Enclosure 4 to E-41224

TN-RAM SAR, Revision 13
(Non-Proprietary)

Non-Proprietary

SAFETY ANALYSIS REPORT for the TN-RAM

E-10621

March 2015

Revision 13

AREVA Inc.
7135 Minstrel Way, Suite 300
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TN-RAM SAR
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0	11/22/88	Original Issue
1	5/18/89	Revised Pages as follows: Chapter 1, pages i, 5, 8, & 11-13A. Chapter 2, pages iii, 1, 2, 5-8, 17, 19, 22, 26-27, 30-31, 33-38, 44, 46, 48-62, 64-73 76, 77, 80-87, 89, 92, 93-95, 98-111, & 112-114. App 2.10.1, pgs. 3, 5, 36, 37, 50, 53, 54, 57, 72, 74, 75, 84, & 85. App. 2.10.2, pgs. 3-8, 11-12A, 16, & 20. App. 2.10.3, pgs. 1-46. App. 2.10.4, pgs. 1-20. App. 2.10.5, pgs. 1-12. App. 2.10.6, pgs. 1-3. App. 2.10.7, pgs. 1-6. Chapter 3, pgs. 1, ii, iii, 1-8, 11-14, 16-24, 26, 29, & 30. Chapter 4, pgs. i, 3, 3A, 5-5C, & 6-8. Chapter 5, pgs. i, ii, 1-5, 8-11, & 14. Chapter 7, pgs. i & 1-11. Chapter 8, pgs. i & 1-9.
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6	12/18/97	Revised Pages as follows: Chapter 1, page 14. Dwg. No. 990-701 Chapter 7, pgs. 8 & 11.
7	8/20/98	Revised pages as follows: Chapter 1, page 14 Dwg. Nos. 990-707 & -708
8	5/7/07	Revised pages as follows: Page 3-7, dwgs 990-703, -705, -708
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10	9/30/08	Revised pages as follows: Revision log pages 2 and 3 SAR pages 2-iii, 2-63 SAR pages 3-ii, 3-iii, 3-4, 3-18, 3-19, 3-19A, 3-19B, 3-20A, 3-21, 3-22A, 3-24, 3-25, 3-26, 3-27, 3-28, 3-29, 3-30 SAR pages 4-ii, 4-5A, 4-5B, 4-5C, 4-6, 4-7, 4-8 SAR pages 7-5, 7-6, 7-7, 7-10, 7-11, 7-12, 7-16 SAR pages 8-8 Revised drawings as follows: none New pages as follows: SAR page 2-xxix SAR Appendix 2.10.9 pages 2.10.9-1 to 2.10.9-9 SAR pages 3-19C, 3-19D, 3-20C, 3-20D SAR pages 4-5D, 4-8A New drawings as follows: none
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12	6/10/14	Revised pages as follows: SAR cover page SAR page 1-14 SAR pages 7-5, 7-10, 7-15 New page as follows: Revision log page 4 Revised drawings as follows: Drawing 990-701 Drawing 990-702 Drawing 990-703 Drawing 990-704 Drawing 990-705 Drawing 990-708 Drawing 990-710 New drawings as follows: none
13	*3/9/15*	*Revised pages as follows:* *SAR Cover sheet* *Revision Log pages 1, 4* *Table of Contents pages i, ii* *SAR pages 1-i, 1-ii, 1-1 through 1-11* *SAR page 2-1* *SAR pages 3-ii, 3-iii, 3-2, 3-3, 3-4, 3-5, 3-8 through 3-18, 3-19A, 3-19D, 3-23 through 3-30* *SAR pages 4-ii, 4-5B, and 4-6* *SAR pages 5-i through 5-iii, 5-1 through 5-34* *SAR pages 7-8, 7-12*

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CHAPTER ONE

GENERAL INFORMATION

1.1 INTRODUCTION

This Safety Analysis Report (SAR) presents the evaluation of a Type B radioactive material transport packaging developed by Transnuclear, Inc. and designated the TN-RAM. This SAR describes the design features and presents the safety analyses which demonstrate that the TN-RAM complies with applicable requirements of 10 CFR 71. The format and content of this SAR follow the guidelines of Regulatory Guide 7.9.

The TN-RAM will be used to transport dry irradiated non-fuel bearing solid materials in secondary containers. Fissile contents shall not exceed the generally licensed limits as specified in 10 CFR 71.22. The TN-RAM is a right circular cylinder with steel containment, lead shielding, and wood filled impact limiters. A detailed description of the packaging is presented in Section 1.2.

1.2 PACKAGE DESCRIPTION

1.2.1 Packaging

The basic structure of the TN-RAM is a right circular cylinder, steel-lead-steel type cask with wood-filled impact limiters attached at both ends. The steel-lead-steel construction of the lid, sides, and bottom provide a shielding effectiveness of approximately 6.9 inches lead equivalent. The overall dimensions of the packaging are 178.12 inches long and 91.75 inches in diameter with the impact limiters installed. The cask is 129.38 inches long and 51.25 inches in diameter. The cask cavity has a length of 111 inches and a diameter of 35 inches. The general arrangement of the TN-RAM is depicted in Figure 1-1. Component terminology used in this SAR is also identified on Figure 1-1. Detailed design drawings for the TN-RAM are provided in Appendix 1.3. Table 1-1 summarizes the materials of construction used in the TN-RAM.

The basic components of the TN-RAM packaging are the cask body, closure lid, lid bolts, and impact limiters. There are two versions of the closure lid. The original lid consists of the lid plate with a lead shield plug attached. The optional lid design consists of a lid plate essentially identical to the original with a separate shield plug that has nearly the same dimensions as the original but is installed separately. Note that Figure 1-1 shows the original lid. The cask body consists of the cylindrical shell assembly and bottom assembly. The closure lid is attached to the cask body with sixteen 1.5 inch diameter bolts. Six trunnions are welded to the cask body with four located at 90° intervals near the lid end and two located with a 180° spacing near the bottom end. Two penetrations into the containment are provided to support cask operations. One is located in the lid and one is located in the cask body near the bottom end. The maximum gross weight of the loaded package is 80,000 pounds including a maximum payload of 9,500 pounds. The TN-RAM is transported in the horizontal orientation with the lid end facing the direction of travel. During transport, the packaging is supported in a transport cradle by two front and two rear trunnions.

The following sections provide a physical and functional description of each major component. Detailed drawings showing dimensions of significance to the safety analyses, welding and NDE information, and a complete materials list are provided in Section 1.3. Reference to these drawings is made in the following physical description sections and in general, throughout this SAR. Fabrication of the TN-RAM packaging is performed in accordance with these drawings.

1.2.1.1 Cask Body

The cask body, also referred to as the shell assembly is shown on drawings 990-702, 990-703, and 990-704. The shell assembly consists of two concentric stainless steel shells for the sidewall and two parallel stainless steel plates for the bottom, with lead between the shells and plates. A forged closure flange (also referred to as the bolting flange or shell flange) is welded to the lid end of the shell assembly. The stainless steel shells and plates are ASTM A-240, Type 304 and the shell flange is ASTM A-182 Grade F304. The outside shell is 1.50 inches thick and the outside bottom plate is 2.50 inches thick. The inner shell is 0.75 inches thick and the inner bottom plate is 0.50 inches thick.

The 5.88 inch thick annular region between the inner and other shells is filled with lead. The lead shielding thickness in the cask body bottom is 6.06 inches. All structural welds in the shell assembly including containment boundary welds are full penetration welds.

Attachments and subassemblies associated with the cask body include:

- Lifting and tiedown trunnions (See Section 1.2.1.4)
- Impact limiter attachment lugs (See Section 1.2.1.3)
- Cask body drain penetration (See Section 1.2.1.6)

1.2.1.2 Closure Lid

The design of the closure lids is shown on drawings 990-705, 990-706, and 990-710. The original closure lid consists of two parallel flat plates separated by lead shielding. The outer plate is 2.50 inches thick and the inner plate is 0.50 inches thick. Both plates are made from ASTM A240, Type 304 stainless steel. The outer plate forms the lid portion of the containment boundary. The lead shielding between the two plates is 5.94 inches thick. The optional closure lid has the same lid plate as the original outer lid plate. The optional closure lid includes a separate shield disk consisting of a lead disk 5.68 inches thick encased by a steel plate (0.375 inch top, 0.5 inch side and bottom). The lid plate is constructed of XM-19 material while the shield disk shell is ASTM A240, Type 304 stainless steel. The perimeter of the outer plate (or lid flange) has 16 equally spaced holes for the closure bolts which are located on a 45 inch diameter bolt circle. The closure bolts are nominally 1.5 inch diameter with an undercut shank diameter of 1.32 inches. Two concentric dovetail seal grooves are machined in the underside of the lid. Silicone O-rings are installed in these seal grooves. A leak test port provides access to the region between the two seals for assembly verification leak testing conducted prior to every transport. The leak test port is closed when not in use by a threaded plug. Only the inner O-ring provides a containment boundary function. The outer O-ring is provided to facilitate the leak testing procedure.

One penetration through the lid is provided for cask operations activities. The configuration of this penetration is described in Section 1.2.1.6. The use of this penetration for cask operations is described in Chapter Seven.

Two 1.032 inch diameter holes are located at the diameter of the closure bolt circle. These holes correspond to the guide pins mounted in the closure flange of the cask body. The asymmetric location of the guide pins and lid holes ensure that the closure lid is always installed in the same orientation with respect to the cask body. Alignment marks on the lid and cask body provide positive indication to operations personnel for lid installation.

Three symmetrically located threaded holes are provided in the top of the lid at a diameter of 36 inches. These holes are provided for attachment of the lid lifting device used during cask operations. This mechanism for lid handling does not require projections from the closure lid during transport.

The lid is recessed into the cask body so that the outside surface of the lid is flush with the rim portion of the closure flange on the shell which extends beyond the sealing surface. This recessed lid design prevents external lateral forces from being applied directly to the edge of the lid. Also the double-step arrangement at the lid-to-cask body interface provides a barrier to radiation streaming.

1.2.1.3 Impact Limiters

Front and rear impact limiters, shown on drawings 990-708 and 990-709, are provided for the TN-RAM packaging during transport. Each impact limiter is attached to the cask by eight 1.75 inch diameter bolts. The bolts are attached between lugs, which are welded to the other shell of the cask, and bolt bosses, which are integral to the impact limiter structure. The impact limiters are constructed of balsa wood and redwood encased in hermetically sealed stainless steel shells in order to prevent changes in the wood properties. Each impact limiter has one cylindrical and twelve radial steel gussets which form compartments for containing the energy absorbing wood. The combination of outer shell and internal gussets provide structural rigidity during normal transport and wood confinement during crushing caused by hypothetical accident drop conditions.

The impact limiters have an overall diameter of 91.75 inches and an overall thickness of 34.75 inches. The outer portion of the impact limiter extends 10.38 inches down the side of the cask.

Each impact limiter has seven fusible plugs which are designed to melt during a fire accident and thereby limit pressure build-up in the shell due to vaporization of moisture in the wood.

Each impact limiter has two lifting lugs for handling and two support angles for placing the impact limiters in a vertical storage position during cask loading/unloading operations. The impact limiters are installed and removed while the cask is in a horizontal orientation. The lifting lugs and support angles are welded to the outer cylindrical steel shells.

1.2.1.4 Lifting and Tiedown Devices

Six single piece trunnions are welded to the outer shell of the cask body. Detailed dimensions of the trunnions are shown on drawing 990-704. Four of the trunnions are identical and are located near the lid end of the cask at 90° intervals around the cask body circumference. Either opposing pair or all four trunnions may be used for cask lifting in the vertical orientation. One trunnion pair is sufficient for lifting the fully loaded package. The second trunnion pair may be used with redundant lifting devices. One pair of front trunnions is located on approximately the same plane as the trunnion pair attached near the bottom end of the cask. The bottom trunnions are offset from the axial centerline by one inch, while the front trunnions are on the axial centerline. In addition to the lifting function, this pair of front trunnions is used for tiedown during transport and for lifting operations where the cask is rotated in the transport frame between horizontal and vertical. The two rear trunnions are slightly different in design than the front trunnions. The functions of the rear trunnions are for rotation between horizontal and vertical and for tiedown during transport. The rear trunnions withstand a greater portion of the regulatory basis tiedown loads than do the front trunnions.

The rear trunnions are designed to permit horizontal lifting using a lift fixture attached to the rear trunnions and the corresponding pair of front trunnions.

The analysis of the trunnions for tiedown and lifting loads is presented in Section 2.5 of Chapter Two.

1.2.1.5 Thermal Shield

The outer shell of the cask body is covered by a stainless steel thermal shield. A 0.125 inch diameter wire is wrapped around the cask body at a spacing of 7.50 inches between successive turns in the helical wrapping. A 0.25 inch stainless steel plate is welded to the cask body over the wire wrapping. The wire and outer plate combination provide an air gap which impedes conductive heat transfer. The effect of this insulating air gap is considered in analysis of decay heat dissipation from the payload and for the analysis of packaging heating from external sources such as insolation and the thermal accident environment.

The thermal shield does not extend to the lid or bottom regions since the impact limiters serve an insulating function at these locations.

1.2.1.6 Penetrations

There are two penetrations through the containment boundary which are used during loading operations. The 1.084 inch diameter straight penetration in the lid is designated as the vent port. The vent port is normally closed by a 5 inch diameter, 0.75 inch thick blind flange which is secured to the lid with three 0.5 inch diameter by 1 inch long socket head cap screws. The penetration cover is recessed into the outer plate of the lid so that the outer surfaces are flush. In the original lid a lead-filled stainless steel tube is attached to the underside of the blind flange to maintain the shielding effectiveness at the penetration location. The optional lid penetration extends only through the lid plate so this tube is not required for the optional lid. A single silicone O-ring is mounted in a dovetail groove machined in the underside of the penetration cover. Leak testing of the penetration is accomplished using a vacuum bell as described in Chapter Seven.

The penetration located near the bottom of the cask body is designated as the drain port. Access to this penetration is located on the side of the cask body near the bottom plate. A double-wall stainless steel tube extends from the access location, through the lead of the bottom assembly, and through the inner bottom plate of the cask cavity. The 0.75 inch nominal diameter, schedule 80 inner pipe serves a containment boundary function. The inner pipe is located within a 1.25 inch nominal diameter schedule 40 outer pipe. The drain pipe layout between the exterior access location and the cavity interior includes two 90° bends. The double-wall arrangement and 90° bending accommodates thermal expansion of the inner tube in the event that temperature differences develop during operations involving the drain port. The drain port permits draining of the cask cavity with the TN-RAM in a vertical orientation. A Hansen quick connect coupling is provided at this penetration. A blind flange which maintains the containment boundary at this point is secured over the drain port by four bolts. A single silicone O-ring is located in the seal

groove machined in the penetration cover. Leak testing of this penetration is accomplished using a vacuum bell as described in Chapter Seven.

1.2.2 Operational Features

There are no complex operational features associated with the TN-RAM. The packaging is designed to accommodate wet or dry loading/unloading operations. Loading/unloading activities can be accomplished with the packaging either horizontal or vertical. The TN-RAM is uprighted from the horizontal transport orientation to the vertical position by lifting at two of the front trunnions and allowing the packaging to pivot about the rear trunnions while supported in the transport cradle. Both impact limiters are removed prior to this handling operation. Cask handling in the vertical position can be accomplished with either pair of opposing top trunnions, or with all four top trunnions if redundancy is required. For horizontal loading/unloading operations, the cask is left in the transport cradle. Significant design features which support wet operations include self-draining bolt holes in the cask body closure flange, two penetrations for draining/drying activities, and smooth stainless steel surfaces to minimize decontamination efforts.

The sequential steps to be followed for cask loading/unloading operations and pre-transport preparations including seal testing are provided in Chapter Seven.

1.2.3 Contents of Packaging

The TN-RAM is designed to transport a payload of 9,500 lbs of dry irradiated and contaminated, non-fuel-bearing solid materials (with only trace quantities of fissile materials present as contamination) in secondary containers.

The safety analysis of the TN-RAM takes no credit for the containment provided by secondary containers.

The quantity of radioactive material is limited to a maximum of *30,000 Ci cobalt-60 or equivalent. Equivalency to other radionuclides is determined by the total energy in its spectrum.* The radioactive material is primarily in the form of neutron activated metals, or metal oxides in solid form. Surface contamination may also be present on the irradiated components. When a wet load procedure (i.e., in-pool) is followed for cask loading, cask cavity draining and drying is performed in order to ensure that free liquids do not remain in the package during transport.

The decay heat load of the radioactive material is limited to a maximum of *500* watts.

The TN-RAM is designed for shipment of various types of irradiated reactor hardware. The payload will vary from shipment to shipment and will consist predominantly of the following components either individually or in combinations:

1. BWR Control Rod Blades
2. BWR Local Power Range Monitors (LPRMs)
3. BWR Fuel Channels
4. BWR Poison Curtains

5. PWR Burnable Poison Rod Assemblies (BPRAs)

The typical Cobalt 60 specific activity ranges for these items are as follows:

1.	Control Rod Blades	1.3×10^{-4}	–	1.1×10^{-2} Ci/g
2.	LPRMs	1.0×10^{-2}	–	4.8×10^{-2} Ci/g
3.	Fuel Channels	7.8×10^{-5}	–	2.0×10^{-4} Ci/g
4.	Poison Curtains	6.2×10^{-4}	–	4.0×10^{-2} Ci/g
5.	BPRAs	3.8×10^{-4}	–	1.3×10^{-3} Ci/g

Due to material averaging required to achieve Class C (or less), the typical Cobalt 60 activity will generally be in the range of 1.8×10^{-3} to 2.6×10^{-3} ci/g for control rod blade and local power range monitor shipments, respectively.

Components with high specific activity are generally placed near the center of the cask. For each shipment, the cask is normally filled to capacity, which prevents shifting of the contents during transport. If the container is not full, appropriate component spacers or shoring will be used to prevent shifting of the contents.

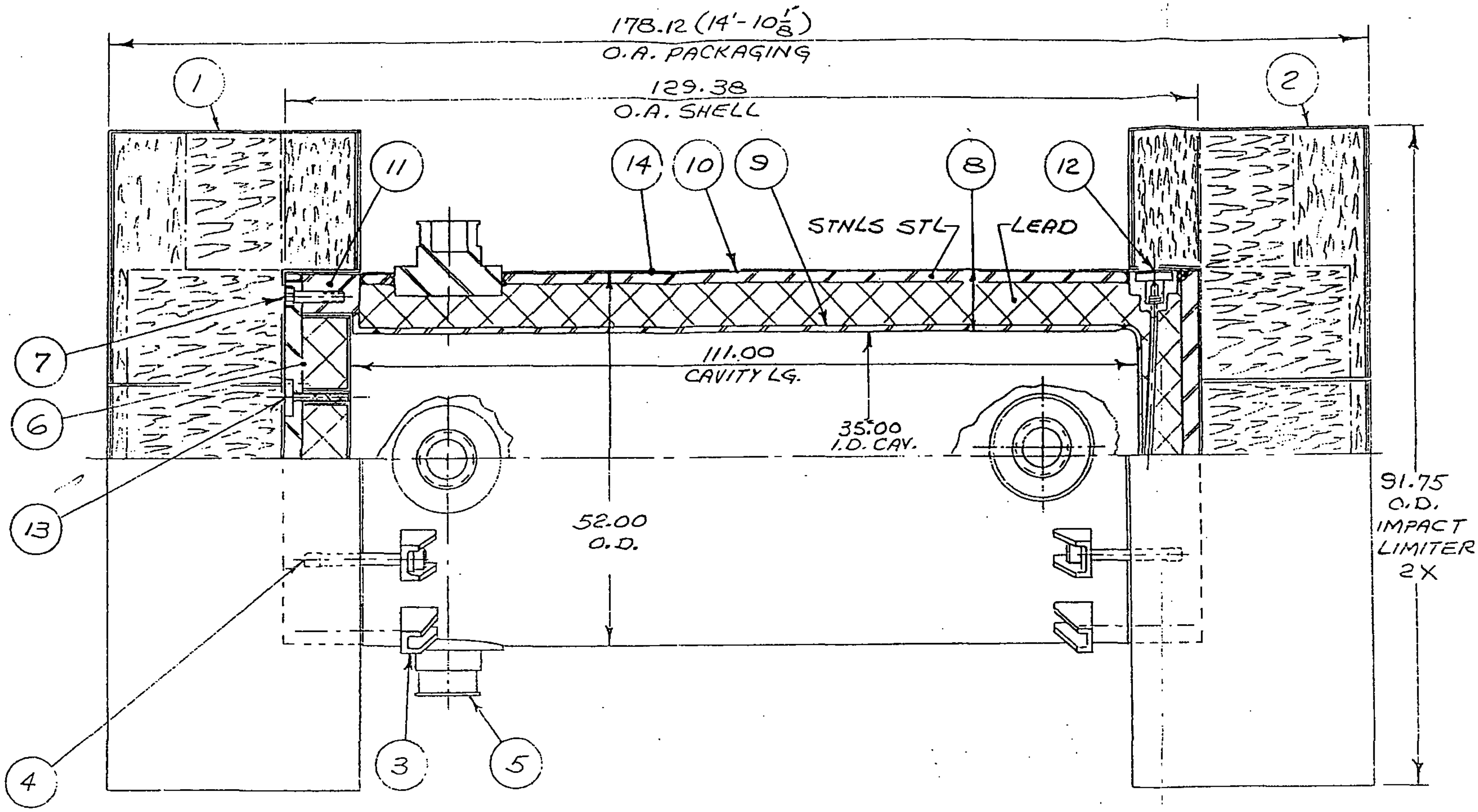
Table 1-1
Materials of Construction Summary

COMPONENT	MATERIAL
Cask Body:	
Inner Shell	ASTM A-240, Type 304
Outer Shell	ASTM A-240, Type 304
Lead Shielding	ASTM B-29
Thermal Shield	ASTM A-240, Type 304
Bolting Flange	ASTM A-182, Grade F304
Impact Limiter Attachment Lugs	ASTM A-479, Type 304
Closure Lid (original):	
Inner Plate	ASTM A-240, Type 304
Outer Plate	ASTM A-240, Type 304
Lead Shielding	ASTM B-29
Closure Lid (optional):	
Outer plate	XM-19
Shield disk	
Plate	ASTM A-240, Type 304
Lead shielding	ASTM B-29
Closure Bolts	ASTM A-564, Type 630
Impact Limiters:	
Energy Absorbing Material	Balsa and Redwood
External Shell and Structure	ASTM A-240, Type 304
Attachment Bolts	ASTM A-564, Type 630
Tiedown/Lifting Devices:	
Cask Trunnions	ASTM A-182 Grade F304

COMPONENTS DEPICTED ON FIGURE 1-1

ITEM NO.	DESCRIPTION
1	Upper (front) Impact Limiter
2	Lower (rear) Impact Limiter
3	Impact Limiter Attachment Lugs
4	Impact Limiter Attachment Bolts
5	Lifting/Tiedown Trunnions
6	Closure Lid with attached shield disk
7	Lid Bolts
8	Cask Body
9	Inner Shell
10	Outer Shell
11	Bolting Flange
12	Drain Port
13	Vent Port
14	Thermal Barrier

Figure 1-1
General Arrangement TN-RAM Packaging



1.3 Appendix

TN-RAM DRAWINGS / DOCUMENTS

DWG/DOC'T NO.	TITLE	REVISION
990-701	TN-RAM Packaging Assembly	9
990-702	Shell Assembly	8
990-703	Shell Parts List & Details	10
990-704	Shell Details	6
990-705	Lid Assembly & Parts List	7
990-706	Lid Details	4
990-707	Impact Limiter Assembly	4
990-708	Impact Limiter Details & Parts List	8
990-709	Impact Limiter Attachment Bolt	2
990-710	Optional Lid Details	2
E-10615	Lead Pouring Requirements	0

PROPRIETARY AND SECURITY RELATED INFORMATION WITHHELD UNDER 10 CFR 2.390

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INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4	SAFETY ANALYSIS REPORT TN-RAM PACKAGING ASSEMBLY
Proprietary Property of Transnuclear, Inc.	

DRAWING NO.	SCALE	SHEET	REVISION
990-701	NONE	1 OF 1	9

SECURITY RELATED INFORMATION
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INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

TRANSNUCLEAR
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SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
SHELL
ASSEMBLY

DRAWING NO.	SCALE	SHEET	REVISION
990-702	NONE	1 OF 1	8

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INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

TRANSNUCLEAR
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SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
SHELL
PARTS LIST & DETAILS

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990-703	NONE	1 OF 1	10

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INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

TRANSNUCLEAR
AN AREVA COMPANY

SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
SHELL DETAILS

DRAWING NO.	SCALE	SHEET	REVISION
990-704	NONE	1 OF 1	6

PROPRIETARY AND SECURITY RELATED INFORMATION WITHHELD UNDER 10 CFR 2.390

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INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

TRANSNUCLEAR
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SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
LID
ASSEMBLY & PARTS LIST

DRAWING NO.	SCALE	SHEET	REVISION
990-705	NONE	1 OF 1	7

Security-Related Information
Figure Withheld Under 10 CFR 2.390

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P.E.	S.R. SPRATHER	2/16/09
NUCLEAR	Prakash Narayanan PAN	02/16/2009
MECHANICAL THERMAL	Prakash Narayanan PAN	02/16/2009
STRUCTURAL	Raheel Haroon/RH	2/16/09
CHECKED	D. GANDOV /DG	02/16/09
DRAWN	[illegible] /JT	02/16/09

ALL DIMENSIONS ARE NOMINAL UNLESS A SPECIFIC TOLERANCE IS INDICATED WITH THE DRAWING DIMENSION

DIMENSIONS ARE IN INCHES AND DEGREES UNLESS OTHERWISE SPECIFIED. DIMENSIONING IN ACCORDANCE WITH ASME Y14.5M

INTERPRETATION OF WELD SYMBOLS PER AWS / AWS 2.4

TRANSNUCLEAR
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SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
LID
DETAILS

990-706 | SCALE NONE | SHEET 1 OF 1 | REVISION 4

Security-Related Information
Figure Withheld Under 10 CFR 2.390

REVISION	DESCRIPTION	DATE
4	REVISED PER OCR 60994-003	2/16/09
3	SEE DCN 990-98	08/20/98

	NAME / INITIAL	DATE
P.E.	S.R. [illegible]	2/16/09
NUCLEAR	Prakash Narayanan PAN	2/16/2009
MECHANICAL THERMAL	Prakash Narayanan PAN	02/16/2009
STRUCTURAL	Raheel Haroon/RH	2/16/09
CHECKED	O. GANOOV/OG	02/16/09
DRAWN	Jianna Tian/JT	02/16/09

ALL DIMENSIONS ARE NOMINAL UNLESS A SPECIFIC TOLERANCE IS INDICATED WITH THE DRAWING DIMENSION

DIMENSIONS ARE IN INCHES AND DEGREES UNLESS OTHERWISE SPECIFIED. DIMENSIONING IN ACCORDANCE WITH ASME Y14.5M

INTERPRETATION OF WELD SYMBOLS PER AWS / AWS 2.4

TRANSNUCLEAR
AN AREVA COMPANY

SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
IMPACT LIMITER
ASSEMBLY

DRAWING NO.	SCALE	SHEET	REVISION
990-707	NONE	1 OF 1	4

PROPRIETARY AND
SECURITY RELATED INFORMATION
WITHHELD UNDER 10 CFR 2.390

ALL DIMENSIONS ARE NOMINAL UNLESS A SPECIFIC TOLERANCE IS INDICATED WITH THE DRAWING DIMENSION

DIMENSIONS ARE IN INCHES AND DEGREES UNLESS OTHERWISE SPECIFIED. DIMENSIONING IN ACCORDANCE WITH ASME Y14.5M

INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

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TRANSNUCLEAR
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SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
IMPACT LIMITER
DETAILS & PARTS LIST

DRAWING NO.	SCALE	SHEET	REVISION
990-708	NONE	1 OF 1	8

Security-Related Information
Figure Withheld Under 10 CFR 2.390

REVISION	DESCRIPTION	DATE
2	REVISED PER DCR 60994-003	2/16/09
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P.E.	S.R. Sprecher	2/16/09
NUCLEAR	Prakash Narayanan PN	02/16/2009
MECHANICAL THERMAL	Prakash Narayanan PN	02/16/2009
STRUCTURAL	Raheel Haroon RH	2/16/09
CHECKED	O. GANDOC / OG	02/16/09
DRAWN	E. VILLAFLORES / EV	02/16/09

ALL DIMENSIONS ARE NOMINAL UNLESS A SPECIFIC TOLERANCE IS INDICATED WITH THE DRAWING DIMENSION

DIMENSIONS ARE IN INCHES AND DEGREES UNLESS OTHERWISE SPECIFIED. DIMENSIONING IN ACCORDANCE WITH ASME Y14.5M

INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

TRANSNUCLEAR
AN AREVA COMPANY

SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
IMPACT LIMITER
ATTACHMENT BOLT

DRAWING NO.	SCALE	SHEET	REVISION
990-709	NONE	1 OF 1	2

PROPRIETARY AND SECURITY RELATED INFORMATION WITHHELD UNDER 10 CFR 2.390

ALL DIMENSIONS ARE NOMINAL UNLESS A SPECIFIC TOLERANCE IS INDICATED WITH THE DRAWING DIMENSION

DIMENSIONS ARE IN INCHES AND DEGREES UNLESS OTHERWISE SPECIFIED. DIMENSIONING IN ACCORDANCE WITH ASME Y14.5M

INTERPRETATION OF WELD SYMBOLS PER ANSI / AWS 2.4

TRANSNUCLEAR
AN AREVA COMPANY

SAFETY ANALYSIS REPORT
TN-RAM PACKAGING
OPTIONAL LID
DETAILS

DRAWING NO.	SCALE	SHEET	REVISION
990-710	NONE	1 OF 1	2

Proprietary Information Withheld Pursuant to 10 CFR 2.390

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CHAPTER TWO
STRUCTURAL EVALUATION

2.1 STRUCTURAL DESIGN

This chapter, including its appendices, presents the structural evaluation of the TN-RAM packaging. This evaluation consists of numerical analyses which demonstrate that the TN-RAM satisfies applicable requirements for a Type B(U)-96 packaging qualified for shipments containing less than *or equal to 30,000 Ci cobalt-60 or equivalent* as listed in 10 CFR 71.

2.1.1 Discussion

The structural integrity of the packaging under normal conditions of transport and hypothetical accident conditions specified in 10 CFR 71 is shown to meet the design criteria described in Section 2.1.2. The TN-RAM is a transport packaging which consists of four major structural components: the shell or cask body assembly, the lid assembly, and the top and bottom impact limiters. These components are described in Chapter One and are shown on drawings provided in Section 1.3, Appendix.

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 and outer ASTM A240 Type 304 stainless steel shells welded to a massive closure flange at the lid end. The annulus between the shells is filled with lead shielding. The lead is poured into the annulus in the molten state using a carefully controlled procedure. A buckling analysis of the inner containment cylinder during the lead pouring process and cool down is provided in Appendix 2.10.4. Trunnions welded to the 1.5-inch thick outer shell are used to lift the packaging and to support it during

transport. The flat bottom end of the outer shell is 2.50 in thick. This cask body assembly is provided with a thermal insulation sleeve, a drain line and impact limiter attachment lugs. The portion of the containment boundary in the cask body cylinder assembly includes the 0.75 in think inner shell cylinder and .50 inch inner shell bottom, the closure flange out to the seal seating surface and the drain line out to the drain coupling housing with its cover, seal and bolts.

Two lid options are available, the original one-piece lid with integral lead shielding and the optional lid design with separate lid plate and shield disk.

The original lid assembly is comprised of a 2.50 in thick outer plate and a 0.50 inch thick inner liner, both made of ASTM A240 Type 304 stainless steel, and 5.94 in of lead shielding.

The optional lid assembly is comprised of a 2.50 in thick lid plate made of XM-19 and a separate shield disk consisting of an ASTM A240 Type 304 stainless steel liner (0.375 inch top, 0.5 inch side and bottom), surrounding a 5.68 in thick lead shielding disk.

The lid flange is grooved to retain the closure seals and is actually an integral radial extension of the outer lid plate. This outer lid plate and the seals complete the packaging containment boundary. The flange of the lid assembly is bolted to the closure flange of the shell or body cylinder assembly with 16 high strength closure bolts.

These two components, the lid and body cylinder, form the cask body. This unit together with the two impact limiters forms the packaging which meets all requirements for the Type B(U)-96 packaging. This packaging is designed to meet all of the applicable 10CFR71 requirements for a maximum normal operating pressure within the containment boundary of 30 psig.

The wall thickness of the outer shell and end plates in the cask body enables the packaging to withstand the hypothetical puncture accident. This shell is designed to be both strong and ductile in order to be capable of withstanding the punch loading. The top and bottom impact limiters absorb the kinetic energy for the 1 ft. normal and 30 ft. hypothetical accident free drops. The thermal insulation sleeve and the impact limiters insulate the cask body assembly and prevent both lead

melting and excessive seal temperatures under the thermal accident.

Table 2.1-1 summarizes the specific evaluation methods that are used to demonstrate compliance with the regulations. Numerical analyses have been performed for the normal and accident conditions as well as for lifting and tiedown loads. In some cases testing was performed to provide input to confirm analytical assumptions (e.g. wood sample static crush tests). Available test results are referenced and applicable data provided in this SAR. In general, numerical analyses have been performed for all of the regulatory events. These analyses, as well as all applicable tests, are summarized in the main body of the section and described in detail in the appendices provided as Section 2.10.

Appendix 2.10.1 presents the structural analysis of the cask body. Appendix 2.10.2 provides the impact limiter structural analysis as well as the overall system dynamic analysis. Appendix 2.10.3 describes the referenced impact limiter tests. Appendix 2.10.4 presents the buckling analysis of the inner container during fabrication and operation. Appendix 2.10.5 presents the structural evaluation of the drain line. Appendix 2.10.8 presents analyses dealing with the optional lid design that is now part of this package.

2.1.2 Design Criteria

The packaging consists of four major components:

- Cask Body Cylinder Assembly
- Lid Assembly
- Top Impact Limiter
- Bottom Impact Limiter

The structural design criteria for these components are described below.

TABLE 2.1-1

EVALUATION METHOD(S) EMPLOYED TO DEMONSTRATE COMPLIANCE WITH SPECIFIC REGULATORY REQUIREMENTS

10CFR71	NUMERICAL ANALYSIS	MATERIAL* TEST	SIMILAR MODEL TESTS
Normal Conditions of Transport:			
Heat	X		
Cold	X		
Reduced External Pressure	X	X	
Increased External Pressure	X	X	
Shock and Vibration	X		
One Foot Free Drop	X	X	
Hypothetical Accident Conditions:			
30 Foot Free Drop	X	X	X
Puncture	X		
Thermal Event	X		
Water Immersion	X		
Other:			
Lift	X		
Tie Down	X		

* Material tests include crush and shear tests of the wood, tensile tests of the containment materials, and charpy tests on the bolt materials.

2.1.2.1 Containment Boundary

The containment boundary consists of the cask body assembly inner shell (both cylinder and bottom) and closure flange out to the seal seating surface and the lid assembly outer plate. The lid bolts and seals are also part of the containment boundary as is the drain tube with its coupling housing, cover plate, bolts and seal. The containment boundary is designed to the maximum practical extent as an ASME Class I component in accordance with the rules of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB. The Subsection NB rules for materials, design, fabrication and examination are applied to all of the above components to the maximum practical extent. In addition, the design meets the requirements of Regulatory Guides 7.6 (or Appendix F of the Code for the unusual conditions of end impact) and 7.8.

The acceptability of the containment boundary under the applied loads is based on the following criteria:

- Title 10, Chapter 1, Code of Federal Regulations, Part 71.
- Regulatory Guide 7.6 Design Criteria
- ASME Code Design Stress Intensities
- Fatigue Failure to be Precluded
- Brittle Fracture to be Precluded
- Buckling to be Prevented

The stress intensity limits for the TN-RAM containment boundary for the normal conditions of transport and hypothetical accident conditions as defined in 10CFR71 are summarized in Table 2.1-2. Each allowable stress intensity is a multiple of the ASME Code design stress intensity, S_m, or S_y or S_u. The numerical values of S_m, S_y and S_u used in the evaluation as listed in Section 2.3 are obtained from Table I-1.0 of the Code Section III Appendices for Class 1 Components.

TABLE 2.1-2

DESIGN CRITERIA FOR TN-RAM CONTAINMENT BOUNDARY (1)

STRESS CATEGORY	CONTAINMENT STRUCTURE ALLOWABLE STRESSES		
	Normal Conditions of Transport	Hypothetical Accident Conditions	
Primary Membrane, General P_m Local P_l(2)	S_m 1.5 S_m	Lesser of: 2.4 S_m or 0.7 S_u 3.6 S_m or S_u(5)	3
Primary Membrane + Bending P_m or $P_l + P_b$	1.5 S_m (2)	Lesser of: 3.6 S_m S_u (5)	3
Range of Primary + Secondary P_m or $P_l + P_b + Q$	3.0 S_m (3)	2 x Sa for 10 cycles (Code Sect. III App.) (Including F)	
Bearing Stress	S_y	S_y for seal surfaces S_u elsewhere	
Pure Shear Stress	0.6 S_m	0.42 S_u	
Fatigue	Cumulative Fatigue Usage Factor 1.0	Not Applicable	
Buckling (4) (Suitable Factors Based on ASME Code)	F.S. 2.0 (Code Case N-284)	F.S. 1.34 (Code Case N-284)	

STRESS CATEGORY	CONTAINMENT FASTENER ALLOWABLE STRESSES	
	Normal Conditions	Accident Conditions
Average Stress	$\frac{2}{3} S_y$	$\frac{2}{3} S_y$
Maximum Combined Stress	S_y	S_y

TABLE 2.1-2 (Continued)

NOTES:

1) These limits are consistent with the ASME Code and Regulatory Guide 7.6 for use in conjunction with linear elastic structural analyses.

2) The local primary membrane stress has the basic characteristics of a secondary stress. It is self-limiting and, when it exceeds yield, the load will be resisted by other parts of the structure. The P_l limits listed are taken directly from Code Article NB-3200 and Appendix F paragraph F-1331.1 and are also recognized in the recently issued NUREG/CF-3966, "Methods for Impact Analysis of Shipping Containers".

3) If the 3 S_m limit is exceeded, Regulatory Guide 7.6, Position C4 provides an alternate acceptance criteria.

4) Code design formulas to preclude buckling are acceptable for TN-RAM.

5) When evaluating the results from the nonlinear elastic plastic analyses for the end drop accidents, the general primary membrane stress intensity, P_m, shall not exceed 0.7 S_u and the maximum primary stress intensity at any location (P_l or P_l+P_b) shall not exceed 0.90 S_u. These limits are in accordance with Appendix F of Section III of the Code.

P_m Primary Membrane Stress

P_l Local Primary Membrane Stress

P_b Bending Stress

Q Secondary Stress

S_a Design Alternating Stress from fatigue curves in Section III Appendices of the ASME Code.

S_m Design Stress Intensity as given in Appendix I, Tables I-1.0 of Section III of the ASME Code for Class 1 Components.

S_u Minimum Ultimate Tensile Strength

S_y Minimum Yield Strength

F.S. Factor of Safety

In the special case of bolting, the average bolt stress is limited to $\frac{2}{3}$ S_y and the maximum stress is limited to S_y for all conditions. The lid bolts are also evaluated against NUREG/CR 6007 allowables in Appendix 2.10.8.

The head-to-shell and flange-to-shell junctions are gross structural discontinuities as defined in NB-3213.2. The membrane stresses in the edges of the heads and the ends of the cylinders produced by mechanical loadings are local primary membrane stresses, P_l, as defined in NB-3213.10. The bending stresses at these locations are secondary stresses, Q, per the examples in Tables NB-3217-1 and Reg. Guide 7.6, Position B3. This classification of stress intensities is limited to the local region of length $1.0\sqrt{Rt}$ as defined in NB-3213.10.

The location where the inner end ring is attached to the cask closure flange is not treated as a local region.

The containment boundary is entirely austentic stainless steel which is ductile even at low temperature. Thus, as indicated in Regulatory Guide 7.6, Section B, brittle fracture is precluded.

The normal and accident conditions are described in detail below. The stress intensity limits from Table 2.1-2 are directly applied to evaluate the results from the analyses for these conditions. These criteria are consistent with Regulatory Guide 7.6 and Section III, Subsection NB, Article NB-3200 and Appendix F of the ASME Boiler and Pressure Vessel Code.

2.1.2.2 Non Containment Structure

The outer shell of the cask body assembly is the primary non containment structure. The trunnions and impact limiter attachment lugs are directly welded to the shell and are also non containment structural

component. In addition, the inner shell or liner of the original lid is a non containment structural component as is the plate of the optional shield disk. The portion of the impact limiter that must remain intact to prevent separation from the cask body during impact is also a non containment structure.

The non containment structures have various structural functions, but containment of radionuclides is not required of these components. These non containment structures position the lead shielding and protect the lead during the puncture and thermal accidents. The trunnions are used to lift the cask and support it during transport. These components also meet Code requirements as far as possible in that they use Code materials, fabrication techniques, weld configurations, etc. One notable exception is the fact that non containment welds need not be radiographed. Non containment structural components are generally welded or attached to the containment boundary components after completion of required examinations of the containment boundary. In many cases, the final (non containment) weld(s) cannot be radiographed because of lack of accessibility to both sides of the weld or because of the presence of lead shielding.

The stress limits for the TN-RAM non containment structure are summarized in Table 2.1-3. Again, the limits are multiples of the ASME Code values of S_m, S_y or S_u as listed below in Section 2.3. These criteria are applied directly to evaluate the results from the analyses of the principal structural components of the cask (in addition to the containment boundary) as outlined in Regulatory Guide 7.6.

It should be noted that exceptions to the linear elastic analysis method generally used are made for the end drop accidents and for the local shearing puncture evaluation of the outer shell of the cask body during the 40 inch drop onto the puncture bar. This local evaluation is performed in Section 2.7.2 using the Nelms puncture equation to ensure that the lead shielding is not exposed before the

TABLE 2.1-3 (1)
DESIGN CRITERIA FOR TN-RAM NON CONTAINMENT STRUCTURE

STRESS CATEGORY	NON CONTAINMENT STRUCTURE ALLOWABLE STRESSES	
	Normal Conditions of Transport	Hypothetical Accident Conditions
Primary Membrane, General P_m Local P_l(2)	S_m 1.5 S_m	0.7 S_u (5) S_u (5)
Primary Membrane + Bending P_m or $P_l + P_b$	1.5 S_m (6)	S_u (5)
Range of Primary + Secondary P_m or $P_l + P_b + Q$	3.0 S_m (3)	Not Applicable
Bearing Stress	S_y	S_u
Pure Shear Stress	0.6 S_m	0.5 S_u
Buckling	Buckling to be Precluded	

4

STRESS CATEGORY	NON CONTAINMENT FASTENER ALLOWABLE STRESSES	
	Normal Conditions	Accident Conditions
Average Stress	$\frac{2}{3}$ S_y	Greater of: S_y or 0.7 S_u
Maximum Combined Stress	S_y	Greater of: 1.5 S_y or S_u

See Page 2-7 for notes 1, 2, 3, and 5.

6) The 1.5 S_m limit may be exceeded for non containment structure if the resulting deflection of the member can be accomodated. See the discussion on page 2-64 for the unusual case involving the 1 ft end drop. 4

thermal event. The Table 2.1-3 criteria are used for evaluation of the other normal and accident events and even for the evaluation of the balance of the outer shell during the puncture event.

2.1.2.3 Impact Limiters (Top and Bottom)

The TN-RAM packaging is provided with impact limiters at each end of the cask body. The limiters are identical and can be used on either end of the cask. The inside diameter of the limiter is determined by the diameter of the cask body. The length and outside diameter of the limiter are sized to limit the cask inertial loads during the 1 foot normal and 30 foot accident drop events to permit the design criteria for the containment boundary (and noncontainment structures) to be met.

The impact limiter stainless steel cylinders, gussets and end plates are designed to position and confine the balsa and redwood blocks so that the impact energy is properly absorbed. The stainless shell is also designed to support and protect the wood blocks under normal environmental conditions (moisture, pressure, temperature, etc.).

The impact limiter attachment bosses, gusset reinforcements and bolts are sized to withstand the applied loads while meeting the Table 2.1-3 criteria for non containment structure to prevent separation of the limiters from the cask during impact. The impact limiters cover the lid closure flange as well as the drain coupling housing and lid shield plug cover plates. Thus the limiters are designed to remain attached in order to protect the lid flange and cover plates during the puncture and thermal accident events.

2.2 WEIGHTS AND CENTER-OF-GRAVITY

The gross weight of the TN-RAM package (including contents) is 80,000 pounds. Approximate weights of major individual components or subassemblies are tabulated below:

Cask Body Cylinder Assembly *(including thermal insulation and all attachments such as tiedown trunnions and impact limiter attachment lugs.)*	59,000
Lid Assembly (optional lid plate is 1400 lb and shield disk is 3300 lb)	4,700
Top Impact Limiter	3,400
Bottom Impact Limiter	3,400
Net Packaging (empty) Weight	70,500
Payload	9,500
Gross Package Weight	80,000

The center of gravity of the unloaded packaging is located on the cylindrical axis at essentially the geometric center of the packaging which is 64.5 inches from either end of the cask body or 87.0 inches from the outside end of the impact limiter.

The center of gravity for a loaded packaging is located below the cylindrical axis and within approximately 6 inches of the geometric center. If the cargo is evenly distributed, the center of gravity of the loaded packaging returns to the geometric center.

2.3 MECHANICAL PROPERTIES OF MATERIALS

The mechanical properties of structural materials used in the TN-RAM are shown on Tables 2.3-1 and the effects of temperature on these properties are shown on Table 2.3-2. The materials are identified and procured by reference to ASTM and corresponding ASME specifications. The yield and ultimate strengths of the structural steels shown on Table 2.3-1 are the minimum values specified in the material specifications. The ASME design stress intensity values (S_m) for Class 1 components are used to establish allowable stresses for the elastic analyses performed for the TN-RAM. Values of S_m are provided on Tables 2.3-1 and 2.3-2. Stress intensity limits for the various stress categories are discussed in Section 2.1.2. The stress vs strain curve for 304 stainless steel used in the nonlinear elastic plastic analyses of the unusual conditions that occur during the end drop accidents is provided in Appendix 2.10.1.

Mechanical properties of the energy absorbing wood used in the impact limiters are listed in Tables 2.3-3 and 2.3-4. Table 2.3-3 identifies four wood property parameters and establishes the specification values for these parameters that are measured and controlled for wood procurement. The crush stress values are directly related to density and moisture content. The crush stress values listed cover the range of expected values of crush stress for the density and moisture content specified. Each wood block is weighed and its moisture content checked. Blocks which do not fall within the specified density and moisture range are rejected. Wood samples are also tested for crush strength. The density and moisture content of the wood is determined by ASTM D2395, Method A and ASTM D2016. The crush strength of the wood is measured for load directions parallel (0°) and perpendicular (90°) to the grain in accordance with ASTM D198 as supplemented by TN Specification 920-1.

Table 2.3-1
Mechanical Properties of Structural Materials

Material Specification (Nominal Composition)	Application (1)	Minimum Yield Strength S_y, psi	Minimum Ultimate Strength S_u, psi	Design Stress Intensity (2) S_m, psi	ASME Data Source (3)
ASTM A240 Type 304 (18 Cr – 8 Ni)	Cask Body and Lid Shells Drain Fitting Insulation Shell Containment Penetration Penetration Covers and Bolts	30,000	75,000	20,000	Table I-1.2
ASTM A240 Type XM-19 (22Cr-12Ni-5Mn)	Optional Lid Plate	55,000	100,000	33,300	Table I-1.2
ASTM A182 Grade F304 (18 Cr – 8 Ni)	Body Flange Trunnions	30,000	70,000	20,000	Table I-1.2
ASTM A479 Type 304 (18 Cr – 8 Ni)	Test Port Plug Impact Limiter Lug	30,000	75,000	20,000	Table I-1.2
ASTM A312 Type 304 LN (18 Cr – 8 Ni)	Shield Plug and Drain Tubing	30,000	75,000	20,000	Table I-1.2
ASTM A193 Grade B8 Class 1 (18 Cr – 8 Ni)	Shield Plug Bolts	30,000	75,000	10,000	Table I-1.3
ASTM A564 Type 630 (17CR - 4Ni – 4Cu)	Lid Closure Bolts Impact Limiter Attachment Bolts	115,000	140,000	38,300	Table I-1.3

TABLE 2.3-1 (Cont'd)

MECHANICAL PROPERTIES OF STRUCTURAL MATERIALS

NOTES:

(1) The components identified are those for which mechanical property data are used in conjunction with the structural analyses presented in this Safety Analysis Report. Refer to Chapter One drawings for additional components.

(2) S_m values shown are for ASME Class 1 components and for metal temperatures up to 100°F. Refer to Table 2.3-2 for temperature dependent values.

(3) Data source refers to tables provided in ASME Section III, Appendix I, 1986.

Table 2.3-2
Temperature Dependent Material Properties

Material Specification	Material Property[1]	Temperature °F							ASME Data Source [2]
		70	100	200	300	400	500	600	
ASTM A240 Type 304 and	S_m (psi)	-	20,000	20,000	20,000	18,700	17,500	16,400	Table I-1.2
ASTM A182 Grade F304 and	E ($x10^6$ psi)	28.3	-	27.6	27.0	26.5	25.8	25.3	Table I-6.0
ASTM A479 Type 304 and	α ($x10^{-6}$ in/in/°F)	-	8.55	8.79	9.00	9.19	9.37	9.53	Table I-5.0
ASTM A312 Type 304 LN									
ASTM A240 Type XM-19	S_m (psi)	-	33,300	33,100	31,400	30,400	29,700	29,200	Table I-1.2
	E ($x10^6$ psi)	20.3	-	27.6	27.0	26.5	25.8	25.3	Table I-6.0
	α ($x10^{-6}$ in/in/°F)	-	8.30	8.48	8.65	8.79	8.92		Table I-5.0
ASTM A193 Grade B8	S_m (psi)	-	10,000	8,500	7,300	6,500	6,100	5,800	Table I-1.3
Class 1	E ($x10^6$ psi)	28.3	-	27.6	27.0	26.5	25.8	25.3	Table I-6.0
	α ($x10^{-6}$ in/in/°F)	-	8.55	8.79	9.00	9.19	9.37	9.53	Table I-5.0
ASTM A564 Type 630	S_m (psi)	-	38,300	35,400	33,900	32,700	31,700	30,700	Table I-1.3
	E ($x10^6$ psi)	28.3	-	27.6	27.0	26.5	25.8	25.3	Table I-6.0
	α ($x10^{-6}$ in/in/°F)	5.89	5.89	5.90	5.90	5.90	5.90	5.91	Table I-5.0

TABLE 2.3-2 (Cont'd)

TEMPERATURE DEPENDENT MATERIAL PROPERTIES | 1

NOTES:

(1) S_m is the design stress intensity value for ASME Class I components. The values shown are for metal temperatures up to the indicated temperature.

E is the modulus of elasticity at the indicated temperature.

α is the mean coefficient of thermal expansion from 70°F to the indicated temperature.

(2) Data source refers to tables available in ASME Section III, Appendix 1, 1986.

TABLE 2.3-3

SPECIFIED PROPERTIES OF IMPACT LIMITER WOOD

			CRUSH STRESS, psi	
WOOD TYPE	DENSITY LB/FT^3	MAX. MOISTURE CONTENT %	S_0 PARALLEL TO GRAIN	S_{90} PERPENDICULAR TO GRAIN
Balsa	10-12	12	1560-2010	300-420
Redwood	18-27.5	15	5000-6500	750-975

TABLE 2.3-4

WOOD CRUSH STRESS (psi)

	BALSA			REDWOOD		
ANGLE	MIN.	AVG.	MAX.	MIN.	AVG.	MAX.
0°	1560	1785	2010	5000	5750	6500
5°	1560	1785	2010	5000	5750	6500
10°	1559	1784	2008	4996	5745	6495
15°	1554	1778	2002	4978	5725	6472
20°	1538	1760	1983	4927	5666	6405
25°	1503	1721	1938	4808	5529	6251
30°	1434	1643	1851	4575	5261	5948
35°	1316	1509	1702	4176	4803	5429
40°	1142	1313	1483	3591	4130	4669
45°	930	1073	1215	2875	3306	3738
50°	718	832	947	2159	2482	2806
55°	544	636	728	1574	1810	2046
60°	426	503	579	1175	1351	1528
65°	357	424	492	942	1083	1224
70°	322	385	447	823	947	1070
75°	306	367	428	772	888	1003
80°	301	361	422	754	867	980
85°	300	360	420	750	863	975
90°	300	360	420	750	863	975

Table 2.3-4 provides the wood crush values for crush orientations between 0° and 90° from the wood grain direction. The intermediate values are determined using the following relationship:

$$R_\alpha = \frac{\cos^4 \alpha + \frac{S_{90}}{S_0} \sin^4 \alpha}{\cos^4 \alpha + \sin^4 \alpha}$$

where:

α is the intermediate crush angle of interest between 0° and 90° from the wood grain direction.

S_{90} is the known crush strength 90° from (perpendicular to) the wood grain.

S_0 is the known crush strength 0° from (parallel to) the wood grain.

The resulting R_α represents the ratio of crush strength for loads applied at the intermediate angle of interest, α, to that parallel to the grain. Therefore, the crush strength, S_α, at intermediate angles is determined by:

$$S_\alpha = R_\alpha S_0$$

These wood properties are used as input to the dynamic analysis of the impact limiters described in Appendix 2.10.2. The impact limiter analysis provides package accelerations and reaction forces which are used for the structural analysis of the TN-RAM cask body components. Tests of other impact limiter designs which verify the validity of the use of the ADOC computer program in conjunction with these wood properties are described in Appendix 2.10.3.

Mechanical properties of the lead shielding material are listed in Table 2.3-5. The lead is procured to the ASTM B29 specification. The lead is not a structural material, but it is a shielding material. In order to ensure that the lead shielding remains intact and in place, it is necessary to determine if lead slump can occur. The ORNL "Cask Designers Guide"* indicates that slump will not occur if the peak hydrostatic stress in the lead is maintained below the indicated dynamic flow stress during all dynamic events. The lead does however apply loadings to the cask body structural components that surround it due to differential thermal expansion and transfer of inertial loadings. The properties of the lead used in the various analyses of these structural components (E, α and γ) are listed in the table. The stress vs strain curve for lead used in the analyses of the unusual conditions that occur during the end impact events is provided in Appendix 2.10.1. 3

*Shappert, L.B., "Cask Designers Guide", ORNL-NSIC-68

TABLE 2.3-5
MECHANICAL PROPERTIES OF ASTM B29 LEAD SHIELDING

PARAMETER	NUMERICAL VALUE	
Dynamic Flow Stress	5000 psi	(1)
Modulus of Elasticity, E	27,750 psi	(3) 3
Coefficient of Thermal Expansion, α		
RT to 600 °F	17.88×10^{-6} °F^{-1}	(2)
RT to 200 °F	16.4×10^{-6} °F^{-1}	(1)
RT to -40 °F	15.55×10^{-6} °F^{-1}	(2)
Density, γ	.41 lb/in^3	(1)

Data Source:

(1) Shappert, L.B., "Cask Designers Guide", ORNL-NSIC-68

(2) Rack and Knarovsky, "An Assessment of Stress-Strain Data Suitable for Finite Element Elastic-Plastic Analysis of Shipping Containers", NUREG/CR-0481

(3) Adams, C.R., et al. "A Comparison of Analytical Techniques for Analyzing a Nuclear-Spent-Fuel Shipping Cask Subjected to an End-On-Impact", NUREG/CR-2018. 3

2.4 GENERAL STANDARDS FOR ALL PACKAGES

The TN-RAM is designed to comply with the general standards for all packages specified by 10CFR71.43.

2.4.1 Minimum Package Size

The overall package dimensions of 178.12 inches long and 91.75 inches in diameter exceed the minimum dimension requirement of 10 cm (4 inches).

2.4.2 Tamperproof Feature

The only access path into the package is through the closure lid and associated closure bolts. During transport, the impact limiters are in position on the package and the top (front) impact limiter prevents all access to the closure lid area. One of the eight top impact limiter attachment bolts incorporates a safety wire seal which is installed prior to each shipment. The presence of this seal demonstrates that unauthorized entry into the package has not occurred.

2.4.3 Positive Closure

Positive containment closure is accomplished entirely by the bolted design. Sixteen bolts are used to close the cask closure lid. Four bolts are used to close the drain port cover and three to close the vent port cover. This extensive bolting configuration prevents unintentional opening of the containment system.

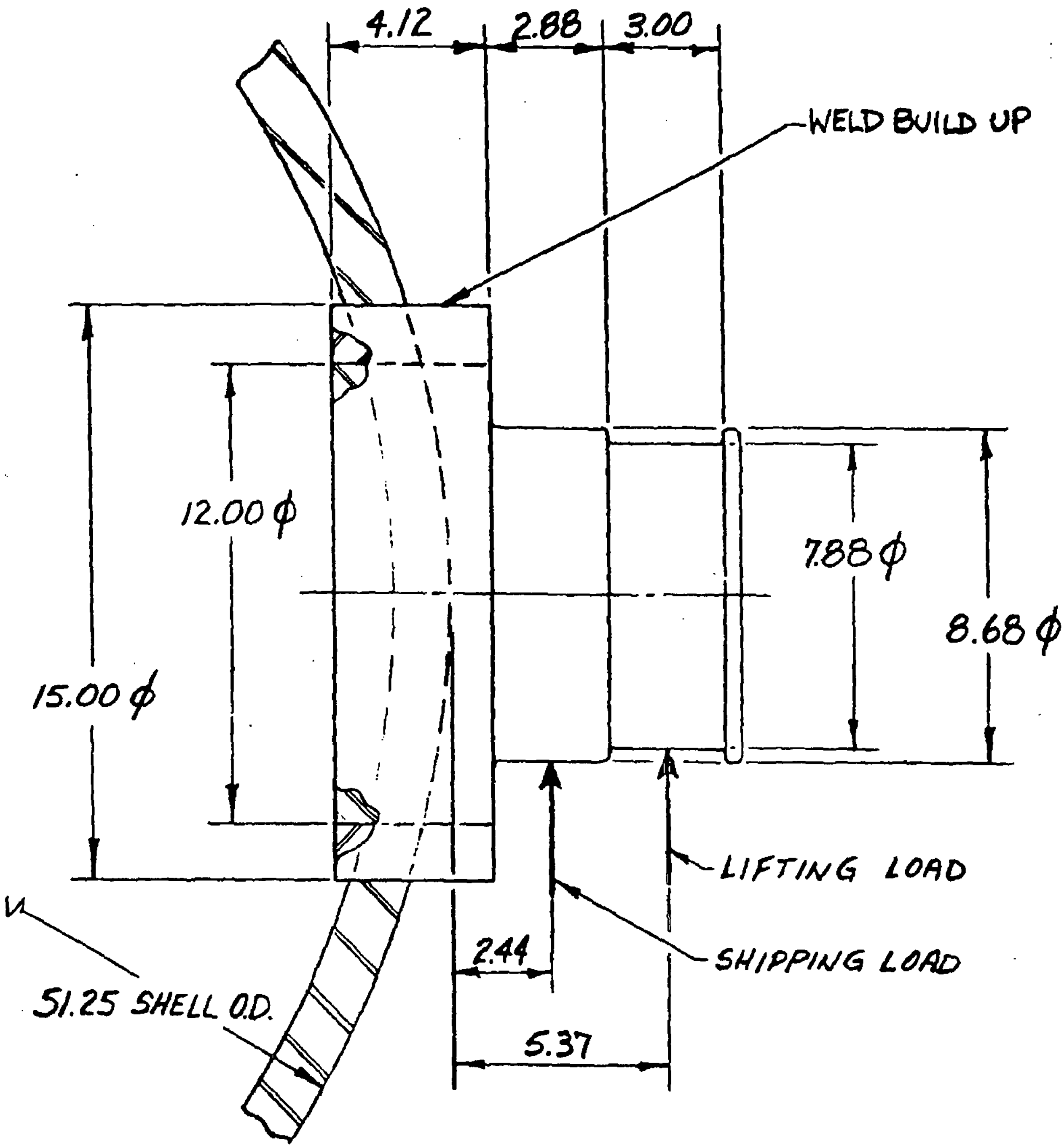
2.4.4 Chemical and Galvanic Reactions

The materials of fabrication are summarized in Section 1.2.1. All structural components are the same or similar alloys of stainless steel and therefore are not subject to chemical or galvanic interaction.

2.5 LIFTING AND TIEDOWN STANDARDS

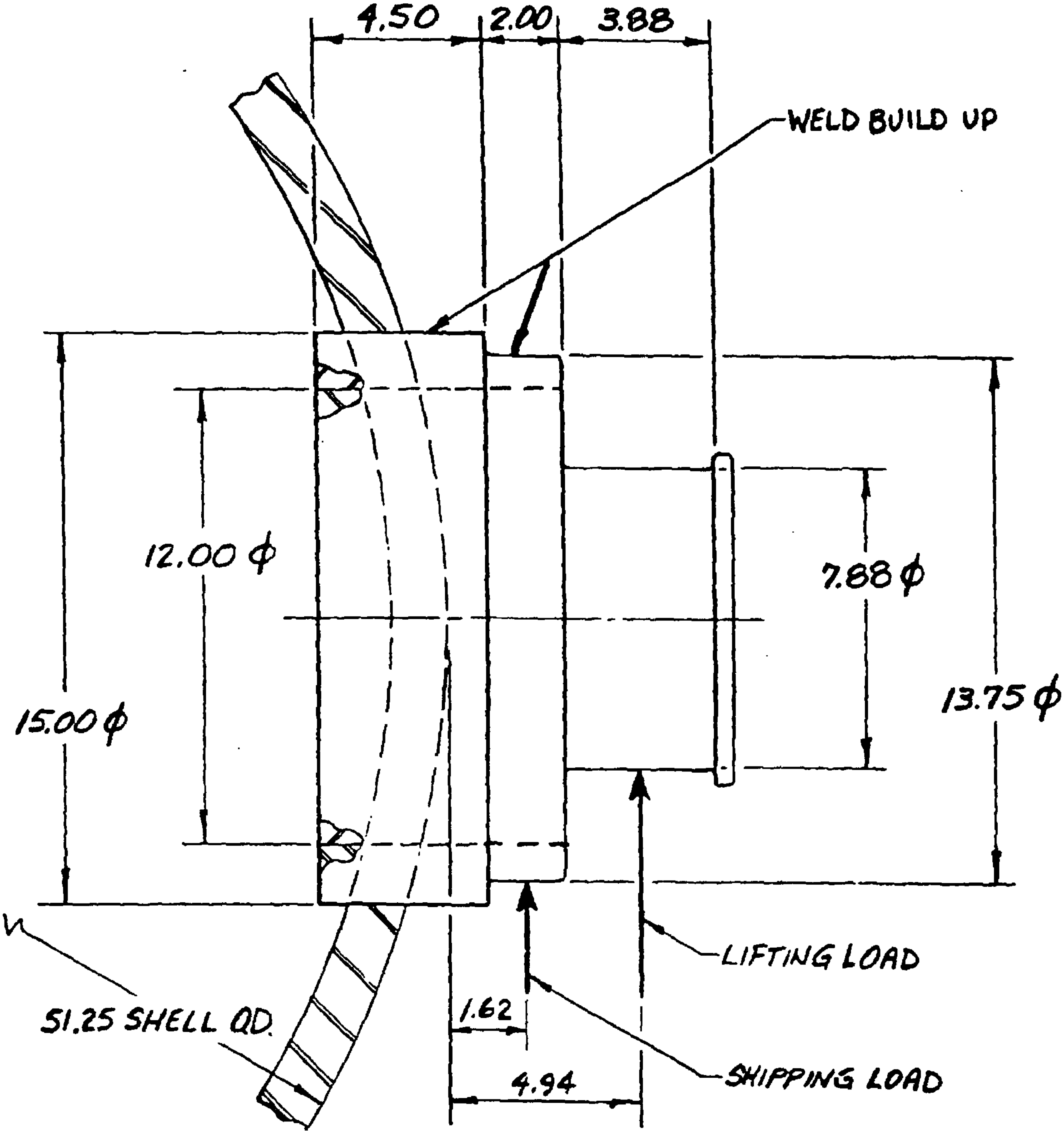
The TN-RAM is equipped with six trunnions which are welded to the outer shell of the cask body as described in Chapter One. Two trunnion pairs are located near the top or front end of the cask and the other pair is located near the bottom or rear end of the cask. All six of the trunnions are single piece forgings which are fitted and welded into penetrations in the cask body outer shell. Full penetration welds rigidly attach the trunnion base plates to the shell at these locations. Two pairs of front trunnions (four total) are provided so that redundant lift beams can be used. The rear trunnions differ slightly from the front trunnions in that the shoulders that rest in the transport frame are larger in diameter. Figures 2.5-1 and 2 summarize the key dimensions and terminology used in the analysis presented in this section.

The four front trunnions are used for lifting and handling the cask with the use of a specially designed lift beam which attaches to the outer shoulder of the trunnions. These front trunnions are designed so that either pair (only two) can be used to lift the cask. The cask is rotated from the horizontal transport orientation to the vertical lifting and loading orientation by lifting at two of the front trunnions and allowing the two rear trunnions to pivot in the transport cradle. During the rotation process the loads are shared between the front and rear trunnions. The limiting analysis condition for lifting occurs when the cask is in the fully vertical orientation and is raised clear of the transport frame so that the cask lifting load, the entire cask weight, is carried only by two of the front trunnions. Since the front and rear impact limiters are removed during any rotation or lifting operation, the maximum loading condition includes the weight of the assembled cask with maximum payload but without impact limiters. The total weight (including limiters and



TN-RAM FRONT TRUNNIONS

FIGURE 2.5-1



TN-RAM REAR TRUNNIONS
FIGURE 2.5-2

payload) of 80,000 lbs. is conservatively used for all lifting and tie down calculations. The lifting condition is analyzed in Section 2.5.1 to demonstrate a minimum safety factor of three against yield in accordance with 10CFR71.45(a).

There are no lifting lugs on the cask lid or shield disk (for optional lid design) for the purpose of lifting and handling the lid. A special fixture will be bolted to the lid or shield disk for that purpose. In the transport configuration, access to the lid lifting fixture bolt holes is prevented by the front impact limiter. Therefore, no transport safety analysis of lid lifting is required.

In the transport configuration, the regulatory tie down loads [10CFR71.45(b)(1)] are shared unequally between the front and rear trunnions because of the design of the transport frame. As described above, the loading condition used for transport includes the total weight of the assembled cask with maximum payload and impact limiters (80,000 lbs.). The 2 G vertical load is equally shared among four trunnions (two front and two rear). The 5 G load component which is transverse to the direction of travel is shared between one front and one rear trunnion on the same side of the cask. The design of the transport frame saddles which support the trunnions is such that the 5 G loading can only result in a uniform compressive force applied to the trunnion base plate flange. The 10 G load component applied in the direction of travel is shared equally between the two rear trunnions. The design of the transport frame allows the front trunnion to move in the cask axial direction (direction of travel) in relation to the transport frame in order to prevent constrained differential thermal expansion between the cask and transport frame. Therefore the front trunnion cradles will not apply any portion of the 10 G load component to the front trunnions.

When the 2/5/10 G load components are combined it is seen that the resultant load on the front trunnions during transport is less than three times the normal lifting load. Since the analysis in Section 2.5.1 demonstrates that the front trunnions have a factor of safety greater than three against yield for the lifting load, it can be concluded that stresses in the front trunnions under the limiting tiedown condition are also well below yield. The tiedown analysis provided in Section 2.5.2 therefore computes stresses resulting from tiedown loads only for the rear trunnions. There are no other structural parts of the package which can be used for tiedown attachments.

The effects of the lifting and tie down loads on the cask body stresses where the trunnions are attached are determined in Appendix 2.10.1. Tables 2.10.1-22 and 2.10.1-23 list the total stresses on the cask including the local stresses due to the trunnion loads for these cases. Note that the stresses do not exceed the 30,000 psi yield strength of the stainless steel at any location.

2.5.1 Lifting Devices

As discussed in the previous section, the maximum loading condition for cask lifting occurs when the weight of the fully loaded assembled cask without impact limiters is carried entirely by one pair of front trunnions with the cask in the vertical orientation. Using a conservatively high gross package weight of 80,000 pounds from Table 2.2-1 results in a net maximum lifting force of 40,000 pounds per trunnion, the normal lifting load.

The front trunnion geometry and lifting load application point are shown in Figure 2.5-1. Note that the moment, M, at the cask body/trunnion base plate interface is due to the offset or moment arm of the lifting force from the trunnion/base plate

intersection. Bending and shear stresses are computed at the base of the outer shoulder and at the base of the inner shoulder. The trunnion base plate is analyzed to determine bending stresses. These stress calculations are performed below. The factor of safety against yielding is always greater than 3.0 which satisfies 10CFR71.45(a).

Trunnion Shoulder Analysis

The trunnion shoulders are analyzed assuming they are cantilevered from the trunnion base plate. The trunnion shoulders are concentric hollow cylinders which are considered fixed at their bases, i.e. outer shoulder fixed to the inner shoulder and the inner shoulder fixed to the base plate.

The bending stresses, average shear stresses and combined stress intensities are calculated at the base of each hollow cylinder for an applied load equal to three times the normal lifting load. The stresses are shown to be less than the material yield strengths demonstrating a minimum factor of safety equal to or greater than three. The stresses are calculated using the following formulas:

1) $\sigma = M/Z$

Where

σ = The bending stress at the outer surface of the shoulder, psi

M = The bending moment at the section of interest, in-lbs.

Z = Section modulus at the section of interest, in^3

$= I/C = (\pi/64)\ (D_o^4 - D_i^4)/(D_o/2)$

2) $\tau = V/A$

Where

τ = Average Shear Stress, psi

V = Shear force at section of interest, lb.

= Applied load, 120,000 lb. (3 times normal lifting load)

A = Shear area = $(\pi/4)(D_o^2 - D_i^2)$

3) $S = \sqrt{\sigma^2 + 4\tau^2}$

Where

S = Combined stress intensity

The diameters used in these calculations are the diameters of the inner and outer shoulders of the trunnions without including the fillet radii. This is conservative since the shear areas and bending section modulii are actually slightly larger than used in the analysis and, therefore, the actual stresses are lower than calculated. Dimensions used in the analysis are shown in Figure 2.5-1. The stresses are calculated below.

The moment arm to the base of the outer shoulder is 1.5 in and the arm to the inner shoulder is 4.38 in. The bending moment at the outer shoulder, for 3 times the normal lifting load, is then 120,000 lb. x 1.5 in or 180,000 in lb. The moment at the inner shoulder is 120,000 lb. x 4.38 in or 525,600 in lb. Z of the outer shoulder is:

$$Z_{\text{outer shoulder}} = \left(\frac{\pi}{64}\right)(7.88^4 - 5.25^4)\left(\frac{2}{7.88}\right) = 38.57 \text{ in}^3$$

$$Z_{\text{inner shoulder}} = \left(\frac{\pi}{64}\right)(8.68^4 - 5.25^4)\left(\frac{2}{8.68}\right) = 55.61 \text{ in}^3$$

The bending stress at the outer shoulder is then 180,000 in lb/38.57 in^3 or 4,666 psi. The bending stress at the inner shoulder is 525,600 in lb/55.61 in^3 = 9,451 psi.

$$A_{\substack{outer\\shoulder}} = \left(\frac{\pi}{4}\right)(7.88^2 - 5.25^2) = 27.12\ in^2$$

$$A_{\substack{inner\\shoulder}} = \left(\frac{\pi}{4}\right)(8.68^2 - 5.25^2) = 37.53\ in^2$$

The shear stress at the outer shoulder is 120,000 lb/27.12 in^2 = 4,424 psi, and the shear stress at the inner shoulder is 120,000 lb/37.53 in^2 = 3,197 psi.

The combined stresses are then:

$$S_{outer\ shoulder} = \sqrt{(4,666)^2 + 4(4,424)^2} = 10,003\ psi$$

$$S_{inner\ shoulder} = \sqrt{(9,451)^2 + 4(3,197)^2} = 11,410\ psi$$

The yield strength of the 304 stainless steel trunnion material is 30,000 psi. The combined stresses calculated above are determined for three times the normal lifting load. Therefore, the minimum factor of safety against yield in the trunnion shoulder is:

$$F.S. = (3)\left(\frac{30,000}{11,410}\right) = 7.88$$

Trunnion Base Plate Analysis

Stresses in the trunnion base plate can be evaluated knowing the bending moment from the applied lifting load. The bending stresses are calculated in the plate adjacent to the base of the inner shoulder. The maximum bending moment at the shoulder/base plate junction is equal to 3 times the weight of

the cask (240,000 lb) divided by the number of effective trunnions (2) multiplied by the distance from the center of the lifting trunnion to the tangent point of the cask outer shell (5.37 in.) or 644,400 in lb.

The bending stress in the base plate adjacent to the trunnion shoulder under this moment is found using the applicable case in Roark, RJ, "Formulas for Stress and Strain", Fifth Edition. This case is #21 on page 368 of Table 25. Then b/a is 8.68 in/15 in or 0.578 and β is 0.84.

The maximum bending stress in the plate occurs at the shoulder diameter (8.68 in.) and is:

$$\sigma_b = \frac{\beta M}{a t^2} = \frac{(.840)(644,400)}{(7.5)\ (4.12)^2} = 4,251 \text{ psi}$$

The shear stress in the plate at the shoulder diameter (8.68 in.) is calculated by equating the applied moment (644,400 in. lbs) and the sum of the shear forces about the diameter (8.68 in.) times the moment arm. Assuming the shear force varies sinusoidally, being a maximum at 90° (top) and 270° (bottom):

$$V = V_{max} \sin \theta$$

where V is the shear force distribution around the circumference of the shoulder in lbs/in of arc length.

The moment arm is $R \sin \theta$
The arc length is $R d\theta$
Therefore, the moment is

$$M = 4 \int_0^{\pi/2} V_{max} R^2 \sin^2 \theta \, d\theta$$

$$= 4 V_{max} R^2 \left[-1/4 \sin 2\theta + 1/2\, \theta\right]_0^{\pi/2}$$

$$= 4V_{max} R^2 [\pi/4]$$

$$V_{max} = \frac{M}{R^2\pi}$$

$$= \frac{(644,400)}{(4.34)^2 \pi} = 10,890 \text{ lbs/in}$$

The maximum shear stress is

$$\tau = \frac{V_{max}}{t} = \frac{10890}{4.12} = 2643.2 \text{ psi}$$

The combined stress is:

$$S = \sqrt{(\sigma_b)^2 + 4(\tau)^2} = 6,784 \text{ psi}$$

Therefore yielding will not occur in this area since the stress is well below yield for a loading of three times the lifting load.

The shear stress at the forging and weld overlay interface is calculated by the same method as above:

$$V_{max} = \frac{M}{R^2\pi} = \frac{644400}{(6)^2\pi} = 5697.7 \text{ lbs/in}$$

$$\tau = \frac{V_{max}}{4.12} = 1382.9 \text{ psi}$$

The bending stress at the weld overlay is calculated from the applicable case in Roark, "Formulas for Stress and Strain," 5th Edition. This is case 21. Assuming the trunnion is fixed at the 12 inch diameter:

$$\sigma_r = \frac{\beta r_o M}{a^2 t^2}$$

Where β is a function of $\frac{b}{a} = \frac{4.34}{6} = .723$

From the table in Roark, B = .420

The radial stress is

$$\sigma_r = \frac{(.42)(4.34)(644400)}{(6)^2\ (4.12)^2}$$

$$\sigma_t = 1922 \text{ psi}$$

The combined stress at the 12 inch diameter is:

$$S = \sqrt{(1922)^2 + 4(1382.9)^2} = 3368 \text{ psi}$$

The minimum factor of safety against yielding under the normal lifting load is:

$$F.S. = \frac{(3)\ (30,000)}{(\ 6,784)} = 13.3$$

If all four trunnions are used to lift the cask in the horizontal orientation, the load is shared by four trunnions rather than two. Therefore the loading will be less and the factor of safety greater. The rear trunnion base plate is the same thickness as that of the front trunnion and the rear trunnion shoulder is larger. Therefore, the rear trunnion stresses will be lower than the front trunnion stresses during lifting.

The above results demonstrate a factor of safety greater than three against yield for all lifting devices.

2.5.2 Tiedown Devices

The front and rear trunnions serve as the packaging tiedown attachments which are designed to withstand the 2/5/10 G tie down loads. As previously discussed in Section 2.5, the tiedown load applied to the front trunnion is less than the normal handling load analyzed in Section 2.5.1. Therefore only

the rear trunnions are analyzed under tiedown loads. The calculation is performed using the same methodology as that used in the front trunnion lifting analysis (Section 2.5.1). Terms pertaining to the trunnion geometry are the same in both cases. Tiedown loads are applied to the trunnion inner shoulder so that a calculation of stresses in the outer shoulder is not required.

The 2 G vertical and the 10 G axial tie down load components are combined into a single resultant force. Based on a conservatively high cask weight during transport of 80,000 pounds, the resultant longitudinal tiedown force is 402,000 pounds applied at the midpoint of the inner shoulder and in a direction 5.7° from horizontal. The dimensions and geometry terms required for the analysis are shown on Figure 2.5-2. The stresses are calculated below.

Trunnion Shoulder Analysis

Following the same method as that used for the lifting analysis of the front trunnions, the maximum stress in the inner shoulder, under the tie down loading condition is:

Bending stress, $\sigma = \frac{M}{Z}$

$M = (402{,}000)\ (1.00) = 402{,}000$ in lb.

$Z = 249.8\ in^3$

Therefore, $\sigma_b = 1{,}609$ psi

Shear stress, $\tau = \frac{V}{A} = \frac{402{,}000}{148.5} = 2{,}707$ psi

The transport loading condition also includes the 5G transverse load shared between one front and one rear trunnion. This load

is applied directly to the trunnion flange and does not influence the shoulder stress.

Therefore the total bending plus direct stress is:

$$\sigma_T = \pm 1,609 \text{ psi}$$

Combining this result with the shear stress to obtain the stress intensity gives:

$$S = \sqrt{(1,609)^2 + 4(2,707)^2}$$

$$= 5,648 \text{ psi}$$

This is well below the 30,000 psi trunnion material yield stress and is therefore acceptable.

<u>Rear Trunnion Base Plate</u>

The trunnion base plate analysis is performed using the same methodology as that used in the lifting analysis of Section 2.5.1. The bending moment at the base plate junction is 651,240 in lb. Using the same reference as in the analysis of the front trunnion in Section 2.5.1, b/a = .8 and β = .262. Therefore, the bending stress is:

$$\sigma_b = \frac{\beta M}{at^2} = \frac{(.262)(651,240)}{(7.5)\ (4.5)^2} = 1,120 \text{ psi}$$

The shear stress in the plate at the shoulder diameter (13.75 in) is calculated below:

$$F_{max} = \frac{M}{R^2\pi}$$

$$= \frac{651240}{(6.875)^2 \pi} = 4385.8 \text{ lbs/in}$$

$$\tau = \frac{V_{max}}{t} = \frac{4385.8}{4.5} = 974.6 \text{ psi}$$

The combined stress is:

$$S = \sqrt{(1,120)^2 + 4(975)^2} = 2,249 \text{ psi}$$

The factor of safety against yielding under the tie down loadings is at least 5.4 for all trunnion sections.

2.6 NORMAL CONDITIONS OF TRANSPORT

Overview

This section describes the response of the TN-RAM package to the loading conditions specified by 10CFR71.71. The design criteria established for the TN-RAM for the normal conditions of transport are described in Section 2.1.2. These criteria are selected to ensure that the package performance standards specified by 10CFR71.43 and 71.51 are satisfied.

Detailed structural analyses of various TN-RAM cask components subjected to individual loads are provided in the Appendices to this chapter. The limiting results from these analyses are used in this section to quantify package performance in response to the normal condition of transport load combinations specified in 10CFR71.71 and Regulatory Guide 7.8. Table 2.6-1A provides an overview of the performance evaluations reported in each load combination subsection. Each subsection provides the limiting structural analysis result for the affected cask component(s) in comparison to the established design criteria. This comparison permits the minimum margin of safety for a given component subjected to a given loading condition to be readily identified. In all cases, the acceptability of the TN-RAM cask design with respect to established criteria and consequently with respect to 10CFR71 performance standards is demonstrated.

TABLE 2.6-1A

NORMAL CONDITIONS OF TRANSPORT

TN-RAM PERFORMANCE EVALUATION OVERVIEW

LOADING CONDITION	SAR SECTION	SCOPE OF EVALUATION
Heat	2.6.1	
	2.6.1.1	Maximum component temperatures for material allowables
	2.6.1.2	Cask cavity maximum pressure (MNOP = 30 psig)
	2.6.1.3	Cask body thermal gradients
	2.6.1.4	Cask body stresses (steady-state)
Cold	2.6.2	• Suitability of fabrication materials • Cask cavity minimum pressure • Cask body thermal stresses
Increased External Pressure (20 psia)	2.6.3	Cask body stresses (ΔP = 20 psid, thermal stresses) (cask internal pressure conservatively assumed to be 0 psia)
Reduced External Pressure (3.5 psia)	2.6.4	Cask body stresses (ΔP = 41.2 psid, thermal stresses) (cask internal pressure is MNOP, 30 psig)

TABLE 2.6-1A (Continued)

NORMAL CONDITIONS OF TRANSPORT

TN-RAM PERFORMANCE EVALUATION OVERVIEW

LOADING CONDITION	SAR SECTION	SCOPE OF EVALUATION
Shock/Vibration	2.6.5	
	2.6.5.1	Cask body stresses for maximum transport shock loading
	2.6.5.2	Cask body stresses for vibration normally incident to transport
	2.6.5.3	Fatigue evaluation
Water Spray	2.6.6	Negligible for TN-RAM
Free Drop	2.6.7	Cask body stresses: • 1 foot end drop (bottom) • 1 foot side drop
Corner Drop	2.6.8	Not Applicable
Compression	2.6.9	Not Applicable
Penetration	2.6.10	Negligible

The stress analysis results for the impact limiter structure can be taken directly from the analysis in Appendix 2.10.2. The structural analysis of the cask body is presented in Appendix 2.10.1 and covers a wide range of individual loading conditions. The stress results from the various individual loads must be combined in order to represent the stress condition in the cask body under the specified condition evaluated in this section. An explanation of the results reporting format and stress combination technique used to apply the results from Appendix 2.10.1 is provided here.

Reporting Method for Cask Body Stresses

Appendix 2.10.1 provides the detailed description of the structural analyses of the TN-RAM cask body. That appendix describes the detailed ANSYS models used to analyze various applied loads. Table 2.6-1B identifies the individual loads (IL) analyzed which are applicable to normal conditions of transport. Some of these individual loads are axisymmetric (e.g. pressure) and others are asymmetric (e.g. gravity). Table 2.6-1B also identifies several individual load cases (IL-16 and IL-18) performed using the Bijlaard method as described in Section 2.10.1.3. 3

Figure 2.6-1 shows the selected locations on the cask body numbered 1 through 25 where stress results for these analyses are reported. Detailed stresses are actually available at as many locations as there are nodes in the finite element model. However, for practical considerations, the reporting of stress results is limited to those locations shown on Figure 2.6-1. These locations were selected to be representative of the stress distribution in the cask body with special attention given to areas subject to high stresses. The maximum stress may occur at a different location for each individual load.

TABLE 2.6-1B

INDIVIDUAL LOAD CASES FOR CASK BODY ANALYSIS

(Normal Conditions of Transport)

LOAD CASE NUMBER	INDIVIDUAL LOAD DESCRIPTION	STRESS RESULTS TABLE(1)
IL-1	Bolt Preload and Lid Seating Pressure	2.10.1-1
IL-2	Thermal Stresses at Hot Environment Conditions	2.10.1-2
IL-3	Thermal Stresses at -20°F Environment Conditions	2.10.1-3
IL-4	Thermal Stresses at -40°F Environment Conditions	2.10.1-4
IL-5	Internal Pressure (P = 30 psig)	2.10.1-5
IL-6	External Pressure (P = 14.7 psig)	2.10.1-6
IL-7	1 G Down with Horizontal Cask Supported by all Four Trunnions	2.10.1-7
IL-9	Shock Loading with Horizontal Cask Supported by all Four Trunnions	2.10.1-9
IL-11A	1 Ft End Drop on Bottom	2.10.1-11A 3
IL-13	Side Drop (Note 2)	2.10.1-13
Local Stresses at Trunnion/Cask Body Outer Shell Interface (Bijlaard Analysis) with Cask Horizontal in Transport Cradle:		
IL-16	• with 1 G Vertical Loading	2.10.1-16
IL-18	• with Limiting Transport Shock Loading	2.10.1-18

NOTES:

1. Stress result tables listed appear in Appendix 2.10.1
2. The loading conditions are analyzed for the 30 foot hypothetical accident drop. Stress results for the 1 foot normal condition drop are determined by ratio.

Notes:

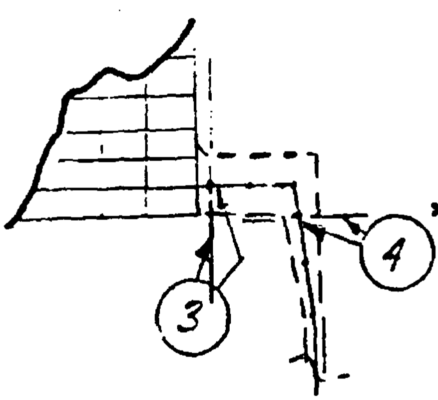
1) The locations shown are at the ends of the elements where they are connected to the nodes.

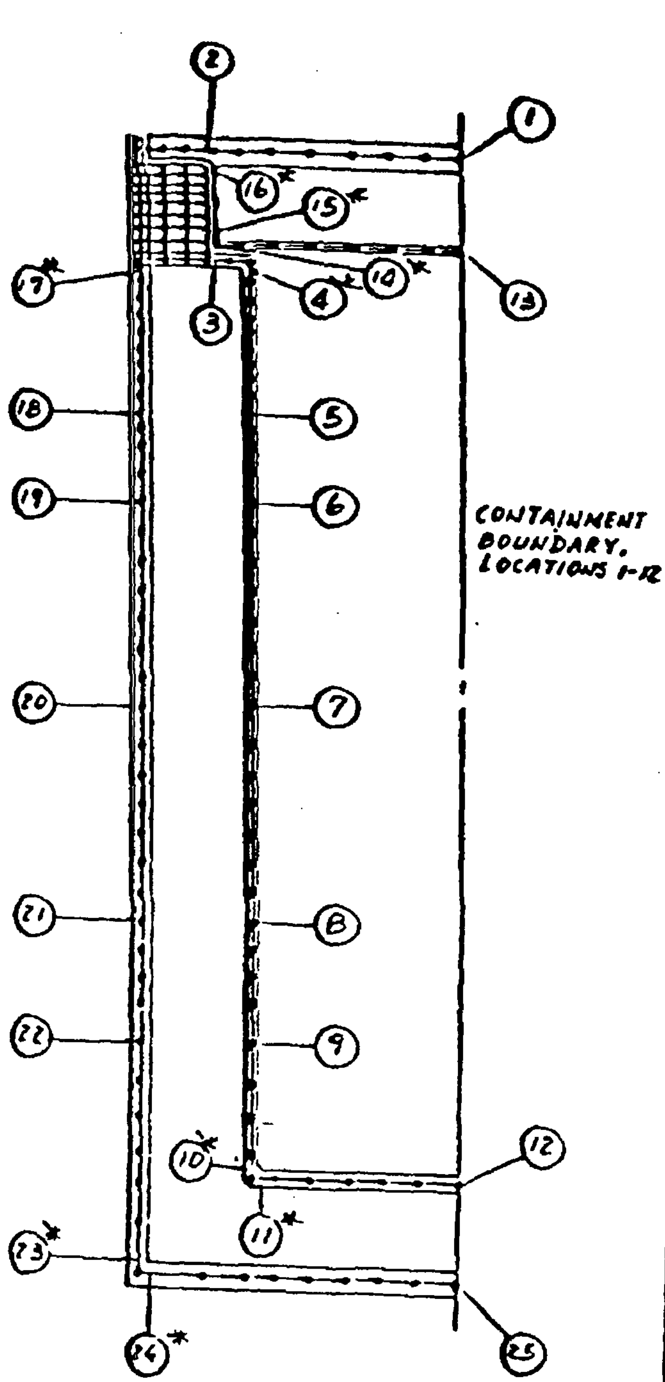
2) The stress summary tables present the membrane stress intensities based on components averaged through the thickness and the membrane plus bending stress intensities at both surfaces for all 25 locations.

3) The indicated junctions (*) are considered structural discontinuities and the stress intensities are classified as discussed in Section 2.1.2.1.

4) At shell junctions such as (23) and (24) one location is on the end of the cylinder (23) and the other on the edge of the bottom (24).

5) Locations (3) and (4) are shown clearly below. Location (3) is not treated as a discontinuity.





STANDARD STRESS REPORTING LOCATIONS

FIGURE 2.6-1

The stresses in the portion of the cask body that form the containment boundary are listed in the upper part of each table, locations 1 through 12. All of the locations shown are in the relatively thin portions of the package modeled with shell elements. The stresses in the flange region are much lower than these shell stresses and are not reported.

It should be noted than thin shell theory assumes that the bending stress distribution through the thickness of a thin shell member is linear. Therefore, the bending stress components in a given direction are equal and opposite on the inner and outer surfaces of the shell. The membrane plus bending stress components at the inner and outer surfaces are then equal to the membrane stress components $\pm$ the bending stress components. The principal membrane stresses and membrane stress intensities are determined directly at each location from the membrane stress components (and shear stresses where applicable) and are equal through the entire section. The principal membrane plus bending stresses and membrane plus bending stress intensities at the inner and outer surfaces are determined from the membrane $\pm$ bending stress components at the surfaces.

The stress results for the individual load case tables for 3
normal conditions* reported in Section 2.10.1 are generally limited to the meridional and hoop membrane stress components and meridional and hoop bending stress components. Two or more individual load cases must be combined to determine the total stresses at the standard stress reporting locations for the various load combinations. This is accomplished using the ANSYS Post 1 postprocessor which algebraicly adds the meridional and hoop membrane stress components and the meridional and hoop bending stress components at each of the standard locations. The membrane stress intensity is then found from the membrane stress components and the inner and

*The membrane and membrane plus bending stress intensities are listed in Table 2.10.1-11A for the one foot end drop. 3

outer surface membrane plus bending stress intensities are determined from the membrane ± bending stress components. These load combination stress results are reported for the various normal conditions of transport in Tables 2.6-1 through 2.6-12 provided below.

Several other items should be noted. In the TN-RAM, thermal stresses occur due to the effects of differential thermal expansion between the lead and stainless steel. When evaluating stresses, these thermal stresses are conservatively calculated assuming elastic behavior of the lead. The resulting stresses are treated as primary stresses and the combined stresses due to primary loads (like pressure) and differential expansion (such as heating from 70°F to hot thermal conditions) are evaluated as primary stresses. Lead creep and relaxation are properly accounted for in the buckling evaluation performed in Appendix 2.10.4. Also, one individual load case in Appendix 2.10.1 was performed for the corresponding hypothetical accident condition (the side drop for 128.5G) and is scaled for the normal condition (F = 0.28 for 36 G normal side drop). 3

For the axisymmetric cases, the stress is constant around the circumference of the cask at each stress reporting location. For asymmetric analyses with significant differences in stress magnitudes on the extreme opposite sides of the cask (usually top and bottom for a horizontal cask) the stresses at locations on both sides are reported in separate tables (e.g. contact side in Table 2.6-9 for the 1 foot side drop and side opposite contact in Table 2.6-10).

In those cases where the cask is supported on the trunnions, the stresses under transverse loadings (such as gravity) are nearly equal in magnitude on the top and bottom. Therefore only the tensile results for the bottom side are listed for these cases.

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. These local stresses really occur on the sides of the cask (not the top and bottom where the ANSYS results are reported). However, they are still conservatively added absolutely to the ANSYS stress intensities (membrane to membrane and membrane plus bending to membrane plus bending).

Table 2.6-1C provides a matrix of the individual loads and how they are combined to determine the cask body stresses for the specified normal conditions of transport. The thermal stresses due to the hot and cold conditions are actually secondary stresses that could be evaluated using higher allowables than for primary stresses. They are calculated assuming elastic behavior of the lead and are conservatively added to the primary stresses and the combined stresses are evaluated using primary stress allowables. An X in Table 2.6-1C indicates that the stress results for the individual load case are used directly. A quantitative number (e.g. F = 1.36) indicates the load factor applied to the individual stresses.

Table 2.6-1D lists the stress vs. strain material properties used for each of the individual load cases. Note that the 1 foot end drop is analyzed plastically using the lead plastic stress-strain curve. The stainless steel is modeled elastically. The remaining normal condition stresses are calculated elastically using a lead modulus of 27,750 psi. The combined stresses are conservatively calculated by summing the stresses from each of the individual load cases. 4

For the increased external pressure load combination, it is conservatively assumed that the TN-RAM cask cavity is at 0 psia. Since the specified load combination condition is 20 psia., the net differential pressure acting on the cask body is 20 psi.

2.6.1 Heat

Chapter Three describes the thermal analyses performed for the TN-RAM package subjected to hot environment conditions. These thermal analysis results are used to support various aspects of

the structural evaluations as described in the following subsections.

2.6.1.1 Maximum Temperatures

Stress allowables for packaging components are a function of component temperature. Stress allowables are based on actual maximum calculated temperatures or conservatively selected higher temperatures. Chapter Three summarizes significant temperatures calculated for the TN-RAM subjected to hot environment conditions. These temperatures are used to establish the allowables for every normal and accident (except the thermal accident which has higher temperatures) load combination evaluated in this Safety Analysis Report.

2.6.1.2 Maximum Pressure

The thermal analysis presented in Chapter Three also provides the average cavity gas temperature under hot environment conditions. This value is used in Chapter Three, Section 3.4.4, to determine the Maximum Normal Operating Pressure (MNOP). For purposes of the structural analysis of containment, a value of 30 psig (much higher than the Chapter Three value) is conservatively assumed for MNOP. This pressure loading is analyzed using the ANSYS model of the cask body as described in Appendix 2.10.1 and the results are reported in Table 2.10.1-5 of that Appendix. This load case and corresponding results are designated as individual load IL-5. IL-5 is used to support various load combination evaluations as listed in Table 2.6-1C.

2.6.1.3 Thermal Stresses

The thermal analysis of the TN-RAM is performed as described in Chapter Three. The temperature distribution from that analysis

TABLE 2.6-1C
SUMMARY OF LOAD COMBINATIONSFOR NORMAL CONDITIONS OF TRANSPORT

LOAD COMBINATIONS	APPLICABLE INDIVIDUAL LOAD IL-1	IL-2	IL-3	IL-4	IL-5	IL-6	IL-7	IL-9	IL-11A	IL-13	IL-16	IL-18	STRESS RESULT TABLES
HOT ENVIRONMENT (100F AMB. TEMP.)	X	X			X		X				X		2.6-1
COLD ENVIRONMENT (-40F AMB. TEMP.)	X			X		X	X				X		2.6-2
INCREASED EXT. PRESSURE (ΔP = 20 PSI EXTERNAL)	X		X			X F = 1.36	X						2.6-3
MIN. EXT. PRESSURE (ΔP=41.2 PSIG INTERNAL	X	X			X F = 1.38		X				X		2.6-4
TRANSPORT SHOCK	X	X			X			X				X	2.6-5
	X		X			X		X				X	2.6-6
1 FT END DROP -30G (BOTTOM)	X	X			X				X				2.6-7
	X		X			X			X				2.6-8
1 FT SIDE DROP - 36G	X	X			X					X F = .28			2.6-9 CONTACT SIDE; 2.6-10 SIDE OPP. CONT.
	X		X			X				X F = .28			2.6-11 CONTACT SIDE; 2.6-12 SIDE OPP. CONT.

NOTE: F = LOAD FACTOR

TABLE 2.6-1D
SUMMARY OF STRESS VS. STRAIN PROPERTIES FOR INDIVIDUAL LOAD CASES

INDIVIDUAL LOAD DESCRIPTION	MATERIAL PROPERTIES USED IN ANALYSIS, E (PSI)		REMARK
	LEAD	304 S.S.	
BOLT PRELOAD	27750	28.3×10^6	
THERMAL STRESS AT HOT ENVIRONMENT CONDITION	27750	28.3×10^6	
THERMAL STRESS (-20°F)	27750	28.3×10^6	
THERMAL STRESS (-40°F)	27750	28.3×10^6	
INTERNAL PRESSURE (30 PSIG)	27750	28.3×10^6	
EXTERNAL PRESSURE (-14.7 PSI)	27750	28.3×10^6	
GRAVITY (1G DOWN)	27750	28.3×10^6	
VIBRATION	27750	28.3×10^6	
SHOCK	27750	28.3×10^6	
TIEDOWN	27750	28.3×10^6	
30 FT BOTTOM END DROP (70G)	PLASTIC LEAD FIG. 2.10.1-1B	PLASTIC S.S. FIG. 2.10.1-1C	
1 FT BOTTOM END DROP (30G)	PLASTIC LEAD FIG. 2.10.1-1B	28.3×10^6	
30 FT LID END DROP (70G)	PLASTIC LEAD FIG. 2.10.1-1B	PLASTIC S.S. FIG. 2.10.1-1C	
30 FT SIDE DROP (128.5G)	27750	28.3×10^6	
30 FT C.G. OVER CORNER DROP (68.5G)	27750	28.3×10^6	
THERMAL ACCIDENT	27750	28.3×10^6	

4

is used to perform an ANSYS structural analysis of the cask body thermal stresses with stress results reported at the standard locations shown on Figure 2.6-1. The stress results for this load case are reported on Table 2.10.1-2 of Appendix 2.10.1. This load case is designated as IL-2 and is used to support various load combinations. The thermal stresses are elastically calculated, strain controlled secondary stresses that can be evaluated separately from primary stresses using higher allowables. However, the thermal stresses are conservatively combined with the various primary stresses in the following load combinations and are evaluated as primary stresses.

2.6.1.4 Cask Body Stresses - Hot Environment

Cask body stresses for the hot environment normal condition of transport are obtained by a combination of individual loads as summarized in Table 2.6-1C. For this condition, it is assumed that the cask is in its normal transport configuration, mounted horizontally on the transport cradle, and support by the four cask trunnions. Lid bolt preload effects and local stresses at the trunnion locations due to the trunnion reactions to the dead weight loading are included. No transport inertia loadings are included in this load combination.

Table 2.6-1 lists the total membrane and membrane plus bending stress intensities at each of the standard reporting locations for both the inner and outer surfaces. Locations designated by the (*) in Table 2.6-1 are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1.

TABLE 2.6-1
CASK BODY STRESSES UNDER HOT ENVIRONMENT
(Bolt Preload, Hot Thermal, 30 psig Internal, 1G Down)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	395	370	395	1,727	2,468
C	2	324	384	384	1,009	1,128
O	3	964	-1,379	2,343	1,000	4,748
N	4	-48	-1,463	* 1,463	* 2,881	* 2,145
T	5	-44	-1,319	1,319	1,315	1,291
A	6	-25	-1,260	1,260	1,274	1,234
I	7	1	-1,272	1,273	1,309	1,237
N	8	0	-1,286	1,286	1,314	1,258
M	9	-1	-1,268	1,268	1,285	1,248
E	10	-58	-298	* 298	* 2,105	* 2,022
N	11	-420	-407	* 420	* 2,300	* 1,489
T	12	-433	-438	438	695	253
	13	348	358	358	229	624
C	14	382	451	* 451	* 3,821	* 4,615
O	15	324	438	* 438	* 3,914	* 4,561
N	16	328	385	* 385	* 3,716	* 4,372
T	17	501	252	* 501	* 4,340	* 3,337
N A	18	515	1,599	1,599	2,306	892
O I	19	505	1,468	1,468	1,442	1,495
N N	20	596	1,470	1,470	1,419	1,521
M	21	528	1,481	1,481	1,438	1,523
E	22	478	1,532	1,532	2,109	968
N	23	536	372	* 536	* 6,735	* 5,664
T	24	260	289	* 289	* 2,541	* 2,352
	25	282	261	282	2,381	2,902

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

The maximum membrane stress intensity calculated for this load combination is 2,343 psi which occurs at location 3 and the maximum membrane plus bending stress intensity is 6,735 psi at location 23. These stress intensities represent the cask body and non containment structure stresses under hot initial conditions. These stresses are well below the allowable membrane stress intensity of 20,000 psi, local membrane stress intensity of 30,000 psi, and membrane plus bending stress intensity of 30,000 psi. The evaluation of the range of primary plus secondary stresses during normal conditions is provided in Section 2.6.7.

2.6.2 Cold Environment

The Regulatory Guide 7.8 cold environment load combination results in all cask components in thermal equilibrium at -40°F. Containment vessel thermal stresses do occur in this case due to the differential thermal expansion between the lead and steel. The thermal stresses are determined in load case IL-4 with results tabulated in Table 2.10.1-4. The cask cavity pressure at the cold environment condition is conservatively assumed to be 0 psia. This results in a net external pressure loading of 14.7 psig, load case IL-6 with results in Table 2.10.1-6. Again, lid bolt preload, gravity and trunnion local loads are included.

The maximum stress intensities for the load combination are listed on Table 2.6-2. Locations designated by the (*) are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1.

TABLE 2.6-2
CASK BODY STRESSES UNDER COLD ENVIRONMENT
(Bolt Preload, -40°F Cold Thermal, 14.7 psi External, 1 G Down)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-11	-35	35	400	436
C	2	-37	-8	37	457	368
O	3	1	30	30	223	224
N	4	-69	-61	* 69	* 160	* 295
T	5	-51	-168	168	189	144
A	6	-32	-157	157	190	120
I	7	-7	-144	144	197	102
N	8	-7	-158	158	202	122
M	9	-10	-156	156	177	132
E	10	-66	30	* 96	* 3,156	* 3,028
N	11	-394	-68	* 394	* 3,596	* 2,808
T	12	-440	-445	445	504	1,389
	13	12	23	23	174	221
C	14	49	117	* 117	* 577	* 674
O	15	51	118	* 118	* 608	* 711
N	16	30	10	* 30	* 125	* 65
T	17	-99	14	* 113	* 334	* 150
N A	18	-42	-12	42	795	819
O I	19	-55	-117	117	170	79
N N	20	36	-118	154	187	133
M	21	-32	-110	110	169	64
E	22	-83	-29	83	499	557
N	23	-117	-44	* 117	* 1,568	* 1,320
T	24	-55	-25	* 55	* 606	* 534
	25	-32	-54	54	813	912

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

The highest membrane stress intensity is 445 psi at location 12 and the highest membrane plus bending stress intensity is 3,596 psi at location 11. These stresses are well below the allowables for membrane stress intensity of 20,000 psi, and membrane plus bending stress intensity of 30,000 psi. The evaluation of the range of primary plus secondary stresses during normal conditions is provided below in Section 2.6.7. 3

Brittle fracture of the cask body components is precluded by the choice of austentic stainless steel for fabrication of the TN-RAM.

In addition, a buckling evaluation of the compressive stresses in the inner containment cylinder under limiting normal conditions is provided in Appendix 2.10.4. That section shows that the buckling limits of Code Case N-284 are met.

2.6.3 Increased External Pressure

Cask body stresses for the increased external pressure, 20 psia, normal condition of transport are obtained by a combination of individual loads as summarized in Table 2.6-1C. The conservatively assumed minimum cask cavity pressure of 0 psia results in a net external pressure loading of 20 psi. The stresses due to this pressure condition are obtained by multiplying those due to the 14.7 psi external pressure, I1-6, by a factor of 20/14.7 or 1.36. For this condition, the cask

is assumed to be in the horizontal orientation supported on the transport cradle by four trunnions. Lid bolt preload, gravity and the local trunnion effects are included. In addition, the thermal stresses for the -20°F minimum temperature during transport are calculated as IL-3 and are included in the combination. No transport inertia loadings are included in this load combination.

Table 2.6-3 lists the combined stress results at each of the standard reporting locations for this case. Locations designated by the (*) are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1.

The maximum membrane stress intensity for this condition is 388 psi at location 12, and the maximum membrane plus bending stress intensity is 3,590 psi at location 11. These stresses are well below the allowables for membrane stress intensity of 20,000 psi and membrane plus bending stress intensity of 30,000 psi. The evaluation of the range of primary plus secondary stresses during normal conditions is provided below in Section 2.6.7. A buckling evaluation of the compressive stresses in the inner containment cylinder under limiting normal conditions is provided in Appendix 2.10.4. That section shows that the buckling limits of Code Case N-284 are met. 3

TABLE 2.6-3
CASK BODY STRESSES UNDER INCREASED EXTERNAL PRESSURE
(Bolt Preload, -20°F Cold Thermal, 20 psi External, 1 G Down)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI) MERIDIONAL	HOOP	STRESS INTENSITIES (PSI) MEMBRANE Pm or (Pl)* AVERAGE	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)* INNER SURFACE	OUTER SURFACE
	1	-33	-58	58	534	620
C	2	-60	-31	60	618	491
O	3	-3	32	35	268	263
N	4	-90	-70	* 90	* 237	* 415
T	5	-73	-150	150	171	127
A	6	-54	-139	139	173	102
I	7	-29	-127	127	180	71
N	8	-30	-141	141	185	94
M	9	-32	-143	143	166	117
E	10	-100	63	* 163	* 3,228	* 3,031
N	11	-337	-8	* 337	* 3,590	* 2,916
T	12	-382	-388	388	504	1,273
	13	17	28	28	82	139
C	14	53	122	* 122	* 675	* 782
O	15	55	123	* 123	* 703	* 814
N	16	31	-7	* 38	* 269	* 207
T	17	-136	4	* 141	* 492	* 239
N A	18	-176	-151	176	172	242
O I	19	-91	-197	197	257	158
N N	20	0	-198	198	273	177
M	21	-68	-189	189	256	143
E	22	-184	-150	184	181	226
N	23	-159	-72	* 159	* 2,166	* 1,827
T	24	-76	-47	* 76	* 837	* 745
	25	-54	-76	76	1,095	1,247

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

2.6.4 Reduced External Pressure

Cask body stresses for the 3.5 psia ambient normal condition of transport are obtained by a combination of individual loads as summarized in Table 2.6-1C. The conservatively assumed MNOP of 30 psig results in a net internal pressure loading of 41.2 (30+14.7-3.5) psi. For this condition, the cask is in the horizontal orientation supported on the transport cradle by four trunnions. No transport inertia loadings are included in this load combination. The thermal stresses for the hot thermal condition are included in the load combination.

Table 2.6-4 lists the combined stress intensities at each of the standard stress reporting locations. Locations designated by the (*) are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1.

The maximum primary membrane stress intensity is 2,359 psi at location 3 and the highest membrane plus bending stress intensity is 7,378 psi at location 23. These stresses are well below the allowable membrane stress intensity of 20,000 psi, and membrane plus bending stress intensity of 30,000 psi.

The evaluation of the range of primary plus secondary stresses during normal conditions is provided below in Section 2.6.7.

TABLE 2.6-4
CASK BODY STRESSES UNDER MIN. EXTERNAL PRESSURE
(Bolt Preload, Hot Thermal, 41.2 psig Internal, 1 G Down)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	418	394	418	2,264	3,052
C	2	339	405	405	1,342	1,474
O	3	954	-1,405	2,359	914	4,527
N	4	19	-1,394	* 1,413	* 2,782	* 1,985
T	5	24	-1,079	1,103	1,095	1,111
A	6	43	-1,020	1,063	1,101	1,024
I	7	68	-1,032	1,101	1,136	1,065
N	8	68	-1,046	1,114	1,142	1,086
M	9	67	-1,023	1,090	1,118	1,063
E	10	63	-312	* 375	* 434	* 720
N	11	-306	-422	* 422	* 630	* 173
T	12	-311	-316	316	573	142
	13	330	340	340	285	578
C	14	365	433	* 433	* 2,992	* 3,763
O	15	267	410	* 410	* 3,182	* 3,715
N	16	289	390	* 390	* 4,441	* 5,020
T	17	525	231	* 525	* 4,439	* 3,389
N A	18	537	1,609	1,609	2,328	890
O I	19	528	1,478	1,478	1,452	1,504
N N	20	619	1,480	1,480	1,429	1,531
M	21	550	1,490	1,490	1,448	1,533
E	22	501	1,545	1,545	2,127	967
N	23	566	396	* 566	* 7,378	* 6,246
T	24	281	310	* 310	* 2,788	* 2,602
	25	303	281	303	2,899	3,461

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

2.6.5 Transport Inertia Loading

2.6.5.1 Shock

The transport shock loadings used to evaluate the TN-RAM cask are based on truck bed accelerations in ANSI N14.23* which are 2.3 G in the longitudinal direction, 1.6 G in the horizontal direction and 2.5 G in the vertical direction. Gravity is added to the vertical acceleration giving 3.5 G. The resultant transverse loading is $\sqrt{1.6^2 + 3.5^2}$ or 3.85 G's.

Other individual loads included in this transport shock load combination are bolt preload, thermal stresses, pressure and local stresses at the cask trunnion interface. Table 2.6-5 lists the combined stresses under hot thermal conditions where the load combination is performed for the maximum temperature thermal stresses and MNOP internal pressure. Locations designated by the (*) are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1.

The maximum membrane stress intensity calculated for this load combination is 4,075 psi which occurs at location 18 and the maximum membrane plus bending stress intensity is 12,890 psi, also at location 18. In addition, the load combination is performed for the -20°F thermal stress case (rather than the hot thermal case) and the minimum internal pressure case (14.7 psi external pressure rather than MNOP internal pressure). The shock loading, bolt preload, and local trunnion loads are the same as above. The combined stress results for this case are provided in Table 2.6-6. The highest membrane stress intensity is 2,726 psi and the highest membrane plus bending stress intensity is 11,380 psi. 4

* Draft American National Standard Design Basis for Resistance to Shock and Vibration, ANSI N14.23, May, 1980.

TABLE 2.6-5
CASK BODY STRESSES UNDER TRANSPORT SHOCK
(Bolt Preload, Hot Thermal, 30 psig Internal, Shock)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	714	620	714	3,774	5,014
C	2	559	707	707	2,105	2,345
O	3	769	-1,907	2,677	2,713	6,514
N	4	-677	-2,733	* 2,733	* 6,177	* 6,553
T	5	-636	-2,002	2,002	2,060	1,902
A	6	-554	-1,776	1,776	1,861	1,649
I	7	-438	-1,403	1,403	1,567	1,196
N	8	-421	-1,101	1,101	1,230	929
M	9	-421	-914	914	978	807
E	10	-743	-128	* 743	* 4,866	* 3,423
N	11	-347	-8	* 347	* 4,410	* 3,746
T	12	-457	-477	477	405	1,289
	13	372	410	410	234	1,115
C	14	505	771	* 771	* 4,872	* 5,912
O	15	467	764	* 764	* 5,108	* 6,041
N	16	447	673	* 673	* 5,668	* 6,562
T	17	1,144	233	* 1,144	* 6,583	* 4,296
N A	18	3,282	4,075	4,075	12,890	4,740
O I	19	1,285	2,145	2,145	2,024	2,267
N N	20	1,655	1,899	1,899	1,702	2,097
M	21	1,413	1,683	1,683	1,519	1,847
E	22	2,446	3,458	3,458	11,493	4,577
N	23	486	454	* 486	* 6,230	* 5,259
T	24	278	392	* 392	* 2,380	* 2,219
	25	364	281	364	1,996	2,581

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.6-6
CASK BODY STRESSES UNDER TRANSPORT SHOCK
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External, Shock)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	308	214	308	1,751	2,165
C	2	198	315	315	826	866
O	3	-195	-497	497	1,928	1,921
N	4	-698	-1,325	* 1,325	* 3,457	* 4,722
T	5	-643	-824	824	907	729
A	6	-562	-647	647	773	537
I	7	-446	-249	446	501	378
N	8	-429	53	482	476	601
M	9	-430	221	651	591	712
E	10	-746	215	* 960	* 5,533	* 4,054
N	11	-249	366	* 614	* 5,242	* 4,745
T	12	-389	-409	409	1,496	2,314
	13	38	76	76	477	661
C	14	172	438	* 438	* 1,648	* 1,993
O	15	195	445	* 445	* 1,821	* 2,211
N	16	149	298	* 298	* 1,825	* 2,123
T	17	543	-5	* 547	* 1,907	* 806
N A	18	2,726	2,485	2,726	11,380	6,450
O I	19	725	560	725	638	797
N N	20	1,095	311	1,095	958	1,218
M	21	853	93	853	814	967
E	22	1,885	1,898	1,898	9,884	6,088
N	23	-167	38	* 205	* 2,073	* 1,724
T	24	-37	77	* 114	* 894	* 675
	25	49	-34	83	1,289	1,261

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

These stresses are well below the allowable membrane stress intensity of 20,000 psi, local membrane stress intensity of 30,000 psi, and membrane plus bending stress intensity of 30,000 psi. The evaluation of the range of primary plus secondary stresses during normal conditions is provided below in Section 2.6.7. A buckling evaluation of the compressive stresses in the inner containment cylinder under limiting normal conditions is provided in Appendix 2.10.4. That section shows that the buckling limits of Code Case N-284 are met.

2.6.5.2 Vibration

The input loading conditions used to evaluate the TN-RAM for transport vibration are also obtained from truck bed accelerations in ANSI N14.23. The peak inertia values used are 0.30 G, 0.30 G, and 0.60 G for the longitudinal, lateral and vertical directions, respectively. These values are less than the shock loadings analyzed in Section 2.6.5.1. Therefore, the shock values are used in 2.6.5.1 to perform the load combinations to evaluate the combined stresses under the transport inertia load combination. The vibration loading, however, is used to evaluate the acceptability of the TN-RAM with respect to fatigue. The stress intensity at each standard location is readily obtained from Table 2.10.1-8 in Appendix 2.10.1. Each bending stress component is added to and subtracted from the corresponding membrane stress component. Then the surface stress intensities are determined from the membrane plus bending stress components at the surface (which are actually principal stresses since the shear stresses are negligible). Only the local trunnion stresses from Table 2.10.1-17 are combined with these vibratory stresses for use in the fatigue evaluation below.

2.6.5.3 Fatigue Analysis

The purpose of the fatigue analysis is to show quantitively that the TN-RAM cask body stress level is within acceptable limits under

normal transport vibration to prevent fatigue damage. The highest surface stress intensity under vibration loading in the containment boundary is 622 psi at location 4 and in the non containment structure is 378 psi at location 15. The numerical values are determined from Table 2.10.1-8 using the approach described above. If we conservatively add the local stress intensity (Ref. Table 2.10.1-27) of 1,929 psi at location 18 due to trunnion loading (actually occurs at the side of the cask, not top or bottom) the resulting maximum vibratory stress is 2,307 psi.

If we consider the alternating stress to be 2,307 psi and apply a stress concentration factor of 4 for structural discontinuities as specified by Regulatory Guide 7.6, a simplified fatigue evaluation can be performed. If we examine Figure I-9.2.2 of the Code Section III Appendix I, we see that austenitic stainless steel can withstand an alternating stress of over 12,000 psi for 10^{11} cycles. Therefore, the cask body alternating stress of 2,307 psi x 4 or 9,228 psi is well below the range where fatigue failure can occur.

A fatigue analysis for the lid bolts is presented in Appendix 2.10.9 to show quantitatively that the fatigue damage to the bolts during normal transport conditions is acceptable. This is done by determining the fatigue damage factor for each normal transport event. For this analysis it is assumed that the bolts are replaced after *250* round trip shipments. The total cumulative damage or fatigue usage for all events was conservatively determined by adding the usage factors for the individual events. The sum of the individual usage factors was checked to make certain that for the *250* round trip shipments of the TN-RAM cask, the total usage factor was less than one. The total fatigue damage factor is less than one (*0.86*) for the TN-RAM cask lid bolts. Thus the bolts will not fail due to fatigue under normal transport conditions for an assumed *250* round trips.

2.6.6 Water Spray

All exterior surfaces of the TN-RAM cask are metal and therefore not subject to soaking or structural degradation from water absorption. The water spray condition is therefore of no consequence to the TN-RAM.

2.67 Free Drop

Two drop orientations are considered credible for the normal condition of transport one-foot free drop. The structural response of the TN-RAM cask body is evaluated for a one-foot end drop on the bottom and a one-foot side drop. Any other drop event for a different height or orientation is considered to be an accident. The assessment of cask body stresses follows the same logic as that established in the previous sections. For both drop cases, the

evaluations are performed for both the hot environment condition and at the -20°F minimum transport temperature. Note that the stresses for the 1 ft side drop are obtained by ratio from the 30 ft side drop which is a completely linear analysis. The 1 ft end drop is analyzed as a specific load case (IL-11A) performed using linear elastic behavior for the 304 stainless shells and the actual stress vs strain behavior of the lead.

The load combinations performed to evaluate these drop events are indicated in Table 2.6-1C. In all cases, bolt preload effects are included. For the hot environment condition, the thermal stress load case for that temperature, the 30 psi MNOP pressure load case and the impact load case factored for the normal condition G level are combined. For the cold temperature evaluation, the -20°F thermal stress load case, the 14.7 psi external pressure case and the factored load case are combined.

The free drop load combination results are listed in Tables 2.6-7 through 2.6-12. Locations designated by the (*) are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1.

Table 2.6-7 lists the combined stress intensities for the end drop under hot environment conditions. The maximum local membrane stress intensity is 18,822 psi. The maximum membrane plus bending stress intensity is 38,659 psi. This stress at the center of the outer end plate is slightly higher than the basic Table 2.1-3 allowable of 1.5 S_m (30,000 psi) but well below 1.5 S_y (45,000 psi) where uncontrolled yielding could occur. This is a location where permanent deformation of the non containment structure can be readily accomodated. Therefore this stress level is acceptable for this unusual impact condition. See the discussion below based on *Timoshenko. The maximum membrane plus bending stress intensity in the containment is 11,787 psi. The maximum primary plus secondary stress intensity is 53,193 psi.

Table 2.6-8 lists the combined stress intensities for the end drop under cold conditions. The maximum membrane stress intensity is 18,105 psi. The maximum membrane plus bending stress intensity is 37,718 psi. Again this stress at the center of the outer end plate is slightly above the basic Table 2.1-3 allowable, but well below 1.5 S_y. Therefore, this stress is acceptable for this unusual condition. See the discussion below based on *Timoshenko. The maximum membrane plus bending stress intensity in the containment is 10,097 psi. The maximum primary plus secondary stress intensity is 48,841 psi.

Timoshenko* provides guidance for investigation of the deformation of a structure at stress levels beyond the yield stress of the material. The magnitude of the bending moment on a rectangular section of elastic, perfectly plastic material as yielding begins at the surface is:

$$M_{yp} = S_y \frac{bh^2}{6}$$ 4

If the moment is increased above Myp, the fibers below the surface begin to yield and the relationship between M and the radius of curvative becomes nonlinear. The bending deformation increases at a higher rate than the applied moment. A percentage increase in bending produces a greater percentage increase in bending deformation. The moment where the bending deformation becomes uncontrolled is equal to:

$$M_{ult} = S_y \frac{bh^2}{4}$$

*Timoskenko, "Strength of Materials", Part II, 3rd Edition, pages 346-348

This moment equals 1.5 times the yield moment, M_{yp}. The corresponding surface stresses obtained in linear analyses assuming primary loading and elastic material behavior are S_y, when the section moment equals M_{yp}, and 1.5 S_y at M_{ult}. Therefore the bending stress at the surface of a beam or plate can be permitted to exceed S_y when some permanent deformation of the member can be accomodated. The bending stress can be permitted to approach 1.5 S_y for primary loads if deformation is not limited. 4

TABLE 2.6-7
CASK BODY STRESSES UNDER 1 FOOT END DROP
(Bolt Preload, Hot Thermal, 30 psig Internal, 30 G BTM End Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI) MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-174	-174	633	4,497	5,763
C	2	-5	-116	545	4,630	4,527
O	3	-152	855	1,109	3,475	2,350
N	4	-1,283	123	* 1,761	* 3,029	* 6,146
T	5	-1,417	-924	3,660	3,796	3,769
A	6	-1,528	7	2,915	2,938	2,893
I	7	-1,767	-16	3,177	3,198	3,155
N	8	-2,006	-449	3,398	3,328	3,468
M	9	-2,145	-842	3,739	3,418	4,060
E	10	-4,109	13,084	* 18,822	* 53,193	* 42,836
N	11	-4,438	120	* 5,415	* 41,312	* 31,125
T	12	-4,003	-4,032	4,682	2,676	11,787
	13	1,526	1,526	1,604	2,082	1,401
C	14	1,526	1,526	* 1,604	* 5,964	* 6,675
O	15	1,779	684	* 2,902	* 3,090	* 7,340
N	16	1,798	1,057	* 2,125	* 3,956	* 1,072
T	17	-693	1,668	* 2,612	* 3,370	* 2,312
N A	18	-2,004	801	3,122	3,233	3,040
O I	19	-2,190	304	3,103	3,045	3,161
N N	20	-2,465	767	3,566	3,565	3,567
M	21	-2,735	750	3,867	3,496	4,355
E	22	-3,386	2,212	5,929	4,987	6,947
N	23	-3,868	7,187	* 12,323	* 36,487	* 27,475
T	24	-1,027	-1,027	* 1,980	* 18,588	* 18,588
	25	-1,027	-1,027	1,980	34,698	38,659

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.6-8
CASK BODY STRESSES UNDER 1 FOOT END DROP
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External, 30 G BTM End Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-442	-442	528	3,706	4,762
C	2	-221	-365	454	4,073	3,804
O	3	-152	653	819	2,402	1,584
N	4	-1,353	-59	* 1,408	* 2,391	* 5,099
T	5	-1,487	-58	1,512	1,489	1,546
A	6	-1,596	-59	1,648	1,648	1,647
I	7	-1,835	-57	1,885	1,885	1,885
N	8	-2,074	-501	2,124	2,031	2,217
M	9	-2,212	-788	2,260	1,916	2,606
E	10	-4,203	13,632	* 18,105	* 48,841	* 39,468
N	11	-4,532	123	* 4,752	* 35,178	* 26,553
T	12	-4,106	-4,136	3,992	2,340	10,097
	13	1,100	1,100	1,271	2,010	842
C	14	1,100	1,100	* 1,271	* 2,318	* 2,365
O	15	1,464	396	* 1,700	* 631	* 3,834
N	16	1,485	766	* 1,704	* 3,201	* 638
T	17	-923	337	* 1,296	* 2,132	* 1,044
N A	18	-2,431	-199	2,591	2,778	2,432
O I	19	-2,620	-498	2,737	2,674	2,800
N N	20	-2,893	-33	3,203	3,213	3,194
M	21	-3,162	-176	3,215	2,908	3,638
E	22	-3,818	1,376	5,570	4,553	6,587
N	23	-4,333	7,679	* 12,012	* 35,302	* 26,621
T	24	-1,296	-1,296	* 1,875	* 17,879	* 17,879
	25	-1,296	-1,296	1,875	33,969	37,718

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.6-9
CASK BODY STRESSES UNDER 1 FOOT SIDE DROP - CONTACT SIDE
(Bolt Preload, Hot Thermal, 30 psig Internal, 36 G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-5,373	-451	5,373	7,453	5,537
C	2	-6,229	-6,013	6,229	6,982	6,453
O	3	-242	-6,780	6,780	6,574	7,517
N	4	57	-5,570	* 5,627	* 12,295	* 9,870
T	5	3,001	1,270	3,001	2,874	3,272
A	6	4,669	900	4,669	4,427	5,057
I	7	5,236	541	5,236	5,064	5,702
N	8	2,463	-389	2,852	3,028	2,703
M	9	346	-1,513	1,859	1,601	2,117
E	10	-778	-2,359	* 2,359	* 7,577	* 6,447
N	11	-2,060	-2,726	* 2,726	* 6,895	* 3,797
T	12	-1,106	-582	1,106	2,007	895
	13	502	1,169	1,169	705	1,663
C	14	1,753	5,732	* 5,732	* 20,623	* 23,918
O	15	1,861	5,769	* 5,769	* 21,827	* 25,549
N	16	753	-3,918	* 4,671	* 18,714	* 20,219
T	17	2,152	-6,185	* 8,337	* 21,316	* 16,751
N A	18	5,604	4,827	5,604	3,966	8,204
O I	19	8,424	4,470	8,424	7,988	8,859
N N	20	11,458	4,630	11,458	10,599	12,316
M	21	9,166	5,018	9,166	8,664	9,668
E	22	5,028	7,166	7,166	6,352	8,964
N	23	240	-2,679	* 2,919	* 31,456	* 28,385
T	24	-4,630	-4,673	* 4,673	* 18,445	* 9,186
	25	-3,937	-360	3,937	9,968	6,719

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.6-10
CASK BODY STRESSES UNDER 1 FOOT SIDE DROP - SIDE OPPOSITE CONTACT
(Bolt Preload, Hot Thermal, 30 psig Internal, 36 G Side Drop)

LOCATION			MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
					MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
			MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
		1	-2,191	819	3,010	4,381	3,578
	C	2	-1,938	2,866	4,804	4,662	4,947
	O	3	1,114	-579	1,692	1,299	4,684
	N	4	-326	-389	* 389	* 4,595	* 5,214
	T	5	-1,393	-1,538	1,538	1,732	1,312
	A	6	-2,276	-1,532	2,276	2,357	2,162
	I	7	-3,024	-1,489	3,024	3,136	2,879
	N	8	-1,508	-679	1,508	1,483	1,500
	M	9	-97	366	463	394	659
	E	10	1,775	2,058	* 2,058	* 15,654	* 12,070
	N	11	143	1,569	* 1,569	* 14,434	* 14,118
	T	12	-721	506	1,228	1,492	1,733
		13	40	-301	340	593	88
	C	14	-1,211	-3,918	* 3,918	* 15,242	* 17,633
	O	15	-1,352	-3,956	* 3,956	* 16,227	* 18,932
	N	16	-786	3,211	* 3,998	* 5,766	* 8,677
	T	17	-2,012	-43	* 2,012	* 2,442	* 1,699
N	A	18	-4,890	-1,691	4,890	4,013	5,768
O	I	19	-6,812	-1,352	6,812	6,652	6,972
N	N	20	-9,067	-1,421	9,067	8,820	9,313
	M	21	-8,186	-1,737	8,186	7,785	8,587
	E	22	-6,162	-2,582	6,162	5,485	6,839
	N	23	-716	4,974	* 5,690	* 13,102	* 9,640
	T	24	-1,055	4,857	* 5,912	* 7,095	* 7,879
		25	-1,748	958	2,706	4,989	6,430

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

Tables 2.6-9 and 10 list the combined stress intensities for the side drop under hot environment conditions. The highest stress intensities of all categories occur on the contacting side, Table 2.6-9. The highest membrane stress intensity is 11,458 psi at location 20. The highest membrane plus bending stress intensity is 12,316 psi also at location 20. The maximum primary plus secondary 3 stress intensity of 31,456 psi occurs at location 23.

Tables 2.6-11 and 12 list the combined stress intensities for the side drop under the -20°F cold temperature conditions. The highest membrane stress intensity of 10,898 psi, and the highest membrane plus bending stress intensity of 11,759 psi occur on the contacting side, Table 2.6-11. 3 The highest primary plus secondary stress intensity of 39,760 psi also occurs on the contact side, Table 2.6-11.

These stresses are below the allowable membrane stress intensity of 20,000 psi and membrane plus bending stress intensity of 30,000 psi (except at the center of the outer end plate - see discussion above for Tables 2.6-7 and 2.6-8). 3 The range of primary plus secondary stresses during normal conditions is evaluated below.

The <u>range</u> of primary plus secondary stresses at any location on the containment is limited to $3S_m$ or 60,000 psi. The primary plus secondary stress intensity never exceeds 30,000 psi at any location on the containment structure except at locations 10 and 11. Therefore, the stress range between any 2 events cannot exceed 3 60,000 psi except at these locations. (See Tables 2.6-1 through 2.6-12). For these locations, the individual stress components are evaluated to verify that the stress range does not exceed $3S_m$ or 60,000 psi.

TABLE 2.6-11
CASK BODY STRESSES UNDER 1 FOOT SIDE DROP - CONTACT SIDE
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External, 36 G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-5,779	-857	5,779	5,438	6,134
C	2	-6,590	-6,405	6,590	7,283	5,981
O	3	-1,206	-5,370	5,370	6,419	5,668
N	4	36	-4,162	* 4,198	* 9,574	* 8,039
T	5	2,993	2,448	2,993	2,868	3,234
A	6	4,662	2,029	4,662	4,366	5,072
I	7	5,229	1,695	5,229	4,872	5,701
N	8	2,455	765	2,455	2,325	2,702
M	9	338	-378	716	463	968
E	10	-782	-2,016	* 2,016	* 8,244	* 6,796
N	11	-1,961	-2,353	* 2,353	* 7,726	* 4,385
T	12	-1,038	-514	1,038	982	1,095
	13	168	836	836	625	1,209
C	14	1,420	5,400	* 5,400	* 18,012	* 19,999
O	15	1,589	5,450	* 5,450	* 18,540	* 21,718
N	16	455	-4,294	* 4,748	* 14,871	* 15,780
T	17	1,551	-6,423	* 7,974	* 18,102	* 13,262
N A	18	5,048	3,217	5,048	2,774	7,307
O I	19	7,864	2,884	7,864	7,382	8,331
N N	20	10,898	3,042	10,898	10,022	11,759
M	21	8,606	3,428	8,606	8,089	9,109
E	22	4,467	5,606	5,606	4,729	8,557
N	23	-413	-3,095	* 3,095	* 39,760	* 35,368
T	24	-4,944	-4,987	* 4,987	* 21,592	* 11,689
	25	-4,251	-674	4,251	6,821	4,600

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.6-12
CASK BODY STRESSES UNDER 1 FOOT SIDE DROP - SIDE OPPOSITE CONTACT
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External, 36 G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
CONTAINMENT	1	-2,596	414	3,010	2,450	3,570
	2	-2,300	2,474	4,773	6,079	3,482
	3	149	831	831	1,493	260
	4	-347	1,019	* 1,366	* 2,692	* 3,383
	5	-1,400	-361	1,400	1,473	1,323
	6	-2,284	-403	2,284	2,417	2,291
	7	-3,032	-335	3,032	3,180	3,307
	8	-1,516	474	1,990	1,634	2,346
	9	-106	1,501	1,607	1,495	1,809
	10	1,772	2,401	* 2,401	* 14,987	* 11,439
	11	242	1,943	* 1,943	* 13,602	* 13,118
	12	-654	574	1,228	911	1,544
NON CONTAINMENT	13	-295	-634	634	776	492
	14	-1,543	-4,250	* 4,250	* 18,466	* 21,553
	15	-1,624	-4,275	* 4,275	* 19,514	* 22,762
	16	-1,084	2,836	* 3,920	* 9,609	* 11,778
	17	-2,612	-280	* 2,612	* 7,001	* 1,791
	18	-5,446	-3,302	5,446	4,243	6,665
	19	-7,372	-2,937	7,372	7,259	7,501
	20	-9,626	-3,009	9,626	9,397	9,870
	21	-8,746	-3,327	8,746	8,360	9,146
	22	-6,723	-4,143	6,723	6,215	7,245
	23	-1,368	4,558	* 5,927	* 19,481	* 16,624
	24	-1,369	4,542	* 5,912	* 9,980	* 7,497
	25	-2,062	644	2,706	1,842	4,913

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.6-13A

MEMBRANE PLUS BENDING STRESSES ON INNER SURFACE OF INNER CONTAINER AT LOCATION 10 UNDER NORMAL CONDITIONS

LOAD COMBINATION	MERIDIONAL STRESS	HOOP STRESS
HOT ENVIRONMENT	-2137	-931
COLD ENVIRONMENT (-40F)	-3159	-882
INCREASED EXTERNAL PRESSURE	-3230	-859
MINIMUM EXTERNAL PRESSURE	-421	-483
SHOCK (HOT)	-4908	-1370
SHOCK (COLD)	-5553	-1194
1 FT END DROP (HOT)	-49281	-184
1 FT END DROP (COLD)	-49918	-8
1 FT SIDE DROP (HOT)		
CONTACT SIDE	-10709	-4437
SIDE OPPOSITE CONTACT	12625	6054
1 FT SIDE DROP (COLD)		
CONTACT SIDE	-11346	-4261
SIDE OPPOSITE CONTACT	11988	6230

3

TABLE 2.6-13B

MEMBRANE PLUS BENDING STRESSES ON OUTER SURFACE OF INNER CONTAINER AT LOCATION 10 UNDER NORMAL CONDITIONS

LOAD COMBINATION	MERIDIONAL STRESS	HOOP STRESS
HOT ENVIRONMENT	2023	333
COLD ENVIRONMENT (-40F)	3029	942
INCREASED EXTERNAL PRESSURE	3033	59
MINIMUM EXTERNAL PRESSURE	587	-142
SHOCK (HOT)	3424	1112
SHOCK (COLD)	4055	1626
1 FT END DROP (HOT)	40724	26527
1 FT END DROP (COLD)	41355	27039
1 FT SIDE DROP (HOT)		
CONTACT SIDE	6172	-281
SIDE OPPOSITE CONTACT	-12062	-1938
1 FT SIDE DROP (COLD)		
CONTACT SIDE	6796	231
SIDE OPPOSITE CONTACT	-11438	-1426

3

TABLE 2.6-13C

MEMBRANE PLUS BENDING STRESSES ON INNER SURFACE OF

INNER CONTAINER AT LOCATION 11 UNDER NORMAL CONDITIONS

LOAD COMBINATION	MERIDIONAL STRESS	HOOP STRESS
HOT ENVIRONMENT	-2350	-1081
COLD ENVIRONMENT (-40F)	-3596	-966
INCREASED EXTERNAL PRESSURE	-3589	-832
MINIMUM EXTERNAL PRESSURE	-609	-675
SHOCK (HOT)	-4441	-1172
SHOCK (COLD)	-5242	-837
1 FT END DROP (HOT)	-36975	-1735
1 FT END DROP (COLD)	-37779	-1402
1 FT SIDE DROP (HOT)		
CONTACT SIDE	-6924	-4580
SIDE OPPOSITE CONTACT	14403	4816
1 FT SIDE DROP (COLD)		
CONTACT SIDE	-7825	-4245
SIDE OPPOSITE CONTACT	13602	5151

3

TABLE 2.6-13D

MEMBRANE PLUS BENDING STRESSES ON OUTER SURFACE OF INNER CONTAINER AT LOCATION 11 UNDER NORMAL CONDITIONS

LOAD COMBINATION	MERIDIONAL STRESS	HOOP STRESS
HOT ENVIRONMENT	1488	267
COLD ENVIRONMENT (-40F)	2808	742
INCREASED EXTERNAL PRESSURE	2915	814
MINIMUM EXTERNAL PRESSURE	-6	-590
SHOCK (HOT)	3745	3434
SHOCK (COLD)	4744	1569
1 FT END DROP (HOT)	27209	1164
1 FT END DROP (COLD)	28208	1575
1 FT SIDE DROP (HOT)		
CONTACT SIDE	2803	-3202
SIDE OPPOSITE CONTACT	-14118	-3886
1 FT SIDE DROP (COLD)		
CONTACT SIDE	3802	-583
SIDE OPPOSITE CONTACT	-13119	-1267

Tables 2.6-13A through 2.6-13D list the algebraic values of primary plus secondary stress components for the inner and outer surfaces of the inner container at locations 10 and 11 in the meridional and hoop directions for the various normal loading conditions. The stresses presented in Tables 2.16-13A through 2.6-13D are obtained by combining the individual load cases presented in Appendix 2.10.1.

The maximum compressive stress at location 10 on the inner surface is -49918 psi. The maximum tensile stress is 12,625 psi. Therefore, the stress range is 62,543 psi.

The maximum compressive stress at location 10 on the outer surface is -11,436 psi. The maximum tensile stress is 41,355 psi. Therefore, the maximum stress range is 52,791 psi.

The maximum compressive stress at location 11 on the inner surface is -37,779 psi. The maximum tensile stress is 14,403 psi. The stress range is 52,182 psi.

The maximum compressive stress at location 11 on the outer surface is -14,118 psi. The maximum tensile stress on the outer surface is 28,208 psi. Therefore the stress range is 42,326 psi.

The maximum range of primary plus secondary stress during normal conditions of transport at a single location is 62,543 psi, slightly more than the 3 S_m (60,000 psi) limit of Section 2.1.2. Since nearly all of this stress is primary stress (rather than thermal bending), a simple shakedown analysis was performed in accordance with Code Paragraph NB-3228.4. As required by NB-3228.4(a), the stresses are calculated elastically. NB-3228.4(b) permits an exception to NB-3222.2 (the 3 S_m limit on range of primary plus secondary stress) if shakedown rather than continuing deformation occurs. Shakedown will occur since this stress range is primarily bending at the corner junction between the inner containment cylinder and end plate, both of which remain essentially elastic during all conditions. NB-3228.4(c) can be met since the 62,543 psi

stress range corresponds to an alternating stress of 31,271 psi. Even if a stress concentration factor of 4 is used, the junction can withstand an alternating stress of 4 x 31,271 psi for 900 cycles. Thus the 62,543 psi is acceptable since a life of 900 cycles (including the 1 ft drop) is more than adequate.

The vent port and drain port are not affected by the 1 foot drop because they are recessed and are covered by the impact limiters.

2.6.8 Corner Drop

This test does not apply to the TN-RAM Packaging since the packaging weight is in excess of 100 kg (220 lbs.).

2.6.9 Compression

This test does not apply to the TN-RAM Packaging since the packaging weight is in excess of 5,000 kg (11,000 lbs.).

2.6.10 Penetration

Due to lack of sensitive external protuberances, the one meter (40 in.) drop of a 13 pound hemispherically-headed, 1-1/4 inch diameter, steel cylinder is of negligible consequence to the TN-RAM Packaging.

2.7 HYPOTHETICAL ACCIDENT CONDITIONS

Overview

This section describes the response of the TN-RAM package to the loading conditions specified by 10CFR71.73. The design criteria established for the TN-RAM for the hypothetical accident conditions are described in Section 2.1.2. These criteria are selected to ensure that the package performance standards specified by 10CFR71.51 and 71.55 are satisfied.

The presentation of the hypothetical accident condition analyses and results is accomplished in the same manner as that used for the normal condition of transport. The detailed analyses of the various packaging components under different loading conditions are presented in the Appendices to this Chapter. The limiting results for the specified hypothetical accident loading conditions are taken from the Appendices and summarized here with a comparison made to the established design criteria. The possibility of lead slump with a subsequent loss of shielding is addressed below in Section 2.7.1.1. In all cases, the acceptability of the TN-RAM cask design with respect to hypothetical accident loads is demonstrated.

Table 2.7-1A provides an overview of the performance evaluations presented in this section. Stress analysis results for the lid bolts and impact limiter attachments are taken directly from the corresponding analysis appendix. The stress results for the cask body are obtained by combining or superimposing the stresses from appropriate individual load cases reported in Appendix 2.10.1 to represent the stress condition under the specified hypothetical accident condition. This combination method is essentially the same as that

TABLE 2.7-1A
HYPOTHETICAL ACCIDENT CONDITIONS
TN-RAM PERFORMANCE EVALUATION OVERVIEW

LOADING CONDITION	SAR SECTION	SCOPE OF EVALUATION
Free Drop (30-Foot)	2.7.1	
	2.7.1.1	• Cask body stresses for end drop on bottom and on lid.
	2.7.1.2	• Cask body stresses for side drop.
	2.7.1.3	• Cask body stresses for center-of-gravity over corner drop on lid.
		Component evaluation during worst case oblique drops: • Lid bolt stresses - 85° oblique angle • Impact limiter attachments - slapdown after 10° oblique angle impact
Puncture	2.7.2	• Cask body evaluation for 40 inch drop onto the puncture bar.
Thermal	2.7.3	• Maximum component temperatures • Cask body time-temperature history • Cask body thermal stresses (transient)
Immersion	2.7.5	• Cask body stresses for immersion in 50 feet of water

presented in Section 2.6. A buckling evaluation of the inner containment cylinder is provided in Appendix 2.10.4.

Reporting Method for Cask Body Vessel Stresses

The structural analysis of the cask body was performed using two ANSYS finite element models. Stress results are reported 3
at selected representative locations as described in Section 2.6. Because of the asymmetric characteristic of most of the hypothetical accident loads, stress results are generally reported on two opposite sides of the cask body.

Appendix 2.10.1 provides the detailed description of the structural analyses of the TN-RAM cask body. That appendix describes the detailed ANSYS models used to analyze various 3
applied loads. Table 2.7-1B identifies the individual loads (IL) analyzed using the ANSYS model which are applicable to the hypothetical accident conditions. Some of these individual loads are axisymmetric (e.g. pressure) and others are asymmetric (e.g. side impact). None of the load cases in this section involve loadings applied locally at the trunnions. Figure 2.7-1 shows the selected locations on the cask body numbered 1 through 25 where stress results for these analyses are reported. Detailed stresses are actually available at as many locations as there are nodes in the finite element model. However, for practical considerations, the reporting of stress results is limited to those locations shown on Figure 2.7-1. These locations were selected to be representative of the stress distribution in the cask body with special attention given to areas subject to high stresses. The maximum stress may occur at a different location for each individual load.

It should be noted once again that thin shell theory assumes that the bending stress distribution through the thickness of a thin shell member is linear. Therefore, the bending stress

Notes:

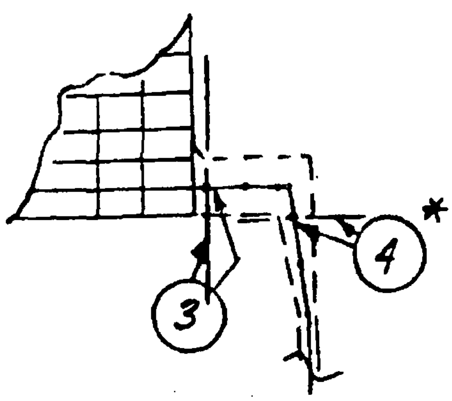
1) The locations shown are at the ends of the elements where they are connected to the nodes.

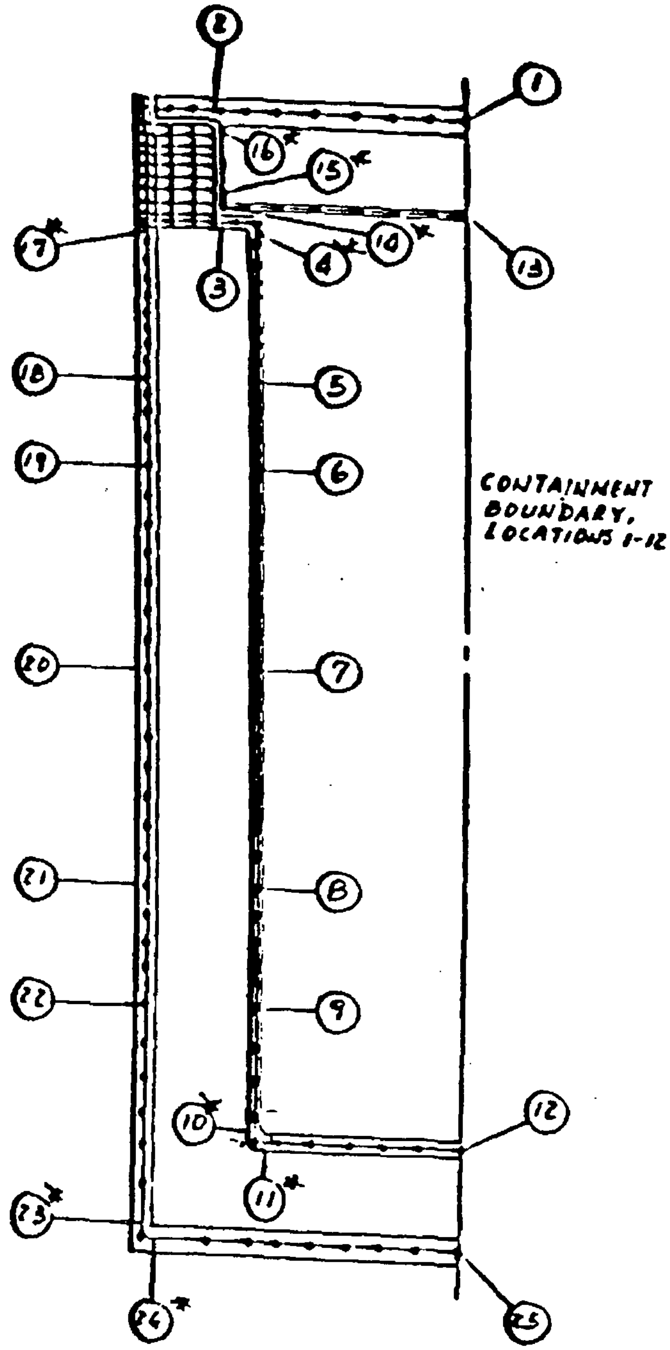
2) The stress summary tables present the membrane stress intensities based on components <u>averaged</u> through the thickness and the membrane plus bending stress intensities at both surfaces for all 25 locations.

3) The indicated junctions (*) are considered structural discontinuities and the stress intensities are classified as discussed in Section 2.1.2.1.

4) At shell junctions such as (23) and (24) one location is on the end of the cylinder (23) and the other on the edge of the bottom (24).

5) Locations (3) and (4) are shown clearly below. Location (3) is not treated as a discontinuity.





STANDARD STRESS REPORTING LOCATION

FIGURE 2.7-1

TABLE 2.7-1B
INDIVIDUAL LOAD CASES FOR CASK BODY ANALYSIS
(Hypothetical Accident Conditions)

LOAD CASE	INDIVIDUAL LOAD DESCRIPTION	STRESS RESULTS TABLE[1]
IL-1	Bolt Preload and Lid Seating Pressure	2.10.1-1
IL-2	Thermal Stresses at Hot Environment Conditions	2.10.1-2
IL-3	Thermal Stresses at -20°F Environment Conditions	2.10.1-3
IL-5	Internal Pressure (P = 30 psig)	2.10.1-5
IL-6	External Pressure (P = 14.7 psid)	2.10.1-6
IL-11	End Drop on Bottom	2.10.1-11
IL-12	End Drop on Lid	2.10.1-12
IL-13	Side Drop	2.10.1-13
IL-14	CG-over Corner Drop on Lid	2.10.1-14
IL-15	Thermal Accident Stresses	2.10.1-15 and 15A

NOTES

1. Stress results tables listed appear in Appendix 2.10.1. IL-1, IL-2, IL-3, IL-5 and IL-6 are the same individual load cases previously described in Section 2.6 for Normal Condition load combinations.

components in a given direction are equal and opposite on the inner and outer surfaces of the shell. The membrane plus bending stress components at the inner and outer surfaces are then equal to the membrane stress components ± the bending stress components.

The stress results for the individual load case tables reported in Section 2.10.1 are limited to the meridional and hoop membrane stress components and meridional and hoop bending stress components. Two or more individual load cases must be combined to determine the total stresses at the standard stress reporting locations for the various load combinations. This is accomplished using the ANSYS Post 1 postprocessor which algebraicly adds the meridional and hoop membrane stress components and the meridional and hoop bending stress components at each of the standard locations. The membrane stress intensity is then found from the membrane stress components and the inner and outer surface membrane plus bending stress intensities are determined from the membrane ± bending stress components. These load combination stress results are reported for the various hypothetical accident conditions in Tables 2.7-1 through 2.7-14 provided herein.

Several other items also described in Section 2.6 should be noted. For the axisymmetric cases such as the end drop on the lid and bottom, the stress is constant around the circumference of the cask at each stress reporting location. For asymmetric analyses with significant differences in stress magnitudes on the extreme opposite sides of the cask, the stress at locations on both sides of the cask are reported in separate tables (e.g. contact side in Table 2.7-5 for the 30 foot side drop and side opposite contact in Table 2.7-6).

Table 2.7-1C provides a matrix of the individual loads and how they are combined to determine the cask body stresses for the

hypothetical accident conditions. The thermal stresses due to the hot and cold conditions are actually secondary stresses that could be evaluated using higher allowables than for primary stresses. The two end drop cases are analyzed plastically. The remaining hypothetical cases are analyzed elastically. Table 2.7-1D summarizes the stress-strain properties used for each individual load case. The combined stresses are conservatively calculated by adding the stresses due to the individual load cases together. An X in Table 2.7-1C indicates that the stress results for the individual load case are used directly. A quantitative number (e.g., F = 1.38) indicates the load factor applied to the individual stresses. 4

For the minimum internal pressure load combination, it is conservatively assumed that the TN-RAM cask cavity is at 0 psia. The net differential pressure acting on the cask body is then 14.7 psi (external pressure).

2.7.1 30 Foot Free Drop

The response of the TN-RAM is evaluated for a free drop from a height of 30 feet onto an unyielding surface at various orientations. The inertial loading applied to the TN-RAM components is determined in the dynamic analysis presented in Appendix 2.10.2.

Cask body stresses are reported for the standard drop orientations of end, side and center-of-gravity over corner.

In addition, certain other component evaluations are performed for worst case oblique drops. These include the lid bolt stresses for 85° oblique impact and the impact limiter attachments during slapdown after a 10° oblique impact. The stress results for these cases are provided in Section 2.7.1.4.

TABLE 2.7-1C
SUMMARY OF LOAD COMBINATIONS
FOR HYPOTHETICAL ACCIDENT CONDITIONS OF TRANSPORT

LOAD COMBINATIONS	APPLICABLE INDIVIDUAL LOAD IL-1	IL-2	IL-3	IL-5	IL-6	IL-11	IL-12	IL-13	IL-14	IL-15	STRESS RESULT TABLES
30 FT END DROP - 70G (BTM END)	X	X		X		X					2.7-1
	X		X		X	X					2.7-2
30 FT END DROP - 70G (LID END)	X	X		X			X				2.7-3
	X		X		X		X				2.7-4
30 FT SIDE DROP-128.5G	X	X		X				X			2.7-5 CONT. SIDE 2.7-6 SIDE OPP CONT.
	X		X		X			X			2.7-7 CONT. SIDE 2.7-8 SIDE OPP CONT.
30 FT CORNER DROP- 68.5G	X	X		X					X		2.7-9 CONT. SIDE 2.7-10 SIDE OPP CONT.
	X		X		X				X		2.7-11 CONT. SIDE 2.7-12 SIDE OPP CONT.
THERMAL ACCIDENT	X			X F = 1.38					X		2.7-13 t=0.56 HRS. 2.7-13 A t=0.83 HRS.
IMMERSION	X			X F = 2.45							2.7-14

NOTE: F = LOAD FACTOR

TABLE 2.7-1D
SUMMARY OF STRESS VS. STRAIN PROPERTIES FOR INDIVIDUAL LOAD CASES

INDIVIDUAL LOAD DESCRIPTION	MATERIAL PROPERTIES USED IN ANALYSIS, E (PSI)		REMARK
	LEAD	304 S.S.	
BOLT PRELOAD	27750	28.3×10^6	
THERMAL STRESS AT HOT ENVIRONMENT CONDITION	27750	28.3×10^6	
THERMAL STRESS (-20°F)	27750	28.3×10^6	
THERMAL STRESS (-40°F)	27750	28.3×10^6	
INTERNAL PRESSURE (30 PSIG)	27750	28.3×10^6	
EXTERNAL PRESSURE (-14.7 PSI)	27750	28.3×10^6	
GRAVITY (1G DOWN)	27750	28.3×10^6	
VIBRATION	27750	28.3×10^6	
SHOCK	27750	28.3×10^6	
TIEDOWN	27750	28.3×10^6	
30 FT BOTTOM END DROP (70G)	PLASTIC LEAD FIG. 2.10.1-1B	PLASTIC S.S. FIG. 2.10.1-1C	
1 FT BOTTOM END DROP (30G)	PLASTIC LEAD FIG. 2.10.1-1B	28.3×10^6	
30 FT LID END DROP (70G)	PLASTIC LEAD FIG. 2.10.1-1B	PLASTIC S.S. FIG. 2.10.1-1C	
30 FT SIDE DROP (128.5G)	27750	28.3×10^6	
30 FT C.G. OVER CORNER DROP (68.5G)	27750	28.3×10^6	
THERMAL ACCIDENT	27750	28.3×10^6	

The drain port and vent port are not affected by the 30 foot free drops, since they are both recessed into the outer shell (or lid) and are covered by the impact limiters.

2.7.1.1 End Drop

The dynamic impact analysis of the TN-RAM shows that the maximum expected inertia loading from the 30-foot end drop is 69.6 g's. Because of the symmetry of the cask and impact limiters, this value is applicable for both the bottom end drop and lid end drop. The following calculation is performed to evaluate the possibility of lead slump (which could result in a loss of shielding):

Axial G Load = 70 G

Lead Cylinder O.D. = 48.25 in.

Lead Cylinder I.D. = 36.50 in.

$$\text{Cross Section Area} = \frac{\pi}{4}(OD^2 - ID^2)$$
$$= 782 \text{ sq in.}$$

Lead Weight = 39,600 lb.

Deceleration Load = 70(39,600) = 2,772,000 lb.

$$\text{Deceleration End Stress} = \frac{2,772,000}{782} = 3,545 \text{ psi}$$

Since the Dynamic Flow Stress of Lead is 5,000 psi (Section 2.3)

The Factor of Safety:

$$F.S. = \frac{5,000}{3,545} = 1.41$$

The structural analysis of the cask body for this loading condition was performed using an inertial loading of 70 g. The analyses for the two 30 ft end drops were performed using the axisymmetric finite element model with refined mesh shown in Figure 2.10.1-1A. The analyses for the end drops were performed plastically. The stress strain curves used for lead and stainless steel are shown in Figures 2.10.1-1B and 2.10.1-1C respectively. The stresses due to the end drop were combined with the stresses due to the hot and cold environments. 4

As shown in Table 2.7-1C, the stresses due to the bottom end (Table 2.10.1-11) drop are combined with the hot environment stresses and MNOP stresses in Table 2.7-1 for the selected standard locations shown in Figure 2.7-1. Note that the hot environment and MNOP stresses were calculated elastically and simply added to the stresses calculated plastically for the end 3
drops. The actual stresses will therefore be lower than these calculated stresses. The maximum general primary membrane stress intensity is 20,330 psi and the maximum primary stress intensity at any location is 49,646 psi.

The stresses due to the bottom end drop combined with preload, cold environment thermal stresses and zero internal pressure (14.7 psi external pressure) are listed in Table 2.7-2. The maximum general primary membrane stress intensity is 19,972 psi and the maximum primary stress intensity at any location is 3
45,294 psi.

The stresses due to the lid end drop combined with preload, hot environment thermal stresses and MNOP (30 psi) internal pressure are listed in Table 2.7-3. The maximum general primary membrane stress intensity is 17,859 psi and the maximum primary stress intensity at any location is 42,536 psi.

The stresses due to the lid end drop combined with preload, cold environment thermal stresses and zero internal pressure are listed in Table 2.7-4. The maximum general primary membrane stress intensity is 17,328 psi and the maximum primary stress intensity at any location is 41,979 psi.

Stress intensity values for all end drops are much less than the allowables for plastic analysis of 0.7 S_u (49,000 psi) general membrane stress intensity and 0.9 S_u (63,000 psi) for primary stress intensity at any location. 3

The evaluation of the extreme total stress intensity range between the initial state, normal operating conditions and accident conditions is provided below in Section 2.7.6. A buckling evaluation of the compressive stresses in the inner containment cylinder under limiting accident conditions is provided in Appendix 2.10.4. That section shows that the buckling limits of Code Case N-284 are met.

2.7.1.2 Side Drop

The dynamic analysis of the 30-foot side drop provided a maximum expected inertial loading of 82.7 g. The ANSYS analysis (Asymmetric) of the cask body was performed using a conservatively high inertia loading of 128 g. The stresses due to this inertial loading are first combined with the stresses due to preload, the hot environment, and MNOP internal pressure. Tables 2.7-5 and 2.7-6 provide the resulting maximum stress intensities. Table 2.7-5 is for the side which contacts the target and Table 2.7-6 is for the opposite side. Locations designated by the (*) are at the junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress

intensity classification discussion in Section 2.1.2.1. The maximum calculated membrane stress intensity is 39,739 psi and the maximum membrane plus bending stress intensity is 42,804 psi. The maximum primary plus secondary stress intensity is 129,420 psi. All of these maxima occur on the contact side.

The stresses due to the 30 foot side drop are also combined with the stresses due to preload, cold environment and minimum internal pressure (0 psia or 14.7 psi external pressure) in Tables 2.7-7 and 2.7-8 for the contact side and side opposite contact, respectively. The maximum membrane stress intensity is 39,179 psi and the maximum membrane plus bending stress intensity is 42,248 psi. The maximum primary plus secondary stress intensity is 137,720 psi. Again, all of the maxima occur on the contacting side.

A few conclusions can be drawn from the combined stress tables for the side drop (Tables 2.7-5 through 8). The maximum membrane stress intensity occurs at location 20 on the contact side at the mid point of the outer shell. This is primarily an axial stress due to the bending moment developed at this section. This stress is significantly higher than that calculated previously using a higher lead elastic modulus since the EI of the lead is now negligable (compared to that of the steel shells) and the entire moment is reacted by the shells. The highest membrane plus bending plus secondary stress occurs at location 23 at the end of the outer shell where it joins the thicker end plate. This stress is also significantly higher than that calculated previously with the higher lead modulus since the lead now behaves much more like a fluid developing significant hydrostatic pressure on the end plate. 4

These values are less than the allowables for general primary membrane stress intensity of 48,000 psi, local membrane stress intensity of 72,000 psi and membrane plus bending stress intensity of 72,000 psi. The evaluation of the extreme total stress intensity range between the initial state, normal operating conditions and accident conditions is provided below in Section 2.7.6. A buckling evaluation of the compressive stresses in the inner containment cylinder under limiting accident conditions is provided in Appendix 2.10.4. That section shows that the buckling limits of Code Case N-284 are met.

2.7.1.3 Corner Drop

The response of the TN-RAM to the 30-foot corner drop was analyzed for impact on the top or lid end corner which is the more critical cask orientation (than the bottom corner) because it is the closure end. The analysis was performed using the ANSYS model as described in Appendix 2.10.1. The center-of-gravity over corner drop occurs at a drop angle of approximately 70°. That is, the longitudinal axis of the cask is at an angle of 70° from the impact surface. The dynamic analysis (Appendix 2.10.2) of the 70° drop orientation resulted in maximum inertia loadings of 61.1 G (axial) along the cask longitudinal axis and 13.9 G transverse to the longitudinal axis at the cask CG. The ANSYS analysis was conservatively performed using higher inertial loadings of 17.0 G transverse and 66.4 G axial.

The stress results for the 30 foot corner drop combined with stresses due to bolt preload, hot thermal conditions and MNOP (30 psi) internal pressure are presented in Tables 2.7-9 and 2.7-10 for the contacting side and side opposite contact respectively. Locations designated by the (*) are at the

junctions of cylinders and heads where the membrane stress is a local membrane stress and the bending stress is a secondary stress. See the stress intensity classification discussion in Section 2.1.2.1. The maximum membrane stress intensity is 39,520 psi and the maximum membrane plus bending stress intensity is 67,836 psi. The maximum primary plus secondary stress intensity is 94,253 psi. The maxima all occur on the contact side.

The stress results for the 30 foot corner drop combined with stresses due to bolt preload, the cold thermal conditions and minimum (0 psia) internal pressure (14.7 psi external pressure) are presented in Tables 2.7-11 and 2.7-12 for the contacting side and side opposite contact respectively. The maximum membrane stress intensity is 40,121 psi and the maximum membrane plus bending stress intensity is 67,992 psi. The maximum primary plus secondary stress intensity is 92,422 psi. The maxima again all occur on the contact side.

A few conclusions can also be drawn from these combined stress tables for the corner drops (Tables 2.7-9 through 12). The maximum membrane stress intensity occurs at location 17 on the contact side near the lid end of the outer shell. This is primarily an axial stress component due to the axial impact force. This stress is significantly higher than that calculated previously using a higher lead elastic modulus since the EA of the lead is now negligable (compared to that of the steel shells) and the entire impact load is reacted by the shells. The highest membrane plus bending and membrane plus bending plus secondary stresses occur at locations 3 and 4 at the lid end of the inner shell where it is attached to the thick flange. 4

These stresses are also significantly higher than those calculated previously with the higher lead modulus since the lead now behaves much more like a fluid developing significant hydrostatic pressure on the shell tending to bend it away from the flange.

These stress intensity values for both of the corner drop cases are less than the allowables for general primary membrane stress intensity of 48,000 psi and membrane plus bending stress intensity of 72,000 psi.

The evaluation of the extreme total stress intensity range between the initial state, normal operating conditions and accident conditions is provided below in Section 2.7.6. A buckling evaluation of the compressive stresses in the inner

containment cylinder under limiting accident conditions is provided in Appendix 2.10.4. That section shows that the buckling limits of Code Case N-284 are met.

Lid Bolts

The limiting hypothetical accident condition for the closure lid bolts is the 85°, near perpendicular, oblique 30-foot drop in which the lid end strikes the target first and the cask contents impact on the inner side of the lid. The 85° drop orientation is the most severe because, based on the dynamic impact analysis (Appendix 2.10.2), this drop orientation results in the highest axial inertia forces which result in the highest lid bolt tensile stresses. No credit is taken for the forces pushing on the lid due to impact limiter crushing. The results in Section 2.10.1-3 of Appendix 2.10.1 show that bolt stresses do not exceed the yield strength and are therefore acceptable.

Impact Limiter Attachments

The impact limiters must remain attached to the cask body before, during and after all hypothetical accident drop conditions. The limiting loading condition for the impact limiter attachments is the secondary impact (slapdown) associated with the 10° oblique 30-foot drop.

This loading condition applies the greatest impact force and overturning moment on the impact limiter to cask body interface. Although this loading condition is not limiting with respect to any other cask components, an evaluation of the attachments is performed to demonstrate that the affected impact limiter remains in place to insulate the cask during the subsequent hypothetical accident thermal event.

The analysis and results, summarized here, are provided in detail in Section 2.10.2.7 of Appendix 2.10.2.

Each impact limiter is secured to the cask body at eight lugs welded to the outer shell by eight threaded bolts. The bolts are made of ASME SA-564, Type 630 material which has an ultimate strength of 140,000 psi at the applicable temperature. The bolts apply tensile loadings to the limiter to react the overturning moment due to the impact force. The shear loading is applied directly to the side of the cask by the impact limiter as a bearing load. The tensile stresses in the bolts are acceptable based on the criteria of Section 2.1.2. The allowable tensile stress is equal to the S_u of 140,000 psi.

The loading applied to the bolts is determined from the magnitude and location of the impact force on the outside of the limiter. The bolts prevent the impact limiter from pivoting away from the end of the cask body by reacting the moment of the impact force about this point. The inertial loading of the impact limiter tends to decrease the moment so this effect is conservatively ignored in the bolt analysis. The tensile stress in the highest loaded bolt is calculated to be 66,506 psi.

The analysis concludes that the impact limiter attachment design is sufficiently strong to ensure that the impact

limiters remain attached to the cask body during and following all hypothetical accident conditions.

2.7.2 Puncture

The impact limiters will protect the ends of the cask body from the 40 inch drop onto a 6 inch diameter bar. The most severe damage to the body resulting from the puncture drop will occur on the sidewalls of the cylindrical outer shell of the cask between the impact limiters. This portion of the package is not the containment boundary so release of the contents cannot occur. However, analysis of the shell for possible puncture is performed to ensure lead is not exposed before the thermal accident.

The Nelms puncture relation (*) is given as:

$$t = (W/S_u)^{0.71}$$

where:

t = shell thickness
= 1.5 in. outer shell and 0.25 in. in thermal sleeve
W = package weight, lbs.
S_u = ultimate tensile strength of outer shell, 75,000 psi

The package weight that can result in puncture is:

$$W = S_u t^{1.41}$$

*Shappert, L.B., "Cask Designers Guide", ORNL-NSIC-68, Page 18

During puncture impact, the thermal sleeve would be forced into direct contact with the outer shell. Therefore, the package weight that would puncture the total 1.75 in. outer shell and sleeve thickness is:

$$W_s = (75{,}000)(1.75)^{1.41} = 165{,}100 \text{ lbs.}$$

The actual package weight is less than 80,000 lbs.; therefore, the factor of safety for puncture resistance on an energy basis is:

$$F.S. = \frac{165{,}100}{80{,}000} = 2.06$$

When the package contacts the puncture bar, the force applied to the package is:

$$F_I = \text{Impact Force} = \sigma_s A_p$$

σ_s = Dynamic flow pressure of stainless steel = 45,000 psi*

$$A_p = \text{Area of Puncture Bar} = \frac{\pi}{4}(6^2) = 28.27 \text{ in.}^2$$

$$F_I = (45{,}000)(28.27) = 1.272 \times 10^6 \text{ lbs.}$$

This force produces a cask deceleration and induces a bending moment at the midsection of the cask. If the cask is considered as a beam uniformly loaded (downward) by its inertial load and supported at the puncture bar at the center:

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* Shappert, L.B. "Cask Designers Guide", ORNL-NSIC-68.

$$G = \text{The cask deceleration} = \frac{F_I}{W} = \frac{1.272 \times 10^6}{80{,}000} = 15.9 \text{ G's}$$

This deceleration is small compared to that which will occur during impact after the 30 foot free drop. Therefore, global stresses that result from the inertial forces will be small. The bending stress at the center of the cask body will, however, be determined to demonstrate low stress magnitude.

If the cask body is considered to be uniformly loaded and supported as described above:

$$M_{center} = \frac{F_I \, l}{8} = \frac{1.272 \times 10^6 \times 129.12}{8} = 2.053 \times 10^7 \text{ in. lb.}$$

The moment of inertia of the outer shell, ignoring the lead and inner shell, is:

$$I = \pi R^3 t = \pi \times 24.875^3 \times 1.5 = 72{,}532 \text{ in.}^4$$

The section bending stress is then equal to $\frac{M \, R_o}{I}$:

$$\text{Bending Stress} = \frac{2.053 \times 10^7 \times 25.625}{72{,}532} = 7{,}253 \text{ psi}$$

Since this stress is nearly constant through the wall thickness, it should be treated as a membrane stress, P_m. The allowable stress for this accident condition is 0.7 Su or 52,500 psi. The factor of safety for the outer shell is then:

$$F.S. = \frac{52{,}500}{7{,}253} = 7.24$$

Therefore, as stated above, global stresses due to the puncture accident are small compared to those from the 30 foot drop event.

The drain port and vent port are not affected by the puncture accident, since they are recessed into the outer container shell (and lid) and the cover diameters (4.94 inches and 5.25 inches) are smaller than the puncture bar diameter. In addition, both ports are located beneath the impact limiters which provide additional protection during the puncture accident. No additional evaluation of the puncture event is necessary.

2.7.3 Thermal

2.7.3.1 Summary of Pressures and Temperatures

The thermal analysis of the thermal accident is presented in Chapter Three. Negligible pressure increase occurs in the cask cavity during the event. The structural analysis is, however, performed conservatively assuming the same outward pressure differences across the cask wall as during the reduced external pressure case, 41.2 psi.

An ANSYS transient thermal analysis of the cask for the 30 minute thermal accident is reported in Chapter Three. 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 temperatures from the thermal analysis are reported for each time-step during the transient.

FIGURE 2.7-2

TEMPERATURE INPUT FOR THERMAL ACCIDENT AT t = .56 hr.

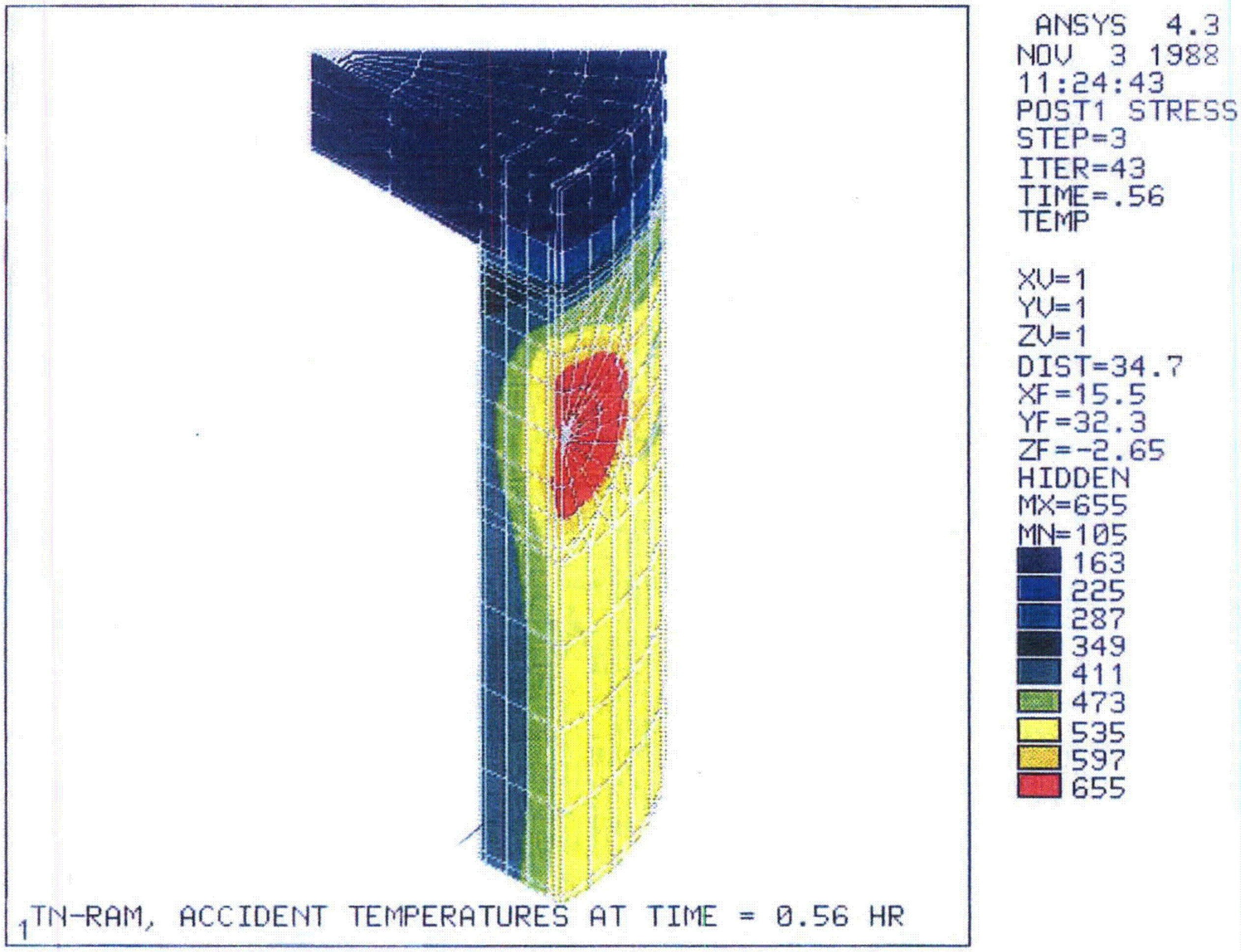
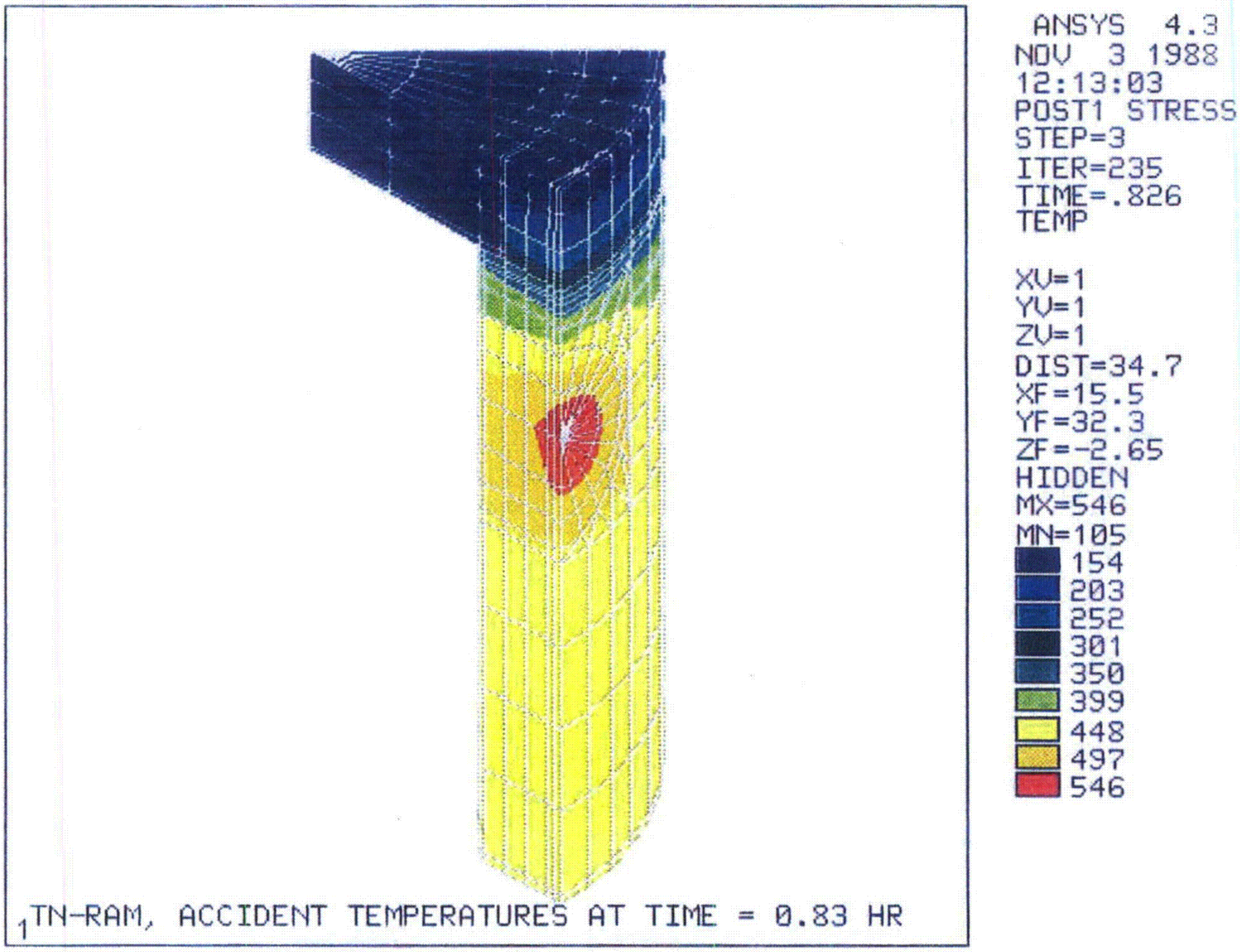


FIGURE 2.7-3

TEMPERATURE INPUT FOR THERMAL ACCIDENT AT t = .83 hr.



The temperatures throughout the package at the time where the individual temperatures peak (0.56 hrs.) and after they equalize (0.83 hrs.) are shown in Figures 2.7-2 and 2.7-3. For a given axial and radial location, the average temperature around the shell was input, since the ANSYS structural model is two dimensional.

2.7.3.2 Thermal Stresses

Stress analyses of the cask body due to the differential thermal expansion under the above temperature distributions at 0.56 hrs and 0.83 hrs are performed as individual load cases, IL-15 and IL-15A. The stress component results of these analyses using the same ANSYS structural model are presented in Tables 2.10.1-15 and 2.10.1-15A in Appendix 2.10.1. These results are tabulated for the same standard locations shown in Figure 2.7-1. The stresses are found to be higher in case IL-15A after the temperatures in the various components equalize. This indicates the stresses are primarily due to differential expansion (lead to steel) rather than temperature differences. Tables 2.10.1-15 and 2.10.1-15A are therefore secondary stresses, Q.

2.7.3.3 Combined Stresses

The stress component results from these thermal stress cases are combined with those due to lid bolt preload and internal pressure using the same procedure described above for the 30 foot drop events. Tables 2.7-13 and 2.7-13A present the combined stress intensities at the standard locations. Table 2.7-13 presents the combined stress results at 0.56 hrs, just after the heating ends, and Table 2.7-13A presents the results at 0.83 hrs, after the component temperatures equalize. 3

The maximum membrane stress intensity is 20,219 psi and the maximum membrane plus bending stress intensity is 23,836 psi. The maxima occur at 0.83 hrs., after the temperatures have equalized.

These stresses are evaluated for a metal temperature of 600°F, which is somewhat higher than the temperatures input to the model. These stress results are less than the allowables for membrane stress intensity of 39,360 psi and membrane plus bending stress intensity of 59,040 psi. The evaluation of the extreme total stress intensity range between the initial state, normal operating conditions and accident conditions is provided below in Section 2.7.6.

2.7.4 Immersion – Fissile Material

The criticality evaluation presented in Section 6.0 considers the effect of water in leakage. Thus, the requirements of 10CFR71.73 (c) (4) are met.

2.7.5 Immersion – All Packages

The combination of 21 psig external pressure and minimum internal pressure (assumed conservatively as 0 psia) produces a maximum differential pressure across the wall of the packaging of 35.7 psi. Note that the immersion pressure currently required by 10CFR71.73(c) is 21.7 psig. This difference is considered negligible due to the low stress levels reported below. The stresses in the cask body due to the inward pressure difference of 36 psi combined with bolt preload are presented in Table 2.7-14. The stresses presented are very low compared to the stress allowables of Section 2.1.2. The highest stress intensity of any category is 4,071 psi, almost negligible compared to the allowables, always in excess of 48,000 psi.

2.7.6 Summary of Damage

From the analyses presented in Section 2.7.1 through 2.7.5, it can be shown that the accident test sequence will not result in any structural damage of the TN-RAM Packaging.

In the 30 foot drop event, the top and bottom impact limiters absorb the impact energy. The flange and seal area will not be affected by the 30 foot drop.

The stresses due to the 30 foot lid and bottom end drops were calculated plastically. The stresses due to these drops are presented in Table 2.7-1 through 2.7-4. The general primary membrane stress is less than $.7S_u$ and the maximum primary stress intensity does not exceed 0.90 S_u, in accordance with Appendix F of Section III of the ASME B&PV Code.

The stresses due to the corner and side drops are presented in Tables 2.7-5 through 2.7-12. These stresses were calculated elastically using a lead modulus of elasticity of 27,750 psi. The primary membrane stresses due to these hypothetical accident conditions do not exceed 2.4 S_m, or 48,000 psi. Neither the local primary membrane stresses nor the membrane plus bending stresses exceed 3.6 S_m or 72,000 psi. 4

It is also shown in Appendix 2.10.4 that the stresses in the inner shell during the hypothetical accidents are small enough to preclude buckling in accordance with Code Case N-284.

The lid bolts do not yield during the hypothetical 30 ft drop accidents as shown in Appendix 2.10.1.3.

During the 40 inch drop onto a 6.0 inch diameter puncture bar, the packaging may deform locally under the punch. It has been shown by analysis that the package will not be punctured and that the containment boundary will remain intact.

During the 30 minute hypothetical thermal accident, the wood within the impact limiters which is exposed to the radiation environment may char but will not burn. The seals will not reach a temperature high enough to cause damage. The stresses due to the thermal accident are quite low as shown in Tables 2.7-13 and 2.7-13A. 4

The immersion test will not cause damage to the packaging. The stresses during the immersion test are quite low as shown in Table 2.7-14.

The range of primary plus secondary stresses in the containment under all conditions does not exceed 2 X S_a at 10 cycles. 4
The highest and second highest stress intensities for each of the stress reporting locations of the containment are listed in Table 2.7-15. The total stress intensity range is conservatively calculated by adding the two highest stress intensities (assuming opposite algebraic signs) and applying a stress concentration factor of K=4. The highest stress intensity range obtained using this approach is 460.4 Ksi, at location 10. This is much less than the allowable stress range of 2 X S_a at 10 cycles, which is equal to 1,386 Ksi. 4

The stress intensity range for the noncontainment stress reporting locations are listed in Table 2.7-16. The highest stress intensity range for noncontainment locations is 710.0 Ksi at location 23. This is also much less than the allowable stress range of 2 x S_a at 10 cycles.

As described above, the integrity of the TN-RAM is not compromised by the accident test sequence set forth in 10 CFR71. 4

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TABLE 2.7-1
CASK BODY STRESS UNDER 30 FOOT END DROP-BOTTOM END
(Bolt Preload, Hot Thermal, 30 psig Internal Pressure, 70G BTM End Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI) MEMBRANE	MEMBRANE + BENDING	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-779	-779	1,270	8,737	11,277
C	2	-443	-663	1,123	9,088	8,626
O	3	205	2,447	2,540	7,844	6,265
N	4	-2,912	74	3,391	5,068	11,443
T	5	-3,219	-875	5,499	5,677	5,566
A	6	-3,474	7	4,861	4,885	4,838
I	7	-4,033	-22	5,442	5,458	5,425
N	8	-4,592	-8,081	9,429	9,476	9,382
M	9	-4,873	-17,506	18,936	18,531	20,842
E	10	-23,819	17,210	42,657	49,646	45,813
N	11	-30,545	-758	31,007	49,430	44,915
T	12	-19,274	-19,364	19,821	31,824	34,845
	13	3,626	3,626	3,704	6,243	1,531
C	14	3,626	3,626	3,704	8,633	9,888
O	15	3,840	427	4,962	5,856	14,280
N	16	3,872	2,010	4,199	8,183	1,378
T	17	-1,756	3,008	5,015	4,752	8,107
N A	18	-5,859	158	6,943	5,040	8,846
O I	19	-6,317	-445	7,229	6,791	7,668
N N	20	-6,958	629	7,921	7,869	7,973
M	21	-7,564	3,370	11,296	8,958	13,637
E	22	-9,073	10,927	20,330	14,373	22,767
N	23	-24,344	11,913	37,525	46,383	44,112
T	24	-2,888	-4,737	6,451	38,026	37,899
	25	-7,990	-8,016	9,731	41,469	43,041

TABLE 2.7-2
CASK BODY STRESSES UNDER 30 FOOT END DROP - BOTTOM DROP
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External Pressure, 70G BTM End Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-1,047	-1,047	1,165	7,946	10,275
C	2	-658	-913	1,032	8,530	7,902
O	3	205	2,246	2,250	6,770	5,499
N	4	-2,982	-108	* 3,038	* 4,429	* 10,396
T	5	-3,289	-9	3,351	3,370	3,343
A	6	-3,542	-59	3,594	3,595	3,592
I	7	-4,101	-63	4,150	4,145	4,155
N	8	-4,660	-8,133	8,155	8,179	8,131
M	9	-4,941	-17,452	17,457	17,029	19,389
E	10	-23,912	17,757	* 41,940	* 45,294	* 42,445
N	11	-30,639	-756	* 30,344	* 43,297	* 40,344
T	12	-19,377	-19,468	19,130	31,488	33,155
	13	3,200	3,200	3,371	6,171	972
C	14	3,200	3,200	* 3,371	* 4,987	* 5,577
O	15	3,524	139	* 3,760	* 3,398	* 10,773
N	16	3,559	1,718	* 3,777	* 7,428	* 945
T	17	-1,986	1,677	* 3,699	* 3,514	* 6,839
N A	18	-6,286	-842	6,411	4,586	8,237
O I	19	-6,746	-1,247	6,863	6,419	7,307
N N	20	-7,387	-171	7,559	7,517	7,600
M	21	-7,992	2,445	10,644	8,370	12,920
E	22	-9,505	10,091	19,972	13,940	22,407
N	23	-24,809	12,405	* 37,214	* 45,199	* 43,258
T	24	-3,156	-5,005	* 6,345	* 37,316	* 37,190
	25	-8,258	-8,284	9,625	40,740	42,101

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-3
CASK BODY STRESSES UNDER 30 FOOT END DROP - LID END
(Bolt Preload, Hot Thermal, 30 psig Internal Pressure
70G Lid End Drop)

LOCATION			MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI) MEMBRANE	MEMBRANE + BENDING	
			MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
		1	-11,404	-11,406	13,104	38,218	39,831
	C	2	-8,551	-7,600	10,190	42,536	40,558
	O	3	1,388	13,127	13,220	24,630	21,881
	N	4	-5,779	5,278	11,337	7,860	15,856
	T	5	-5,546	-8,484	9,770	9,692	10,093
	A	6	-5,304	-7,329	8,681	8,789	8,573
	I	7	-4,743	-21	6,152	6,169	6,135
	N	8	-4,184	-4	5,576	5,596	5,556
	M	9	-3,856	-1,192	5,450	5,159	5,741
	E	10	-13,294	14,048	28,970	40,618	37,840
	N	11	-6,050	16	6,922	30,707	23,628
	T	12	-5,089	-5,126	5,921	5,017	8,062
		13	15,874	16,013	16,405	31,964	27,421
	C	14	21,285	14,968	21,363	37,957	42,041
	O	15	11,325	9,475	12,447	28,794	38,108
	N	16	9,868	29,166	29,434	34,436	33,528
	T	17	-13,439	8,722	22,412	26,378	16,129
N	A	18	-10,188	7,354	17,859	16,928	18,790
O	I	19	-7,390	6,791	14,516	14,806	14,225
N	N	20	-6,749	636	7,719	7,674	7,763
	M	21	-6,110	-184	7,243	6,839	7,650
	E	22	-5,580	-23	6,506	7,091	5,996
	N	23	-1,239	1,773	4,279	17,223	13,470
	T	24	-300	-300	739	8,790	8,790
		25	-300	-300	739	13,129	14,608

TABLE 2.7-4
CASK BODY STRESSES UNDER 30 FOOT END DROP - LID END
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External Pressure 70G Lid End Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE	MEMBRANE + BENDING	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-11,672	-11,674	12,999	37,426	38,829
C	2	-8,767	-7,850	10,099	41,979	39,835
O	3	1,388	12,925	12,929	23,557	21,115
N	4	-5,849	5,096	10,984	7,222	14,810
T	5	-5,617	-7,618	7,622	7,385	7,870
A	6	-5,371	-7,395	7,413	7,499	7,327
I	7	-4,811	-62	4,860	4,856	4,865
N	8	-4,252	-56	4,302	4,299	4,305
M	9	-3,923	-1,138	3,971	3,657	4,288
E	10	-13,388	14,595	28,253	36,266	34,472
N	11	-6,144	18	6,258	24,573	19,057
T	12	-5,192	-5,230	5,230	4,681	6,372
	13	15,448	15,587	16,073	31,891	26,863
C	14	20,859	14,541	21,030	34,311	37,730
O	15	11,009	9,188	11,245	26,336	34,601
N	16	9,555	28,875	29,013	33,682	33,095
T	17	-13,669	7,391	21,096	25,141	14,861
N A	18	-10,615	6,354	17,328	16,473	18,182
O I	19	-7,819	5,988	14,150	14,435	13,865
N N	20	-7,177	-164	7,357	7,323	7,390
M	21	-6,538	-1,110	6,591	6,250	6,934
E	22	-6,012	-859	6,147	6,658	5,637
N	23	-1,704	2,265	3,969	16,038	12,616
T	24	-568	-568	634	8,080	8,080
	25	-568	-568	634	12,400	13,667

TABLE 2.7-5
CASK BODY STRESS UNDER 30 FOOT SIDE DROP - CONTACT SIDE
(Bolt Preload, Hot Thermal, 30 psig Internal Pressure, 128.5G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-20,145	-2,565	20,145	22,412	19,568
C	2	-23,089	-22,395	23,089	24,412	22,640
O	3	-3,363	-20,693	20,693	23,593	22,283
N	4	304	-16,218	* 16,522	* 36,840	* 30,136
T	5	10,854	7,934	10,854	10,411	11,739
A	6	16,813	6,478	16,813	15,807	18,260
I	7	18,838	5,262	18,838	17,600	20,517
N	8	8,934	1,940	8,934	8,503	9,806
M	9	1,371	-2,148	3,519	2,606	4,432
E	10	-2,457	-7,500	* 7,500	* 21,073	* 18,417
N	11	-6,158	-8,549	* 8,549	* 18,118	* 10,035
T	12	-2,794	-922	2,794	5,688	3,015
	13	920	3,301	3,301	2,396	4,395
C	14	5,386	19,599	* 19,599	* 66,745	* 75,061
O	15	5,929	19,766	* 19,766	* 69,251	* 81,109
N	16	1,919	-14,892	* 16,811	* 57,812	* 61,650
T	17	6,407	-22,666	* 29,073	* 68,656	* 51,436
N A	18	18,842	13,691	18,842	10,858	27,321
O I	19	28,903	12,460	28,903	27,282	30,524
N N	20	39,739	13,023	39,739	36,673	42,804
M	21	31,555	14,403	31,555	29,767	33,343
E	22	16,772	22,179	22,179	19,156	31,215
N	23	-516	-10,438	* 10,438	* 129,420	* 115,700
T	24	-17,188	-17,342	* 17,342	* 72,317	* 37,940
	25	-14,714	-1,938	14,714	29,525	16,576

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

3

TABLE 2.7-6
CASK BODY STRESS UNDER 30 FOOT SIDE DROP - SIDE OPPOSITE CONTACT
(Bolt Preload, Hot Thermal, 30 psig Internal Pressure)
128.5G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-8,779	1,971	10,751	11,440	12,573
C	2	-7,767	9,314	17,081	19,268	14,893
O	3	1,478	1,454	1,478	4,526	4,573
N	4	-1,063	2,287	* 3,350	* 11,423	* 13,507
T	5	-4,836	-2,097	4,836	5,095	4,535
A	6	-7,993	-2,207	7,993	8,419	7,525
I	7	-10,665	-1,987	10,665	11,158	10,855
N	8	-5,249	902	6,151	5,250	7,422
M	9	-214	4,561	4,775	4,573	5,484
E	10	6,663	8,275	* 8,275	* 61,894	* 48,526
N	11	1,711	6,792	* 6,792	* 58,055	* 54,603
T	12	-1,420	2,964	4,384	3,851	6,633
	13	-731	-1,947	1,947	2,185	1,680
C	14	-5,197	-14,866	* 14,866	* 62,974	* 73,338
O	15	-5,547	-14,966	* 14,966	* 66,657	* 77,750
N	16	-3,577	10,571	* 14,148	* 29,617	* 37,714
T	17	-8,463	-728	* 8,463	* 19,249	* 2,322
N A	18	-18,639	-9,590	18,639	14,699	22,578
O I	19	-25,512	-8,332	25,512	25,007	26,017
N N	20	-33,562	-8,588	33,562	32,681	34,444
M	21	-30,418	-9,722	30,418	28,980	31,855
E	22	-23,191	-12,637	23,191	21,158	25,223
N	23	-3,929	16,896	* 20,825	* 58,288	* 48,760
T	24	-4,421	16,692	* 21,113	* 31,250	* 27,362
	25	-6,896	2,769	9,665	11,743	17,595

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-7
CASK BODY STRESSES UNDER 30 FOOT SIDE DROP - CONTACT SIDE
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External Pressure, 128.5 G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-20,550	-2,971	20,550	20,397	20,718
C	2	-23,450	-22,787	23,450	24,817	22,099
O	3	-4,327	-19,283	19,283	23,438	20,433
N	4	283	-14,810	* 15,093	* 34,120	* 28,305
T	5	10,847	9,112	10,847	10,405	11,701
A	6	16,805	7,607	16,805	15,747	18,275
I	7	18,830	6,416	18,830	17,556	20,516
N	8	8,926	3,093	8,926	8,460	9,804
M	9	1,362	-1,013	2,375	1,467	3,283
E	10	-2,460	-7,157	* 7,157	* 21,739	* 18,536
N	11	-6,059	-8,175	* 8,175	* 18,950	* 10,623
T	12	-2,726	-855	2,726	4,663	2,775
	13	586	2,968	2,968	2,435	3,941
C	14	5,053	19,266	* 19,266	* 64,133	* 71,141
O	15	5,657	19,447	* 19,447	* 65,965	* 77,279
N	16	1,621	-15,268	* 16,889	* 53,969	* 57,211
T	17	5,806	-22,903	* 28,709	* 65,442	* 47,946
N A	18	18,285	12,080	18,285	10,133	26,423
O I	19	28,343	10,874	28,343	26,676	29,996
N N	20	39,179	11,435	39,179	36,096	42,248
M	21	30,995	12,813	30,995	29,192	32,784
E	22	16,212	20,618	20,618	17,533	30,808
N	23	-1,169	-10,854	* 10,854	* 137,720	* 122,690
T	24	-17,503	-17,657	* 17,657	* 75,464	* 40,443
	25	-15,028	-2,253	15,028	26,378	16,454

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-8
CASK BODY STRESSES UNDER 30 FOOT SIDE DROP - SIDE OPPOSITE CONTACT
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External Pressure, 128.5 G Side Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-9,185	1,566	10,751	9,425	12,565
C	2	-8,128	8,921	17,050	20,685	13,414
O	3	513	2,864	2,864	5,314	414
N	4	-1,084	3,694	* 4,778	* 9,520	* 11,676
T	5	-4,843	-919	4,843	5,101	4,573
A	6	-8,001	-1,077	8,001	8,480	8,384
I	7	-10,672	-833	10,672	11,202	12,017
N	8	-5,257	2,055	7,313	6,042	8,583
M	9	-222	5,696	5,918	5,674	6,633
E	10	6,660	8,618	* 8,618	* 61,228	* 47,896
N	11	1,810	7,165	* 7,165	* 57,223	* 53,603
T	12	-1,352	3,032	4,384	3,285	5,604
	13	-1,066	-2,281	2,281	2,427	2,134
C	14	-5,530	-15,199	* 15,199	* 66,198	* 77,258
O	15	-5,819	-15,285	* 15,285	* 69,943	* 81,581
N	16	-3,875	10,195	* 14,070	* 33,460	* 41,210
T	17	-9,064	-966	* 9,064	* 23,925	* 5,812
N A	18	-19,195	-11,200	19,195	14,928	23,476
O I	19	-26,072	-9,918	26,072	25,613	26,545
N N	20	-34,122	-10,177	34,122	33,258	35,000
M	21	-30,978	-11,313	30,978	29,556	32,414
E	22	-23,751	-14,198	23,751	21,888	25,630
N	23	-4,582	16,480	* 21,062	* 65,299	* 55,744
T	24	-4,736	16,377	* 21,113	* 34,136	* 26,979
	25	-7,211	2,454	9,665	8,596	17,571

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-9
CASK BODY STRESSES UNDER 30 FOOT CORNER DROP - CONTACT SIDE
(Bolt Preload, Hot Thermal, 30 psig Internal Pressure
68.5G Corner Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI) MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-7,106	-1,483	7,106	33,274	38,733
C	2	-9,338	-13,759	13,759	34,200	31,496
O	3	1,494	16,147	16,147	67,836	66,014
N	4	-24,212	4,753	* 28,965	* 45,913	* 94,253
T	5	-23,553	-1,371	23,553	29,221	19,588
A	6	-22,871	-11,153	22,871	20,453	25,205
I	7	-19,554	-411	19,554	24,776	23,391
N	8	-14,482	10,642	25,124	28,125	22,124
M	9	-10,920	-2,102	10,920	8,914	16,000
E	10	-10,625	2,603	* 13,228	* 12,722	* 13,735
N	11	-2,148	5,155	* 7,303	* 6,323	* 8,283
T	12	-2,878	627	3,505	31,850	32,136
	13	-776	2,735	3,511	18,093	18,323
C	14	308	15,263	* 15,263	* 18,525	* 22,968
O	15	348	15,280	* 15,280	* 15,539	* 15,891
N	16	-6,512	-14,875	* 14,875	* 24,194	* 28,962
T	17	-39,520	-347	* 39,520	* 59,092	* 24,014
N A	18	-32,699	6,485	39,184	39,472	39,202
O I	19	-29,490	9,312	38,802	44,242	33,362
N N	20	-22,045	2,519	24,564	30,922	26,434
M	21	-14,810	-4,430	14,810	14,817	19,173
E	22	-6,290	-718	6,290	9,104	8,073
N	23	-1,269	1,593	* 2,861	* 25,065	* 22,524
T	24	-546	1,825	* 2,371	* 11,778	* 8,337
	25	40	847	847	10,480	8,896

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-10
CASK BODY STRESSES UNDER 30 FOOT CORNER DROP - SIDE OPPOSITE CONTACT
(Bolt Preload, Hot Thermal, 30 psig Internal Pressure, 68.5G Corner Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-4,079	974	5,053	30,314	20,208
C	2	-2,941	2,575	5,515	15,201	8,932
O	3	3,129	5,999	5,999	9,602	6,930
N	4	7,162	12,150	* 12,150	* 22,615	* 30,243
T	5	2,902	-3,302	6,204	1,012	13,222
A	6	-1,784	-11,933	11,933	5,380	18,629
I	7	-9,400	-1,643	9,400	13,511	13,054
N	8	-11,893	9,233	21,126	24,099	18,154
M	9	-10,970	-3,971	10,970	7,037	16,120
E	10	-12,405	322	* 12,727	* 22,600	* 5,275
N	11	-3,093	3,116	* 6,209	* 14,084	* 6,908
T	12	-3,060	47	3,106	31,558	32,823
	13	-1,141	1,600	2,742	12,040	10,144
C	14	-2,055	7,813	* 9,869	* 51,831	* 55,911
O	15	-2,435	7,704	* 10,139	* 42,754	* 47,625
N	16	-6,889	1,332	* 8,221	* 32,081	* 18,304
T	17	1,049	701	* 1,049	* 1,846	* 2,541
N A	18	-336	3,022	3,358	9,345	5,278
O I	19	-3,410	6,597	10,007	15,912	5,198
N N	20	-8,220	-150	8,220	14,611	12,349
M	21	-9,506	-7,019	9,506	6,904	15,826
E	22	-4,187	-3,223	4,187	4,518	8,530
N	23	-1,361	256	* 1,617	* 29,110	* 26,244
T	24	-980	365	* 1,345	* 11,372	* 9,302
	25	-1,763	506	2,270	10,042	10,237

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-11
CASK BODY STRESSES UNDER 30 FOOT CORNER DROP - CONTACT SIDE
(Bolt Preload, -20°F Cold Thermal, 14.7 psi External Pressure, 68.5 G Corner Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-7,511	-1,888	7,511	35,297	41,582
C	2	-9,699	-14,151	14,151	35,479	32,975
O	3	529	17,557	17,557	67,992	63,270
N	4	-24,233	6,161	* 30,394	* 44,010	* 92,422
T	5	-23,561	-194	23,561	30,380	19,627
A	6	-22,879	-10,024	22,879	20,513	25,190
I	7	-19,562	743	20,305	25,938	23,393
N	8	-14,490	11,796	26,286	29,286	23,286
M	9	-10,929	-967	10,929	10,052	16,010
E	10	-10,628	2,946	* 13,574	* 13,533	* 13,617
N	11	-2,049	5,528	* 7,578	* 7,460	* 7,695
T	12	-2,811	695	3,505	32,984	33,055
	13	-1,111	2,402	3,513	17,851	18,741
C	14	-24	14,931	* 14,955	* 19,138	* 25,579
O	15	76	14,961	* 14,961	* 16,287	* 18,335
N	16	-6,810	-15,251	* 15,251	* 27,170	* 33,401
T	17	-40,121	-585	* 40,121	* 63,769	* 21,527
N A	18	-33,256	4,874	38,130	38,177	40,100
O I	19	-30,050	7,726	37,776	43,236	32,471
N N	20	-22,604	930	23,534	29,893	26,991
M	21	-15,370	-6,020	15,370	13,785	19,732
E	22	-6,850	-2,278	6,850	8,210	8,480
N	23	-1,921	1,177	* 3,098	* 33,369	* 29,507
T	24	-860	1,511	* 2,371	* 14,664	* 10,840
	25	-274	533	807	13,651	12,711

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-12
CASK BODY STRESSES UNDER 30 FOOT CORNER DROP - SIDE OPPOSITE CONTACT
(Bolt Preload, -20°F Cold Thermal, 14.7 psig External Pressure
68.5G Corner Drop)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI) MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-4,484	569	5,053	30,322	20,216
C	2	-3,302	2,182	5,484	16,480	9,473
O	3	2,164	7,409	7,409	10,387	11,524
N	4	7,141	13,558	* 13,558	* 25,336	* 32,075
T	5	2,895	-2,125	5,020	1,972	12,011
A	6	-1,792	-10,803	10,803	4,232	17,488
I	7	-9,408	-488	9,408	14,673	13,055
N	8	-11,901	10,387	22,288	25,259	19,315
M	9	-10,978	-2,836	10,978	8,176	16,131
E	10	-12,408	665	* 13,073	* 23,266	* 5,156
N	11	-2,994	3,489	* 6,483	* 15,221	* 7,907
T	12	-2,992	114	3,106	32,692	33,743
	13	-1,476	1,267	2,743	11,797	10,561
C	14	-2,388	7,480	* 9,868	* 55,055	* 59,831
O	15	-2,707	7,385	* 10,092	* 46,040	* 51,455
N	16	-7,186	957	* 8,143	* 28,238	* 13,865
T	17	448	464	* 464	* 5,060	* 5,589
N A	18	-893	1,411	2,304	7,819	6,176
O I	19	-3,970	5,011	8,981	14,906	5,726
N N	20	-8,780	-1,739	8,780	13,582	12,906
M	21	-10,066	-8,609	10,066	5,872	17,414
E	22	-4,748	-4,783	4,783	3,624	10,042
N	23	-2,014	-160	* 2,014	* 37,413	* 33,227
T	24	-1,295	50	* 1,345	* 14,519	* 11,805
	25	-2,078	192	2,270	13,213	14,028

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-13
CASK BODY STRESSES UNDER THERMAL ACCIDENT (TIME = 0.56 HRS)
(Bolt Preload, 41.2 psig Internal Pressure, Thermal Accident)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	4,051	4,051	4,051	11,103	3,000
C	2	4,481	4,180	4,481	18,422	9,460
O	3	-78	-228	228	4,998	4,584
N	4	181	-10,686	* 10,867	* 13,573	* 17,721
T	5	252	893	893	1,041	868
A	6	250	887	887	937	879
I	7	250	884	884	934	875
N	8	250	883	883	928	878
M	9	236	1,321	1,321	4,016	4,414
E	10	560	-12,866	* 13,426	* 17,189	* 14,803
N	11	1,227	2,782	* 2,782	* 8,659	* 6,164
T	12	1,098	1,098	1,098	4,593	2,355
	13	616	616	616	2,917	1,643
C	14	616	616	* 616	* 9,353	* 10,626
O	15	545	601	* 601	* 9,448	* 10,538
N	16	136	2,877	* 2,877	* 20,792	* 20,521
T	17	604	2,619	* 2,619	* 8,574	* 7,594
N A	18	427	480	480	8,984	9,837
O I	19	543	772	772	2,216	1,401
N N	20	523	575	575	577	574
M	21	526	373	526	1,005	229
E	22	418	-900	1,319	10,257	11,094
N	23	731	199	* 731	* 20,750	* 19,287
T	24	-30	-30	* 30	* 6,767	* 6,826
	25	-30	-30	30	1,924	1,983

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-13A
CASK BODY STRESSES UNDER THERMAL ACCIDENT (TIME = 0.83 HRS)
(Bolt Preload, 41.2 psig Internal Pressure, Thermal Accident)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI)		
				MEMBRANE Pm or (Pl)*	MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	4,280	4,280	4,280	11,255	2,696
C	2	4,727	4,414	4,727	18,550	9,096
O	3	-970	-3,517	3,517	7,715	2,403
N	4	238	-17,690	* 17,928	* 18,173	* 19,172
T	5	244	1,182	1,182	1,509	1,418
A	6	251	805	805	866	785
I	7	250	884	884	934	875
N	8	249	875	875	908	884
M	9	234	1,273	1,273	3,775	4,135
E	10	660	-19,559	* 20,219	* 23,836	* 21,652
N	11	1,846	4,699	* 4,699	* 10,602	* 6,160
T	12	1,617	1,617	1,617	7,302	4,026
	13	578	578	578	2,876	1,679
C	14	578	578	* 578	* 8,807	* 10,004
O	15	504	562	* 562	* 8,920	* 9,928
N	16	99	3,025	* 3,025	* 20,848	* 20,651
T	17	722	-70	* 793	* 5,197	* 6,642
N A	18	733	1,313	1,313	4,029	5,494
O I	19	796	996	996	1,984	1,032
N N	20	782	949	949	951	948
M	21	783	764	783	1,078	676
E	22	733	713	733	4,859	6,325
N	23	1,029	425	* 1,029	* 23,806	* 21,749
T	24	166	166	* 166	* 7,967	* 7,635
	25	166	166	166	1,575	1,243

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

TABLE 2.7-14
CASK BODY STRESSES UNDER IMMERSION
(Bolt Preload, 36 psig External Pressure)

LOCATION		MEMBRANE STRESS COMPONENTS (PSI)		STRESS INTENSITIES (PSI): MEMBRANE Pm or (Pl)*	STRESS INTENSITIES (PSI): MEMBRANE + BENDING Pm + Pb or (Pl + Pb + Q)*	
		MERIDIONAL	HOOP	AVERAGE	INNER SURFACE	OUTER SURFACE
	1	-126	-126	126	917	1,204
C	2	-125	-125	125	1,111	961
O	3	-7	52	59	372	358
N	4	-146	-56	* 146	* 356	* 648
T	5	-150	-58	150	147	152
A	6	-150	-59	150	149	150
I	7	-150	-59	150	150	150
N	8	-150	-59	150	150	150
M	9	-150	-69	150	172	129
E	10	-264	124	* 388	* 3,101	* 2,574
N	11	-104	172	* 276	* 3,117	* 2,909
T	12	-117	-117	117	419	652
	13	27	27	27	262	208
C	14	27	27	* 27	* 503	* 556
O	15	23	26	* 26	* 491	* 537
N	16	5	-92	* 97	* 916	* 906
T	17	-253	-51	* 253	* 1,057	* 586
N A	18	-245	-562	562	583	578
O I	19	-246	-546	546	592	536
N N	20	-245	-545	545	588	537
M	21	-245	-544	544	587	536
E	22	-246	-570	570	614	561
N	23	-290	-190	* 290	* 4,071	* 3,454
T	24	-147	-147	* 147	* 1,571	* 1,436
	25	-147	-147	147	1,946	2,276

*Per Table NB-3217-1 of the ASME Code, the Membrane Stress at the Flat Plate Junction to the Shell is classified as Local Membrane Stress, Pl, and the Bending Stress is classified as a Secondary Stress, Q. Therefore the Membrane Stresses at locations noted (*) are considered to be Local Membrane Stresses and the Bending Stresses are Secondary Stresses. The Surface Stress Intensities are Pl + Pb + Q at these locations.

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TABLE 2.7-15

HIGHEST STRESS INTENSITIES AND STRESS RANGE FOR

CONTAINMENT STRESS REPORTING LOCATIONS

LOCATION	HIGHEST STRESS (KSI) INNER SURFACE	HIGHEST STRESS (KSI) OUTER SURFACE	2ND HIGHEST STRESS INNER SURFACE	2ND HIGHEST STRESS OUTER SURFACE	MAX. POSSIBLE TOTAL STRESS RANGE (K=4) INNER SURFACE	MAX. POSSIBLE TOTAL STRESS RANGE (K=4) OUTER SURFACE
1	38.2 (2.7-4)	41.6 (2.7-11)	11.3 (2.7-13A)	6.1 (2.6-11)	197.9	190.9
2	42.5 (2.7-3)	40.6 (2.7-3)	18.6 (2.7-13A)	9.5 (2.7-13)	244.4	200.4
3	68.0 (2.7-11)	66.0 (2.7-9)	7.7 (2.7-13A)	7.5 (2.6-9)	302.8	294.0
4	45.9 (2.7-9)	94.3 (2.7-9)	18.2 (2.7-13A)	19.2 (2.7-13A)	256.4	454.0
5	30.4 (2.7-11)	19.6 (2.7-11)	3.8 (2.6-7)	3.8 (2.6-7)	136.8	93.6
6	20.5 (2.7-11)	25.2 (2.7-9)	4.4 (2.6-9)	5.1 (2.6-9)	99.6	121.2
7	25.9 (2.7-11)	23.4 (2.7-11)	5.1 (2.6-9)	5.7 (2.6-11)	124.0	116.4
8	29.3 (2.7-11)	23.3 (2.7-11)	3.3 (2.6-7)	3.5 (2.6-7)	130.4	107.2
9	18.5 (2.7-1)	20.8 (2.7-1)	4.0 (2.7-13)	4.4 (2.7-13)	90.0	100.8
10	61.9 (2.7-6)	48.5 (2.7-6)	53.2 (2.6-7)	42.8 (2.6-7)	460.4	365.2
11	58.1 (2.7-6)	54.6 (2.7-6)	41.3 (2.6-7)	31.1 (2.6-7)	397.6	342.8
12	33.0 (2.7-11)	34.8 (2.7-11)	7.3 (2.7-13A)	11.8 (2.6-7)	161.2	186.4

4

4

(See page 2-114 for loading descriptions.)

LOADING DESCRIPTIONS FOR TABLES 2.7-15 AND 2.7-16

LOADING	CONDITION
2.6-7	1 foot end drop, hot thermal
2.6-8	1 foot end drop, cold thermal
2.6-9	1 foot side drop, contact side, hot thermal
2.6-11	1 foot side drop, contact side, cold thermal
2.7-1	Bottom end drop, hot thermal
2.7-3	Lid end drop, hot thermal
2.7-4	Lid end drop, cold thermal
2.7-5	Side drop, contact side, hot thermal
2.7-6	Side drop, side opposite contact, hot thermal
2.7-7	Side drop, contact side, cold thermal
2.7-8	Side drop, side opposite contact, cold thermal
2.7-9	Corner drop, contact side, hot thermal
2.7-11	Corner drop, contact side, cold thermal
2.7-13	Thermal accident (0.56 hours)
2.7-13A	Thermal accident (0.83 hours)

3

TABLE 2.7-16

HIGHEST STRESS INTENSITIES AND STRESS RANGE FOR

NONCONTAINMENT STRESS REPORTING LOCATIONS

LOCATION	HIGHEST STRESS (KSI) INNER SURFACE	HIGHEST STRESS (KSI) OUTER SURFACE	2ND HIGHEST STRESS INNER SURFACE	2ND HIGHEST STRESS OUTER SURFACE	MAX. POSSIBLE TOTAL STRESS RANGE (K=4) INNER SURFACE	MAX. POSSIBLE TOTAL STRESS RANGE (K=4) OUTER SURFACE
13	32.0 (2.7-3)	27.4 (2.7-6)	2.9 (2.7-13)	1.7 (2.7-13A)	139.6	116.4
14	66.7 (2.7-5)	77.3 (2.7-8)	20.6 (2.6-9)	23.9 (2.6-9)	349.2	404.8
15	69.9 (2.7-8)	81.6 (2.7-8)	21.8 (2.6-9)	25.5 (2.6-9)	366.8	428.4
16	57.8 (2.7-5)	61.7 (2.7-5)	20.8 (2.7-13A)	20.7 (2.7-13)	314.4	329.6
17	68.7 (2.7-5)	51.4 (2.7-5)	21.3 (2.6-9)	16.8 (2.6-9)	360.0	272.8
18	39.5 (2.7-9)	40.1 (2.7-11)	9.0 (2.7-13)	9.8 (2.7-13)	194.0	199.6
19	44.2 (2.7-9)	33.4 (2.7-9)	8.0 (2.6-9)	8.8 (2.6-9)	208.8	168.8
20	36.7 (2.7-5)	42.8 (2.7-5)	10.6 (2.6-9)	12.3 (2.6-9)	189.2	220.4
21	29.8 (2.7-5)	33.3 (2.7-5)	8.7 (2.6-9)	9.7 (2.6-9)	154.0	172.0
22	21.9 (2.7-8)	31.2 (2.7-5)	10.3 (2.7-13)	11.1 (2.7-13)	128.8	169.2
23	137.7 (2.7-7)	122.7 (2.7-7)	39.8 (2.6-11)	35.4 (2.6-11)	710.0	632.4
24	75.5 (2.7-7)	40.4 (2.7-7)	21.6 (2.6-11)	18.6 (2.6-7)	388.4	236.0
25	41.5 (2.7-1)	43.0 (2.7-1)	34.7 (2.6-7)	38.7 (2.6-7)	304.8	326.8

(See page 2-114 for loading descriptions.)

2.8 SPECIAL FORM

This section does not apply to the TN-RAM Packaging.

2.9 FUEL RODS

This section does not apply to the TN-RAM Packaging.

APPENDIX 2.10.1
STRUCTURAL ANALYSIS OF CASK BODY

This appendix presents the structural analyses of the TN-RAM cask body including the cylindrical shell assembly and bottom assembly, the lid, the lid bolts, the penetration covers, and trunnions. The specific methods, models and assumptions used to analyze the cask body for the various individual loading conditions specified in 10CFR71.71 and 10CFR71.73 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 are performed and the results evaluated against the ASME Code and Regulatory Guide 7.6 design criteria described in Section 2.1.2.

The TN-RAM cask body structural analyses generally use static or quasistatic linear elastic methods so that combinations of loads can be examined by superimposing the results from individual loads. The stresses and deformations due to the applied loads are generally determined using the ANSYS* computer program. Exceptions include the analyses for the unusual conditions of end impact where unbonded lead may slide relative to the inner and outer shells and those for the local effects at the trunnions and the lid bolts.

The analyses contained in this appendix were done using the original one-piece lid option. The optional two-piece lid/shield disk design is analyzed in Appendix 2.10.8 and is shown to be stronger than the original lid. Therefore the stresses calculated in this Appendix are bounding.

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* ANSYS, Engineering Analysis Systems User's Manual, Revision 4.3, Volumes I and II.

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

- ANSYS Analysis – Axisymmetric and Asymmetric Loads — Section 2.10.1.1
- Bijlaard Trunnion Analysis — Section 2.10.1.2
- Lid Bolt Analysis — Section 2.10.1.3

The Bijlaard trunnion analysis is performed to determine the local stresses in the outer shell at locations that correspond to stress reporting locations selected for the ANSYS analyses. This permits the localized trunnion induced stresses to be easily combined with stresses obtained from appropriate ANSYS load cases. The method of combining stress results from individual load cases to evaluate the required load combinations is discussed in Section 2.6 of Chapter Two for normal conditions of transport and Section 2.7 for hypothetical accident conditions.

The lid bolt analysis consists of two hand calculations which determine the maximum stresses in the lid bolts under the worst accident loading condition. The results from the lid bolt analysis are not combined with results from any other analysis. The first analysis is discussed in Section 2.10.1.3 and is based on the original lid design. The second analysis of the optional lid design follows the methodology of NUREG/CR-6007 and is presented in Appendix 2.10.8.

The evaluation of the cask body under the 40 inch puncture event is described in Section 2.7.2.

2.10.1.1 ANSYS FINITE ELEMENT ANALYSIS

Model Description

The cask body consists of the inner and outer cylindrical shells, the lead shielding between the shells, the lid and the lid bolts. The elements used to model the inner and outer shells, the lid plates, and the end closure plates are axisymmetric conical shell elements. The lead shielding between the shells and the reinforced end closure is modeled using axisymmetric solid elements. The loading applied to these two types of elements is axisymmetric for some cases and asymmetric for other cases. The model geometry is based on Drawings 990-701 and 990-702 provided in Section 1.3. The contact surfaces at the closure flange and between the lead shielding and shells are modeled using separate nodes in the interfacing components. These nodes are coupled or left uncoupled for specific constraint conditions as discussed below. 3

The thickness of the wall of the inner containment cylinder has been increased to .75 in., and the thickness of the inner end ring of the flange that is joined to the lid end of the inner containment cylinder has been increased to 1.50 in. (from the Rev. 0 SAR values). In addition a .38 in radius is provided at the junction of the ring and flange. These design changes have necessitated a complete reanalysis of the TN-RAM cask body. 3

Two different models were used to perform the various analyses. The bulk of the analyses were performed using the model shown in Figure 2.10.1-1. This model uses ANSYS STIF 61 shell elements and STIF 25 solid elements which can be used to perform analyses involving axisymmetric or asymmetric loadings for linear elastic material behavior. The mechanical properties for the materials in this model are the linear values described in Section 2.3.

A second model, shown in Figure 2.10.1-1A, was developed to perform elastic-plastic analyses for the unusual conditions of end impact (1 ft and 30 ft end drops) where unbonded lead may slide axially relative to the stainless steel shells and apply significant radial loadings on the shells. This model has approximately four times as many lead elements as the first model to ensure that the lead behavior is properly represented for these unusual cases. 3

The trunnion to lead interface region was carefully modeled so that the proper axial steel to lead bearing area was achieved. The bearing area at each trunnion plane in the axisymmetric model is a ledge with the total area equal to that of the number of trunnions at that plane. The ledge area at the front trunnion plane equals the bearing area of four trunnions, and the ledge area at the rear trunnion plane equals the area of two trunnions.

The ANSYS elements used in the second model for the elastic-plastic analyses were STIF 42 solid elements and STIF 51 shell elements. The stress vs strain curve used for the lead shown in Figure 2.10.1-1B was obtained from Figure 28 of *NUREG-CR/0481. The curve used for the 304 stainless steel shells shown in Figure 2.10.1-1C was obtained from page 62 of the **Structural Alloys Handbook. Both lead and steel plastic behavior were considered for the 30 ft drop cases, but only the lead plastic behavior was considered in the 1 ft drop (elastic shells).

<u>Finite Element Model Internal Constraints</u>

The connections between various portions of the model were made using node coupling. Connections within a component (i.e. welded connections) were modeled by coupling all degrees-of-freedom at

* Rock and Knorovsky, An Assessment of Stress-Strain Data Suitable for Finite-Element Elastic-Plastic Analysis of Shipping Containers, NUREG/CR-0481, SAND 77-1872, Sandia Laboratories, September 1978 3

** Structural Alloys Handbook, 1986 Edition, Volume 2, Battelle's Columbus Division, Metals and Ceramics Information Center

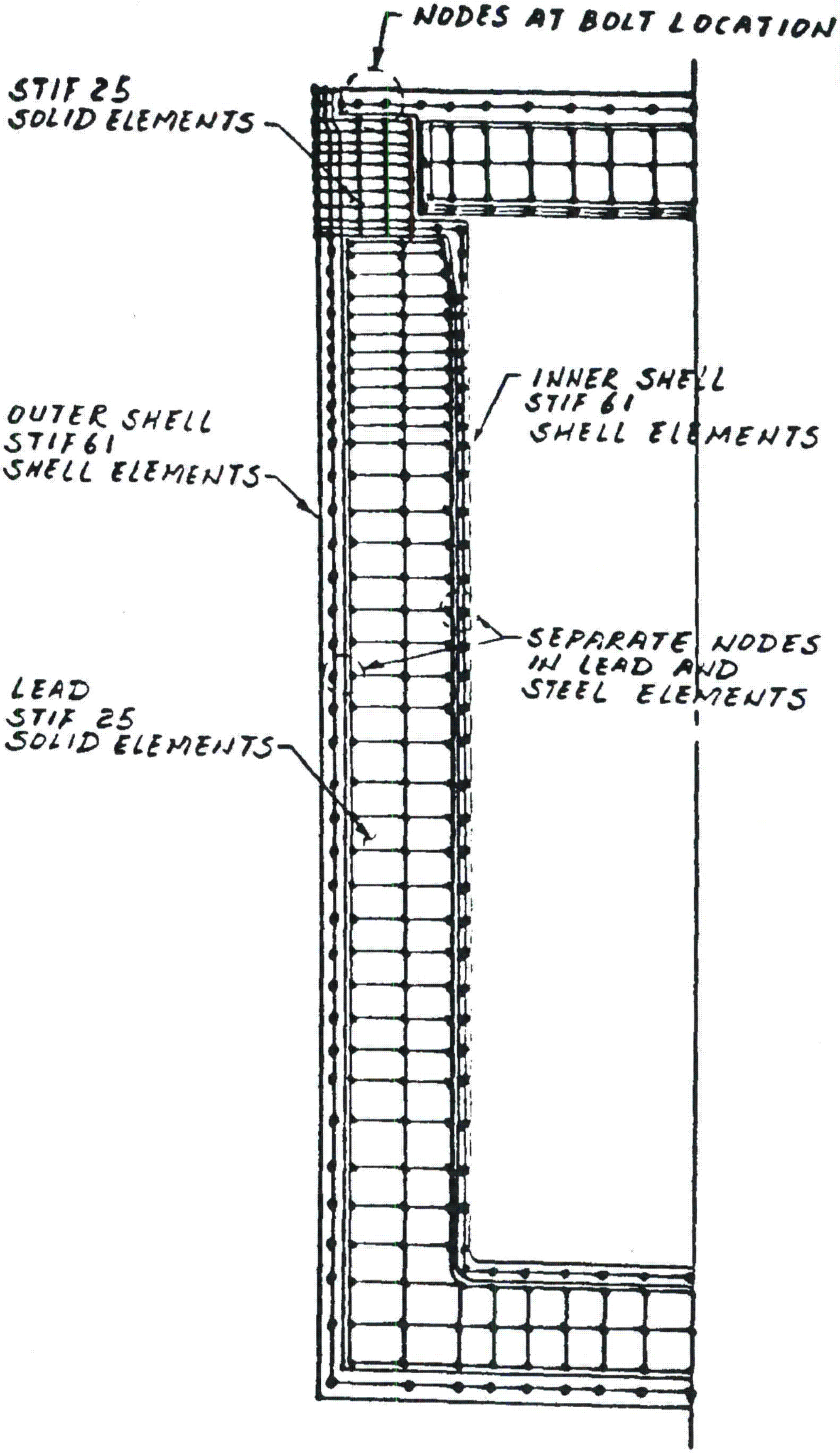
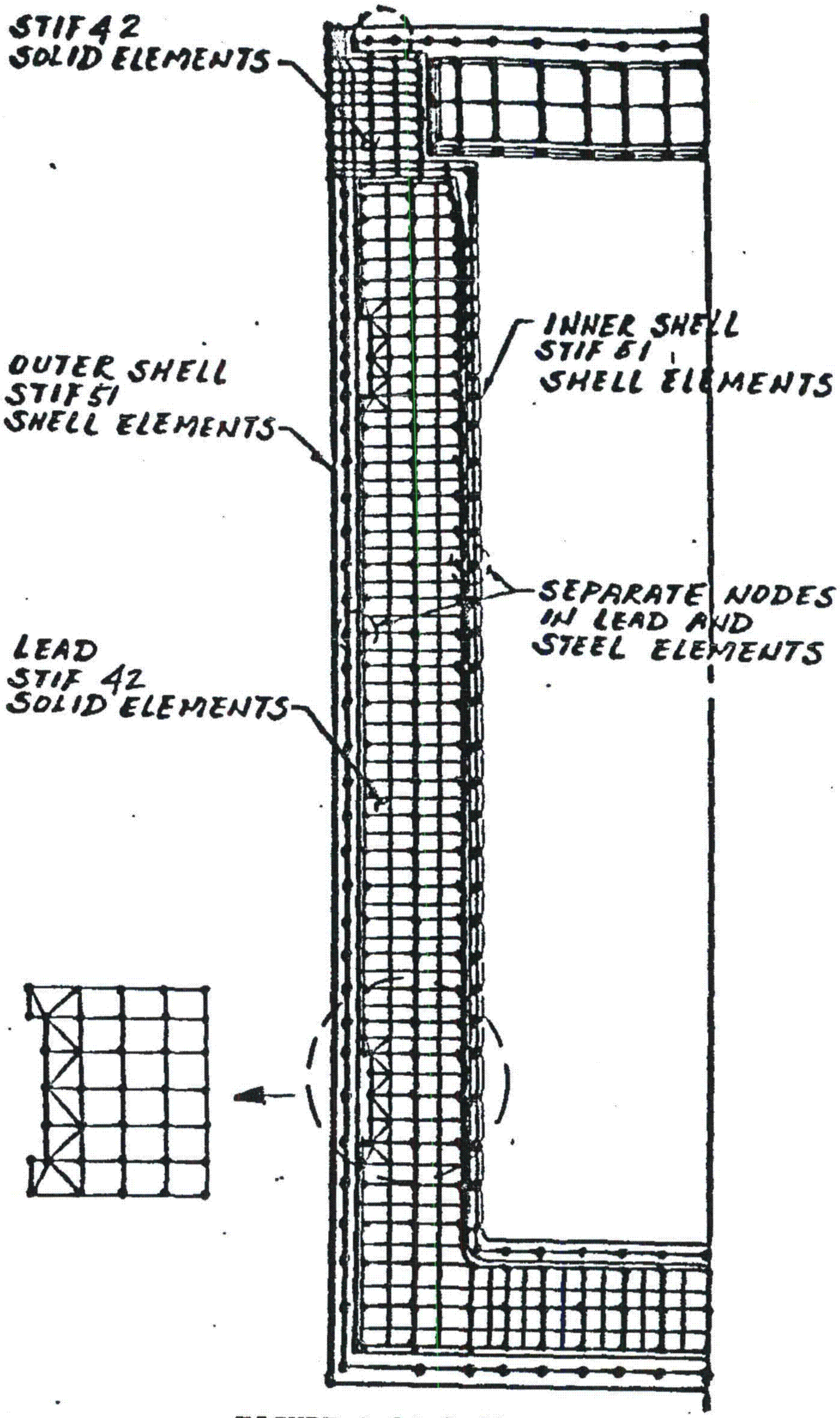


FIGURE 2.10.1-1

TN-RAM CASK BODY-AXISYMMETRIC FINITE ELEMENT MODEL

C-1419



3

FIGURE 2.10.1-1A

TN-RAM CASK BODY-AXISYMMETRIC FINITE ELEMENT MODEL WITH REFINED MESH USED FOR PLASTIC ANALYSES UNDER END IMPACT

Figure 28. Quasi-static true stress-strain curves for chemical lead test specimens in compression [45].

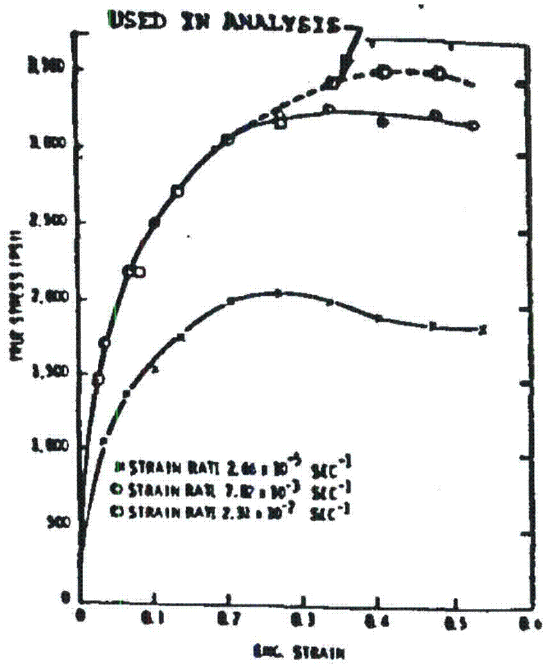


FIGURE 2.10.1-1B

STRESS-STRAIN CURVE FOR CHEMICAL LEAD USED FOR DYNAMIC ANALYSIS

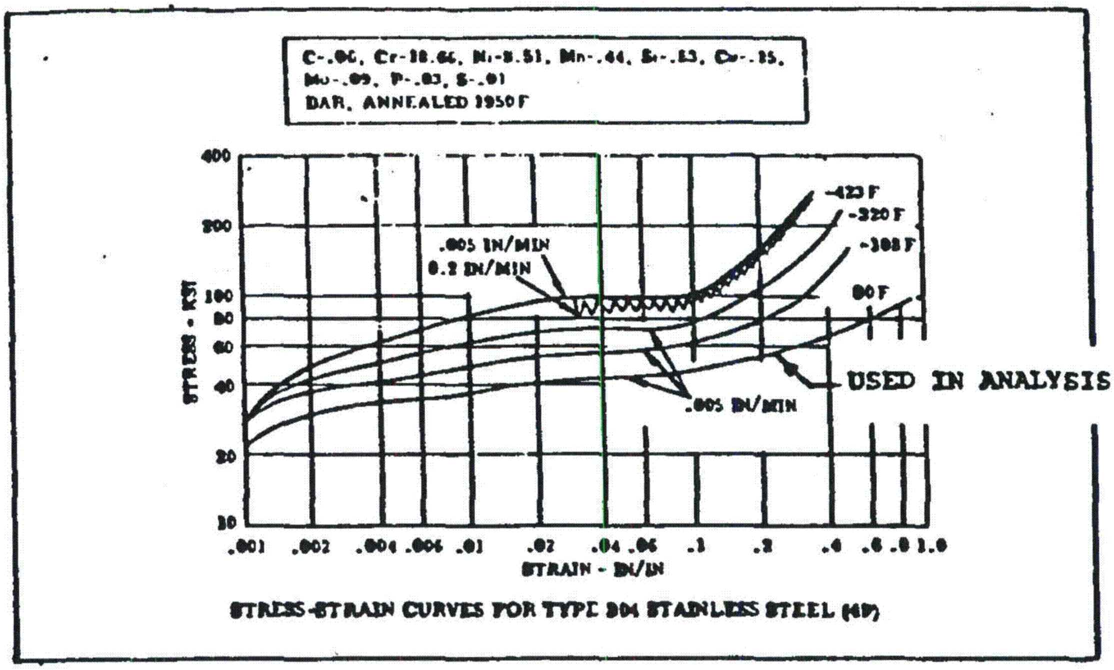


FIGURE 2.10.1-1C

STRESS-STRAIN CURVE FOR 304 STAINLESS STEEL SHELLS USED FOR DYNAMIC ANALYSIS

3

adjacent nodes. The bolted connection between the lid and lid closure was modeled by coupling the nodes at the location of the bolt in the radial and axial directions.

Loading Conditions

Since no bonding is assumed between the lead and the steel shells, the adjacent nodes in the lead and steel components were allowed to have relative motion with respect to each other in the tangential and axial directions. They were coupled in only the radial direction. The adjacent lead and outer shell nodes were coupled axially at the two trunnion planes where the trunnions penetrate into the lead and provide axial restraint to lead motion. On the two ends, the lead nodes were coupled to the steel nodes in the axial direction if the lead had a tendency to move toward the steel, and the nodes were permitted to separate if the lead moved away from the steel.

Finite Element Model Boundary Conditions

For a static finite element structural analysis the structure must be restrained in such a way that there is no rigid body motion. For the drop analyses, the dynamic equilibrium problem is solved using D'Alembert's principle, i.e. the total inertia loading is balanced by the total reaction force. In an actual dynamic event, there are no physical locations in the structure that are stationary and, unless suitable boundary conditions are selected for analysis, rigid body motion may occur. To eliminate the rigid body motion problem, the cask model was carefully restrained in such a way that no appreciable forces were developed at the restraints. When only small reactions are developed at the restrained nodes the inertia loadings and reactions are well balanced. This is true for all loading conditions analyzed.

Figures 2.10.1-2 and 2.10.1-3 show the boundary conditions used for the different loading conditions.

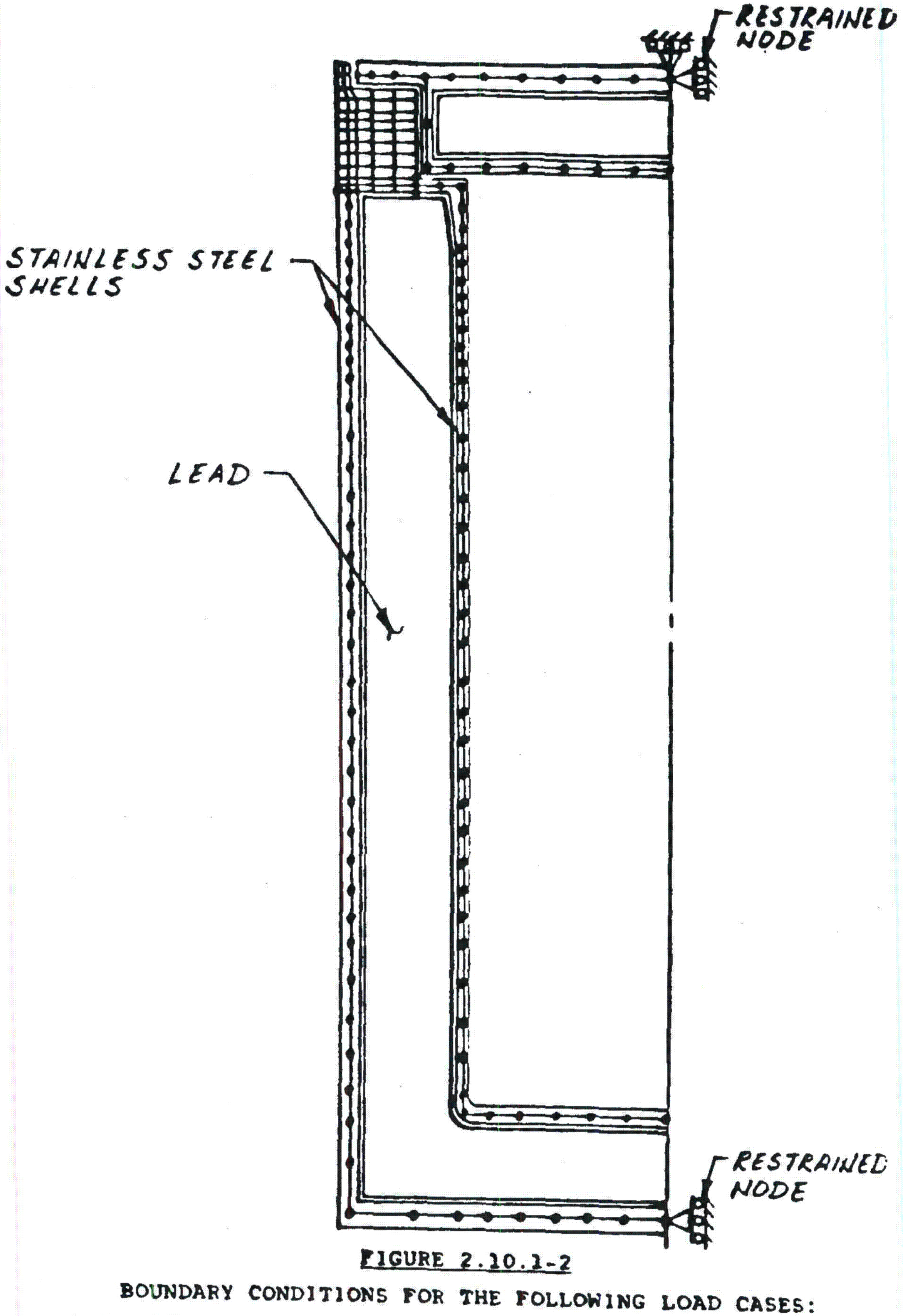


FIGURE 2.10.1-2

BOUNDARY CONDITIONS FOR THE FOLLOWING LOAD CASES: PRESSURE, 1G DOWN, VIBRATION, SHOCK, TIEDOWN, SIDE DROP, THERMAL, IMPACT AT LID END

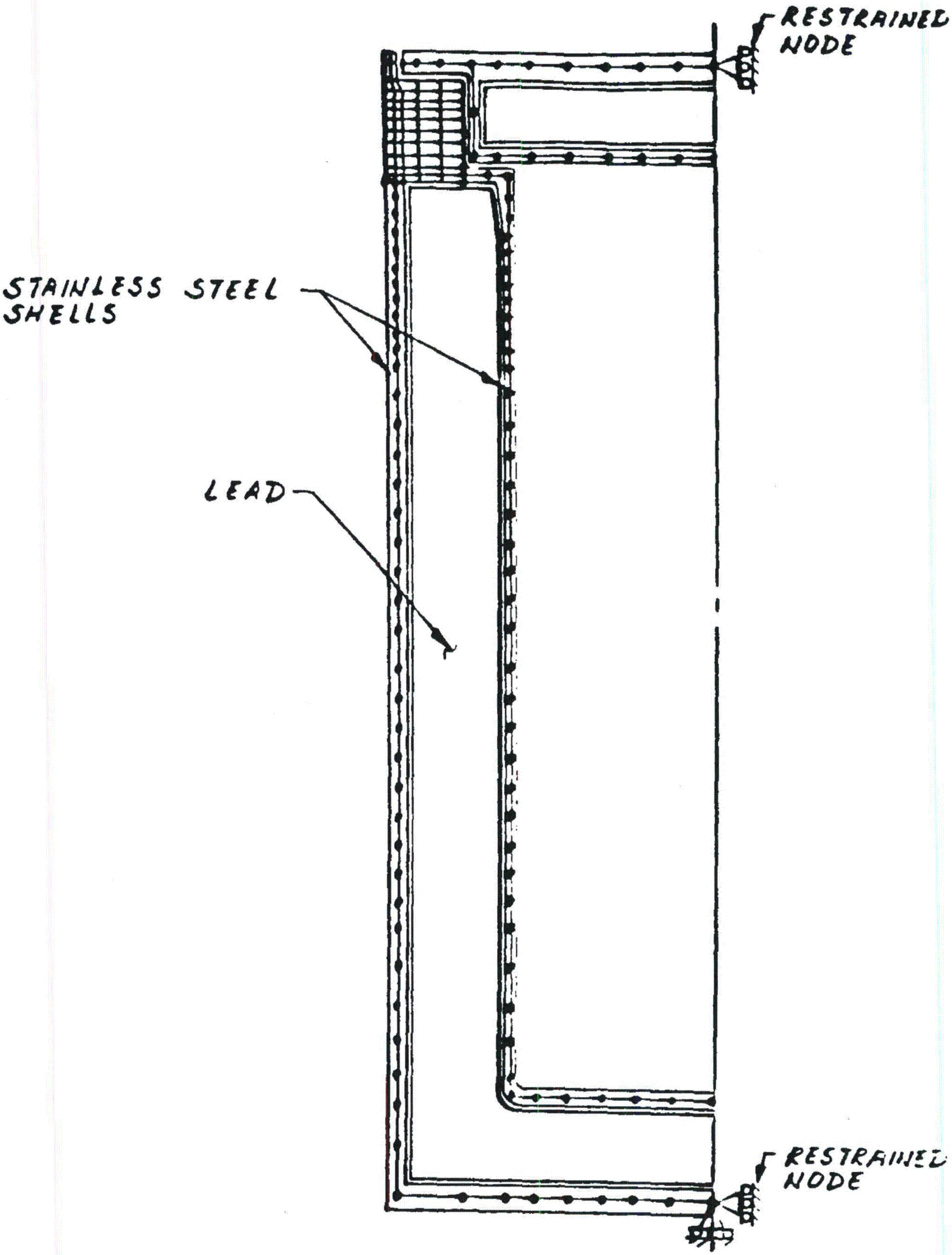


FIGURE 2.10.1-3

BOUNDARY CONDITIONS FOR IMPACT AT BOTTOM END

The loading conditions analyzed simulate or represent various effects due to the normal conditions of transport and hypothetical accident conditions specified in 10CFR71. These individual loading conditions, called load cases, are superimposed or combined as specified in Regulatory Guide 7.8 in Sections 2.6 and 2.7 of this SAR.

A. Axisymmetric Loadings

The following individual axisymmetric load cases analyzed using the two ANSYS models are described in this section. 3

(1) Bolt preload and lid seating pressure

(2) Internal pressure loading

(3) External pressure loading

(4) 30 foot end drop on bottom

(4A) 1 foot end drop on bottom 3

(5) 30 foot end drop on lid

(6) Thermal stresses for hot environment at 100°F ambient temperature

(7) Thermal stresses for cold environment at -20°F ambient temperature

(8) Thermal stresses for cold test at -40°F ambient temperature

(9) Thermal accident condition

Since most of the individual load cases are linearly elastic, their results can be ratioed and superimposed as required in order to perform the normal and hypothetical accident condition load combinations. The unusual conditions of end impact are analyzed using a nonlinear elastic-plastic approach. The stainless shells are analyzed elastically (with plastic lead behavior) for the normal condition one foot drop. The load combination approaches for these cases are described in Sections 2.6 and 2.7. The magnitudes of the loads used in each individual load case analysis are computed as described in the following paragraphs: 3 3

1. <u>Bolt Preload and Lid Seating Pressure</u>

A lid seating load corresponding to 28,000 psi axial stress in the bolt shank is simulated by applying a 2,900 psi pressure on an annular ring on the outside of the lid flange under the lid bolt heads and a corresponding internal element in the threaded region of the closure. This pressure is derived as follows:

Number of Bolts:	16
Diameter of Bolt:	1.5 in.
Diameter of Shank:	1.32 in.
Stress at Shank:	28,000 psi

$$\text{Total bolt load} = 16 \times \frac{\pi(1.32)^2}{4} \times 28{,}000 = 613{,}000 \text{ lb.}$$

$$\text{Lid seating pressure} = \frac{613{,}000}{\pi(23.2475^2 - 21.7475^2)} = 2{,}900 \text{ psi}$$

2. Internal Pressure Loading

An internal pressure of 30 psig is applied to the cavity surface as shown in Figure 2.10.1-4.

3. External Pressure Loading

An external pressure of 14.7 psi is applied to the outer surface of the cask body as shown in Figure 2.10.1-5.

4. 30 Foot End Drop on Bottom

The dynamic analysis described in Appendix 2.10.2 determined the inertial loads on the TN-RAM packaging for a 30 foot end drop onto an unyielding surface. That analysis concluded that the maximum axial deceleration is 69.6 g for this case. In this appendix, the stress analysis is performed for a slightly higher deceleration than predicted in Appendix 2.10.2. Stresses are determined for a 70 g load. A quasistatic analysis of the cask body is performed with inertial forces balanced by the impact force. Since the payload or cargo and the impact limiters are not included in the model, their loading effects are simulated as distributed pressures applied on the cask at the appropriate locations. The contacting impact limiter force on the cask is applied as the reaction pressure on the bottom required to balance the inertial forces of the system. Thus, the cask body vessel is in equilibrium under the applied forces. The system of forces on the cask body is presented on Figure 2.10.1-6. 3

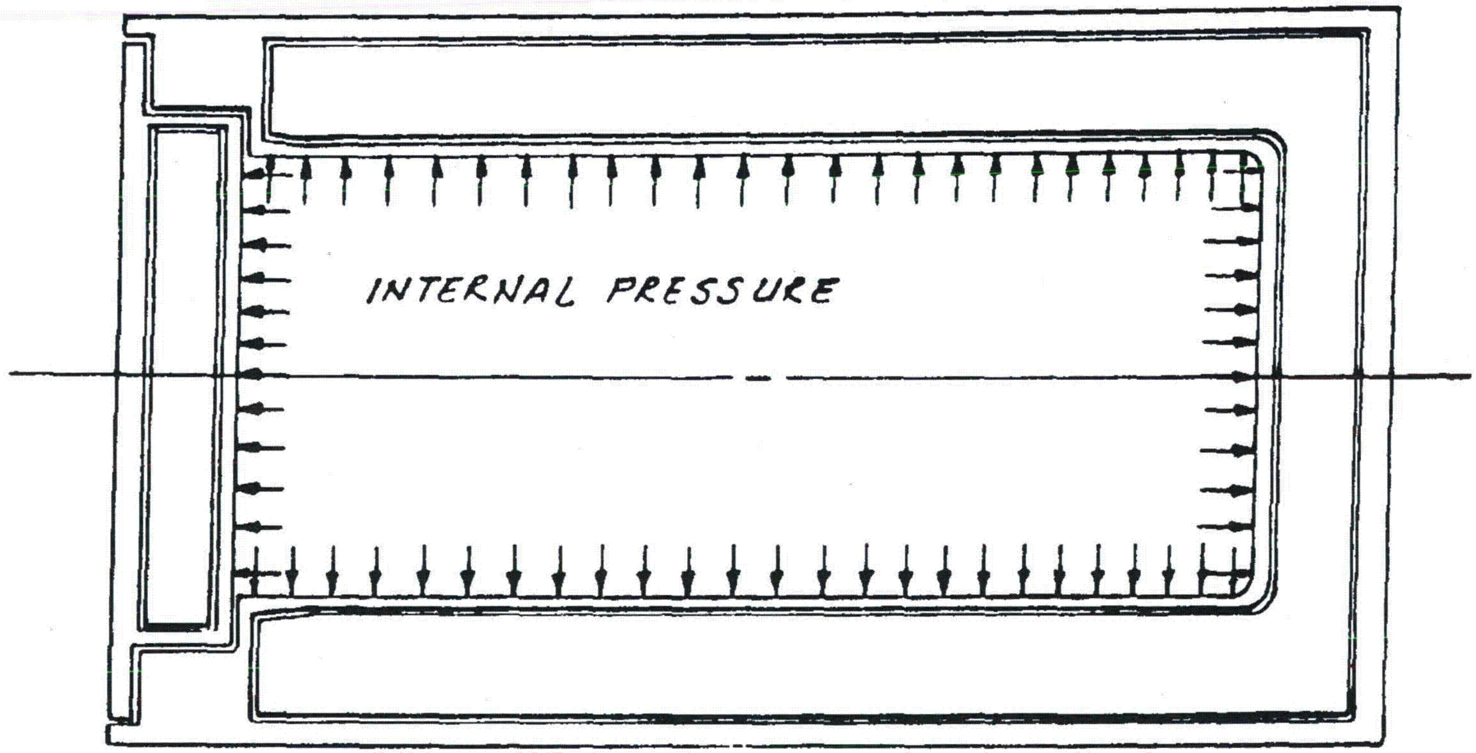


FIGURE 2.10.1-4

LOAD DISTRIBUTION-INTERNAL PRESSURE

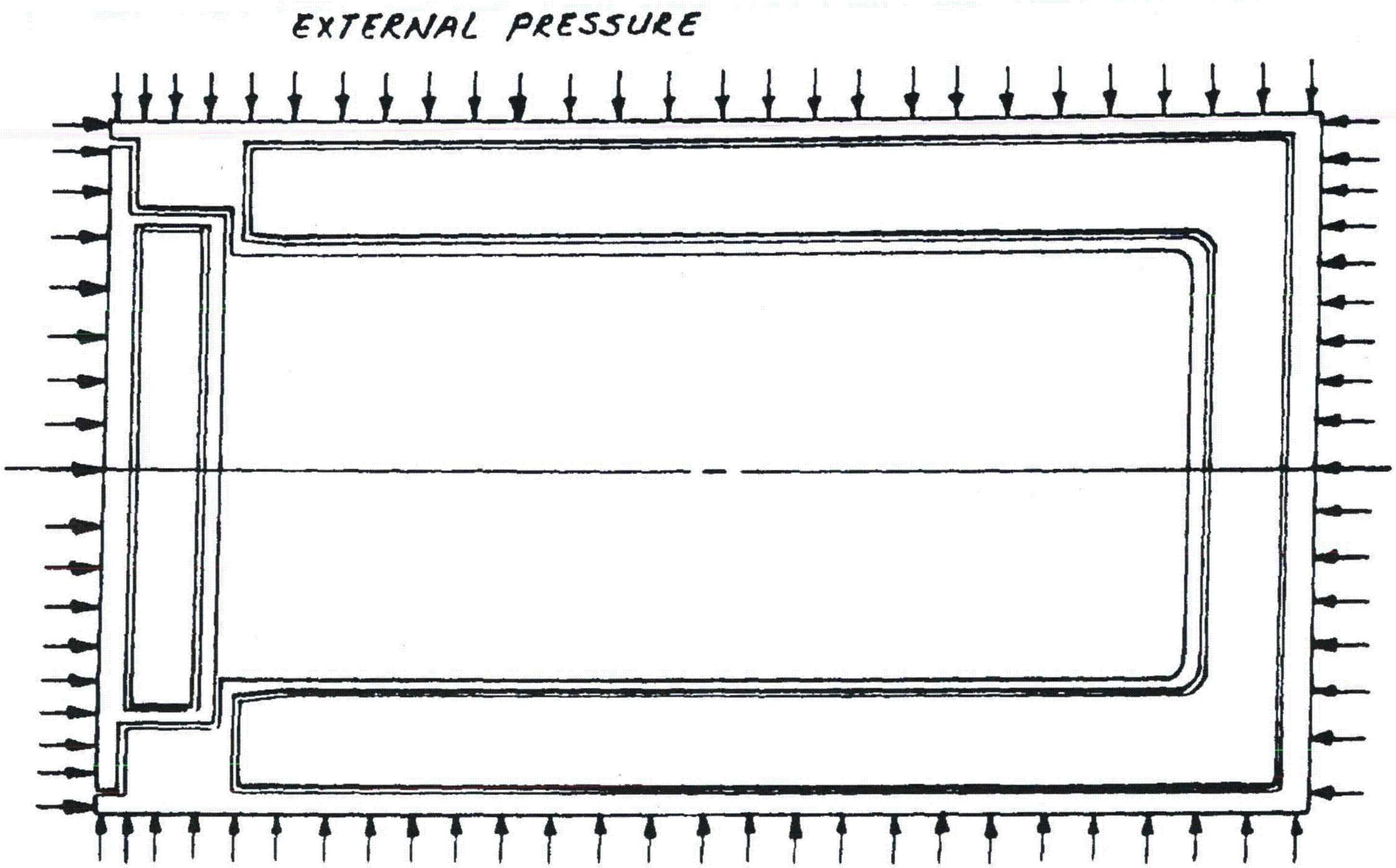


FIGURE 2.10.1-5

LOAD DISTRIBUTION-EXTERNAL PRESSURE

Following is the derivation of the inertia load (pressure) magnitudes for the ANSYS model run:

- Weight of Cask Body: 62,557 lb.
- Weight of Top Impact Limiter: 3,232 lb.
- Weight of Bottom Impact Limiter: 3,232 lb.
- Weight of Cargo: 9,500 lb.
- Maximum Deceleration: 70 g

- Pressure due to cargo inertia load

$$P_I = \frac{70 \times 9,500}{\pi(17.6875)^2} = 677 \text{ psi}$$

- Pressure due to top impact limiter inertia load

$$P_T = \frac{70 \times 3,232}{\pi(25.625)^2} = 110 \text{ psi}$$

- Reaction pressure at bottom

$$P_T = \frac{70\ (62,557 + 3,232 + 9,500)}{\pi(24.875)^2} = 2,708 \text{ psi}$$

The loadings applied by the cargo and impact limiters are calculated similarly for a 30 g inertial load due to the one foot bottom drop. 3

5. <u>30 Foot End Drop on Lid</u>

An analysis similar to that for the 30 foot free drop on the bottom is performed for the 30 foot drop on the lid. The same inertial forces (70 g) are used for the lid or top impact case 3

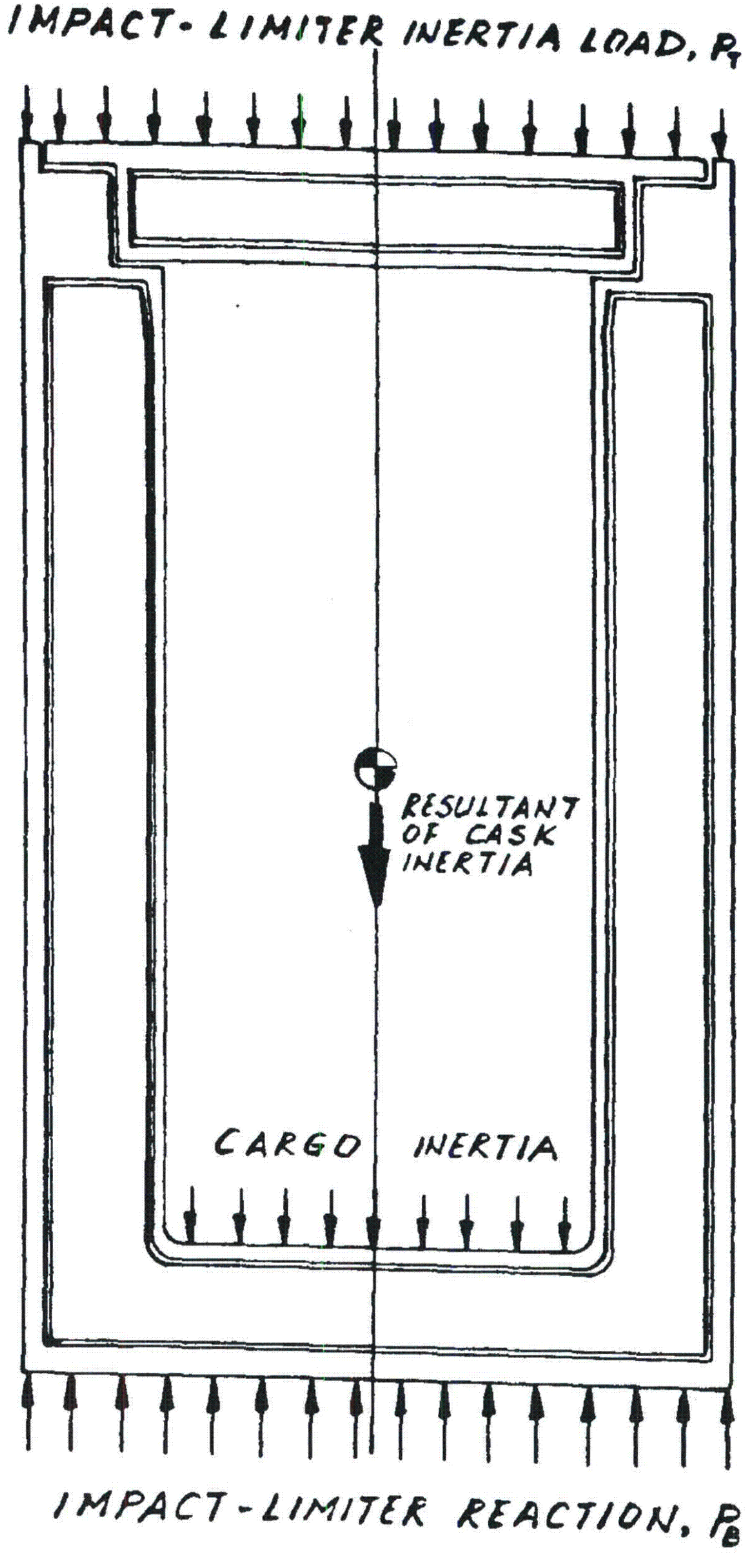


FIGURE 2.10.1-6

LOAD DISTRIBUTION-IMPACT AT BOTTOM END

as for the bottom impact case. The system of forces on the cask body is presented on Figure 2.10.1-7, and the derivation of the magnitudes follows:

- Weight of Cask Body: 62,500 lb.
- Weight of Top Impact Limiter: 3,230 lb.
- Weight of Bottom Impact Limiter: 3,230 lb.
- Weight of Cargo: 9,500 lb.
- Maximum Deceleration: 70 g 3

- Pressure due to cargo inertia load

$$P_I = \frac{70 \times 9{,}500}{\pi(18)^2} = 653 \text{ psi}$$ 3

- Pressure due to bottom impact limiter inertia load

$$P_B = \frac{70 \times 3{,}232}{\pi(24.875)^2} = 117 \text{ psi}$$ 3

- Reaction pressure at lid end

$$P_T = \frac{70\ (62{,}557 + 3{,}232 + 9{,}500)}{\pi(25.625)^2} = 2{,}558 \text{ psi}$$ 3

P_I, P_B and P_T are slightly different for the drop on the lid end compared to the drop on the bottom end because of the slight geometry and configuration differences of the model at each end.

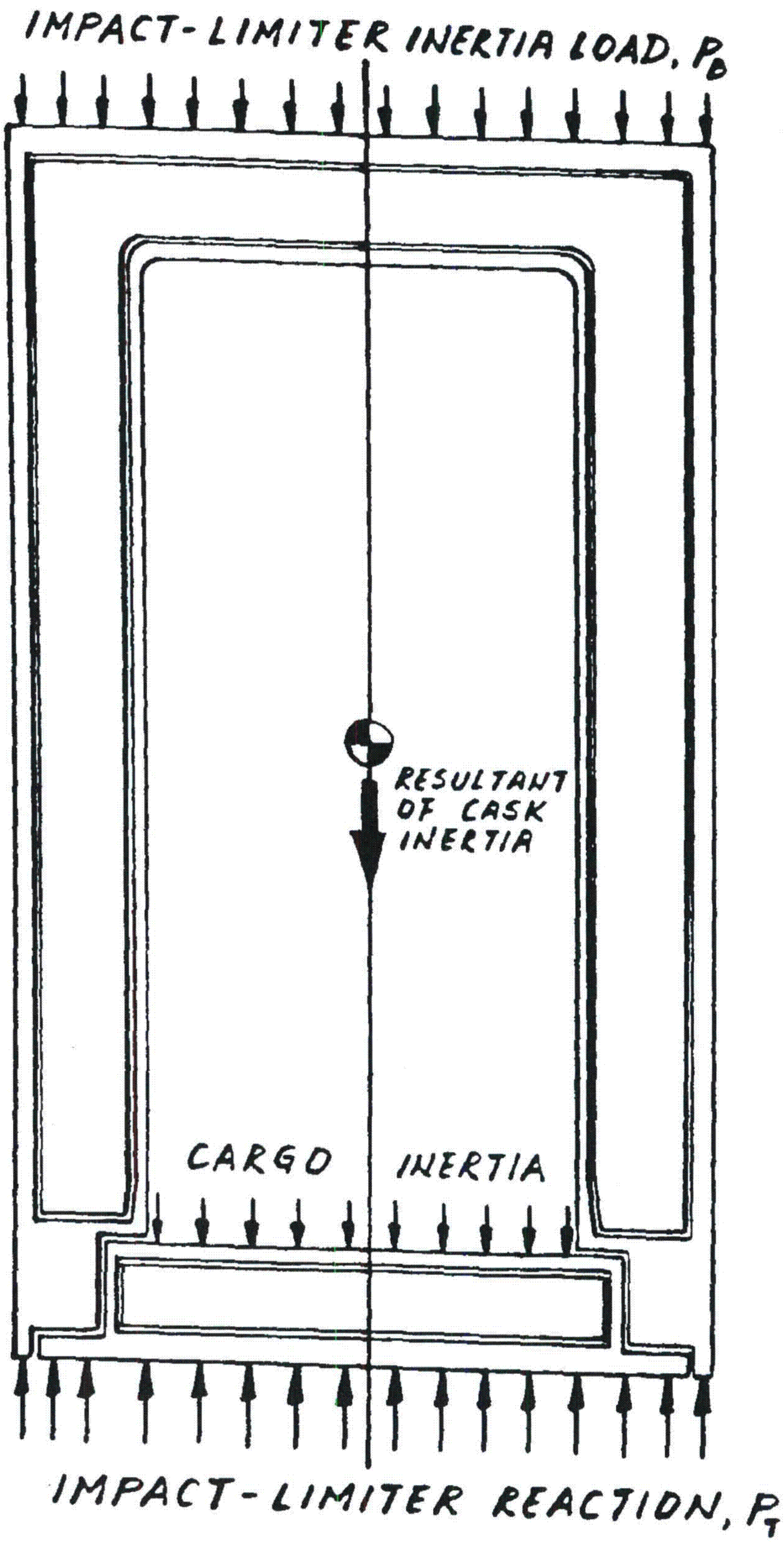


FIGURE 2.10.1-7

LOAD DISTRIBUTION-IMPACT AT LID END

6. <u>Thermal Stress for Hot Environment Condition at 100°F Ambient Temperature</u>

The thermal analysis of the cask body is as described in Chapter Three. That analysis was performed to determine the steady state stainless steel and lead temperatures in the cask body for the condition with maximum solar heating, maximum decay heat from the cask contents, and 100°F ambient air. The temperatures from that thermal analysis are used directly in this axisymmetric finite element structural model to calculate the cask body stresses due to differential thermal expansion of its components.

It is assumed that there is a stress free state at 70°F for this case and 7 and 8 below.

7. <u>Thermal Stresses for Cold Environment Condition at -20°F Ambient Temperature</u>

A uniform temperature of -20°F is input to the structural model to calculate the containment stresses due to differential thermal expansion between the two shells of the cask and the lead. This differential expansion is entirely due to the difference in coefficients of expansion of the lead and stainless steel since the temperature is uniform.

8. <u>Thermal Stresses for Cold Test at -40°F Ambient Temperature</u>

A uniform temperature of -40°F is input to the structural model to calculate the stresses due to differential thermal expansion

between the two shells of the cask and the lead. Stresses occur due to the difference in coefficients of expansion of lead and stainless steel.

9. Thermal Accident Condition

An ANSYS transient thermal analysis of the cask for the 30 minute thermal accident is reported in Chapter Three. 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 temperatures from the thermal analysis are reported for each time-step during the transient.

The thermal stresses calculated in this section are based on temperatures that were obtained in the original thermal accident analysis. The thermal analysis in Chapter 3, Section 3.5.3 in this revision of the SAR is an updated analysis that was done to meet current post-fire ambient conditions. Specifically insolation is now applied after the fire. The results of the analysis documented in Chapter 3, Section 3.5.5 show that the temperatures used in the thermal stress calculations below are bounding.

The temperatures throughout the package at the time where the individual temperatures peak (0.56 hrs.) and after they equalize (0.83 hrs.) are summarized below:

Temperature (time=0.56 hrs.)			Temperature (time=0.83 hrs.)		
Inner Shell	=	411°F	Inner Shell	=	460°F
Outer Shell Sides	=	560°F	Outer Shell Sides	=	470°F
Outer Shell Ends	=	163°F	Outer Shell Ends	=	154°F
Lead	=	473°F	Lead	=	460°F

These two sets of temperatures are input to the axisymmetric finite element model to calculate the component stresses due to differential thermal expansion (2 cases).

B. Asymmetric Loadings

The asymmetric loadings of the axisymmetric cask body are applied to special ANSYS harmonic elements. Each load acting on the cask 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 node number. The number of terms in the Fourier series required to adequately represent a load varies with the type of load (whether it is a concentrated or a distributed load) and the degree of accuracy required. In the particular case where the applied loads are distributed over a large area (i.e., 180 degrees of the cask circumference), a few terms of the series are sufficient to represent the desired loading within a few percent. See Figures 2.10.1-8 and 2.10.1-9 which show the Fourier series approximations of cosine functions acting on the arc from 90° to 270° and from -90° to +90°, respectively.

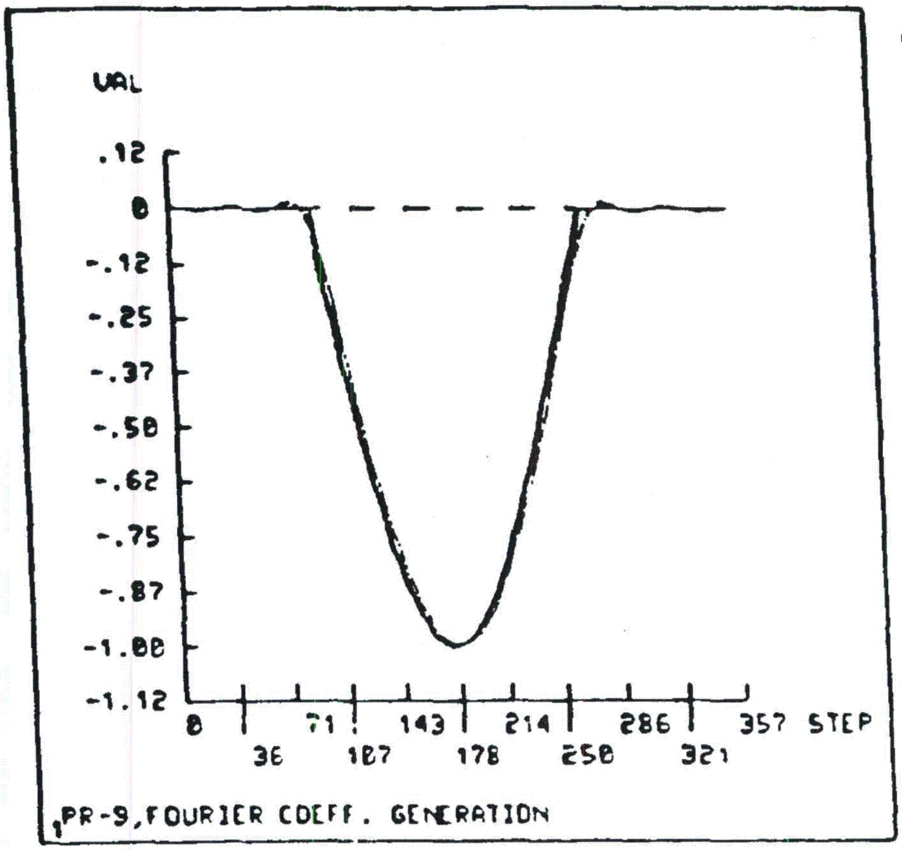
The following individual asymmetric load cases analyzed (using the same two-dimensional ANSYS model previously discussed) are described in this section.

(1) 1g loading in the longitudinal direction with the cask axis horizontal, held at the rear trunnion plane.

(2) 1g downward loading with the cask axis horizontal, supported vertically on four trunnions (two trunnion planes).

(3) 30 foot side drop with the cask axis parallel to the target.

(4) 30 foot C.G. over top corner (lid end) drop.



***** FOURIER COEFFICIENTS *****

TERM	MODE*ISYM	COEFFICIENT
1	0	-0.31780103E+00
2	1	0.49931477E+00
3	2	-0.21206110E+00
4	3	-0.22109894E-13
5	4	0.42528724E-01
6	5	0.38194530E-13
7	6	-0.18310183E-01
8	7	-0.27529862E-13
9	8	0.10237762E-01

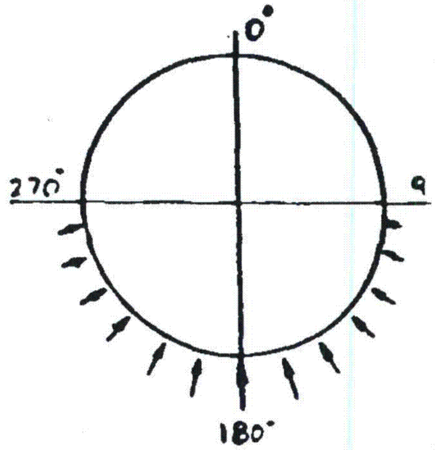
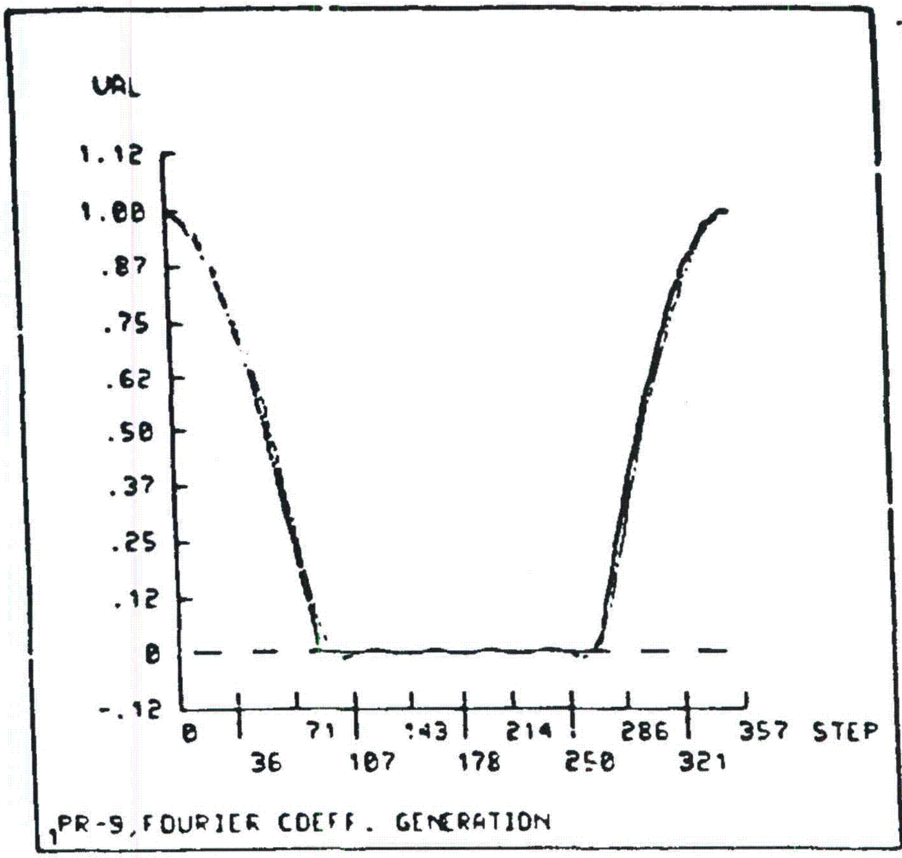


FIGURE 2.10.1-8

FOURIER COEFFICIENTS FOR THE FUNCTION: COSθ | 270° 90°



NUMBER OF FOURIER TERMS= 9

***** FOURIER COEFFICIENTS *****

TERM	MODE*ISYM	COEFFICIENT
1	0	0.31780103E+00
2	1	0.49931477E+00
3	2	0.21206110E+00
4	3	-0.29048323E-13
5	4	-0.42528724E-01
6	5	0.24207093E-13
7	6	0.18310183E-01
8	7	-0.74144193E-13
9	8	-0.10237762E-01

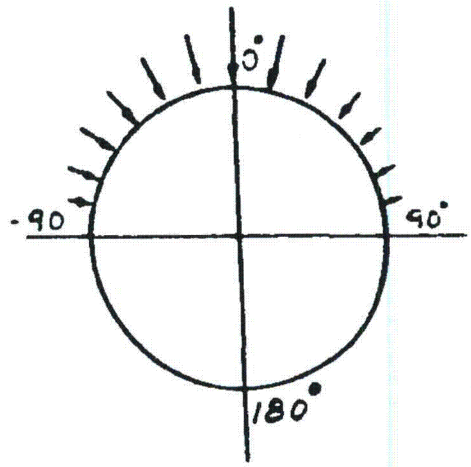


FIGURE 2.10.1-9

FOURIER COEFFICIENTS FOR THE FUNCTION: $\cos\theta \Big|_{-90°}^{90°}$

Since these individual load cases are generally linear and elastic (except for the 30 ft end drops), their results can be ratioed and superimposed as required in order to perform most of the normal and hypothetical accident load combinations. Figure 2.10.1-10 illustrates the model, the locations of the key reactions and the CG. The magnitudes of the loads used in each individual load case analysis are computed in the following paragraphs: 3

1. <u>1G Unit Loading (Longitudinal)</u>

Figure 2.10.1-11 shows the inertia forces acting on the cask due to a 1G loading acting in the -Y direction (toward the lid end). These forces are:

(a) F_B = 62,557 lb. resultant of all of the distributed inertia forces acting on the cask body. This force is actually distributed throughout the model.

(b) P_I = pressure applied to the inner surface of the closure simulating the loading due to the inertia force of the cargo.

$$P_I = \frac{W_I}{A_B} = \frac{9,500}{\pi \times 15^2} = 13.44 \text{ psi}$$

Where W_I = 9,500 lb. weight of the cargo

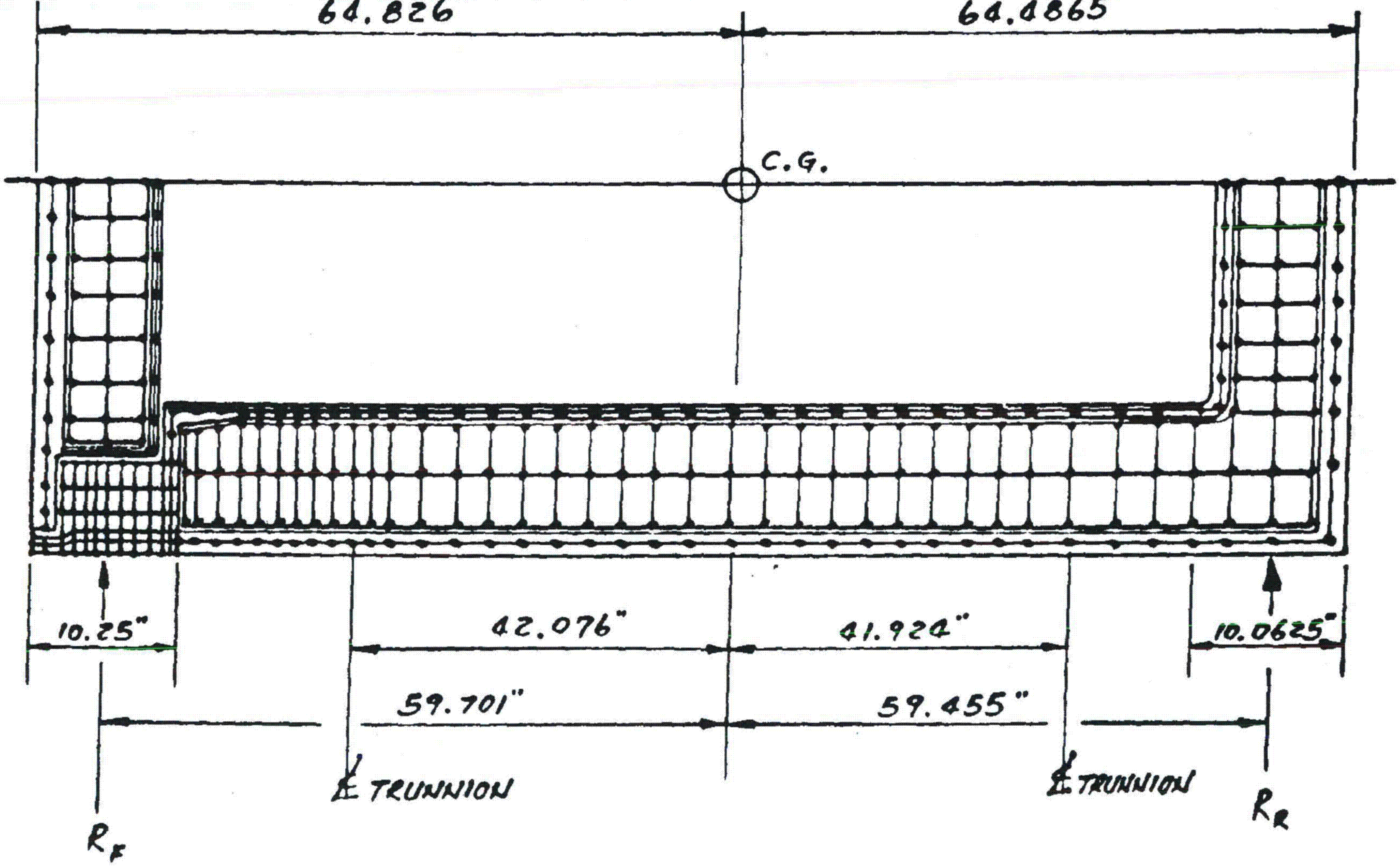


FIGURE 2.10.1-10

LOCATIONS OF C.G. AND TRUNNIONS

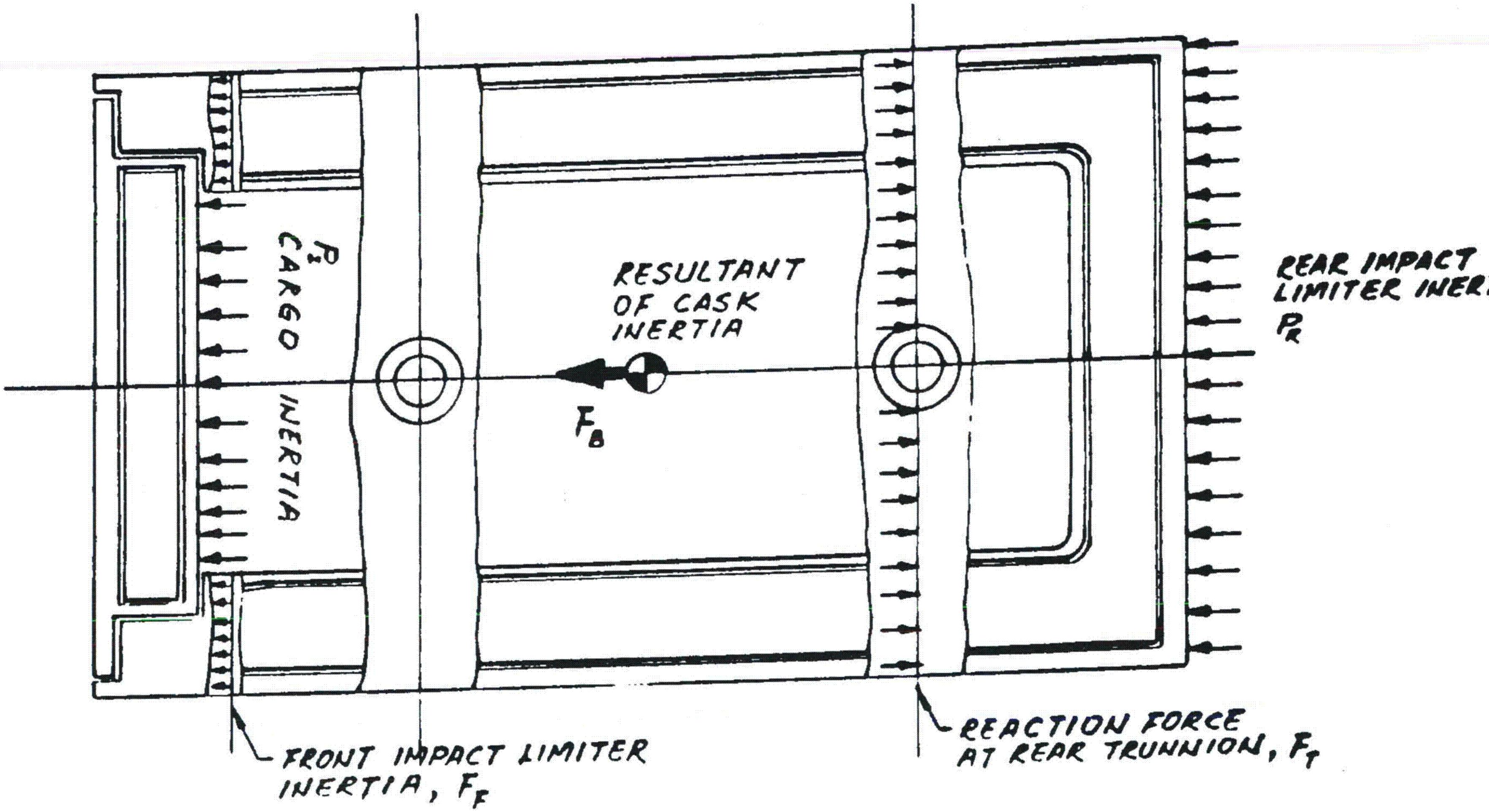


FIGURE 2.10.1-11

LOAD DISTRIBUTION-1G LONGITUDINAL (CASK HORIZONTAL SUPPORTED BY 2 REAR TRUNNIONS)

(c) F_F = inertia force of the front impact limiter represented by a line load acting at the attachment bolt circle:

$$F_F = \frac{W_F}{2\pi} = \frac{3,232}{2\pi} = 514 \text{ lb/radian}$$

Where W_F = 3,232 lb. weight of the front impact limiter

(d) P_R = uniform pressure applied to the bottom outer surface of the cask simulating the inertia force of the rear impact limiter:

$$P_R = \frac{W_R}{A_R} = \frac{3,232}{\pi \times 24.875^2} = 1.660 \text{ psi}$$

Where W_R = 3,232 lb. = weight of the rear impact limiter

(e) F_T = uniform line load applied around the trunnion plane

$$F_T = \frac{F_B + W_I + W_F + W_R}{2\pi}$$

$$= \frac{62,557 + 9,500 + 3,232 + 3,232}{2\pi} = 12,500 \text{ lb/radian}$$

Note that the local trunnion stresses are calculated in Section 2.10.1.3 using the Bijlaard method. The total stress at the trunnion locations is obtained by superimposing the nominal or average stress at each location from this load case and the local stress from Section 2.10.1.3. These stresses are treated

as individual load cases and are combined as described in the load combination discussion in Section 2.6 of Chapter Two.

2. <u>1G Unit Loading (Transverse)</u>

Figure 2.10.1-12 shows the forces acting on the cask body due to gravity during transport. The support at the front and rear trunnions is simulated with tangential line forces, F_{ZF} and F_{ZR}, varying sinusoidally on each side around the outer circumference of the cask so that the system of forces is in equilibrium. The cask is held at two nodes (one at each end) to prevent rigid body motion. The restraint forces at these nodes are small (they compensate only for slight errors in the force balance).

The forces acting on the cask in this case are:

(a) F_B = 62,557 lb. downward resultant of the distributed inertia force acting on the mass of the cask, shown applied at the C.G.

(b) P_I = the downward force acting on the lower half of the inside surface of the cavity due to the cargo which is represented as a pressure varying sinusoidally around the bottom half of the cavity as shown below:

$$W_I = \int_{\pi/2}^{3\pi/2} P_I \cos\theta \; L \cos\theta r d\theta = (P_I)\ (r)(L)(\pi)/2$$

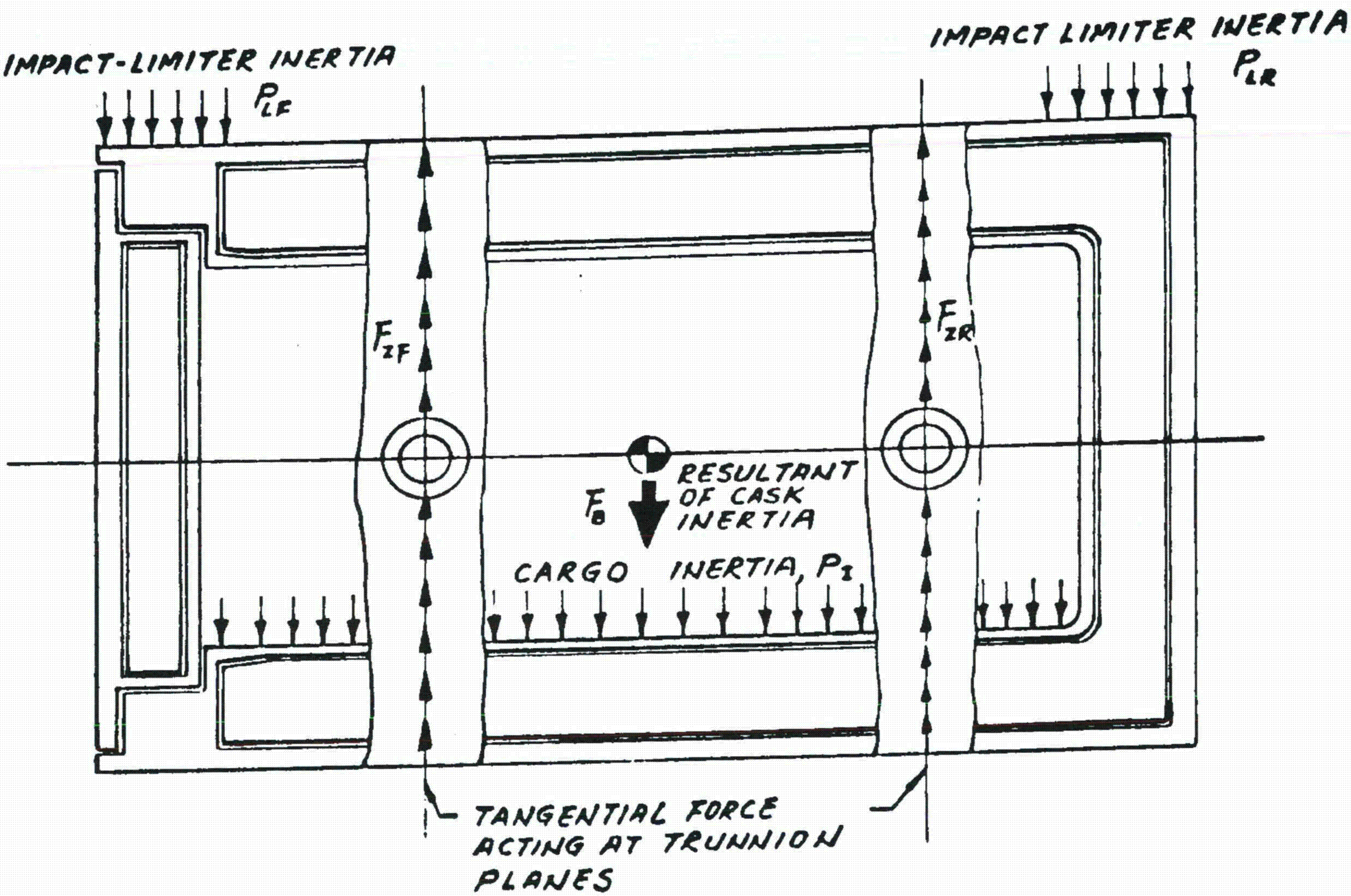


FIGURE 2.10.1-12

LOAD DISTRIBUTION-1G VERTICAL DOWN (CASK HORIZONTAL SUPPORTED BY 4 TRUNNIONS)

$$P_I = \frac{2 W_I}{(\pi)(r)(L)} = \frac{2 \times 9,500}{3.14 \times 17.5 \times 111} = 3.11 \text{ psi}$$

(c) P_{LF} and P_{LR} are downward pressures applied by the front and rear impact limiters to the outer surfaces of the cask. These pressures are assumed to vary sinusoidally around the top half of the surface and have the same form found for P_I above:

$$P_{LF} = \frac{2 \times W_F}{(\pi)(r_o)(L_F)} = \frac{2 \times 3,232}{3.14 \times 25.625 \times 10.25} = 7.83 \text{ psi}$$

$$P_{LR} = \frac{2 \times W_R}{(\pi)(r_o)(L_R)} = \frac{2 \times 3,232}{3.14 \times 25.625 \times 10.0625} = 7.98 \text{ psi}$$

(d) F_{ZF} and F_{ZR} are tangential line loads simulating the upward reactions at the front and rear trunnion planes and are assumed to vary sinusoidally. The line load, F_{ZF}, is related to the total reaction force F_{VF}, at the front trunnion as follows:

$$F_{VF} = \int_0^{2\pi} \frac{F_{ZF}}{r} \sin\theta (r d\theta) (-\sin\theta) = (\pi)(F_{ZF})$$

The value of F_{VF} is found from statics by summing moments of all the forces acting on the cask about the rear trunnion pivot point (see Figure 2.10.1-10). This yields:

$$F_{VF} = \frac{41.924 \times W}{84} = \frac{41.924 \times 78,521}{84} = 39,190 \text{ lb.}$$

$$F_{ZF} = \frac{39,189}{\pi} = 12,470 \text{ lb/radian}$$

Similarly taking moments of all the forces acting on the cask about the front trunnion pivot point yields:

$$F_{VR} = 39{,}332 \text{ lb.}$$

$$F_{VR} = \int_0^{2\pi} \frac{F_{ZR}}{r} \sin\theta (r d\theta)\ (-\sin\theta) = (\pi)(F_{ZR})$$

$$F_{ZR} = \frac{39{,}332}{\pi} = 12{,}519 \text{ lb/radian}$$

The local stresses at the trunnion location are determined below in Section 2.10.1.3 using the Bijlaard Method. Section 2.6 of Chapter Two discusses the superposition or combination of these stresses.

3. <u>30 Foot Side Drop</u>

Figure 2.10.1-13 shows the free body diagram for the 30 foot free drop on the side of the packaging with all of the forces acting on the cask. These forces are assumed to vary sinusoidally around the circumference, and are:

(a) F_B, the resultant body inertia force shown acting at the cask C.G.

(b) P_I, the lateral pressure from the internals inertia load applied to the lower half of the inner surface of the cask body cavity.

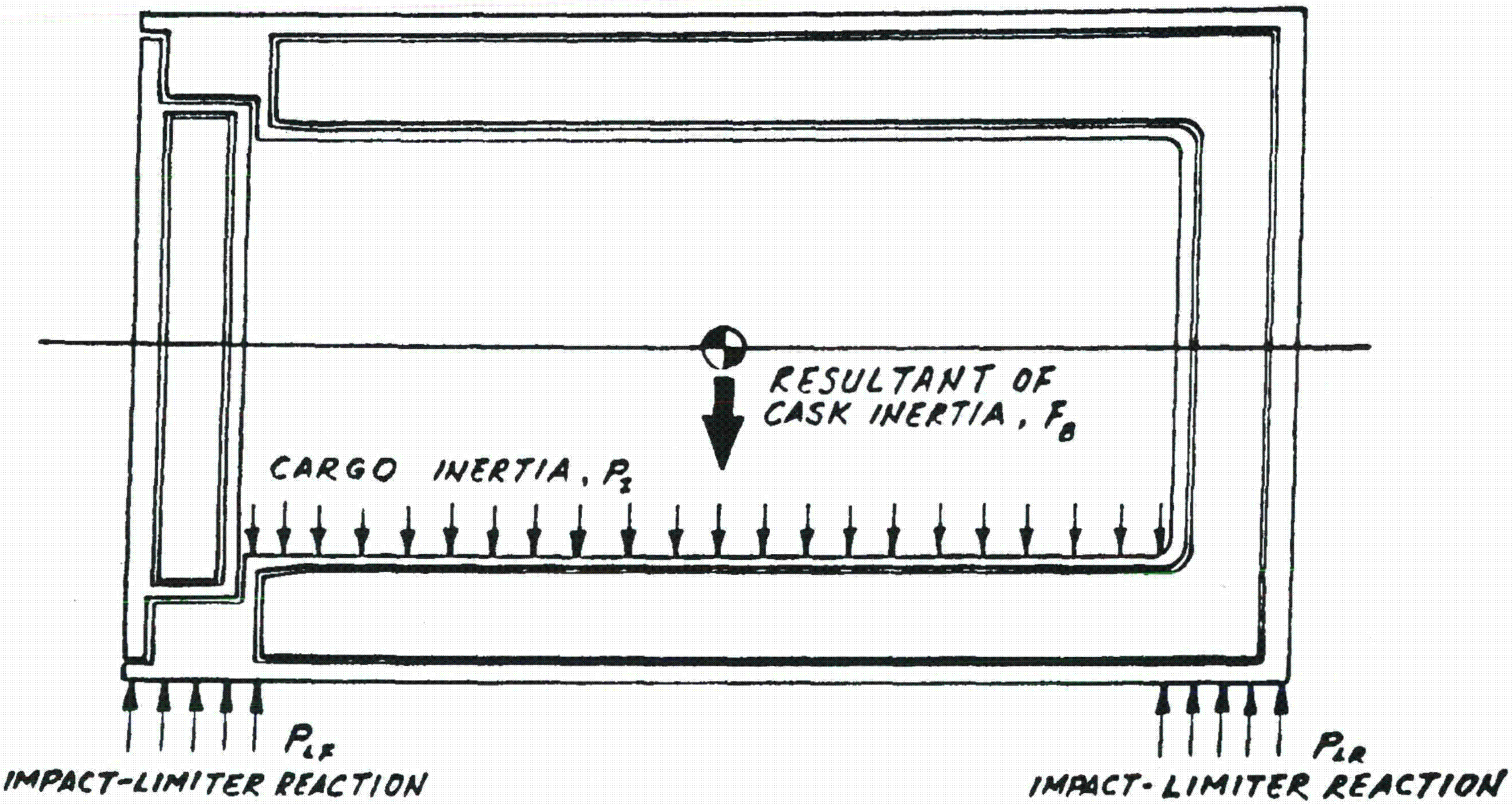


FIGURE 2.10.1-13

LOAD DISTRIBUTION - SIDE DROP

(c) P_{LF}, the pressure applied by the front impact limiter reaction on the bottom half of the cask body outer surface during impact.

(d) P_{LR}, pressure applied by the rear impact limiter to the bottom half of the cask body outer surface during impact.

The dynamic analysis reported in Appendix 2.10.2 indicates a maximum deceleration of 82.7 G for this drop orientation. The analysis is conservatively performed for a higher deceleration value and reaction forces than predicted in Appendix 2.10.2. The structural analysis uses the following loading as input.

Cask Deceleration,	N_g = 128.5 g	
Front Impact Limiter Reaction,	R_F = 4,620,000 lb.	Total reactions at the cask outer surface
Rear Impact Limiter Reaction,	R_R = 4,640,000 lb.	

(See Fig. 2.10.1-10 for locations of reaction forces R_F and R_R).

The maximum force for the 10° impact angle is 3.7×10^6 lb. versus the forces of 4.62×10^6 lb. and 4.64×10^6 lb. used in the analysis. Since forces in terms of pressures, applied to the model of the cask body are higher, resulting stresses will be higher. The pressures applied to the analysis model resulting from R_F and R_R are as follows:

$$R_F = \int_{\pi/2}^{3\pi/2} (L_F P_{LF} \cos\alpha r d\alpha)\cos\alpha = \frac{(r)(L_F)(P_{LF})(\pi)}{2}$$

$$P_{LF} = \frac{2 \times 4,620,000}{3.14 \times 25.625 \times 10.25} = 11,200 \text{ psi}$$

Similarly:

$$P_{LR} = \frac{2 \times 4,640,000}{3.14 \times 25.625 \times 10.0625} = 11,460 \text{ psi}$$

Again the model is held at the ends to prevent rigid body motion. The small reactions at the ends due to the applied load unbalance have negligible effect on stress results. The equilibrium condition is verified since the loads are small ensuring that the model input loading is correct.

4. <u>30 Foot C.G. Over Corner Drop</u>

The crush footprint of the impact limiter was projected to the cask surface. The impact force was determined from the inertia loading reported in Appendix 2.10.2. Since the impact angle is approximately 70° the axial load is 61.1g and the transverse load is 13.9g. The analysis is conservatively performed for a higher deceleration than predicted in Appendix 2.10.2. 66.4g (axial) and 17g (transverse) are the values used in the analysis, these two components correspond to a deceleration value of 68g through the CG of the cask body. An equivalent surface pressure (which varies in both the circumferential and axial directions) was then determined using the components of 66g and 17g. Figure 2.10.1-14 shows the free body diagram for the 30 foot free drop

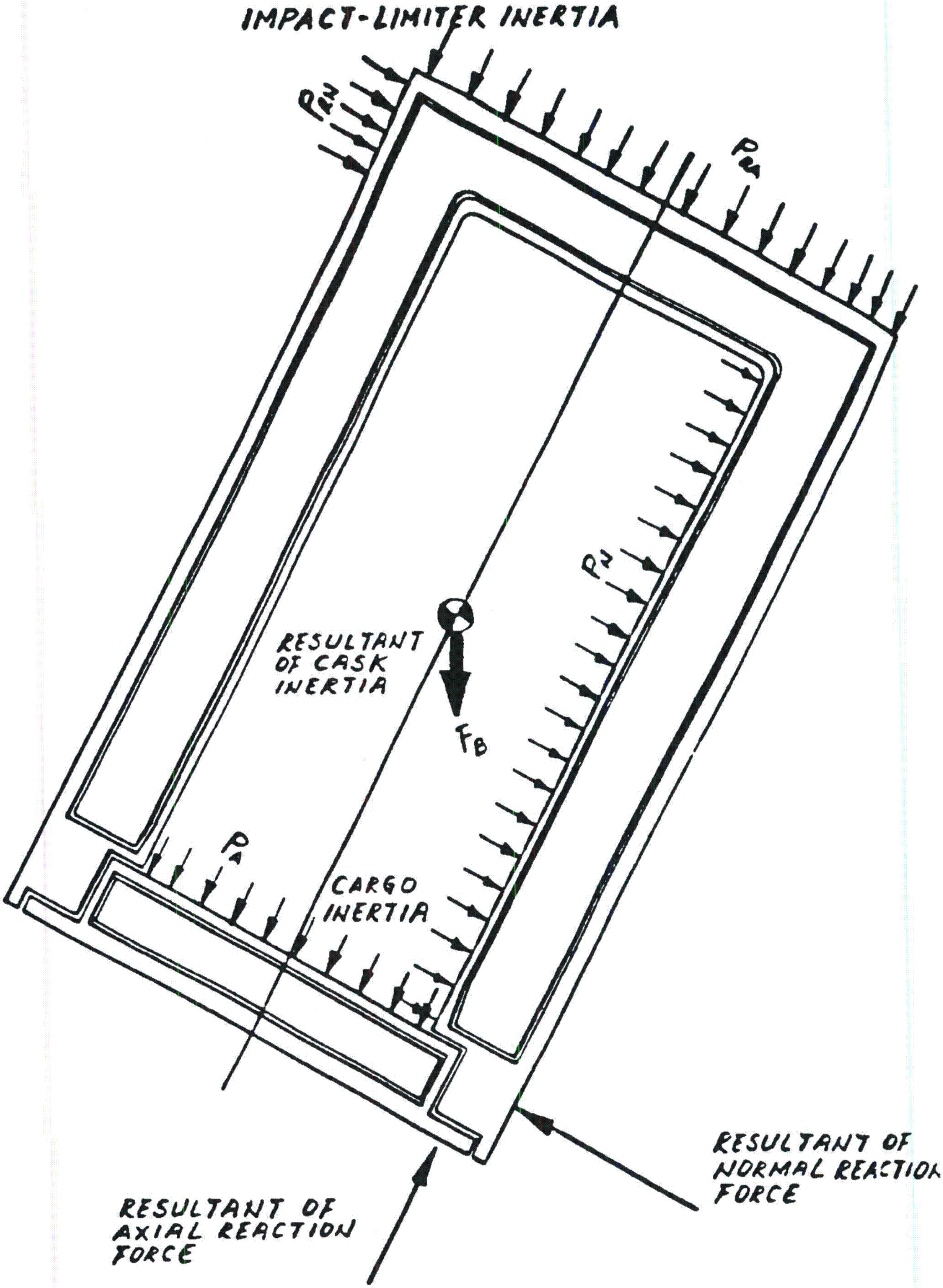


FIGURE 2.10.1-14

LOAD DISTRIBUTION - CORNER DROP

on the corner of the packaging showing all of the forces acting on the cask. These are:

(a) F_B, the resultant body inertia force shown acting at the cask C.G.

(b) The cargo inertia loading was applied in two mutually perpendicular directions (one along the axis of the cask and the other perpendicular to it). The component along the axial direction (P_A) was distributed uniformly over the inside surface of the lid. The other component (P_N) was assumed to vary sinusoidally around the lower half of the inside surface of the inner shell.

(c) The inertia load of the nonstriking impact limiter was also applied to the cask in two mutually perpendicular directions. The axial component (P_{RA}) was applied as a uniform pressure over the outside surface at the interface with the impact limiter on the bottom end. The other component (P_{RN}) was assumed to vary sinusoidally around the upper side of the cask.

Stress Results

Detailed stresses and displacements in the ANSYS models of the cask body are obtained and stored (on magnetic tape) for every node location for each individual load case. These stored results are postprocessed to printout the stresses at the 25 standard locations on the cask body structure shown in Figure 2.10.1-15. The locations selected as shown in Figure 2.10.1-15 are key points that, when

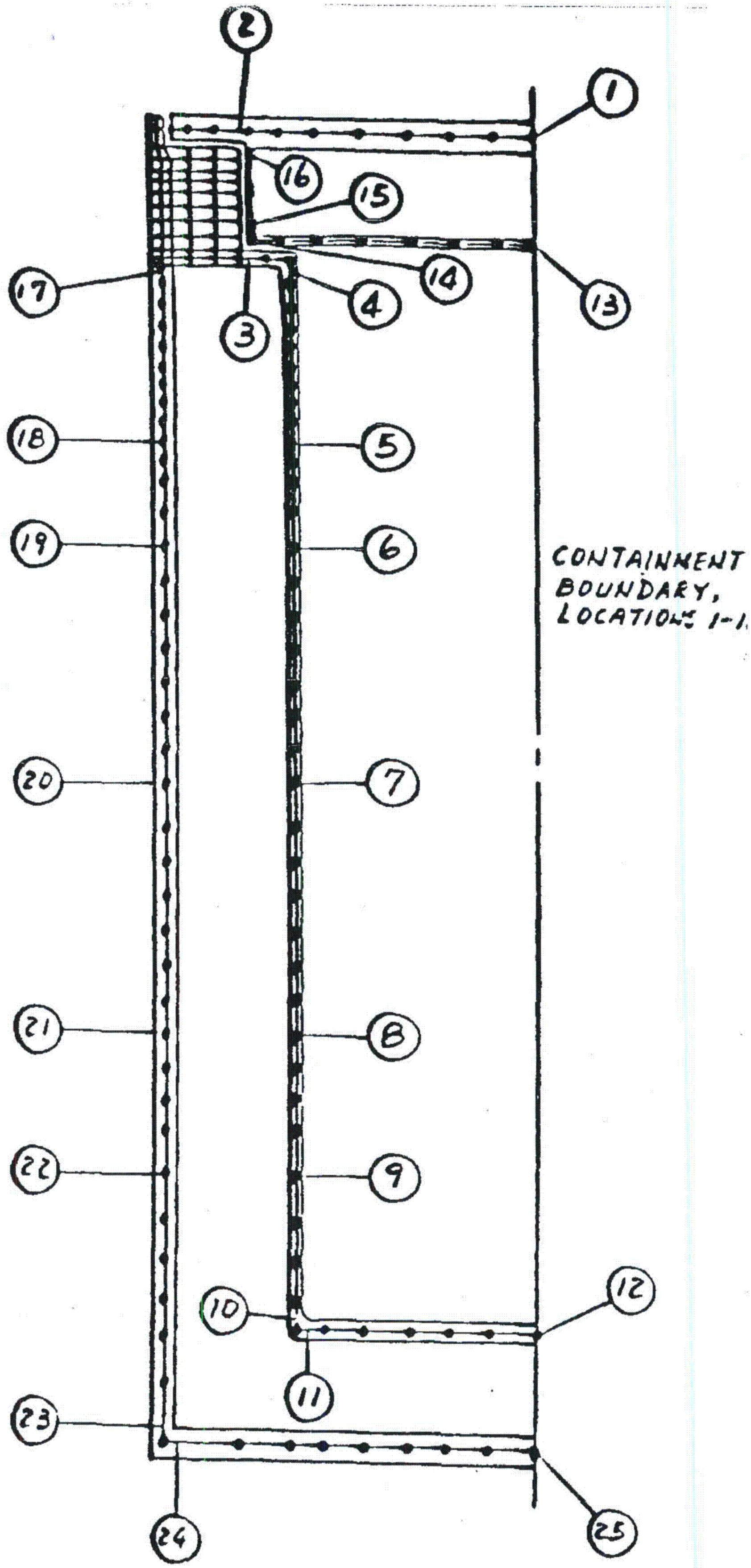


FIGURE 2.10.1-35

STANDARD STRESS REPORTING LOCATIONS