000	0.5000	1.0000
1.0000	0.0000	-1.0000
2.0000	-0.2124	-1.0000
2.0000	0.0000	-1.0000
3.0000	0.0000	1.0000
3.0000	0.0000	-1.0000
4.0000	0.0426	1.0000
4.0000	0.0000	-1.0000
5.0000	0.0000	1.0000
5.0000	0.0000	-1.0000
6.0000	-0.0183	1.0000
6.0000	0.0000	-1.0000
7.0000	0.0000	1.0000
7.0000	0.0000	-1.0000
8.0000	0.0103	1.0000
8.0000	0.0000	-1.0000
9.0000	0.0000	1.0000
9.0000	0.0000	-1.0000
10.0000	-0.0066	1.0000
10.0000	0.0000	-1.0000

FOURIER OUTPUT CURVE FOR COS FUNCTION OVER 90-270 DEGREES

FIGURE 3A.2-5
FOURIER COFFICIENTS FOR
1G LATERAL



SEAL LOAD F_S = 2 x 1399 #/IN = 2798 #/IN AT D_{av} = 72.10"

SEAL PRESSURE $P_S = \frac{\pi\ (72.10)(2798)}{\pi\ /4\ (72.90^2 - 71.30^2)} = 3498$ psi

BOLT PRELOAD STRESS: 35,000 psi

** The actual lid bolt preload stress is 25,000 psi, however, lid bolt preload corresponding to 35,000 psi is used for all load combinations.

FIGURE 3A.2-6
BOLT PRELOAD
AND
SEAL REACTION

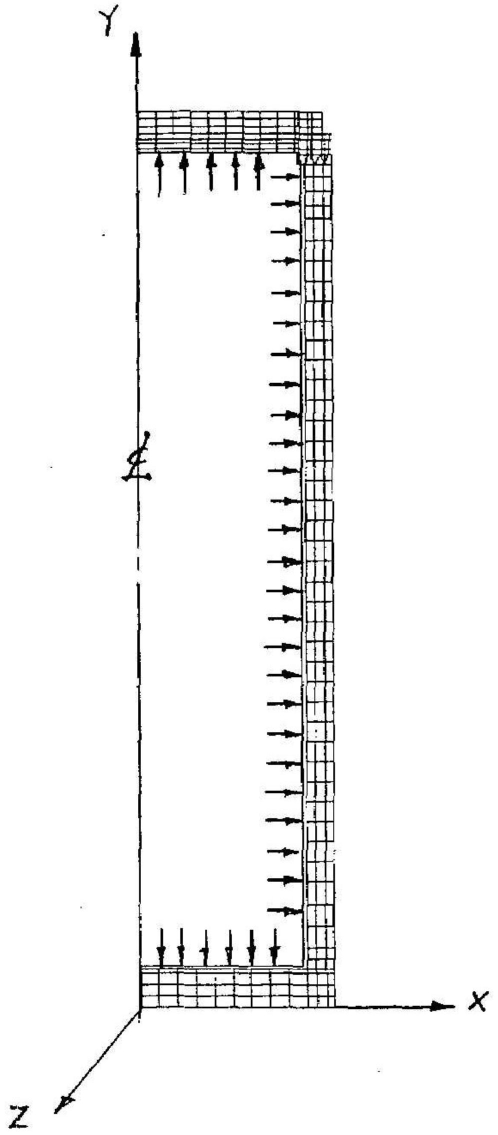


FIGURE 3A.2-7
DESIGN INTERNAL
PRESSURE (100 PSIG)

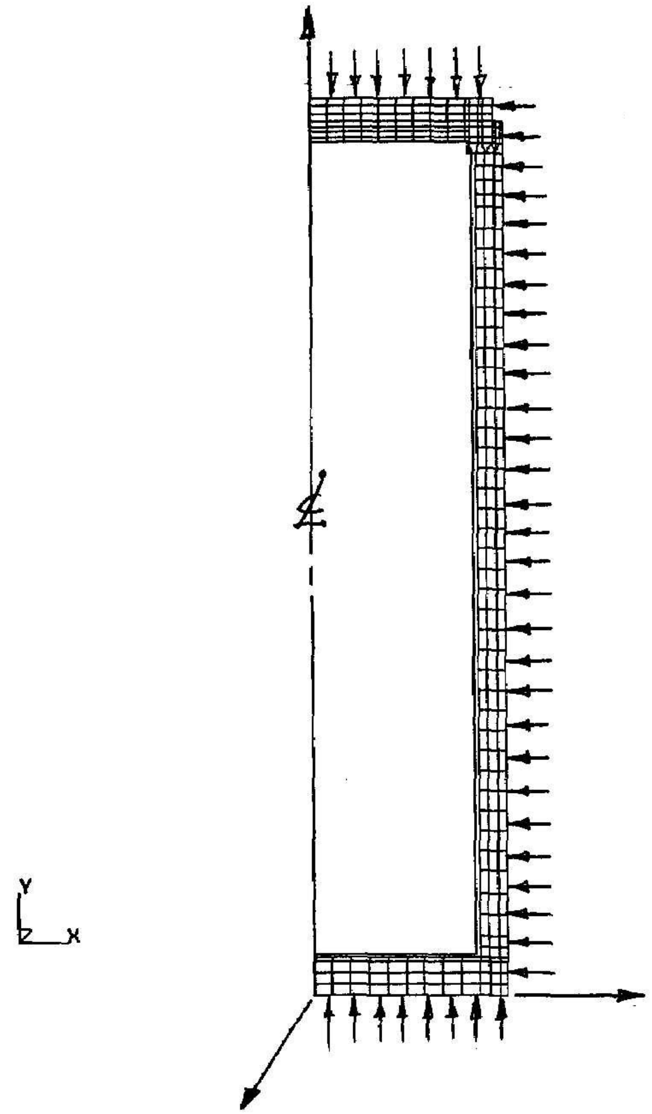


FIGURE 3A.2-8
EXTERNAL PRESSURE
LOADING (25 PSIG)

W- TOTAL WEIGHT OF CASK
(BASED ON 240,000 LBS.)
-TOTAL WEIGHT OF INTERNALS
(BASED ON 77,240 LBS)
- 162,760 LBS.

Pi - PRESSURE ON CONTAINMENT BOTTOM INNER SURFACE DUE TO WEIGHT OF INTERNALS

$$= \frac{77,240}{\pi(35.5^2)}$$

= 19.509 psi

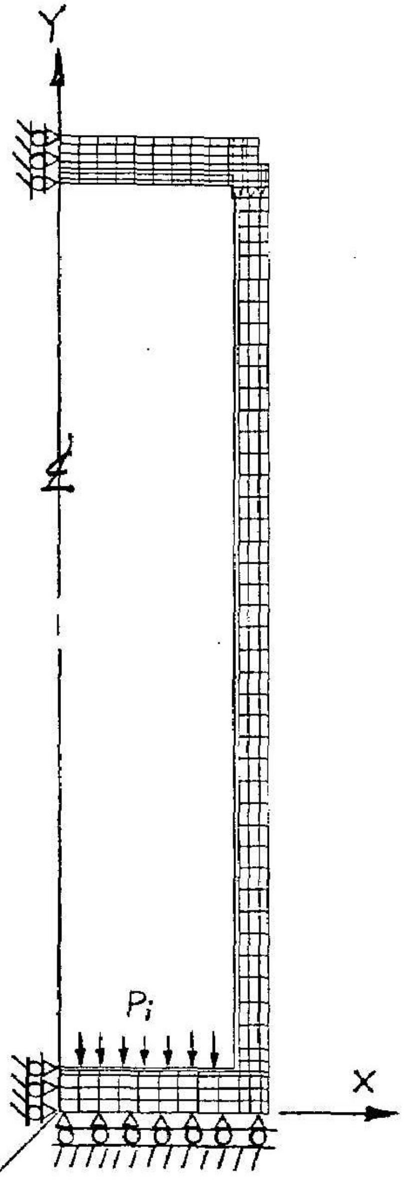
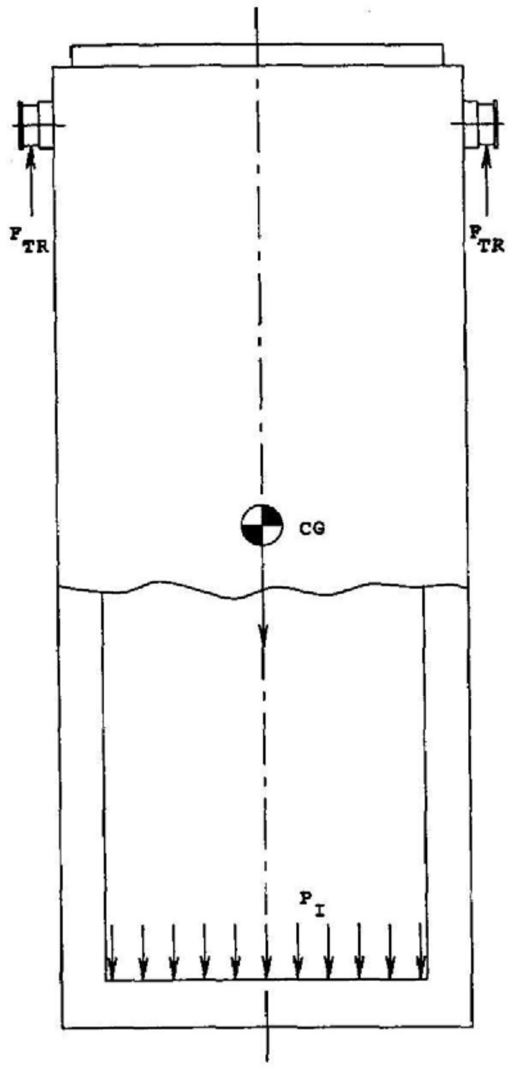


FIGURE 3A.2-9
1g DOWN LOADING



$$F_{TR} = \frac{6W \times 1.15}{2} = \frac{6 \times 240{,}000 \times 1.15}{2} = 828{,}000 \text{ LBS.}$$

$$P_I = \frac{6 \times 77{,}240 \times 1.15}{\pi(35.5)^2} = 134.61 \text{ psi}$$

FIGURE 3A.2-10
LIFTING : 6G
VERTICAL UP

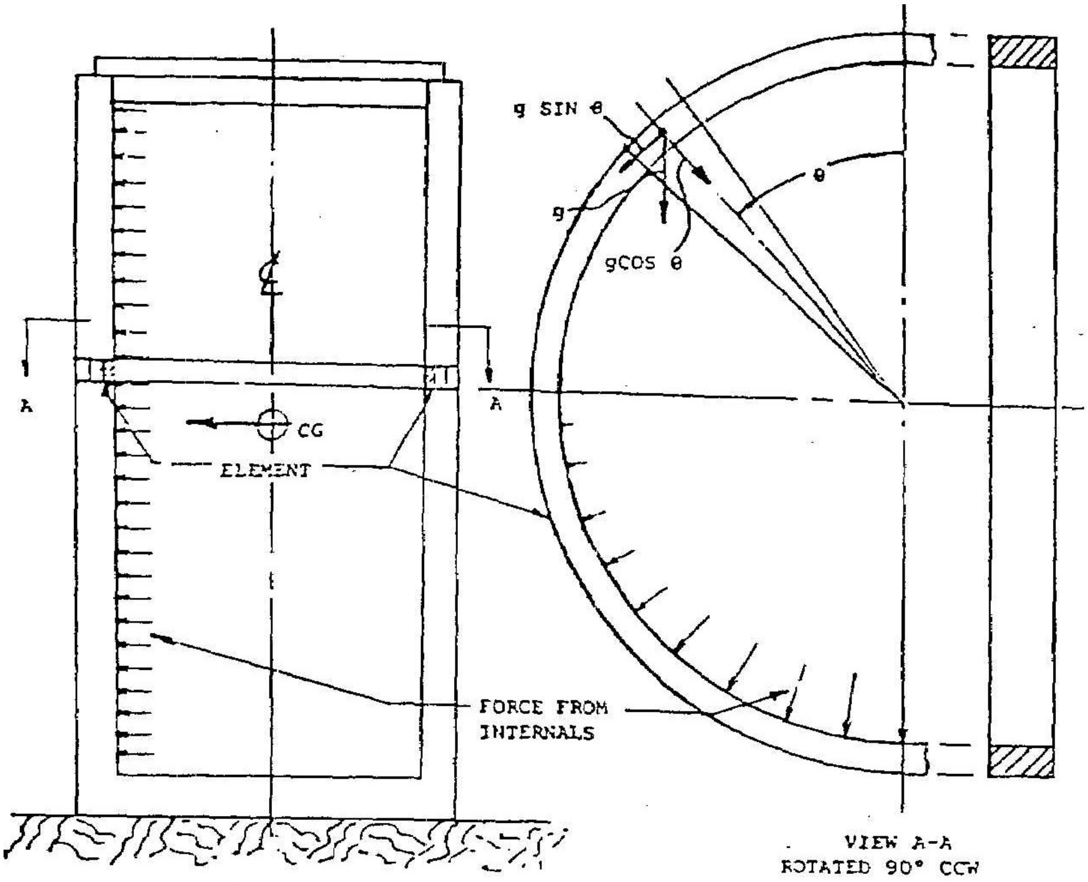
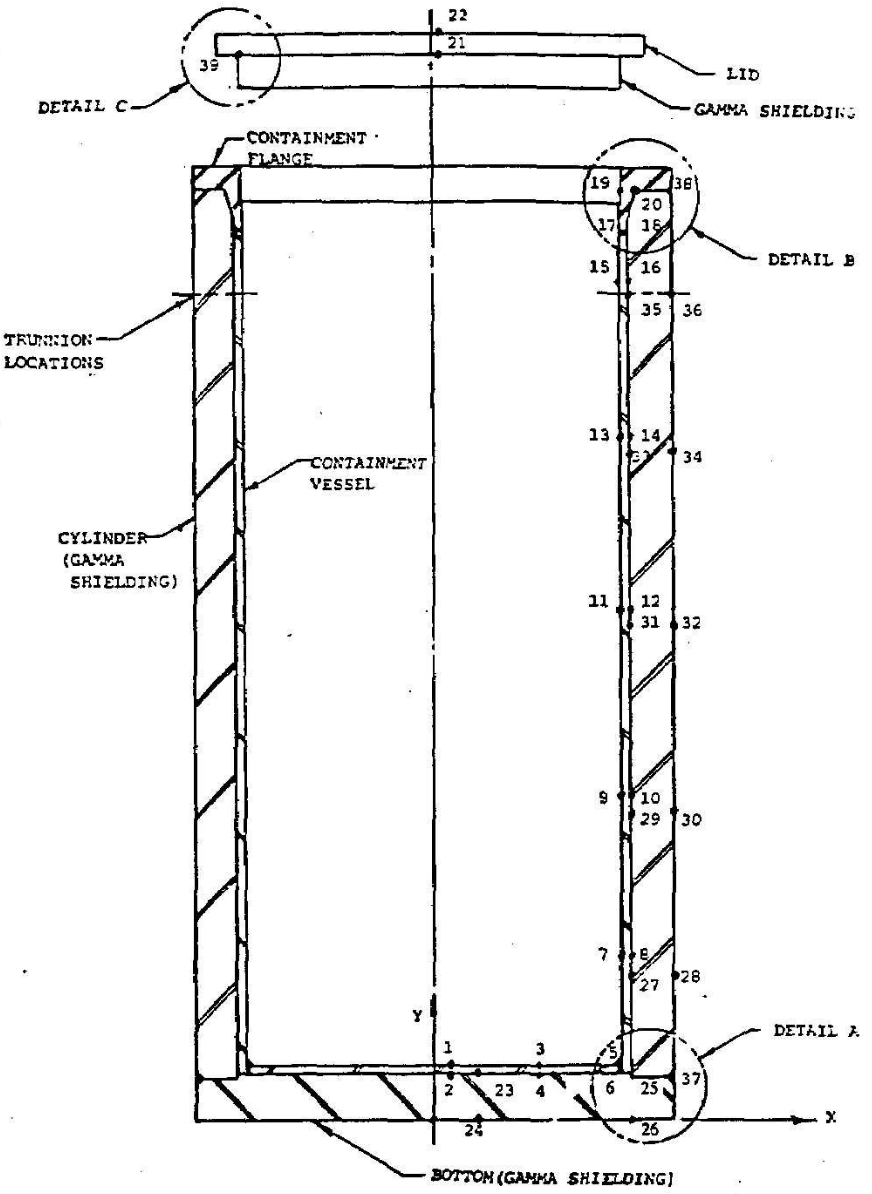
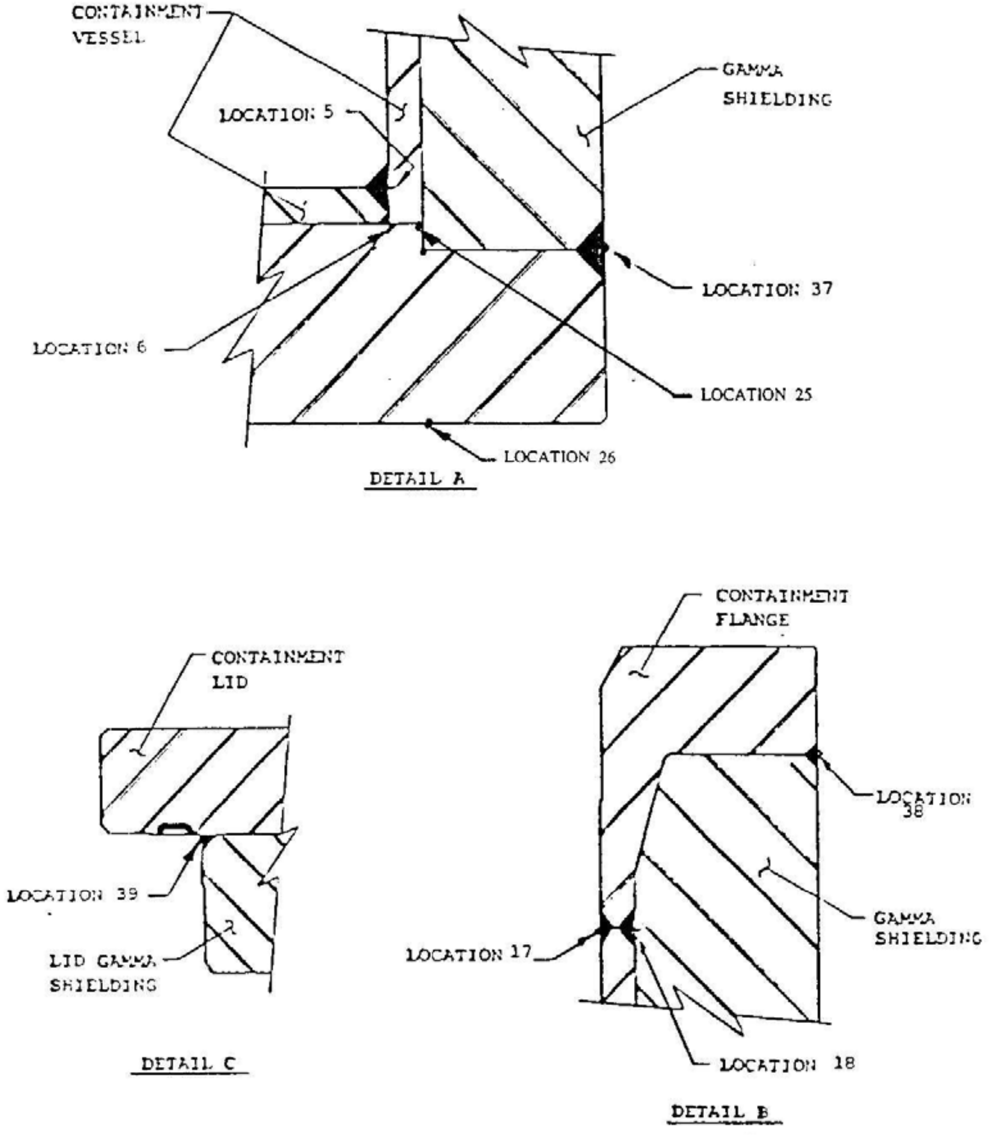


FIGURE 3A.2-11
1g LATERAL



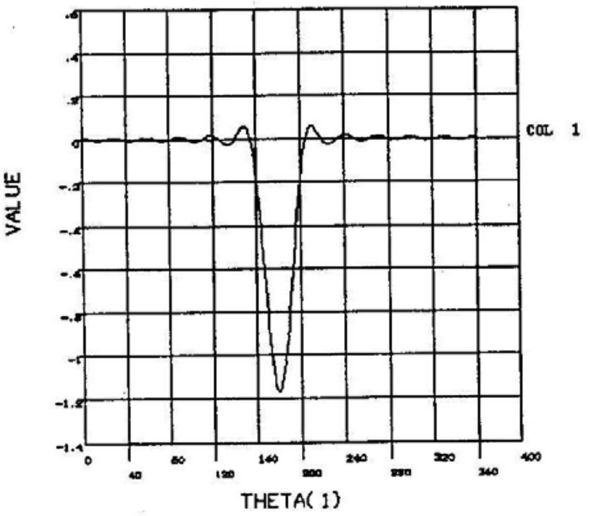
See Figure 3A.2-13 for details A, B & C.

FIGURE 3A.2-12
STANDARD REPORTING
LOCATIONS FOR CASK BODY



Details taken from Figure 3A.2-12

FIGURE 3A.2-13
WELD STRESS LOCATIONS



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FOURIER COEFFICIENTS

MODE        COEFF     ISYM

 0.0000   -0.0851    1.0000
 1.0000    0.1681    1.0000
 1.0000    0.0000   -1.0000
 2.0000   -0.1620    1.0000
 2.0000    0.0000   -1.0000
 3.0000    0.1523    1.0000
 3.0000    0.0000   -1.0000
 4.0000   -0.1391    1.0000
 4.0000    0.0000   -1.0000
 5.0000    0.1233    1.0000
 5.0000    0.0000   -1.0000
 6.0000   -0.1053    1.0000
 6.0000    0.0000   -1.0000
 7.0000    0.0860    1.0000
 7.0000    0.0000   -1.0000
 8.0000   -0.0661    1.0000
 8.0000    0.0000   -1.0000
 9.0000    0.0465    1.0000
 9.0000    0.0000   -1.0000
10.0000   -0.0278    1.0000
10.0000    0.0000   -1.0000
11.0000    0.0107    1.0000
11.0000    0.0000   -1.0000
12.0000    0.0042    1.0000
12.0000    0.0000   -1.0000
```

FOURIER OUTPUT FOR COS FUNCTION OVER 165-195 DEGREES

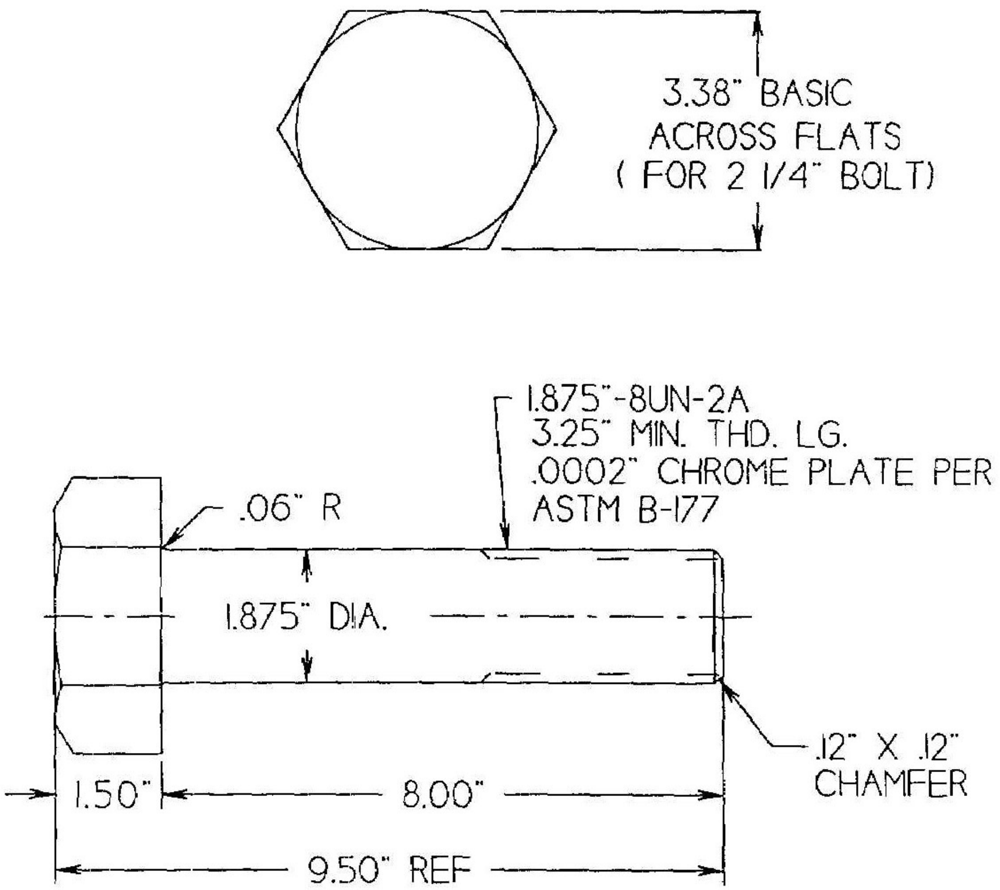
FIGURE 3A.2-14
FOURIER SERIES APPROXIMATION
OF THE FOOTPRINT PRESSURE FOR
THE SIDE DROP

Figure Withheld Under 10 CFR 2.390

FIGURE 3A.2-15
TRUNNION GEOMETRY

Figure Withheld Under 10 CFR 2.390

FIGURE 3A.3-1
TN-68 CASK LID CLOSURE ARRANGEMENT



MATERIAL: ASME SA-540 GRADE B24. CLASS I

FIGURE 3A.3-2
TN-68 CASK LID BOLT

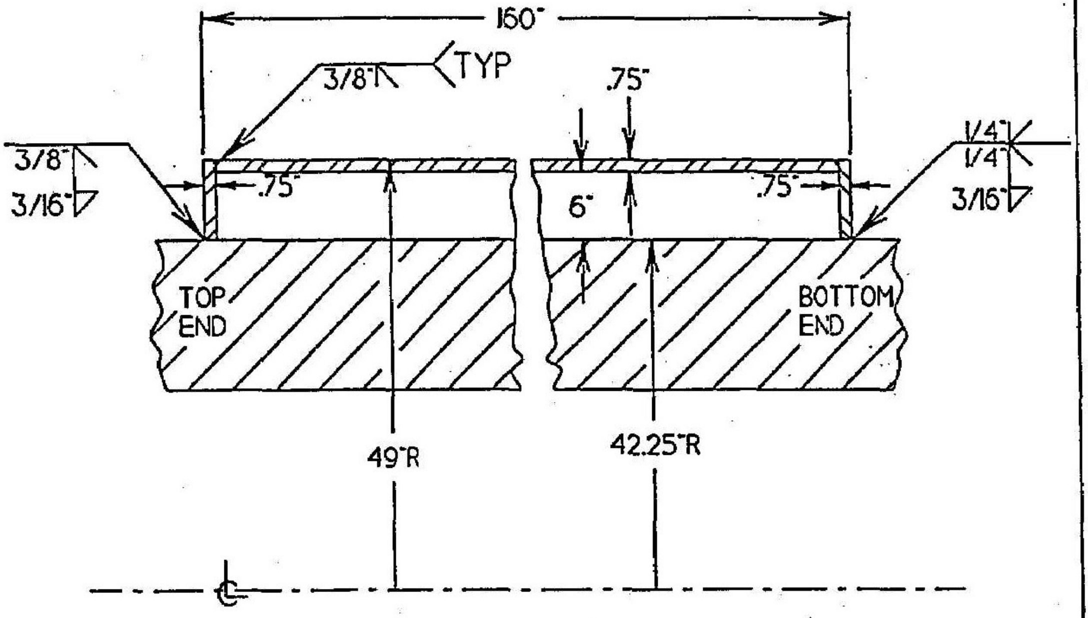
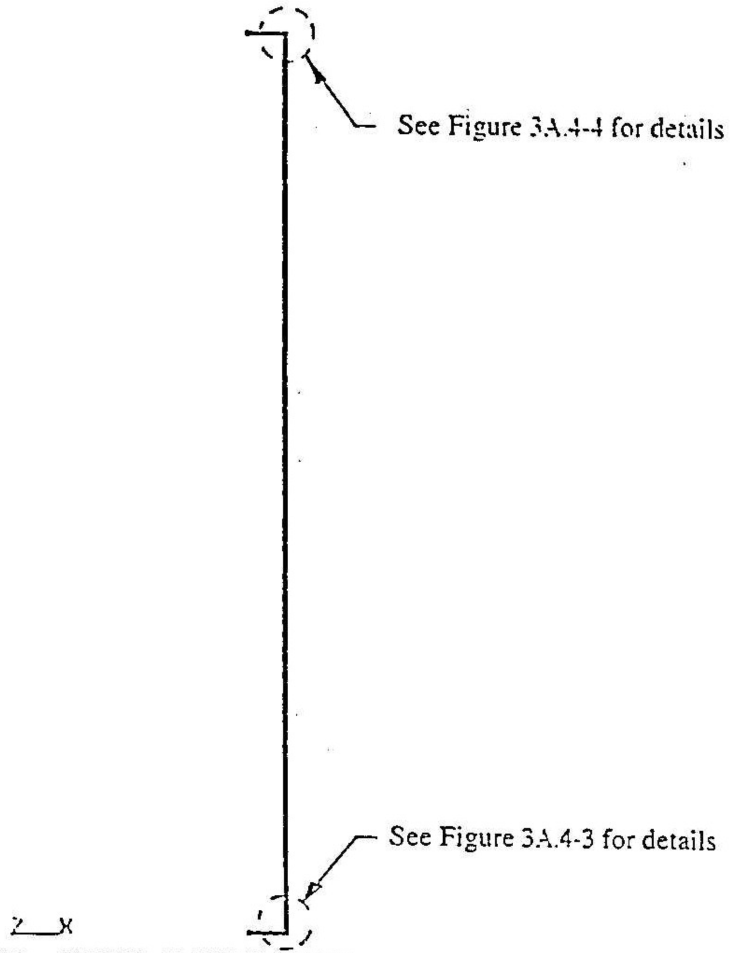


FIGURE 3A.4-1
CASK OUTER SHELL AND
CONNECTION WITH CASK BODY



See Figure 3A.4-4 for details

See Figure 3A.4-3 for details

TN-68 OUTER SHELL, FINITE ELEMENT MODEL

FIGURE 3A.4-2
FINITE ELEMENT MODEL
OUTER SHELL

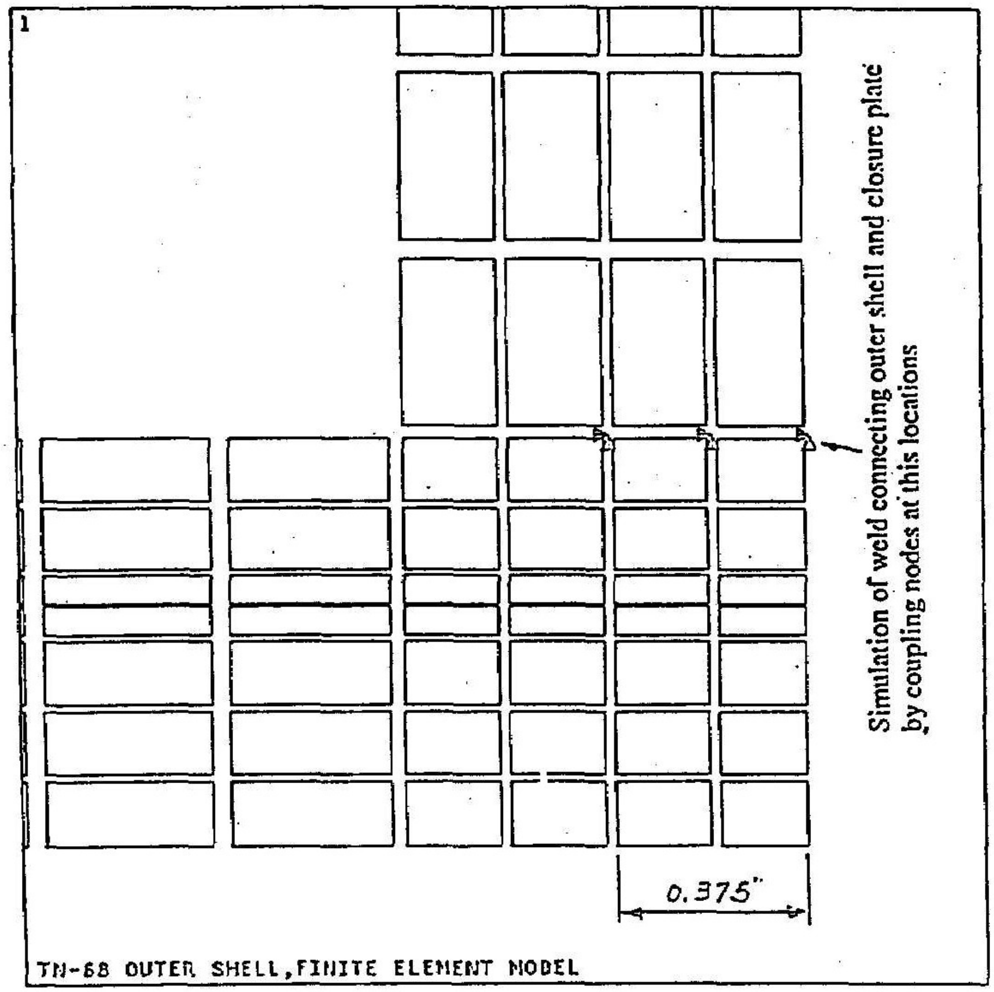


FIGURE 3A.4-3
FINITE ELEMENT MODEL
BOTTOM CORNER

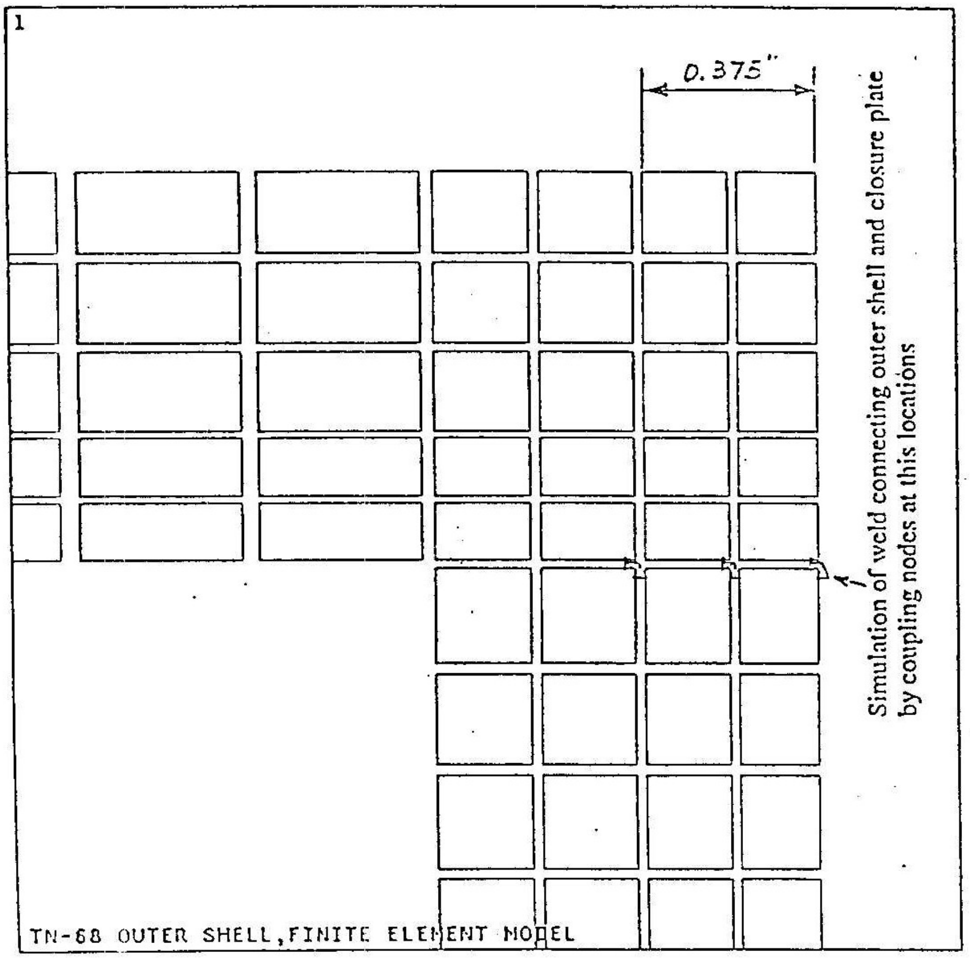


FIGURE 3A.4-4
FINITE ELEMENT MODEL
TOP CORNER

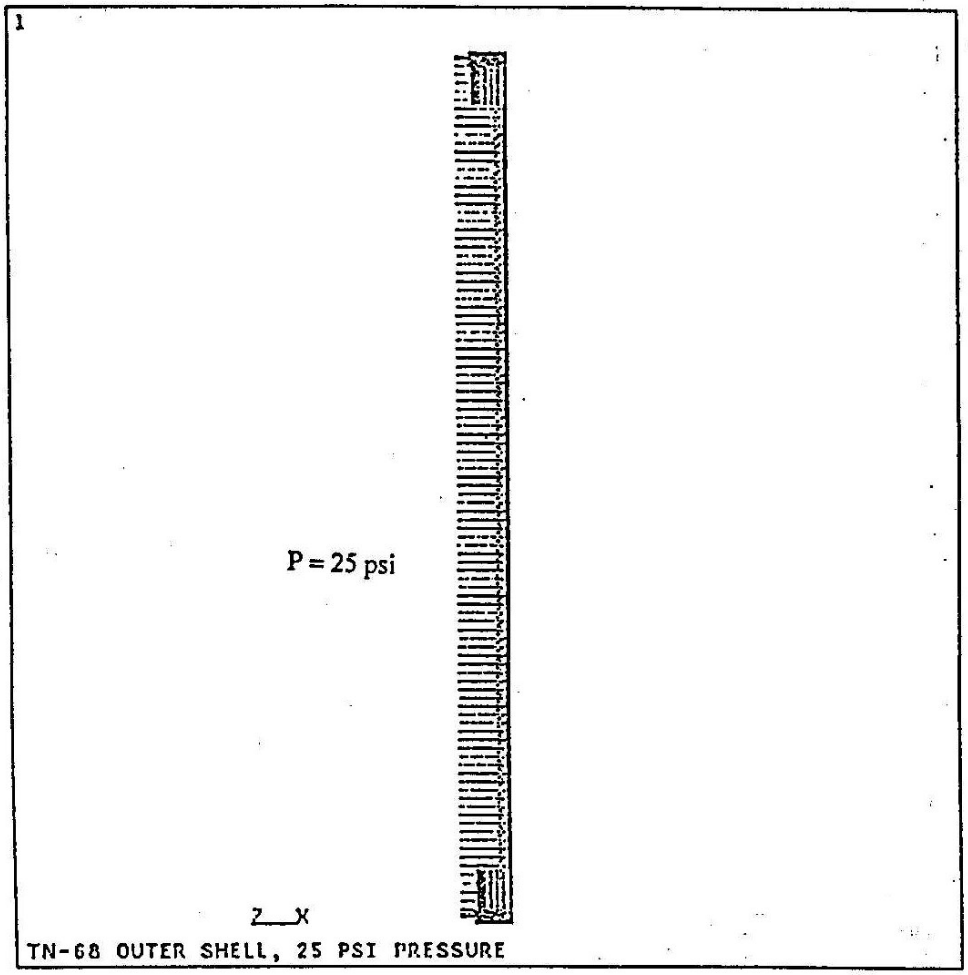
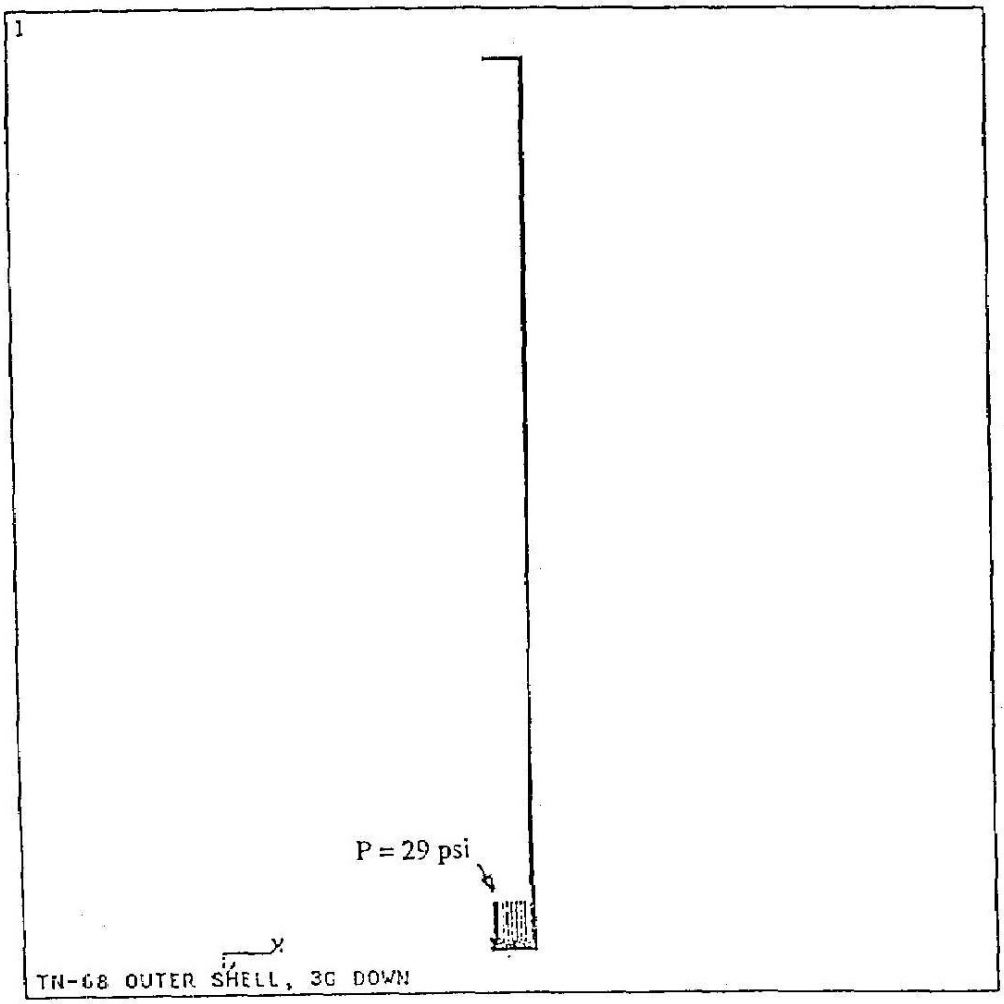


FIGURE 3A.4-5
INTERNAL PRESSURE
(25 PSIG)



$$P = (2{,}502 + 13{,}957) \times 3 / (48.25^2 - 42.25^2) \times \pi = 29 \text{ psi}$$

FIGURE 3A.4-6
3 G DOWN