E-48635

Application for Revision 15 to Certificate of Compliance No. 9233 for the Model No. TN-RAM Transportation Packaging

Docket No. 71-9233

(Part 2 of 2)

Enclosed in this binder is part of the submittal package, including transmittal letter and all associated enclosures.

Enclosure 3 to E-48635

TNF-RAM SAR, Revision 16A;
Revision Log, Chapter 1,
Chapter 2 (Sections 2.3, 2.5, 2.7,
Appendices 2.10.2, 2.10.6, 2.10.7, 2.10.10),
Chapter 5, Chapter 7, and Chapter 8
(Non-Proprietary)

Non-Proprietary

SAFETY ANALYSIS REPORT for the TN-RAM

E-10621

July 2017

Revision *16A*

TN Americas LLC
7135 Minstrel Way, Suite 300
Columbia, Maryland 21045

TN-RAM SAR
REVISION LOG
E-10621

Rev. No.	Date	Description
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.
2	7/21/89	Revised Pages as follows: Chapter 1, pages 2-6. Chapter 2, pages iii, xxvi, 2, 3, 13, 14, & 16. App. 2.10.1, pages 72, 79, 82, 82A, 82B, 82C, 83 & 85. App. 2.10.4, pages 20-28. Chapter 3, pages 3 & 3A. Chapter 5, pages 2, 3, 6 & 12.
3	7/28/89	Revised Pages as follows: Chapter 1, page 14. Chapter 2, pgs. iii, vi, viii, xiii, xvi, xxiii, xxvi, 5-10, 12, 13, 21, 22, 42, 43, 45, 46, 49, 51-73, 76, 81-87, 93-95, 98-115, 64A, 72A, 72B, 72C, 73A, 86A & 95A. App. 2.10.1, pgs. 1-3, 3A, 4A, 4B, 5, 8-10, 13, 15, 22, 34, 36, 37-49, 49A, 50-56, 83, 83A, 83B & 83C. Changed 82A-C to 83A-C. Deleted 36A. App. 2.10.4, pgs. 1-5, 9-11 & 13-18. Deleted 19-28.
4	8/11/89	Revised Pages as follows: Chapter 2, pgs. vi, ix, xv, 10, 47, 47A, 49A, 51, 53, 58, 59, 60, 61, 64, 64A, 64B, 80, 81A, 82, 85, 85A, 86A, 95, 95A, 106 & 113. App. 2.10.1, pgs 36, 38A & 85. Deleted 86. App. 2.10.2, page 20A.

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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
9	10/19/07	Revised pages as follows: SAR Cover sheet Revision log page 2 SAR pages 1-1, 1-2, 1-3A, 1-4, 1-6, 1-11, 1-13, 1-14 SAR pages 2-iii, 2-xxviii, 2-1, 2-2, 2-3, 2-8, 2-9, 2-12, 2-14, 2-16, 2-28, 2-94 SAR Appendix 2.10.1 pages 2.10.1-1, 2.10.1-2, 2.10.1-18 SAR pages 3-ii, 3-iii, 3-2, 3-3A, 3-4, 3-6, 3-17, 3-18, 3-19, 3-20, 3-21, 3-22, 3-23, 3-24, 3-25, 3-26, 3-27, 3-28, 3-29, 3-30 SAR pages 4-ii, 4-1, 4-3, 4-5C, 4-7, 4-9 SAR pages 5-1, 5-2, 5-4, 5-5 SAR pages 7-i, 7-1, 7-2, 7-3, 7-4, 7-5, 7-6, 7-7, 7-8, 7-9, 7-10, 7-11 SAR pages 8-i, 8-2, 8-3, 8-4, 8-6 Revised drawings as follows: Drawings 990-701, -703, -704 New pages as follows: SAR Appendix 2.10.8 pages 2.10.8-1 to 2.10.8-22 SAR pages 3-19A, 3-19B, 3-20A, 3-20B, 3-22A SAR pages 4-11, 4-12 SAR pages 7-12, 7-13, 7-14, 7-15, 7-16 New drawings as follows: Drawing 990-710

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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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14	5/21/15	Revised pages as follows: SAR cover sheet SAR page 1-6 SAR pages 3-2, 3-4, 3-7, 3-14, 3-16, 3-17, 3-24, 3-28, 3-30 SAR pages 5-i, 5-ii, 5-1, 5-4 through 5-6, 5-8 through 5-10, 5-12, 5-14 through 5-17, 5-20a, 5-21 through 5-24, 5-26, 5-27, 5-27a, 5-28 through 5-30, 5-33, 5-34
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CHAPTER ONE
GENERAL INFORMATION

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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 *having a larger diameter inner shoulder used for the tiedown attachment point. Both the front and rear trunnion inner shoulders are used as tiedown attachment points designed to* withstand the regulatory basis tiedown.

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. 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. 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.

The contents limit for all radionuclides is 3,000 A_2. 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 safety analysis of the TN-RAM takes no credit for the containment provided by secondary containers.

The quantity of gamma emitting radioactive material is limited to a maximum of 30,000 Ci cobalt-60 or equivalent, *with an exception for TN-RAM No. 02 that limits the maximum of 18,000 Ci cobalt-60 or equivalent due to reduced shielding capability as-fabricated.* The average specific activity of the contents is limited to 10 Ci/kg of Co-60 or equivalent. Equivalence is described in Section 5.5.3. Materials must have the shielding capability of steel or greater.

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

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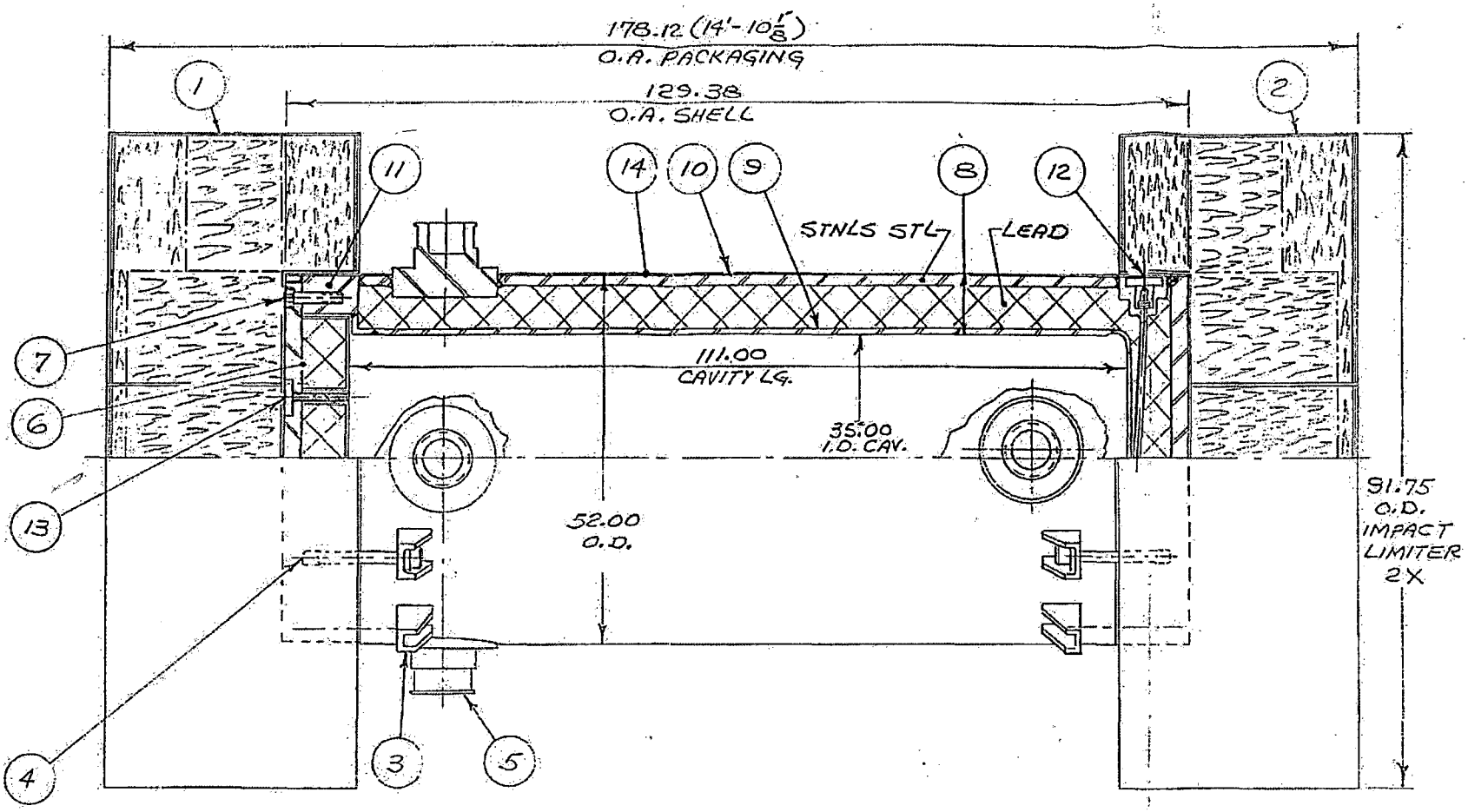
Table 1-1
Materials of Construction Summary

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	10
990-702	Shell Assembly	*10*
990-703	Shell Parts List & Details	11
990-704	Shell Details	7
990-705	Lid Assembly & Parts List	8
990-706	Lid Details	5
990-707	Impact Limiter Assembly	*6*
990-708	Impact Limiter Details & Parts List	*10*
990-709	Impact Limiter Attachment Bolt	2
990-710	Optional Lid Details	2

Proprietary and Security Related Information on the Drawings in Appendix 1.3 Withheld Pursuant to 10 CFR 2.390

CHAPTER TWO
STRUCTURAL EVALUATION

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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 (Sm) for Class 1 components are used to establish allowable stresses for the elastic analyses performed for the TN-RAM. Values of Sm 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 five wood property parameters (density, moisture content, crush strength parallel to the grain, and crush strength perpendicular to the grain) and values that are typical of the wood supply. Crush strength and locking strain are the two properties used as design input for analytical evaluation of impact limiter performance. A minimum moisture specification ensures the wood maintains its structure, and maximum moisture is specified to ensure the crush strength is not significantly affected over the range of normal operating temperatures. Density may be measured as an indicator of crush strength during the selection process for wood that will be subject to acceptance testing. The selected wood has inherent perpendicular properties, but the performance of the impact limiter is not sensitive to the specified value. Therefore, only specified values for parallel properties (crush strength and locking strain) and moisture content are measured and controlled for wood procurement.

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	75,000	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 STRUCURAL 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 l 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	a ($x10^{-6}$in/in/°F)	-	8.55	8.79	9.00	9.19	9.37	9.53	Table I-5.0
ASTM A312 Type 304 LN									
	S_m (psi)	-	33,300	33,100	31,400	30,400	29,700	29,200	Table I-1.2
ASTM A240 Type XM-19	E ($x10^6$ psi)	20.3	-	27.6	27.0	26.5	25.8	25.3	Table I-6.0
	a ($x10^{-6}$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
	a ($x10^{-6}$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
	a ($x10^{-6}$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

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.

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

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

Table 2.3-3
SPECIFIED PROPERTIES OF IMPACT LIMITER WOOD

WOOD TYPE	DENSITY [1] LB/FT^3	MOISTURE CONTENT %	CRUSH STRESS, psi		
			S_0 PARALLEL TO GRAIN	S_{90} PERPENDICULAR TO GRAIN[1]	*LOCKING STRAIN*
Balsa	10-12	10-12	1560-2010	300-420	*0.8*
Redwood	18-27.5	10-15	5000-6000	750-975	*0.6*

Note 1: Typical values are provided for density and perpendicular crush stress (S_{90}). These specifications are not important to the performance of the packaging.

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
75°	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. a 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 3 provided in Appendix 2.10.1.*

*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)*
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

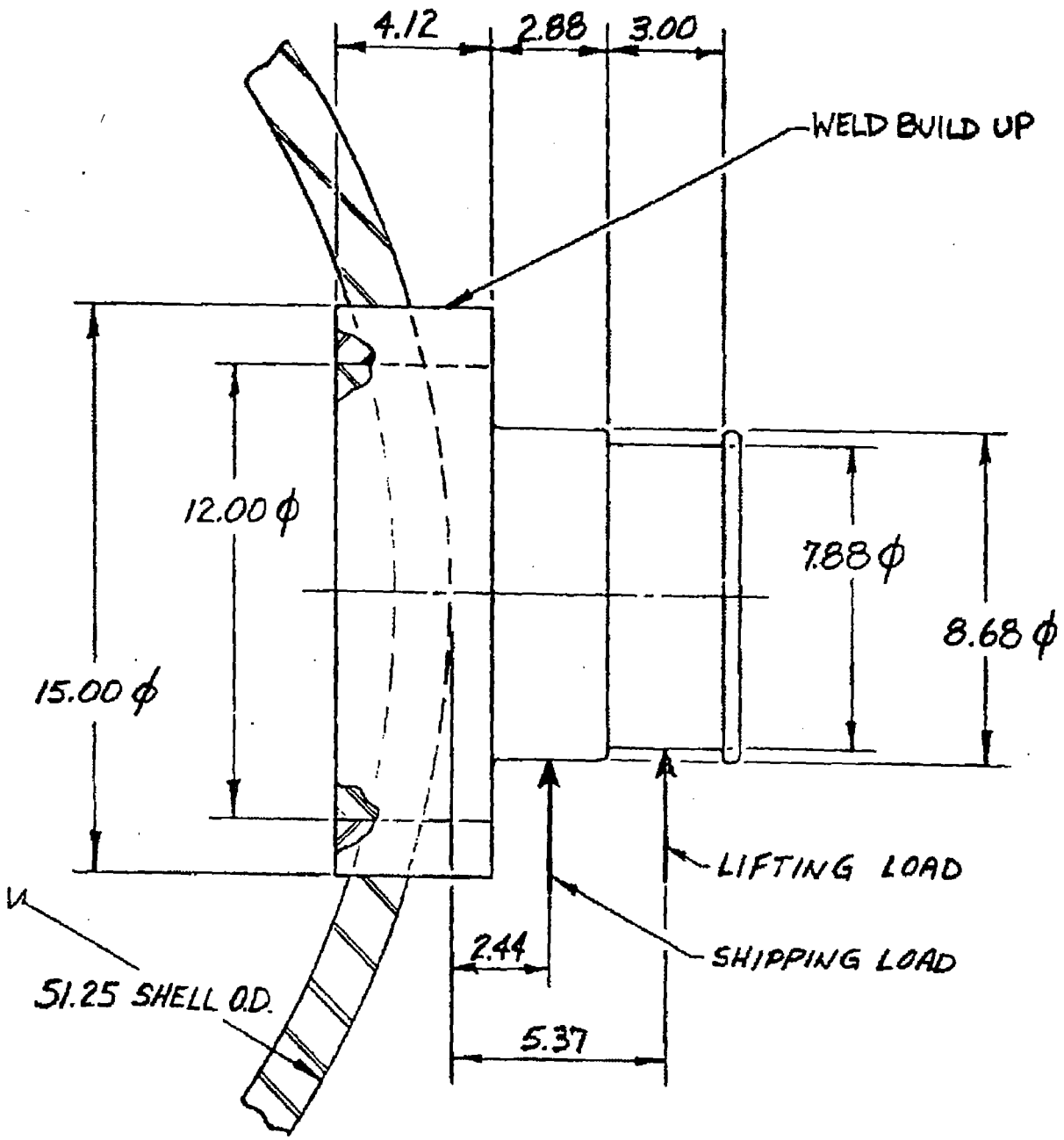
(2) Rack and Knarovsky, "An Assessment of Stress-Strain Data Suitable for Finite Element Elastic-Plastic Analysis of Shipping Containers", NUREG/CR-0481

(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.

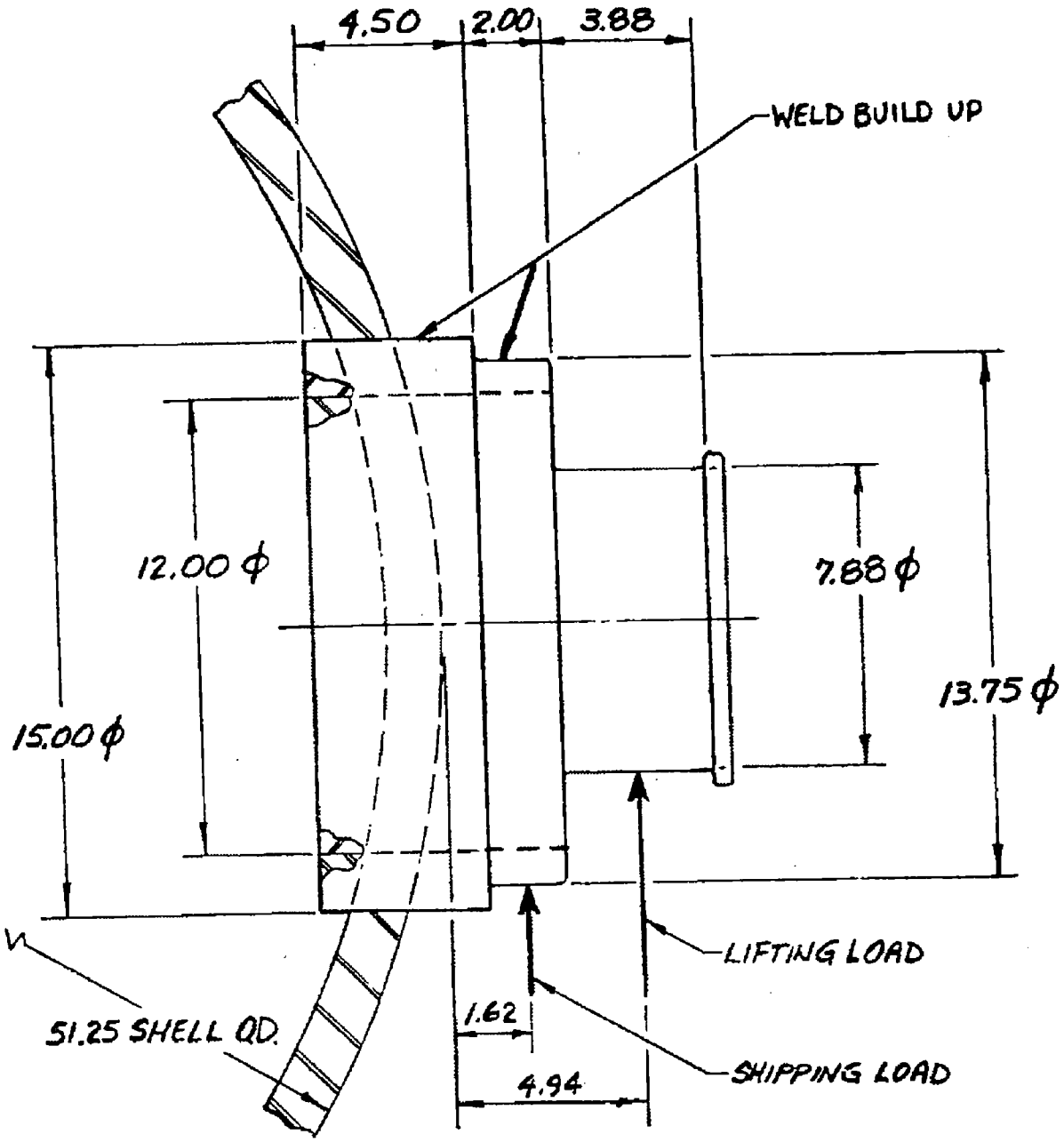
2.5 LIFTING AND TIEDWON STANDARDS

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 *inner* shoulders that rest in the transport *trailer trunnion tie-down* are larger in diameter. Figures 2.5-1 and 2.5-2 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 attaching a lifting device to* 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. *Lifting lugs are welded to the outer shell of the impact limiters, and these lugs are intended for lifting the impact limiters only during removal and installation. The impact limiter lifting lugs are rendered inoperable when the impact limiters are installed on the cask body. Therefore, any lifting attachment points on the cask that are not intended for lifting the full weight of the package are rendered inoperable during transport operations.*

In the transport configuration the cask the front and rear trunnion inner shoulders provide the tie-down attachment points to the package. Four trunnion pedestals, which are welded to the transport trailer frame, are the tie-down members that secure the load during routine transport conditions. Each of the trunnion inner shoulders is secured in a bearing frame member with a metal strap. The loading condition used for evaluation of the tie-down attachment point strength includes the total width of the assembled cask with maximum payload and impact limiters (80,000 lbs). The 2 G vertical load is shared equally between the four trunnions inner shoulders (two front and two rear). The 5 G load component, which is transverse to the direction of travel, is shared between one front trunnion and one rear trunnion on the same side of the cask. The trunnion pedestal tie-down allows for some movement transverse to the direction of travel in such a way that the 5 G loading only results in a uniform compressive force applied to the trunnion base plate flange. Nominal dimensions and tolerances for the trunnion shoulders and trunnion pedestal weldments provide an allowance that compensates for the uncertainty that the 10 G load would be shared equally between the front and rear trunnions. The 10 G load component applied in the direction of travel is assumed to be applied to either the two front trunnion inner shoulders, or to the two rear trunnion inner shoulders. The front or rear trunnions share the 10 G load component in the direction of travel.

The tiedown analysis provided in Section 2.5.2 therefore computes stresses resulting from tiedown loads for the *front and* rear trunnions. There are no other structural parts of the package which *are intended to 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) $S=\sqrt{\sigma^2 + 4\pi^2}$

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:

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

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

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.

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

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

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

The combined stresses are then:

$$S_{\text{outer shoulder}} = \sqrt{(4{,}666)^2 + 4(4{,}424)^2} = 10{,}000 \text{ psi}$$

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

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:

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

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

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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 usin9 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 8 is 0.84.

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

$$\sigma_b = \frac{\beta M}{at^2} = \frac{(.840)(644.400)}{(7.5)(4.12)^2} = 4{,}251 \text{ psi}$$

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 θ
The arc length is Rdθ
Therefore. the moment is

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

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

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

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

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

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:

$$v_{max} = \frac{M}{R^2\pi} = \frac{644400}{(6)^2\pi} = 5687.7 \text{ lbs/in}$$

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

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 $\frac{b}{a} = \frac{4.34}{6} = .723$

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From the table in Roark, $\beta = .420$
The radial stress is

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

$\sigma_t = 1922$ 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:

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

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.

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The calculation is performed using the same methodology as that used in the front trunnion lifting analysis (Section 2.5.l). 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.

Rear 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

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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 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.

Rear Trunnion Base Plate

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 (13.75in) is calculated below:

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

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

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

The combined stress is:

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

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

Front Trunnion Shoulder Analysis

The inner trunnion shoulder is analyzed assuming it is cantilevered from the trunnion base plate, which is welded to the outer shell of the cask. Although there is a ∅5.25-inch × 4.12-inch deep recess in the trunnion, the recess only extends 0.62 inches into the ∅8.68-inch × 2.88-inch thick inner shoulder. Therefore, this recess does not affect the sectional properties at the base of the shoulder, and can be ignored.

The maximum bending stress, σ_b, for the tie-down load is computed as follows:

$$\sigma_b = \frac{M}{Z}$$

where:

σ_b = *bending stress, psi*
M = moment at base of inner shoulder, lb-in
Z = section modulus = $(\pi/32)(D^3)$, in^3

From Section 2.5.2 of the TN-RAM SAR, the resultant tie-down load for the 10g longitudinal and 2g vertical loads is 402,000 pounds at an angle of 5.7 degrees relative to the horizontal direction. This resultant load acts at the midpoint of the 2.88-inch thick trunnion (1.44 inches). The applied moment, M, is then:

$$M = (402{,}000)(1.44) = 578{,}880 \text{ } lb\text{-}in$$

The section modulus, Z, for the ∅8.68-inch inner trunnion is:

$$Z = \left(\frac{\pi}{32}\right)(8.68^3) = 64.204\ in^3$$

The bending stress at the base of the inner shoulder is:

$$\sigma_b = \frac{578{,}880}{64.204} = 9{,}016\ psi$$

The shear stress, τ, on the inner shoulder section is:

$$\tau = \frac{V}{A} = \frac{402{,}000}{\pi/_4\,(8.68^2)} = 6{,}794\ psi$$

For the 5g transverse load, Section 2.5.2 of the TN-RAM SAR states that the load is applied directly to the trunnion flange, and does not influence the shoulder stress. Therefore, the total bending-plus-direct tension stress, σ_T, is:

$$\sigma_T = \sigma_b = 9{,}016\ psi$$

Combining the tension stress with the shear to obtain the stress intensity, SI, yields:

$$SI = \sqrt{9{,}016^2 + 4(6{,}794)^2} = 16{,}307\ psi$$

The TN-RAM trunnions are fabricated of Type 304 stainless steel, which has a minimum yield strength of 30,000 psi. The resultant MS for this stress intensity on the inner shoulder is:

$$MS = \frac{30{,}000}{16{,}307} - 1 = +0.84$$

Front Trunnion Base Plate Analysis

The ∅15.0-inch × 4.12-inch thick trunnion base plate is analyzed as a fixed circular plate with a bending moment applied by a circular boss at the center of the plate. As noted in Section 2.5.1 of the TN-RAM, this configuration is analyzed per Case 21 in Table 24 of Roark's Formulas for Stress and Strain, Fifth Edition [7]. For this case, b/a = 0.578 and β = 0.84. Therefore, the bending stress, σ_b, is:

$$\sigma_b = \frac{\beta M}{at^2}$$

where:

σ_b = *bending stress, psi*
M = *moment at base plate junction with outer cask shell*
= *(402,000 lb)(2.44 in) = 980,880 lb-in*
a = *radius of base plate = 7.5 in*
t = *thickness of base plate = 4.12 in*

Substituting these values into the above equation yields the base plate bending stress:

$$\sigma_b = \frac{(0.84)(980{,}880)}{7.5(4.12)^2} = 6{,}472\ psi$$

The shear stress, τ, in the base plate at the shoulder diameter (∅8.68 inches) is calculated as analyzed in Section 2.5.2 of the TN-RAM SAR:

$$V_{max} = \frac{M}{R^2\pi} = \frac{980{,}880}{4.34^2(\pi)} = 16{,}576\ lb/in$$

$$\tau = \frac{V_{max}}{t} = \frac{16{,}576}{4.12} = 4{,}023\ psi$$

Combining the bending stress with the shear to obtain the stress intensity, SI, yields:

$$SI = \sqrt{6{,}472^2 + 4(4{,}023)^2} = 10{,}326\ psi$$

The resultant MS for this stress intensity on the inner shoulder is:

$$MS = \frac{30{,}000}{10{,}326} - 1 = +1.91$$

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 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. 3

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 2.7-1B 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. 3

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:

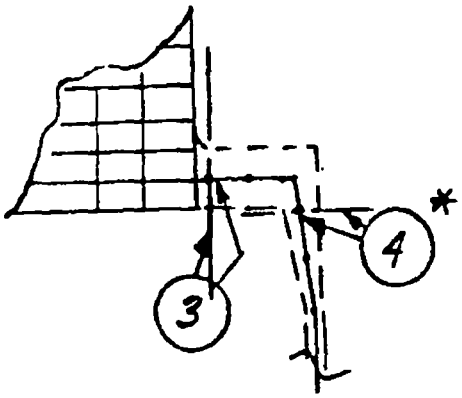
1) The locations shown are at the ends of the elements where they are connected to the nodes.

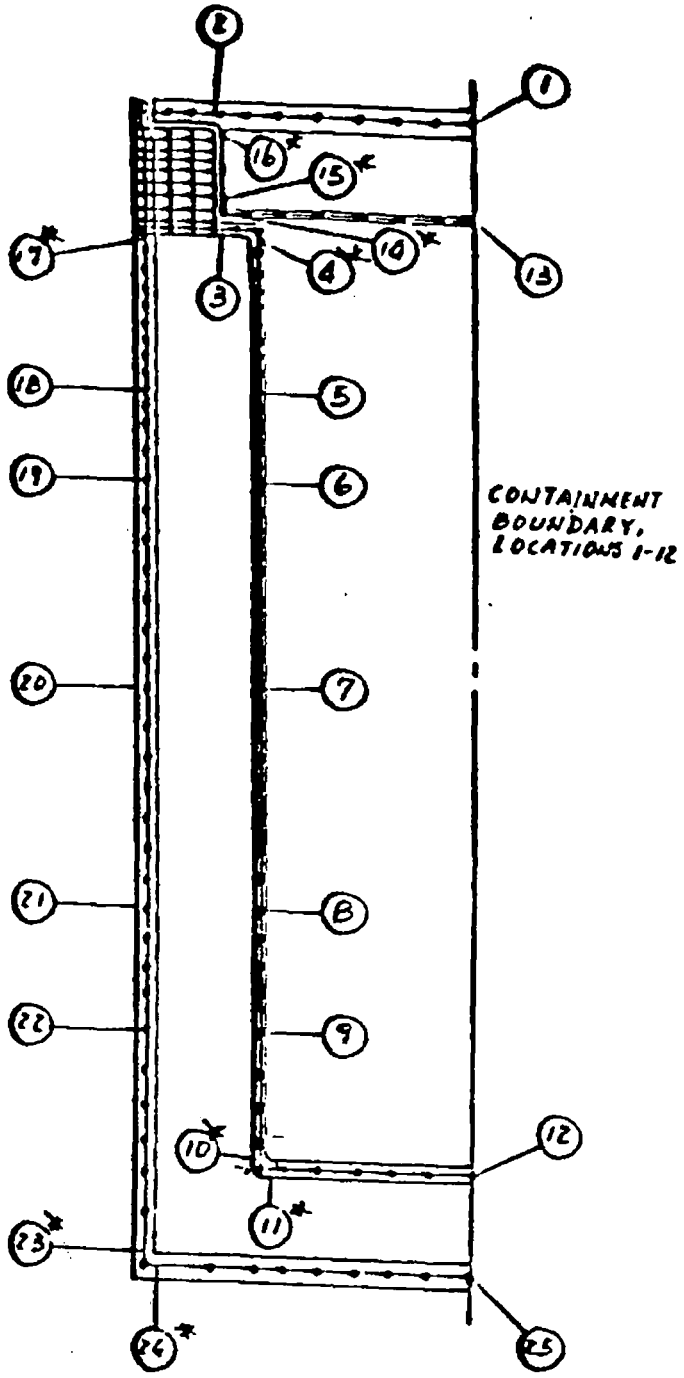
2) The stress summary tables present the membrane stress intensities based on components <u>averaged</u> through the thickness and the membrane plus bending stress intensities at both surfaces for all 25 locations.

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										STRESS RESULT TABLES
	IL-1	IL-2	IL-3	IL-5	IL-6	IL-11	IL-12	IL-13	IL-14	IL-15	
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:

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

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.

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 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. 3

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 45,294 psi. 3

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.

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.

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. 4

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:

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

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*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.

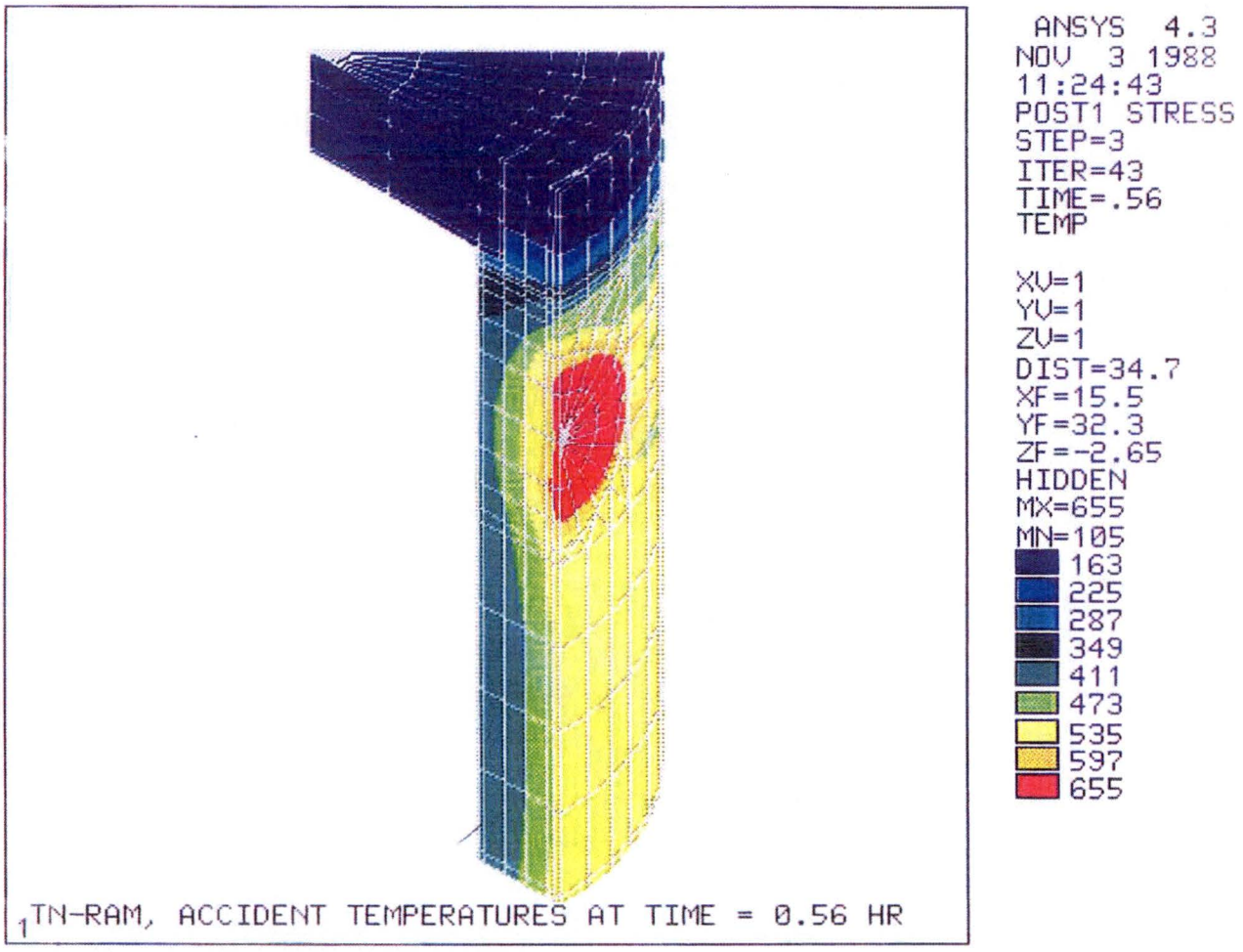
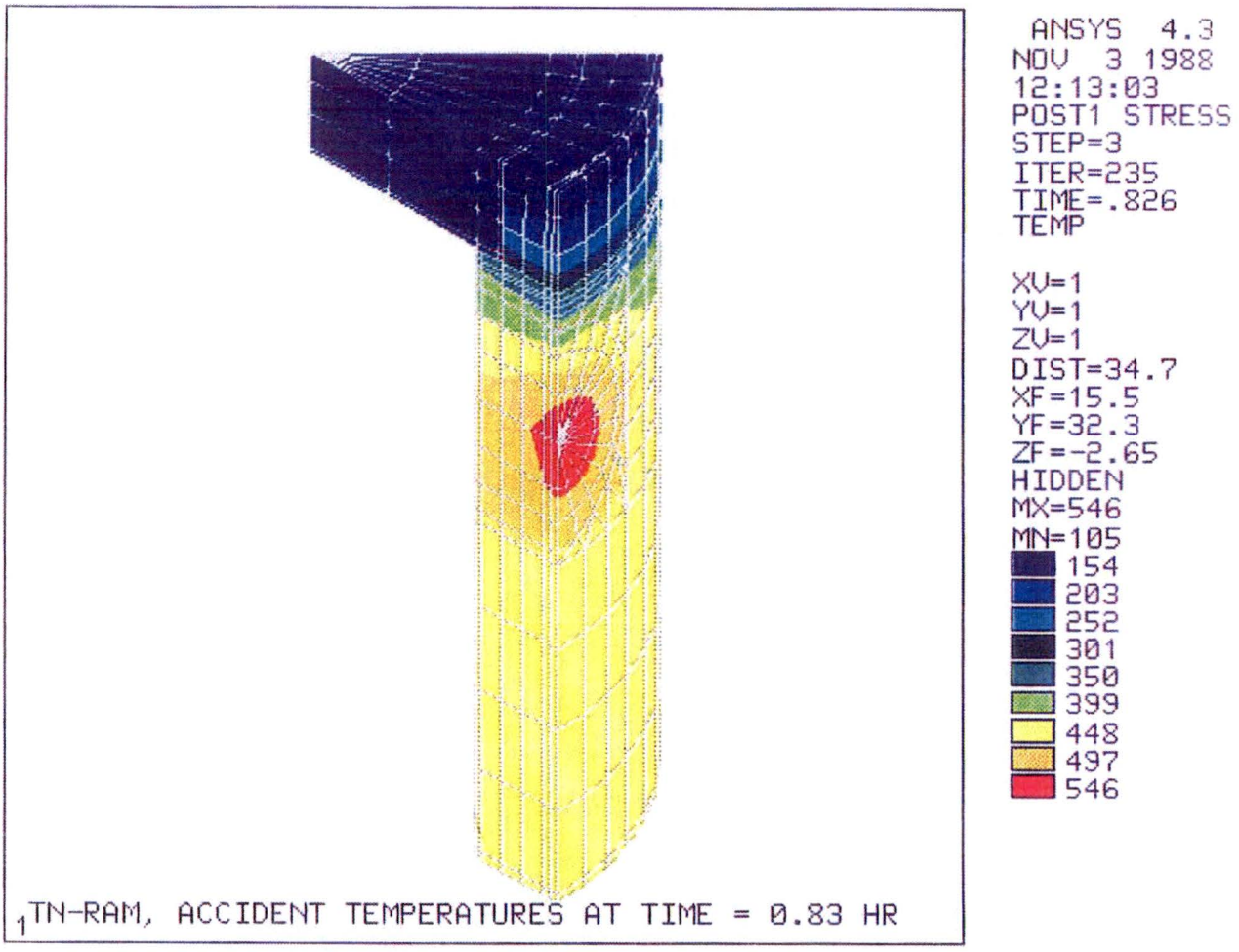


FIGURE 2.7-3

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 hr, 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 TN-RAM is not a fissile material package. Thus, the requirements of 10 CFR 71.73 (c) (*5*) are *not applicable*.

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 10 CFR 71.73(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.

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. 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.

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.

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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

3

*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.

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	MEMBRANE + BENDING	
				Pm or (Pl)*	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)*	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.

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)	397.4	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

(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

Rev. 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

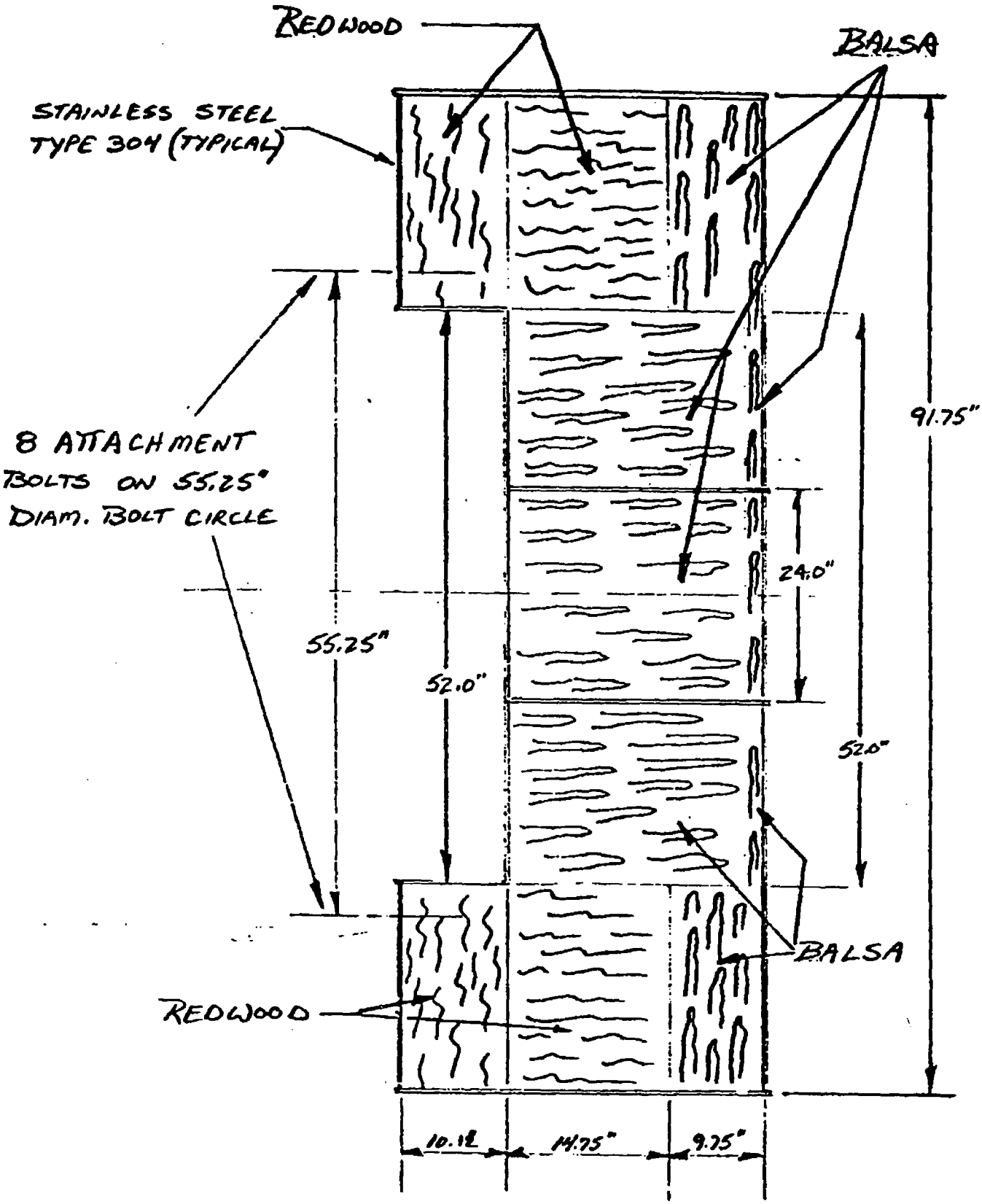
(See page 2-114 for loading descriptions.)

APPENDIX 2.10.2
STRUCTURAL ANALYSIS OF IMPACT LIMITERS

2.10.2.1 INTRODUCTION

This appendix presents the details of the structural analysis of the TN-RAM impact limiters. The impact limiters are designed to absorb the kinetic energy resulting from the one (1) foot and thirty (30) foot normal and hypothetical accident free drop events specified by 10 CFR 71. Redwood and balsa wood are used as the primary energy absorption material(s) in the impact limiters. A sketch of the impact limiter is shown in Figure 2.10.2-1. A functional description of the impact limiters is given in Section 2.10.2.2. The impact limiter design criteria are described in Section 2.10.2.3.

A computer model of the TN-RAM Packaging was developed to perform a system dynamic analysis during the impact after the 30 foot drop accident. The model was developed for use with the ADOC (Acceleration Due To Drop On Covers) computer code described in detail in Section 2.10.2.5 which determines the deformation of the impact limiters, the forces on the containment and the packaging deceleration due to impact on an unyielding surface. Numerous cases were run to determine the effects of the wood properties and initial drop angle. A description of the computer model, input data, the ADOC computer code, analysis results and conclusions are given in Sections 2.10.2.4 through 2.10.2.5. The forces and decelerations calculated by ADOC have been used in the cask body structural analysis which is presented in detail in Appendix 2.10.1. Test



IMPACT LIMITER

FIGURE 2.10.2-1

programs on wood filled limiters of similar designs have been completed and are discussed in Appendix 2.10.3. Test results indicate that ADOC predicts conservatively high deceleration values and crush forces.

The dynamic analysis of the TN-RAM for the one foot normal condition free drop is presented in Section 2.10.2.6. The analysis of the impact limiter attachments and the analysis of the impact limiter under normal pressure fluctuations are described in Sections 2.10.2.7 and 2.10.2.8, respectively.

2.10.2.2. DESIGN DESCRIPTION

The impact limiters absorb energy during impact events by crushing of balsa and redwood. The size, location and orientation of each wood block is selected to provide protection for the cask during all normal conditions of transport and hypothetical accident conditions.

The top and bottom impact limiters are identical and interchangeable. Each has a diameter of 91.75 inches and a height of 34.62 inches. The inner and outer shells are Type 304 stainless steel joined by radial gussets of the same material. The gussets limit the stresses in the 0.125 in. thick steel outer cylinder and end plates due to pressure differentials caused by elevation and temperature changes during normal transport and provide wood confinement during impact. The metal structure positions, supports, confines and protects the wood energy absorption material. The metal structure does contribute to the energy absorbing capability of the impact limiter. However, the contribution for a side drop or oblique angles is negligible because contact starts at a single point with the unyielding surface (target) and initiates buckling of a single gusset. After the drop event is complete, relatively few gussets are buckled. Each limiter has 13 wood compartments: a central circular region 24 inch diameter surrounded by 12 radial pie shaped compartments.

The region of the impact limiter which is backed-up by the cask body is filled with balsa wood orientated with the grain direction perpendicular to the end of the cylindrical cask (See Figure 2.10.2-1). The material and grain orientation are selected to provide acceptably low deceleration to prevent lead slump during impact after

the thirty foot end drop. A 2.0 inch layer of balsa wood with the grain parallel to the end of the cylindrical cask is provided on the outer face of the impact limiter to minimize decelerations under the one foot end drop.

A 10.12 inch wide ring of redwood (consisting of 12 segments or blocks of wood) is located in the sides of the pie shaped compartments which surround the end of the cylindrical surface of the cask with the grain direction oriented radially. This ring of redwood absorbs most of the kinetic energy during a side drop. Redwood was selected for this portion of the impact limiter because of its high crush strength and hence the ability of a small amount of wood to absorb a large amount of energy in a relatively short crush distance.

The corners of the pie shaped compartments are filled with redwood and balsa blocks. A 14.75 inch section of redwood is located next to the side redwood and a 9.75 inch block of balsa wood is located in the outer corner. The grain orientation in the redwood block is parallel to the side of the cask body and that in the balsa block is parallel to the end (radial). The primary function of the redwoood block is energy absorption during corner drops while the balsa wood limits the decelerations to acceptable levels during the one foot normal condition end drop.

All wood blocks used in the impact limiters are composed of individual boards glued together with a Phenol Resorcinol Adhesive. This adhesive was selected for its superior strength and moisture resistance. The glue is waterproof up to a temperature of 200°F. The adhesive used conforms to the requirements of Federal

Specification MMM-A-l88b. The wood blocks are assembled and glued together in accordance with an approved QA procedure. Minimum properties of the adhesive are listed in Table 2.10.2-1. Ranges of shear and tensile strengths of each type of wood are also listed. The adhesive is significantly stronger than any of the wood used in the limiter in terms of shear and tension strength. Therefore the boards or blocks of wood will not fail along the glue joints.

The other mechanical properties of the wood used in the analysis of the impact limiters are shown in Table 2.10.2-2. The crush stress properties used cover the range of expected values for the density and moisture content specified in the procurement specification. These ranges also cover the expected variation in wood properties over the operating temperature range of interest; i.e., -20°F to 16S°F.* During procurement, wood samples are tested for moisture content and crush stress *parallel to the wood grain* in accordance with an approved sampling plan.

If *crush stress measured parallel to the wood grain, locking strain,* and moisture content are not within the specified range, the wood blocks from which samples are taken will be rejected.

* Von *Riesemann*, W. A. and *Guess*, T. R., The Effects of Temperature on the Energy-*Absorbing* Characteristics of Redwood, Sandia Laboratories SAND-77 1509, Aug. 1978

Knoell, A. C., *Physical and* Environmental Effects *on the* Energy Dissipation *Characteristics of* Balsa Wood, Jet Propulsion Laboratory, Technical Report No. 32-944, June 15, 1966

TABLE 2.10.2-1

MECHANICAL PROPERTIES OF WOOD AND WOOD ADHESIVE

Minimum Properties of Phenol Resorcinol Adhesive

Shear Strength by Compression Loading	2,800 lbs/in^2	(1)
Shear Strength by Tension Loading	340 lbs/in^2	(1)

Properties of Heavy Balsa (10-12 lb/ft^3)

Shear Strength Parallel to Grain	315-385 psi max.	(2)
Tensile Strength Perpendicular to Grain	140-160 psi	(2)

Properties of Redwood

Shear Strength Parallel to Grain	940 psi	(3)
Tensile Strength Perpendicular to Grain	240 psi	(3)

(1) Federal Specification MMM-A-188b

(2) Dreisback, J.F., Balsa Wood and Its Properties, Columbia Graphs, Columbia, CT 1952

(3) Marks Standard Handbook for Mechanical Engineers, Eighth Edition, pg. 6-124

For the end drop, all of the wood in the central part of the impact limiter that is directly "backed-up" by the cask body will crush. The wood in the corner and side of the limiter will tend to slide around the side of the cask since it is not supported or backed-up by the body and it will not crush or absorb energy as effectively as the wood that is backed-up. During the side or oblique drop the wood backed up by the cask will crush, while the wood beyond the end of the cask body will have a tendency to slide around the end of the cask. The analyses assume that the effectiveness of the portion of the wood that is not backed-up may be as small as 20% or as large as 80%. Effectiveness is defined as the actual crush force developed at the target by this material divided by the theoretical force required to deflect the material. The analysis also assumes a range of wood crush strengths. When determining maximum deceleration, the maximum crush strengths are used and the non backed-up material is assumed to be 80% effective. When determining crush depth, the minimum wood crush strengths are used and the non backed-up wood is considered to be only 20% effective.

Each impact limiter is attached to eight local lugs welded to the side of the cask using high strength bolts. The attachments have been sized to withstand the loads transmitted during a side drop. This analysis is described in Section 2.10.2.7 of this Appendix.

2.10.2.3 DESIGN CRITERIA

The outside dimensions of the impact limiter are sized to be well within federal and state highway height and width restrictions. The balsa and redwood distribution and densities have been selected to limit the maximum cask body inertia loads due to the one foot normal condition drop and the thirty foot hypothetical accident drop so that the design criteria specified for the containment boundary, the non containment structure and shielding (See Section 2.1) are met.

The welded stainless steel structure of the impact limiter is designed so that the wood is maintained in position and is confined during crushing of the impact limiters. The outer shell and gussets are designed to buckle and crush during impact. Local failure of the shell is allowed during impact limiter crushing. The welded stainless steel shell and its internal gussets are designed to withstand pressure differences and normal handling and transport loads with stresses limited to the material yield strength.

The impact limiters are designed to remain attached to the cask body during all normal and hypothetical accident conditions.

2.10.2.4 ANALYSIS FOR 30 FT FREE DROP ACCIDENT CONDITIONS

2.10.2.4.1 Approach

The kinetic energy due to the hypothetical 30 ft drop accident is absorbed by crushing of the impact limiters on the ends of the packaging. The limiters contain materials, i.e. balsa and redwood, which provide controlled deceleration of the packaging by crushing between the target surface and the cask body.

The applicable regulation, 10CFR71.73, requires that the packaging be oriented for the drop so that it strikes the target in a position for which maximum damage is expected. Dynamic impact analyses were performed for different packaging orientations using the ADOC computer code described in Section 2.10.2.5. This computer code has been validated by comparing its dynamic results with those from hand calculations for relatively simple problems, comparing its calculated force-deflection curves with those obtained from static crush tests, and by correlating dynamic results with actual measured cask behavior on other programs (see Appendix 2.10.3).

2.10.2.4.2 Assumptions and Boundary Conditions

The assumptions and boundary conditions are as follows:

1. The cask body is assumed to be rigid and absorbs no energy. This assumption is realistic since the design criteria of Section 2.1.2 limit metal deformations to small values. All of the impact energy is therefore assumed to be absorbed by the impact limiters.

2. The crushable material is one or several anisotropic materials. The different wood regions are modeled individually.

3. The crush strengths of the wood sections are obtained from the properties parallel to and perpendicular to the grain based on the orientation of the cask at impact.

4. Each wood region is modeled as a one dimensional elastic, perfectly plastic material up to a specific locking strain. After reaching the locking strain, the stress increases linearly with additional strain. The wood properties (modulus of elasticity, average crush strength, locking modulus, and locking strain) are taken from force-deflection curves of sample blocks of wood. Typical force-deflection curves for redwood and balsa are shown in Figures 2.10.2-1A and 2.10.2-1B. Since the locking strain varies from sample to sample, conservatively low locking strains of 80% for balsa and 60% for redwood are used.

5. The crush properties of the wood are varied with the initial angle of impact and do not change during the drop event being evaluated.

6. The cask and impact limiters are axisymmetric bodies.

7. The crushing resistances of the impact limiter shell and gussets have a negligible effect on the crush strength of the limiter and, therefore, a negligible effect on the impact forces and inertia loads.

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FIGURE 2.10.2-1A

SAMPLE FORCE-DEFLECTION CURVE FOR BALSA

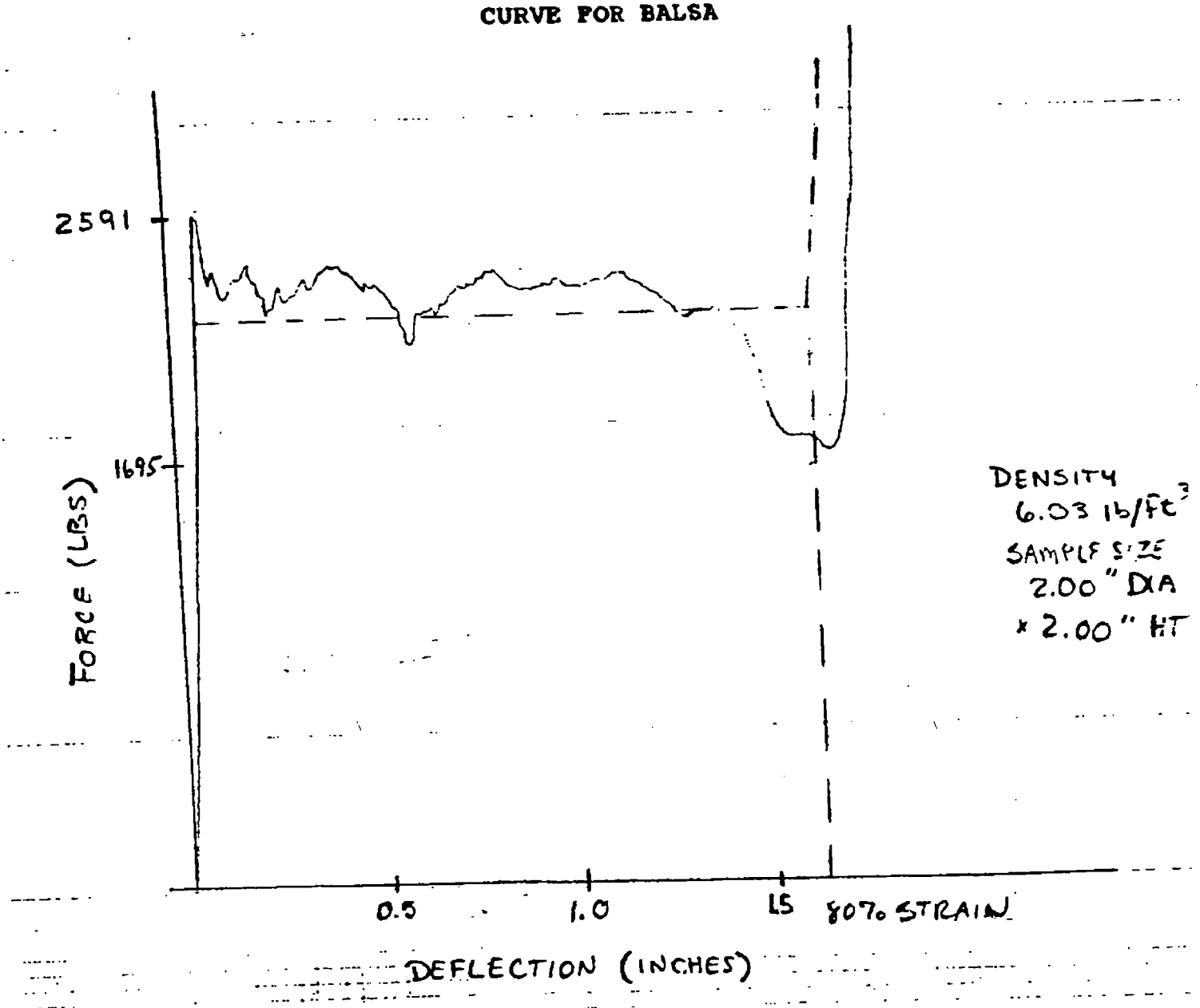
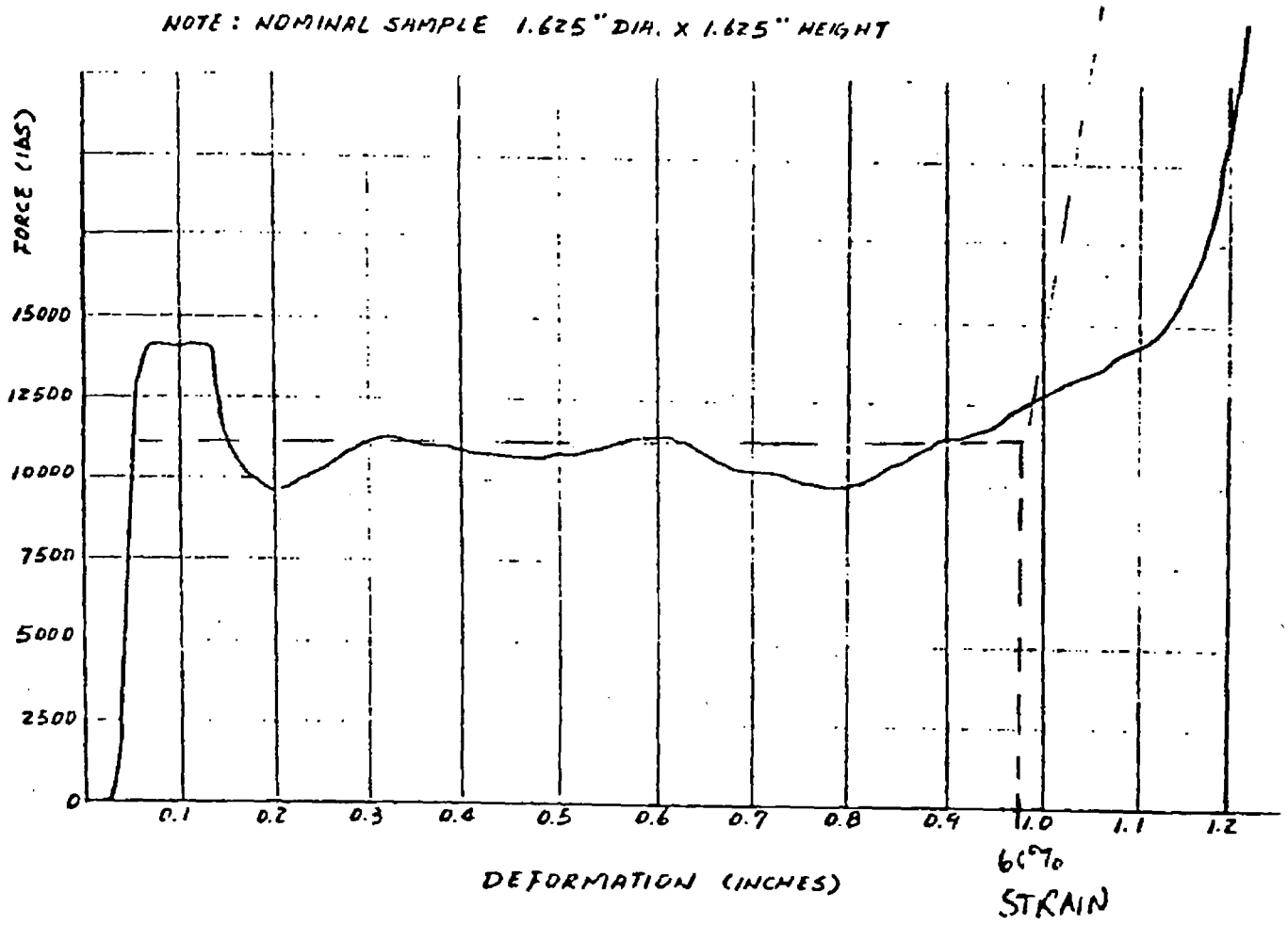


FIGURE 2.10.2-1B

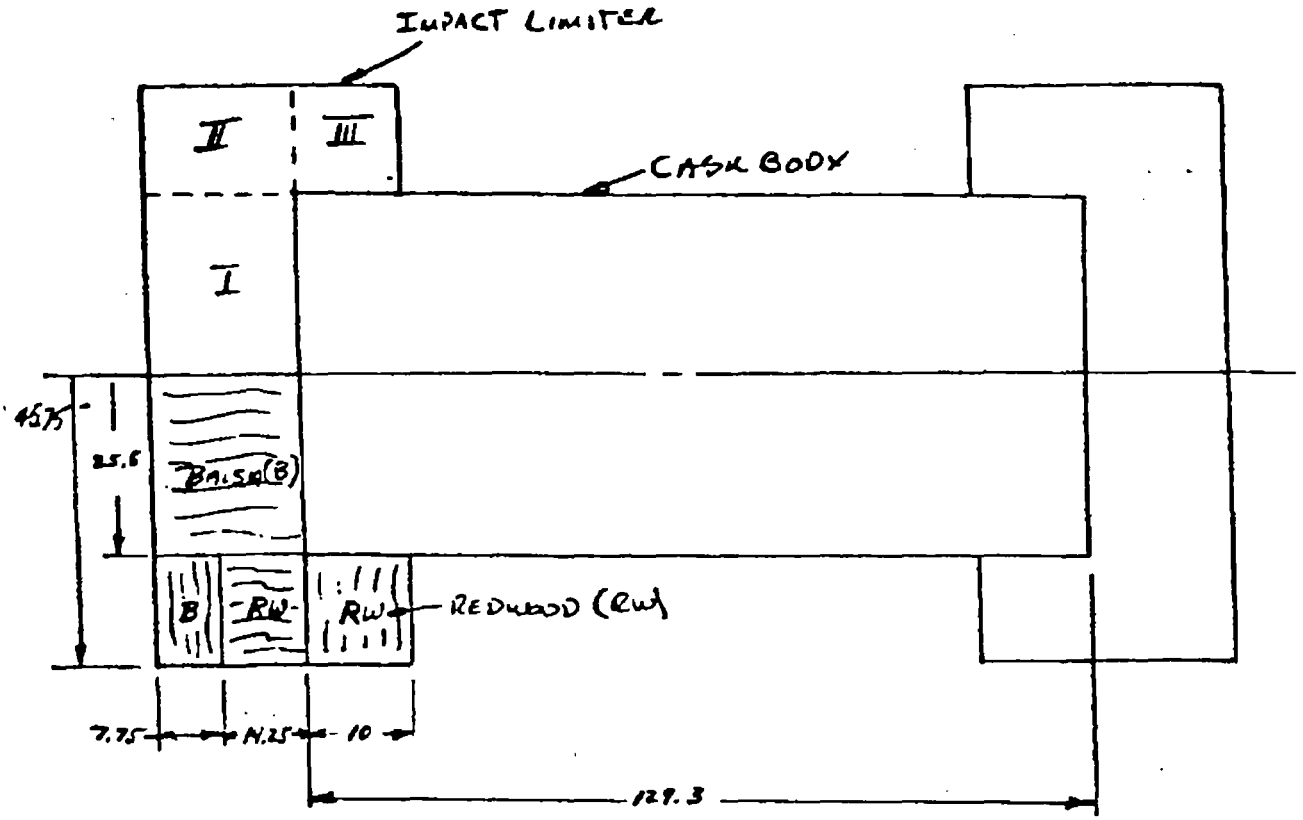
SAMPLE FORCE-DEFLECTION CURVE FOR REDWOOD



2.10.2.4.3 Packaging Dynamic Computer Model

Figure 2.10.2-2A illustrates the computer model used for all packaging orientations. Regions I, II, and III in the model are used to delineate regions where different impact limiter materials are used. It should be noted that the properties of the three regions have been designed by choosing wood types and orientations to accommodate the crush requirements of the three significant drop orientations. The crushable materials of Regions I, II, and III are selected to control the decelerations resulting from vertical, corner, and side drop orientations, respectively. Table 2.10.2-2 tabulates the wood properties that were used to describe the wood stress-strain behavior in the analysis.

A portion of the impact limiter crushable material is backed up by the cask body as it crushes against the impact surface. The remaining material overhangs the cask body and is not backed up. Backed up regions project vertically from the target footprint to the cask body, while unbacked regions do not project vertically to the cask. The effectiveness of the energy absorbing crushable material varies depending on whether it is "backed up" by the cask or is unsupported. Two cases are analyzed to bound impact limiter performance. In one case the non backed up material is assumed to be 80% effective and maximum wood crush strength is used (maximum of the possible range based on specified density). In the other case the non-backed up material is assumed to be only 20% effective and minimum wood strength is used. Evaluating impact limiter performance in this way results in a large range of deceleration values, crush forces and crush depth. This in combination with



ADOC COMPUTER MODEL FOR TN-RAM PACKAGING

FIGURE 2.10.2-2A

close control of wood properties during procurement assures that the effects of wood properties variation (including temperature effects) and the effectiveness (or lack of effectiveness) of the non backed-up portions of the limiter are covered.

2.10.2.4.4 Analysis Results Predicted by ADOC

The peak inertia loadings or cask body decelerations (in terms of g's) versus initial angle of impact are presented in Tables 2.10.2-3 and 2.10.2-4 for the 30 foot drop. The depth of crush versus initial angle of impact is shown in Tables 2.10.2-5 and 2.10.2-6. Since the packaging CG is within a few inches of the center and the impact limiters are identical, these tables are valid for impact on either end.

In order to determine the cask stresses, these maximum g loads are converted to forces and applied as quasistatic loadings on the outer cask body. A detailed ANSYS finite element model of the TN-RAM cask is used to perform this analysis. Cask body stress analyses are performed for end, side and CG over corner (70°) impact orientations. The lid bolts are analyzed for the maximum axial g load of 80.9 which occurs at an angle of 85°. The full details of the stress analyses are presented in Section 2.10.1.

Based on the crush depths for the side drop from Tables 2.10.2-5 and 2.10.2-6, the trunnions would not hit the target. For the maximum wood properties and 80% effectiveness of non backed-up wood the clearance after the limiters crush would be approximately be 3 1/2 inches. For the minimum wood properties and 20% effectiveness of

Table 2.10.2-2

TYPICAL WOOD MATERIAL PROPERTIES

PROPERTY	BALSA	REDWOOD
Density[1]	10-12 lb/ft^3	18.7-27.5 lb/ft^3
Parallel to Grain		
Crush Stress	1560-2010 psi	5000-6500 psi
Locking Strain	0.8	0.6
Unloading Modulus	32,000 psi	1,247,000 psi
Locking Modulus	3,400 psi	4,100 psi
Perpendicular to Grain[1]		
Crush Stress	300-420 psi	750-975 psi
Locking Strain	0.8	0.6
Unloading Modulus	32,000 psi	1,247,000 psi
Locking Modulus	3,400 psi	4,100 psi

Note:

1 *Typical values are provided for density and perpendicular crush stress (S_{90}). These specifications are not important to the performance of the packaging.*

TABLE 2.10.2-3

MAXIMUM INERTIA G LOAD VERSUS INITIAL ANGLE OF IMPACT

FOR 30 FEET DROP

MAXIMUM WOOD CRUSH STRESS

EFFECTIVENESS OF NON-BACKED UP WOOD: 80%

	MAXIMUM G LOAD DURING FIRST IMPACT			
		TRANSVERSE		
Initial Angle Of Impact	Axial @ C.G.	Primary Impact End	@ C.G.	Opposite End
90°	69.6	0	0	0
85°	80.9	- 8.5	- 5.0	- 1.5
80°	77.2	-11.8	- 7.47	- 3.18
70°	61.1	-19.4	-13.9	- 8.48
60°	64.7	-31.9	-23.4	-15.0
50°	61.4	-64.0	-35.1	- 6.14
40°	42.1	-67.6	-37.4	- 7.12
30°	34.1	-87.4	-42.4	2.49*
20°	19.7	-86.6	-37.2	12.3 *
10°	13.6	-99.4	-38.5	22.4 *
5°	10.2	-106	-39.2	28.1 *
0°	0	-82.7	-82.7	-82.7
	MAXIMUM G LOAD DURING SECOND IMPACT			
30°	- 4.8	33.5	-34.4	-102
20°	- .23	45.3	-41.1	-128
10°	- .33	49.5	-45.3	-140**
5°	- 0.7	48.9	-45.3	-139

* MAXIMUM ACCELERATION OCCURRED DURING SECOND IMPACT
** MAXIMUM IMPACT FORCE 3,707,000 LB. AT DISTANCE OF 61.14 IN. FROM C.G.

TABLE 2.10.2-4

MAXIMUM INERTIA G LOAD VERSUS INITIAL ANGLE OF IMPACT

FOR 30 FEET DROP

MINIMUM WOOD CRUSH STRESS

EFFECTIVENESS OF NON-BACKED UP WOOD: 20%

Initial Angle Of Impact	MAXIMUM G LOAD DURING FIRST IMPACT			
	Axial @ C.G.	TRANSVERSE		
		Primary Impact End	@ C.G.	Opposite End
90°	47.5	0	0	0
85°	45.3	- 4.7	- 2.32	0
80°	49.6	- 7.89	- 5.51	- 3.12
70°	60.1	-19.4	-14.3	- 9.15
60°	70.4	-35.4	-27.2	-19.0
50°	48.2	-50.7	-27.6	- 4.57
40°	40.4	-76.2	-37.0	2.17
30°	35.4	-106	-46.1	14.2
20°	25.3	-119	-46.9	25.7
10°	7.96	-67.1	-25.2	16.7 *
5°	6.53	-63.6	-23.6	16.4 *
0°	0	-52.7	-52.7	-52.7
	MAXIMUM G LOAD DURING SECOND IMPACT			
10°	-1.36	42.4	-40.3	-123
5°	-0.64	38.0	-36.3	-111

* MAXIMUM ACCELERATION OCCURRED DURING SECOND IMPACT

TABLE 2.10.2-5

DEPTH OF CRUSH VERSUS INITIAL ANGLE OF IMPACT

MAXIMUM WOOD CRUSH STRESS/EFFECTIVENESS OF
NON BACKED-UP WOOD: 80%

INITIAL ANGLE OF IMPACT	MAXIMUM CRUSH DEPTH, IN.
90°	6.01
70° (CG Over Corner)	20.5
0°	9.12

TABLE 2.10.2-6

DEPTH OF CRUSH VERSUS INITIAL ANGLE OF IMPACT

MINIMUM WOOD CRUSH STRESS/EFFECTIVENESS OF NON BACKED-UP WOOD: 20%

INITIAL ANGLE OF IMPACT	MAXIMUM CRUSH DEPTH, IN.
90°	9.05
70° (CG Over Corner)	23.8
0°	12.48

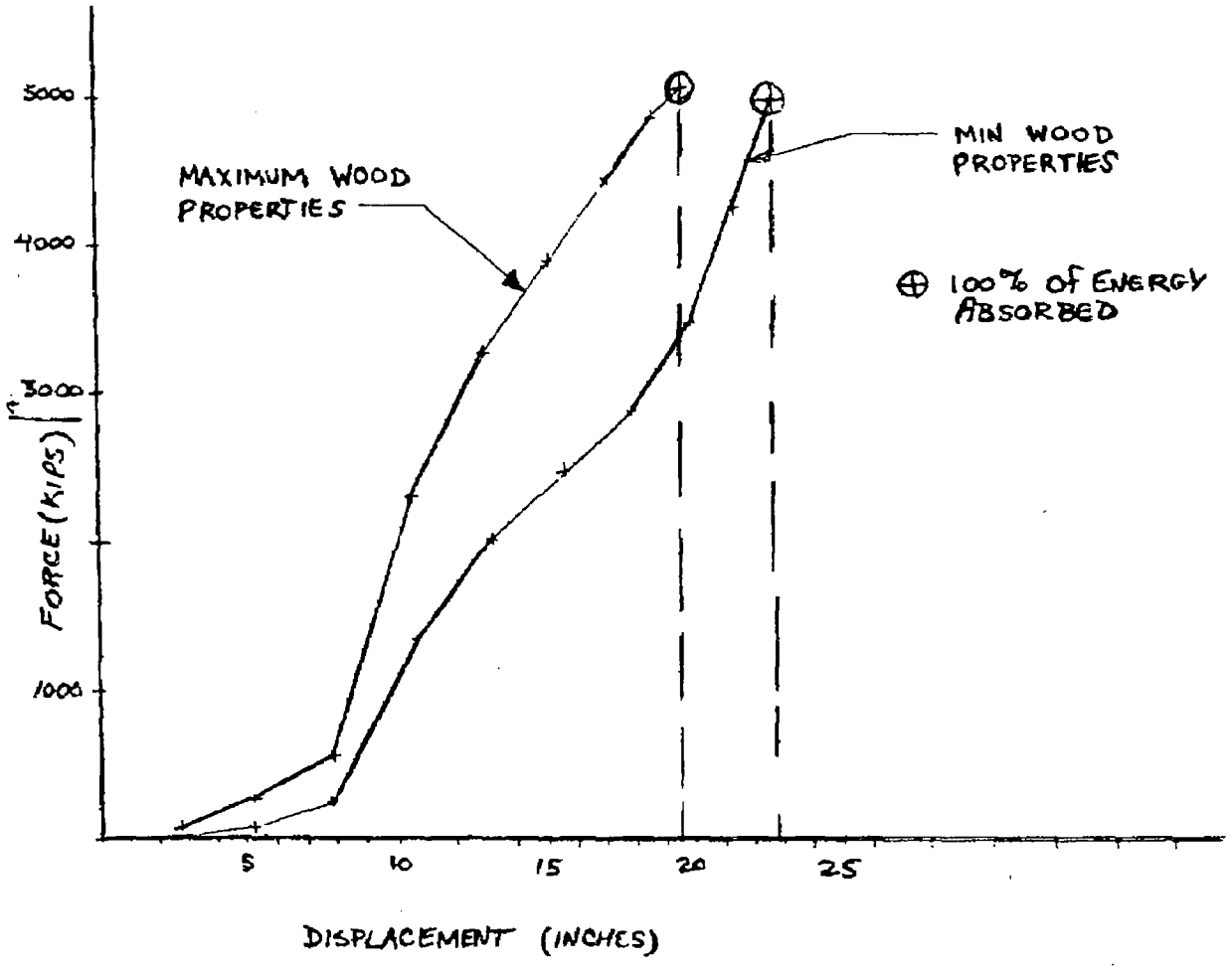


FIGURE 2.10.2-1C

FORCE-DEFLECTION CURVE-CRUSH ON CORNER THRU CASK CENTER OF GRAVITY

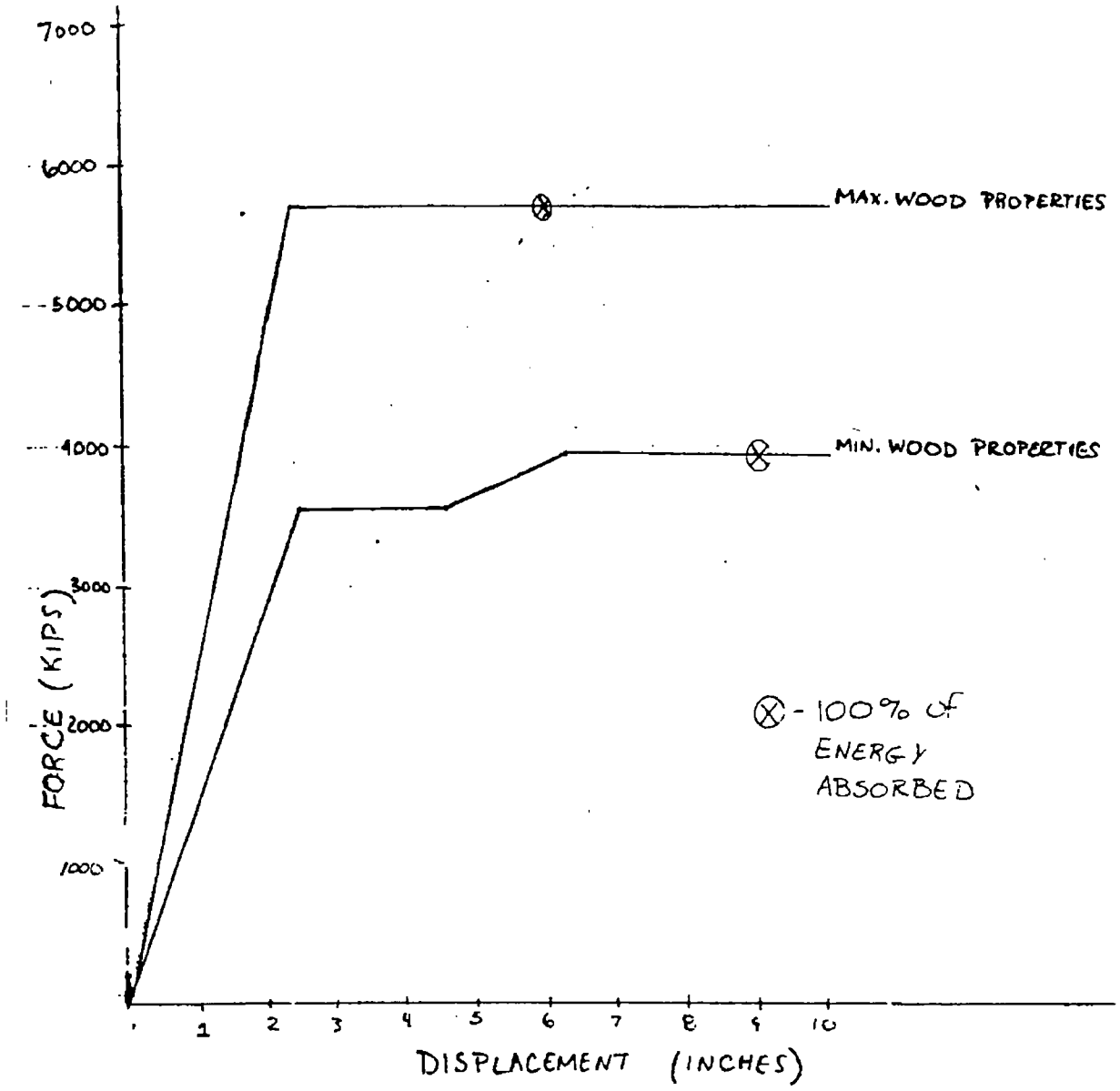
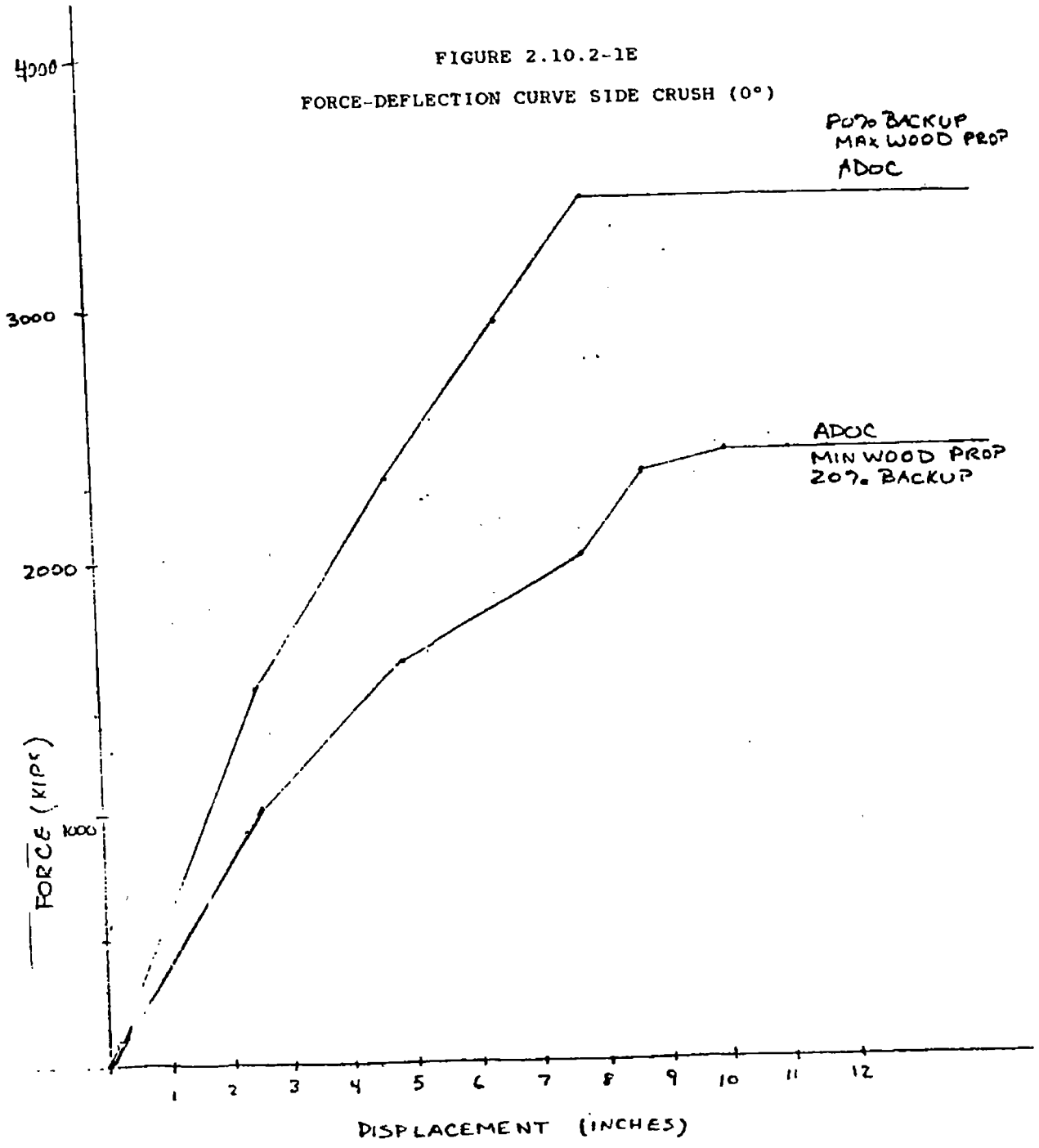


FIGURE 2.10.2-1D

FORCE DEFLECTION CURVE END CRUSH (90°)

FIGURE 2.10.2-1E

FORCE-DEFLECTION CURVE SIDE CRUSH (0°)



non backed-up wood, the clearance after the limiter crush would be slighly less than 1/2 inch. It is expected that the crush depth would be somewhere between the two bounding cases.

2.10.2.4.5 Results Based on Hand Calculations

The deceleration and crush depths for the end and side drop angles evaluated can be determined by relatively simple hand calculations. These hand calculations were performed and the results are shown below.

End Drop

The deceleration value can be determined by the expression:

$$F = \frac{w\,a}{g}$$

Where

F = crush force, lbs.
w = weight of cask
a = deceleration value
g = acceleration constant

Also

$$F = \sigma_c A$$

Where

σ_c = crush stress, psi
A = crush area, in^2

Therefore

$$\frac{a}{g} = \frac{\sigma_c A}{w}$$

The crush stresses of concern for an end drop are those for the balsa.

For the central region (see Figure 2.10.2-2)

$$\sigma_c = 1{,}560\text{-}2010 \text{ psi}$$
$$A = \pi(25.5^2) = 2{,}042 \text{ in}^2$$

For the outer region (see Figure 2.10.2-2)

$$\sigma_c = 300\text{-}420 \text{ psi}$$

$$A = \pi(45.75^2 - 25.5^2)\, k$$
$$= 4{,}533 \text{ in}^2$$

Where

K_{20} = .20 for non backed portion being 20% effective

And

K_{80} = 0.80 for non backed portion being 80% effective

Therefore

$$A_{20} = 4{,}533 \times 0.2 = 906 \text{ in}^2$$
$$A_{80} = 4{,}533 \times 0.8 = 3{,}626 \text{ in}^2$$

The deceleration values are for minimum wood properties:

$$A_{20} = \frac{1,560 \times 2,042 + 300 \times 906}{80,000}$$

$$= 43.2 \text{ g (ADOC Value = 47.5 g)}$$

For maximum wood properties

$$A_{80} = \frac{2,010 \times 2,042 + 420 \times 3,626}{80,000}$$

$$= 70.3 \text{ g (ADOC Value = 69.6 g)}$$

The maximum crush depths can be determined as follows:

$$F \Delta = W \times h$$

Since

$$F = \frac{w\ a}{g}$$

$$\Delta = \frac{h}{a/g}$$

Therefore for the two bounding cases

$$\Delta_{20} = 360/43.2$$
$$= 8.33 \text{ in (ADOC Value = 9.05 in.)}$$

And

$$\Delta_{80} = 360/70.3$$
$$= 5.12 \text{ in. (ADOC Value = 6.01 in)}$$

As can be seen, the deceleration values calculated by hand agree well with the values predicted by ADOC. The crush depths predicted by ADOC are conservatively higher.

Side Drop

The force crush depth and foot print as each of the limiters crush is shown in Figure 2.10.2-2B. The force (d_f) acting on an element $Rd\theta$ is

$$d_f = \sigma_c B R_o \cos\theta d\theta$$

The energy absorbed as this element deforms is

$$d_E = d_f [A-R_o(1-\cos\theta)]$$
$$= \sigma_c (R_o)^2 B \cos\theta[\cos\theta-\cos\theta]d\theta$$

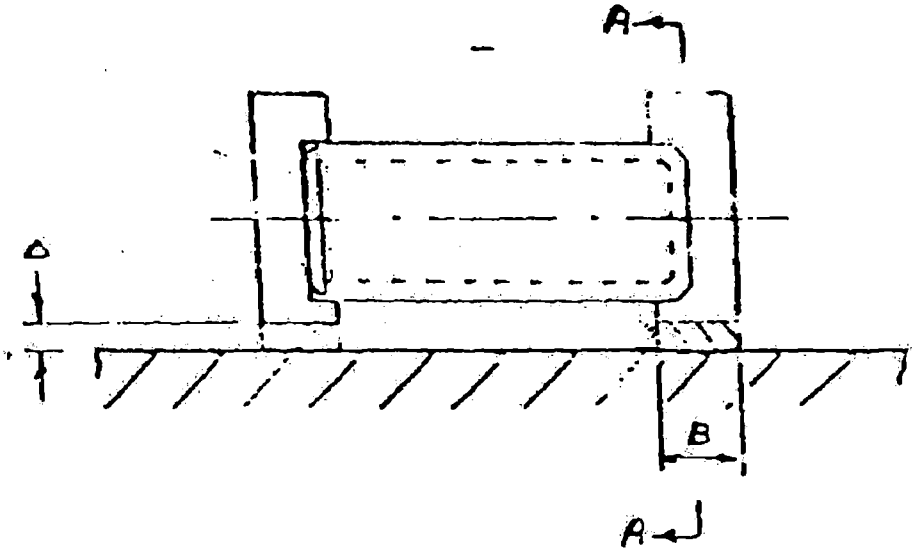
The total energy absorbed in each of the limiters is obtained by integrating the above,

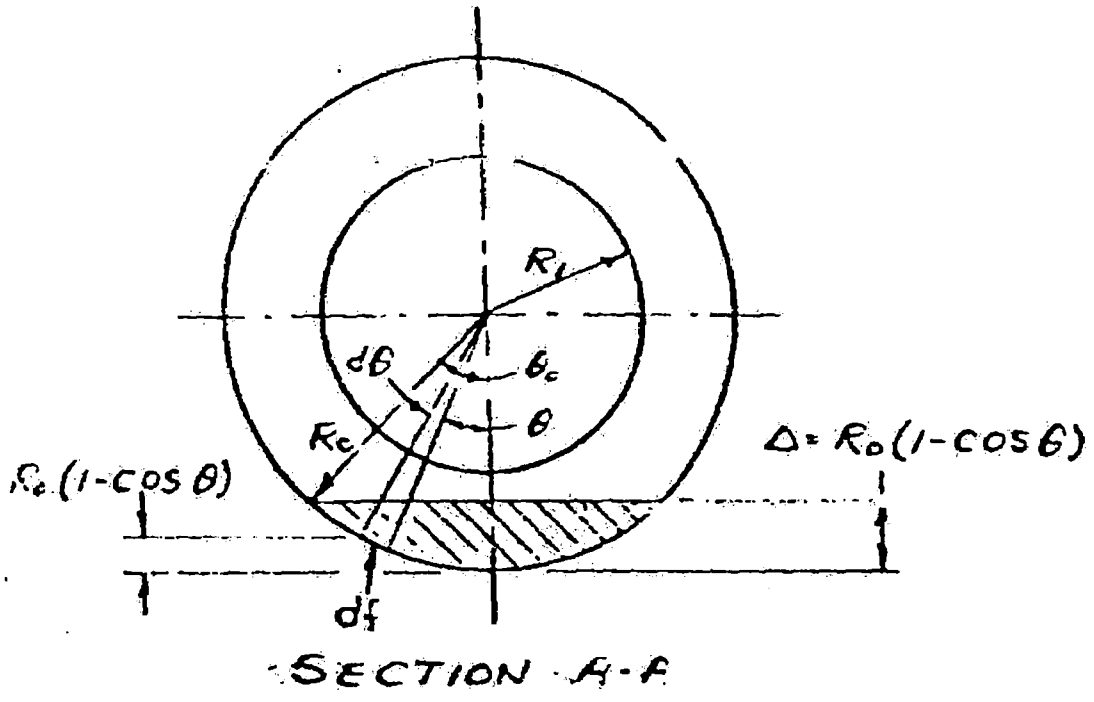
$$E = 2\sigma_c (R_o)^2 B \int_o^{\theta_o} \cos\theta[\cos\theta-\cos\theta_o]d\theta$$

$$= \sigma_c (R_o)^2 B(\theta_o - \frac{\sin 2\theta_o}{2})$$

The total force in each of the limiters is

$$F = 2\sigma_c B R_o \sin\theta_o$$





CRUSHING OF IMPACT LIMITER FOR SIDE DROP PROBLEM

FIGURE 2.10.2-28

A horizontal drop case is evaluated using the following parameters:

R_o = outside radius of limiters, 45.75 in.
R_i = inside radius of limiter, 25.5 in.
σ_c = average of crush stress, 3,140 psi
B = length of limiter on side which crushes, 24.25 in.
W = 80,000 lb.
H = 360 in.

The total energy to be absorbed is

$$WH = 80,000 \times 360$$

This must be equal to the energy absorbed by deformation of each of the two covers.

$$WH = 2\theta_o(R_o)^2 B\left(\theta_o - \frac{\sin 2\theta_o}{2}\right)$$

$$80,000 \times 360 = 2(3,140)(45.75^2 \times 24.25)\left(\theta_o - \frac{\sin 2\theta_o}{2}\right)$$

The solution indicates that

θ_o = 30 degrees, $F = 2\sigma_c B R_o \sin 30$
$= 3,482,500$ lbs.

Therefore

$\delta = R_o(1-\cos\theta_o)$
$= 45.75(1-\cos 30)$
$= 6.13$ in.

The peak deceleration, g, is

$$a = \frac{\sigma_c A}{W} = 2(3.140 \times 24.25 \times 45.75 \sin 30)/80,000$$

$$= 87.1 \text{ g}$$

This problem solved with ADOC program gives the following results:

$\theta_o = 36.8°$
$\delta = 9.12$ in.
$a = 82.3$
$F = 3,350,000$ lb.

Again, there is good agreement between ADOC and the hand calculation. It should be noted that the g values and forces used in the analysis for the cask body for the side drop are much higher than predicted by hand calculation or ADOC.

2.10.2.5 SUMMARY DESCRIPTION OF ADOC COMPUTER CODE

One of the critical loadings which must be considered in the design of transport packagings to be used for the shipment or radioactive material is a free drop from thirty-foot height onto an unyielding surface (10CFR71). The packaging must be dropped at an orientation that results in the most severe damage. Impact limiters are usually provided on the packaging to cushion the effects of such impact on the containment portion of the packaging. The limiters are usually hollow cylindrical cups which encase each end of the containment and are filled with an energy absorbing material such as wood or foam.

A computer code, ADOC (Acceleration due to Drop On Covers), has been written to determine the response of a packaging during impact. The analysis upon which this code is based in discussed in this section. The overall analysis of the packaging response is discussed in Section 2.10.2.5.1, and the methods used to compute the forces in the limiters as they crush are presented in Section 2.10.2.5.2.

2.10.2.5.1 General Formulation

The general formulation used to compute the response of the packaging as it impacts with a rigid target is discussed in this section. The assumptions upon which the analysis is based are first presented followed by a detailed development of the equations of motion used to calculate the packaging dynamic behavior. This is followed by a discussion of the numerical methods and the computer code used to implement the analysis. A significant part of the

development is concerned with the prediction of forces developed in the impact limiters as the impact occurs. This aspect of the problem is discussed in Section 2.10.2.5.2.

ASSUMPTIONS

The cask body is assumed to be rigid and axisymmetric. Therefore, all of the energy absorption therefore occurs in the impact limiters which are also assumed to have an axisymmetric geometry. Several assumptions are made in calculating the forces which develop in the limiters as they crush. These are discussed in Section 2.10.2.5.2. Since the packaging is axisymmetric, its motion during impact will be planar. The vertical, horizontal, and rotational components of the motion of the packaging center of gravity (CG) are used to describe this planar motion.

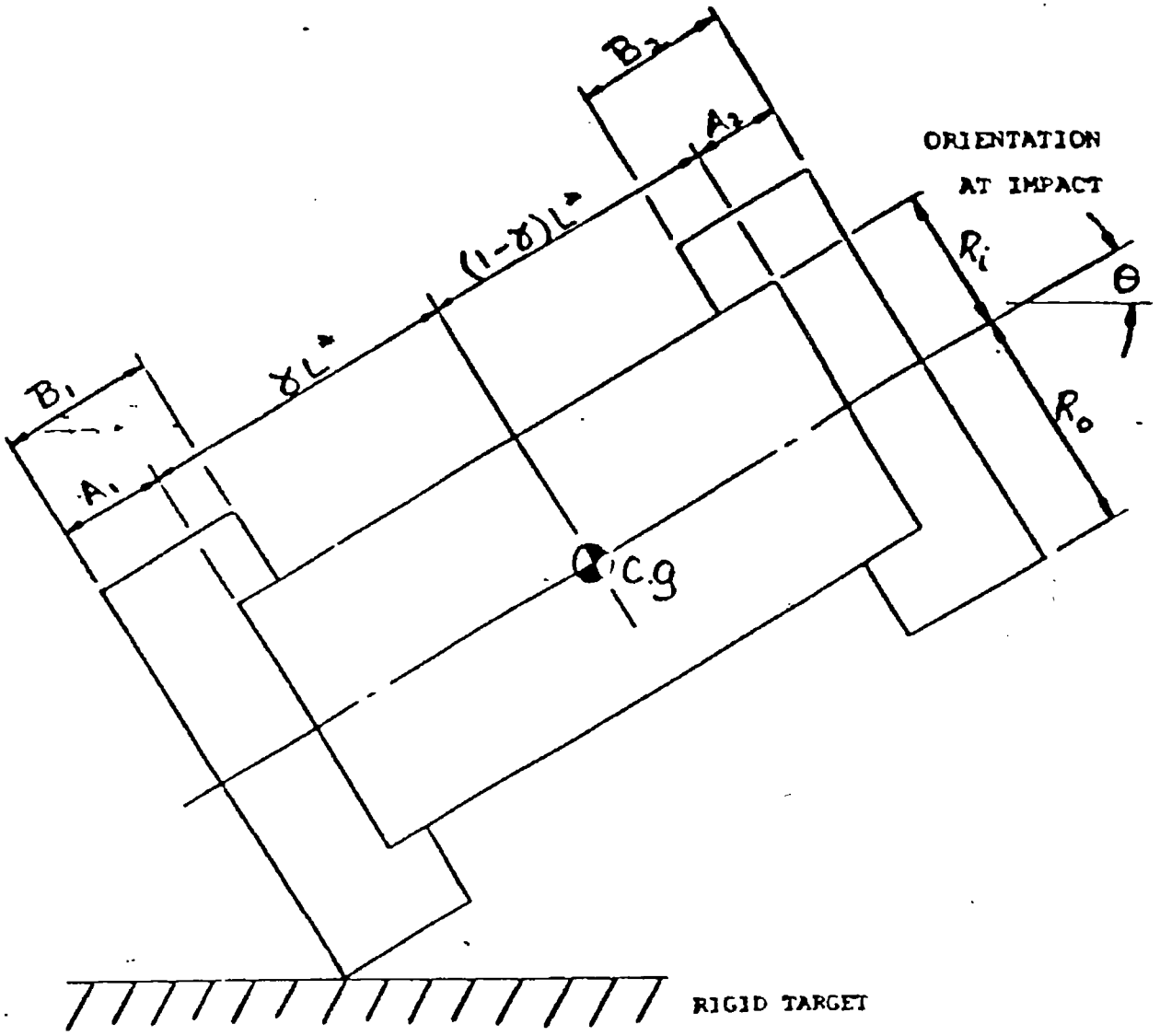
EQUATIONS OF MOTION

A sketch of the packaging at the moment of impact is shown on Figure 2.10.2-3. The packaging is dropped from a height (H), measured from the lowest point on the packaging to the target. The packaging is oriented during the drop, and at impact, so that the centerline is at an angle (θ) with respect to the horizontal. At the instant of impact, the packaging has a vertical velocity of:

$$V_0 = \sqrt{2gH} \qquad (1)$$

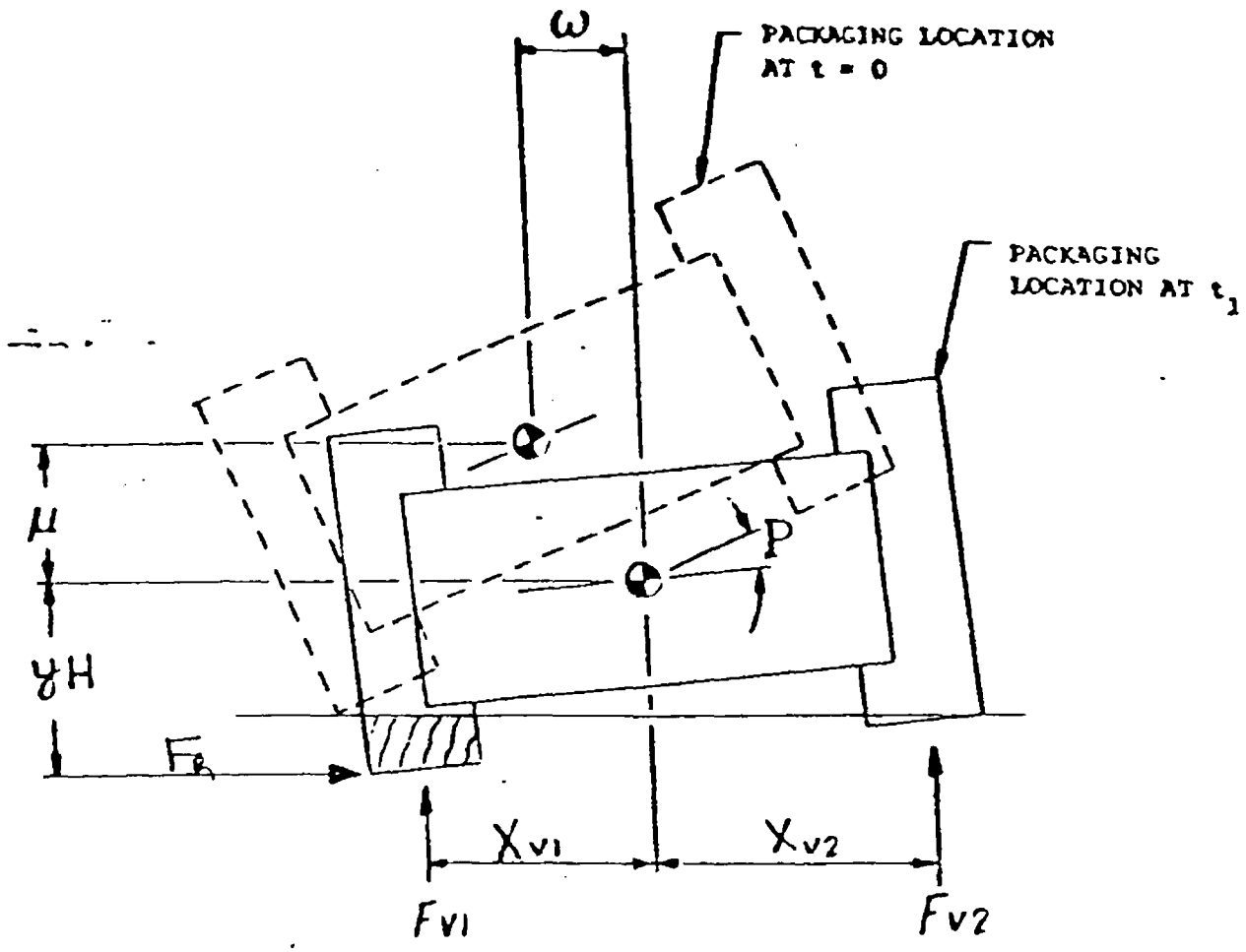
Where,

g = gravitational constant



GEOMETRY OF PACKAGING

FIGURE 2.10.2-3



PACKAGING LOCATION AT TIME (t)

FIGURE 2.10.2-4

At some time (t) after first impact, the packaging has undergone vertical (u), horizontal (w), and rotational (ρ) displacements. The location of the packaging at this time is shown on Figure 2.10.2-4. One or both of the limiters have been crushed as shown. The resulting deformations (and strains) in the limiters result in forces which the limiters exert on the packaging, thereby decelerating it. These forces, and their points of application on the packaging, are shown on Figure 2.10.2-4 as F_{v1}, F_{v2} and F_h. The method used to calculate these forces and the points of application is given in Section 2.10.2.5.2, below.

The three equations of motion describing the motion of the cask are:

$$M\ddot{u} + F_{v1} + F_{v2} - W = 0 \qquad (2)$$

$$M\ddot{w} - F_h = 0 \qquad (3)$$

$$J\ddot{\rho} - F_{v1} X_{v1} + F_{v2} X_{v2} + F_h Y_h = 0 \qquad (4)$$

Where,

M = mass of packaging

J = polar moment of inertia of the packaging about its CG

($\ddot{}$) = acceleration

At impact (t = 0), all of the initial conditions are zero except that $u' = V_0$.

COMPUTER SOLUTION

The computer code is written to compute the motion of the packaging during impact. The solution is obtained by numerically integrating the equations of motion (equations 2, 3, and 4) from the time of impact (t = 0) to a specified maximum time (t_{max}). The integrations are carried forward in time at a specified time increment (Δt). Parametric studies indicate that a time increment of 1 msec is sufficiently small so that further reduction of the time increment does not affect the results. Solutions are usually carried out to about 150 msec for the near horizontal drops and to about 50 msec for the near vertical drops. The significant motions of the packaging normally occur within these time periods.

A standard fourth order Runge Kutta numerical integration method is used to perform the numerical integrations. The following procedure is used to carry the solution from time (t_i) to time (t_{i+1}). Note that at time (t_i) the displacements and velocities of the three degrees of freedom describing the motion of the CG of the packaging are known.

(1) Calculate the deformation of each of the limiters based on the packaging geometry and the motion of the packaging's CG (see Section 2.10.2.5.2 for details).

(2) Calculate the forces which the limiters exert on the packaging body using the deformation of the limiters and their stress-strain characteristics (see Section 2.10.2.5.2 for details).

(3) Use Equations 2, 3, and 4 to calculate the accelerations during the time interval.

(4) Use the Runge Kutta equations to calculate the location and velocity of the cask CG at time (t_{i+1}).

(5) Go to step (1) to repeat the process until time = t_{max}.

(6) Generate the output.

Output from the code consists of:

Problem title, packaging geometry, drop conditions, and integration data.

Limiter geometric and material property data.

History of packaging CG motion and amount of crushing in each of the limiters.

Force history data.

Plot of acceleration histories.

Plot of maximum limiter deformations.

2.10.2.5.2 Forces in Limiters

The methods used to calculate the forces (F_{v1}, F_{v2}, and F_h) in the limiter caused by a given crush depth are discussed in this

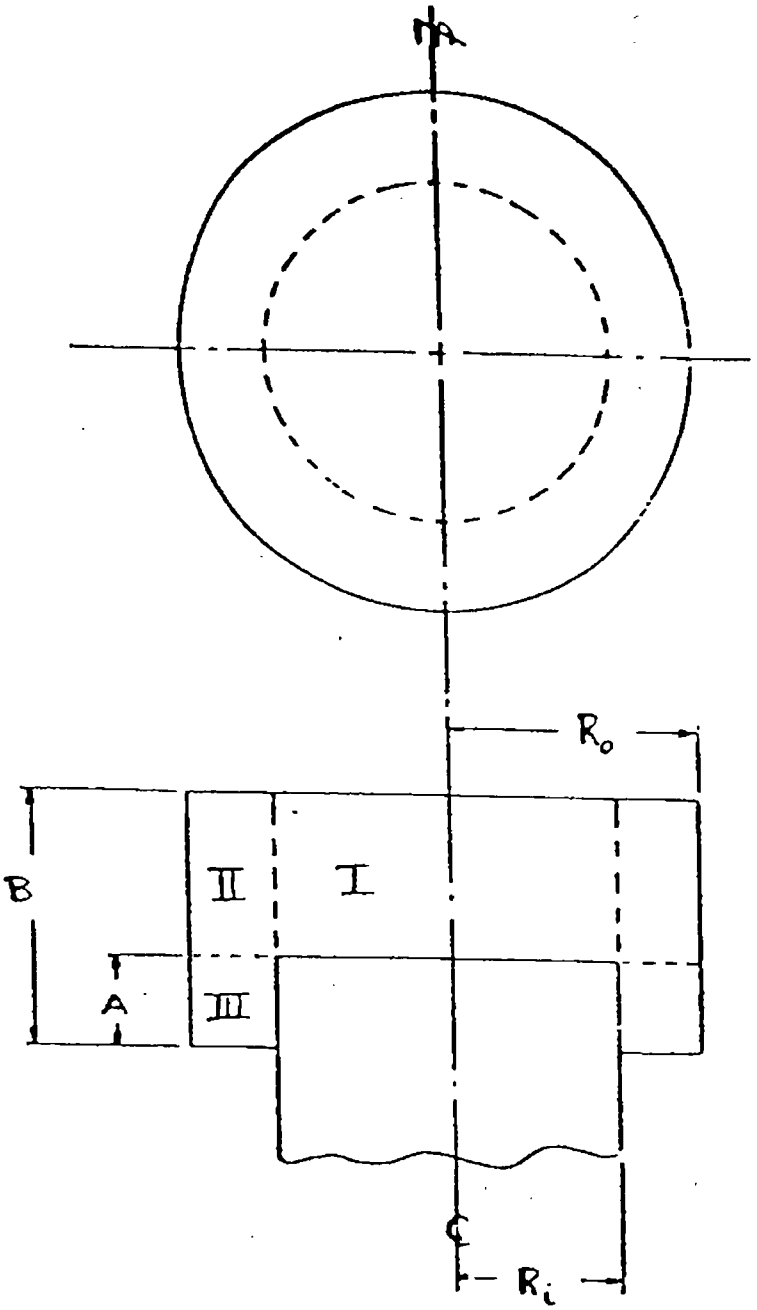
section. These calculations are used to perform steps (1) and (2) above. The limiter geometry and material specification is discussed first. The general methodology used to calculate the forces are then presented which is followed with a detailed development of the equations used to calculate the force-displacement relationships.

LIMITER GEOMETRY

A sketch of the model of a limiter is shown on Figure 2.10.2-5. Regions I, II and III are used to delineate regions where different materials are used. It should be noted that the properties of the three regions are designed to accommodate the crush requirements of the three significant drop orientations. The properties of regions I, II and III are selected to control the decelerations resulting from vertical, corner, and shallow drop orientations, respectively. The properties used to describe the stress-strain behavior of each of the three materials are discussed below. The dimensions (A) and (B) may vary for the limiters at each end of the packaging, but (R_o) and (R_i) are taken to be the same for both limiters. The same material properties are used for each of the limiters.

GENERAL APPROACH

The ideal energy absorbing material is one that has a stress-strain curve that has a large strain region where the stress is constant. Such a materials absorbs the maximum energy while minimizing force (which determines the magnitude of the deceleration). Wood, foam, and honeycomb materials exhibit such behavior and are prime candidates for impact limiter crushable material. If the constant



GEOMETRY OF LIMITER

FIGURE 2.10.2-5

stress region of the stress-strain curve is of primary interest, the forces may be calculated as the crush stress times the area of the surface defined by the intersection of the target with the doughnut shape of the impact limiter. This approach assumes that the crush stress, which acts normal to the crush surface, is not influenced by stresses acting in directions parallel to the crush surface (i.e., the confining stresses). This assumption is made in the computer code. The crush stress used as input to the code is selected to represent that value which is consistent with the degree of confinement afforded by the impact limiter geometry for the drop orientation considered. Therefore, the crushable material is modeled in the code with a one dimensional (oriented normal to the crush surface) stress-strain law. The properties of the stress-strain law are selected to represent the degree of confinement provided by stresses acting in the other two dimensions. The properties of the crushable material are not modified as the packaging rotates but are selected to represent the material properties for the initial crush direction of the material.

A portion of the "crushed" area of the limiter is often not backed up by the packaging body (i.e., a projection of a point in this non backed up area normal to the target (impact surface) does not intersect the cask body). The user must specify the percentage of these forces which are to be included in the calculation. The confinement provided by the overall construction of the limiter will determine the extent to which these non backed up forces are actually effective.

It should be emphasized that the computer code does not perform any computations which would allow the user to judge the adequacy of the selected percentage of non backed-up forces which are counted.

The evaluation of the impact area and its centroid (required to locate the impact forces) is computationally complicated because of the many variations possible in the manner in which the target intersects the limiter. This problem is resolved by dividing the surface of the limiter into many small segments. The segment is located relative to the target at each computation. If the segment's original location is below the target, then it has crushed and it contributes a force equal to the stress times its area projected on the target. The location of this force is also known. The strain at the segment may also be evaluated so that the peak strains may be determined and stresses may be evaluated for strains which fall outside of the constant crush stress region of the stress-strain law.

The forces must be calculated at each time that the solution for the packaging response is computed. The problem, therefore, is to determine the forces acting on the limiters given the current location of the packaging center of gravity. The solution for the location of the packaging center of gravity is discussed in Section 2.10.2.5-1. The procedure used to perform these computations is as follows (each of the steps is detailed below).

(1) Define the location of the target relative to the limiters from the current location of the packaging center of gravity relative to the target.

(2) Divide the surface of the limiter into segments and calculate the strain in a one dimensional element spanning the distance between the center of the segment and the packaging body.

(3) Compute the stress in the element from the stress-strain relationship. Multiply the stress by the area of the element projected onto the target.

(4) After all of the segments on the limiter are evaluated, sum the segment forces and moments of the forces to find the total force and moment acting on the packaging.

(5) Calculate the horizontal force and moment of the horizontal force.

(6) Use equations 2, 3, and 4 to extend the solution to the next time step. The new solution consists of the location of the packaging CG at the new time. The above steps are then repeated. This process is continued until the specified maximum time is reached.

DETAILS OF FORCE COMPUTATIONS

Details of each of the six steps outlined above are given in this section. Note that the location of the packaging CG is known at the beginning of this computational sequence.

Deformation of the Limiter

The first step in the computation is to evaluate the location of the limiters relative to the target given the location of the packaging CG relative to the target. The limiter position relative to the target is defined by the six variables (D_1 through D_6) as shown

on Figure 2.10.2-6. The location of the cask at first contact is shown on Figure 2.10.2-6a with the subscript (o) added to the D's indicating initial values. The initial values of these parameters (when the lowest corner of the packaging first contacts) are found from geometric considerations:

$$
\begin{aligned}
D_{10} &= 2R_0 \cos\theta \\
D_{20} &= 0 \\
D_{30} &= B_1 \sin\theta \\
D_{40} &= D_{30} + D_{10} + L^* \sin\theta + B_2 \sin\theta \\
D_{50} &= D_{40} - D_{10} \\
D_{60} &= D_{30} + L^* \sin\theta
\end{aligned}
\qquad (5)
$$

At a given time (t) the packaging CG has displaced vertically (u), horizontally (w), and has rotated (ρ) and reached the position shown in Figure 2.10.2-6b. Each of the six points have then fallen by an amount:

$$\Delta D = u*l(\sin\theta - \sin(\theta-\rho)) + r(\cos\theta - \cos(\theta-\rho)) \qquad (6)$$

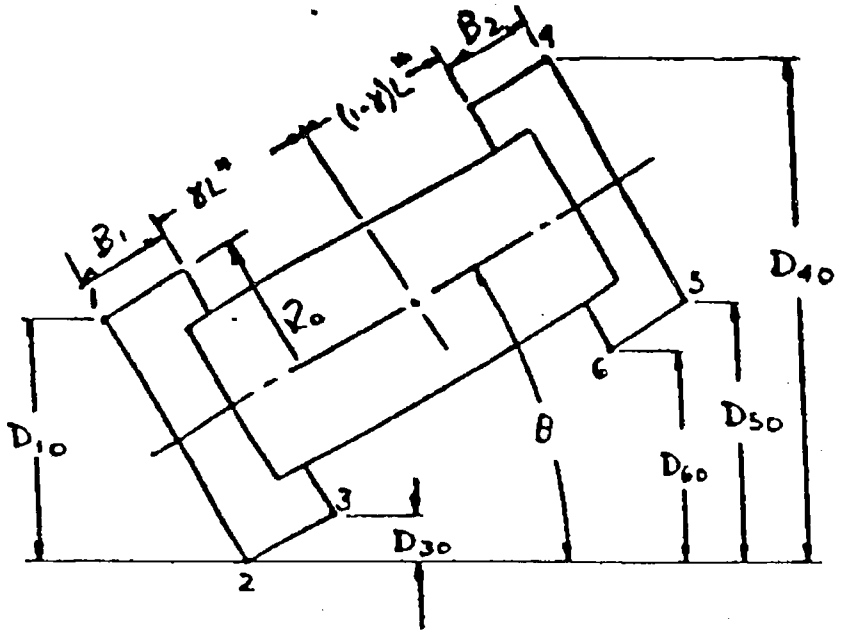
Where,

l = axial distance CG to point (+CG to top)

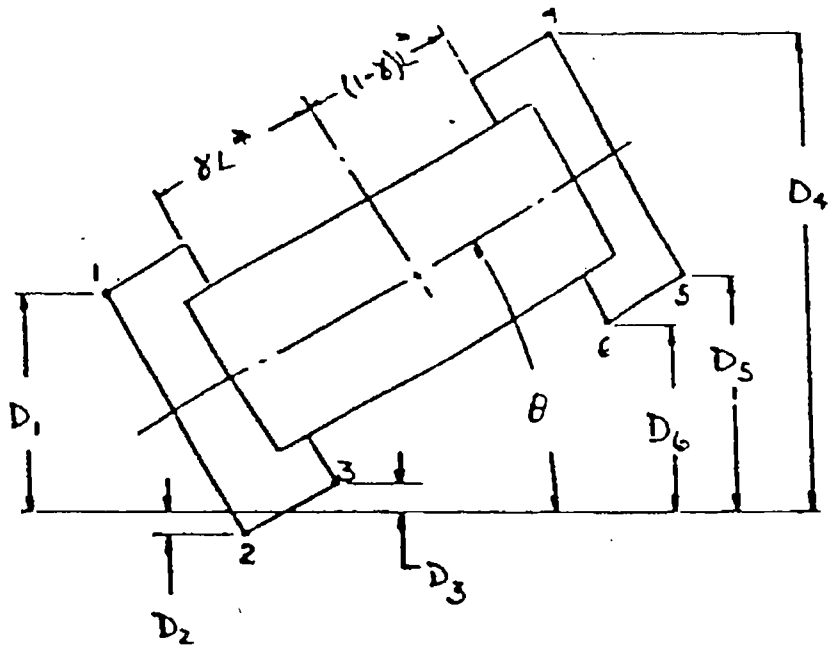
r = radial distance CG to point (+CG to impact)

Then the corner deformations become:

$$D_i = D_i - \Delta D_i$$



a. Impact Limiter Parameters at First Impact



b. Impact Limiter Parameters - General

DEFINITION OF LIMITER DEFORMATION

FIGURE 2.10.2-6

Where,

$$l_1 = l_2 = -yL^* - B_1$$
$$l_3 = -yL^*$$
$$l_4 = l_5 = (1-y)L^* + B_2$$
$$l_6 = (1-y)L^*$$
$$r_1 = r_4 = -R_0$$
$$r_2 = r_3 = r_5 = r_6 = R_0$$

To facilitate the computation of strains in the limiter, the position of the limiter relative to the impact surface is classified as shown in Figure 2.10.2-7. There are three possible locations of the impact surface relative to the limiter. The task is therefore to define which of the three patterns apply, and to determine the parameters (ϕ) and (Δ) in terms of the variables D_1 through D_6, just determined.

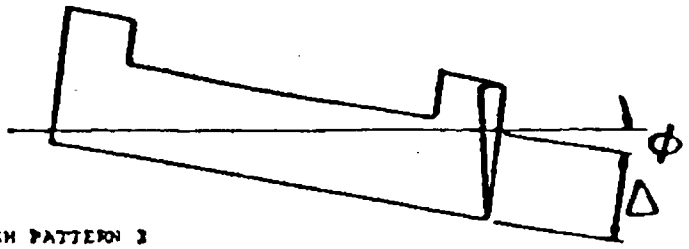
These deformations are next related to the three types of crush patterns for the bottom limiter shown on Figure 2.10.2-7. Crush pattern I applies when:

$$D_1 < 0;\ D_2 < 0;\ D_3 > 0 \qquad (8)$$

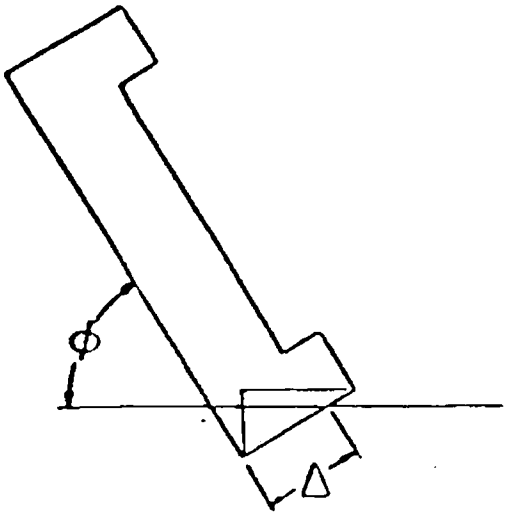
Then,

$$\Delta = -D_2/\cos\phi \qquad (9)$$

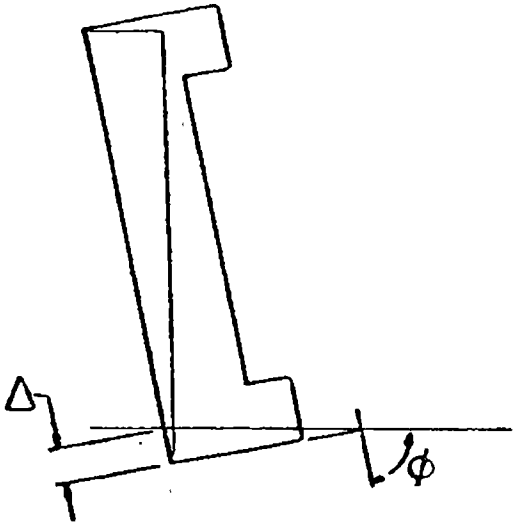
$$\phi = \cos^{-1}\left((D_3-D_2)/B_1\right)$$



a. CRUSH PATTERN I



b. CRUSH PATTERN II



c. CRUSH PATTERN III

CRUSH PATTERN IN LIMITER

FIGURE 2.10.2-7

Crush pattern II applies when:

$$D_1 > 0;\ D_2 < 0;\ D_3 > 0 \tag{10}$$

Then,

$$\Delta = -D_2/\cos\phi \tag{11}$$

$$\phi = \cos^{-1}((D_3-D_2)/B_1)$$

Crush pattern III applies when:

$$D_1 > 0;\ D_2 < 0;\ D_3 < 0 \tag{12}$$

Then,

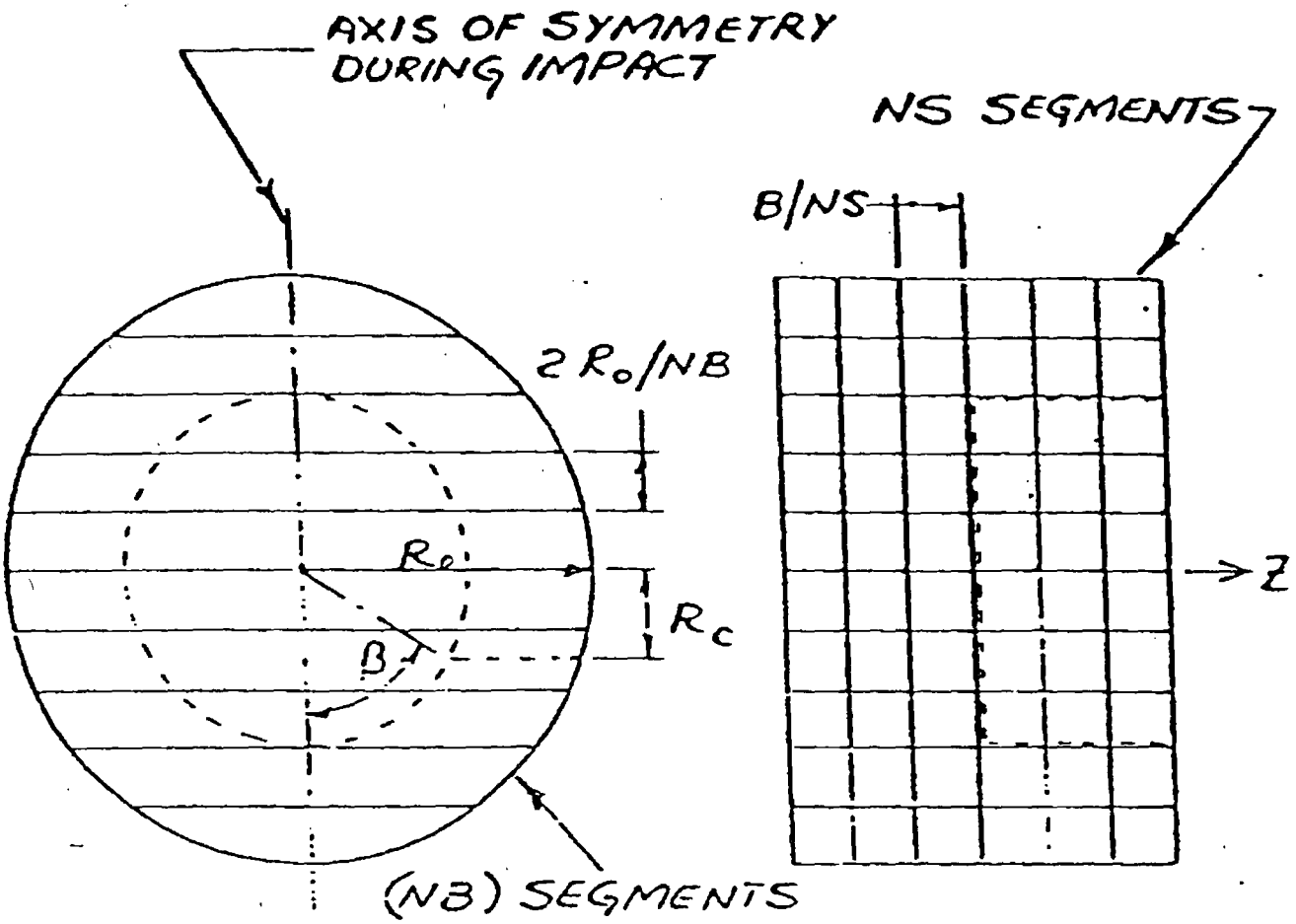
$$\Delta = D_2/\sin\phi \tag{13}$$

$$\phi = \sin^{-1}((D_1-D_2)/2R_0)$$

The same set of equations apply to the top limiter if (D_1, D_2, D_3, B_1) are replaced with (D_4, D_5, D_6, B_2) in equations (8) through (13).

Strains in Limiters

The next step in the computation is to calculate strains in the limiters given the deformation defined above. The limiters are first divided into segments as shown in Figure 2.10.2-8. The number of segments used for the bottom (NB) and the sides (NS) are input by the user. Locations on the surface of the limiters are described in terms of the (R,Z,β) coordinate systems shown on the figure. Strains in the segments along the sides of the limiters are calculated based on the location of the center of the segment (R_0,Z,β). The segments at the bottom are divided into two pieces: one for $R < R_i$ (i.e. in Region 1) and the second for R



SEGMENTED LIMITER

FIGURE 2.10.2-8

$> R_i$. A strain is calculated for each of these two pieces for each segment along the bottom surface.

The strains (ε) are calculated as the deformation of the point normal to the crush surface (δ) divided by the undeformed distance of the point from the surface of the limiter to the outer container (q), again measured normal to the crush surface. Therefore:

$$\varepsilon = \delta/q \qquad (14)$$

Different equations govern each of these parameters for each of the three crush patterns as shown on Figure 2.10.2-7.

The geometry for crush pattern I is shown on Figure 2.10.2-9. Forces resulting from deformation of the side elements are neglected for this crush pattern. It may be shown that the deformation is:

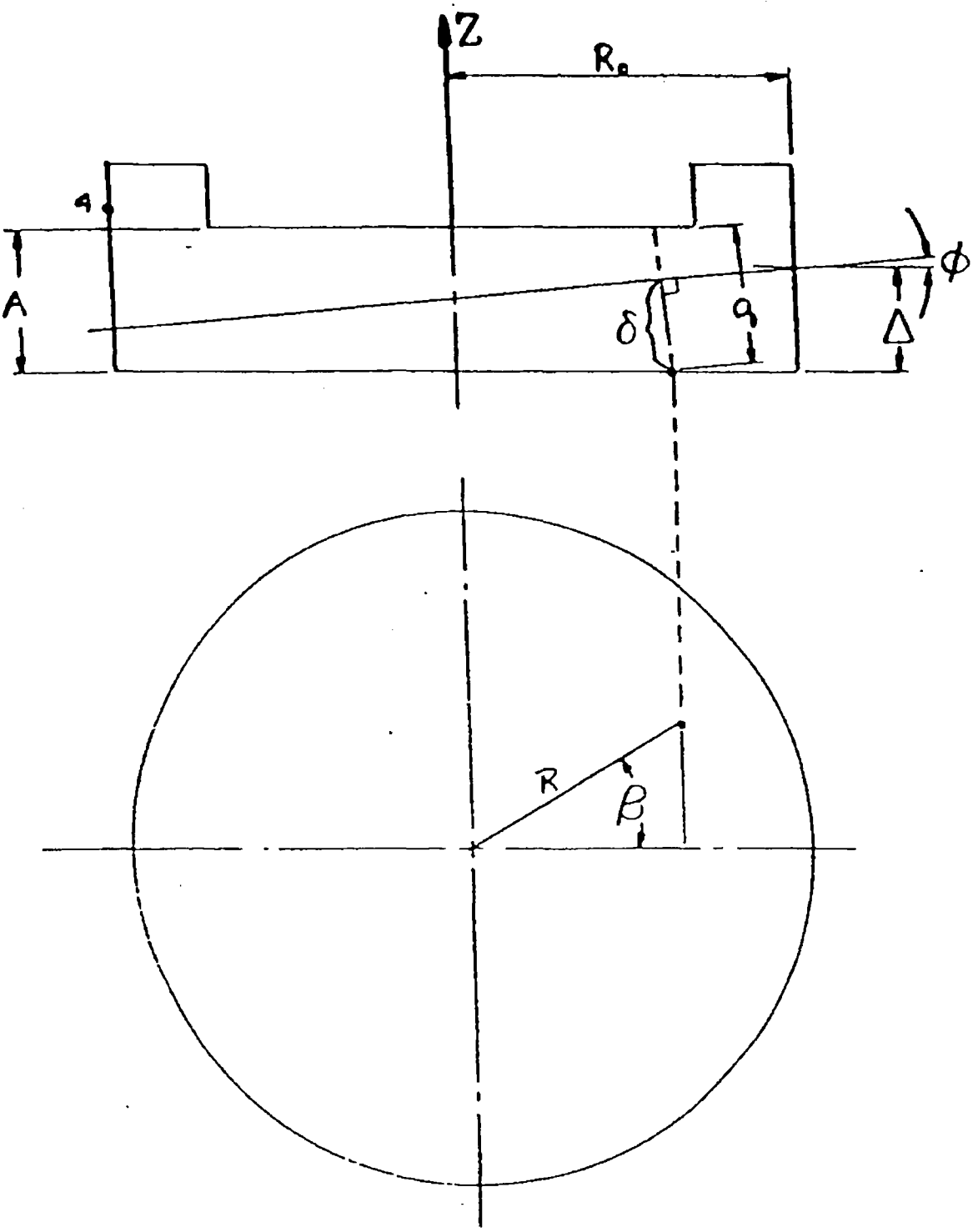
$$\delta = \Delta \cos \phi + (R \cos \beta - R_0) \sin \phi \qquad (15)$$

The undeformed length of the element is taken measured to the plane of the packaging bottom so that:

$$q = A_1 \cos \phi \qquad (16)$$

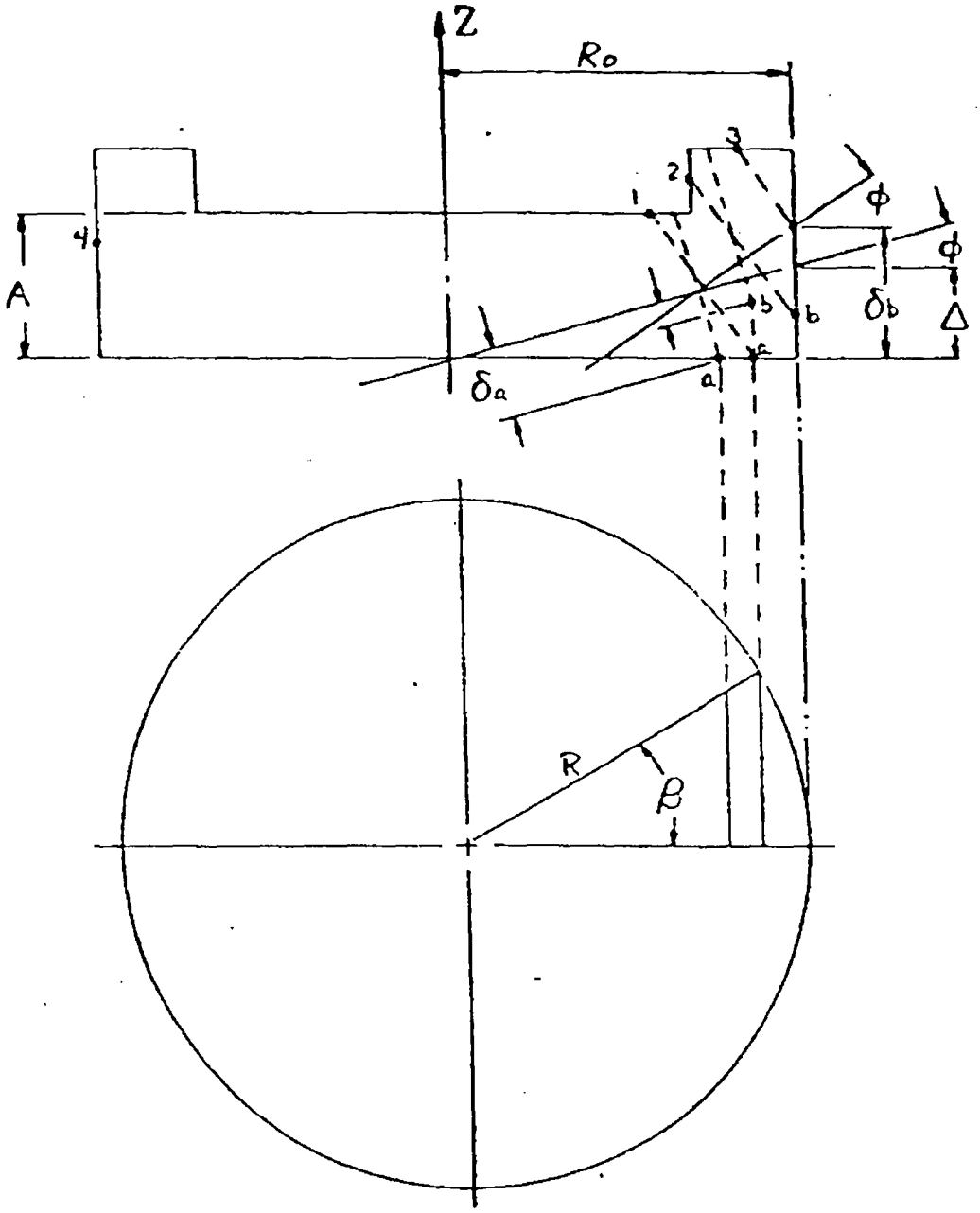
The geometry for crush pattern II is shown on Figure 2.10.2-10. The deformation of the points on the bottom (a) and along the side (b) may be represented with the same equation:

$$\delta = \Delta \cos \phi + (r \cos \beta - R_0) \sin \phi - Z/\cos \phi \qquad (17)$$



STRAIN COMPUTATION FOR CRUSH PATTERN I

FIGURE 2.10.2-9



STRAIN COMPUTATION FOR CRUSH PATTERN II

FIGURE 2.10.2-10

The original length of the element depends on the intersection of the projection of the point on the impact surface with the outline of the limiter. Four points are identified as shown on Figure 2.10.2-10. The lengths are:

$$\begin{aligned} q_1 &= (A-Z)/\cos\phi \\ q_2 &= X/\sin\phi \\ q_3 &= (B-Z)/\cos\phi \\ q_4 &= ((R_0^2 - R^2\sin^2\beta)^{1/2} + R\cos\beta)\sin\phi \end{aligned} \qquad (18)$$

Where,

$$X = R\cos\beta + (R^2\cos^2\beta - R_2 + R_1^2)^{1/2}$$

The deformation for crush pattern 111 is shown on Figure 2.10.2-11. Deformations of points on the bottom of the limiter are neglected for this crush pattern. The deformation is:

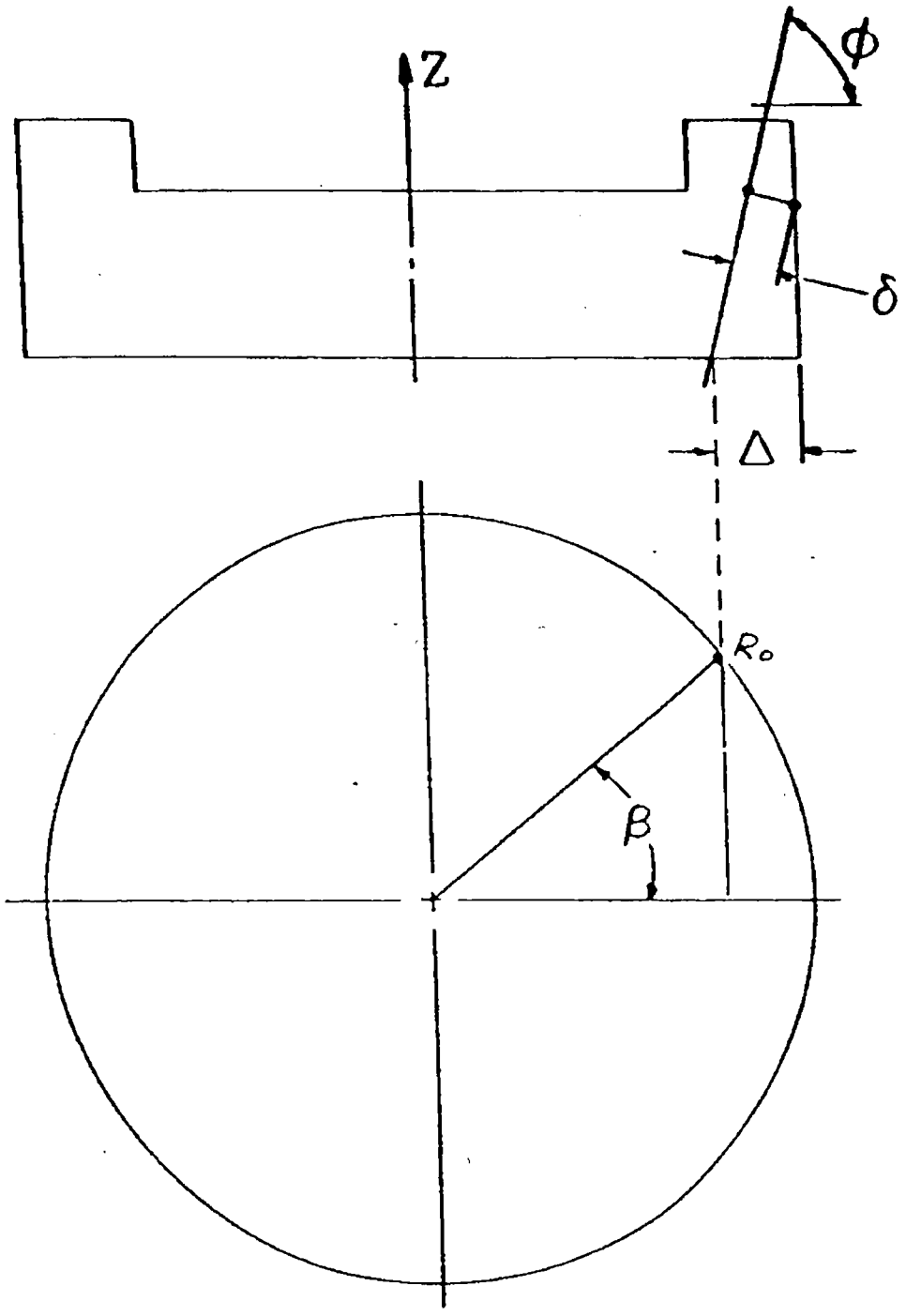
$$\delta = (\Delta - Z/\tan\phi - R_0(1 - \cos\beta))/\sin\phi$$

The original length is measured to (R_i) so that:

$$q = (R_0 - R_i)/\sin\phi \qquad (20)$$

Segment Stress

The stresses in the elements are calculated from the above strains. As mentioned above, three sets of stress-strain laws are input to the code, one for each of the regions defined in Figure 2.10.2-5.



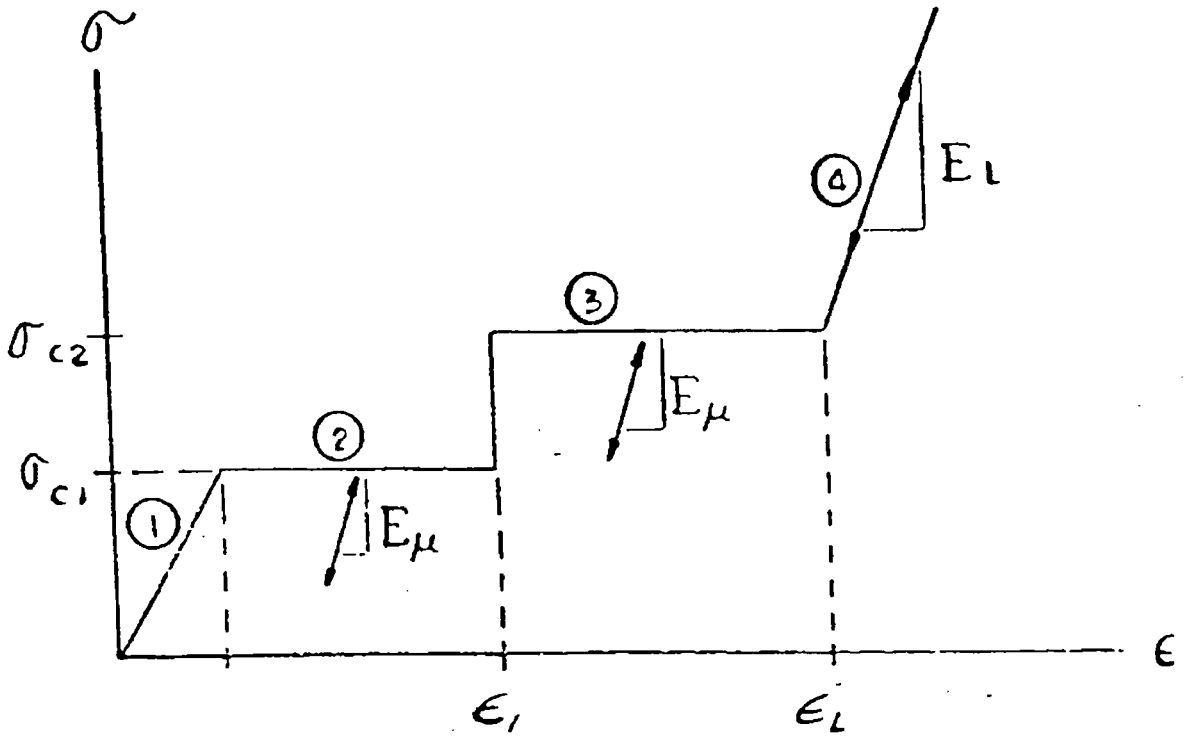
STRAIN COMPUTATION FOR CRUSH PATTERN III

FIGURE 2.10.2-11

The location of the center of the segment on the surface of the limiter is used to determine which of the three stress-strain laws is to be used. The model may be viewed as a set of one dimensional rods which run from the center of the segment, normal to the target, to another boundary of the limiter. The entire rod is given the properties which the limiter material has at the beginning point of the rod (i.e., the intersection with the target).

The stress-strain law used for the materials is shown on Figure 2.10.2-12. Each of the seven parameters shown on the figure is input to the code for each of the three regions of the limiter. The arrows on the figure indicate the load-unload paths used in the model. The step in the crush strength is built into the stress-strain law so that two crushable materials in series may be modeled. The two crush strengths should be specified as the actual crush strengths of the two materials. The first locking strain (ϵ_1) should be specified as the locking strain of the weaker material times the length of the weaker material divided by the total specimen length. The higher locking strain (ϵ_L) should be specified as the first locking strain plus the locking strain of the stronger material times its length and divided by the specimen length.

As stated above, the properties of the limiter material are not varied as the limiter crushes and the packaging rotates. Limiter materials such as wood exhibit anisotropic material properties. This must be accounted for when the properties are input to the code based on the anticipated direction of crushing. Most of the anisotropic wood data is based on tests performed in the elastic



WOOD STRESS - STRAIN CURVE

FIGURE 2.10.2-12

range. The following relationship has been used to represent wood properties for a loading which is applied at an angle (α) with respect to the wood grain:

$$P = (P_1 \cos^4\alpha + P_2 \sin^4\alpha)(/\cos^4\alpha + \sin^4\alpha) \quad (21)$$

Where,

P = property of interest

P_1, P_2 = properties parallel and perpendicular to grain

Evaluation of Forces

The stresses determined above are multiplied by the area of the segment projected onto the crush surface. The areas of the sidewall segments are (see Figure 2.10.2-8):

$$A_s = 2R_0 \, B \cos(\theta - \rho)/(NB \, NS \tan \beta) \quad (22)$$

The area of the bottom segments is divided into two parts, one in region I and the other in region II. These areas are:

$$A_b = 4R_0 L_b \sin(\theta - \rho)/NB \quad (23)$$

Where,

$$L_b = (R_i^2 - R_c^2)^{1/2}; \text{ region I}$$

$$= (R_0^2 - R_c^2)^{1/2} - (R_i^2 - R_c^2)^{1/2}; \text{ region II}$$

These forces are summed for all of the elements to determine the total force acting on the packaging. The forces are also multiplied by their moment arms about the packaging CG to calculate the total moment acting on the packaging. The point on the segment is first projected, normal to the target, to evaluate whether or not it intersects the packaging body. If the projection does not intersect the packaging body, only a percentage of the force is included in the summation. The user specifies the percentage to be used.

Horizontal Force

A horizontal force develops at the limiter/target interface. This force is only considered for the bottom limiter (i.e., the first to impact) since the packaging is always close to horizontal when the top impact limiter is in contact.

The horizontal force (F_h) is first calculated as that required to restrain horizontal motion of the tip of the limiter.

The horizontal acceleration ($\ddot{\Delta}_H$) at the tip of the bottom limiter (point 2 on Figure 2.10.2-6) may be related to the CG motion of the packaging by:

$$\ddot{\Delta}_H = \ddot{w} - \ddot{\rho}[(\gamma L^* + B_1) \cos \phi + R_0 \sin \phi] \qquad (24)$$

Where,

$$\phi = \pi/2 - \theta + \rho$$

Equating $\ddot{\Delta}_H$ to zero would result in no acceleration of the tip in the horizontal direction and provides the solution of w in terms of ρ.

Substituting this solution for w into Equation (3) results in an expression for the horizontal force (F_h), required to restrict horizontal acceleration of the tip, in terms of the rotational acceleration (ρ). Finally, equation 4 is used to eliminate (ρ) with the result,

$$F_h = \frac{M_v W[\gamma L^* + B_1)\cos\phi + R_0 \sin\phi]}{J_g + W[(\gamma L^* + B_1)\cos\phi + R_0 \sin\phi]^2} \qquad (25)$$

Where,

M_v = moment due to vertical forces = $F_{v1}x_{v1} - F_{v2}x_{v2}$
W = packaging weight

This force is restricted to:

$$F_h < \mu F_{v1} \qquad (26)$$

Where,

μ = coefficent of friction specified by user

2.10.2.6 ANALYSIS FOR ONE FOOT DROP NORMAL CONDITION

This section describes the analysis of the TN-RAM for the one foot normal drop condition. The TN-RAM is lifted vertically and is transported horizontally. End and side drop orientations are therefore considered to be credible normal drop events. Any other drop orientation will cause the cask to tip over onto its side, clearly an accident. The accident analyses in Section 2.10.2.4 bound any possible tipping accident. Therefore, the one foot drop analysis is performed only for the end and side drop orientations.

The packaging kinetic energy is again assumed to be absorbed by crushing of the impact limiters. The dynamic system model of Section 2.10.2.4 was used to perform the side drop (0°) analysis using the ADOC computer program described in Section 2.10.2.5. The end drop analysis was performed assuming that the energy would be absorbed by the soft balsa wood (oriented in the weak direction) in the outer end of the limiter. This is a very accurate way to determine g loads on an end drop since the g values can be calculated by the expression F = Ma where F = crush stress times the area and M = package weight divided by the acceleration of gravity g.

The inertial load results of these one foot drop analyses are presented in Table 2.10.2-7. Again, two extreme cases are considered. The upper bound stiffness case assumes maximum wood crush strength and 80% effectiveness of non backed-up wood. The lower stiffness case assumes minimum wood strength and only 20% effectiveness of non backed-up wood. The actual case will be between these upper and lower bounds. Stress analyses in Section 2.10.1 are performed for the case(s) with maximum inertia loads.

TABLE 2.10.2-7

MAXIMUM INERTIAL G LOAD DURING ONE FOOT DROP

	INITIAL ANGLE OF IMPACT	MAXIMUM G LOAD	
		AXIAL (ALL LOCATIONS)	TRANSVERSE (ALL LOCATIONS)
MAXIMUM WOOD CRUSH STRESS AND 80% EFFECTIVENESS OF NON-BACKED UP WOOD	90° (End Drop)	29.8	0
	0° (Side Drop)	0	-36.3
MINIMUM WOOD CRUSH STRESS AND 20% EFFECTIVENESS OF NON-BACKED UP WOOD	90° (End Drop)	21.27	0
	0° (Side Drop)	0	-24.4

2.10.2.7 IMPACT LIMITER ATTACHMENT ANALYSIS

The impact limiter attachments are designed to keep the impact limiters attached to the cask body during all normal and hypothetical accident conditions. The loading which has the highest potential for detaching the impact limiter is the slapdown or secondary impact after a shallow angle 30 foot drop. During this impact, the crushing force on the portion of the impact limiter beyond the cask body (the non backed-up area) tends to pull the limiter away from the cask. The end and corner drops are not critical cases for the impact limiter attachments since the impact force tends to push the impact limiter onto the cask in these orientations.

For the attachment bolt analysis, maximum effectiveness of the non-backed up wood and maximum wood crush strengths of 2010 psi for balsa and 6500 psi for redwood are assumed. The maximum wood properties produce the highest overturning moment on the limiter. Based on the dynamic analysis performed using the ADOC code, the most severe slapdown impact occurs after a shallow angle oblique impact at 10° initial angle. The peak deceleration and contact force at the end of the cask body subjected to secondary impact (slapdown) are maximum for this case. The peak deceleration is 140 g's and the peak force is 3,707,000 lb. as indicated in Table 2.10.2-3.

The maximum moment applied to the impact limiter attachments is conservatively determined ignoring the mass of the impact limiter which tends to reduce the attachment forces. The center of the

external impact force on the limiter is 5.60 in. from the center of the cask reaction force. Therefore, the net moment applied to the limiter by the impact force couple is $3.707 \times 10^6 \times 5.60$ or 20.75×10^6 in. lb. This moment is reacted by the eight impact limiter attachment bolts.

A free body diagram of the impact limiter is shown in Figure 2.10.2-13. It is conservatively assumed that the impact limiter pivots on the edge of the cask end. The maximum force, F, occurs in the bolt farthest from the pivot point, and the bolt force varies linearly with distance from the pivot point.

The moment of inertia of the bolting pattern about the corner of the cask (pivot point) is:

$$I_{xx} = \frac{n r_o^2}{2} A_b + n A_b \left(\frac{d}{2}\right)^2 = 16,614 \text{ in.}^4$$

Where:

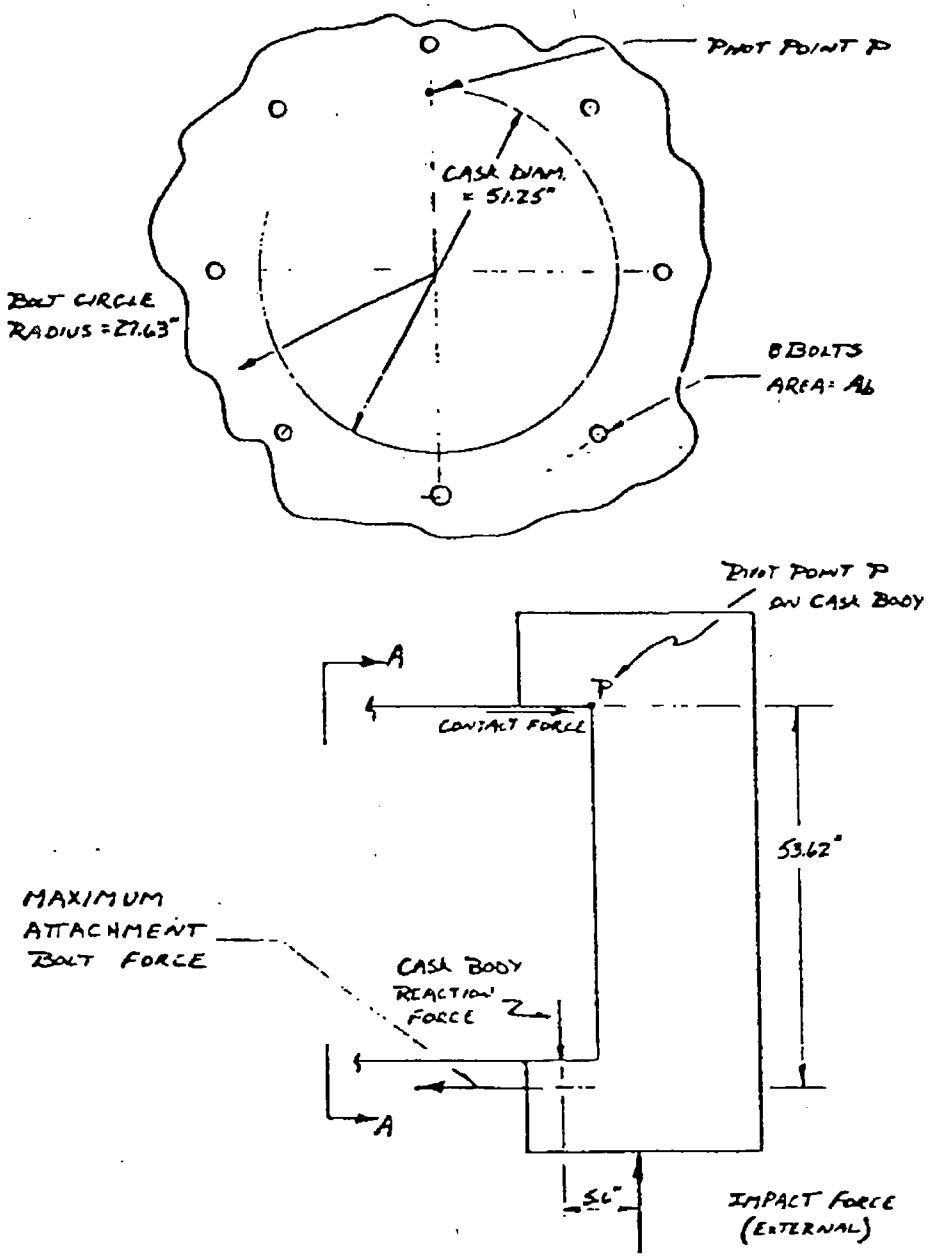
d = cask dia. = 51.25 in.

n = number of bolts = 8

r_o = bolt circle radius = 27.63 in.

A_b = bolt area for $1\frac{3}{4}$ -8 UNC bolts = 2.00 in.^{2}

The distance from the pivot point to the highest stressed (farthest) bolt is 53.25 in. Therefore, the maximum attachment bolt tensile stress is Mc/I or 66,506 psi. This conservatively calculated stress is well below the minimum attachment bolt ultimate tensile strength of 140,000 psi. The factor of safety against bolt failure is 2.10. Therefore, the bolts will not yield and will hold the limiter on the cask.



FREE BODY DIAGRAM OF IMPACT LIMITER FOR DETERMINING ATTACHMENT BOLT LOADS

FIGURE 2.10.2-13

2.10.2.8 IMPACT LIMITER PRESSURE ANALYSIS

The impact limiters are designed to be leaktight during normal transport conditions so that the moisture content, and hence crush strength, of the impact limiter materials is maintained. The outer shell of the impact limiter is designed to withstand pressure differences due to elevation and temperature changes during transit. The impact limiters are equipped with fusible disks which melt during the hypothetical thermal accident thus preventing excessive pressure buildup.

This section presents the analysis of the impact limiter structure during normal transport conditions. The impact limiters are sealed at ambient temperature, 68°F, and pressure, 14.7 psia. The maximum temperature of the limiters during normal transport conditions is 120°F. The pressure increase due to this rise in temperature is:

$$\Delta P = P_i \left(\frac{T}{T_i} \right) - P_i$$

$$\Delta P = 14.7 \ \frac{579.7°R}{527.7°R} - 14.7 = 1.5 \text{ psi}$$

The reduced external pressure due to elevation changes is approximately 3 psi. These pressures are combined resulting in a uniform total pressure of 4.5 psi.

The gussets in the impact limiter are spaced so that the average length of any flat plate section of the outer shell is 18.5 inches.

Assuming the plate edges are fixed and that there is a uniform pressure difference applied on the entire surface, the maximum stress at the center of the plate is:

$$\sigma = \frac{\beta w b^2}{t^2}$$

Roark, RJ, "Formulas for Stress and Strain", Fourth Edition Case 41 pg. 226

where,

b = 18.5 inches
t = 0.125 inches thick
w = uniform load, psi

and $\beta = 0.3078$, a function of the plate geometry.

Limiting the maximum outer plate bending stress to 1.5 times the 30,000 psi yield stress results in an allowable uniform load of:

w = 6.67 psi

Therefore, the impact limiter shell is capable of withstanding simultaneous internal and external pressure fluctuations (1.5 psi plus 3 psi) during normal conditions of transport.

APPENDIX 2.10.6
Not Used

APPENDIX 2.10.7
Not Used

APPENDIX 2.10.10

IMPACT LIMITER PERFOMANCE - SENSITIVITY TO WOOD MECHANICAL PROPERTIES

2.10.10.1 INTRODUCTION

The impact limiter design uses a stainless steel shell to retain wood that absorbs the energy of impacts resulting from normal and accident transport conditions (Figure 2.10.10-1). Impact energy is absorbed through deformation (strain) of the shell and wood. Two wood types are used to absorb the energy, redwood and a heavy balsa wood. Mechanical properties depend on the wood type and the compressive strength is anisotropic. Wood is placed in the steel shell to utilize the compressive strengths associated with the wood type and the orientation of the wood grain (Figure 2.10.10-2). Mechanical properties of the wood for an impact force applied 90 degrees to the grain direction (across the grain) are referred to as "perpendicular", and mechanical properties of wood for an impact force applied 0 degrees to the grain direction (with the grain) are referred to as "parallel." Parallel compressive strength is greater than perpendicular compressive strength due to the cell structure of the wood. Compressive strength of balsa wood is less than that for redwood. The deformation at which the cell structure is crushed in such a way that stress increases rapidly for any further strain or locking strain is greater for balsa wood than the locking strain for redwood. Typical mechanical properties of the wood types are provided in Chapter 2, Section 2.3.

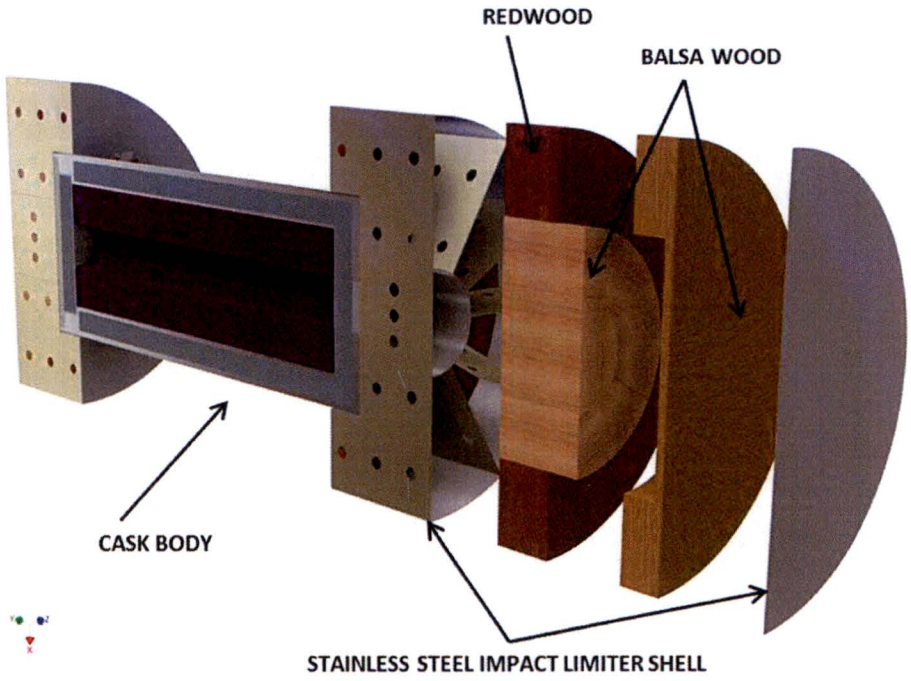


Figure 2.10.10-1 TN-RAM Cask with Exploded View of Impact Limiter

Appendix 2.10.10 is newly added for Revision 16A

Proprietary Information on Pages 2.10.10-2 through 2.10.10-14
Withheld Pursuant to 10 CFR 2.390

Table 2.10.10-3 Summary of Sensitivity Study Results – Deformations

[ ]

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SHIELDING EVALUATION

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CHAPTER FIVE
SHIELDING EVALUATION

The shielding evaluation for the TN-RAM package is performed to demonstrate compliance with 10 CFR 71.47 and 10 CFR 71.51 as applicable.

The TN-RAM *No. 01* package is designed to transport a payload of 9500 lbs. (4309 kg) of dry, irradiated and/or contaminated non-fuel bearing solid materials (with only trace quantities of fissile material as limited by 10 CFR 71.15) in secondary containers containing a maximum of 30,000 Ci of cobalt-60 equivalent as described in this chapter. Material in the secondary container is secured using shoring during transport to prevent movement. No powdered material is authorized for transport. The package is shipped exclusive-use in an open transport vehicle. The cask is designed to be shipped horizontally during transportation with the lid end facing in the direction of travel. The lid end is considered the top in this evaluation. No credit is taken for the presence of the secondary container in this chapter.

The dose rates are computed using MCNP5 v1.40 [5-3].

TN-RAM No. 02 is the same as TN-RAM No. 01 with the exception of the radial lead thickness, which is 5.56 inches minimum. TN-RAM No. 02 as fabricated is able to transport 18,000 Ci of cobalt-60 or equivalent.

5.1 DESCRIPTION OF SHIELDING DESIGN

The TN-RAM package is a Type B shipping cask with steel inner and outer shells. Bulk lead poured between the shells during fabrication is used for shielding radially and axially at the bottom. The lid contains lead for shielding at the top. Impact limiters at the top and bottom are used to provide protection for drops. Four trunnions at the top and two trunnions at the bottom are used for handling and support the cask when it is transported. A cavity drain facilitates the removal of water after loading. A vent through the lid is used for operations as required.

No credit is taken for the secondary container in the TN-RAM package to meet the shielding requirements.

5.1.1 Design Features

The TN-RAM cask contains steel and lead in the radial and axial directions to provide gamma shielding. The inner shell has 0.75 inches of steel radially and 0.5 inches of steel at the bottom. The outer shell has 1.5 inches of steel radially and 2.5 inches of steel at the bottom. Between the shells, lead is poured with a minimum of *5.75 inches (TN-RAM No. 01) or 5.56 inches (TN-RAM No. 02)* radially and 5.69 inches at the bottom. Shielding at the top is provided by either lid option. There are a total of 3 inches of steel and 5.88 inches minimum of lead in the original lid. The optional lid has a total of 3.375 inches of steel and 5.68 inches minimum of lead. A thermal shield between the impact limiters is 0.25 inches thick and provides additional radial shielding.

More detail is provided in Section 5.3.

5.1.2 Summary Table of Maximum Radiation Levels

Normal conditions of transport (NCT) dose rates are computed for an exclusive-use transport in an open vehicle. Therefore, the following limits apply:

- 10 CFR 71.47(b)(1): the external surface of the package must be below 200 mrem/h,
- 10 CFR 71.47(b)(2): the outer surface of the vehicle must be below 200 mrem/h,
- 10 CFR 71.47(b)(3): any point 2 m from the outer lateral surfaces of the vehicle must be below 10 mrem/h, and
- 10 CFR 71.47(b)(4): any normally occupied space must be below 2 mrem/h unless personnel follows the requirements of 10 CFR 20.1502.

Normally occupied space is assumed to be 152 inches from the top of the package.

The NCT surface dose rates use the top and bottom of the impact limiter as the basis for the surface of the package axially. The radial surface of the cask is the basis for the side surface dose rate. The 2 m dose rate basis is from the extents of the impact limiters in all directions. The maximum NCT dose rates are shown in Table 5-1 *for TN-RAM No. 01. The maximum NCT dose rates for TN-RAM No. 02 are shown in Table 5-18.*

Maximum dose rates for a normally occupied space which is assumed to be 152 inches from the top of the TN-RAM package are shown in Table 5-1 *for TN-RAM No. 01. The normally occupied space dose rates for TN-RAM No. 01 bound TN-RAM No. 02 because TN-RAM No. 01 has a higher activity limit than TN-RAM No. 02 and the shielding in this direction is the same.*

Hypothetical accident conditions (HAC) external dose rates are computed using the surfaces of the cask as the basis for the 1 m distance as prescribed by 10 CFR 71.51(a)(2). Compliance with release doses per 10 CFR 71.51(a)(1) and 71.51(a)(2) is shown in Chapter 4. The maximum external HAC dose rates are shown in Table 5-2 *for TN-RAM No. 01. The maximum external HAC dose rates for TN-RAM No. 02 are shown in Table 5-19.*

5.2 RADIATION SOURCE

5.2.1 Gamma Source

The TN-RAM *No. 01* is evaluated to transport 30,000 Ci of cobalt-60 or equivalent consistent with the maximum for Category II packages. *TN-RAM No. 02 is evaluated to transport 18,000 Ci of cobalt-60 or equivalent.*

The source is in the form of dry, solid, non-fuel bearing hardware with a cobalt-60 equivalent specific activity ≤ 10 Ci/kg. The specific activity for each item is defined as the total cobalt-60 activity equivalent of the item divided by the mass of source material. Source materials shall be either steel or a material that provides equivalent or superior gamma shielding than steel. Localized regions of low-density material (e.g., B_4C in a control rod blade) are acceptable if the low-density regions contain negligible source. The mass of any low-density regions shall not be credited in the specific activity calculation.

More than 99% of the disintegrations result in two gammas with energy of 1.17 and 1.33 MeV. Lower energy emission is considered to have the energy of the aforementioned gammas which is conservative. The source intensity *for TN-RAM No. 01* is as follows:

$$(30\ 000\ \text{Ci})\left(3.7\text{x}10^{10}\ \frac{\text{disintegrations}}{\text{Ci s}}\right)\left(2\ \frac{\gamma}{\text{disintegration}}\right) = 2.22\text{x}10^{15}\ \gamma/\text{s}.$$

For TN-RAM No. 02, the source intensity is $1.332\text{x}10^{15}$ γ/s.

In most cases, isotopes other than cobalt-60 will also be present in the waste stream. These isotopes are converted to equivalent quantities of cobalt-60 following the methodology in Section 5.5.3. The equivalence methodology is based upon dose rate considerations.

The source is the same for the NCT and HAC evaluation. The evaluation methodology uses continuous energy cross sections so the energies for the gammas can be input and simulated directly. The energy distribution of the gammas is one half of the total intensity for each energy. The spatial distribution within the various source regions is isotropic in the axial direction and a power law distribution in the radial direction.

5.2.2 Neutron Source

The TN-RAM package is not licensed to transport fissile material greater than the limits prescribed in 10 CFR 71.15. No neutron generating source material beyond an inconsequential amount as a result of surface contamination is to be transported. However, a source of $1\text{x}10^6$ neutrons per second is evaluated. The distribution of the neutron source is the same as the gamma source. The neutron source is based on a Watt fission spectrum for Cm-244.

5.2.3 Beta Source

The TN-RAM package is evaluated to transport 3,000 A_2 of beta emitting radionuclides. Beta emitters can create bremsstrahlung radiation as the electrons are attenuated through high *Z* materials. Therefore, a source of 3,000 A_2 of phosphorus-32 is evaluated to determine the

impact of bremsstrahlung. The distribution of the source is radially outward from the inner surface of the inner shell to amplify the effect. The betas are modeled at the maximum emission energy of phosphorus-32: 1.71066 MeV.

5.3 SHIELDING MODEL

5.3.1 Configuration of Source and Shielding

A full, three dimensional model of the TN-RAM was created in MCNP5. Major features were modeled explicitly. The same cask model was used for the NCT and HAC analysis with minor variations as required. An axial cross section view of the TN-RAM package for NCT is shown in Figure 5-1. *TN-RAM No. 02 is the same as TN-RAM No. 01 except for the radial lead thickness.*

Key dimensions for the cask and impact limiters are shown in Table 5-3. Dimensions are taken from the drawings provided in Section 1.3. The "Dimensions used" column in Table 5-3 corresponds to the sample input file in Section 5.5.2.

Nominal dimensions are used everywhere except for the lead, which is modeled at its minimum respective thickness based on location *and serial number*. The modeling of the lead results in an air gap between the shells, which would not exist in the as-built package. This false gap does not contribute to any lead slumping; rather, it is included to preserve the dimensions of all modeled components.

The four upper and two lower trunnions are modeled because the steel displaces lead used for shielding.

The impact limiter model was simplified. Rather than include all the steel components in the impact limiter, only the steel shell was modeled, and the impact limiter was completely filled with balsa, which has no significant impact on dose rates. However, it preserves external dimensions of the impact limiter in the model. The dimensions form the basis for some of the NCT surface dose rates and all of the 2 m dose rates.

The cavity drain is modeled because it displaces lead in the bottom. The drain sleeve outer diameter is the most critical dimension to ensure the proper amount of lead is removed.

In the HAC evaluation, the model is the same as NCT with the following differences. The combination of the tests prescribed in 10 CFR 71.73 as applicable result in no loss of steel or lead from the cask body which makes up most of the shielding provided by the package. The impact limiters are removed and replaced with air even as they are shown to remain attached under all postulated tests as described in Section 2.7.6. The cavity in the HAC model has no material inside. The cavity is filled completely with air. This allows for the most conservative results because no self-shielding is present.

Lead slump for HAC was not analyzed; per the discussion in Section 2.7.1.1, lead slump is not expected.

A payload mass of 3,000 kg stainless steel is considered to be the mass of the source bearing contents for the shielding evaluation *for TN-RAM No. 01. TN-RAM No. 02 uses 1,800 kg of stainless steel.* The source material is limited to a cobalt-60 equivalent specific activity ≤ 10 Ci/kg. Source materials shall be either steel or a material that provides equivalent or superior gamma shielding than steel.

Four NCT source bearing configurations are modeled. The first configuration is a homogenized cylinder sized to fit the interior of the cavity. The payload mass of 3,000 kg stainless steel is homogenized within the available cavity volume, with a resulting density of 1.71 g/cm^3. The dimensions of the homogenized source are shown in Table 5-5 *for TN-RAM No. 01. TN-RAM No. 02 uses the same homogenized density; however, the axial height is reduced to achieve a mass of 1,800 kg. The source is moved to the top of the cavity. The dimensions of the homogenized source for TN-RAM No. 02 are shown in Table 5-20.*

A disk source is postulated if the source bearing contents are shifted to the top or bottom. The disk is stainless steel at full density and radius to fit inside the cavity. The height is calculated to meet the mass target of 3,000 kg *for TN-RAM No. 01.* The second configuration is a disk source placed at the bottom of the cavity; the third configuration is the same disk source placed at the top of the cavity. The disk source dimensions are shown in Table 5-6 *for TN-RAM No. 01. TN-RAM No. 02 uses a mass of 1,800 kg. Compared to No. 01, No. 02 has the same radius but reduced height. The disk source dimensions are shown in Table 5-21 for TN-RAM No. 02.*

The fourth source configuration is an annulus. This source configuration moves the source bearing contents to the edges of the cavity. The height and outer radius of the annular source are sized to fit the cavity. The inner radius was calculated to meet the mass target of 3,000 kg *for TN-RAM No. 01.* The center of the annulus was filled with air. The annulus is stainless steel at full density. The dimensions of the annular source are shown in Table 5-7 *for TN-RAM No. 01. TN-RAM No. 02 uses a mass of 1,800 kg. The height of the source was reduced to maintain the mass target. The source is moved to the top of the cavity. The annulus source dimensions for TN-RAM No. 02 are shown in Table 5-22.*

The four postulated source configurations are shown in axial views in Figure 5-2 and in radial view in Figure 5-3. The radial views are slices through the approximate center of the respective source region. *These views are for TN-RAM No. 01. TN-RAM No. 02 is similar, and therefore, not shown. Differences are shown in the respective source dimension tables.*

For the HAC evaluation, the source was placed inside the package using the homogenized source dimensions and location. An axial cross section view of the TN-RAM package for HAC is shown in Figure 5-4. Compression of the source was considered for the HAC analysis.

5.3.2 Material Properties

All the steel in the model is assumed to be stainless steel type 304. The elemental composition and density are shown in Table 5-8 [5-2]. The source bearing material was also assumed to be stainless steel type 304.

The elemental composition and density of dry air used in the model are shown in Table 5-9 [5-2].

All the wood in the impact limiter was assumed to be balsa. Balsa has a lower density than redwood. The balsa elemental composition and density used are shown in Table 5-10.

Lead used for shielding was assumed to be pure lead at 11.34 g/cm^3.

5.4 SHIELDING EVALUATION

5.4.1 Methods

The software package, Monte Carlo N-Particle (MCNP5), is used to evaluate the TN-RAM transportation package. MCNP5 is a robust, well-supported Monte Carlo transport code from Los Alamos National Laboratory utilized to compute dose rates for shielding licenses [5-3].

A three-dimensional model is developed that captures all of the relevant design parameters of the package and contents. Dose rates are calculated by tallying the gamma fluxes using mesh tallies in the areas of interest and converting these fluxes to dose rates using flux-to-dose rate conversion factors.

Simple Russian roulette is used as a variance reduction technique for all tallies. The importance of the particles increases as the particles traverse the shielding materials. The mean free path of an average cobalt-60 gamma ray in lead or steel was used as the distance where the importance doubled. The geometry of the package and contents is modeled in a lower universe. This lower universe is filled in the top-level universe where the geometrically based importance splitting occurs.

No source biasing was used in any model.

The acceptance criterion was the same as specified in the MCNP5 manual: variance below 10% is considered reliable for non-point detector tallies. *However, the uncertainty of most dose rate tallies is below 2 %, and the solutions are well converged.* |

5.4.2 Input and Output Data

A sample input file is provided in Section 5.5.2.

5.4.3 Flux-to-Dose-Rate Conversion

The ANSI/ANS 6.1.1-1977 flux-to-dose-rate conversion factors for gamma rays and neutrons are used in this evaluation [5-1]. The factors are shown for gammas in Table 5-11 and for neutrons in Table 5-17.

5.4.4 External Radiation Levels

Dose rates are calculated using the mesh tally feature of MCNP5. For the homogenized, annulus, disk top, and disk bottom, the radial tallies are segmented axially between 20 and 22 cm. Axial tallies are segmented radially approximately 22 cm. There is no angular segmentation for any tally. The beta case used tallies similar to the annulus, disk top, and disk bottom. For the neutron *and* secondary gamma evaluations, the tallies were segmented axially and angularly to be 4 cm x 4 cm to investigate if streaming exists. Axial tallies were Cartesian with 4 cm x 4 cm voxels, except for the tally for the normally occupied space, which was 8 cm x 8 cm. HAC radial tallies were segmented axially 4 cm with no angular segmentation. HAC axial tallies were segmented radially 4 cm with no angular segmentation. The cask is angularly symmetric except for the trunnions and the cavity drain. Dose rates for NCT use the impact limiter surfaces as the basis for the top and bottom. The cask body is the basis for the NCT side dose rates. The width of the vehicle is not defined; therefore, the surface

of the vehicle is assumed to be coincident with the radial surface of the impact limiters. The ends of the vehicle are assumed to be coincident with the top and bottom of the package. Tallies are shown in Figure 5-7. Red lines denote surface tallies used to show compliance with 10 CFR 71.47(b)(1) and 71.47(b)(2). Blue lines denote 1 m HAC tallies used to show compliance with 10 CFR 71.51(a)(2). Green lines denote 2 m NCT tallies used to shown compliance with 10 CFR 71.47(b)(3). The tally numbers correspond to the sample input file in Section 5.5.2.

Tallies used to develop the response functions for the energy dependent activities were surface tallies. The special tally treatment available in MCNP5 was used to track contributions to the tally based on the source energy weight. Only one case was required to develop response functions for all energies. The tally was a band at 2 m in the approximate center of the cask. The tally was 17 cm tall.

Other than the trunnions and the cavity drain, the radial and bottom lead shielding is not displaced. The lead in the original lid contains a penetration for a vent. However, the vent plug contains more lead axially than the lid so the penetration is of no consequence during transportation. The optional lid has no penetration through the lead shielding. The optional lid contains three steel lifting plugs. These displace some lead in the optional lid. These features were modeled in the comparison described in Section 5.4.4.3.

For HAC, dose rates are taken with the surface of the cask as the basis. While the impact limiters are shown to remain attached to the cask during all postulated accidents as prescribed by 10 CFR 71.73 as applicable (Sections 2.10.2 and 2.10.3), for the purpose of the shielding evaluation, the impact limiters are removed from the HAC model and replaced with air.

5.4.4.1 NCT dose rates *for TN-RAM No. 01*

A summary of all the NCT dose rates for all source configurations evaluated is shown in Table 5-12 *for TN-RAM No. 01.*

For the radial 2 m dose rate, the homogenized case has the maximum dose rate of 8.91 mrem/h. This dose rate is below the limit of 10 mrem/h. The relative uncertainty is 0.1 %, which is approximately 0.009 mrem/h. The dose rate is below the 10 CFR 71.47(b)(3) limit.

The 2 m top dose rate from the top of the impact limiter maximum was 1.80 mrem/h with the disk top source configuration. This is below the limit of 10 mrem/h.

The 2 m bottom dose rates from the bottom of the impact limiter maximum was 1.97 mrem/h with the disk bottom source configuration, which is below the limit of 10 mrem/h.

The maximum radial surface dose rate occurred with the disk top source configuration and was 106 mrem/hr, which is below the 10 CFR 71.47(b)(1) limit of 200 mrem/h. The dose rate here was on the surface of the cask body near the lid due to streaming over the side lead.

The maximum top surface dose rate occurred with the disk top source and is 11.5 mrem/h, which is below the limit of 200 mrem/h.

The maximum bottom surface dose rate occurred with the disk bottom source and is 19.3 mrem/h, which is below the limit of 200 mrem/h.

The external surfaces of the package were assumed to be coincident with the external surfaces of the vehicle. These dose rates satisfy both the requirements of 10 CFR 71.47(b)(1) and 10 CFR 71.47(b)(2).

The occupied space for personnel was assumed to be 152 inches from the front end of the package. The maximum dose rate was 0.722 mrem/h with the disk top configuration. Therefore, personnel do not have to conform to the radiation dosimetry requirements of 10 CFR 20.1502.

5.4.4.2 HAC dose rates *for TN-RAM No. 01*

A summary of all the HAC dose rates is shown in Table 5-15 *for TN-RAM No. 01*. All dose rates in this table are taken 1 m from the external surface of the cask. Compression of the source was investigated for HAC. The original source was the same as the NCT homogenized source. The source was then compressed by a factor of 3 and shifted toward the top or bottom in the axial direction to determine the resulting dose rates at 1 m from the surface of the cask. This reduction in height was from 282.66 cm to 94.22 cm. The maximum radial dose rate is 752 mrem/h, which is below the 10 CFR 71.51(a)(2) limit of 1,000 mrem/h. This dose rate occurs above the lead shielding directly below the lid. The secondary container, which was not modeled, would prevent source bearing contents from being in this area. The maximum top HAC dose rate is 245 mrem/h, which is below the limit of 1,000 mrem/h. This occurs when the source is compressed towards the top of the cask. The maximum bottom HAC dose rate is 307 mrem/h, which is below the limit of 1,000 mrem/h. This occurs when the source is compressed towards the bottom of the cask.

5.4.4.3 Original lid versus optional lid

A comparison was made between the original and optional lids. The optional lid has 0.2 in. less lead than the original lid, but adds 0.375 in. of steel. Using the homogenized source configuration, both lids were modeled, and the top surface dose rates for NCT were compared. A dose rate distribution for both cases is shown in Figure 5-6. As shown in the figure, the original lid bounds the optional lid. Therefore, the original lid was used in the development of the NCT and HAC dose rates presented in this chapter.

5.4.4.4 Cavity Drain

The cavity drain was modeled explicitly. The cavity drain tube displaces lead directly under the cavity. Bottom dose rates are marginally higher than the top as a result. However, due to the increased distance from the cask and material of the impact limiters during NCT, the dose rates radially are bounding for all configurations. The cavity drain has no appreciable impact on the dose rates.

5.4.4.5 Materials other than steel

In all cases, the source material is modeled as stainless steel. Because less dense source materials (e.g., zirconium, aluminum) would have a lower density than steel, the source-bearing solid materials shall have a density equivalent to or exceeding the density of steel. Localized regions of low-density (e.g., B_4C in a control rod blade) are acceptable if the low-density regions contain negligible source.

5.4.4.6 Normally occupied spaces

The TN-RAM package is transported on a specially designed, three-axle semi-trailer. For the purpose of evaluating the requirements of 10 CFR 71.47(b)(4), the normally occupied space was considered to be at the front end of the trailer, 152 inches from the top end of the package. The package is only transported horizontally, lid end first. No credit is taken for shielding from the prime mover. *The normally occupied space dose rates for TN-RAM No. 01 bound TN-RAM No. 02 because TN-RAM No. 01 has a higher activity limit than TN-RAM No. 02 and the shielding in this direction is the same.* |

5.4.4.7 Self-shielding versus source distribution

Four different source geometries are examined. The self-shielding of the various source geometries are different, as well as the geometrical distribution of the source. The homogenized and annular geometries result in approximately the same radial 2 m dose rate, which is reasonable because each axial unit length of source contains the same mass and source activity. However, the homogenized source bounds the disk source 2 m dose rate by a large margin. For the homogenized source, the gamma mean free path is approximately 7.7 cm, while for the disk sources, the mean free path is approximately 1.6 cm. The difference in mean free path is due to the lower gram-density of the homogenized source compared to the disk source. For instance, a gamma born at the center of the homogenized source travelling in the radial direction will exit the cask at a higher energy than an equivalent gamma born in the disk source that must traverse a much denser source medium. Although the source per unit volume is larger for the disk sources, the mean free path is much smaller, and the net effect is a reduction in dose rate.

In the axial direction, the disk sources bound the homogenized source because the mean distance to a dose point along the axial centerline is always minimized for the disk source. However, the dose rates for the homogenized source at the same locations are quite similar.

For the source geometries considered, the various trade-offs between self-shielding and source geometry are difficult to determine a priori, although the detailed Monte Carlo results presented in this chapter are tightly converged.

5.4.4.8 Neutron and secondary gammas

With a source of $1x10^6$ neutrons/s, the maximum dose rate on the surface of the package is 1.51 mrem/h. However, this dose rate is inside the trunnion due to the nature of the tally. Other dose rates for this system are all less than 0.1 mrem/h. The maximum dose rate as a result of secondary gammas is 4.30E-03 mrem/h. The NCT results are shown in Table 5-16. No HAC evaluation was performed because the effectiveness of the package to shield neutrons is not reduced after the HAC.

Therefore, the neutron limit is acceptable for incidental radionuclide contamination that generates neutrons. No self-shielding was credited in the neutron and secondary gamma analysis.

5.4.4.9 Streaming

There is a streaming path at the top of the side lead where only steel shielding is present, see Figure 5-1. The dose rates are elevated near this streaming path and the effect will be most pronounced close to the package. The side surface dose rate is a maximum for the disk top configuration because the source is the most concentrated near the streaming path in this configuration. This streaming is also observed in the homogenized and annular source models. This streaming effect may be quantified by comparing the top and bottom disk models, because the bottom disk is far from the streaming path. The maximum side dose rate in the top disk model (106 mrem/hr) is significantly larger than the bottom disk model (68.2 mrem/hr). This result indicates that the mesh tallies are of sufficient resolution to resolve the steaming effect. The maximum dose rate is also far from the limit of 200 mrem/hr.

At a distance of 2 m from the side of the vehicle, the radiation due to streaming does not correspond to the maximum dose rate location and the homogenized source is the bounding configuration. This effect may be observed in Figure 5-8, which is a plot of the 2 m side dose rate as a function of axial location for the homogenized source. The maximum 2 m dose rate occurs at z = 167 cm (8.91 mrem/hr), although a distinct discontinuity in the dose rate is observed at z = 286 cm (7.39 mrem/hr). This discontinuity is due to streaming over the lead, although the resolution of the mesh tallies is sufficient to resolve the streaming effect. Therefore, the effect of streaming is properly accounted for in the dose rate results.

In the actual transportation configuration, the presence of the secondary container will help mitigate the streaming effect by providing additional shielding and providing a barrier so that the source will be farther from the streaming path. However, the secondary container is not credited in this analysis.

5.4.4.10 Beta Emission

Beta emission was considered using the source described in Section 5.2.3. The electrons were simulated with MCNP5 applied to the inner surface of the cavity with the maximum emission energy of phosphorus-32. The distribution of the source was isotropic on the surface, but directed radially outward. No self-shielding was included in the model. The source was only modeled radially. High Z materials create bremsstrahlung radiation. The radial dimension of the cask presents the highest opportunity for interaction because the most material is in the radial direction. The maximum dose rate on the radial surface of the cask was 3.08 ± 8% mrem/h. The maximum dose rate 2 m from the radial surface of the package was 0.122 ± 16% mrem/h.

5.4.4.11 NCT dose rates for TN-RAM No. 02

A summary of all the NCT dose rates for all source configurations evaluated is shown in Table 5-23.

For the radial 2 m dose rate, the homogenized case has the maximum dose rate of 9.13 mrem/h. This dose rate is below the limit of 10 mrem/h. The relative uncertainty is 0.4 %, which is approximately 0.037 mrem/h. The dose rate is below the 10 CFR 71.47(b)(3) limit.

The 2 m top dose rate from the top of the impact limiter maximum was 1.83 mrem/h with the disk top source configuration. This is below the limit of 10 mrem/h.

The 2 m bottom dose rates from the bottom of the impact limiter maximum was 1.95 mrem/h with the disk bottom source configuration, which is below the limit of 10 mrem/h.

The maximum radial surface dose rate occurred with the disk top source configuration and was 127 mrem/h, which is below the 10 CFR 71.47(b)(1) limit of 200 mrem/h. The dose rate here was on the surface of the cask body near the lid due to streaming over the side lead.

The maximum top surface dose rate occurred with the disk top source and is 11.2 mrem/h, which is below the limit of 200 mrem/h.

The maximum bottom surface dose rate occurred with the disk bottom source and is 19.3 mrem/h, which is below the limit of 200 mrem/h.

The external surfaces of the package were assumed to be coincident with the external surfaces of the vehicle. These dose rates satisfy both the requirements of 10 CFR 71.47(b)(1) and 10 CFR 71.47(b)(2).

5.4.4.12 HAC dose rates for TN-RAM No. 02

A summary of all the HAC dose rates is shown in Table 5-19. All dose rates in this table are taken 1 m from the external surface of the cask. Compression of the source was investigated for HAC. The source configuration was the same as HAC for TN-RAM No. 01. This is appropriate because the HAC configuration takes no credit for self-shielding because the cask is empty. The maximum radial dose rate is 612 mrem/h, which is below the 10 CFR 71.51(a)(2) limit of 1,000 mrem/h. This dose rate occurs above the lead shielding directly below the lid. The secondary container, which was not modeled, would prevent source bearing contents from being in this area. The maximum top HAC dose rate is 177 mrem/h, which is below the limit of 1,000 mrem/h. This occurs when the source is compressed towards the top of the cask. The maximum bottom HAC dose rate is 246 mrem/h, which is below the limit of 1,000 mrem/h. This occurs when the source is compressed towards the bottom of the cask.

5.5 APPENDIX

5.5.1 References

5-1 American Nuclear Society, "American National Standard Neutron and Gamma-Ray Flux-to-Dose-Rate Factors," ANSI/ANS-6.1.1-1997 (N666), LaGrange Park, Illinois.

5-2 McConn Jr, R. J. et al., "Compendium of Material Composition Data for Radiation Transport Modeling," PNNL-15870, Revision 1, Pacific Northwest National Laboratory, March 2011.

5-3 X-5 Monte Carlo Team, "MCNP—A General Monte Carlo N-Particle Transport Code," Version 5. Los Alamos National Laboratory, April 2003. Available from RSICC as Software Package C00730MNYCP00.

Proprietary Information on Pages 5-12 through 5-20
Withheld Pursuant to 10 CFR 2.390

5.5.3 Cobalt-60 Equivalence

In order to allow gamma emitting nuclides that are not cobalt-60 in the cask for transportation, energy dependent maximum activities were calculated. The purpose of these activities is to ensure that, regardless of the payload, the dose rates will not exceed the regulatory limits.

The maximum activities are determined by first generating the dose rate response (response function) for various line energies. The dose rate is tallied at 2 m from the side of the package in a band at the same axial location as the maximum 2 m side dose rate reported in Table 5-1. The source configuration is the same as the homogenized case because this configuration results in the limiting 2 m dose rate. The dose rate as a function of line energy is reported in Table 5-14. Based on these results, the 2 m dose rate due to 30,000 Ci cobalt-60, which has line energies of 1.1732 MeV and 1.3325 MeV, is $1.11\text{x}10^{15}(1.98\text{x}10^{-15} + 6.03\text{x}10^{-15}) = 8.90$ mrem/hr, which agrees well with the dose rate reported in Table 5-1.

Based on a dose rate limit of 8.90 mrem/hr, the activity limit for each line energy is computed as 8.90/D, where D is the dose rate for a single source particle. These activity limits are reported in Table 5-14. For all isotopes in the package, a sum of fractions is applied over all source isotopes and all source intensities to ensure the dose rates do not exceed the dose rates from 30,000 Ci cobalt-60:

$$F = \sum_i \frac{S_i(E)}{Activity\ Limit_i(E)} \leq 1$$

Where,

$S_i(E)$ is the line intensity at energy E for isotope i
Activity $Limit_i(E)$ is the activity limit at energy E from Table 5-14

This equation results in a summation of 1.0 for 30,000 Ci cobalt-60. Because the line energies for isotopes other than cobalt-60 will not fall exactly on the line energies provided in Table 5-14, the applicable activity limit may conservatively be taken as the next higher energy line in the table. For instance, the activity limit for a 2.1 MeV gamma would be the 2.5 MeV limit from Table 5-14.

In addition to the package limit of 30,000 Ci cobalt-60 equivalent, each item in the package must have a cobalt-60 equivalent specific activity ≤ 10 Ci/kg. The above equation for F may be applied separately for each item to be shipped, where $F = F_1 + F_2 + \ldots + F_n$, and n is the number of discrete items in the package. The total cobalt-60 equivalent (Ci) for each item is $30{,}000*F_n$. The cobalt-60 equivalent specific activity for an item of mass M (kg) is then $30{,}000*F_n/M$. The cobalt-60 equivalent specific activity should be verified for each item in the package.

This procedure is exactly the same for TN-RAM No. 02 using the activity limits in Table 5-24 and a maximum cobalt-60 activity of 18,000 Ci. |

Table 5-1
Summary of NCT Maximum Dose Rates *for TN-RAM No. 01*

	Dose rate (mrem/h)	Relative 1σ uncertainty	Limit (mrem/h)	Configuration
	Surface			
Side	106	0.001	200	Disk, Top
Top	11.5	0.01	200	Disk, Top
Bottom	19.3	0.01	200	Disk, Bottom
	2 m			
Side	8.91	0.001	10	Homogenized
Top	1.80	0.01	10	Disk, Top
Bottom	1.97	0.01	10	Disk, Bottom
	152 in. from the top of the package			
Top	0.722	0.02	2	Disk, Top

Table 5-2
Summary of HAC Maximum Dose Rates *for TN-RAM No. 01*

	Dose rate (mrem/h)	Relative 1σ uncertainty	Limit (mrem/h)
	1 m		
Side	752	0.01	1000
Top	245	0.07	1000
Bottom	307	0.09	1000

Proprietary Information on Pages 5-22 and 5-23
Withheld Pursuant to 10 CFR 2.390

Table 5-7
Annulus Source Geometric Description *for TN-RAM No. 01*

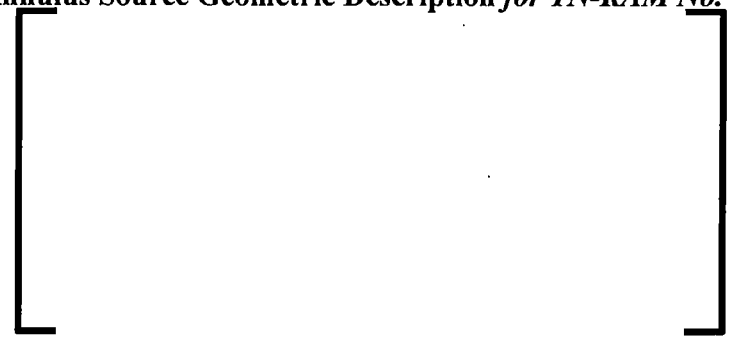

Table 5-8
Stainless Steel Material Composition

Element	Stainless Steel (weight fraction)
Carbon	0.04
Silicon	0.5
Phosphorous	0.023
Sulfur	0.015
Chromium	19
Manganese	1
Iron	70.172
Nickel	9.25
Density	7.92 g/cm^3

Table 5-9
Dry Air Material Composition

Element	Air (weight fraction)
Carbon	0.0124
Nitrogen	75.5268
Oxygen	23.1781
Argon	1.2827
Density	0.0012 g/cm^3

Table 5-10
Balsa Material Composition

Element	Balsa (atoms/b·cm)
Hydrogen	$5.94 \cdot 10^{-3}$
Carbon	$3.57 \cdot 10^{-3}$
Oxygen	$2.97 \cdot 10^{-3}$
Density	0.16 g/cm^3

Table 5-11
Gamma Flux-to-Dose-Rate Conversion Factors

Energy (MeV)	*mrem/h/γ/(s cm^2)*
0.01	*3.96E-03*
0.03	*5.82E-04*
0.05	*2.90E-04*
0.07	*2.58E-04*
0.1	*2.83E-04*
0.15	*3.79E-04*
0.2	*5.01E-04*
0.25	*6.31E-04*
0.3	*7.59E-04*
0.35	*8.78E-04*
0.4	*9.85E-04*
0.45	*1.08E-03*
0.5	*1.17E-03*
0.55	*1.27E-03*
0.6	*1.36E-03*
0.65	*1.44E-03*
0.7	*1.52E-03*
0.8	*1.68E-03*
1	*1.98E-03*
1.4	*2.51E-03*
1.8	*2.99E-03*
2.2	*3.42E-03*
2.6	*3.82E-03*
2.8	*4.01E-03*
3.25	*4.41E-03*
3.75	*4.83E-03*
4.25	*5.23E-03*
4.75	*5.60E-03*
5	*5.80E-03*
5.25	*6.01E-03*
5.75	*6.37E-03*
6.25	*6.74E-03*
6.75	*7.11E-03*
7.5	*7.66E-03*
9	*8.77E-03*
11	*1.03E-02*
13	*1.18E-02*
15	*1.33E-02*

Table 5-12
Summary of All NCT Configurations *for TN-RAM No. 01*

	Dose rate (mrem/h)	Relative 1σ uncertainty	Dose rate (mrem/h)	Relative 1σ uncertainty	Dose rate (mrem/h)	Relative 1σ uncertainty	Dose rate (mrem/h)	Relative 1σ uncertainty
	Annulus		**Disk, Top**		**Disk, Bottom**		**Homogenized Cylinder**	
	Surface							
Radial max:	102	0.001	106	0.001	68.2	0.001	98.7	0.01
Top max:	10.3	0.01	11.5	0.01	1.83	0.01	10.8	0.01
Bottom max:	17.2	0.01	3.36	0.01	19.3	0.01	18.3	0.01
	2 m							
Radial max:	8.84	0.001	5.17	0.001	2.31	0.02	8.91	0.001
Top max:	1.60	0.01	1.80	0.01	0.302	0.02	1.72	0.01
Bottom max:	1.76	0.01	0.481	0.02	1.97	0.01	1.91	0.01
	152 in. from the top impact limiter							
Top max:	0.633	0.03	0.722	0.02	0.138	0.07	0.712	0.06

Table 5-13
Deleted

Table 5-14
Response Functions and Activity Limits by Energy *for TN-RAM No. 01*

Line Energy (MeV)	Dose Rate per Source Particle (mrem/hr)	Activity Limit (γ/s)
0.6	1.17E-17	7.62E+17
0.8	7.14E-17	1.25E+17
1.0	4.38E-16	2.03E+16
1.1732	1.98E-15	4.49E+15
1.3325	6.03E-15	1.47E+15
1.5	1.45E-14	6.15E+14
1.75	3.71E-14	2.40E+14
2.0	7.10E-14	1.25E+14
2.5	1.61E-13	5.52E+13
3.0	2.60E-13	3.42E+13
3.5	3.48E-13	2.55E+13
4.0	4.17E-13	2.14E+13
4.5	4.69E-13	1.90E+13
5.0	4.99E-13	1.78E+13
6.0	5.36E-13	1.66E+13
8.0	5.64E-13	1.58E+13
10.0	5.96E-13	1.49E+13

Table 5-15
Summary of All HAC Configurations *for TN-RAM No. 01*

	Dose rate (mrem/h)	Relative 1σ uncertainty	Dose rate (mrem/h)	Relative 1σ uncertainty	Dose rate (mrem/h)	Relative 1σ uncertainty
	Full		Compressed Top		Compressed Bottom	
1 m radial	258	0.01	752	0.01	223	0.01
1 m top	144	0.09	245	0.07	47.4	0.16
1 m bottom	200	0.15	81.1	0.08	307	0.09

Table 5-16
Neutron and Secondary Gamma NCT Dose Rates *for TN-RAM No. 01*

	Dose rate (mrem/h)	Relative 1σ uncertainty	Dose rate (mrem/h)	Relative 1σ uncertainty
	Neutron		Secondary Gamma	
	2 meters			
radial max:	0.0814	0.02	1.97E-04	0.05
top max:	0.0110	0.06	2.29E-04	0.05
bottom max:	0.0109	0.06	2.61E-04	0.05
	Surface			
radial max:	1.51	0.01	2.93E-03	0.02
top max:	0.0109	0.03	3.21E-03	0.02
bottom max:	0.0635	0.02	4.30E-03	0.02
	152" from the top impact limiter			
top max:	5.27E-03	0.04	7.64E-05	0.04

Table 5-17
ANSI/ANS 6.1.1-1977 Neutron Flux-to-Dose-Rate Conversion Factors

Energy (MeV)	*mrem/h/n/(s cm^2)*
2.50E-08	*3.67E-03*
1.00E-07	*3.67E-03*
1.00E-06	*4.46E-03*
1.00E-05	*4.54E-03*
1.00E-04	*4.18E-03*
1.00E-03	*3.76E-03*
1.00E-02	*3.56E-03*
1.00E-01	*2.17E-02*
5.00E-01	*9.26E-02*
1	*1.32E-01*
2.5	*1.25E-01*
5	*1.56E-01*
7	*1.47E-01*
10	*1.47E-01*
14	*2.08E-01*
20	*2.27E-01*

Table 5-18
Summary of NCT Maximum Dose Rates for TN-RAM No. 02

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Table 5-19
Summary of HAC Maximum Dose Rates for TN-RAM No. 02

	Dose rate (mrem/h)	*Relative 1σ uncertainty*	*Dose rate (mrem/h)*	*Relative 1σ uncertainty*	*Dose rate (mrem/h)*	*Relative 1σ uncertainty*
	Full		*Compressed Top*		*Compressed Bottom*	
1 m radial	*215*	*0.002*	*612*	*0.001*	*230*	*0.001*
1 m top	*94.4*	*0.02*	*177*	*0.012*	*35.8*	*0.03*
1 m bottom	*141*	*0.01*	*60.6*	*0.03*	*246*	*0.01*

Table 5-20
Homogenized Source Geometric Description for TN-RAM No. 02

Location	*Dimension*	*Unit*
Radius	*44.44*	*cm*
Height	*169.6*	*cm*
Volume	*1,052,237*	*cm^3*
Density	*1.71064*	*g/cm^3*
Mass	*1,800*	*kg*

Table 5-21
Disk Source Geometric Description for TN-RAM No. 02

Location	*Dimension*	*Unit*
Density	*7.92*	*g/cm^3*
Mass	*1,800*	*kg*
Volume	*227,273*	*cm^3*
Outer radius	*44.44*	*cm*
Height	*36.63105*	*cm*

Table 5-22
Annulus Source Geometric Description for TN-RAM No. 02

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Table 5-23
NCT Summary of Results for TN-RAM No. 02

	Dose rate (mrem/h)	*Relative 1σ uncertainty*	*Dose rate (mrem/h)*	*Relative 1σ uncertainty*	*Dose rate (mrem/h)*	*Relative 1σ uncertainty*	*Dose rate (mrem/h)*	*Relative 1σ uncertainty*
	Annulus		*Disk, Top*		*Disk, Bottom*		*Homogenized Cylinder*	
	2 meters							
radial max:	*9.13*	*0.004*	*4.91*	*0.004*	*2.00*	*0.006*	*9.13*	*0.004*
top max:	*1.50*	*0.03*	*1.83*	*0.02*	*0.257*	*0.06*	*1.79*	*0.03*
bottom max:	*0.633*	*0.06*	*0.423*	*0.07*	*1.95*	*0.02*	*0.883*	*0.06*
	Surface							
radial max:	*123*	*0.004*	*127*	*0.003*	*73.4*	*0.003*	*118*	*0.004*
top max:	*9.52*	*0.02*	*11.2*	*0.01*	*1.62*	*0.03*	*10.6*	*0.02*
bottom max:	*5.57*	*0.03*	*2.91*	*0.04*	*19.3*	*0.01*	*7.07*	*0.03*

Table 5-24
Response Functions and Activity Limits by Energy for TN-RAM No. 02

Line Energy (MeV)	*Dose Rate per Source Particle (mrem/h)*	*Activity Limit (γ/s)*
0.6	*1.91E-17*	*4.45E+17*
0.8	*1.28E-16*	*6.64E+16*
1	*7.53E-16*	*1.13E+16*
1.1732	*3.23E-15*	*2.63E+15*
1.3325	*9.53E-15*	*8.92E+14*
1.5	*2.22E-14*	*3.84E+14*
1.75	*5.68E-14*	*1.50E+14*
2	*1.10E-13*	*7.76E+13*
2.5	*2.45E-13*	*3.47E+13*
3	*3.82E-13*	*2.22E+13*
3.5	*5.08E-13*	*1.67E+13*
4	*6.03E-13*	*1.41E+13*
4.5	*6.91E-13*	*1.23E+13*
5	*7.21E-13*	*1.18E+13*
6	*7.73E-13*	*1.10E+13*
8	*8.16E-13*	*1.04E+13*
10	*8.77E-13*	*9.69E+12*

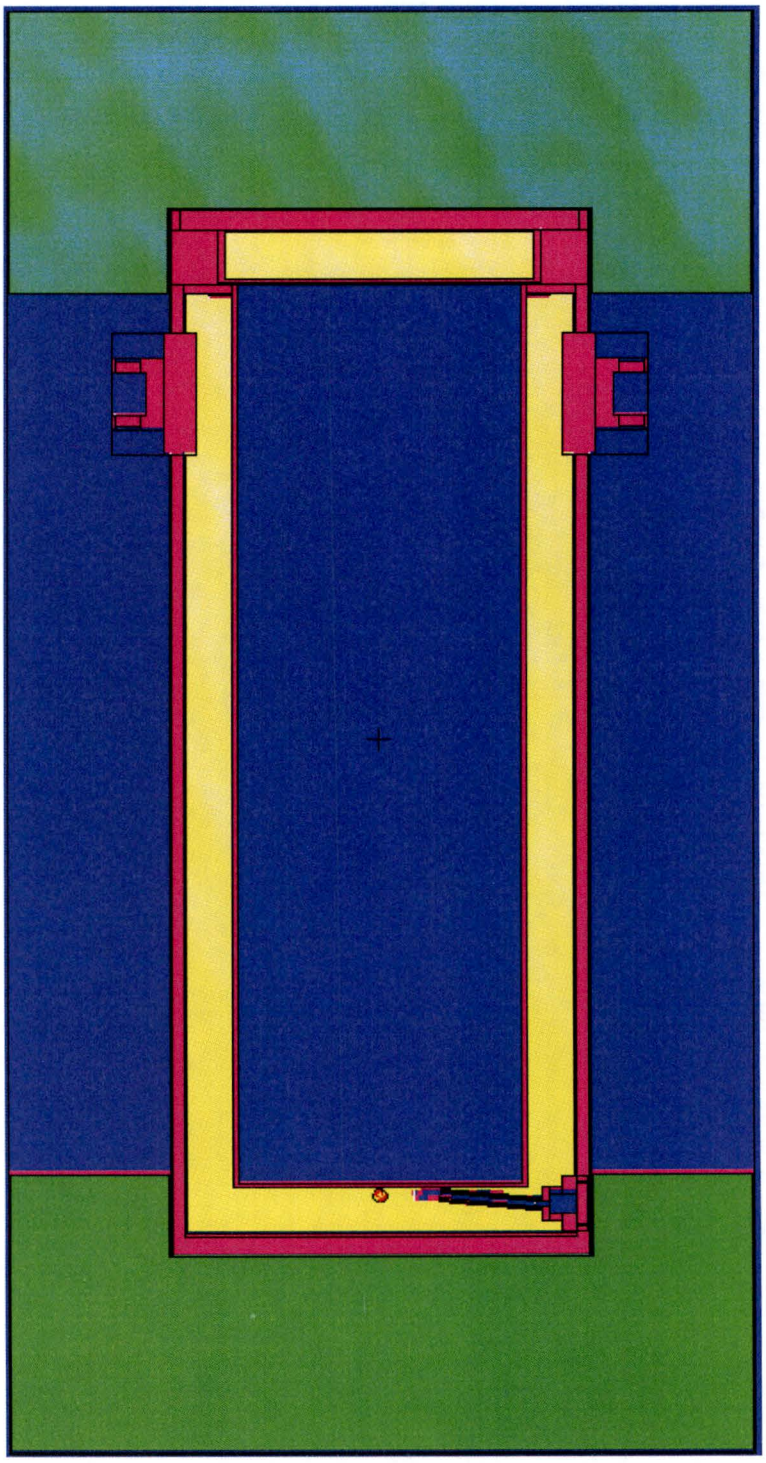
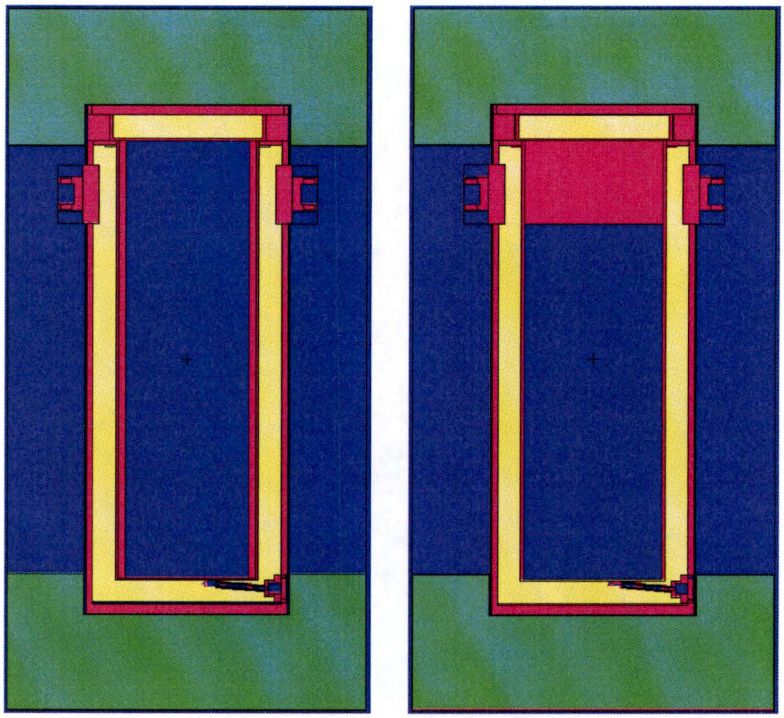
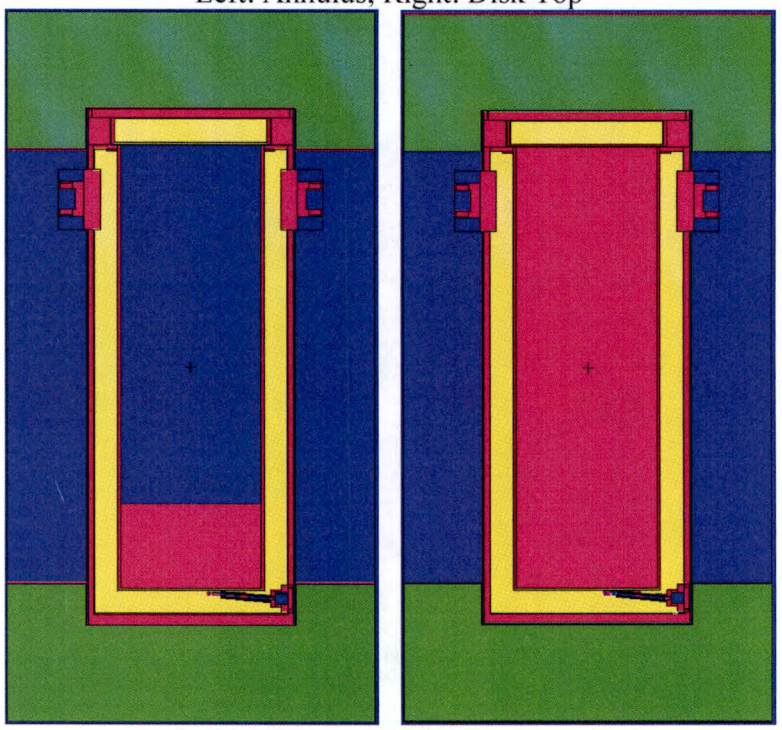


Figure 5-1
TN-RAM *No. 01* NCT Model

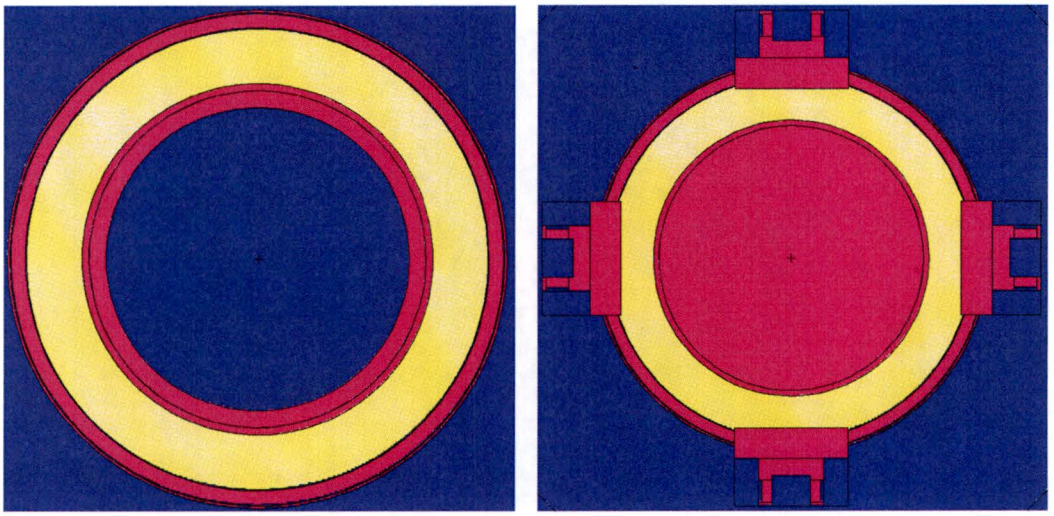


Left: Annulus, Right: Disk Top

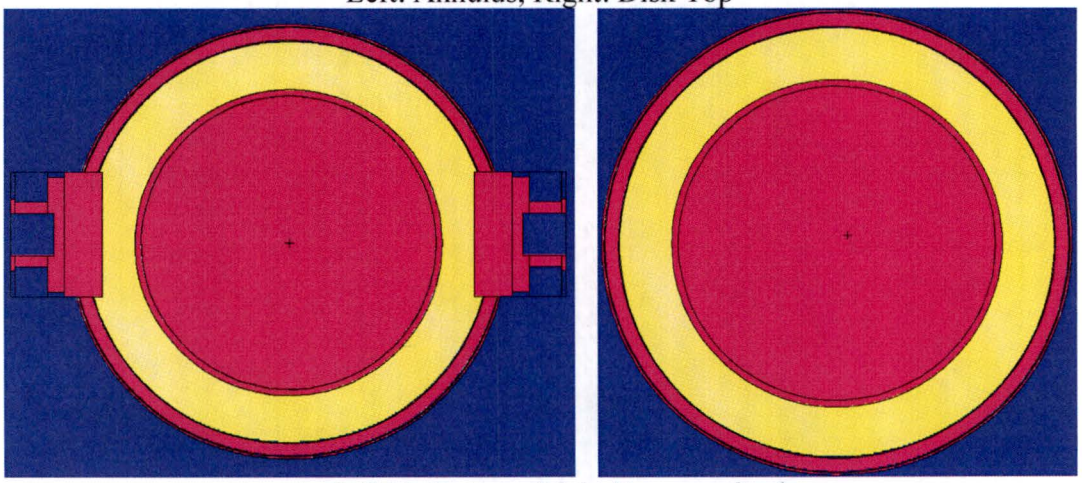


Left: Disk Bottom, Right: Homogenized

Figure 5-2
Source Configurations—Axial View *for TN-RAM No. 01*



Left: Annulus, Right: Disk Top



Left: Disk Bottom, Right Homogenized

Figure 5-3
Source Configurations—Radial View *for TN-RAM No. 01*

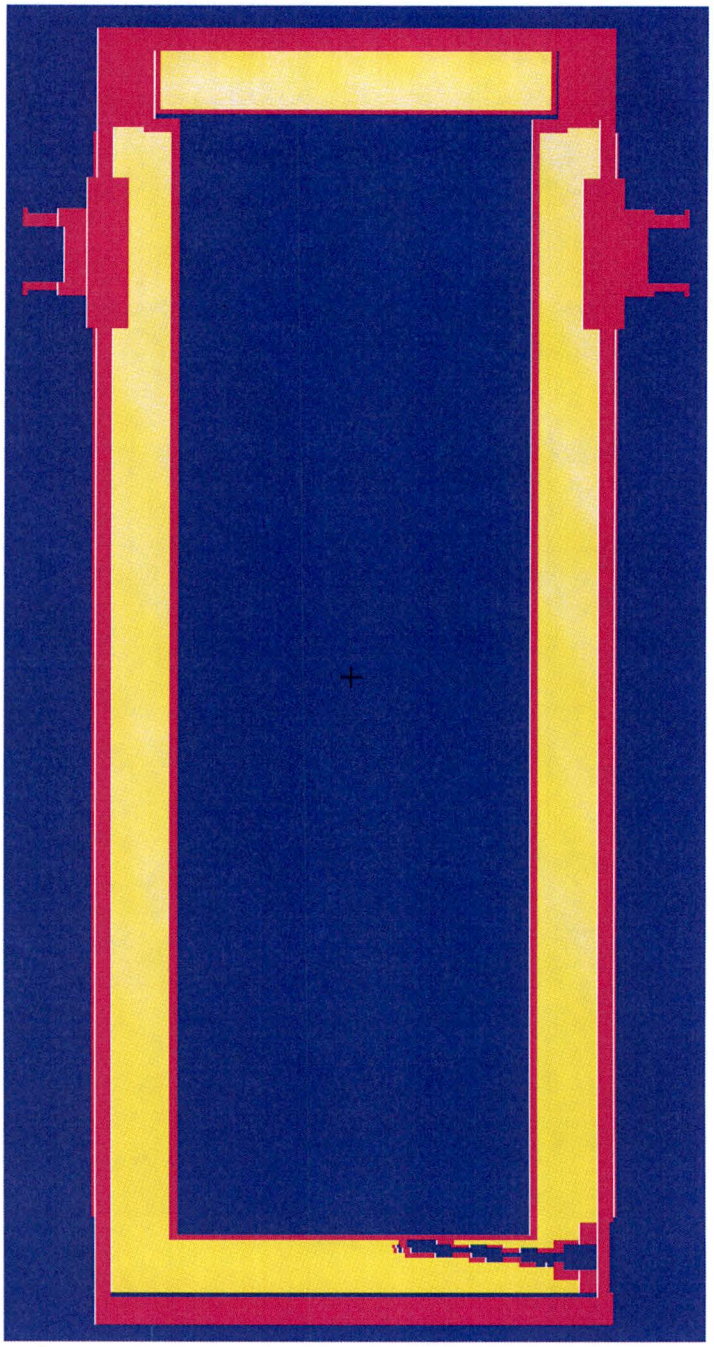


Figure 5-4
TN-RAM HAC Model *for TN-RAM No. 01*

Figure 5-5
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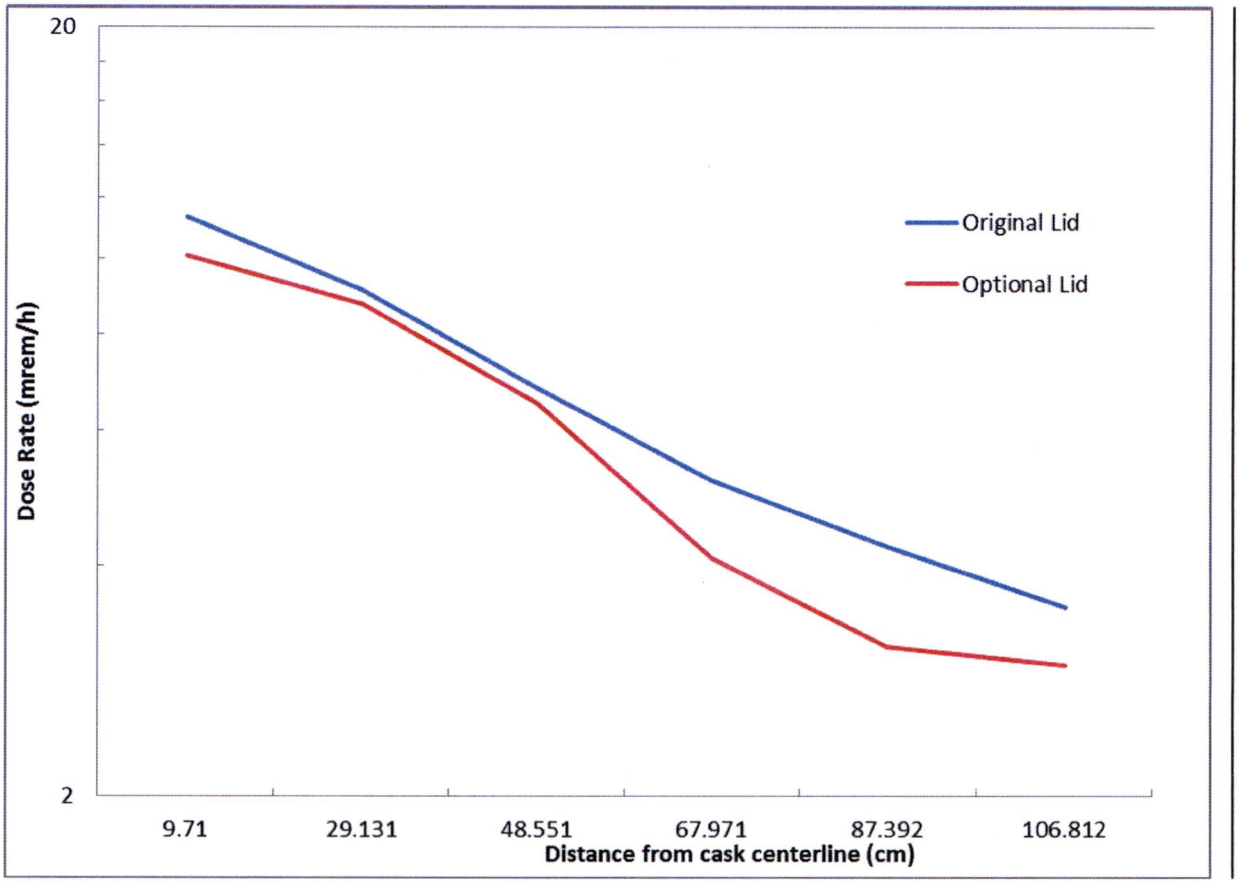

Figure 5-6
Lid Comparison

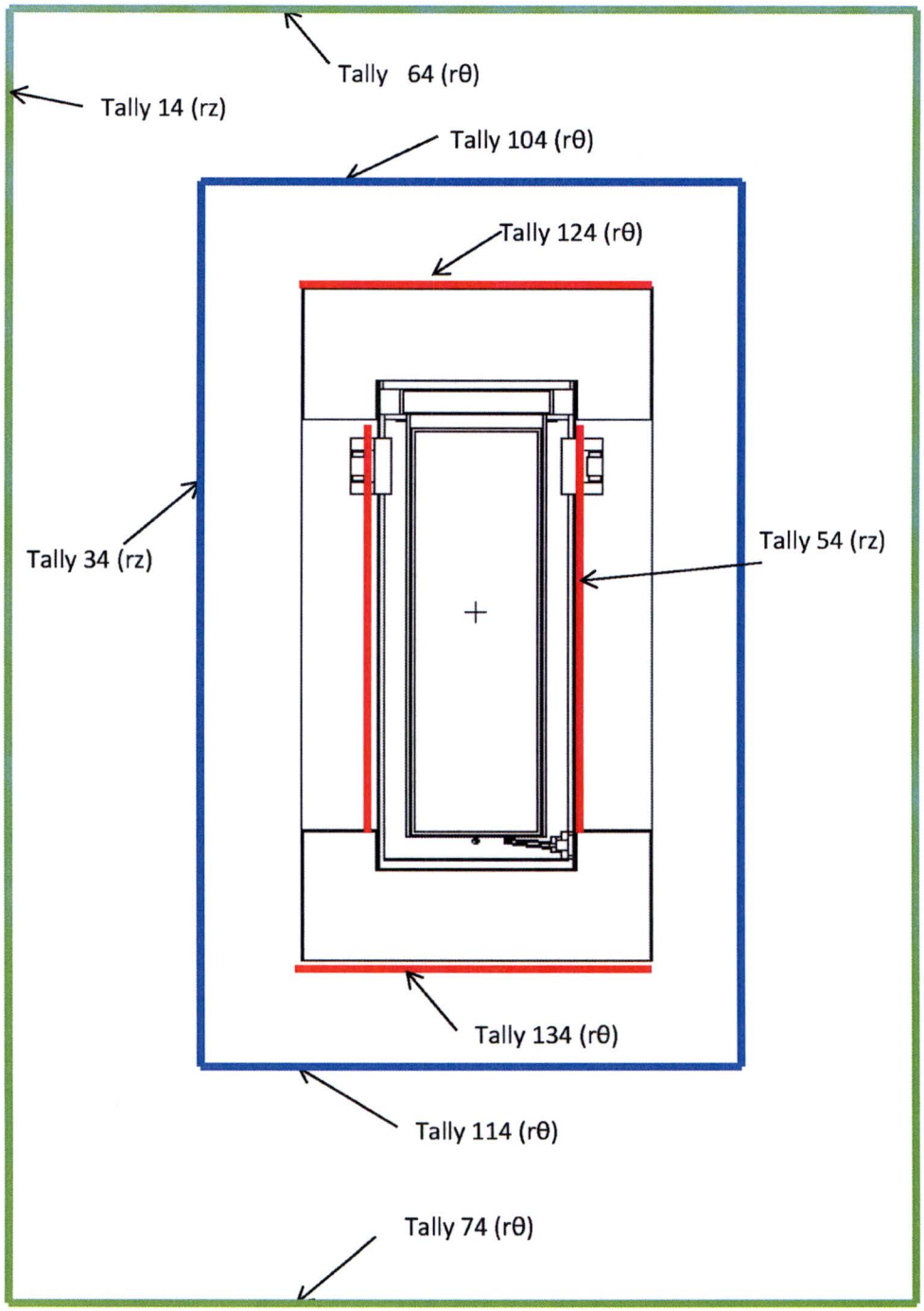

Figure 5-7
Tally Locations

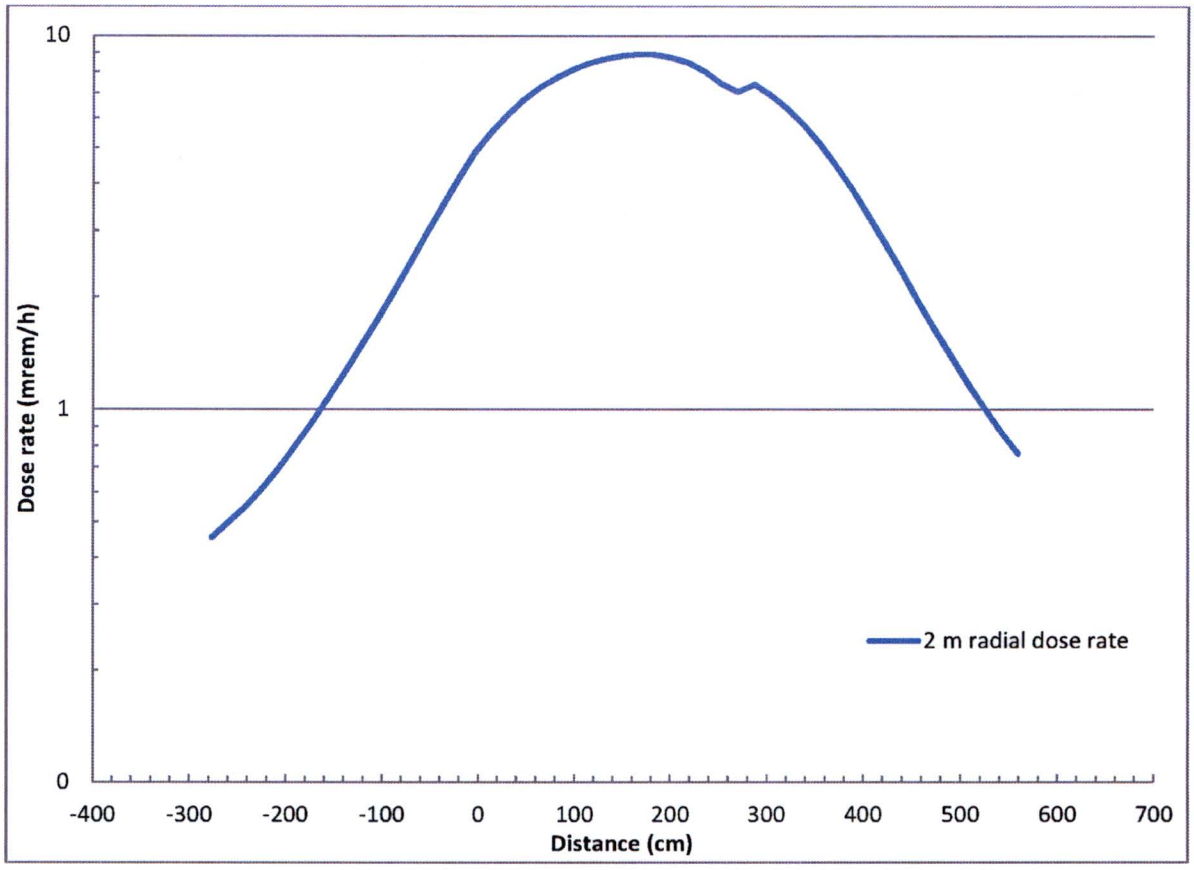

Figure 5-8
Dose Rate Profile at 2 m from Vehicle Side, Homogenized Source *for TN-RAM No. 01*

Figure 5-9
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CHAPTER SEVEN
OPERATING PROCEDURES

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CHAPTER SEVEN
OPERATING PROCEDURES

This chapter contains TN-RAM loading and handling procedure guidelines which show the general approach to cask operational activities. The information in this chapter will be used to prepare site specific procedures. Operational steps which must be performed in order to maintain the validity of cask transport regulations and safety analysis conclusions are identified by underlined procedural steps.

The procedures in this section are for those activities associated with the loading and transport of irradiated materials from user facilities to burial sites. Cask loading is normally performed wet *with the cask oriented vertically* in a spent fuel pool, and cask unloading operations are normally performed dry *with the cask oriented horizontally* at a burial site.

An optional two-piece lid consisting of a shield disk *and outer lid plate can also be used in a dry top-loading facility* and a dry top-unloading facility.

The final steps of cask acceptance testing are performed at the loading site prior to the cask being *transported for the shipment.*

7.1 PROCEDURES FOR LOADING PACKAGE

NOTE: *Compliance with allowed contents limits shall be verified prior to release of the loaded cask for shipment. The allowed contents activity limit for TN-RAM No. 01 is 30,000 Ci equivalent Co-60 and the activity limit for TN-RAM No. 02 is 18,000 Ci equivalent Co-60.*

7.1.1 Receipt of Empty Package

7.1.1.1 Upon cask arrival on the transport vehicle, perform receipt inspection to check for damage or irregularities and perform a radiation survey.

7.1.1.2 After removing the security wires, remove impact limiter attachment bolts and remove the front and rear impact limiters using a suitable crane and two legged sling.

7.1.1.3 Remove the front and rear trunnion tie-downs.

7.1.1.4 Attach the lift beam to a suitable crane hook and engage the lift beam to the two front trunnions.

7.1.1.5 Rotate the cask from the horizontal to the vertical position.

7.1.1.6 Lift the cask from the transport vehicle. Place the cask in the preparation area.

7.1.1.7 Disengage the lift beam from the cask.

7.1.1.8 If necessary, clean the cask external surfaces of road dirt.

7.1.2 Wet Loading

7.1.2.1 Remove the lid gasket port plug and detorque the lid bolts in an approved sequence.

Note: The cask may be filled with water in the preparation area (lid on or off) or as the cask is lowered into the pool with the lid off.

7.1.2.2 Remove the cover from the Vent port.

7.1.2.3 Install the lid lifting attachments.

7.1.2.4 *Remove the cask lid.*

7.1.2.5 Engage the lift beam*(s)* to the *cask.*

7.1.2.6 Lift the cask from the preparation area and position over the cask loading area in the pool.

7.1.2.7 Lower the cask into the pool while spraying the cask with clean water.

7.1.2.8 Continue to lower the cask until it is on the pool bottom.

7.1.2.9 Disengage the lift beam*(s)* from the *cask.*

7.1.2.10 Deleted

7.1.2.11 Deleted

7.1.2.12 Install the cask seal surface protective cover.

7.1.2.13 *Using the appropriate handling tool and suitable hoist, load the cask cavity. Verify* that the cask is full or install appropriate component spacers to restrain the contents during transport. Record the contents and location on the cask loading report to the extent practical.

7.1.2.14 Remove the cask seal surface protective cover.

7.1.2.15 Inspect the O-rings in the lid for damage and replace if defects are noted, with new o-rings which have been determined to be free of defects and have a current shelf life, in accordance with the following. Record inspection results on the cask loading report.

7.1.2.15.1 Remove the defective O-ring.

7.1.2.15.2 Clean the O-ring groove.

7.1.2.15.3 Inspect the new O-ring to determine that it is free of defects.

7.1.2.15.4 Position the O-ring uniformly around the lid over the O-ring groove.

7.1.2.15.5 Press lightly at four diametrically opposite positions.

7.1.2.15.6 Continue to press the O-ring at diametrically opposite positions until it is fully seated in the gasket groove.

7.1.2.15.7 Inspect the new O-ring to verify that it is free of defects. Record inspection results on the cask loading report.

7.1.2.16 Transfer the lid to a position directly over the cask cavity. Establish correct lid orientation and lower the lid until fully seated. Visually verify proper lid installation.

7.1.2.17 Continue lowering the lift beam(s) and engage the lift beam(s) to the cask.

7.1.2.18 Raise the cask to the pool surface, survey the cask for safe radiation levels and check that the lid is properly seated. Wash down exposed cask surfaces and lift beam surfaces with clean water.

7.1.2.19 Install two or more lid bolts hand tight.

7.1.2.20 Slowly remove the cask from the pool while thoroughly washing all exposed surfaces with a clean water spray.

7.1.2.21 Move the cask to the preparation area.

7.1.2.22 Disengage the lid lifting attachments and lift beam(s).

7.1.2.23 Survey and decontaminate the cask surfaces as required to permit safe working conditions.

7.1.2.24 Inspect the lid bolts. Replace defective bolts and note any defect indications on the cask loading report. Apply a light coating of an approved lubricant to the bolt threads and install all 16 lid bolts. Tighten to hand tight. Torque all lid bolts to 950 ±50 ft-lbs. in several stages using an approved torquing sequence.

7.1.2.25 Install the Vacuum Drying System (VDS) to the lid gasket port and vacuum dry the lid O-ring interspace until the pressure is reduced to 10, +2, -0 mbar.

7.1.2.26 Perform a pressure rise leakage test for assembly verification of the cask lid. The leakage rate is calculated as:

$$L_R = \frac{V * \Delta P * 298}{t * 1013 * T}$$

where V = test volume (cc)
ΔP = measured pressure difference (mbar)
t = elapsed time for the test (sec)
and T = temperature of test (°K)

It is assumed that over the relatively short duration of the test (1-2 min.), the change in temperature is insignificant. The acceptance criteria is that L_R be no greater than 1×10^{-3} std-cm^3/sec.

If an O-ring has been replaced, the maximum allowable leak rate is 6.87×10^{-4} ref cm^3/sec with a test sensitivity better than 3.4×10^{-4} ref cm^3/sec. A helium mass spectrometer method or equivalent performed in accordance with written, approved procedures shall be used.

7.1.2.27 Install the lid gasket port plug. Remove the Drain port cover, and drain the cask.

7.1.2.28 Connect the VDS to the Vent port and the drain bottle to the Drain port.

7.1.2.29 Using the VDS, lower the pressure in the cask to approximately 40 mbar. Isolate the vacuum pump and vent the cask to allow residual moisture to condense and collect in the drain bottle. Repeat several times until no more water collects in the drain bottle.

7.1.2.30 Disconnect the drain bottle from the Drain port.

7.1.2.31 Perform the cask dryness verification test as follows:

a. Evacuate the cask cavity until a stable vacuum of 10, +2, -0 mbar is indicated.

b. Isolate the VDS from the cask cavity.

c. Verify that the pressure rise over a period of 10 minutes does not exceed 6 mbar. If this pressure rise is exceeded repeat steps a and b until the acceptance criteria is satisfied.

NOTE: If the pressure rise for successive tests is constant or increases, a leak in the system is indicated and must be corrected before proceeding.

7.1.2.32 Remove the VDS connector from the vent port.

7.1.2.33 Install the Vent and Drain port covers and bolts. Torque the bolts to 25 ±5 ft-lbs.

7.1.2.34 Place the test bell over the vent cover and use the VDS to reduce the pressure in between the vent port O-ring and the O-ring on the test bell to 7-10 mbar. Isolate the VDS and perform a pressure rise leakage rate test of the vent port cover. The calculated leakage rate, using the equation in 7.1.2.26, shall be no greater than 1×10^{-3} std-cm^3/sec.

If an O-ring has been replaced, the maximum allowable leak rate is 6.87×10^{-4} ref cm^3/sec with a test sensitivity better than 3.4×10^{-4} ref cm^3/sec. A helium mass spectrometer method or equivalent performed in accordance with written, approved procedures shall be used.

7.1.2.35 Repeat the test of Steps 7.1.2.34 for the Drain port cover.

7.1.2.36 If any test indicates a leakage greater than the allowable rate, the leakage area shall be identified, repaired as needed and the test repeated until the acceptance criteria is satisfied.

7.1.2.37 Re-engage the lift beam to the cask.

7.1.2.38 Lift the cask off preparation area, place the rear trunnions on transport vehicle rear trunnion supports and rotate cask from the vertical to horizontal position. Disengage the lift beam from the cask.

7.1.2.39 Install and torque front and rear trunnion tie-downs.

7.1.2.40 Perform a temperature survey to verify compliance with 10 CFR 71.43(g) and 10 CFR 71.87(k).

NOTE: *Lifting lugs for impact limiters are designed for lifting impact limiters only. Lifting lugs shall not be used as attachment points to lift or tie-down the cask. Lifting lugs shall be rendered inoperable once impact limiters are attached to the cask shell and not being installed or removed. A bolt installed through the lifting lug hole or equivalent means shall be used to render the lifting lug inoperable.*

7.1.2.41 Install the front and rear impact limiters and torque attachment bolts diametrically to 40-50 ft-lbs. Repeat torquing sequence to 300 ±20 ft.-lb. for unlubricated bolts or to 180 ±20 ft-lbs. for lubricated bolts.

7.1.2.42 Install security seals on impact limiter bolts.

7.1.2.43 Perform final radiation and contamination surveys to assure compliance with 10 CFR 71.47 and 71.87.

7.1.2.44 Apply appropriate labels to the package and vehicle in accordance with 49 CFR 172.

7.1.2.45 Prepare final shipping documentation.

7.1.2.46 Release the loaded cask for shipment.

7.1.3 *Dry* Loading

Note: *This section assumes the optional two-piece lid is used for all dry loading.*

7.1.3.1 Remove the lid gasket port plug and detorque the lid bolts in an approved sequence.

7.1.3.2 Remove the cover from the Vent port.

7.1.3.3 Install the lid lifting attachments.

7.1.3.4 *Remove* the *cask lid.*

7.1.3.5 Engage the lift beam*(s)* to the *cask.*

7.1.3.6 Lift the cask from the preparation area and *move to loading area.*

7.1.3.7 Disengage the lift beam*(s)* from the *cask.*

7.1.3.8 *Attach* a suitable *crane to lid lifting sling.*

7.1.3.9 *Install the cask seal surface protective cover.*

7.1.3.10 *Remove* the shield disk.

7.1.3.11 Using the appropriate handling tool and hoist, load the cask cavity. Verify that the cask is full or install appropriate component spacers to restrain the contents during transport. Record the contents and location on the cask loading report to the extent practical.

7.1.3.12 *Replace* the shield disk.

7.1.3.13 Remove the cask seal surface protective cover.

7.1.3.14 *Move* the *cask to* the preparation *area for lid installation.*

7.1.3.15 Inspect the O-rings in the lid for damage and replace if defects are noted, with new o-rings which have been determined to be free of defects and have a current shelf life, in accordance with the following. Record inspection results on the cask loading report.

7.1.3.15.1 Remove the defective O-ring.

7.1.3.15.2 Clean the O-ring groove.

7.1.3.15.3 Inspect the new O-ring to determine that it is free of defects.

7.1.3.15.4 Position the O-ring uniformly around the lid over the O-ring groove.

7.1.3.15.5 Press lightly at four diametrically opposite positions.

7.1.3.15.6 Continue to press the O-ring at diametrically opposite positions until it is fully seated in the gasket groove.

7.1.3.15.7 Inspect the new O-ring to verify that it is free of defects. Record inspection results on the cask loading report.

7.1.3.16 Attach the lid lifting attachment to cask lid.

7.1.3.17 Transfer the lid to a position directly over the cask cavity. Establish correct lid orientation. Install the lid. Visually verify that the lid is correctly oriented and fully seated. |

7.1.3.18 Move the cask to the preparation area.

7.1.3.19 Disengage the lid lifting attachments and lift beam(s).

7.1.3.20 Survey and decontaminate the cask surfaces as required to permit safe working conditions.

7.1.3.21 Inspect the lid bolts. Replace defective bolts and note any defect indications on the cask loading report. Apply a light coating of an approved lubricant to the bolt threads and install all 16 lid bolts. Tighten to hand tight. Torque all lid bolts to 950 ±50 ft-lbs. in several stages using an approved torquing sequence.

7.1.3.22 Install the Vacuum Drying System (VDS) to the lid gasket port and evacuate the lid O-ring interspace until the pressure is reduced to 10, +2, -0 mbar.

7.1.3.23 Perform a pressure rise leakage test for assembly verification of the cask lid. The leakage rate is calculated as:

$$L_R = \frac{V * \Delta P * 298}{t * 1013 * T}$$

Where V = test volume (cc)
ΔP = measured pressure difference (mbar)
t = elapsed time for the test (sec)
and T = temperature of test (°K)

It is assumed that over the relatively short duration of the test (1-2 min.), the change in temperature is insignificant. The acceptance criteria is that L_R be no greater than 1 x 10^{-3} *ref* cm^3/sec.

If an O-ring has been replaced, the maximum allowable leak rate is 6.87 x 10^{-4} ref cm^3/sec with a test sensitivity better than 3.4 x 10^{-4} ref cm^3/sec. A helium mass spectrometer method or equivalent performed in accordance with written, approved procedures shall be used.

Install the lid gasket port plug.

7.1.3.24 Perform the cask dryness verification test as follows:

a. Evacuate the cask cavity until a stable vacuum of 10, +2, -0 mbar is indicated.
b. Isolate the VDS from the cask cavity.
c. Verify that the pressure rise over a period of 10 minutes does not exceed 6 mbar. If this pressure rise is exceeded repeat steps a and b until the acceptance criteria is satisfied.

NOTE: If the pressure rise for successive tests is constant or increases, a leak in the system is indicated and must be corrected before proceeding.

7.1.3.25 Remove the VDS connector from the vent port.

7.1.3.26 Install the Vent port cover and bolts. Torque the bolts to 25 ±5 ft-lbs.

7.1.3.27 Place the test bell over the vent cover and use the VDS to reduce the pressure in between the vent port O-ring and the O-ring on the test bell to 7-10 mbar. Isolate the VDS and perform a pressure rise leakage rate test of the vent port cover. The calculated leakage rate, using the equation in 7.1.3.23, shall be no greater than 1×10^{-3} ref cm^3/sec.

If an O-ring has been replaced, the maximum allowable leak rate is 6.87×10^{-4} ref cm^3/sec with a test sensitivity better than 3.4×10^{-4} ref cm^3/sec. A helium mass spectrometer method or equivalent performed in accordance with written, approved procedures shall be used.

7.1.3.28 Repeat the test of Step 7.1.2.27 for the Drain port cover.

7.1.3.29 If any test indicates a leakage greater than the allowable rate, the leakage area shall be identified, repaired as needed and the test repeated until the acceptance criteria is satisfied.

7.1.3.30 Re-engage the lift beam to the cask.

7.1.3.31 Lift the cask off preparation area, place the rear trunnions on transport vehicle rear trunnion supports and rotate cask from the vertical to horizontal position.

7.1.3.32 Install and torque front and rear trunnion tie-downs.

7.1.3.33 Perform a temperature survey to verify compliance with 10 CFR 71.43(g) and 10 CFR 71.87(k).

NOTE: *Lifting lugs for impact limiters are designed for lifting impact limiters only. Lifting lugs shall not be used as attachment points to lift or tie-down the cask. Lifting lugs shall be rendered inoperable once impact limiters are attached to the cask shell and not being installed or removed. A bolt installed through the lifting lug hole or equivalent means shall be used to render the lifting lug inoperable.*

7.1.3.34 Install the front and rear impact limiters and torque attachment bolts diametrically to 40-50 ft-lbs. Repeat torquing sequence to 300 ±20 ft.-lb. for unlubricated bolts or to 180 ±20 ft-lbs. for lubricated bolts.

7.1.3.35 Install security seals on impact limiter bolts.

7.1.3.36 Perform final radiation and contamination surveys to assure compliance with 10 CFR 71.47 and 71.87.

7.1.3.37 Apply appropriate labels to the package and vehicle in accordance with 49 CFR 172.

7.1.3.38 Prepare final shipping documentation.

7.1.3.39 Release the loaded cask for shipment.

7.2 PROCEDURES FOR UNLOADING PACKAGE

7.2.1 Unloading a Loaded Package Horizontally

7.2.1.1 Upon arrival of the loaded cask at the burial site, perform receipt inspection. Inspect for damage, verify security seals are intact and perform radiation survey.

7.2.1.2 Remove the front impact limiter using a suitable crane and two legged sling. *Rear impact limiter may also be removed.*

7.2.1.3 *Remove* the front and rear trunnion tie-downs.

7.2.1.4 Attach the horizontal lift device to *a suitable* crane and then engage the front and rear trunnions.

7.2.1.5 Lift the cask slowly in the horizontal position and *transfer it onto an unloading cradle.*

7.2.1.6 Disengage the lift *device* from the cask.

7.2.1.7 Install a horizontal lid lifting fixture to lid.

7.2.1.8 Remove the lid gasket port plug. *Detorque the lid bolts in an approved sequence.*

NOTE: *Perform the following steps remotely using manipulator crane, appropriate remote tooling, viewing equipment and personnel radiation protection as appropriate for the facility.*

7.2.1.9 Slowly remove the lid from the cask.

7.2.1.10 *If the optional two-piece lid is used, install the* shield disk *horizontal lifting fixture to the* shield disk. *Slowly remove* shield disk *from the cask and place in* a *lay down area.*

7.2.1.11 Place the cask seal protector on front face of the cask and attach liner or waste removal tools.

7.2.1.12 Unload the cask contents into disposal area in accordance with site-approved procedures.

NOTE: *The following steps may be performed hands-on.*

7.2.1.13 Remove the cask seal protector plate and install the shield disk *and* cask lid.

7.2.1.14 Install and tighten all lid bolts to hand tight. Torque all bolts so 950 *±50* ft-lbs. in several stages using an approved torquing sequence. Install the lid gasket port plug.

7.2.2 *Unloading a Loaded Package Vertically*

7.2.2.1 *Upon arrival of the loaded cask at the burial site, perform receipt inspection. Inspect for damage, verify security seals are intact and perform radiation survey.*

7.2.2.2 *After removing the security wires,* remove the *impact limiter* attachment bolts and *remove the front and rear impact limiters using a suitable crane and two legged sling.*

7.2.2.3 Re*move* the front and rear trunnion tie-downs.

7.2.2.4 Attach a lift beam to *a suitable* crane hook and engage the lift beam to the two front *trunnions.*

7.2.2.5 *Rotate the cask from the horizontal to the vertical position.*

7.2.2.6 Lift the cask from the transport vehicle. Place the cask in the preparation area.

7.2.2.7 Disengage the lift beam from the cask.

7.2.2.8 *If necessary, clean the cask external surfaces of road dirt.*

7.2.2.9 *Remove the lid gasket port plug and detorque the lid bolts in an approved sequence.*

7.2.2.10 Remove the cover from the Vent port.

7.2.2.11 *Install the lid lifting attachments.*

7.2.2.12 Engage the lift beam(s) to the cask.

7.2.2.13 Lift the cask from the preparation area and move to the unloading area.

7.2.2.14 Disengage the lift beam(s) from the cask.

7.2.2.15 Attach a suitable crane to lid lifting sling and remove the lid.

7.2.2.16 Install the cask seal surface protective cover.

7.2.2.17 Remove the shield disk.

NOTE: Perform the following steps remotely using manipulator crane, appropriate remote tooling, viewing equipment and personnel radiation protection as appropriate for the facility.

7.2.2.18 Using the appropriate handling tool and hoist, unload the cask contents into the disposal area in accordance with site-approved procedures.

NOTE: The following steps may be performed hands-on.

7.2.2.19 Replace the shield disk.

7.2.2.20 Remove the cask seal surface protective cover.

7.2.2.21 Move cask to the preparation area for lid installation.

7.2.2.22 Attach the lid lifting attachment to the cask lid.

7.2.2.23 Transfer the lid to a position directly over the cask cavity. Establish correct lid orientation and lower the lid until fully seated. Visually verify proper lid installation.

7.2.2.24 Disengage the lid lifting attachments and lift beam(s).

7.2.2.25 Survey and decontaminate the cask surfaces as required to permit safe working conditions.

7.2.2.26 Install all 16 lid bolts. Tighten to hand tight. Torque all lid bolts to 950 ±50 ft-lbs. in several stages using an approved torquing sequence. Install the lid gasket port plug.

7.3 PREPARATION OF EMPTY PACKAGE FOR TRANSPORT

7.3.1 *Perform radiation surveys to ensure the internal contamination is within the limits of 49 CFR 173 as appropriate for the package classification.*

7.3.2 Install the lid with the 16 lid bolts and torque all lid bolts to 950 ± 50 ft lb using an approved torquing sequence.

7.3.3 Engage the lifting device to the cask trunnions. Lift the cask off preparation area, place the rear trunnions on transport vehicle rear trunnion supports and rotate cask from the vertical to horizontal position. Disengage the lift beam from the cask.

7.3.4 Perform *external* radiation and contamination surveys to show that the radiation and contamination levels are within the limits of 49 CFR 173 *as appropriate for the package classification.*

NOTE: *Lifting lugs for impact limiters are designed for lifting impact limiters only. Lifting lugs shall not be used as attachment points to lift or tie-down the cask. Lifting lugs shall be rendered inoperable once impact limiters are attached to the cask shell and not being installed or removed. A bolt installed through the lifting lug hole or equivalent means shall be used to render the lifting lug inoperable.*

7.3.5 Install the front impact limiter and torque attachment bolts diametrically to 40-50 ft-lbs. Repeat torquing sequence to 300 ±20ft-lb for unlubricated bolts or to 180 ±20 ft-lb for lubricated bolts.

7.3.6 *Affix* appropriate transport labels to the package and *display required placards on the* vehicle.

7.3.7 Release empty cask for shipment.

CHAPTER EIGHT
ACCEPTANCE AND MAINTENANCE PROGRAMS

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CHAPTER EIGHT
ACCEPTANCE AND MAINTENANCE PROGRAMS

8.0 INTRODUCTION

This chapter describes the *acceptance tests for the TN-RAM packaging to comply with the requirements of 10 CFR Part 71 for the packaging design and maintenance program to ensure acceptable packaging performance throughout its service life.*

8.1 ACCEPTANCE TESTS

The following reviews, inspections and tests shall be performed on the TN-RAM cask prior to the first transport. Most of these inspections and tests will be performed at the Fabricator's facility prior to delivery to the loading site. These tests will be performed in accordance with written procedures prepared by the Fabricator and approved by Transnuclear.

The *shielding effectiveness* test (paragraph 8.1.*7*) shall be performed at the site *following* initial loading and prior to transport. This test shall be performed in accordance with approved written procedures.

8.1.1 Visual Inspection

After fabrication and prior to first use, v*isual inspection* sh*a*ll b*e performed* of all accessible cask surfaces. *The visual inspection includes verifying that all specified coatings are applied and the packaging is clean and free of cracks, pinholes, uncontrolled voids or other defects that could significantly reduce its effectiveness. The sealing surfaces on the flange, lid and covers are also inspected to ensure that there are no gouges, cracks or scratches that could result in an unacceptable leakage.*

8.1.2 Structural and Pressure Tests

All of these tests shall be performed by the Fabricator. Prior to use, some tests, as indicated, will be repeated.

8.1.2.1 Lid and *Shield Disk* Lifting Attachment Load Tests

The lid lifting attachment bolt holes and *shield disk lifting attachment bolt holes* shall be load tested in the following manner: A ¾-10 UNC-2A eyebolt shall be inserted into each of the three tapped holes in the lid surface. Weights shall be added to the lid such that the total load of the lid and added weight is twice the lid weight. The eyebolts shall be attached to a sling system with a lifting angle of approximately 60 degrees from horizontal. The lid shall be lifted using the sling system and held for a period of *at least* ten (10) minutes. *A ¾ – 10 UNC–2A eyebolt shall also be inserted into each of the three tapped holes in the shield disk upper surface. Weights shall be added to the* shield disk *such that the total load of the shield disk and added weight is twice the shield* disk *weight. The eyebolts shall be attached to a sling system with a lifting angle of approximately 60 degrees from horizontal. The shield disk shall be lifted using the sling system and held for a period of at least ten (10) minutes.* At the conclusion of *each* test, the bolt holes shall be:

a) Visually examined for defects and permanent deformations.

b) Checked with a go/no-go gauge to verify that no damage to the threads have occurred.

8.1.2.2 Trunnion Load Test

a) A force equal to 1.5 times the design lift load will be applied for a period of 10 minutes on the top and bottom trunnion pairs at the center of the outer shoulders.

b) Following completion of the trunnion load tests the trunnion external surfaces will be examined by the liquid penetrant method for defects. Acceptance standards will be in accordance with Articles NC-5350 of Section III of the ASME Boiler and Pressure Vessel Code.

8.1.2.3 Hydrostatic Test

After the shielding integrity test, the TN-RAM cask body will be hydrostatically tested using demineralized water in accordance with the requirements of the ASME B&PV Code, Section III, Article NB-6200.

The test pressure of 45 psig (equals 1.5 MNOP of 30) psig will be maintained for a minimum time of ten (10) minutes. The cask body and closures will then be examined for any deformations or leakage.

8.1.2.4 Cask Weight Measurements

The assembled cask, as well as major individual components, shall be weighed with a precision of ± 0.5 percent.

8.1.3 Leakage Rate Tests

8.1.3.1 Containment System Fabrication Verification

A Containment System Fabrication Verification leakage rate test of the TN-RAM will be performed at the Fabricator's facility in accordance with the requirements of ANSI N14.5 and Section V of the ASME B&PV Code.

The following tests will be performed in accordance with approved, written procedures on the containment boundary. The gas pressure rise method or the helium mass spectrometer method will be used to perform these tests.

The test cavities will be evacuated to a pressure of less than 10^{-2} mbar. The total leakage rate for the containment boundary shall be no greater than 6.87×10^{-4} *ref* cm^3/sec with a test procedure sensitivity of no greater than 3.4×10^{-4} *ref* cm^3/sec.

a) A preliminary test will be performed on the interspace between the inner and outer O-rings of the lid through a test port using an O-ring sealed test connector. This will show that the lid is seated properly.

b) The next test will be performed on the containment boundary formed by the cask cavity and the lower Drain port cover (Hansen coupling removed) and the inner O-ring of the cover. Evacuation will be through the Vent port using an O-ring sealed test connector.

c) The next test will be performed after the Vent port cover is installed. The O-ring seal of the cover will be leak tested using a test bell. The test bell fits over the vent cover and has a O-ring which seals against a machined surface on the cask.

An acceptable alternative test method is to perform the test in paragraph b) through the drain port, and then testing the drain port cover and seal by the method described in paragraph c). The Hansen coupling must be removed for the test described in paragraph b).

8.1.3.2 Impact Limiter Leakage Rate Test

Following final closure welding, each impact limiter will be tested for leakage in accordance with the methods of ANSI N14.5 and the requirements of Section V of the B&PV Code, using either the helium snifffer or bubble leak test methods. The differential pressure will be limited to less than 3 psi.

8.1.3.3 Humidity Test

After performing the impact limiter leakage rate test, a humidity test will be performed to determine that there is no in-leakage of water into the impact limiter container during fabrication. The dew point of a gas sample from the impact limiter container will be determined. The dew point measured shall be less than the equilibrium temperature of the impact limiter. The difference between the measured dew point and the impact limiter wall temperature shall be greater than twice the accuracy of the humidity test system.

8.1.4 Functional Tests

Installation and removal tests will be performed for the lid, *shield* disk, impact limiters, drain and vent port covers, shield plug and other fittings and inserts.

Each component will be observed for difficulties in installation and removal. After removal, each component will be visually examined for indications of deformation, galling, ease of use and proper functioning. Any such defects will be corrected prior to acceptance of the cask.

8.1.5 Test for Shielding Integrity

A gamma scan or equivalent test shall be performed on the cask after lead installation to detect any shielding deficiencies

from lead voids equal to or greater than -5% of shielding thickness. The test shall be performed on a maximum grid spacing of four (4) inches.

8.1.6 Review of Fabrication Records

A review of the Fabricator's records will be performed by Transnuclear in the areas of deviation requests and approvals, inspection, tests, nonconformances and record retention to assure that the cask was fabricated, inspected and tested in accordance with the *conditions for approval of the packaging design* as described in *the NRC Certificate of Compliance*, and is correctly shown on as-built drawings.

8.1.7 Shielding Effectiveness Test

Follow initial loading of the TN-RAM cask, a shield effectiveness test shall be performed prior to delivery to a carrier for transport. Measurements shall be made of the neutron and gamma dose rates of the loaded package to verify that the loaded cask meets the transport dose rate limitations of 10CFR71 and the applicable USDOT regulations.

8.1.8 Thermal Effectiveness Test

There are no thermal tests required for the TN-RAM.

8.2 MAINTENANCE PROGRAM

8.2.1 Structural and Pressure Tests

There are no periodic structural tests required on the TN-RAM.

8.2.2 Leak Tests

After the TN-RAM is loaded and before it is released for transport, a series of pressure rise tests shall be performed on the cask openings to verify proper assembly. See Chapter 7.0 for details of these tests.

No leak tests will be done on the empty cask before it is shipped.

After the third use and every twelve months thereafter, the Containment System Fabrication Verification Test, Section 8.1.3.1, shall be repeated, unless the cask is not is service. Prior to use, the cask shall have been tested within the preceding 12-month period.

8.2.3 Subsystems Maintenance

The lid bolts, vent, drain and overpressure transport cover bolts shall be inspected after each use, and annually, for deformed or stripped threads. Damaged parts shall be evaluated for continued use and replace as required. At a minimum, the lid bolts shall be replaced at least once per 250 round trips. |

8.2.4 Valves, Rupture Discs and Gaskets on Containment Vessel

All gaskets and the Drain port Hansen quick connect plug will be replaced prior to the third use test and annually thereafter unless the cask is not service. Prior to use, the maintenance shall have been completed within the preceding 12-month period.

No other maintenance is required prior to transport.

8.2.5 Shielding

A shielding integrity test using gamma scan or equivalent shall be performed after fabrication, and a shield effectiveness test shall be performed following initial loading. See paragraphs 8.1.5 and 8.1.7. Dose rate measurements are required to be taken prior to each shipment. There are no periodic shield effectiveness tests required.

8.2.6 Thermal

There are no thermal tests required for the TN-RAM.

8.2.7 Miscellaneous

This section does not apply.

Enclosure 4 to E-48635

Proposed Changes to CoC 9233 Revision 14

NRC FORM 618
(8-2000)
10 CFR 71

U.S. NUCLEAR REGULATORY COMMISSION

CERTIFICATE OF COMPLIANCE
FOR RADIOACTIVE MATERIAL PACKAGES

a. CERTIFICATE NUMBER	b. REVISION NUMBER	c. DOCKET NUMBER	d. PACKAGE IDENTIFICATION NUMBER	PAGE	PAGES
9233	~~14~~ 15	71-9233	USA/9233/B(U)-96	1 OF	4

2. PREAMBLE

a. This certificate is issued to certify that the package (packaging and contents) described in Item 5 below meets the applicable safety standards set forth in Title 10, Code of Federal Regulations, Part 71, "Packaging and Transportation of Radioactive Material."

b. This certificate does not relieve the consignor from compliance with any requirement of the regulations of the U.S. Department of Transportation or other applicable regulatory agencies, including the government of any country through or into which the package will be transported.

3. THIS CERTIFICATE IS ISSUED ON THE BASIS OF A SAFETY ANALYSIS REPORT OF THE PACKAGE DESIGN OR APPLICATION

a. ISSUED TO *(Name and Address)*

TN Americas LLC
7135 Minstrel Way, Suite 300
Columbia, MD 21045

TN Americas LLC

b. TITLE AND IDENTIFICATION OF REPORT OR APPLICATION

~~AREVA Inc.~~ application
dated ~~December 8, 2015.~~

TBD

4. CONDITIONS

This certificate is conditional upon fulfilling the requirements of 10 CFR Part 71, as applicable, and the conditions specified below.

5.

(a) Packaging

(1) Model No.: TN-RAM

(2) Description

The package is a steel encased lead shielded cask with wood impact limiters attached at both ends. The cask is a right circular cylinder. The overall dimensions of the packaging are approximately 178 inches long and 92 inches diameter with the impact limiters installed. The cask body is approximately 129 inches long with an outer diameter of 51 inches. The cask cavity has a length of approximately 111 inches and an inside diameter of 35 inches. The cask body is made of a 0.75-inch stainless steel inner shell, a 5.88-inch thick lead annulus, a 1.5-inch thick stainless steel outer shell, a 0.5-inch thick inner bottom plate and a 2.5-inch thick outside bottom plate. The lead shielding is approximately 6 inches thick in the bottom end of the cask. The outer shell of the cask body is covered with a stainless steel thermal shield. The closure lid consists of a 2.5-inch thick outer stainless steel plate and a 0.5-inch thick inner stainless steel plate separated by approximately 6 inches of lead shielding. An optional lid, with the lead shielding in the form of a separate shielding disk, can also be used. The lid is secured by sixteen 1.5-inch diameter closure bolts. Two concentric silicone O-rings are installed in grooves on the underside of the lid. The cask is equipped with a sealed leak test port between the O-rings, a vent port in the closure lid and a sealed drain port in the bottom of the cask. Each impact limiter is attached to the cask by eight 1.75-inch diameter bolts. The cask is equipped with 6 trunnions, four at the top and two at the bottom. The gross weight of the package is approximately 80,000 pounds, including maximum contents of 9,500 pounds.

NRC FORM 618 (8-2000) 10 CFR 71			U.S. NUCLEAR REGULATORY COMMISSION		
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5.(a) Packaging (continued)

(3) Drawings

The packaging is constructed in accordance with Transnuclear, Inc. Drawing Nos. 990-701, Rev. 10; 990-702, ~~Rev. 9~~; 990-703, Rev. 11; 990-704, Rev. 7; 990-705, Rev. 8; 990-706, Rev. 5; 990-707, ~~Rev. 5~~; 990-708, ~~Rev. 9~~; 990-709, Rev. 2; and 990-710, Rev. 2.

Rev. 10

Rev. 6

Rev. 10

(b) Contents

(1) Type and Form of Material

Dry irradiated and contaminated non-fuel-bearing solid materials contained within a secondary container. No powdered material is authorized.

Radioactive source and self-shielding material shall be distributed throughout. This means the material can be divided into ten or more equal volumes. The volume of each portion shall be no greater than 0.1 m^3. The specific activity of each volume must be assessed (through measurements, calculations, or process knowledge) and compared. Specific activity differences between any two volumes shall not vary by more than a factor of 10.

Materials other than steel must show shielding equivalence or better to steel for ^{60}Co. Localized regions of low-density material (e.g., B_4C in a control rod blade) are acceptable if the low-density regions contain negligible source. The mass of any low-density regions shall not be credited in the specific activity calculation.

(2) Maximum quantity of material per package

(i) Greater than Type A quantities of radioactive material which may include fissile material provided that the fissile material does not exceed the mass limits of 10 CFR 71.15. The combined quantity of all radioactive material per package is limited to 3,000 times an A_2 quantity (as determined by using Table A-1 of Appendix A to 10 CFR Part 71).

Pure Alpha and Beta emitting nuclides are limited to 3,000 times an A_2 quantity. Significant neutron sources are not allowed.

The maximum total package neutron source is 1×10^6 neutrons/second for materials that produce neutrons (other than fissile neutrons) through any means, including spontaneous fission, alpha-neutron reactions, and gamma-neutron reactions.

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5.(b)(2) Maximum quantity of material per package (continued)

See Insert 1

(ii) ~~Gamma emitting radionuclides are limited to a combined total of 30,000 Ci of ^{60}Co or equivalent as determined by the following equation:~~

$$\sum_i \frac{S_i(E)}{ActivityLimit_i(E)} \leq 1$$

Where E is the energy of the gamma emitter, $S_i(E)$ is the source strength of the gamma emitter, and *Activity Limit* $_i(E)$ is the limit in gammas per second (γ/s) as a function of energy. For gammas with energies that do not correspond exactly to one of the energies in the table, the *Activity Limit* $_i(E)$ used shall correspond to the next highest energy. Limits can be found in the following table:

Energy (MeV)	Activity Limit (γ/s)
0.6	7.62×10^{17}
0.8	1.25×10^{17}
1	2.03×10^{16}
1.1732	4.49×10^{15}
1.3325	1.47×10^{15}
1.5	6.15×10^{14}
1.75	2.40×10^{14}
2	1.25×10^{14}
2.5	5.52×10^{13}
3	3.42×10^{13}
3.5	2.55×10^{13}
4	2.14×10^{13}
4.5	1.90×10^{13}
5	1.78×10^{13}
6	1.66×10^{13}
8	1.58×10^{13}
10	1.49×10^{13}

See Insert 2 for the updated table

The average specific activity of discrete components is limited to 10 Ci/kg of ^{60}Co or equivalent.

Materials other than steel must show shielding equivalence or better to steel for ^{60}Co. Localized regions of low-density material (e.g., B_4C in a control rod blade) are acceptable if the low-density regions contain negligible source. The mass of any low-density regions shall not be credited in the specific activity calculation.

The decay heat of the contents may not exceed 500 W.

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5.(b)(2) Maximum quantity of material per package (continued)

The maximum gross weight of the contents, which includes the secondary container and shoring, is limited to 9,500 lb (4,309 kg).

6. As appropriate, shoring must be used in the secondary container sufficient to prevent significant movement of the contents under accident conditions.

7. Both the inner cask cavity and the secondary container must be free of water when the package is delivered to a carrier for transport.

8. In addition to the requirements of Subpart G of 10 CFR Part 71:

   (a) Prior to each shipment, the lid seals must be inspected. The seals must be replaced with new seals if inspection shows any defects or every 12 months, whichever occurs first;

   (b) The package shall be prepared for shipment and operated in accordance with the Operating Procedures of Section 7.0 of the application; and

   (c) The package must meet the Acceptance Tests and Maintenance Program of Section 8.0 of the application.

9. The package authorized by this certificate is hereby approved for use under the general license provisions of 10 CFR 71.17.

10. Revision No. ~~13~~ 14 of this certificate may be used until ~~January 31, 2018.~~ TBD

11. Expiration date: January 31, 2021.

REFERENCES

~~AREVA Inc., application dated December 8, 2015; TN Americas LLC letter dated November 18, 2016.~~ TBD

FOR THE U.S. NUCLEAR REGULATORY COMMISSION

John McKirgan, Chief
Spent Fuel Licensing Branch
Division of Spent Fuel Management
Office of Nuclear Material Safety
and Safeguards

Date: TBD

Insert 1 (for Page 3 of 4 to CoC):

Gamma emitting radionuclides are limited to a combined total of 30,000 Ci of ^{60}Co for TN-RAM No. 01, 18,000 Ci of ^{60}Co for TN-RAM No. 02, or equivalent as determined by the following equation:

Insert 2 (for Page 3 of 4 to CoC):

Energy (MeV)	Activity Limit (γ/s)	
	TN-RAM No. 01	TN-RAM No. 02
0.6	7.62E+17	4.45E+17
0.8	1.25E+17	6.64E+16
1	2.03E+16	1.13E+16
1.1732	4.49E+15	2.63E+15
1.3325	1.47E+15	8.92E+14
1.5	6.15E+14	3.84E+14
1.75	2.40E+14	1.50E+14
2	1.25E+14	7.76E+13
2.5	5.52E+13	3.47E+13
3	3.42E+13	2.22E+13
3.5	2.55E+13	1.67E+13
4	2.14E+13	1.41E+13
4.5	1.90E+13	1.23E+13
5	1.78E+13	1.18E+13
6	1.66E+13	1.10E+13
8	1.58E+13	1.04E+13
10	1.49E+13	9.69E+12

Enclosure 5 to E-48635

Listing of Computer Files Contained in Enclosure 6

Listing of Computer Files Contained in Enclosure 6
(All files are Proprietary)

Disk ID No. (size)	Discipline	System/Component	File Series (topics)	Number of files
Enclosure 6 *One DVD* (1.07 GB)	**Shielding**	TN RAM Shielding Analysis for Reduced Radial Lead Thickness	NCT homogenized cylinder source input and output files.	3
			NCT disk top cylinder source input and output files.	3
			NCT disk bottom cylinder source input and output files.	3
			NCT annulus cylinder source input and output files.	3
			Energy equivalence response function input and output files	2
			HAC full height input and output files	3
			69998-0501 Rev. 0.pdf	1
			69998-0500 Rev. 3.pdf	1
		TN-RAM N0. 2 Engineering Evaluation of Gamma Scan	Calculation No. 49944-801 R0 Lead thickness evaluation spreadsheets	1 2
	Structural	TN-RAM LS-DYNA Model Development and Benchmarking	CN-16001-201 Rev1.pdf	1
			CN-16001-201 Rev1 Input and Output Files	16
		TN-RAM LS-DYNA Perpendicular Wood Crush Strength Sensitivity Studies	CN-16001-202 Rev1.pdf	1
			CN-16001-202 Rev1 Input and Output Files	117
		Reference 7 listed in TN-RAM SAR Chapter 2, Appendix 2.10.10	AREVA TN, Wood Testing Data for Impact Limiter Design, No. 65200-105 Rev. 0	1

Enclosure 7 to E-48635

Description and Justification of Proposed SAR Changes (Non-Proprietary)

Description, and Justification of Proposed Changes
(Safety Analysis Report, TN-RAM Revision 16A)

Section A of this enclosure provides a general description of proposed changes in the safety analysis report (SAR). Section B provides details of the Chapters and Sections revised with a brief description and justification for the changes described in Section A.

Section A

There are four proposed changes to the SAR, as described below. The changes affect the shielding evaluation, structural evaluation, and operations and maintenance.

1. TN-RAM No. 02 - As-fabricated non-conformance with respect to the lead thickness in the annulus.

[ ]

Shielding Evaluation

The reduction in annular lead thickness has a significant impact on the shielding evaluation for the TN-RAM package design. An analysis of the TN-RAM with the reduced annular lead thickness was performed to determine the allowable contents activity. The contents limit is reduced from 30,000 Ci approved for the TN-RAM to 18,000 Ci equivalent Co-60 activity for TN-RAM No. 02. NRC approval of the reduced activity limit is required prior to placing TN-RAM No. 02 into service.

Structural Evaluation

There is no impact on the design basis structural evaluation due to the non-conformance as explained below:

Description, and Justification of Proposed Changes
(Safety Analysis Report, TN-RAM Revision 16A)

[

]

Thermal Evaluation

Due to the actual clearance between the inner and outer shells, the acceptance test gamma scan of as-fabricated annulus shielding indicates an effective lead thickness of at least 5.56 inches in TN-RAM No. 02. A review of the existing thermal evaluations, the reduced minimum lead thickness has no impact on design basis thermal evaluation for normal (NCT) and accident conditions (HAC) of transport as reported in SAR Table 3-4 and Table 3-7, respectively.

[

]

Description, and Justification of Proposed Changes
(Safety Analysis Report, TN-RAM Revision 16A)

2. Specification of Material Properties regarding the Impact Limiters

The density and perpendicular crush strength are removed as a condition of approval for wood used in the impact limiters. Density and perpendicular crush strength do not need to be specified as critical characteristics for the package design to ensure compliant package design requirments.

The critical characteristics (parallel compressive strength, locking strain, and moisture content) for the wood used in the impact limiters are specified as conditions of approval on the SAR drawings. These critical characteristics are verified by acceptence testing during fabrication. Additional specifictions typical of the wood and useful in the selection of wood for impact limiters are maintained as a controlled specification document under the TN Americas LLC Quality Assurance (QA) program. The impact limiter wood specification is maintained and controlled as a design document separate from the SAR as Specification No. 990-1 (E-10536), Procurment

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Specification for the TN-RAM Packaging. The specfication document may be referenced in the SAR but is not intended to be included as a condition of approval in the certificate of compliance (CoC).

3. Operations (Chapter 7) and Maintenance and Acceptance Testing (Chapter 8)

Several changes have been made to Chapter 7 to provide additional guidance and flexibility for operations. A note has been added to clarify the intended use of impact limiter lifting lugs and requirement for rendering the impact limiter lifting lugs inoperable during transport. A statement has been added to note an exception for TN-RAM No. 02, which requires reduction in activity limit from 30,000 Ci ^{60}Co to 18,000 Ci ^{60}Co. The radiation and contamination requirements for shipping the TN-RAM after unloading have been revised to allow package classification as other than an empty excepted package.

A revision to Chapter 8 has been made for clarification of the applicability of other sections of the SAR, and to correct the acceptance criteria regarding the lead thickness. The acceptance criteria for lead voids in SAR Section 8.1.5 is intended for localized areas where the shielding effectiveness is reduced by the presence of voids in the lead. The specification has been revised to specify minus 5% of the nominal shielding thickness instead of ±5%. Any lead thickness greater than nominal is acceptable. This acceptance criterion is specific to allow for localized voids and are not intended to be applied to the minimum lead thickness dimension provided on the SAR Chapter 1.0 engineering drawing.

4. Tie-down and Lifting Standards

A revision to Chapter 2, Section 2.5, provides clarification regarding tie down and lifting attachment points.

Tie-down standards

The TN-RAM package has trunnions intended as attachment points for tie-down. The trunnions are a structural part of the package that is designed to meet the requirements of the regulations for lifting and tie-down. The TN-RAM SAR describes front trunnion supports that move in the 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 trunnions had not been analyzed for any portion of the required 10G load applied in the direction of travel. The TN-RAM transport trailer has fixed front trunnion supports that may react to part of the 10G load on the front trunnions. The front trunnions were analyzed for a component of the 10G load and the strength of the front trunnion has been shown to meet the requirements of 71.45(b).

Lifting attachment points standards

The TN-RAM package uses trunnions that are designed and intended as attachment points for lifting and tie-down. The trunnions are a structural part of the package that is designed to meet

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the requirements of the regulations for lifting and tie-down. Other attachment points for lifting the impact limiters or cask lid during operation are structural parts of the TN-RAM package that should be rendered inoperable when installed for transport. Inadvertent use of the impact limiter lifting lugs to lift or tie-down the TN-RAM may impair the ability of the package to meet requirements for transport. However, operation of the TN-RAM had not included any controls to render the impact limiter lifting lugs inoperable during transport operations. An explanation is provided in operating procedures to identify the intended use for the lifting lugs and requirement to render the lifting lugs inoperable when the impact limiters are installed.

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Section B

	Chapter/Appendix/Section	Description and Justification
1	Proprietary Information Notice	Added the Proprietary Information Notice page. A Proprietary Information Notice page was not previously included in the SAR.
2	Chapter 1, Section 1.2.1.4	Description and calculations for tie-down revised to be consistent with transport trailer anchor points. The front trunnions are restrained in the direction of travel and are analyzed to demonstrate compliance with 10 CFR 71.45(b) when the 10G force component is included.
3	Chapter 1, Sections 1.2.2	Deleted inaccurate statement regarding horizontal operations. The cask is removed from the transport trailer for horizontal loading and unloading operations.
4	Chapter 1, Sections 1.2.3	Description of activity limit revised to add reduced activity exception for TN-RAM No. 02.
5	Chapter 1, Appendix 1.3, DWG 990-702	Added Note 6 to DWG 990-702 to allow a reduced minimum radial thickness to 5.56 inches for TN-RAM No. 02.
6	Chapter 1, Appendix 1.3, DWG 990-707	Changed DWG No. from "909" to "990" to make editorial correction.
7	Chapter 1, Appendix 1.3, DWG 990-708	Removed the detailed specification for impact limiter wood from DWG 990-708 and replaced with SPEC 990-1, 4.3.2 IMPACT LIMITERS for items 17 and 18 in parts list. Impact Limiter Wood Specification is maintained and controlled in Specification 990-1 (E-10536). Specification on DWG 990-708 is incorporated by reference as condition of approval in CoC and changes require prior NRC approval.
8	Chapter 1, Appendix 1.3, E-10615	Deleted Appendix 1.3 E-10615, "Lead Pouring Requirements." The Lead Pouring Procedure is maintained and controlled as a QA document in the document management system.
9	Chapter 2, Section 2.3	Added Locking Strain and Note to Table 2.3-3, "Specified Properties of Impact Limiter Wood," indicating that density and perpendicular crush strength are provided for information only.

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	Chapter/Appendix/Section	Description and Justification
10	Chapter 2, Section 2.5	Revised the structural evaluation of lifting and tie-down standards to include an evaluation to demonstrate that the front trunnion strength meets the 10 CFR 71.45(b) requirements including a component of 10G force in the direction of travel. Added clarification on intended use for impact limiter lifting lugs.
11	Chapter 2, Section 2.7	Revised to state that immersion requirements for fissile package are not applicable. TN-RAM is not a fissile material package.
12	Chapter 2, Appendix 2.10.2	Revised page 2.10.2-6 for clarification regarding the impact limiter wood properties. Revised the two listed references for editorial corrections to the authors names and the document titles.
13	Chapter 2, Appendix 2.10.2	Added a note to Table 2.10.2-2, "Typical Wood Material Properties," indicating that density and perpendicular crush strength are provided for information only.
14	Chapter 2, Appendix 2.10.6	Deleted Appendix 2.10.6, "Impact Limiter Wood Specification." Specification 990-1 (E-10536) is maintained and controlled as a QA document in the document management system.
15	Chapter 2, Appendix 2.10.7	Deleted Appendix 2.10.7, "Lead Pouring Procedure." E-10615, TN-RAM Packaging Lead Pouring Procedure is maintained and controlled as a QA document in the document management system.
16	Chapter 2, Appendix 2.10.10	Added Appendix 2.10.10, "Evaluation of Impact Limiters" to demonstrate the sensitivity of performance to wood properties.
17	Chapter 5	Added an additional evaluation to determine an activity limit for TN-RAM No. 02 that was fabricated with a non-conforming minimum annular lead thickness of 5.56 inches.
18	Chapter 7, Sections 7.1.2, 7.1.3, 7.3.4	Added a NOTE to emphasize the intended use of impact limiter lifting lugs and requirement to render inoperable for transport.
19	Chapter 7, Section 7.1	Added a NOTE to identify the allowed activity limits specific to TN-RAM No. 01 and TN-RAM No. 02 .

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	Chapter/Appendix/Section	Description and Justification
20	Chapter 7, Section 7.3	Revised the radiation and contamination survey steps to refer to and be within the limits specified in 49 CFR173. TN-RAM may be shipped with package classifications other than Empty after unloading. Internal contamination may not meet limits for Empty excepted package.
21	Chapter 8, Sections 8.0 and 8.1.6	Revised these sections to clarify that all parts of the SAR are not incorporated by reference to Chapter 8.0 in the TN-RAM CoC.
22	Chapter 8, Section 8.1.5	The acceptance criteria for lead voids in SAR Section 8.1.5 is intended for localized areas where the shielding effectiveness is reduced by the presence of voids in the lead. The specification is revised from ±5% to allow -5% of the nominal shielding thickness. These acceptance criteria are specific for localized voids and are not intended to be applied to the dimensions provided in SAR Chapter 1.0.