APPENDIX 2-1

ISSUE SUMMARY
Form SOP-0402-03, Revision 2

DESIGN CONTROL SUMMARY			
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PROJECT NAME:	**Big Rock Point Major Component Removal**		
PROJECT NO.:	**10525-020**	☐ NUCLEAR SAFETY-RELATED	
CALC. NO.:	**S-10525-020-012**	☐ NOT NUCLEAR SAFETY-RELATED	QA SERIAL NO.
TITLE:	**Reactor Vessel Transport Cask Stress Analysis**	☒ IMPORTANT TO SAFETY CATEGORY A	
EQUIPMENT NO.:			

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NOTE: PRINT AND SIGN IN THE SIGNATURE AREAS

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Client: BNFL, Inc.		Prepared by: P. H. Hoang	Date
Project: Big Rock Point Major Component Removal		Reviewed by: C. W. Mak	Date
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TABLE OF CONTENTS

DESCRIPTION **PAGE NO.**

LIST OF FIGURES

LIST OF TABLES

LIST OF ATTACHMENTS

1.0 Purpose and Scope

A major stage of the Big Rock Point decommissioning project involves removing the Reactor Vessel (RV) from its cavity in the Reactor Building and placing it in a cylindrical steel package for transport. Once assembled and filled with low-density cellular concrete (LDCC), the transport package is a single, welded, integral container, which provides adequate radiological shielding and containment of radioactive waste, and is here after referred to as the Reactor Vessel Transport System (RVTS) cask in this report. To ensure safe structural behavior of the RVTS while transporting radioactive material, the shipping cask must be designed to withstand specific load conditions that encompass the static, dynamic and thermal loading that may be experienced by the cask during transport and burial conditions. The design of the RVTS Cask is in accordance with the requirements of Part 71, Title 10 of the Code of Federal Regulations, Subpart E, Parts 41, 43 and 51. The RVTS cask is a Type B package and is therefore designed to withstand the loading conditions outlined in 10 CFR 71, Subpart F, Parts 71 and 73, which are the Normal Condition of Transport (NCT) and the Hypothetical Accident Conditions (HAC).

The purpose of this calculation is to document the structural evaluation of the Big Rock Point RVTS Cask. The calculation demonstrates that the RVTS Cask design meets the requirements of 10 CFR 71.35, "Package Evaluation", which states that packages used to transport radioactive materials must demonstrate adequacy for the NCT and HAC specified in Subparts E and F of 10 CFR 71. The evaluation will also comply with Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels", for linear elastic analyses, Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material", and Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches". In addition, the RVTS cask is designed to sustain the vertical, lateral and longitudinal accelerations given by both the guidelines of the Association of American Railroads (AAR) set forth in Part 1 of the "Open Top Loading Rules Manual" and the ANSI N14.2 (Draft) "Tie-down for Truck Transport of Radioactive Materials". Finally, the RVTS Cask is designed to withstand the constant pressure resulting from the burial conditions given by the disposal facility at Barnwell, SC.

It should be noted that the lifting devices utilized to remove the RV from the Reactor Cavity and down-end the RVTS before it is loaded onto the hydraulic transporter (i.e. lifting lugs and trunnions) will be removed prior to the RVTS Cask transport. The lifting devices are evaluated in separate calculations, References 3.6.4 and 3.6.5. The tie-down devices utilized to secure the RVTS Cask to the hydraulic transporter and railcar (support saddles, ties, bumpers, etc.) are evaluated in separate calculations, Reference 3.6.6, 3.6.7 and 3.6.8.

2.0 Design Input

2.1 Dimensional Data

The RVTS components with their respective geometries are shown in Figure 2.1. The dimensional data given in Table 2.1 is obtained from the indicated references.

Table 2.1 RVTS Cask Shell and RV Dimensional Data

Parameter			Value	Reference
Reactor Vessel	Thickness with cladding		5.25" + 5/32"	3.12.1
	Height (from top of flange to inside surface of dome)		282.375"	3.12.1
	Inside Radius		53.063"	3.12.1
	Flange	Thickness	14"	3.12.1
		Bolt Circle Diameter	128"	3.12.1
	RV Shell and Flange Material		SA-302 Gr. B	3.12.2
RV Flange Bolt	Size		4 1/2" – 8N – 2A	3.3.1
	Material		A193 Conforms AISI-4340	3.3.1
RV Flange Nut	Size		4 1/2" – 8N – 2B	3.3.1
	Material		SA 105 or SA-266 Grade 2	3.3.1
RVTS Cask Shell	Thickness		3"	3.3.1
	Height		299.5"	3.3.1
	Material		SA-516 Gr. 70	3.3.1
RVTS Cask Top and Bottom Plate	Thickness		4"	3.3.1
	Material		SA-516 Gr. 70	3.3.1
Donut-shape RV Base Support	Plate Thickness		4"	3.3.1
	Stiffener Thickness		2"	3.3.1
	Distance from center of RVTS bottom plate to center of Donut plate		25"	3.3.1
	Material		SA-516 Gr. 70	3.3.1
RVTS Cask Shield Plate	Thickness		4"	3.3.1
	Width		96"	3.3.1
	Material		SA-516 Gr. 70	3.3.1
Trunnion Reinforcing Ring Plate	Thickness		3"	3.3.1
	Width		40"	3.3.1
	Material		SA-516 Gr. 70	3.3.1
Saddle Support	Width		18"	3.3.2
	Saddle Center to Center Spacing		59"	3.3.2

2.2 Material Properties

Temperature dependent material properties are obtained from the ASME Code, Section II, Part D, and are listed in Attachment A.

2.3 Loading Data

2.3.1 Thermal Load Case Temperature Distribution

The RVTS Cask temperature distribution for the NCT and HAC per Reference 3.6.1 are used as the boundary conditions for thermal heat transfer and thermal structural analyses.

2.3.2 Pressure

The RVTS Cask internal pressure under the ambient temperatures of 100 °F with maximum insolation and –20 °F without insolation, as stipulated in 10 CFR 71.71(c)(1) has been determined in Reference 3.6.2. The maximum and minimum internal pressures are 20 psig and –3 psig, respectively. Internal pressure for –40 °F ambient temperature load case is –3.3 psig. The test pressure is 1.5 times the maximum normal operating pressure per 10CFR71.85(b). The maximum HAC fire accident pressure is 95 psig per Reference 3.6.2.

2.3.3 Weight

The total weight of the RVTS assembly (excluding the lifting lug and trunnions, which will not be attached during transport) is 564.3 kips per reference 3.6.3.

2.3.4 Vibration and Shock Accelerations

Shock loads produced by coupling, switching, etc., in rail transport and by bumps, potholes, etc., in truck transport are considered to be bounded by the governing inertial loads specified for the tie-down component design. The enveloped vertical, lateral, and longitudinal accelerations given per the governing ANSI N14.2, "Tie-down for Truck Transport of Radioactive Materials", Reference 3.14, and Association of American Railroads (AAR) guidelines set forth in Part 1 of the "Open Top Loading Rules Manual" Reference 3.11, are listed in Table 2.2.

Table 2.2 Vibration and Shock Accelerations

Direction	Inertial Load
Vertical	2.0
Longitudinal (in direction of travel)	3.0
Lateral (perpendicular to direction of travel)	2.0

2.3.5 NCT Loading

Refer individual section in section 4.1 for detail description.

2.3.6 Handling Accident Loading

Refer individual section in section 4.2 for detail description.

2.3.7 HAC Loading

Refer individual section in section 4.3 for detail description.

2.3.8 Burial Condition Loading

Refer individual section in section 4.4 for detail description.

FIGURE WITHHELD UNDER 10 CFR 2.390

3.0 References

3.1 ASME Boiler and Pressure Vessel, Section II, Part D, "Properties", and Section III, Subsection NA, NB, NF and Appendices, 1995 Edition.

3.2 United States Nuclear Regulatory Commission Rules and Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Materials", January 30, 1998.

3.3 S&L Design Drawings:
- 3.3.1 SD-10525-020-001, Rev. 1.
- 3.3.2 SD-10525-020-002, Rev. 1.

3.4 ASTM Standards:
- 3.4.1 ASTM A 193/A 193M – 00.
- 3.4.2 ASTM A 516/A 516M – 90.
- 3.4.3 ASTM A 302/A 302M – 97.
- 3.4.4 ASTM A 105/A 105M – 98.
- 3.4.5 ASTM A 266/A 266M – 99.

3.5 Intentionally blank .

3.6 S&L Calculations:
- 3.6.1 S&L Calculation No. M-10525-020-001, "Thermal Response of Reactor Vessel Transport System", Rev. 1.
- 3.6.2 S&L Calculation No. M-10525-020-002,"Bounding Normal Operating Pressure for RVTS", Rev. 2.
- 3.6.3 S&L Calculation No. S-10525-020-002, "Volume and Weight of Reactor Vessel Transport System", Rev. 2.
- 3.6.4 S&L Calculation No. S-10525-020-003, "Structural Evaluation of RVTS Lifting Lug Assembly", Rev. 2.
- 3.6.5 S&L Calculation No. S-10525-020-004, "Structural Evaluation of RVTS Trunnion Assembly", Rev. 1.
- 3.6.6 S&L Calculation No. S-10525-020-006, "Structural Evaluation of RVTS Tie-Down System – Cable Tie Assembly", Rev. 2.
- 3.6.7 S&L Calculation No. S-10525-020-007, "Structural Evaluation of RVTS Tie-Down System – Center Box Beam and Bumper Assembly", Rev. 1.
- 3.6.8 S&L Calculation No. S-10525-020-008, "Structural Evaluation of RVTS Tie-Down System – Saddle Assembly", Rev. 1.
- 3.6.9 S&L Calculation No. S-10525-020-009, "RVTS Brittle Fracture Protection Criteria", Rev. 0.
- 3.6.10 S&L Calculation No. N-10525-041-001, "Breach of Containment", Rev. 2.
- 3.6.11 S&L Calculation No. S-10525-020-013, "Top Plate Dimple Evaluation", Rev. 0.

3.7 Computer Software:
- 3.7.1 Finite Element Program ANSYS, Version 5.6, Sargent and Lundy Validated Program Number ANSYS 03.7.596.
- 3.7.2 Mathcad 8 Professional, Sargent and Lundy Program No. 03.7.548-8.03o. (PC# 5485, Windows NT Version 4.0)

3.8 Mark's Standard Handbook for Mechanical Engineers, 8th Edition.

3.9 Roark R.J., "Formulas for Stress and Strain", 5th Edition, Table 33, Case 4.

3.10 AISC, "Manual of Steel Construction", 9th Edition.

3.11 Association of American Railroads (AAR), "Open Top Loading Rules Manual", Part 1, dated March 1, 2000.

3.12 Combustion Engineering Drawings:

3.12.1 F-230-791-2, "General Arrangement – Reactor Vessel", Rev. 2.
3.12.2 E-201-806-4, "Closure Head Forming & Welding – Reactor Vessel", Rev. 4.
3.12.3 E-201-805-5, "Stud, Nut, Washers & O-Ring Details", for Reactor Vessel – General Electric Co – BWR– Consumers Power, 8/15/1960.

3.13 ASCE Manual, "Structural Analysis and Design of Nuclear Plant Facilities", 1980 Edition.

3.14 ANSI N14.2, "Tie-down for Truck Transport of Radioactive Materials", Draft.

3.15 Regulatory Guides:

3.15.1 Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels", Rev. 1, March 1978.

3.15.2 Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material". Rev. 1, March 1989.

3.15.3 Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches", Rev. 0, June 1991.

3.16 NUREGs:

3.16.1 NUREG/CR-1815, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick", August 1981.

3.16.2 NUREG/CR-3966, "Methods for Impact Analysis of Shipping Containers", November, 1987.

3.16.3 NUREG/CR-0128, "Shock and Vibration Environments For A Large Shipping Container During Truck Transport (Part II)", May, 1978.

3.17 CHEM-NUCLEAR SYSTEMS Letter No. 44053-001, "Big Rock Point RPV-Design Basis for Disposal Vaults", dated 1-21-2000.

3.18 Machinery's Handbook, 23rd Edition.

3.19 Blodgett O.W., "Design of Welded Structures", 1966.

3.20 ASCE Manuals and Reports on Engineering Practice No. 78, "Structural Fire Protection".

4.0 Methodology

The RVTS cask is designed to meet the approval standards identified in 10 CFR 71 Subpart E and the cask complies with the standards identified in 10 CFR71.41. The RVTS cask is a Type B package and must therefore be evaluated for the loads resulting from both the NCT and the HAC per 10 CFR 71.71 and 10 CFR 71.73, respectively. The design criteria for the RVTS cask structural analysis meets the requirement of 10 CFR 71.35, "Package Evaluation", which states that packages used to transport radioactive materials must demonstrate adequacy for the NCT and HAC specified in Subparts E and F of 10 CFR 71. These conditions and acceptance criteria are described in the following sections. Analytical methodology for each case is also discussed.

The associated initial conditions required per 10 CFR 71 and stipulated in Table 1 of Reg. Guide 7.8 are used for the structural analysis. The applicable initial conditions for the analysis are:

- Maximum and minimum ambient temperatures of -20° F and 100° F for the evaluation of each NCT and HAC except for cold environment described in Section 4.1.2.
- Maximum insolation at 400 g cal/cm^2 on its horizontal curved surfaces, and 200 g cal/cm^2 on the top and bottom vertical, flat surfaces for a duration of 12 hours.
- Maximum decay heat generated by the radioactive material. For Big Rock RVTS Cask, a total of 485 BTU/hr maximum decay heat was used in the thermal heat transfer analysis, References 3.6.1.
- The maximum or the minimum normal operating pressure that is consistent with the ambient temperature, insolation and decay heat.
- Fabrication stresses caused by interference fits and the shrinkage of bonded concrete are negligible for the Big Rock Point RVTS Cask design. Bolt load is the only assembly stress which is required to be evaluated. Per the design drawings, References 3.3.1 and 3.3.2, the flange bolts and the trunnion bolts are snug tight; therefore, the RVTS Cask bolt assembly stresses are negligible. Note that the residual stresses due to plate formation and welding are not considered to be fabrication stresses as noted in Regulatory Guide 7.8.

4.1 Normal Conditions of Transport

4.1.1 Hot Environment

Per 10 CFR 71.71(c)(1), the effect of an ambient temperature of 100 °F in still air, maximum insolation, maximum decay heat and maximum internal normal operating pressure are considered in the design of the cask.

Thermal response and internal pressure of the RVTS cask due to the aforementioned conditions are evaluated in References 3.6.1 and 3.6.2, respectively. Based on the temperature distribution determined in Reference 3.6.1, the temperatures at the mid span of the cask shell, top and bottom plate, and RV wall are used as boundary conditions for a heat transfer analysis that determines temperature distribution throughout the rest of the model. Structural thermal analyses are then performed and combined with other primary loads. The RVTS Cask maximum and minimum internal pressures determined in Reference 3.6.2 are 20 psig and –3 psig, respectively. The cask is initially resting on its saddle supports and is subjected to the normal primary loading condition (normal weight and maximum pressure). The cask is then analyzed for a primary plus secondary loading condition that includes 100°F ambient temperature, maximum insolation and maximum decay heat. The Finite Element Analysis Program ANSYS, Reference 3.7.1, is utilized to analyze the RVTS cask for these loading conditions. Element type SHELL181, which is a 3-D shell element with both bending and membrane capabilities, is used to represent the cask shell, top and bottom plates, donut support, shield plate and trunnion reinforced ring plate. The weight of the LDCC is included in the model; however, the concrete structural stiffness is negligible and is not considered in this analysis.

4.1.2 Cold Environment

Per 10 CFR71.71(c)(2), the effect of an ambient temperature of -40 °F in still air and shade is considered in the design of the cask. The analysis is similar to the analysis for the Hot condition in Section 4.1.1 except that the RVTS is subjected to a minimum pressure of -3.3 lbf/in^2 (from Reference 3.6.2), zero decay heat, zero insolation and an ambient temperature of -40 °F (from Reference 3.6.1).

4.1.3 Reduced External Pressure

Per 10 CFR 71.71(c)(3), the cask is designed for the effects of an external absolute pressure of 3.5 lbf/in^2. The analysis is similar to the analysis for the Hot condition in Section 4.1.1 except that the RVTS is subjected to an external absolute pressure of 3.5 lbf/in^2 combined with the cask maximum internal pressure of 20 psig, corresponding to the initial ambient temperature of 100° F and including the effects of insolation and decay heat (Reference 3.15.2, Table 1).

4.1.4 Increased External Pressure

Per 10 CFR 71.71(c)(4), the cask is designed for the effects of an external absolute pressure of 20 lbf/in^2. The analysis is similar to the analysis for the Hot condition in Section 4.1.1 except that the RVTS is subjected to an external absolute pressure of 20 lbf/in^2 combined with the cask minimum internal pressure of -3 psig, corresponding to the initial ambient temperature of -20° F, not including the effects of insolation or decay heat (Reference 3.15.2, Table 1). Buckling of the cask shell under external pressure is checked using the maximum allowable external pressure per ASME Section III, Article NB-3133 (Reference 3.1).

4.1.5 Vibration and Fatigue

The RVTS is evaluated for vibration and shocks normally incident to transport as required by 10 CFR 71.71 (c)(5). Shock loads produced by coupling, switching, etc., in rail transport and by bumps, potholes, etc., in truck transport are considered to be bounded by the governing inertial loads specified for the tie-down component design. The enveloped vertical, lateral, and longitudinal accelerations given per the ANSI N14.2, "Tie-down for Truck Transport of Radioactive Materials", Reference 3.14, and Association of American Railroads (AAR) guidelines set forth in Part 1 of the "Open Top Loading Rules Manual", Reference 3.11, are:

- Vertical direction: 2.0g
- Transverse direction: 2.0g
- Longitudinal direction: 3.0g

These shock accelerations are conservative since the cask is being transported by a hydraulic road transporter and a special use rail car.

The RVTS is evaluated for shock normally incident to transport under two extreme thermal conditions, per Reference 3.15.1, Table 1. First, the RVTS is evaluated for the effects of vibration at an ambient temperature of 100° F, considering maximum insolation and decay heat along with corresponding maximum internal pressure. Next, the RVTS is evaluated for the effects of vibration at an ambient temperature of -20° F, considering zero insolation, zero decay heat, and the corresponding minimum internal pressure. Fatigue evaluation of the cask is conservatively based on these two bounding conditions assuming one cycle of shocks per mile during the 1500-mile trip to the burial site (Assumption 6.1). The total number of cycles of shock per lifetime is 1500.

The number of normal vibration cycles is expected to be much higher than the number of shock cycles. The normal vibration stress will be shown to be less than the material endurance limit such that an infinite number of cycles of normal vibration is acceptable. The vibration stress calculation is based on the vibratory motion data produced by small excitations to the cask-vehicle system, which is reported in NUREG/CR-0128, Reference 3.16.3, for cask weights more than 50,000 lbs and a travel speed of less than 55 mph. The maximum zero-to-peak accelerations are:

- Vertical direction: 0.52g
- Transverse direction: 0.19g
- Longitudinal direction: 0.27g

4.1.6 Water Spray

10 CFR 71.71 (c)(6) requires an evaluation of the cask for water spray that simulates exposure to a rainfall of approximately two inches per hour for at least one hour. The RVTS is a sealed steel structure with no openings; therefore, the water spray test condition has no effect on the cask.

4.1.7 Free Drop

Per 10 CFR 71.71 (c)(7), a free drop test of the cask through a distance of one foot onto a flat, essentially unyielding, horizontal surface is required. Considering the cask orientation and position during transportation and loading operations, the size of the cask, as well as the stress margins of the horizontal five-foot drop and the primary oblique five-foot drop for the handing accident condition documented in Table 7.4.1, the governing one-foot drop orientation to be analyzed for the NCT is horizontal.

4.1.8 Corner Drop

Per 10 CFR 71.71 (c)(8), the corner drop test condition is not applicable because the RVTS is not constructed of fiberboard or wood and does not contain fissile material.

4.1.9 Compression

Per 10 CFR 71.71 (c)(9), the compression test condition does not apply since the RVTS weighs more than 11,000 lbs.

4.1.10 Penetration

Per 10 CFR 71.71 (c)(10), the RVTS is evaluated for the impact of a vertical hemispherical end steel cylinder with a 1.25" diameter and a mass of 13 lbs dropped from a height of 40" onto the exposed surface of the cask that is expected to be most vulnerable to puncture. The recommended minimum design thickness per the Ballistic Research Laboratory given in Reference 3.13, is used to check the thickness of the shipping cask for puncture drop requirements.

4.1.11 Test Pressure

Per 10 CFR 71.85 (b), the RVTS is evaluated for a test pressure of 30 psig, which is 1.5 times the maximum normal operating pressure.

4.2 Handling Accident Conditions

In addition to the Hypothetical Accident Conditions (HAC) described in Section 4.3, the following handling accident conditions are evaluated using linear elastic acceptance criteria as outlined in Section 5.0. The initial temperature and pressure conditions associated with the handling accident evaluations are the same as those listed for the evaluations of NCT.

4.2.1 Free Drop

After the RV is loaded into the RVTS and the top closure plate is welded to the cask, the RVTS will be moved into a horizontal position via the lifting lug on the top closure plate, the trunnions, and the A-frame pivot device. Once the cask is ready for shipment, it will be tied down to the saddle support system by cables to ensure it remains in place during transportation. The RVTS cask will be transferred by jacking from the road transporter to the rail car and will not be lifted during transport to the Barnwell (Dunbarton) site. Considering that the above handling scenario will be carried out in a controlled environment, the potential handling accidents consists of dropping the cask from the road transporter or the rail car to the ground. Therefore, based on the maximum height of the transport flatbed of 4'-10", a five-foot free drop of the RVTS cask is considered in this analysis as a credible handling accident condition.

As noted above, the RVTS will remain in a horizontal position during handling. Therefore, two free drop orientations are considered: a horizontal drop for which the entire cask shell will strike the flat horizontal surface, and an oblique drop where one end strikes the ground while the other end remains supported on the transporter. Under the oblique drop scenario, the effect of free body rotation and the secondary impact of the other end are also considered.

In the handling accident conditions, the flat, horizontal ground surface for the drop analyses is considered to be an infinitely thick concrete slab with a maximum compression strength of 4000 psi (see Assumption 6.4). Lumped parameter dynamic analysis methodology per NUREG/CR –3966, Reference 3.16.2, is employed to calculate the maximum dynamic responses of the cask lumped parameter models for the limiting free drop orientations discussed above. The maximum impact accelerations at the cask Center of Gravity (CG) in both the vertical and the horizontal directions and rotational acceleration are then applied to the RVTS three-dimensional finite element analysis (FEA) model for stress recovery analysis and structural buckling analysis. Since the lumped parameter dynamic analysis captures the maximum structural dynamic responses and the effects of free body motion and rotations, no additional dynamic load factor is needed for the stress analysis. The stress is performed with various initial conditions per Table 1 of Reg. Guide 7.8 as discussed in Section 4.1 of this report.

4.2.2 Crush

The dynamic crush test, per 10 CFR 71.73 (c)(2), is not required for casks weighing more than 1100 lbs.

4.2.3 Puncture

The puncture drop analysis, per 10 CFR 71.73(c)(3), is not required for the handling accident conditions.

4.2.4 Thermal Accident

The thermal accident, per 10 CFR 71.73(c)(4), is not required for the handling accident conditions.

4.2.5 Water Immersion

Immersion under 50 feet of water (21.7 psig), per 10 CFR 71.73 (c)(6), is not required for the handling accident conditions.

4.3 Hypothetical Accident Conditions

Reference 3.2, 10 CFR 71.73, outlines the HAC to be considered during the design of the RVTS. The initial temperature and pressure conditions associated with the HAC evaluations are the same as those listed for the evaluations of the NCT.

The following tests and conditions are to be applied in the order noted to determine the cumulative effect on the RVTS cask (with the exception of the final test, water immersion, which may be evaluated independently):

4.3.1 Free Drop

10 CFR 71.73(c)(1) requires a free drop test of the cask specimen through a distance of 30 feet onto a flat, essentially unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected. The maximum damage is limited such that the maximum potential radiation activity meets the limitations for shipping casks per Section 71.51 of 10 CFR Part 71. Reference 3.6.10 provides limitations of damage at several locations of the cask so that the requirements in Section 71.51 of 10 CFR Part 71 are satisfied.

The assessment of cask damage resulting from a 30-foot drop onto an essentially unyielding surface is performed by finite element non-linear elastic plastic dynamic impact analyses. The FEA model consists of the RV, which is supported by the top plate and the donut support at the bottom, and the cask shell with the stiffener ring plate and the shield ring plate. The connection of the RV top flange to the top plate is modeled using short beam elements that represent the RV flange bolts. Several contact surfaces between the cask and the essentially unyielding horizontal surface are modeled depending on the drop orientations. Potential contacts between the RV and the cask shell interior surface are also modeled at some local locations as described in each individual drop orientation. A damping ratio of 1% is used in the dynamic analyses

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The cask stresses are monitored for failure. Failure is considered to occur at any element at which the maximum principal stress exceeds the material tensile strength. The failed elements are effectively removed and the process is continued until the cask displacements reach their maximum. Several drop orientations and potential damage are discussed as follows:

- Vertical drop on the cask bottom plate:
  The RV bottom head is supported by the donut support. A vertical drop on the bottom plate may fail the donut support and the RV bottom head may come into contact with the bottom plate. The RV mass would crush the donut support, pull the top plate down, and thus compress the cask shell. In a vertical drop on the top plate, the RV mass is in direct contact with the top plate. Therefore, the damage of a vertical drop on the cask bottom plate is more severe than the damage due to the vertical drop on the top plate. The drop on the bottom plate could cause a buckling failure in the donut support and the cask shell. The effect of the cask shell buckling could cause longitudinal cracks or circumferential cracks on the cask shell. In the vertical drop analysis, the cask FEA model is in the vertical position and the bottom plate is in full contact with the essentially unyielding horizontal surface. Potential local contact between the RV bottom head and the bottom plate is included in the model. The initial conditions include the

temperatures and pressures described in 10 CFR 71 and an initial impact velocity of 527.4 in/sec, which is the impact velocity resulting from a 30-foot free drop.

- Horizontal drop:
  The damage to the shipping cask in a horizontal drop is expected to be concentrated at the two ends where the top plate and the bottom plate impact the essentially unyielding, horizontal surface. The bottom plate and the donut plate share the impact load at the bottom end while the impact load at the top end is taken by only the top plate. Local buckling failure is expected in the ligament of the top plate located between the RV bolt circle and the top plate corner. Potential local contact between the RV flange and the cask shell is included in the model. Some bolts may also fail, which will cause the RV flange to drop down and come into contact with the cask shell. In such cases, the failed bolts are removed by reducing the bolt strength to a negligible value. The shipping cask FEA model is in the horizontal position, and the cask cylindrical shell is in contact with the essentially unyielding horizontal surface along the longitudinal direction. The initial conditions include the temperatures and pressures described in 10 CFR 71 and an initial impact velocity of 527.4 in/sec, which is the velocity at contact resulting from a 30-foot free drop.

- Corner drop through the cask center of gravity (CG drop):
  Local crushing at the impact corner is the potential damage mechanism of a corner drop through the cask CG. The damage due to a CG drop on a bottom corner is more critical than the damage due to a CG drop on a top plate corner because of the distance between the RV and the point of impact. Therefore, a CG drop on the bottom corner is considered. The shipping cask FEA model is in an oblique position in which the CG is on top of the impact corner of the bottom plate. The oblique angle is about 60 degrees from the horizontal plane. The model includes contact of an essentially unyielding horizontal surface with both of the bottom plate and the cask shell areas which are adjacent to the impact corner. The initial conditions include the temperatures and pressures described in 10 CFR 71 and an initial impact velocity of 527.4 in/sec. Under the corner drop scenario, the effect of free body rotation and the secondary impact at the top end, which is referred to as flap down drop, are also considered in the following cases.

- Flap-down drops:
  The dynamic responses of the RVTS cask in several oblique drop orientations are investigated using the lumped parameter dynamic analysis methodology per NUREG/CR –3966, Reference 3.16.2. The cask lumped parameter model is a beam which has the same distributed mass, lumped masses and cross sectional moment of inertia as the RVTS. The thirty-foot drop dynamic impact analyses of the lumped parameter model are performed for several oblique drop angles ranging from 60 degrees to 5 degrees off the horizontal plane. The beam is dropped onto a spring which represents the local stiffness of the cask corner. The spring rate is determined from the force-displacement curve of the cask end plate in the corner drop analysis of the 3-dimensional plate model. The vertical and horizontal velocities of the two ends of the beam are calculated at the time the other end strikes the ground. The results are shown in Table 7.5.1.4a and b. The maximum vertical flap-down velocity at the cask top plate corresponds to a primary 10 degree oblique drop. The maximum horizontal flap-down velocity of the top plate corresponds to a primary 50-degree oblique drop. In these limiting cases, the cask flaps down onto the horizontal surface with a linearly distributed velocity in both vertical and horizontal directions. The damage of a flap-down secondary drop is expected to be the most critical among all drop positions because of a higher impact velocity combined with a horizontal impact velocity. The analyses will determine the potential breaches of the cask containment boundary. The acceptability of the breach of containment is determined in the calculation N-10525-041-001, Reference 3.6.10 as stated in the acceptance criteria stated in section 5.2 of this report.

4.3.2 Crush

The dynamic crush test, per 10 CFR 71.73 (c)(2), is not required for casks weighing more than 1100 lbs.

4.3.3 Puncture

10 CFR 71.73(c)(3) requires that the RVTS cask be dropped through a distance of 40 inches onto the upper end of a solid, vertical, 6" OD steel bar mounted on an essentially unyielding, horizontal surface. During this test, the position of the RVTS is such that maximum damage is expected.

Local punching shear damage resulting in a 6-inch diameter hole through the RVTS cask wall is within the limitation of the acceptance criteria stated in Section 5.2 of this report. However, the effects of the puncture drop on the existing damaged cask resulting from a 30-foot drop are the main concern of the puncture drop analysis. The damaged elements in the 30-foot flap-down drop FEA model are removed prior to initializing the puncture drop. The greatest effect on the existing damage is expected to occur from a horizontal cask drop onto a steel bar near the damaged location at the top plate corner. The 6" OD steel bar is assumed to be a rigid, circular, flat plate located 8 inches above the essentially unyielding horizontal surface. In addition, a second puncture location near the middle of the cask shell between the shield ring and the top plate is considered.

4.3.4 Thermal Fire Accident

10 CFR 71.73(c)(4) requires that the entire RVTS cask be subjected to a 30 minute fire at a temperature of 1475° F with an emissivity coefficient of 0.9. The surface absorption coefficient of the cask is considered to be 0.8. The structural response of the cask to these conditions is considered up to the time when the temperature distributions reach a steady state.

The thermal heat transfer analysis for the thermal exposure accident condition is performed and documented in Reference 3.6.1. From this analysis, the maximum thermal gradient distribution at several key locations is applied as the thermal boundary conditions for the evaluation of the cask's structural response during this HAC. Per Reference 3.6.1, the RVTS cask bottom plate temperature reaches the maximum flame temperature of 1445° F while the temperature of the Reactor Vessel (RV) inside the RVTS cask remains several hundred degrees lower during the 30 minute fire exposure. Figure 7.2.4 shows the RVTS temperature distribution after the fire.

During the 30-minute fire, differential thermal expansion occurs between the RVTS cask and the RV in both longitudinal and radial directions. This differential thermal expansion may cause a gap between the base of the RV and the internal donut ring support. Therefore, the RV could potentially become a cantilevered beam supported only by the damaged cask top plate through the RV flange connection. Although the LDCC between the annulus of the RVTS cask could provide compressive support during this scenario, the effect of the LDCC is conservatively neglected in the structural analysis to ensure that the cumulative damage of the cask remains within the limit of the acceptance criteria.

A maximum internal pressure of 95 psi (Reference 3.6.2) is conservatively applied to the damaged RVTS cask during the HAC fire accident analysis. The damaged elements in the top plate resulting from the thirty-foot drop are removed. The connection between the RV bottom head and the donut support is removed. Temperature dependent material properties per the ASME Code, Reference 3.1, are used in the analysis to account for a strength reduction at high temperature. For temperature above 1000°F, a correlation of strength vs. temperature from Reference 3.20 is used.

4.3.5 Water Immersion

The RVTS cask is subjected to an external pressure equivalent to immersion under 50 feet of water (21.7 psig) per 10 CFR 71.73 (c)(6). This HAC is evaluated independently of the other accident conditions. The vessel buckling effects are checked by combining the minimum internal pressure (resulting from initial temperature condition of -20° F) with the above immersion pressure to maximize the total pressure effect. The resulting pressure is compared to the maximum allowable external pressure determined using ASME Section III, Reference 3.1, Article NB-3133.

4.4 Burial Condition

Once the RVTS reaches Barnwell, SC, its final destination, it will be placed in a burial trench. The RVTS cask will then be buried under a column of soil 40 feet deep with a density of 120 pcf, Reference 3.17. Therefore, the RVTS is designed to withstand the constant pressure of 33 psig resulting from these burial conditions. The resulting pressure is compared to the maximum allowable external pressure determined using ASME Section III, Reference 3.1, Article NB-3133.

4.5 Load Combinations

Load combinations applicable to the analysis for the NCT and HAC will be taken from Regulatory Guide 7.8. Evaluations for the HAC will be taken in the order as noted in Table 4.5 to determine the cumulative effect on the cask. The final test, water immersion, is evaluated independently and is not shown in Table 4.5. The load combinations with the initial condition for all applicable cases as discussed in Sections 4.1 and 4.3 are shown in table 4.5. The load combination and the initial condition for all applicable cases in handling accident conditions as discussed in Sections 4.2 are considered to be the same as the corresponding cases in HAC.

Table 4.5: Load Combinations with Applicable Initial Conditions

Conditions			Load Case No.	Applicable Initial Conditions								
				Ambient Tempera-ture		Insolation		Decay Heat		Internal Pressure		Fabrica-tion Stress
	Section	Description		100 °F	-20 °F	Max	Zero	Max	Zero	Max	Min	
NCT	4.1.1	Hot 100 °F ambient temp.	N1	√		√		√		√		√
	4.1.2	Cold -40 °F ambient temp.	N2				√		√		√	√
	4.1.4	Increased 20 psia external pressure	N3		√		√		√		√	√
	4.1.3	3.5 psia external pressure	N4	√		√		√		√		√
	4.1.5	Shock normally incident to transport in the vertical, transverse and longitudinal directions	N5	√		√		√		√		√
			N6		√		√		√		√	√
			N7	√		√		√		√		√
			N8		√		√		√		√	√
			N9	√		√		√		√		√
			N10		√		√		√		√	√
	4.1.7	1-foot drop	N11	√		√		√		√		√
			N12		√		√		√		√	√
	4.1.10	Steel cylinder drop onto cask	Hand Calc.	√		√		√		√		√
					√		√		√		√	√
HAC	4.3.1	Vertical free drop	VD1	√		√		√		√		√
			VD2		√		√		√		√	√
		Horizontal free drop	HD1	√		√		√		√		√
			HD2		√		√		√		√	√
		Corner free drop	CD1	√		√		√		√		√
			CD2		√		√		√		√	√
		Flap down drop	FD11, FD21	√		√		√		√		√
			FD12, FD22		√		√		√		√	√
	4.3.3	Puncture drop onto steel bar	PTD1,PMD1	√		√		√		√		√
			PTD2,PMD2		√		√		√		√	√
	4.3.4	Thermal fire accident	THACC1	√		√		√		√		√
			THACC2		√		√		√		√	√

4.6 Bolt and Fillet Weld Stresses

4.6.1 Bolt Stress

The existing RV Flange studs will be cut and rethreaded to fit the RVTS design. The bolt material specification is A-193 with a minimum yield strength of 120 ksi and a minimum tensile strength of 140 ksi as specified in Ref. 3.12.3. The nominal bolt diameter would be reduced to 4.5", which is a ¼ inch less than the OD of bolts in current analyses. Since the bolt strengths are significantly higher than the strengths of the bolt material used in the analysis (SA-193 Grade B7), the current analyses are conservative and remain valid.

The nut minimum engagement length is determined such that the threads are sufficient to carry the full load necessary to break the bolt without stripping the threads. The minimum engagement length calculation methodology is given in Ref. 3.18.

Nodal forces are extracted from the ANSYS POST1 processor output for all NCT and handling accident condition loading combinations. The average resultant shear force and the maximum tension load are used to calculate bolt stresses in accordance with ASME B&PV Section III, NB-3232 and Appendix F, F-1335. For HAC loading, the bolts are modeled using ANSYS plastic pipe element PIPE20. Bolt stress intensity is calculated by ANSYS POST26 processor and is a part of the ANSYS output.

4.6.2 Shield Plate and Ring Plate Fillet Weld Stresses

The shield plate and the ring plate are welded continuously around the circumference of cask cylindrical shell interior surface. The fillet welds are modeled in the cask FEA by degree of freedom (DOF) couplings with the connecting cask shell nodes. The fillet welds are designed to support the shield plate and the ring plate from axial sliding. Thus, the total axial force of the DOF coupled nodes are used to calculate the average shear stress in the shield plate fillet welds and the ring plate fillet welds. For the HAC 30-foot drop dynamic time history analyses, the axial force on the shield plate fillet weld is calculated as the product of the impact acceleration times the mass of the shield plate. The same impact acceleration is used for the axial force on the ring plate fillet weld.

4.6.3 Donut Plate and Stiffener Fillet Weld Stresses

The junctures of the donut plate, stiffener plates, cask shell and the bottom plate are modeled as rigid links in all six DOFs. That means the double fillet welds are transmitting all forces and moments across the junctions. However, loads on the donut support structure are predominantly in compression. Compressive forces are transmitted directly by contact between the plates. Therefore, fillet welds are not directly on the main load paths for all loading conditions. Moment loading resulting from plate distortion can be resisted by the fillet welds because the cross sectional modulus per unit length, Z_w, (b= 1") of the double fillet welds is greater than the plate section modulus per unit length, Z_p, as calculated below:

- For 4" thick donut plate with 1" double fillet welds: b = 1 in h = 4 in t_w = 1 in

$$Z_p := \frac{b \cdot h^2}{6} \qquad Z_p = 2.667 \cdot in^3$$

$$Z_w := .707 \cdot t_w \cdot b \cdot \left[\frac{(.5 \cdot h + .5 \cdot t_w)^2}{(.5 \cdot h + t_w)} \cdot 2 \right] \qquad Z_w = 2.946 \cdot in^3$$

- For 2" thick stiffener plate with 1" double fillet welds: b = 1 in h = 2 in t_w = 1 in

$$Z_p = 0.667 \cdot in^3 \qquad Z_w = 1.591 \cdot in^3$$

Therefore, the double fillet weld is considered to be as strong as the connecting plates, and the weld stress is approximately the same as the stress in the plate at the junctures.

5.0 Acceptance Criteria

The design of the Big Rock Point RVTS Cask consists of criteria for both linear elastic analyses and nonlinear plastic failure analyses.

The Big Rock Point RVTS linear elastic design criteria conforms to the guidance provided in Regulatory Guide 7.6, Reference 3.15.1, for meeting the structural requirements for shipping casks in Section 71.35 of 10 CFR Part 71. Per the Reg. Guide, material properties, design stress intensity (Sm) and design fatigue curves for Class 1 components given in Subsection NA of Section III of ASME Boiler and Pressure Vessel Code (Reference 3.1) should be used. Creeping and thermal ratcheting are not considered for the RVTS design for all loading conditions as discussed in Regulatory Guide 7.8, Reference 3.15.2.

The criteria for Big Rock Point RVTS nonlinear plastic analyses are established to assess the extent of the local failures of the cask when subjected to the HAC, and to meet the radiation activity requirements for shipping casks set forth in Section 71.51 of 10 CFR Part 71. Calculation N-10525-041-001, Reference 3.6.10, sets the limits for breaches of the containment that satisfy the requirements of Section 71.51 of 10 CFR Part 71.

5.1 Allowable Stresses for Linear Elastic Analyses

5.1.1 For the NCT and Final Burial Conditions:

RVTS Cask Shell, Top Closure and Bottom Plate (SA-516 Gr. 70)

The allowable primary membrane stress is Sm per Section NB-3221.1 (Reference 3.1).
The allowable primary membrane plus bending stress is 1.5Sm per Section NB-3221.3 (Reference 3.1).
The allowable primary plus secondary stress is 3Sm per Section NB-3222.2 (Reference 3.1).
At a temperature of less than 200°F, Sm = 23.1 ksi for SA-516 Gr. 70 (See Attachment A)

Top Plate Closure Studs

The allowable average stress is 2Sm per Section NB-3232.1 (Reference 3.1).
The allowable maximum stress is 3Sm per Section NB-3232.2 (Reference 3.1).
At a temperature of less than 200°F, Sm = 23.3 ksi for SA-193 Gr. B7 (See Attachment A)

Top Closure Plate Full Penetration Weld

The allowable stress value for the full penetration weld is the same as the base material.

Fillet Weld

The allowable shear stress on the effective area is 0.3 times nominal tensile strength of the weld material per Section NF-3226.2 (Reference 3.1).

Fatigue stress analysis for stresses under the NCT shall be performed in accordance with the cumulative damage given in Article NB-3222.4 of ASME B&PV Code, Section III and the guidelines given in Regulatory Guide 7.8.

5.1.2 For the Handling Accident Conditions:

RVTS Cask Shell, Top Closure and Bottom Plate (SA-516 Gr. 70)

Allowable primary membrane stress intensity is the lesser of 2.4Sm or 0.7Su, where Su denotes the Ultimate Tensile Strength of the material (Reference 3.1).

Allowable primary membrane plus primary bending stress Intensity is the lesser of 3.6Sm or Su. (Reference 3.1).At a temperature of less than 200°F, Su = 70.0 ksi for SA-516 Gr. 70 (see Attachment A).

In the linear elastic drop analyses for the handling accident conditions, the maximum compressive stress (principal stress S3) occurs near the contact area. Thus, the compressive stress at these locations is a contact stress and is considered as a self-limiting secondary stress. Therefore, the stress intensity at the maximum compressive stress is checked against the acceptance criteria for extreme stress (Regulatory Guide 7.8, Reference 3.15.2). The extreme total stress intensity range between the initial state, the fabrication state, the normal conditions and the accident conditions should be less than two times Sa at 10 cycles, given in the applicable design fatigue curve. In addition, the compressive stress is checked for shell buckling, as stated in Section 5.3. The stress intensity at the location with the maximum principal stress S1, however, is checked against the primary stress allowable.

Top Plate Closure Studs Per ASME Section III, Appendix F, F-1335 (Reference 3.1)

The allowable average stress is the smaller of 0.7 Su and Sy.
The allowable maximum stress, excluding stress concentration, is Su.
The allowable sheer stress is the smaller of 0.42 Su and 0.6Sy.
At a temperature of less than 200°F, Su = 102 ksi, Sy= 69.9 ksi for SA-197 Gr. B7 (see Attachment A).

Top Closure Plate Full Penetration Weld

The allowable stress value for the full penetration weld is the same as the base material.

Fillet Weld

The allowable shear stress for on the effective area is 0.45 times the nominal tensile strength of the weld material per NF-3226.2 (Reference 3.1).

5.2 Acceptance Criteria For Nonlinear Elastic Plastic Analyses

In the nonlinear dynamic impact analyses of the cask, the element maximum principal stress is monitored interactively. If the maximum principal stress at any element exceeds the Code specified ultimate tensile stress, Su, a local failure is assumed at that element. The structural stiffness of the failed element is effectively removed from the analysis so that load is transferred to the adjacent elements. The process is continued until the impact velocity diminishes. The cumulative local damage, or the total failed element area, is then considered to be the total opening area of the cask after the HAC.

The total damaged area of the cask during the HAC shall be less than any of the following limits provided in Reference 3.6.10 to satisfy the radiation activity requirements for shipping casks in Section 71.51 of 10 CFR Part 71.

- A horizontal 1 inch wide segment of the RV and insulation is unshielded around the circumference of the vessel at the core mid-plane.
- A vertical 1 inch wide by 48 inch long segment of the RV and insulation is unshielded, centered on the core mid-plane.
- A 6 inch diameter segment of the RV and insulation is unshielded, centered on the core mid-plane.
- The entire top shield plate is removed.

As stated above, creeping and thermal ratcheting are not considered in the RVTS design for all the loading conditions as discussed in the Regulatory Guide 7.8. However, for the HAC fire condition, temperature dependent material properties with reduced strength values at elevated temperatures are considered to assess the cumulative damage. The values of E, Su and Sy at temperatures can be found in Attachment A.

Under impact, local stresses at contact areas are primarily compressive. Compressive contact yielding will increase the local contact area and would not cause a gross structural failure. Potential buckling of the structure under a compressive load is included in the analysis by utilizing the large deformation feature of the FEA as discussed in Section 5.3. Therefore, the failure criterion, based on the maximum principal stress, is justified for the cask 30-feet drop analyses.

5.3 Buckling Check

Structural buckling of the RVTS is checked for NCT and HAC. Buckling of the cask shell under external pressure is checked using maximum allowable external pressure per the ASME Section III, Reference 3.1, Article NB-3133. Buckling of the cask shell under HAC impact loading is checked by using the large deformation option in ANSYS Finite Element Analysis (FEA) Program. With large deformation occurring in the FEA, load is applied and updated gradually in the deformed configuration to ensure that the deformed structure is stable and can sustain the maximum applied load.

5.4 Fracture Toughness Criteria

10 CFR Part 71 requires that casks used to transport radioactive material must be designed considering that the NCT and HAC might occur at the lowest service temperature (LST = –20°F).

The provisions of Regulatory Guide 7.11, " Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels With a Maximum Wall Thickness of Four Inches", and NUREG/CR-1815, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick", are used in the measurement and determination of the Nil Ductility Transition (NDT) temperature for the cask plate material to meet the 10 CFR 71 requirements.

6.0 Assumptions and Limitations

6.1 The RVTS Cask is designed to sustain shock and vibration during transportation. The maximum shock accelerations per the AAR guidelines, Reference 3.11, which envelop the shock accelerations given by ANSI N14.2, Reference 3.14, are used in the cask shock stress analysis and fatigue evaluation. These maximum shock loads are produced by coupling, switching, etc., in rail transport and by bumps, potholes, etc., in truck transport; thus, the number of shock incidents should be limited. One cycle of full magnitude shock per mile is a reasonable assumption. Therefore, 1500 cycles of shock is assumed for the whole trip to the disposal site at Barnwell, SC. A higher number of cycles is expected for vibrations of a lesser magnitude produced by small excitations of the flat bed rail car or road transporter during transportation. This high cycle fatigue loading is evaluated using the material fatigue endurance limit. No verification is required.

6.2 No friction is assumed at the saddle support for the longitudinal shock analysis. This assumption is valid since the longitudinal bumpers will be designed to take all loads. No verification is required.

6.3 A nominal normal and tangential contact stiffness of 1.0E+8 lbf/in is used at all nodes of the saddle supports. This nominal stiffness is required for solution convergence of contact elements and does not affect the analysis results. No verification is required.

6.4 In the handling accident drop analyses, the ground surface is considered as an infinitely thick concrete slab with a maximum compressive strength of 4000 psi. The assumed impact surface is conservative for all feasible ground conditions during the cask handling condition. The assumed concrete compressive strength is at the high end of the typical concrete strength range of 2500 psi to 4000 psi, Reference 3.8. No verification is required.

6.5 The compressive strength of the Low Density Cellular Concrete (LDCC), which fills the voids in the RV and Cask/RV annulus, has a negligible contribution to the RVTS structural stiffness. Therefore, the LDCC is not included in the model. No verification is required.

6.6 For the HAC 30-feet drop analyses, bi-linear elastic plastic material stress-strain curves are constructed from the ASME Code elastic modulus (E), yield strength (Sy), ultimate strength (Su) and the elongation from the ASTM Code. The Code elastic modulus, yield strength and ultimate strength do not vary in the temperature range of –20°F to 100°F; therefore, the constructed stress-strain curves at room temperature are applicable for a lowest service temperature of –20°F. The material stress-strain curves used in the analyses are conservative since they are constructed from the Code specified engineering stress-strain values. In addition, the effect of the strain rate on material strengths, which typically increases the material strength by 20%, is conservatively not considered in the drop analyses

6.7 Rough and bonded contact between the cask and the essentially unyielding surface is modeled for the drop analyses. This means that once the RVTS contacts the essentially unyielding surfaces, no sliding or separation will occur between the contact surfaces. This modeling technique is conservative since no loss of impact energy occurs from sliding and separation.

6.8 Even though there are 14 bolts connecting the top closure plate to the RV flange, only 12 RV bolts are included in the HAC analyses due to the existing nodal spacing of the top plate mesh. The discrepancy has a minor and conservative effect on the results, considering that the actual total bolt area is actually higher, and less bolt deformation would result.

6.9 There is a possibility that local shielding on the cask exterior surface may be required depending on the final dose rate survey. The local shielding is a half inch thick plate with a rounded edge that is rolled to fit, and it is tack welded to locations on the cask exterior surface as required. A total of 800 lbs of local shielding weight is judged to have no significant effect on the structural analysis results because of the

following reasons:

- The additional weight is only 0.15% of the cask weight.
- Increased localized stress due to the additional fillet weld on the cask shell is not a concern since a stress riser of 4 is used in the cask fatigue evaluation.
- The additional 0.5-inch thickness on the cask exterior surface may cause an additional local 0.5 inch dent on the cask shell but would not cause a gross structural failure. In the puncture drop on a 6-inch OD steel rod, the cask shell is locally dented 8 inches without a gross structural failure.

6.10 Per Reference 3.3, the following dimensional tolerances are used to fabricate the RVTS cask components:

Table 6.1 Dimensional Tolerances

Component size	Tolerance (inch)
0 to less than 2 inch	± 1/16
2 inch to less than 3 ft	± 1/8
3 ft to less than 10 ft	± 3/16
10 ft and over	± 1/4
Cask shell height of 24'-11 ½"	+ 1/2, - 0

In addition, a maximum gap size of 1/16" will be provided for the inner shield plate fit-up. The dimensional tolerances and gap are small and do not have any significant effect on the current stress analysis.

6.11 Fourteen of the existing RV bolts will be reused to secure the RV flange to the top plate. The remaining 28 bolts will be removed by cutting off at as close as possible to the RV flange surface. It is possible that some bolts may remain extending beyond the flange surface and interference with the top plate. It is estimated that the cut-off bolt will not extend more than ¼ of an inch beyond the RV flange surface. To avoid interference the top plate will be locally ground to form 28 dimples along the bolt circle. The effects of the dimples on the structural strength of the top plate have been evaluated in Ref 3.6.11, and the result shows that the dimples have no effect on the structural strength of the top plate. Therefore, the dimples are not considered in the FEA models of this calculation.

7.0 Calculations and Results

7.1 Description of the RVTS Cask Finite Element Models and Element Types

The RVTS Cask analyses are performed using ANSYS, a finite element analysis (FEA) program, Reference 3.3.1. The program validation and installation verification are in accordance with the Sargent & Lundy Quality Assurance Standards. The ANSYS element type SHELL181, a 3-D 4-node shell element, is used to model the RVTS Cask shell and plates. The element is well suited for linear elastic and elastic plastic materials, large strain, and large deformation applications. The element has 5 integration points through the element thickness, and has both in-plane and out-of-plane bending and membrane loading capabilities. The SHELL181 element, with full integration option KEYOPT(2)=2, is highly accurate even with coarse meshes. A benchmark analysis documented in Section 7.5.2, shows good comparison to experimental results for the SHELL181 element in an analysis of a bar impacting a rigid wall. A result verification was also performed to verify that the RVTS cask FEA model is adequate for assessing the structural plastic deformation under a 30-foot drop impact loading The verification documented in Section 7.5.2 is based on the principle of energy conservation. The verification shows that the total impact energy of $\frac{1}{2} mv^2$ is transformed into the total plastic work done at the final load step of the analyses.. Thus, the FEA model is adequate and suitable for the purpose of the analyses.

The SHELL181 element does not support the "birth and death feature", which is convenient for removing the failed elements to simulate a local structural failure behavior. The ANSYS solution processors, however, allow modifying the material properties of individual elements between load steps. Thus, any failed element can be effectively removed from the model by reducing the material strength to a very small fraction of the original value.

The detailed description for each analysis model is provided in the corresponding calculations. These analyses share the same RVTS Cask base model, which includes the cask cylindrical shell, cask top and bottom plates, Reactor Vessel (RV), donut supports, shield plate and ring plate. The nodal spacing of the cask cylindrical shell matches the saddle support locations as shown in Figure 7.1.2 and 7.1.3. Figure 7.1.4 shows half of the model with tie-down cables. Figure 7.1.5 shows the element mesh of the vertical drop model.

Connections between the RVTS Cask components are described as follows:

- The bolt/nut connection between the RV flange and the cask top plate is modeled as translational rigid links in all linear elastic analyses. The bolt loads are then extracted from nodal loads and are qualified by hand calculation in Attachment F. In elastic plastic analyses for HAC, potential failures of bolts are considered; therefore, bolts are modeled explicitly using the plastic beam element, PIPE20. If the stress intensity of a bolt exceeds the material ultimate tensile strength, Su, the failed bolt is removed by reducing the element stiffness to a very small value. The normal contact of the top plate and the RV flange is modeled by axial links. Due to element spacing, only 12 bolts out of the total 14 bolts are included in the model. This deficiency is judged to have a minimal effect on the analysis results (see Section 6.8).

- The RV hemispherical bottom is supported by contact at the donut ring plate. Therefore, the connection between the two components depends on the loading conditions. To accommodate various loading conditions, the contact circle between the RV hemispherical bottom and the donut ring support plate is divided into four segments as shown in Figure 7.1.1. Depending on the loading direction, the appropriate directional links of nodes on each segment will be activated. For example, the radial links of the nodes on segments 3 & 4 are established for vertical support of RV weight load in the Z direction. Similarly, radial links of the nodes on segments 1 & 4 are established for lateral support of the RV under inertial load in the X direction. Longitudinal (Y direction) links for all four segments are activated during the cold condition, where the thermal contraction of the cask shell is constrained by the RV.

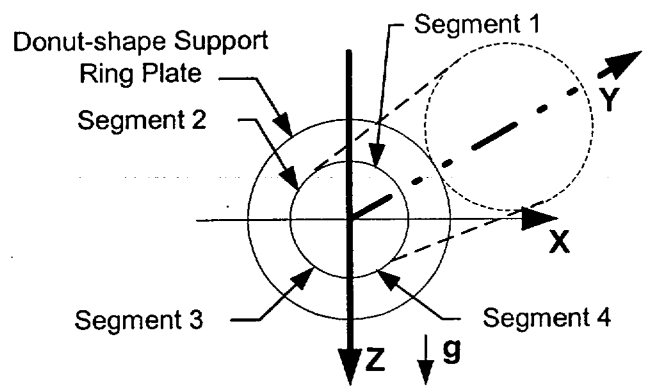


Figure 7.1.1 Donut Support Ring Segments

FIGURE WITHHELD UNDER 10 CFR 2.390

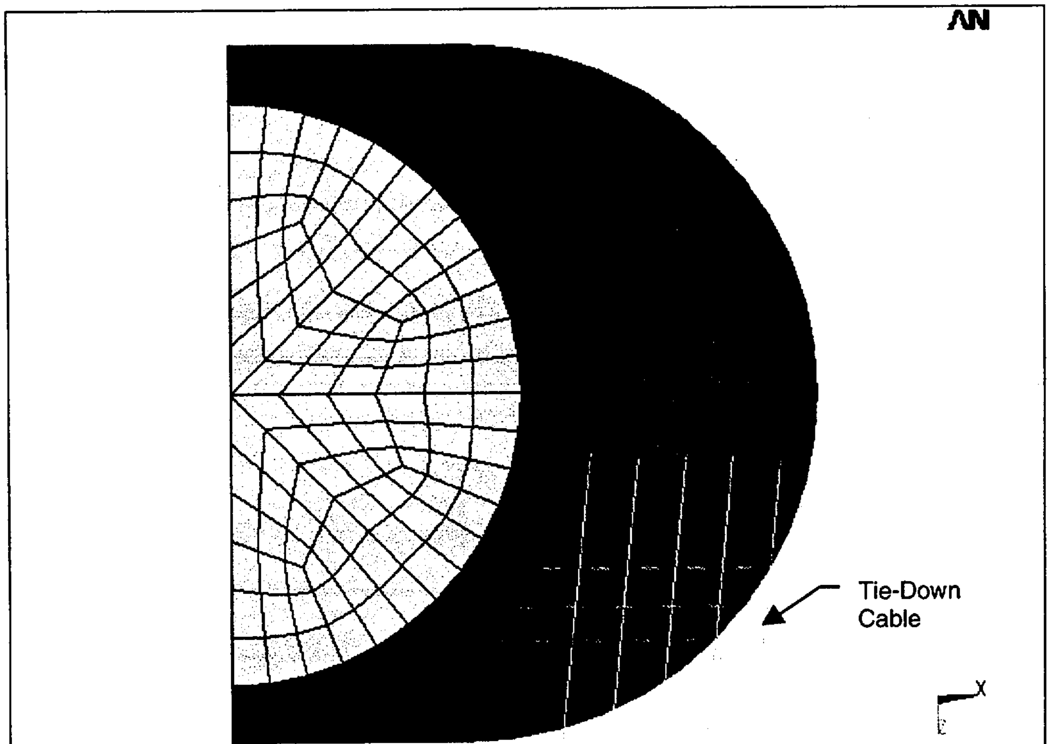


Fig. 7.1.4 RVTS with Tie-Down Cables

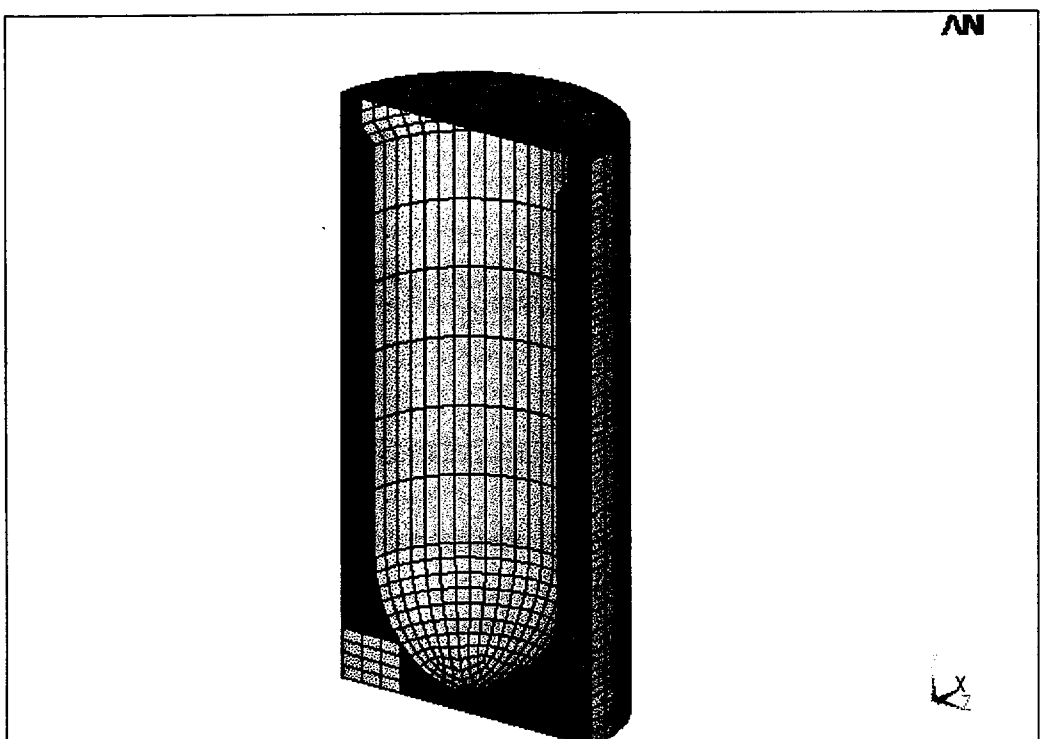


Fig. 7.1.5 RVTS Cask Model

- Rigid links are used to model the fillet welds of the shield plate and the ring stiffener plate to the inside of the cask shell. These plates are modeled at the center of the cask cylindrical shell. The final design length of the shield plate is a little longer than the length used in the model. Therefore, an equivalent density of the final shield plate design is used so that the correct weight is modeled in the analyses.

- The weight of the RV internals and LDCC are included in the model. However, the LDCC structural stiffness is negligible and is not considered in the analyses.

- The RV flange thickness is reduced such that the flange elements are centered at the bolt circle and maintaining the true gap between the flange and the cask shell. An equivalent density is used so that the correct RV flange weight is modeled in the analyses.

Depending on the boundary conditions of the analyzed loading, additional element types are used as follows:

- For weight and shock analysis of the RVTS Cask during transportation, saddle supports are modeled as contact elements in the radial direction using the ANSYS CONTAC52 element. Figure 7.1.3 shows the points of location of the saddle supports.

- Tie-down cables are modeled for the longitudinal shock analysis as tension only link elements using the ANSYS LINK10 element. The link elements are placed on the shell nodes where the cables contact the cask. The cables connect to the support structure with an offset angle of 6 degrees from the vertical direction. Figure 7.1.4 show the RVTS Cask with tie-down cables.

- BEAM3 and MASS21 are used for the lumped parameter dynamic model of the RVTS Cask drop analyses. A nonlinear load-deflection spring element, COMBIN39, is used to model the contact stiffness of the flat concrete surface.

- Surface contact element, CONTAC173, and target surface element, TARGET171, are also used to model the contacts of several portions of the cask elastic-plastic model with the unyielding, horizontal surface.

The output stresses are the stress intensities taken at the integration points and at the top, bottom and middle layer of the shell element. Stress at the middle shell layer is membrane stress (Pm). Stress at the shell top and bottom layers are membrane plus bending stress (Pm+Pb). Stress due to thermal expansion, localized stresses at the impact surface, and stresses at the junction of the cylindrical shell and the flat head, are classified as self-limiting secondary stresses (Pm+Pb+Q). All load carrying welds such as the top and bottom plate corner welds and the cask seam welds are ASME Section III, Subsection NB full penetration welds and therefore, are qualified as base metal. The double fillet welds on the donut-shape support plate and stiffeners are considered to be as strong as the connecting plate, per discussion in Section 4.6.3. The fillet welds between the cask shell and the shield plate and stiffener ring plate are qualified in Section 7.4.3 for both NCT and handling accident conditions. Loads on these fillet welds due to HAC loading are addressed in Section 7.5.6. No calculation is required for other non-load-carrying welds.

7.2 Thermal Analyses

Thermal response of the RVTS package due to the aforementioned conditions has been evaluated in Reference 3.6.1. Based on the temperature distribution determined in that calculation, the temperatures at the mid span of the cask shell, top and bottom plates and RV wall are used as boundary conditions for performing heat transfer analyses. The resulting temperature distribution of the RVTS Cask is then used for

the structural thermal analyses. The following five thermal heat transfer and thermal structural analysis load cases are performed:

- T1 = Hot Condition, 100 °F Ambient, Max Decay Heat, Max Insolation
- T2 = Cold Condition, -40 °F Ambient, Zero Decay Heat, Zero Insolation
- T3 = Cold Condition,-20 °F Ambient, Zero Decay Heat, Zero Insolation
- T4 = Fire Condition, 100 °F Ambient, Zero Decay Heat, Zero Insolation
- T5 = Fire Condition, -20 °F Ambient, Zero Decay Heat, Zero Insolation

Note that the T4 thermal load case (initial ambient temperature of 100 °F) for the hypothetical fire accident was analyzed with zero decay heat and zero insolation conditions instead of the maximum decay heat and the maximum insolation conditions. This yields a slightly conservative temperature gradient across the RVTS section, and therefore, this discrepancy has no impact on the analysis results. The RVTS temperature distributions are shown in Figures 7.2.1 through 7.2.3 for thermal load cases T1 through T3 and Figures 7.5.4a through 7.5.4b for thermal load cases T4 through T5, respectively. Due to differences in nodal and element numbering of the linear elastic analyses and elastic plastic analyses, two separate thermal analysis models are generated for use in the NCT and HAC analyses.

Since the RVTS support system components, such as saddles, tie-down cables and bumpers, are exposed to the same thermal conditions as the RVTS Cask, only the cask rigid body motions are constrained in the thermal structural analyses. The secondary thermal load cases are then combined with the primary load cases as required to calculate the stress ranges among the various loading conditions.

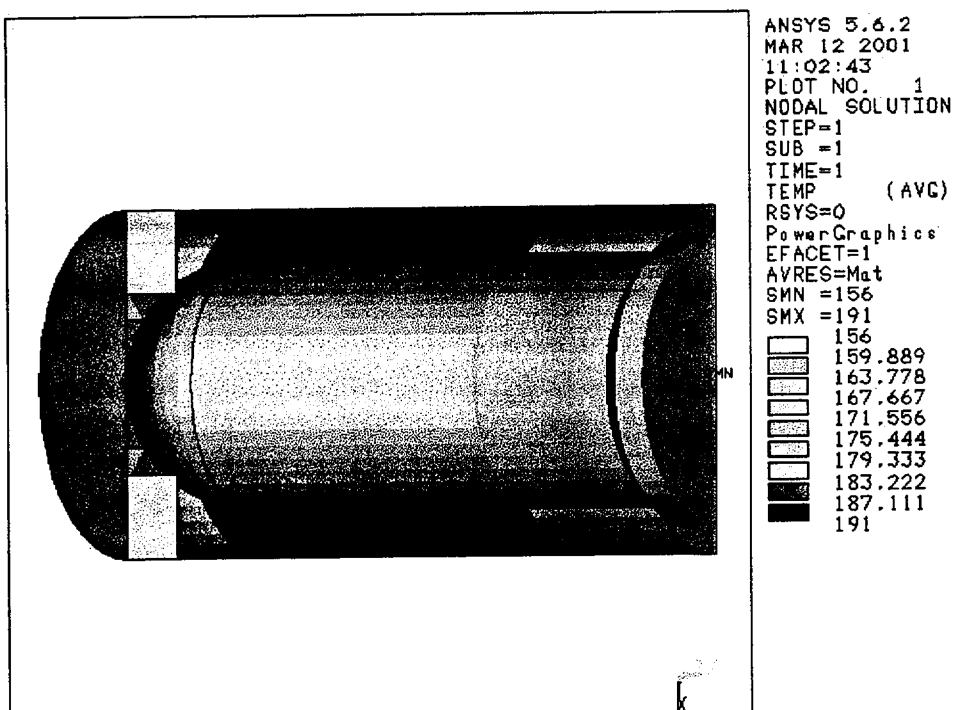


FIG. 7.2.1 100F Ambient, Max Insolation, Max Decay Heat

Sargent & Lundy	Calc For: Reactor Vessel Transport Cask Stress Analysis	Calc. No. S-10525-020-012	
	● Important to Safety Category A / Non-Safety-Related	Rev. 0	Date:
		Page 35	
Client: BNFL, Inc.		Prepared by: P. H. Hoang	Date
Project: Big Rock Point Major Component Removal		Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

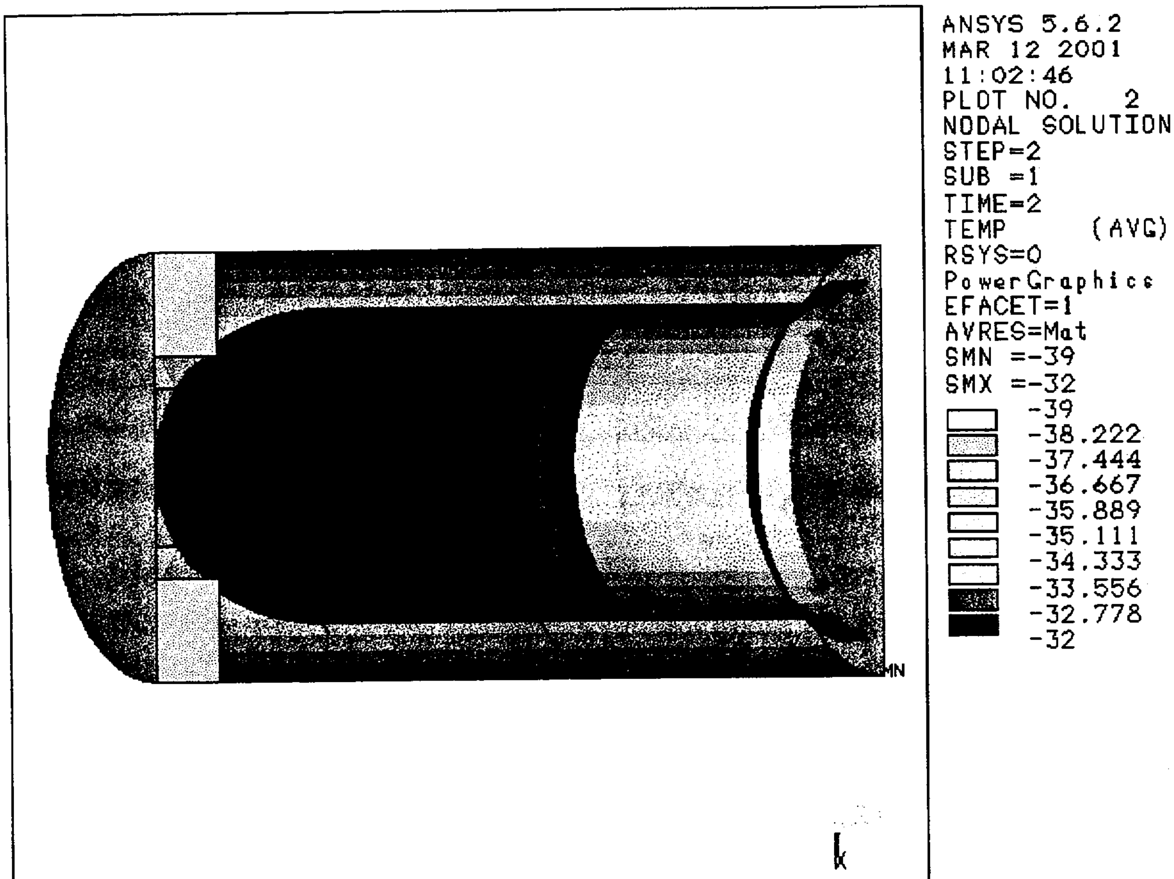


FIG. 7.2.2 -40 F Ambient, Zero Insolation, Zero Decay Heat

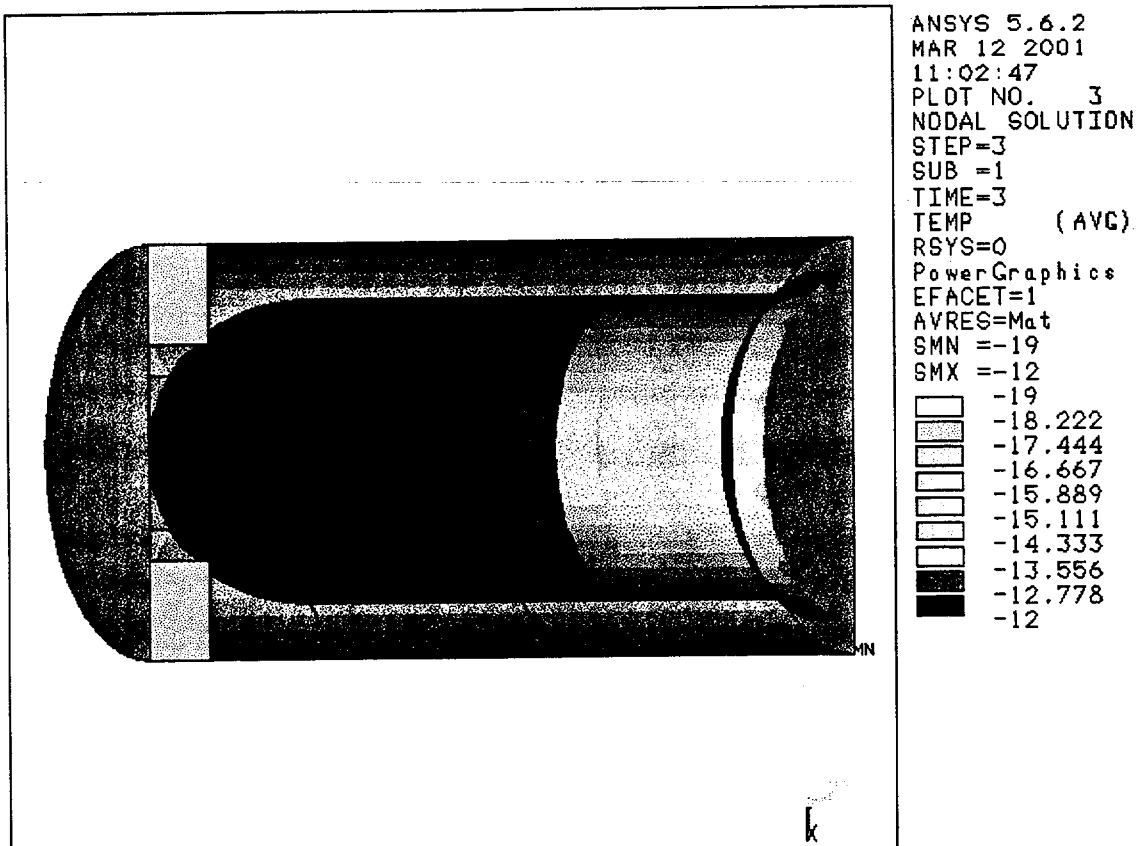


FIG. 7.2.3 -20 F Ambient, Zero Insolation, Zero Decay Heat

7.3 Normal Conditions of Transport

The following analyses are performed using the static dead weight of the RVTS with various pressure loading conditions:

- P1= Maximum Internal Pressure plus RVTS Weight
- P2= Minimum Internal Pressure plus RVTS Weight
- P3= Increased External Pressure plus RVTS Weight
- P4= Decreased External Pressure plus RVTS Weight
- P5= Internal Test Pressure plus RVTS Weight

The calculation of the center of gravity (CG) of the RVTS cask is performed and documented in Attachment H. The CG is located 150.05" + 2" = 152.05" from the bottom of the cask with a half-model total mass of 730.38 lbf-sec^2/in.

7.3.1 Hot Environment (Load Case N1)

The primary weight load (1g inertial load in the Z direction) and maximum internal pressure (20 psig) are applied on the cask during transport as load case P1. The cask is positioned on saddles, and the donut support ring, segment Nos. 3 and 4, supports the RV hemispherical bottom in the radial direction. Load case P1 is then combined with the load case T1 (100 $^{\circ}$F ambient) to form the normal hot condition, load case N1. The 20 highest stress intensity values are shown in Attachment H. The maximum primary membrane stress intensity (Pm), primary membrane plus bending stress intensity (Pm+ Pb), and primary plus secondary stress intensity (Pm+Pb+Q) for load case N1 are summarized in Table 7.3.1. Figure 7.3.1 shows the stress contour of the Pm+Pb+Q stress intensity for load case N1.

7.3.2 Cold Environment (Load Case N2)

The primary weight load (1g inertial load in the Z direction) and the minimum internal pressure (-3 psig) are applied on the cask during transport as load case P2. The cask is positioned on saddles and the donut support ring, segment Nos. 3 and 4, supports the RV hemispherical bottom in the radial direction. Load case P2 is then combined with load case T2 (-40 $^{\circ}$F ambient) to form the normal cold condition, load case N2. The 20 highest stress intensity values are shown in Attachment H. Figure 7.3.2 shows the stress contour of the Pm+Pb+Q stress intensity for load case N2. Since the internal pressure for load case T2 (-40 $^{\circ}$F ambient) is –3.3 psig which is 10% higher than the analyzed pressure of –3 psig, a factor of 1.1 is used to adjust the stress intensities for load case N2. The adjusted stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N2 are summarized in Table 7.3.1.

7.3.3 Increased External Pressure (Load Case N3)

The primary weight load (1g inertial load in the Z direction), the minimum internal pressure (-3 psig) and an external pressure of 20 psia are applied on the cask during transport as load case P3. The cask is positioned on saddles, and the donut support ring, segment Nos. 3 and 4, supports the RV hemispherical bottom in the radial direction. Load case P3 is then combined with load case T3 (-20 $^{\circ}$F ambient) to form the increased external pressure condition, load case N3. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N3 are summarized in Table 7.3.1. Figure 7.3.3 shows the stress contour of the Pm+Pb+Q stress intensity for load case N3.

7.3.4 Reduced External Pressure (Load Case N4)

The primary weight load (1g inertial load in the Z direction), the maximum internal pressure (20 psig) and an external pressure of 3.5 psia are applied on the cask during transport as load case P4. The cask is positioned on saddles, and the donut support ring, segment Nos. 3 and 4, supports the RV hemispherical bottom in the radial direction. Load case P4 is then combined with load case T1 (100 °F ambient) to form the reduced external pressure condition, load case N4. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N4 are summarized in Table 7.3.1. Figure 7.3.4 shows the stress contour of the Pm+Pb+Q stress intensity for load case N4.

7.3.5 Vibration and Shock

Shock loads produced by coupling, switching, etc., during rail transport and by bumps, potholes, etc., during truck transport are considered to be bounded by the governing inertial loads specified for the tie-down component design. The enveloping vertical, lateral, and longitudinal accelerations given per the governing ANSI N14.2, "Tie-down for Truck Transport of Radioactive Materials", Ref. 3.14, and the Association of American Railroads (AAR) guidelines set forth in Part 1 of the "Open Top Loading Rules Manual" Reference 3.11, are:

- Vertical direction: 2.0g
- Transverse direction: 2.0g
- Longitudinal direction: 3.0g

These shock accelerations are conservative since the package will be transported by a hydraulic road transporter and a special use rail car.

The RVTS is evaluated for shock normally incident to transport under two extreme thermal conditions, per Reference 3.2, Table 1. First, the RVTS is evaluated for the effects of vibration at an ambient temperature of 100° F, considering maximum insolation and decay heat along with corresponding maximum internal pressure (20 psig). Next, the RVTS is evaluated for the effects of vibration at an ambient temperature of -20° F, considering zero insolation, zero decay heat, and the corresponding minimum internal pressure (-3 psig). The following inertial and internal pressure load cases are analyzed:

- V1 = Vertical Shock plus Maximum Internal Pressure plus RVTS Weight
- V2 = Vertical Shock plus Minimum Internal Pressure plus RVTS Weight
- V3 = Side Shock plus Maximum Internal Pressure plus RVTS Weight
- V4 = Side Shock plus Minimum Internal Pressure plus RVTS Weight
- V5 = Longitudinal Shock plus Maximum Internal Pressure plus RVTS Weight
- V6 = Longitudinal Shock plus Minimum Internal Pressure plus RVTS Weight

These load cases are combined with the corresponding thermal load case T1 (hot) or T3 (cold) as follows:

- Case N5 = V1 + T1, Vertical Shock, Hot Environment
- Case N6 = V2 + T3, Vertical Shock, Cold Environment
- Case N7 = V3 + T1, Lateral Shock, Hot Environment
- Case N8 = V4 + T3, Lateral Shock, Cold Environment
- Case N9 = V5 + T1, Longitudinal Shock, Hot Environment
- Case N10= V6 + T3, Longitudinal Shock, Cold Environment

Vertical Shock Analysis (Load Cases V1 and V2):

The model for the weight analysis is used for two vertical shock analyses: load case V1 with the maximum internal pressure and load case V2 with the minimum internal pressure. An inertial

acceleration of 2g is applied to the cask vertical, downward direction. The vertical upward shock is restrained by ten tie-down wire rope cables. The tie-down cables are qualified in a separate calculation, Reference 3.6.6. Stress on the cask due to the vertical upward shock is bounded by the vertical downward shock load case and is not calculated in this report. The cask is positioned on the saddles, and the donut support ring, segment Nos. 3 and 4, support the RV hemispherical bottom in the radial direction.

Load case V1 is combined with load case T1 (hot condition) to form load case N5. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N5 are summarized in Table 7.3.1. Figure 7.3.5.1 shows the stress contour of the Pm+Pb+Q stress intensity for load case N5. Load case V2 is combined with load case T3 (cold condition) to form load case N6. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N6 are summarized in Table 7.3.1. Figure 7.3.5.2 shows the stress contour of the Pm+Pb+Q stress intensity for load case N6.

Lateral Shock Analysis (Load Cases V3 and V4):

The model for weight analysis is used for two lateral shock analyses: load case V3 with the maximum pressure and load case V4 with the minimum pressure. An inertial acceleration of 2g is applied to the cask lateral direction, and 1g is applied in the vertical downward direction. Tie-down cables, which restrain vertical upward motion, are not modeled in the lateral shock analysis. Friction is considered at the saddle supports to restrain the cask free body axial rotation. The cask is positioned on saddles, and the donut support ring, segment Nos. 1 and 4, supports the RV hemispherical bottom in the radial direction.

Load case V3 is combined with load case T1 (hot condition) to form the reduced external pressure condition load case N7. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N7 are summarized in Table 7.3.1. Figure 7.3.5.3 shows the stress contour of the Pm+Pb+Q stress intensity for load case N7. Load case V4 is combined with load case T3 (cold condition) to form load case N8. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N8 are summarized in Table 7.3.1. Figure 7.3.5.4 shows the stress contour of the Pm+Pb+Q stress intensity for load case N8.

Longitudinal Shock Analysis (Load Cases V5 and V6):

Due to the model and loading symmetry, half the model is used for the weight analysis during the two longitudinal shock analyses: load case V5 with the maximum pressure and load case V6 with the minimum pressure. An inertial acceleration of 3g is applied to the cask longitudinal direction, and 1g is applied in the vertical downward direction. The longitudinal bumpers are located below the RVTS center of gravity; therefore, the tie-down cables are modeled to restrain the up-lift displacement resulting from the cask rotation around the bumper. The cask is positioned on saddles, and the donut support ring, segment Nos. 1 and 2, supports the RV hemispherical bottom in the radial direction.

Load case V5 is combined with load case T1 (hot condition) to form the reduced external pressure condition, load case N9. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N9 are summarized in Table 7.3.1. Figure 7.3.5.5 shows the stress contour of the Pm+Pb+Q stress intensity for load case N9. Load case V6 is combined with load case T3 (cold condition) to form load case N10. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm, Pm+ Pb, and Pm+Pb+Q for load case N10 are summarized in Table 7.3.1. Figure 7.3.5.6 shows the stress contour of the Pm+Pb+Q stress intensity for load case N10.

Table 7.3.1 Stress Intensity Summary for Normal Conditions of Transport

Normal Conditions of Transport		Load Case No.	Primary Membrane Stress Pm			Primary Membrane plus Bending Stress Pm+Pb			Primary Plus Secondary Stress Pm+Pb+Q			
			Node No.	ksi	Sm ksi	Node No.	ksi	1.5 Sm	Node No.	ksi	3m Sm	Minimum Stress Margin
Hot 100 °F ambient temp.		N1	10304	1.85	23.1	966	5.41	34.65	968	7.29	69.3	6.4
Cold -40 °F ambient temp.		N2	10304	2.0	23.1	3082	6.52	34.65	3082	6.4	69.3	5.4
Increased 20 psia external pressure		N3	10304	1.81	23.1	3082	6.20	34.65	3082	6.11	69.3	5.6
Minimum 3.5 psia external pressure		N4	3802	2.77	23.1	966	7.51	34.65	968	9.70	69.3	4.6
Vertical Shock	Hot	N5	10304	4.62	23.1	3082	9.82	34.65	3082	9.81	69.3	3.5
	Cold	N6	10304	4.11	23.1	3082	9.36	34.65	3082	9.28	69.3	3.7
Lateral Shock	Hot	N7	3838	4.84	23.1	3302	18.3	34.65	3302	18.3	69.3	1.9
	Cold	N8	3838	5.20	23.1	3302	17.6	34.65	3302	17.5	69.3	2.0
Longitudinal Shock	Hot	N9	10304	9.93	23.1	3082	14.9	34.65	1085	16.0	69.3	2.3
	Cold	N10	10304	9.96	23.1	3082	15.5	34.65	3082	15.4	69.3	2.2
1' Free Drop	Hot	N11	3853	19.3	23.1	3853	19.7	34.65	3853	22.4	69.3	1.2
	Cold	N12	3853	19.2	23.1	3853	19.7	34.65	3853	18.5	69.3	1.2
Test Pressure	Hot	TP1	3802	2.67	23.1	966	7.27	34.65	968	9.44	69.3	4.8
	Cold	TP2	3802	2.67	23.1	966	7.27	34.65	10446	6.97	69.3	4.8

Vibration Fatigue:

Vibratory motion data produced by small excitations in the cask-vehicle system is reported in NUREG/CR-0128, Reference 3.16.3, for packages that weigh more than 50,000 lbs and for travel speeds less than 55 mph. The maximum zero-to-peak accelerations are:

- Vertical direction: 0.52g
- Transverse direction: 0.19g
- Longitudinal direction: 0.27g

These maximum accelerations are considered to be the bounding values for both road and rail transports. Based on the results of load cases N5 through N10, the maximum stress intensity, Pm+Pb, in the cask due to the above vibratory accelerations are approximated as follows:

- Vertical direction: 0.52g * (9.82 /2g) = 2.55 ksi
- Transverse direction: 0.19g * (18.3 /2g) = 1.74 ksi
- Longitudinal direction: 0.27g * (16.0 /3g) = 1.44 psi

These stresses are the local contact stresses at the saddle support (see the stress contour for load cases V1 through V6) that include local stress concentration. Additionally, the above contact stresses are the full range vibratory stress, which is two times the S_{alt} stress. A peak stress index of K = 4 is considered to envelop the stress concentration at the threaded holes for the LDCC plugs and the trunnion bolts. Hence, the maximum vibratory stress S_{alt} is 0.5 x 4 x 2.55 = 5.1 ksi. Based on the fatigue curve Figure I.9.1, ASME Section III, Appendix I, at 1.0E+6 cycles, Su < 80 ksi, and E = 30E+06 psi, the endurance limit of carbon steel material is 12.5 ksi. Since the maximum

vibratory stress S_{alt} is less than the endurance limit, vibration would not have a significant contribution in the normal condition fatigue evaluation.

The normal condition shock fatigue evaluation of the cask is conservatively based on the enveloped stress intensity range of the normal condition load cases N1 through N10. Longitudinal shock load cases N9 and N10 are the two highest stress load cases for the normal transport shock loading. As discussed above, these are the maximum local contact stresses at the saddle supports, which are $2S_{alt}$ stress. Stress range, $2S_{alt}$, for the following load cases F1 through F5 are calculated based on the alternating stress intensity definition given in Reg. Guide 7.6. (Combination rule is based on principle stress). These stress ranges are listed in the ANSYS Post Processing Results documented in Attachment H. The results of five extreme alternating stress ranges are as follows:

Table 7.3.2 Stress Intensity Range for Normal Conditions of Transport

Load Range (I - J)	Load Case I	Load Case J	Stress Range $2S_{alt}$ (ksi)	Node No.(*)
F1	Longitudinal shock, hot, Pmax, (N9)	Inc. ext. pressure, cold, (N3).	13.5	942
F2	Longitudinal shock, cold, Pmin (N10)	Min. ext. pressure, hot, (N4).	12.3	3082
F3	Longitudinal shock, hot, Pmax, (N9)	Vert. shock, cold, Pmin, (N8)	13.0	942
F4	Longitudinal shock, cold, Pmin (N10)	Vert. shock, hot, Pmax, (N7)	12.6	10304
F5	Longitudinal shock, hot, Pmax, (N9)	Zero stress state	17.3	3082

(*) Saddle Support

The maximum stress intensity range, $2S_{alt}$, is equal to 17.3 ksi, which includes the local stress at the saddle support. This stress is less than 3Sm = 69.3 ksi. The RVTS Cask shell has four 3" OD threaded holes, which are used to fill the RVTS with LDCC and several bolt holes at the trunnion locations. These holes are not located near the high fatigue stress area. However, a local stress concentration factor, K = 4 (the maximum concentration factor suggested by Reg. Guide 7.6) is used as a bounding peak stress index for fatigue evaluation. The enveloped peak stress range, which is calculated from the maximum local stress range, and the bounding stress concentration, is 4 x 17.3 ksi = 69.2 ksi. The maximum alternating stress, S_{alt} = 0.5 x 69.2 = 34.6 ksi, from which the allowable number of cycles determined from the fatigue curve shown in Figure I.9.1, ASME Section III, Appendix I, Su < 80 ksi, and E = 30E+06 psi, is 1.38E+04 cycles. The number of allowable fatigue cycles is greater than the conservatively assumed number of shocks equal to 1500 cycles. The cumulative fatigue usage factor is 0.109, which is less than the allowable of 1 per Section NB-3222.4 of ASME B&PV Code, Reference 3.1. Since the fatigue usage factor is several times less than the allowable of 1, the shipping distance can be extended to at least twice of the of assumed value of 1500 miles if needed.

7.3.6 Penetration

A hand calculation, documented in Attachment E, determines the required cask shell thickness to prevent puncture caused by a vertical, steel cylinder with a hemispherical end and a diameter of 1.25" weighing 13 lbs that is dropped from a height of 40" onto the exposed surface of the RVTS cask. The recommended minimum design thickness calculated from the Ballistic Research Laboratory formula and Modified Stanford Equation, Reference 3.13, is 0.55 inch. Since the

minimum thickness of the cask is 3", the cask shell thickness is adequate for resisting the required puncture loading.

7.3.7 One-Foot Free Drop

The one-foot free drop, load cases N11 and N12, stresses are obtained by applying a linear scale to the stress results for the five-foot horizontal drop, load cases I1 and I2 (documented in Section 7.4.2). The linear scale is based on the ratio of the impact velocity of one-foot drop vs. five-foot drop.

For 5' free drop, the impact velocity is: $V5 = \sqrt{(2*32.2*5)} = 17.92$ ft/s

For 1' free drop, the impact velocity is: $V1 = \sqrt{(2*32.2*1)} = 8.01$ ft/s

Therefore, the scale factor is 8.01/17.92 = 0.45.

The 20 highest stress intensity values are shown in Attachment H. The maximum primary membrane stress intensity (Pm), primary membrane plus bending stress intensity (Pm+ Pb), and the primary plus secondary stress intensity (Pm+Pb+Q) for load cases N11 and N12 are summarized in Table 7.3.1. Figures 7.3.7.1 and 7.3.7.2 show the stress contour of the Pm+Pb+Q stress intensity for load cases N11 and N12, respectively.

7.3.8 Test Pressure

The primary weight load (1g inertial load in the Z direction) and test pressure of 30 psig are applied on the cask as load case P5. The cask is considered in horizontal position, and the donut support ring, segment Nos. 3 and 4, support the RV hemispherical bottom in the radial direction. Load case P5 is then combined with the thermal load cases T1 (Hot Condition,100 °F ambient) and T2 (Cold Condition, -40 °F Ambient) to form load cases TP1 and TP2, respectively. The 20 highest stress intensity values are shown in Attachment H. The maximum primary membrane stress intensity (Pm), primary membrane plus bending stress intensity (Pm+ Pb), and the primary plus secondary stress intensity (Pm+Pb+Q) for load cases TP1 and TP2 are summarized in Table 7.3.1. Figures 7.3.8.1 and 7.3.8.2 show the stress contour of the Pm+Pb+Q stress intensity for load cases TP1 and TP2, respectively.

7.3.9 Fillet Weld Evaluation

Evaluation has been performed in section 7.4.3 to determine the adequacy of the 1 inch fillet weld between the shield plate and cask shell, and the 0.5" fillet weld at reinforced ring plate.

Since the weld stresses due to Handling Accident Condition loading are within the NCT stress allowable, the aforementioned weld sizes are adequate for NCT loadings.

7.3.10 RV Flange Stud & Nut Evaluation

The RV flange stud and nut evaluation for NCT is documented in the Attachment F of this report. The maximum stresses in the bolts are:

Criteria	Stress (psi)	Allowable Stress (psi)
Tensile Stress	11,320	46,600
Shear Stress	11,510	46,600

The nut minimum engagement length is 6 inches such that threads are sufficient to carry the full load necessary to break the bolt without stripping the threads

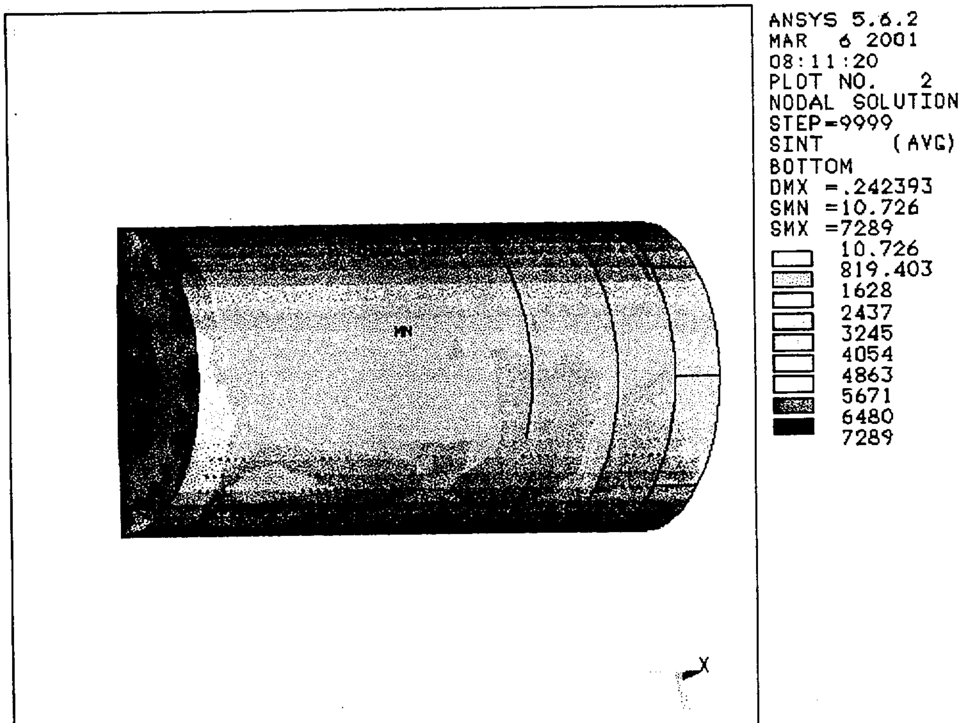


Fig.7.3.1 Hot Envir. Primary Plus Secondary Stress

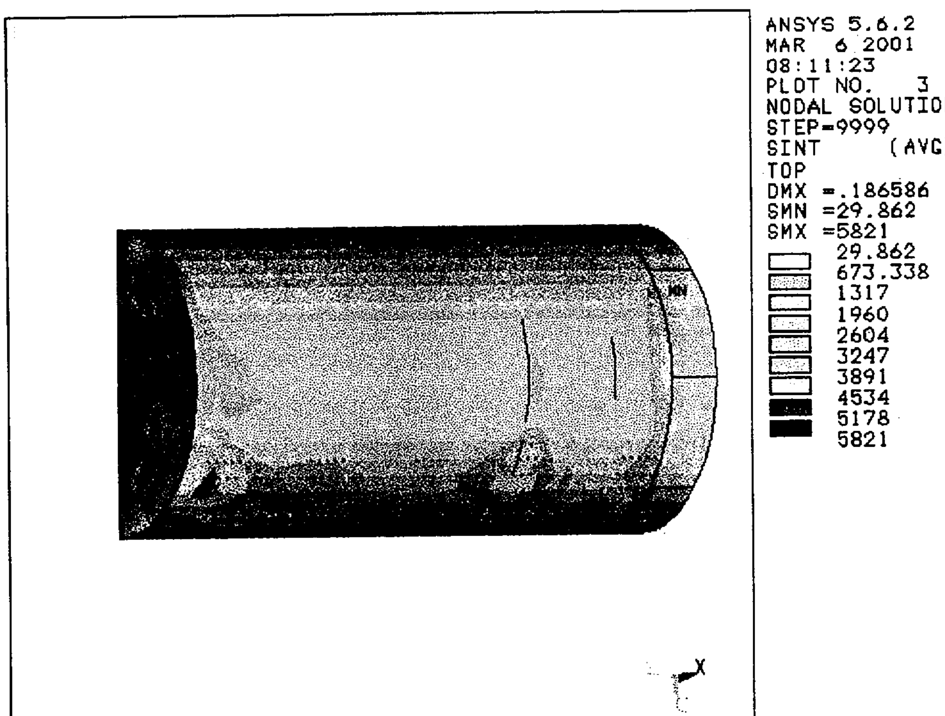


Fig.7.3.2 - 40 F Cold Envir. Primary Plus Secondary Stress

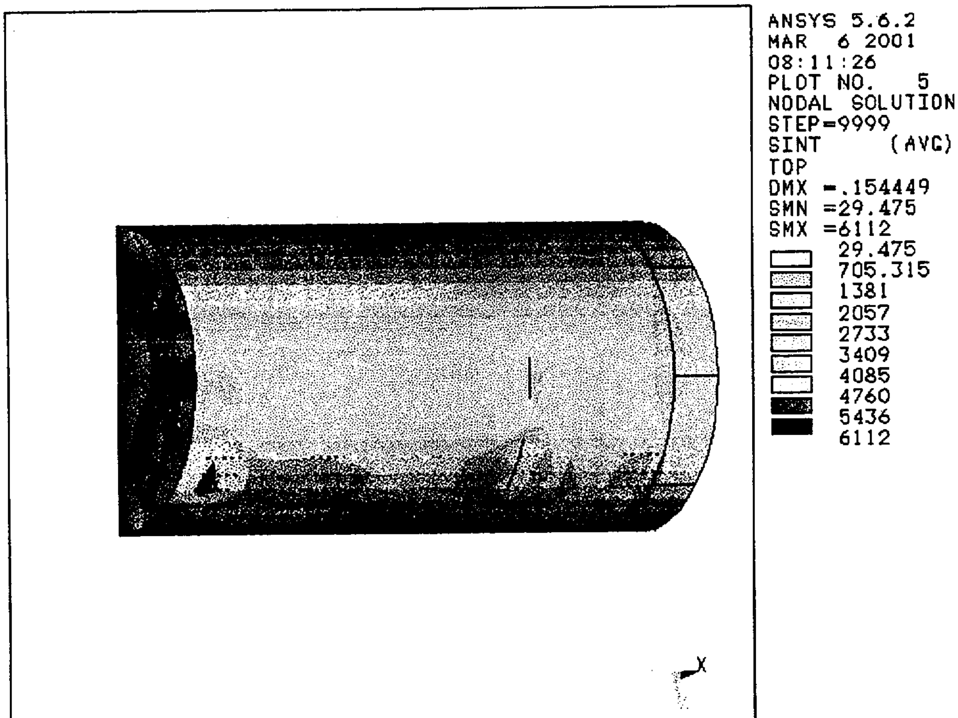


Fig.7.3.3 Increased External Pressure Primary Plus Secondary Stress

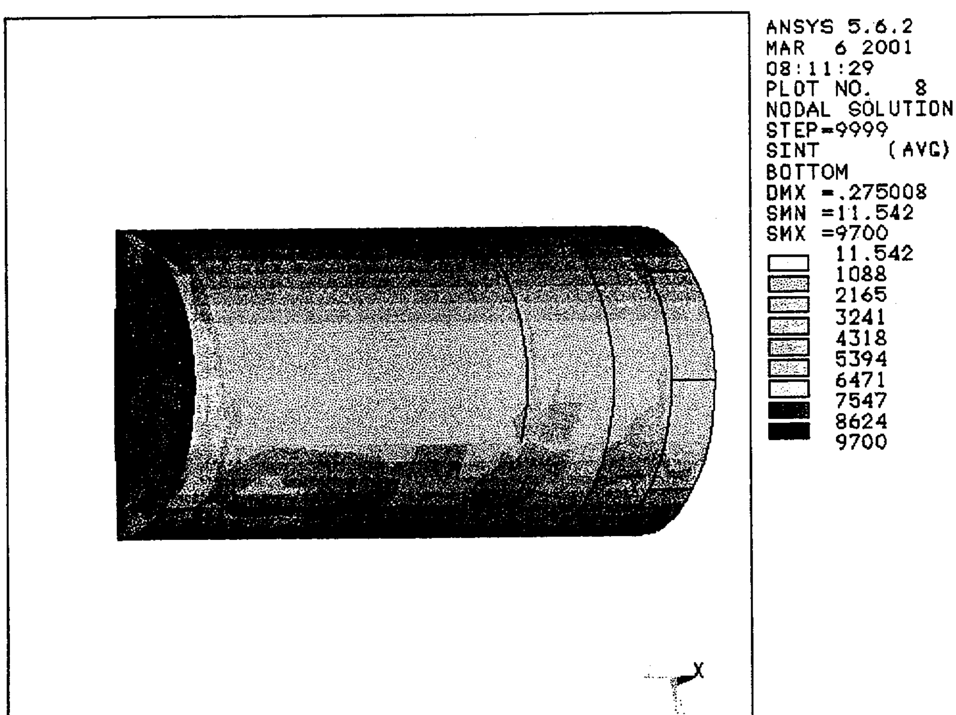


Fig.7.3.4 Minimum External Pressure Primary Plus Secondary Stress

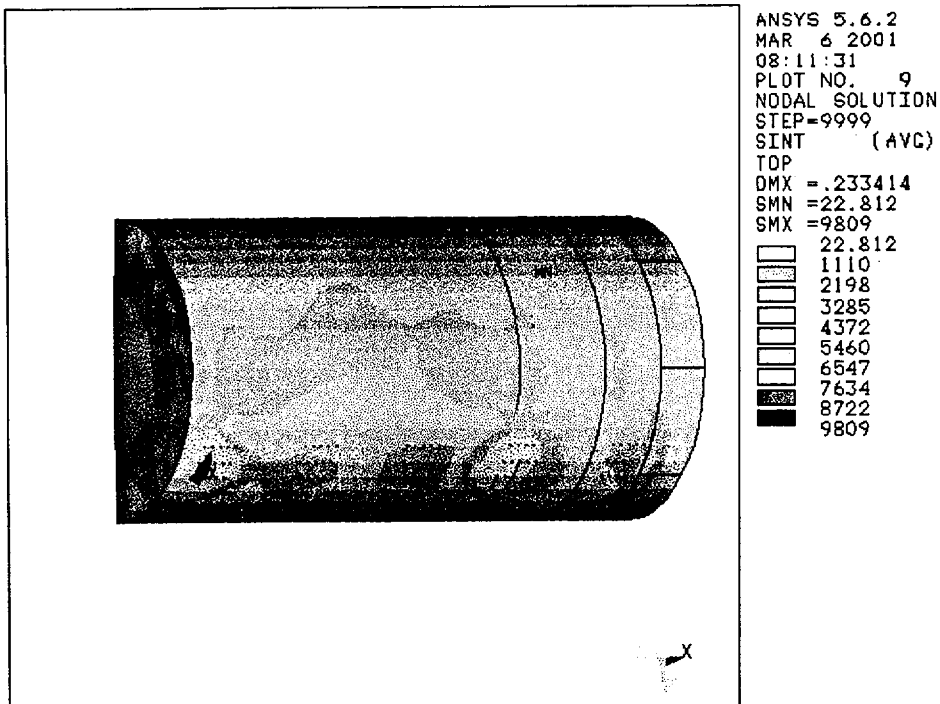


Fig.7.3.5.1 Max P, Hot, Vertical Shock, Pm+Pb+Q Stress

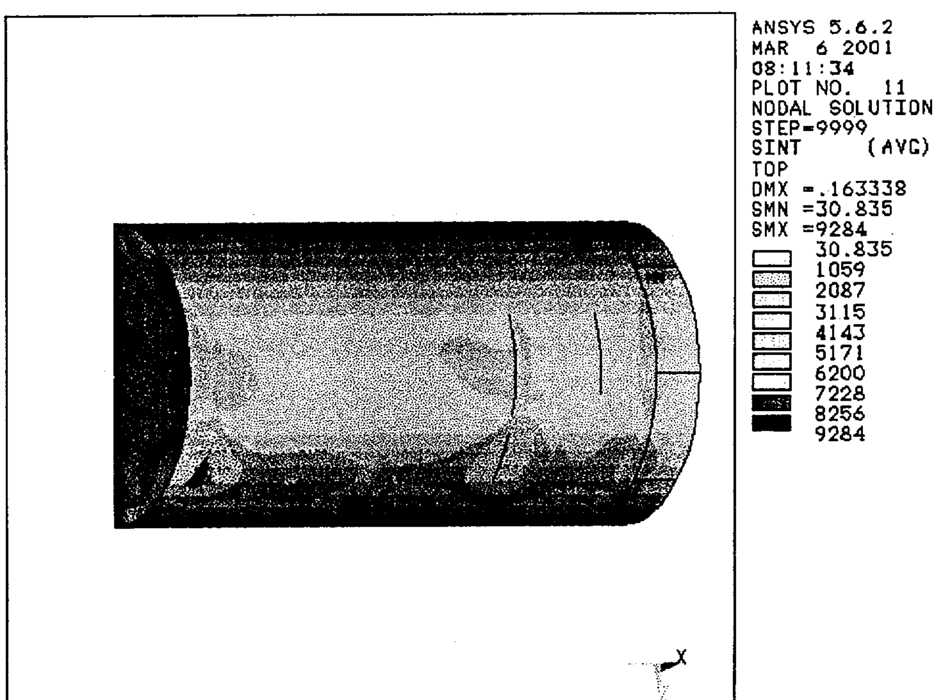


Fig.7.3.5.2 Min P, Cold, Vertical Shock, Pm+Pb+Q Stress

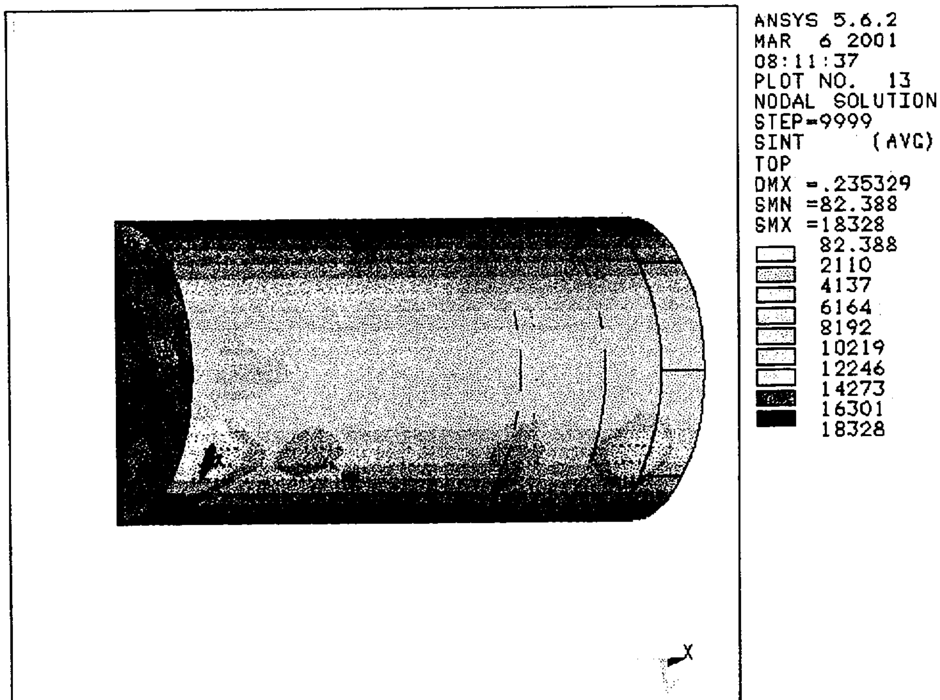


Fig.7.3.5.3 Max P, Hot, Lateral Shock, Pm+Pb+Q Stress

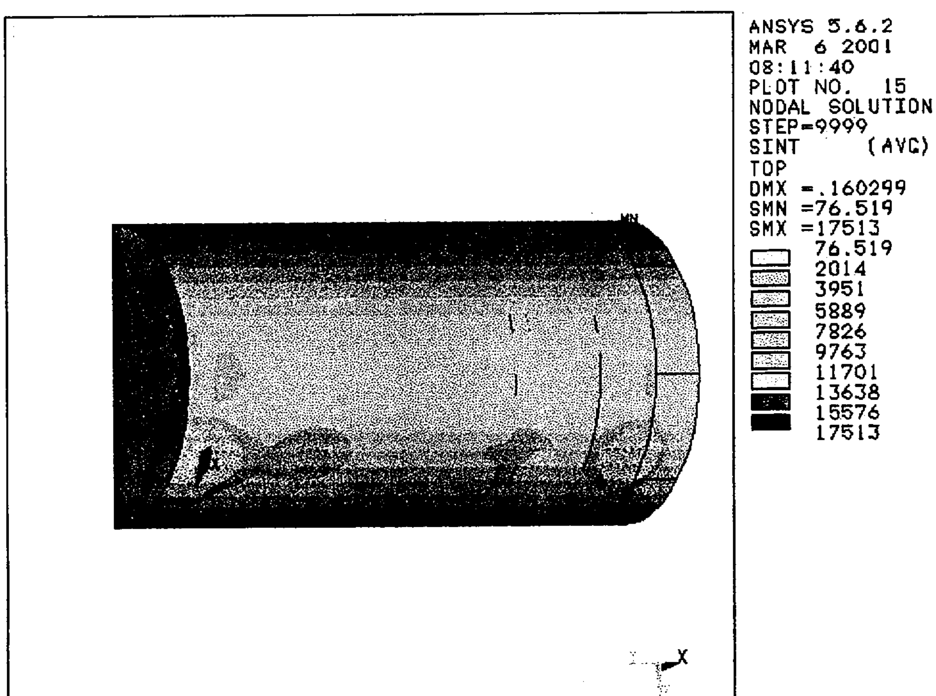


Fig.7.3.5.4 Min P, Cold, Lateral Shock, Pm+Pb+Q Stress

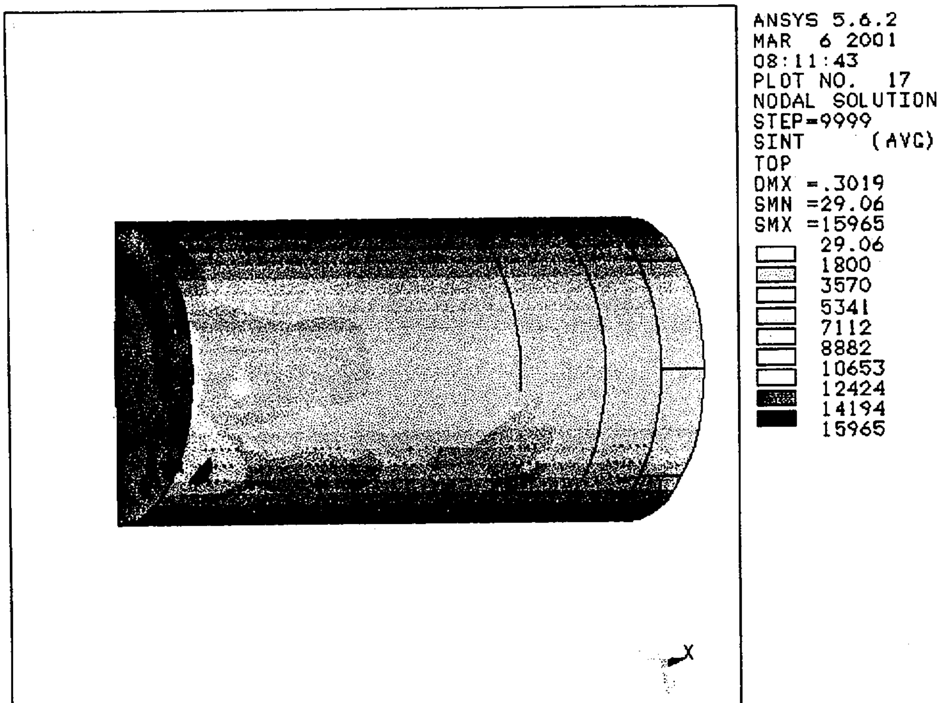


Fig.7.3.5.5 Max P, Hot, Longitudinal Shook, Pm+Pb+Q Stress

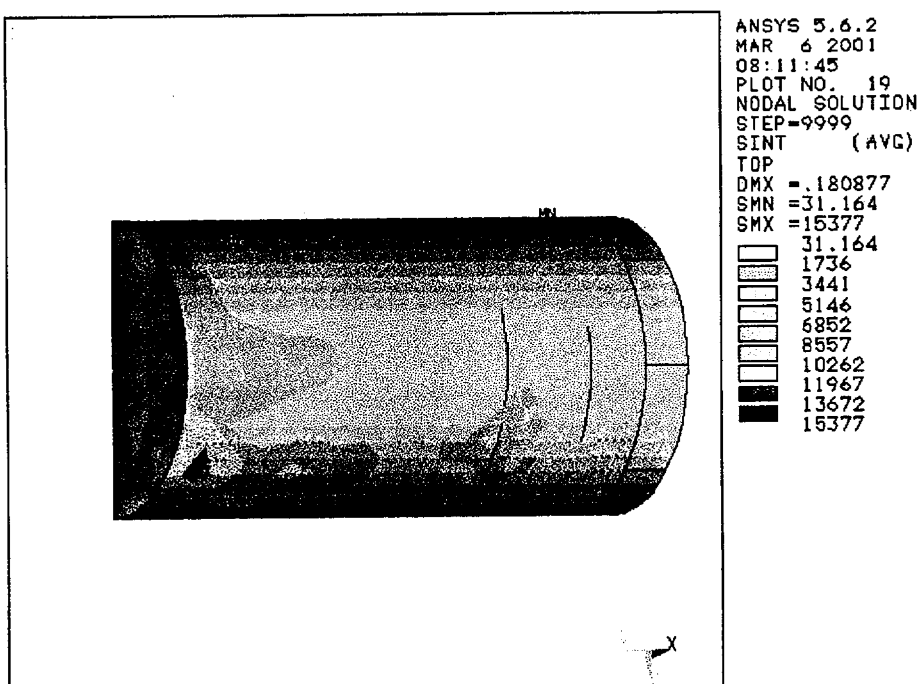


Fig.7.3.5.6 Min P, Cold, Longitudinal Shook, Pm+Pb+Q Stress

Sargent & Lundy	Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
	● Important to Safety Category A	Non-Safety-Related	Rev. 0	Date:
			Page	48

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

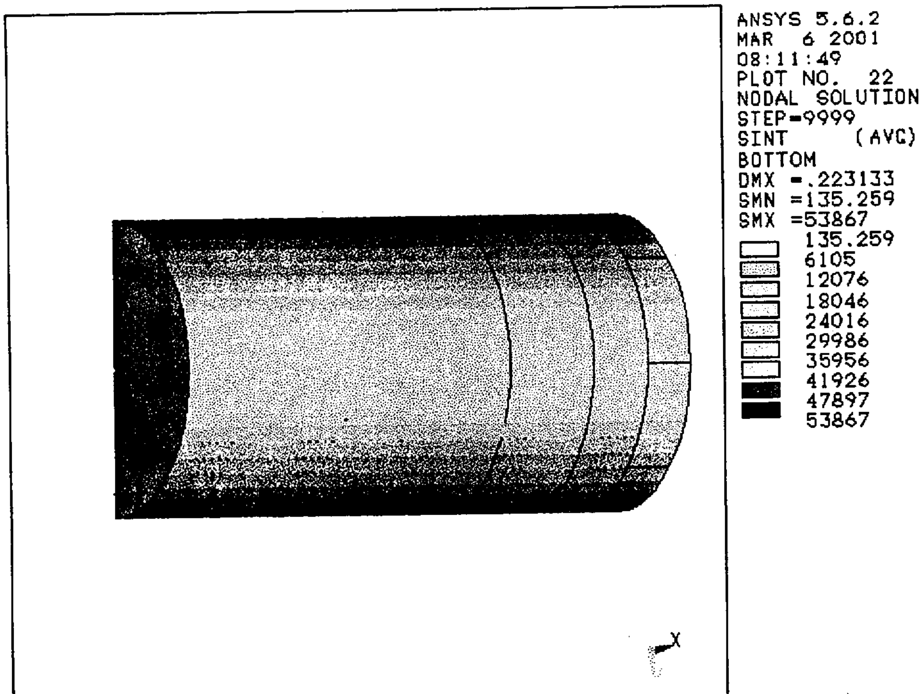


Fig.7.3.7.1 1' Horizontal Drop, Hot, Max Pressure, Pm+Pb+Q Stress

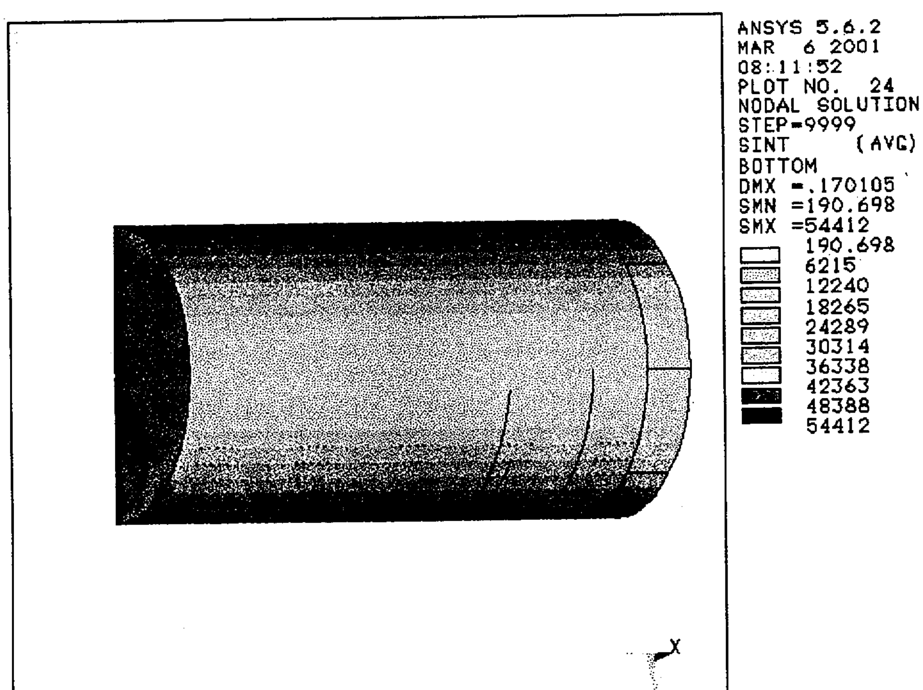


Fig.7.3.7.2 1' Horizontal Drop, Cold, Min Pressure, Pm+Pb+Q Stress

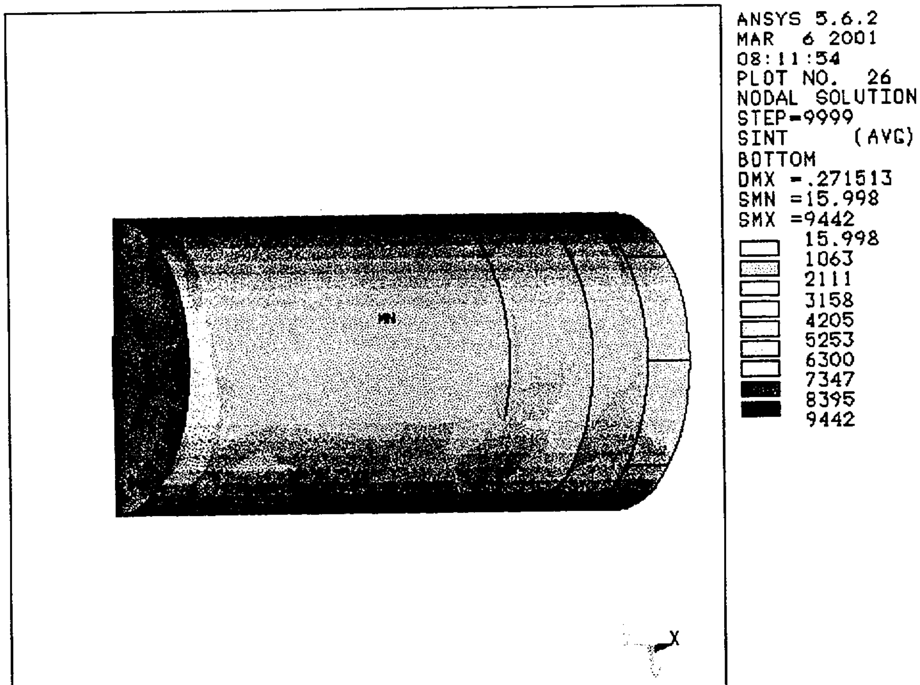


Fig.7.3.8.1 Test Pressure Primary Plus Secondary Stress (Hot Condition)

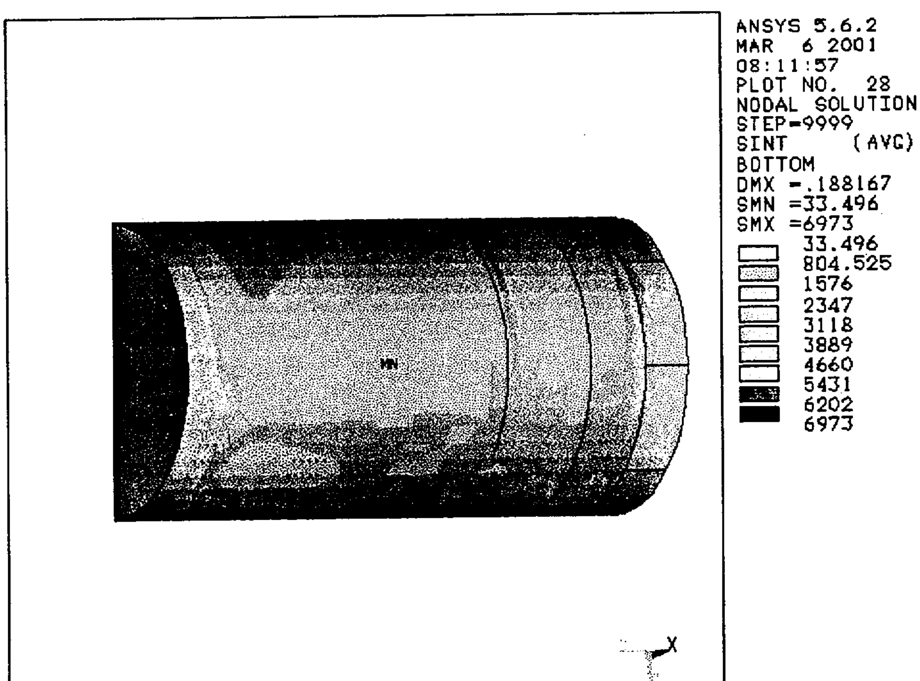


Fig.7.3.8.2 Test Pressure Primary Plus Secondary Stress (Cold Condition)

7.4 Handling Accident Conditions

As discussed in Section 4.2, the RVTS is evaluated for several handling accident load cases with the following two initial conditions:

- A hot environment with an ambient temperature of 100° F, considering maximum insolation and decay heat along with the corresponding maximum internal pressure (20 psig).
- A cold environment with an ambient temperature of -20° F, considering zero insolation, zero decay heat, and the corresponding minimum internal pressure (-3 psig).

  - I1 = 5' Horizontal Drop with Maximum Internal Pressure
  - I2 = 5' Horizontal Drop with Minimum Internal Pressure
  - I3a = 5' Oblique Drop First Impact with Maximum Internal Pressure
  - I4a = 5' Oblique Drop First Impact with Minimum Internal Pressure
  - I3b = 5' Oblique Drop Second Impact with Maximum Internal Pressure
  - I4b = 5' Oblique Drop Second Impact with Minimum Internal Pressure

These load cases are combined with the corresponding thermal load cases T1 (hot) and T3 (cold) as follows:

- Case A1 = I1 + T1, 5' Horizontal Drop, Hot Environment
- Case A2 = I2 + T3, 5' Horizontal Drop, Cold Environment
- Case A3a = I3a + T1, 5' Oblique Drop First Impact, Hot Environment
- Case A4a = I4a + T3, 5' Oblique Drop First Impact, Cold Environment
- Case A3b = I3b + T1, 5' Oblique Drop Second Impact, Hot Environment
- Case A4b = I4b + T3, 5' Oblique Drop Second Impact, Cold Environment

7.4.1 Free Drop Lumped Parameter Dynamic Model for Five-Foot Drop Analysis

The lumped parameter dynamic analysis methodology per NUREG/CR –3966, Ref. 3.16.2, is employed to calculate the maximum dynamic responses in the cask 5-foot free drop analysis. The RVTS Cask lumped parameter model consists of a beam, representing the cask and the RV, and three additional lumped masses that model the end plates, RV flange, donut support and RV internals. A detailed description and calculation for the lumped parameter model is provided in Attachment D.

ANSYS dynamic transient, large deflection analysis is used to calculate the responses of the lumped parameter model when it drops onto a flat, concrete surface from a height of 5 feet. In this analysis, the flat, essentially unyielding, horizontal surface is considered to be an infinitely thick concrete foundation with a maximum compressive strength of 4000 psi.

Roark's "Formulas for Stress and Strain", Ref. 3.9, is used to establish a contact load deflection curve for a cylinder on a flat surface. The calculation of this non-linear contact spring is documented in Attachment C of this analysis. The contact spring is then uniformly distributed at the contact nodes along the lumped parameter beam model. The contact between the beam nodes and the spring nodes is modeled using contact elements with the initial gap equal to the drop height (60 inches). The model for horizontal drop is shown in Figure 7.4.1.1. A pin support is initially modeled at both ends of the beam. Both pin supports are then released to initiate the horizontal drop analysis. The vertical displacement and acceleration time histories of the horizontal drop are provided in Figure 7.4.1.3. The peak vertical acceleration is 27g.

The model for the oblique drop is shown in Figure 7.4.1.2. The oblique model has the spring nodes shifted and rotated such that the spring support is located at the position where the cask strikes the ground in the normal direction of the contact elements. For the oblique drop analysis, the pin support at one end is released while the other end remains pinned. After the first impact is complete, the remaining pin support is released to initiate the second impact. Large deformation analysis is considered to capture the effect of rigid body motion and rotation. The vertical and horizontal displacement and acceleration time histories of the oblique drop are provided in Figures 7.4.1.4a and 7.4.1.4b. The mean vertical and horizontal acceleration time histories at the cask CG are shown in Figure 7.4.1.4c. The rotational acceleration time history is shown in Figure 7.4.1.4d. At the first impact of the oblique drop, the peak vertical and horizontal accelerations at the cask CG are 8.2g and 3.4g, respectively. The maximum rotational acceleration of the first impact is 44 rad/s^2. At the second impact of the oblique drop, the peak vertical and horizontal accelerations at the cask CG are 7.6g and 3.2g, respectively. The maximum rotational acceleration of the second impact is 48 rad/s^2.

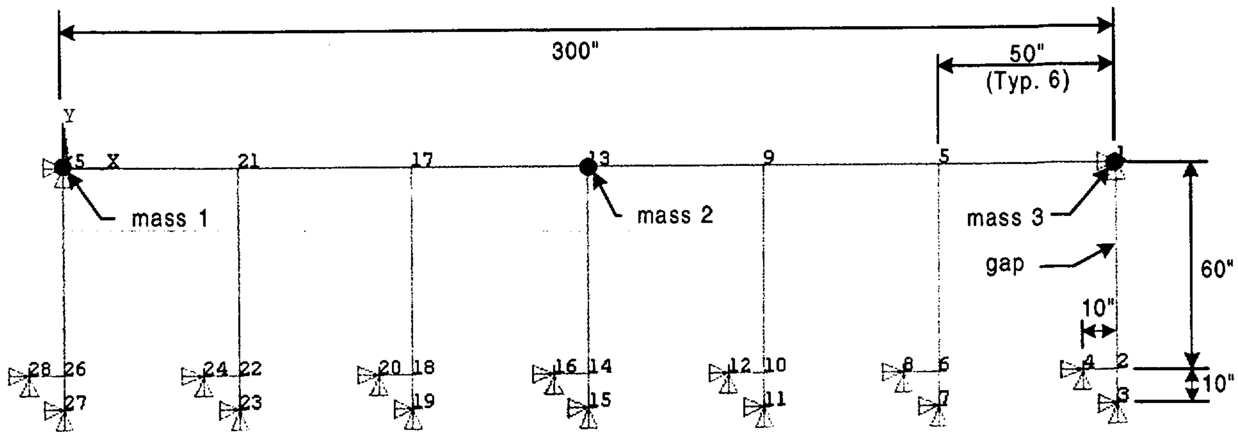


Figure 7.4.1.1: Horizontal Drop Beam Model

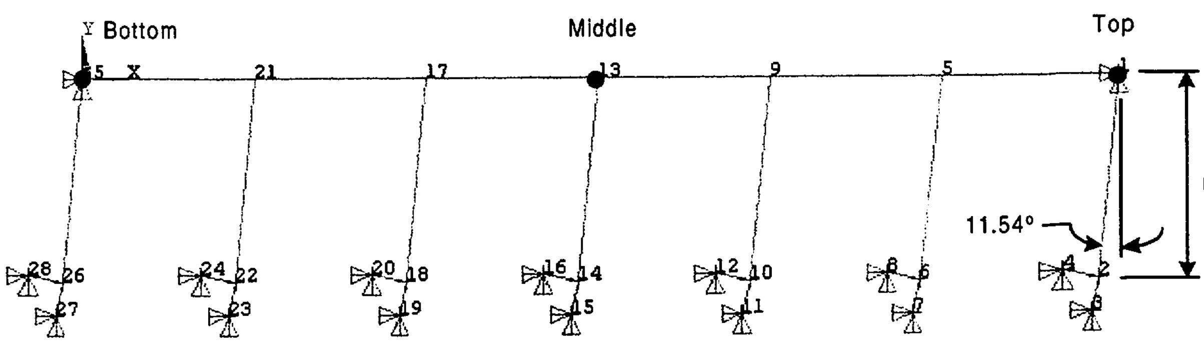


Figure 7.4.1.2: Oblique Drop Beam Model

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
		Rev. 0	Date:
● Important to Safety Category A	Non-Safety-Related	Page	53

Sargent & Lundy

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

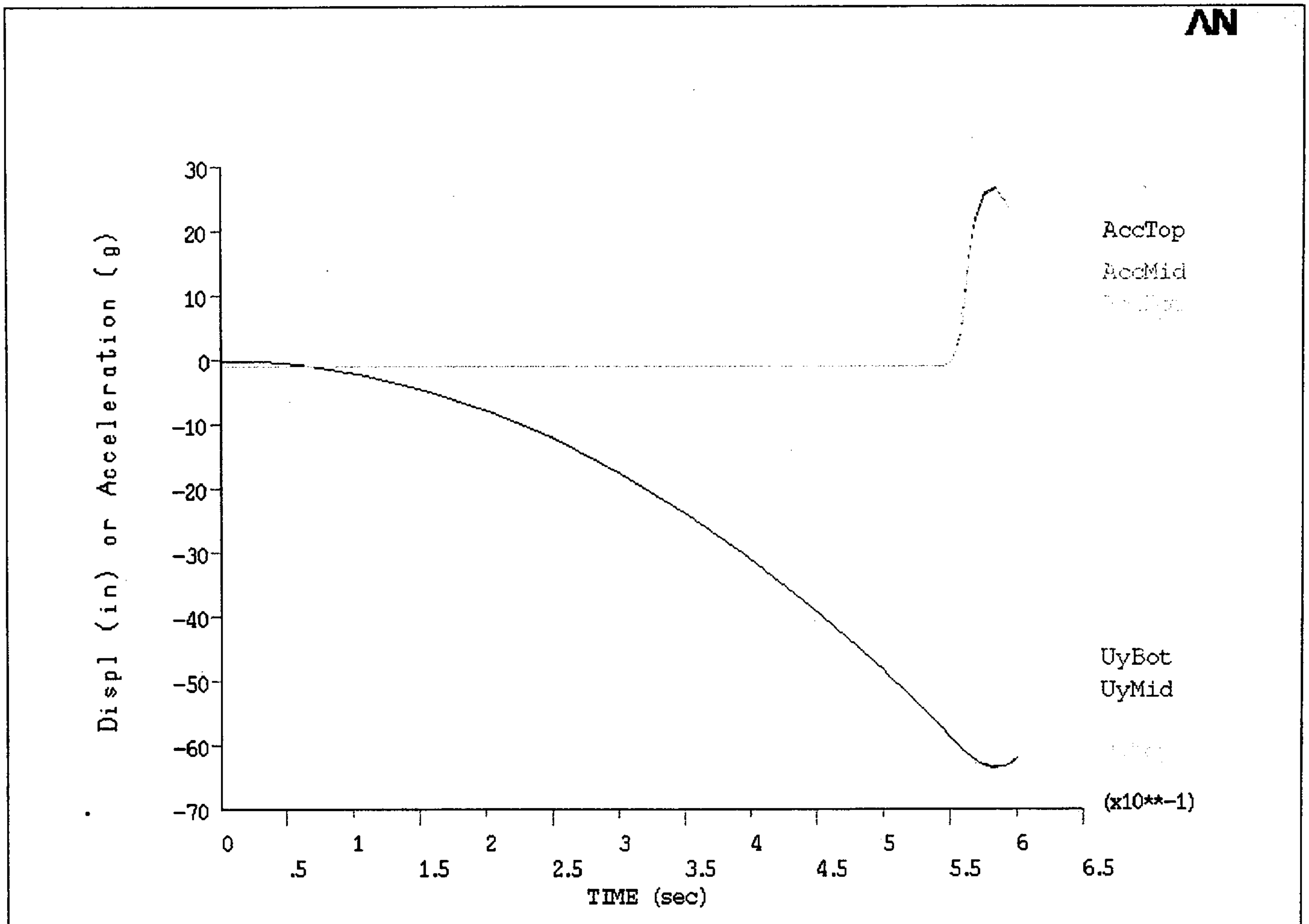


Figure 7.4.1.3 5' Horizontal Drop Displacement and Acceleration

Sargent & Lundy

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
		Rev. 0	Date:
● Important to Safety Category A	Non-Safety-Related	Page	54

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

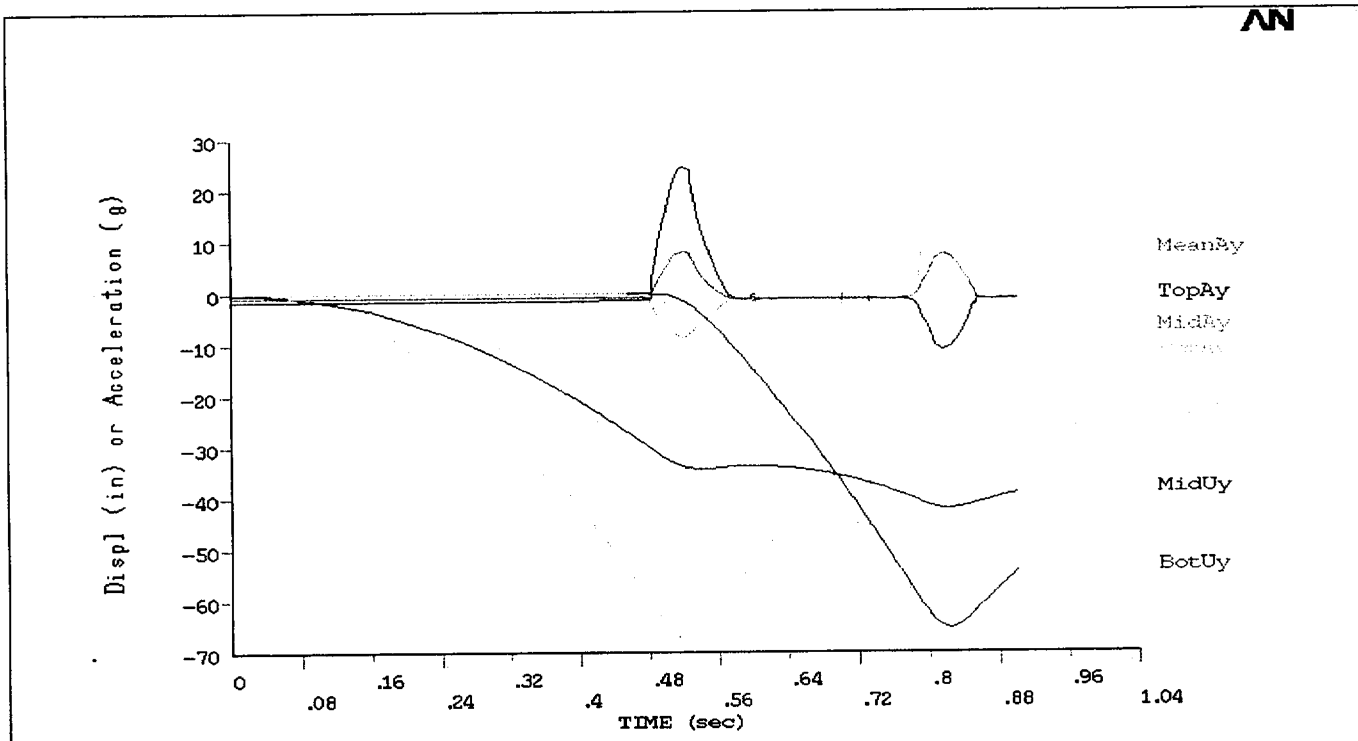


Figure 7.4.1.4a 5' Oblique Drop Vertical Displacement and Acceleration

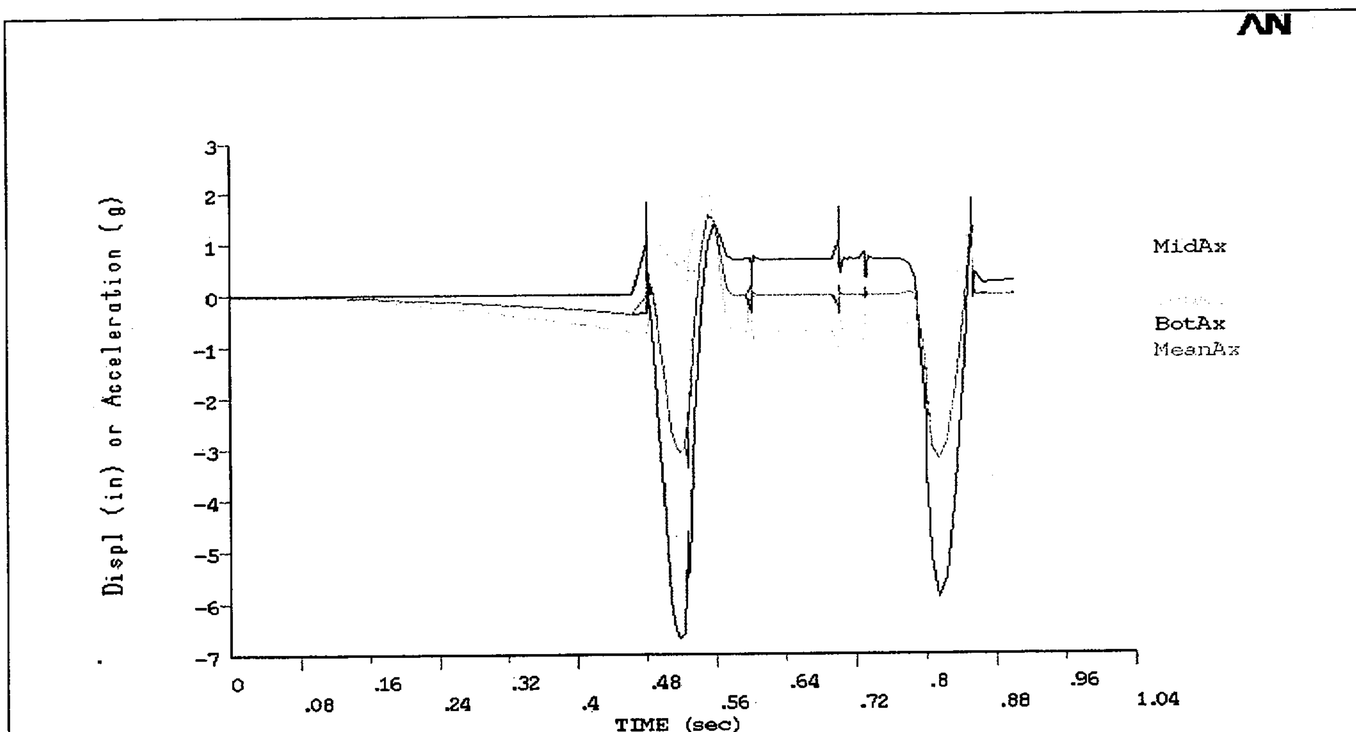


Figure 7.4.1.4b 5' Oblique Drop Horizontal Displacement and Acceleration

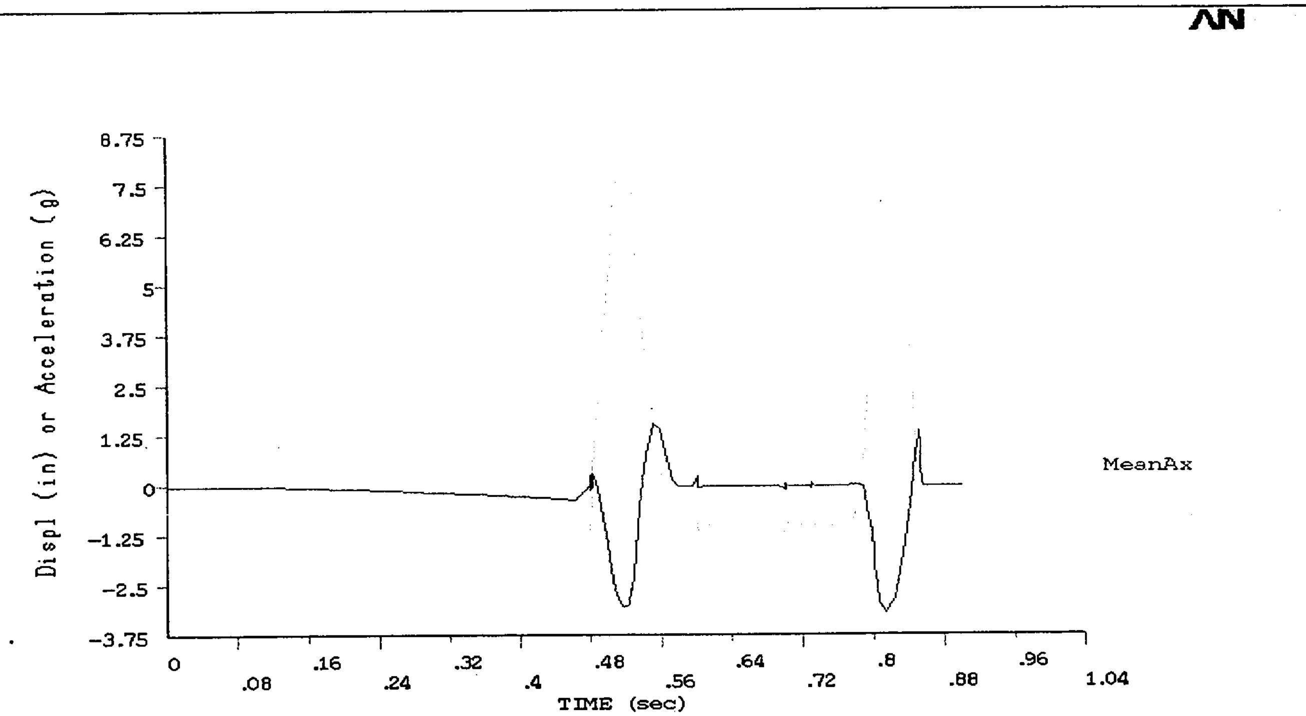


Figure 7.4.1.4c 5' Oblique Drop Mean Vertical and Horizontal Acceleration

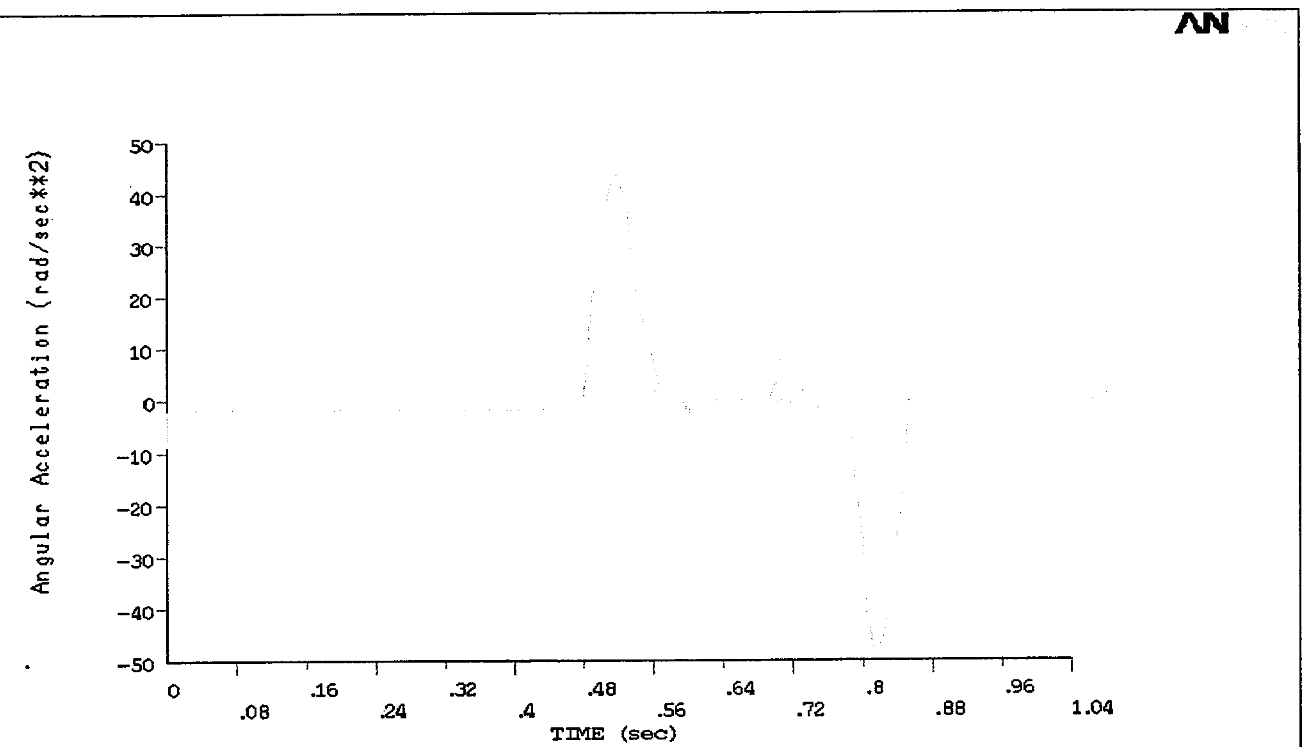


Figure 7.4.1.4d 5' Oblique Drop Angular Acceleration

7.4.2 Five-foot Free Drop Stress Analyses

The peak impact accelerations in both the vertical and horizontal directions are applied to the RVTS three-dimensional finite element model for stress recovery and structural buckling analyses. Since the lumped parameter dynamic analysis captures the maximum structural dynamic responses and the effects of free body motion and rotation, no dynamic load factor is applied in the stress recovery analyses. Due to loading and geometric symmetry, only a half model of the cask is used. The RV bottom radial support at the donut ring are activated. Rigid supports are modeled for nodes that contact with the flat horizontal surface. The large deformation analysis option is used to check buckling of the RVTS Cask shell.

An impact acceleration of 27g is applied in the vertical direction for the horizontal drop analysis for both the maximum and minimum internal pressure conditions. These analyses are labeled as I1, I2 and are combined with thermal load cases T1 (hot) and T3 (cold) to form the accident condition load cases A1 and A2, respectively. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm and Pm+ Pb, for load cases A1 and A2, are summarized in Table 7.4.1. Figures 7.4.2.1 and 7.4.2.2 show the stress contours of the Pm+Pb+Q stress intensity for load cases A1 and A2, respectively.

For the oblique drop analyses, the model is kept the same in the global coordinates, but the impact surface and the impact acceleration directions are rotated an angle of 11.54 degrees (arcsin of 60/300). Pin supports are modeled at the flat surface contact nodes of the top and the bottom plates. For the oblique drop first impact analysis, the top plate strikes the horizontal surface with an impact of 8.2g in the vertical direction and 3.4 g in the horizontal direction. The angular acceleration is 44 rad/s^2, and the center of the angular acceleration is the pin support at the cask bottom plate. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm and Pm+ Pb, for load cases A3a and A4a, are summarized in Table 7.4.1. Figures 7.4.2.3a and 7.4.2.4a show the stress contours of the Pm+Pb+Q stress intensity for load cases A3a and A4a, respectively.

For the oblique drop second impact analysis, the bottom plate strikes the horizontal surface with an impact of 7.6g in the vertical direction and 3.2 g in the horizontal direction. The angular acceleration is 48 rad/s^2, and the center of the angular acceleration is the pin support at the cask top plate. The 20 highest stress intensity values are shown in Attachment H. The stress intensity Pm and Pm+ Pb, for load cases A3b and A4b, are summarized in Table 7.4.1. Figures 7.4.2.3b and 7.4.2.4b show the stress contours of the Pm+Pb+Q stress intensity for load cases A3b and A4b, respectively.

The local stress occurring directly on the flat end plates of the impact contact area is considered secondary stress. Yielding due to high local bearing stress will increase the contact area, thus, reducing the average bearing stress. Therefore, the local stress intensity directly at the contact area will be checked under the provisions of the Regulatory Position No. 7, Reg. Guide 7.6, for the extreme total stress range. The extreme handling accident stress intensity range of the RVTS is shown in Table 7.4.2.

For both the horizontal and the oblique drop analyses, the cask remains stable. No buckling occurs as indicated by the convergence of the solution under the impact load.

Table 7.4.1 Stress Intensity Summary for Handling Accident Conditions

Handling Accident Conditions		Load Case No.	Primary Membrane Stress Intensity(*)			Primary Membrane plus Bending Stress Intensity (*)			
			Node No.	Pm ksi	Lesser of 2.4Sm Or 0.7Su ksi	Node No.	Pm+Pb ksi	Lesser of 3.6Sm Or Su ksi	Minimum Stress Margin
5 Ft Horizontal Drop	Hot	A1	3853	42.81	49	3853	43.88	70	1.14
	Cold	A2	3853	42.75	49	3853	43.79	70	1.15
5 Ft First Oblique Drop	Hot	A3a	1117	30.99	49	968	53.58	70	1.31
	Cold	A4a	1117	31.00	49	968	51.68	70	1.35
5 Ft Second Oblique Drop	Hot	A3b	3802	46.99	49	3802	46.99	70	1.04
	Cold	A4b	3802	45.12	49	3802	45.12	70	1.09

(*) Maximum stress intensity at the maximum principal stress locations.

Pm+Pb stress intensity at the maximum compression stress due to impact contact stress is bearing stress, and is evaluated in the extreme alternating stress range.

The results of four extreme alternating stress ranges are as follows:

Table 7.4.2 Extreme Stress Intensity Range for Handling Accident Conditions

Load Range (I - J)	Load Case I	Load Case J	Node No.	2 x Alternating Stress $2S_{alt}$ (ksi)	Half Peak Stress Intensity (*) KS_{alt} (ksi)	Allowable Stress Sa ksi	Stress Margin
F6	5 Ft Horizontal Drop, hot, Pmax, (A1)	Cold –40 °F, (N2)	1073	121.90	243.80	580	2.38
F7	5 Ft Horizontal Drop, cold, Pmin (A2)	Hot 100 °F, (N1)	1073	119.14	238.28	580	2.43
F8	5 Ft Horizontal Drop, hot, Pmax, (A1)	Longitudinal Shock, Cold, (N10)	1073	114.59	229.18	580	2.53
F9	5 Ft Horizontal Drop, hot, Pmax, (A1)	Zero Stress State	1073	123.24	246.48	580	2.35

Note: 1. (*) Conservatively include a peak stress index of K = 4.
2. Table 7.4.2 is also applicable for NCT cases since stresses resulted from Handling Accident Conditions envelope stresses from NCT and the allowable stress Sa is the same for both conditions.

7.4.3 Fillet Weld Evaluation

For evaluating the adequacy of the fillet weld sizes between:

1. Shield Plate and Cask Shell, and
2. Reinforced Ring Plate and Cask Shell,

the resultant stresses acting on the subject welds are calculated and then compared to the allowable weld stress. By inspecting the stress level summarized in Table 7.4.1, the loads from load case A1 (Horizontal, Hot), A4a (Oblique Drop First Impact, Cold) and A3b (Oblique Drop Second Impact, Hot) are chosen as the governing load cases for evaluation. The physical properties of the welds are listed as follows:

Location, i	Weld Size, Wi (inch)	Weld Length, Li (inch)	Number of Weld, Ni
Shielding Plate, A	1	75 * 3.1416 = 235.62	2
Reinforced Ring Plate, B	1	75 * 3.1416 = 235.62	2

The resultant stresses in the welds are calculated as follows:

$$Sw = \frac{\sqrt{(Fx^2 + Fy^2 + Fz^2)}}{0.707 * Wi * Li * Ni}$$

where Fx is the axial force and Fy and Fz are the shear forces in the local cylindrical coordinate and obtained from ANSYS output (Weld1.out) documented in Attachment H.

Table 7.4.3 Fillet Weld Check for NCT/Handling Accident Condition

Location	Load case	Fx (lbs)	Fy (lbs)	Fz (lbs)	Sw (psi)
Shield Plate	A1	18,723	986,330	173	2,961
	A4a	6,572	767,910	174,000	2,363
	A3b	62,215	782,570	276,090	2,497
Reinforced Ring Plate	A1	19,567	290,940	188	1,750
	A4a	7,240	143,980	54,769	925
	A3b	57,259	354,990	86,774	2,220

Since all calculated weld stresses as shown in Table 7.4.3 are below the NCT stress allowable of 0.3*70,000 = 21,000 psi, the aforementioned weld sizes are adequate for all NCT and Handling Accident Condition loadings.

7.4.4 RV Flange Stud and Nut Evaluation

The RV flange stud and nut evaluation for handling accident events is documented in the Attachment F of this report. The maximum stresses in the bolts are:

Criteria	Stress (psi)	Allowable Stress (psi)
Tensile Stress	39,580	70,000
Shear Stress	28,920	42,000
Interaction Ratio	0.79	1

The nut minimum engagement length is 6 inches such that threads are sufficient to carry the full load necessary to break the bolt without stripping the threads

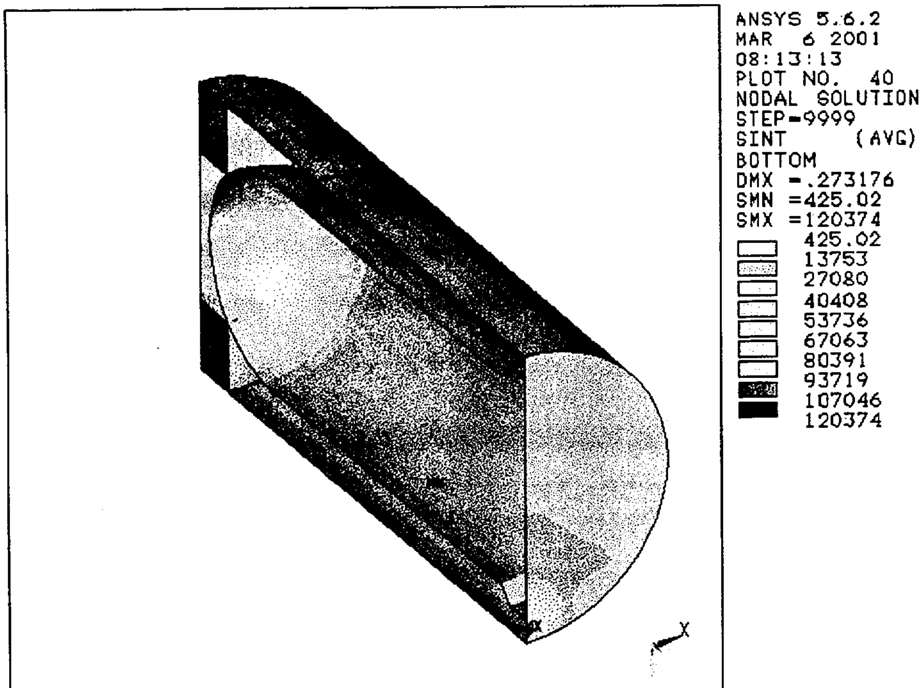


Fig.7.4.2.1 5' Horizontal Drop, Hot, Max Pressure, Pm+Pb+Q Stress

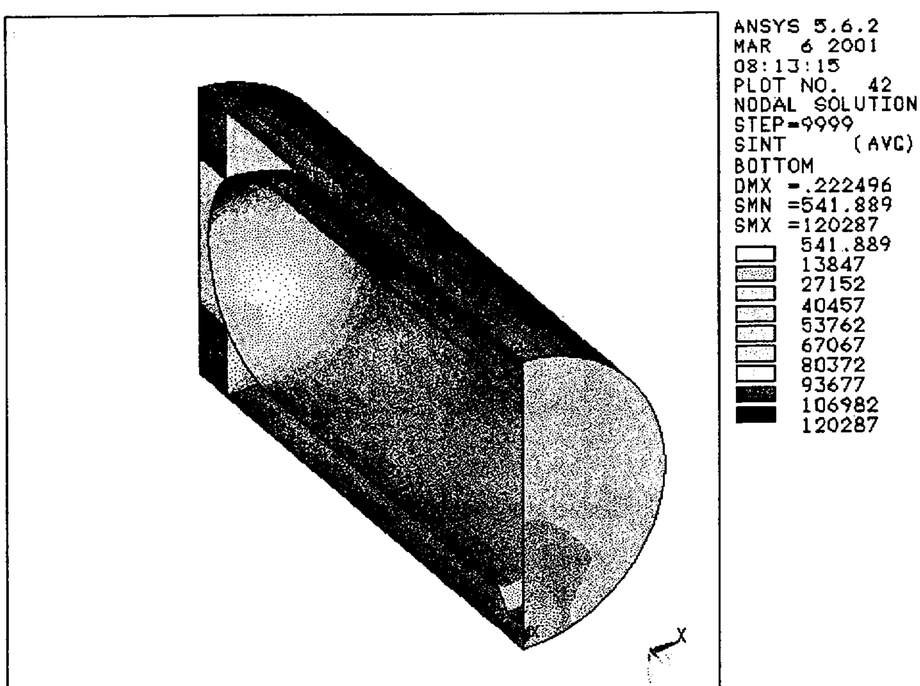


Fig.7.4.2.2 5' Horizontal Drop, Cold, Min Pressure Pm+Pb+Q Stress

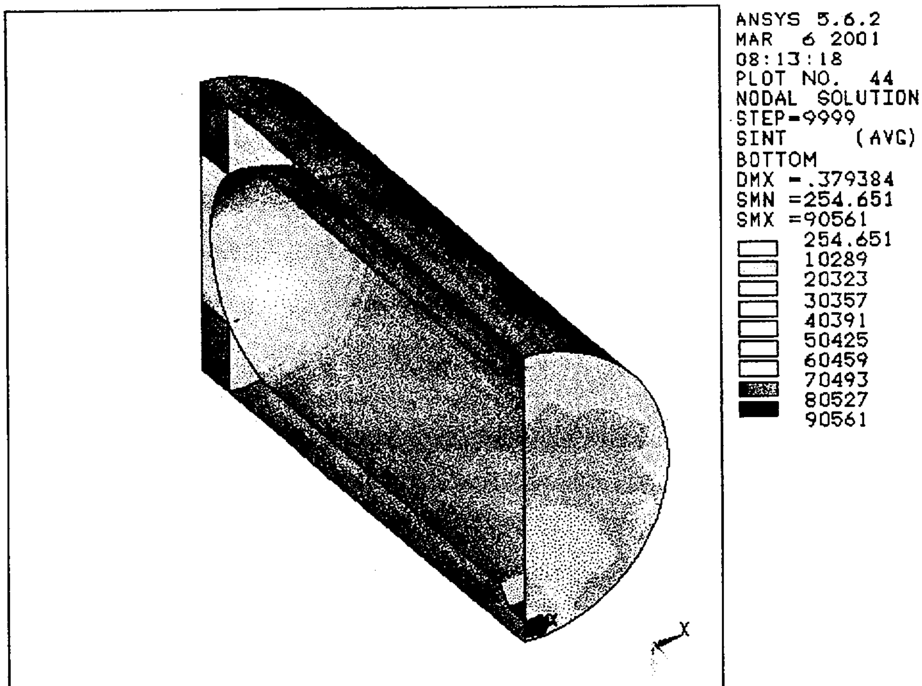


Fig.7.4.2.3a 5' Oblique First Drop, Hot, Max Pressure Pm+Pb+Q Stress

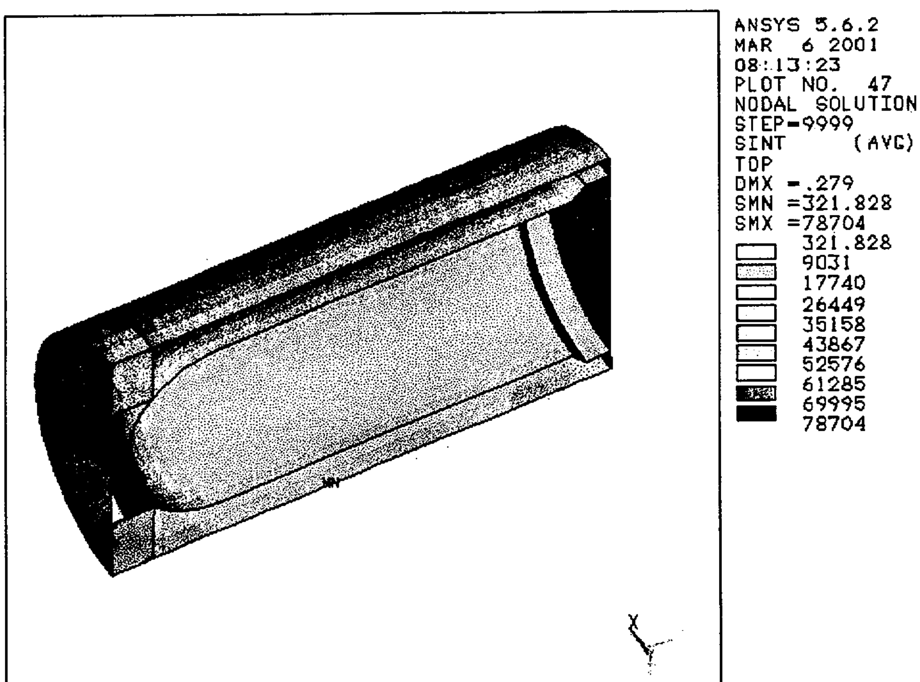


Fig.7.4.2.3b 5' Oblique Second Drop, Hot, Max Pressure Pm+Pb+Q Stress

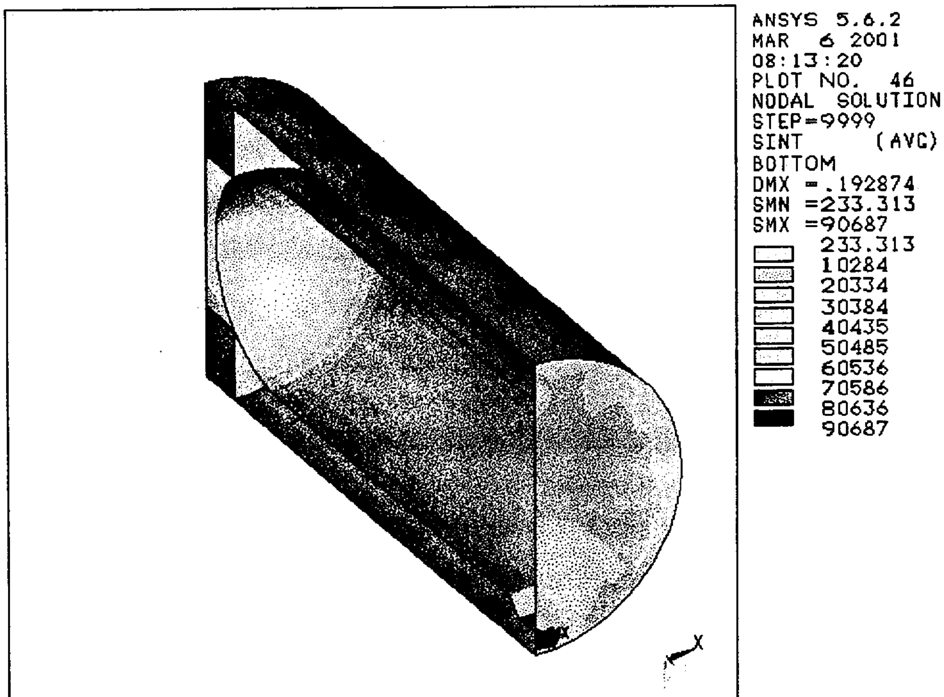


Fig.7.4.2.4a 5' Oblique First Drop, Cold, Min Pressure Pm+Pb+Q Stress

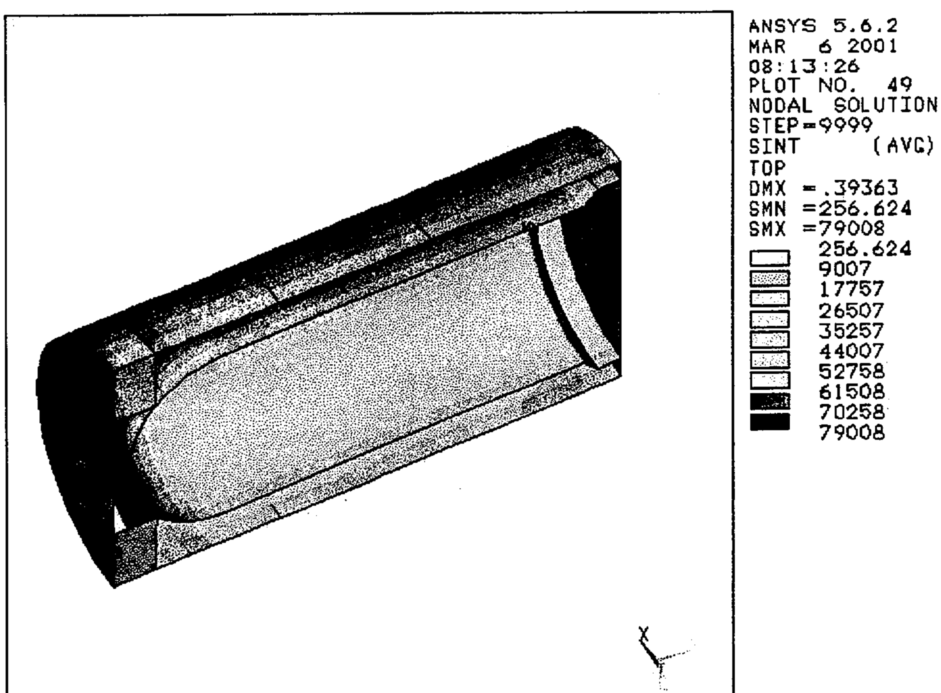


Fig.7.4.2.4b 5' Oblique Second Drop, Cold, Min Pressure Pm+Pb+Q Stress

7.5 Hypothetical Accident Conditions

7.5.1 Thirty-Foot Drop Analyses

As discussed in Section 4.3, the RVTS is evaluated for several hypothetical accident load cases with the following two initial conditions:

- Thermal load case T1, a hot environment with an ambient temperature of 100° F, considering maximum insolation and decay heat along with corresponding maximum internal pressure (20 psig), and
- Thermal load case T3, a cold environment with an ambient temperature of -20° F, considering zero insolation, zero decay heat, and the corresponding minimum internal pressure (-3 psig).

- VD1 = Vertical Drop with Maximum Internal Pressure, Hot Environment
- VD2 = Vertical Drop with Minimum Internal Pressure, Cold Environment
- HD1 = Horizontal Drop with Maximum Internal Pressure, Hot Environment
- HD2 = Horizontal Drop with Minimum Internal Pressure, Cold Environment
- CD1 = Corner CG Drop with Maximum Internal Pressure, Hot Environment
- CD2 = Corner CG Drop with Minimum Internal Pressure, Cold Environment
- FDP11 = Flap-down Drop with Maximum Vertical Velocity, Maximum Internal Pressure, Hot Environment
- FDP12 = Flap-down Drop with Maximum Vertical Velocity, Minimum Internal Pressure, Cold Environment
- FDP21 = Flap-down Drop with Maximum Horizontal Velocity, Maximum Internal Pressure, Hot Environment
- FDP22 = Flap-down Drop with Maximum Horizontal Velocity, Minimum Internal Pressure, Cold Environment

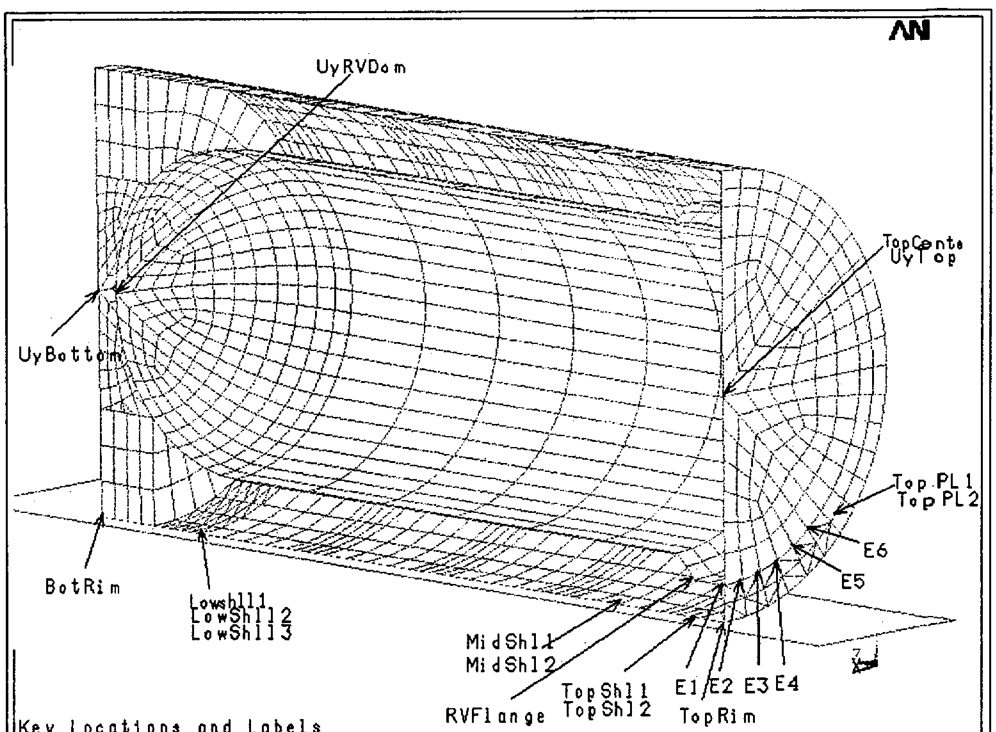


Figure 7.5.1: Key Locations of the RVTS Analysis Output

7.5.1.1 Vertical Drop on the Cask Bottom Plate (Cases VD1 and VD2)

The initial conditions for the VD analyses include nodal temperatures from thermal load cases T1 and T3, pressures of 20 psi and –3 psi as described in 10 CFR 71, and an initial vertical impact velocity of 527.4 in/sec, which is the impact velocity of a 30-feet drop. Contact between the bottom plate and the essentially unyielding, horizontal surface are modeled along with the contact between the RV head and the bottom plate. The output files, VDP1Weld.out and VDP2Weld.out, are documented in Appendix H. The RV bottom head reaches its maximum vertical displacement of -4.314 inches (Figure 7.5.1.1a for VD1) and contacts the bottom plate. The maximum displacement at the center of top plate is - 10.06inches (Figure 7.5.1.1b for VD2). The expected high stress locations are at the center of the top plate, the top plate rim and the lower shell junction to the donut plate. The maximum principal stress time histories at these locations are shown in Figures 7.5.1.1c and 7.5.1.1d. During the impact duration, the peak value of the maximum principal stress is S1 =50 ksi at time T = 0.005312 second, case VD2. This is less than the material tensile strength of 70 ksi. Typical S1 stress contours are shown in Figure 7.5.1.1e. The cask gross structure remains intact after the impact. Therefore, no containment failure and no gross buckling failure in the RVTS cask result from the 30-foot vertical drop. The maximum bolt stress intensity is 93.7 ksi which is less than Su =100 ksi. Typical S1 stress contours are shown in Figure 7.5.1.1.e. The maximum vertical and horizontal displacements are shown in the following figures:

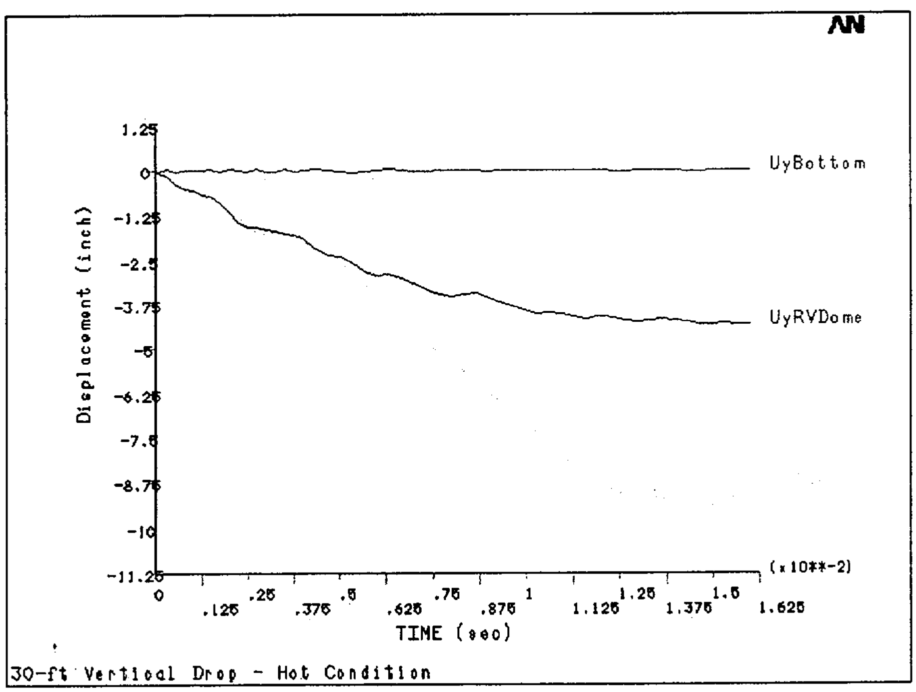


Figure 7.5.1.1a : VD1 Vertical Displacement Time History

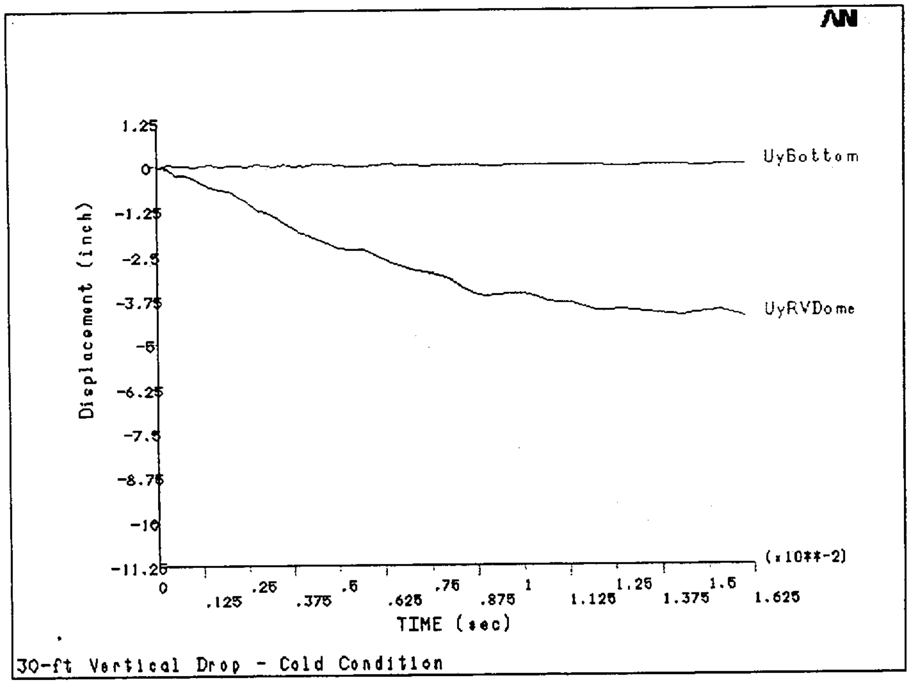


Figure 7.5.1.1b : VD2 Vertical Displacement Time History

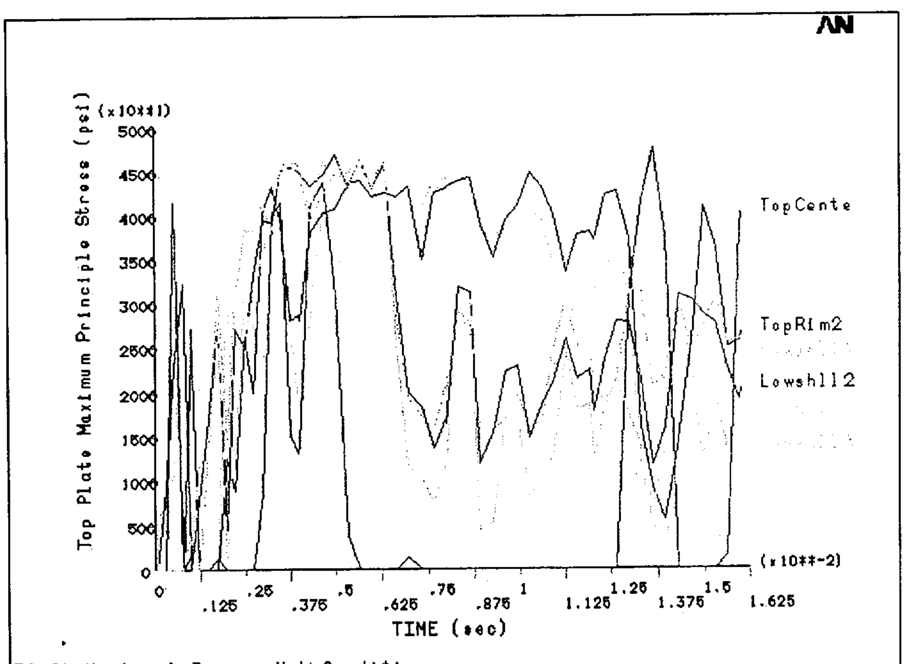


Figure 7.5.1.1c : VD1 Maximum Principal StressTime History

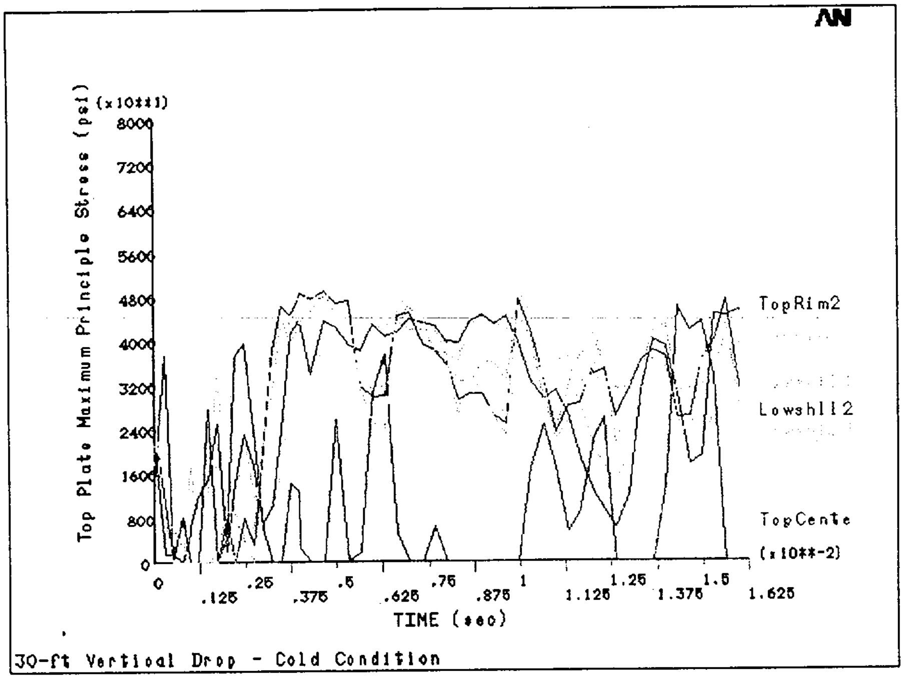


Figure 7.5.1.1d : VD2 Maximum Principal StressTime History

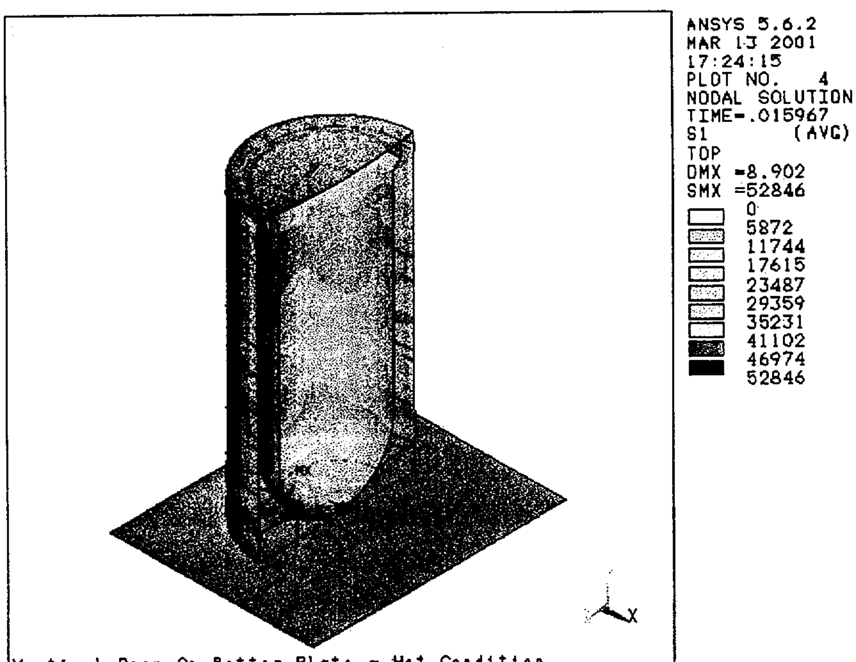


Figure 7.5.1.1e : VD1 Maximum Principal Stress Contours

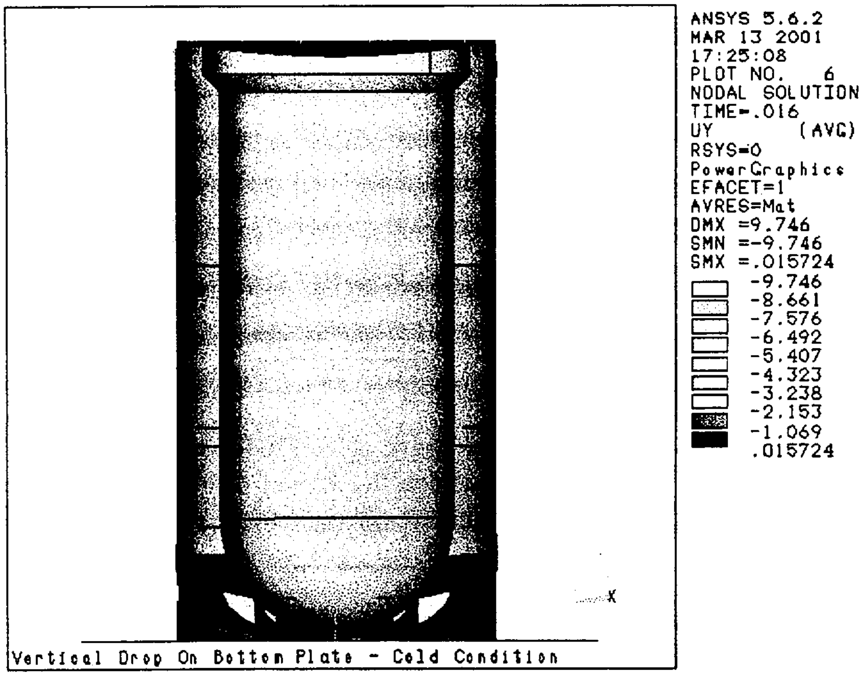


Figure 7.5.1.1f : VD2 Vertical Displacement Contours

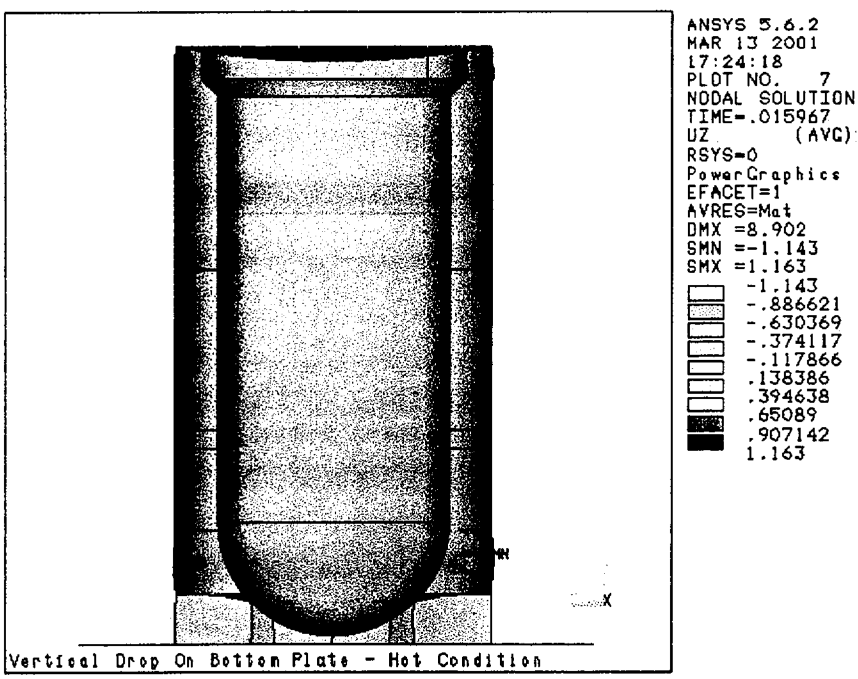


Figure 7.5.1.1g: VD1 Horizontal Displacement Contours

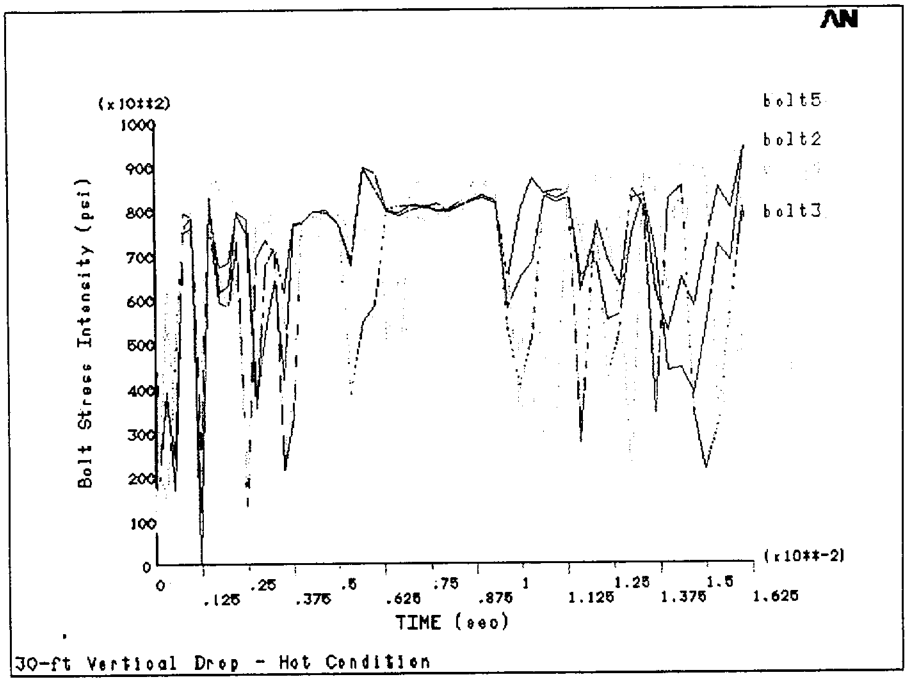


Figure 7.5.1.1h: VD1 Bolt Stress Intensity Time History

7.5.1.2 Horizontal Drop (Cases HD1 and HD2)

The initial conditions for the HD analyses include nodal temperatures from thermal load cases T1 and T3, pressures of 20 psi and –3 psi as described in 10 CFR 71, and an initial vertical impact velocity of 527.4 in/sec, which is the impact velocity of a 30-foot drop. Contact between the cask shell and the essentially unyielding, horizontal surface is modeled along with the contact between the RV flange and the cask shell. The center of top plate reaches its maximum vertical displacement of -6.878 inches at time 0.01995 second (Figure 7.5.1.2b – Case HD2). The maximum principal stress time histories at the top plate rim near the impact location are shown in Figures 7.5.1.2c and 7.5.1.2d. During the impact duration, the peak value of the maximum principal stress is S1 = 67.95 ksi at time 0.01843 second, case HD1. This is less than the material tensile strength of 70 ksi. The cask gross structure remains intact after the impact. Therefore, no containment failure and no gross buckling failure in the RVTS cask result from the 30-foot horizontal drop. The maximum bolt stress intensity is 91.85 ksi which is less than Su =100 ksi. Typical results at the time when the RV head reaches peak vertical displacement are shown in the following figures:

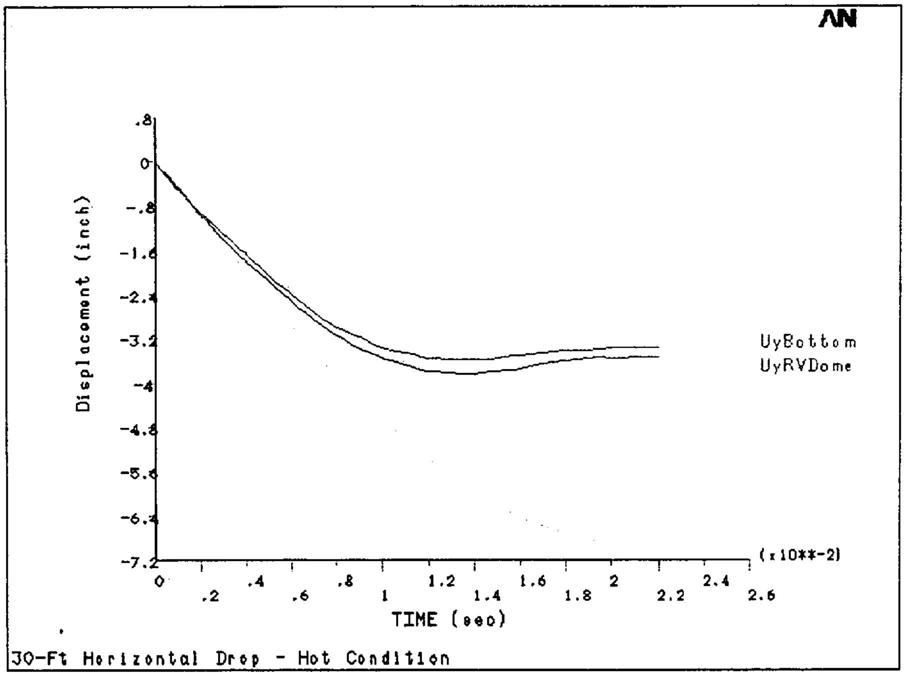


Figure 7.5.1.2a: HD1 Vertical Displacement Time History

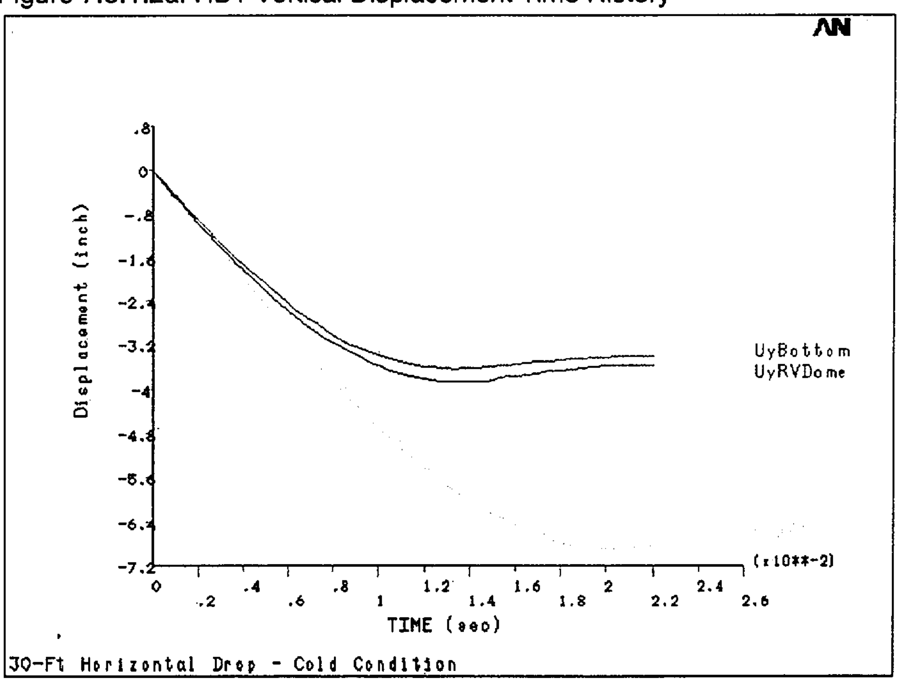


Figure 7.5.1.2b: HD2 Vertical Displacement Time History

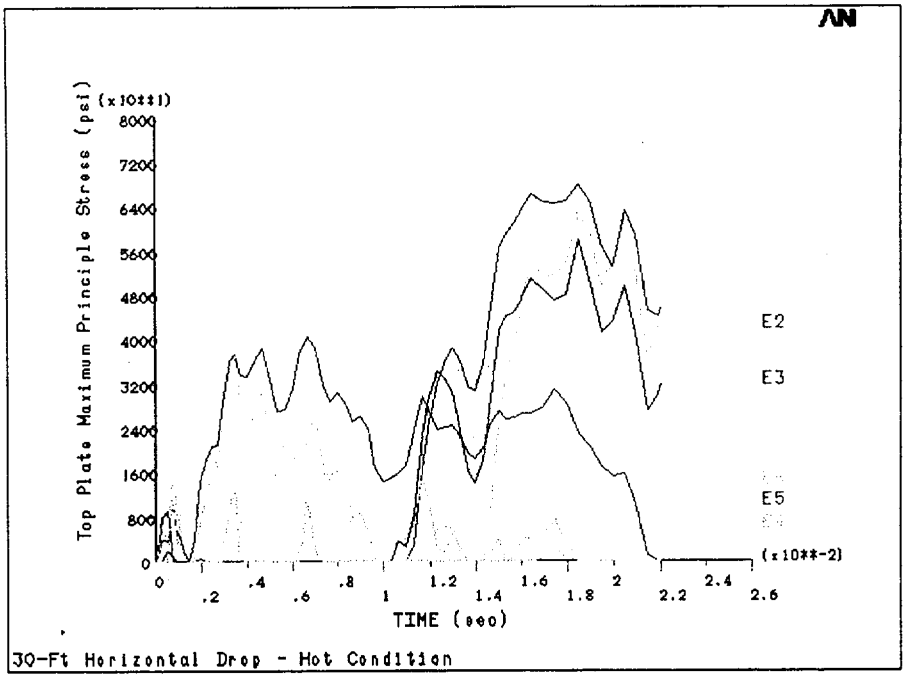


Figure 7.5.1.2c: HD1 Top Plate Maximum Principal Stress Time History

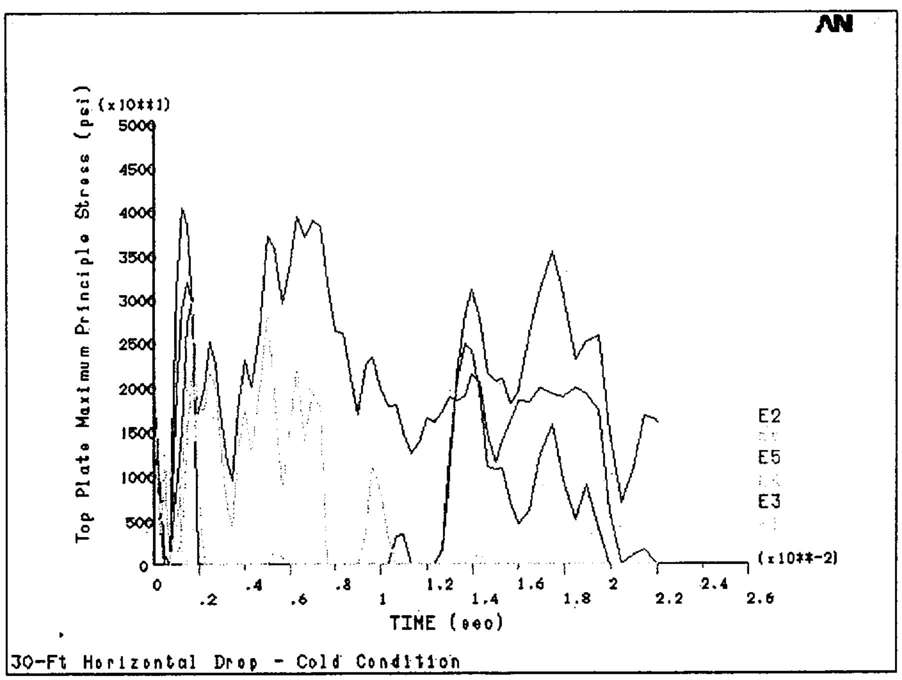


Figure 7.5.1.2d: HD2 Top Plate Maximum Principal Stress Time History

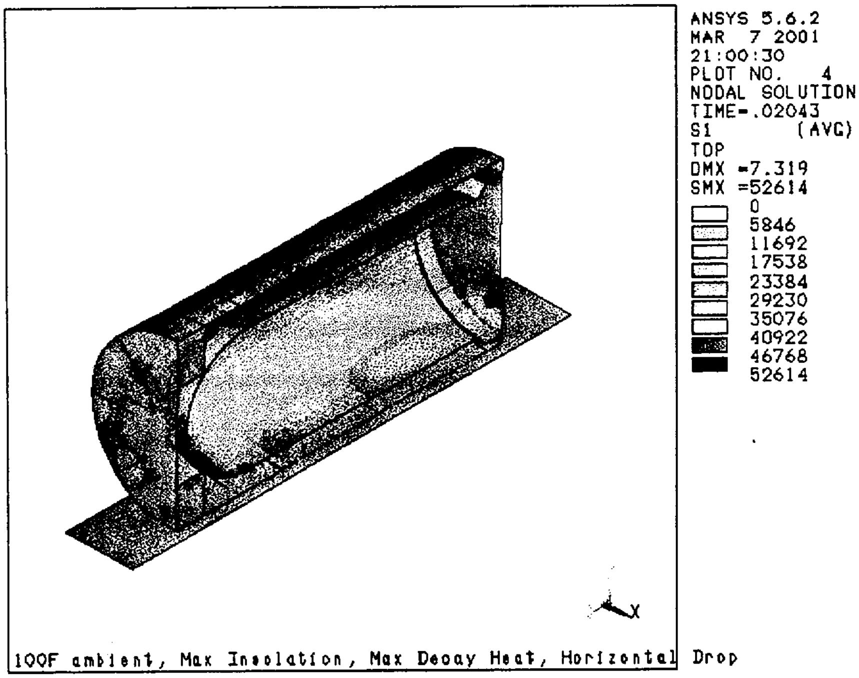


Figure 7.5.1.2e: HD1 Maximum Principal Stress Contours

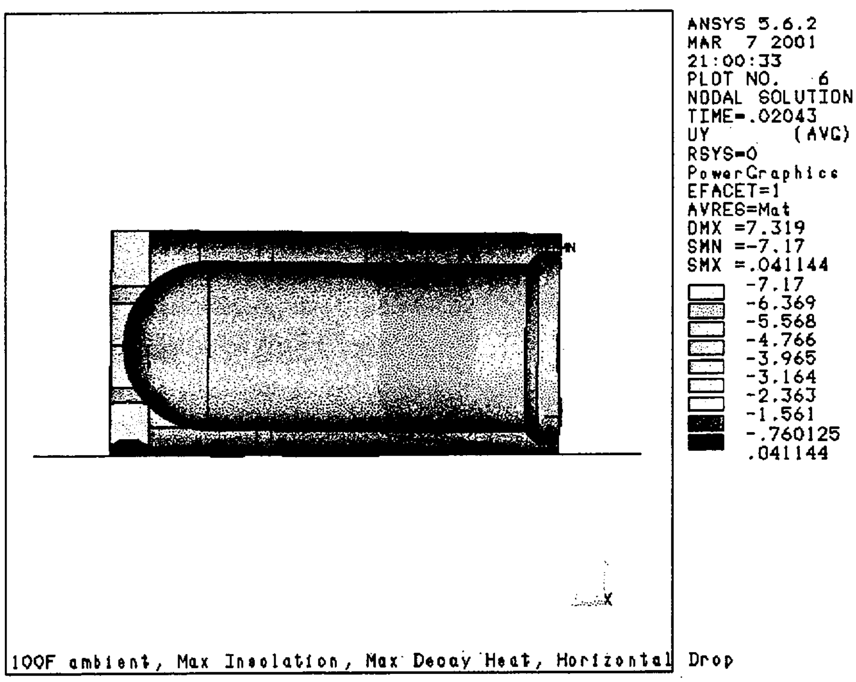


Figure 7.5.1.2f: HD1 Maximum Vertical Displacement Contours

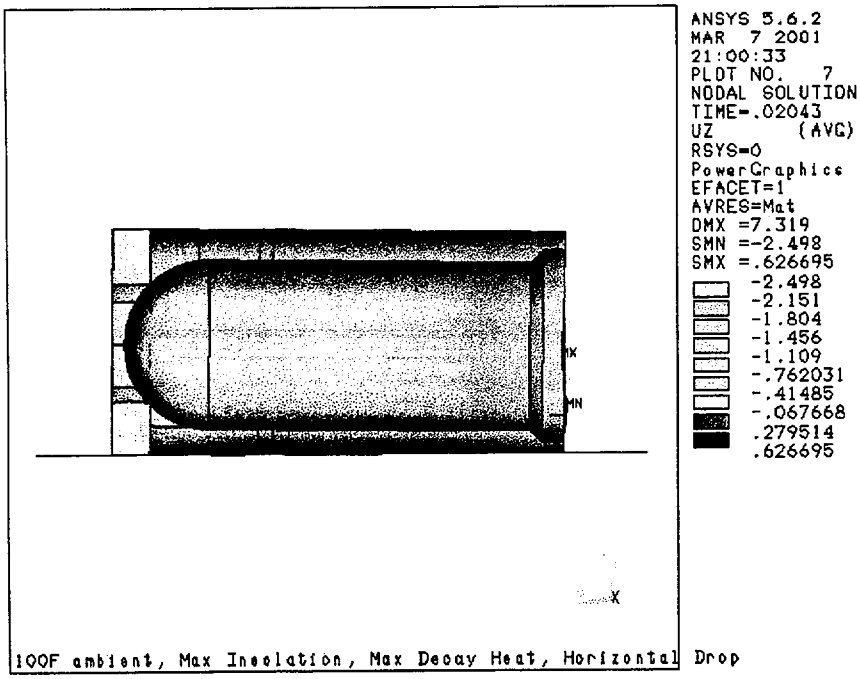


Figure 7.5.1.2g: HD1 Maximum Horizontal Displacement Contours

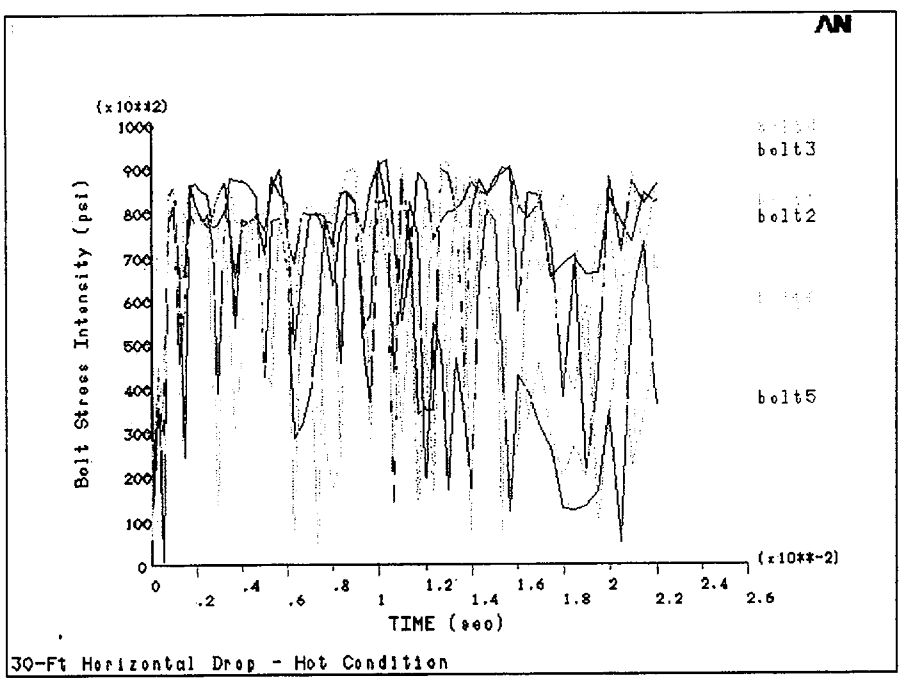


Figure 7.5.1.2h: HD1 Bolt Stress Intensity Time History

7.5.1.3 Corner Drop On The Cask CG (Cases CD1 and CD2)

The initial conditions for the CD analyses include nodal temperatures from thermal load cases T1 and T3, pressures of 20 psi and –3 psi as described in 10 CFR 71, and an initial vertical impact velocity of 527.4 in/sec, which is the impact velocity of a 30-foot drop. Contact between a corner of the bottom plate and the essentially unyielding, horizontal surface is modeled for the CD drop cases. In the CD1 drop case, the RV bottom head reaches its maximum vertical displacement of -10.18 inches at time 0.03595 second (Figure 7.5.1.3a, Case CD1). The run time is extended to 0.040 second for Case CD2 in which the RV bottom head reaches its maximum vertical displacement of. -10.55 inches at time 0.03829 second. Since the displacement has reached a plateau, the run times for both analyses are considered to be adequate. The maximum principal stress time histories at the highest deformation locations are shown in Figures 7.5.1.3c and 7.5.1.3d. The highest stress location occurs at the lower shell junction to the donut support plate. During the impact duration, the peak value of the maximum principal stress is S1 = 71.10 ksi at time 0.03745 second, case CD2. This is slightly greater than the material tensile strength of 70 ksi. A crack initiation may occur at the outer surface layer of the lower shell junction to the donut support plate. However, a local failure is not postulated (failed element removal) because the end of the impact duration has been reached, and the stress at this location has decreased substantially as shown in Figure 7.5.1.3d. The cask gross structure remains intact after the impact. Therefore, no containment failure and no gross buckling failure in the RVTS cask result from the 30-foot vertical drop. The maximum bolt stress intensity is 95.36 ksi, which is less than Su =100 ksi. Typical results at the time when the RV head reaches its peak vertical displacement are shown in the following figures:

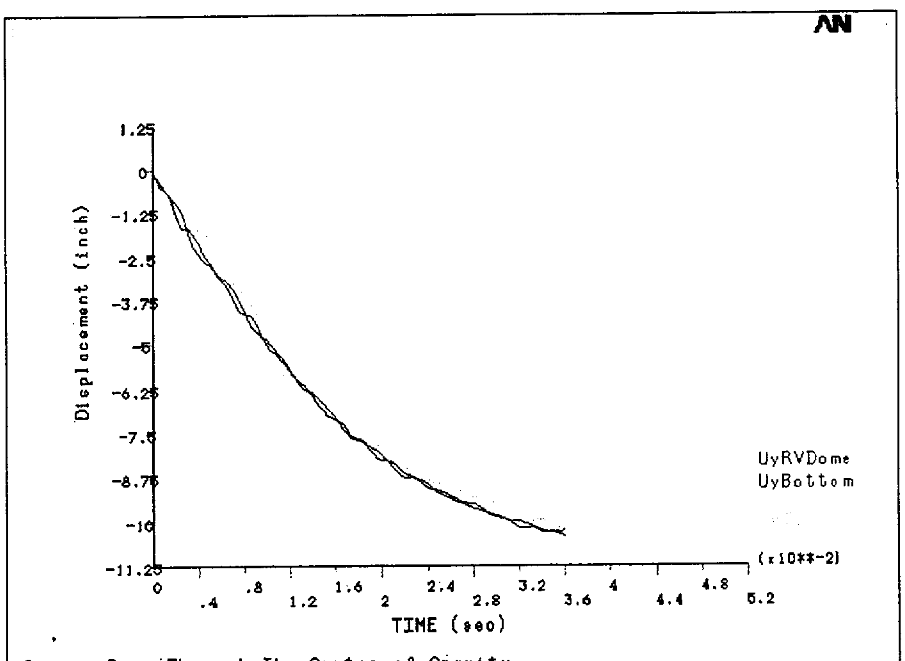


Figure 7.5.1.3a: CD1 Vertical Displacement Time History

Sargent & Lundy

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No. S-10525-020-012
		Rev. 0 / Date:
● Important to Safety Category A	Non-Safety-Related	Page 73

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

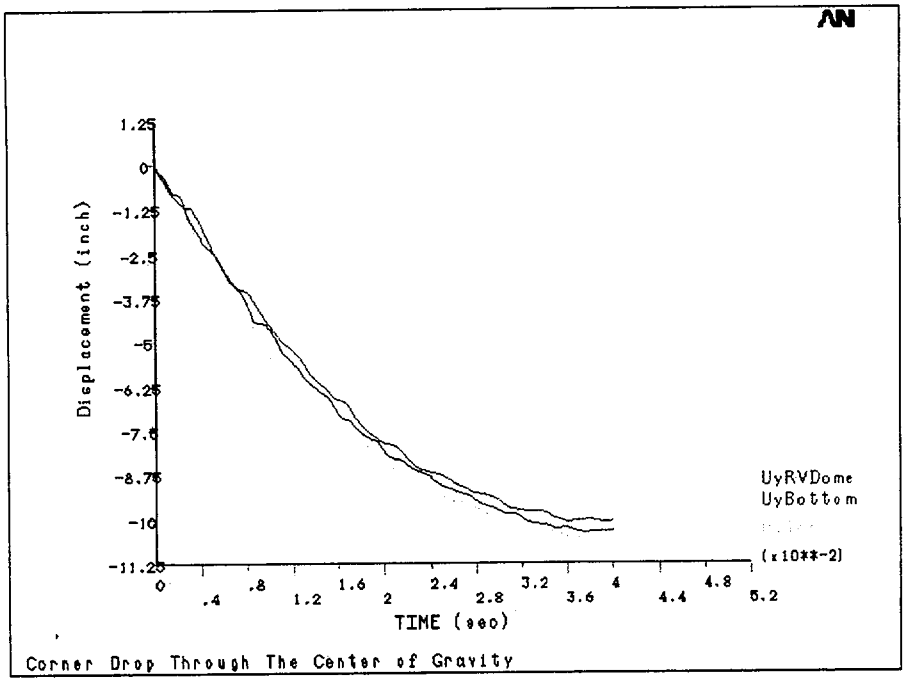


Figure 7.5.1.3b : CD2 Vertical Displacement Time History

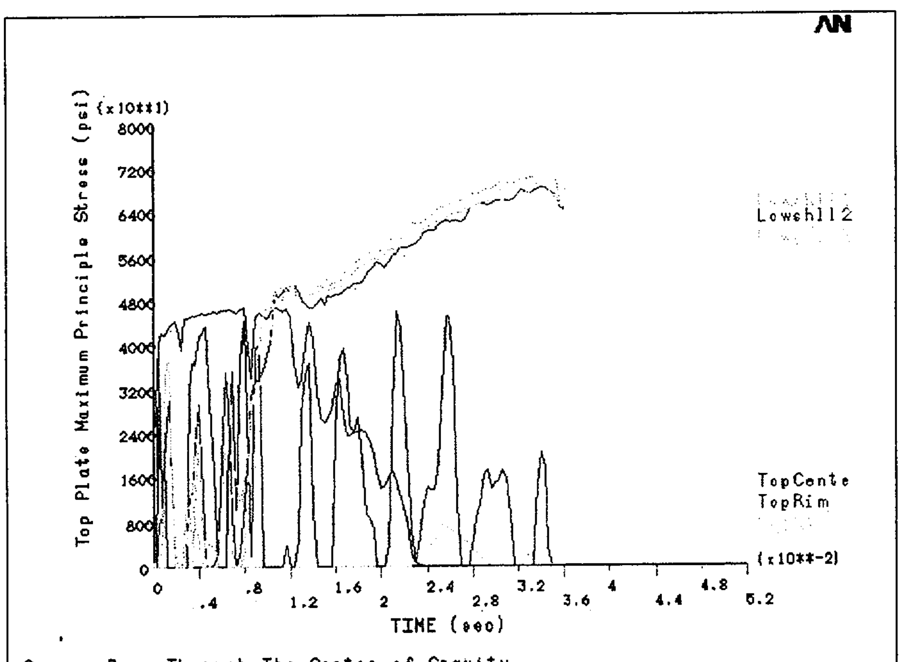


Figure 7.5.1.3c : CD1 Maximum Principal Stress Time History

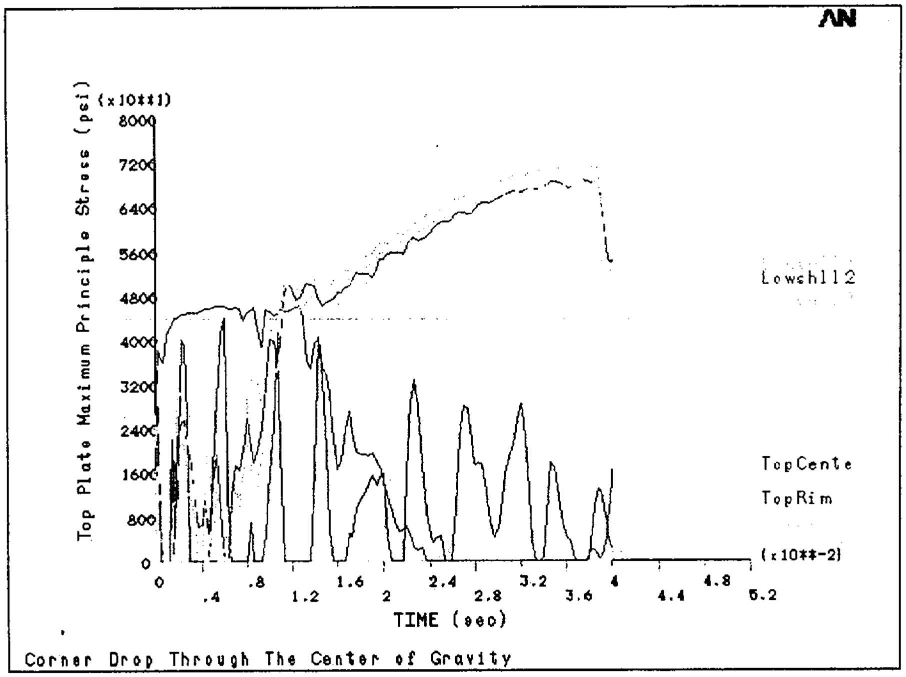


Figure 7.5.1.3d: CD2 Maximum Principal Stress Time History

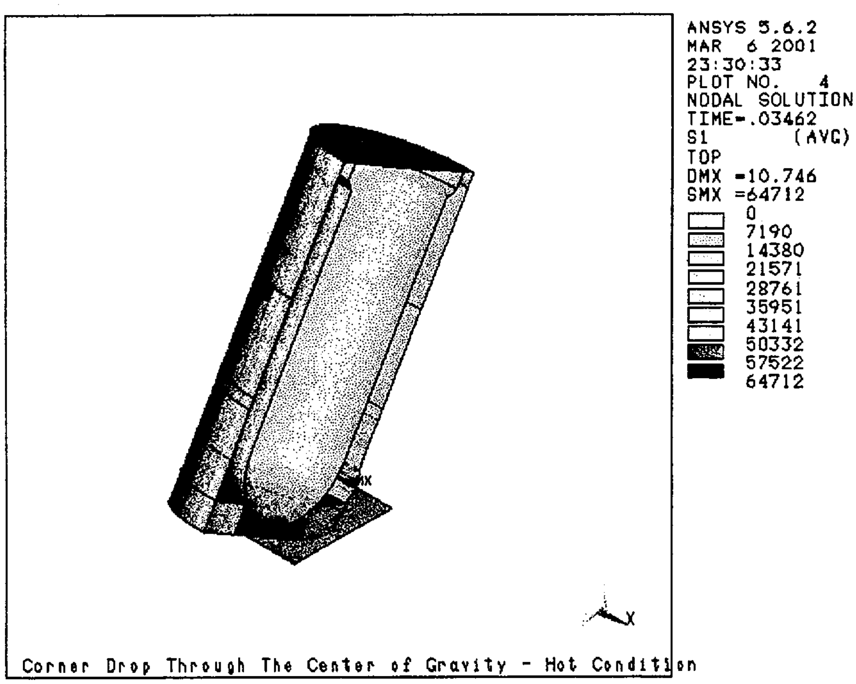


Figure 7.5.1.3e : CD2 Maximum Principal Stress Contours

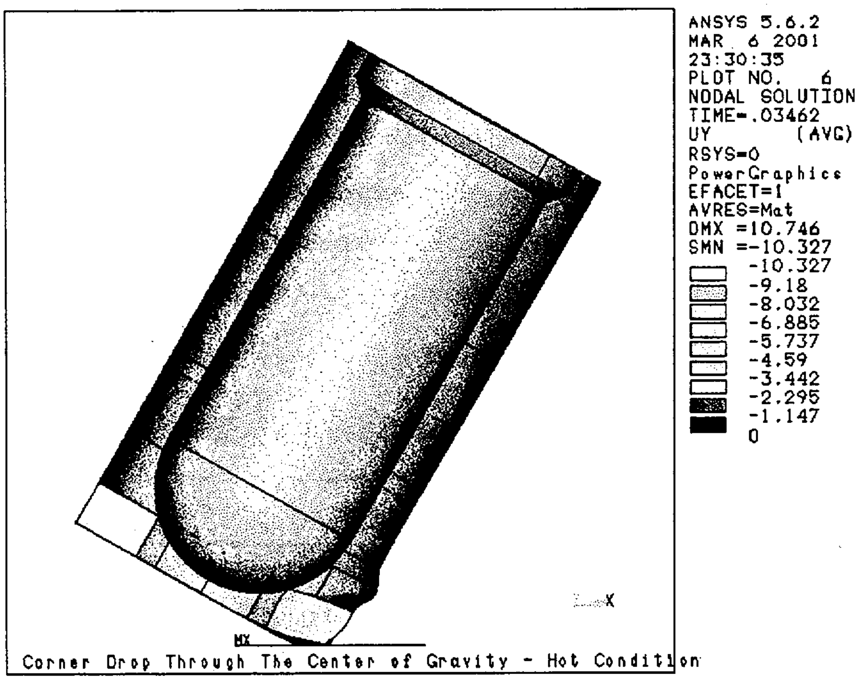


Figure 7.5.1.3f: CD2 Vertical Displacement Contours

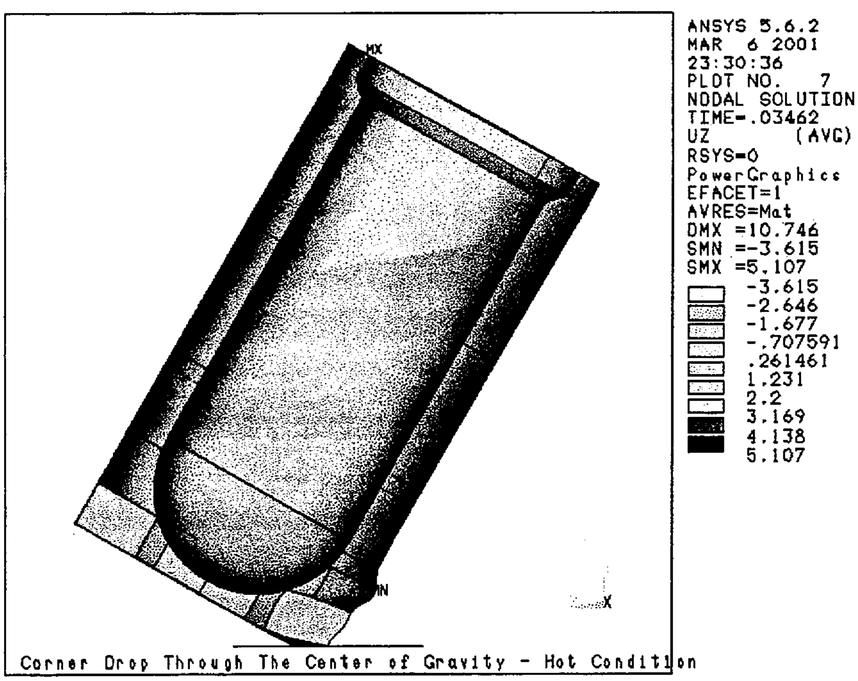


Figure 7.5.1.3g: CD2 Horizontal Displacement Contours

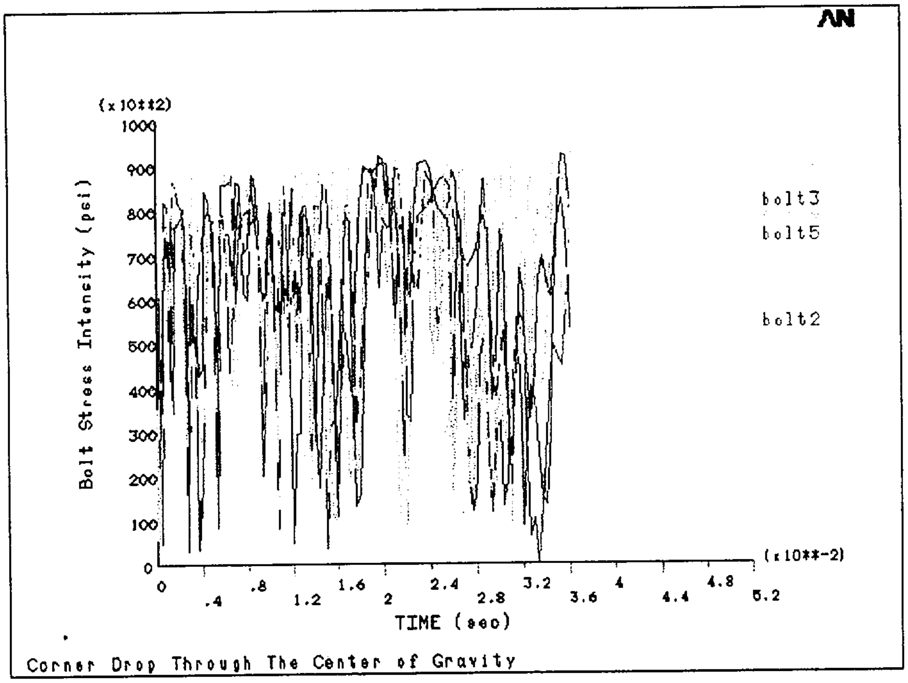


Figure 7.5.1.3h: CD1 Bolt Stress Intensity Time History

7.5.1.4 Flap Down Drop Analyses

The lumped parameter dynamic analysis methodology per NUREG/CR –3966, Ref. 3.16.2, is employed to investigate the maximum dynamic responses of the cask flap down drops with various oblique angles. The cask lumped parameter model is a beam which has the same distributed mass, lumped masses and cross sectional moment of inertia as of the RVTS. Detailed description and calculations for the lumped parameter model are provided in Attachment D. The beam is dropped onto a spring that represents the cask stiffness at the impact corner. The spring force deflection curve is fitted from the impact force and deflection time histories of the bottom plate center (Attachment I). The spring force deflection curve is shown in Figure 7.5.1.4.

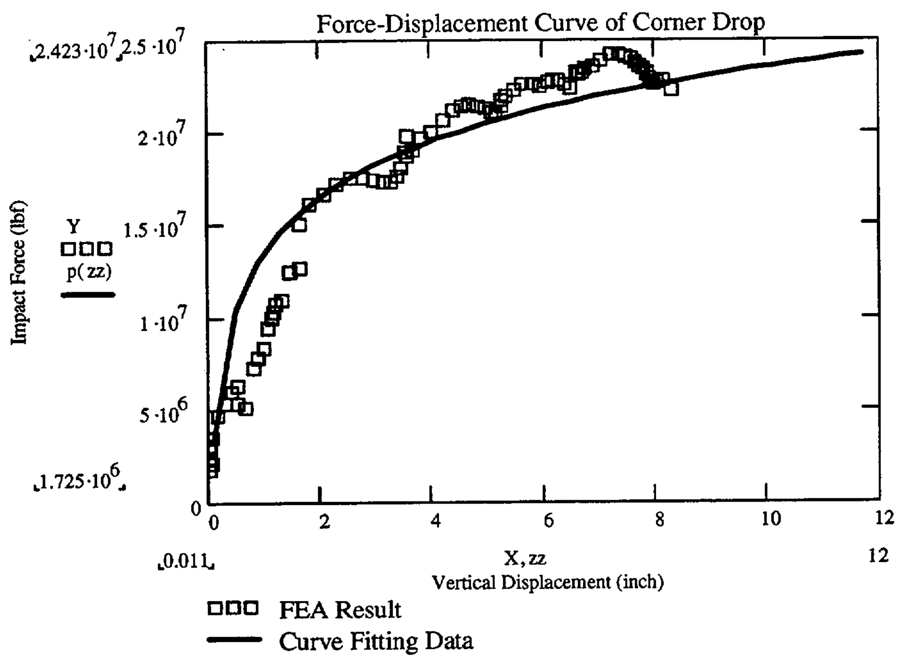


Figure 7.5.1.4 Spring Force Deflection Curve

The flap down velocities for various oblique angles off the horizontal plane are shown in the Table 7.5.1.4a.

Table 7.5.1.4a Flap Down Velocities for Various Oblique Angles

Oblique Angle (Degree)	Top Plate Vertical Displ (in)	Vertical Velocity (in/s)		Horizontal Velocity (in/s)	
		Top Plate	Bottom Plate	Top Plate	Bottom Plate
5	26.1	-793	192	8	12
10	52.1	-798	172	35	45
15	77.6	-793	157	51	81
20	102.6	-781	144	65	113
30	150	-732	124	101	173
40	192.8	-648	91	143	231
50	229.8	-538	13	204	276
60	259.8	-481	-118	237	247

A negative vertical velocity indicates movement toward the target surface, and a positive horizontal velocity indicates movement toward the top plate. The maximum flap down vertical impact velocity does not change significantly for an oblique angle of less than 20 degree from the horizontal surface. The maximum vertical flap-down velocity is corresponding to the 10-degree oblique drop angle. The maximum flap down horizontal impact velocity corresponds to the 50-degree oblique drop angle. Table 7.5.1.4b shows the impact velocities for the Cases FDP1 and FDP2 analyses, which are higher than the bounding velocity listed in Table 7.5.1.4.a. Flap down analyses are performed with the following initial velocity distributions:

Case FDP1: Flap down drop with maximum vertical velocity (in/sec)
FDP11 and FDP12 are the subsets of FDP1 with different thermal and pressure conditions.
Case FDP2: Flap down drop with maximum horizontal velocity (in/sec)
FDP21 and FDP22 are the subsets of FDP2 with different thermal and pressure conditions.

Table 7.5.1.4.b Flap Down Velocities Used in the Analyses

Case	Top Plate Vertical Velocity	Bottom Plate Vertical Velocity	Top Plate Horizontal Velocity	Bottom Plate Horizontal Velocity
FDP1	-810	194	46	46
FDP2	-547.5	34.2	276	276

The model for the FD analyses is similar to the model for the HD analyses except with a linearly distributed initial impact velocity. The initial linearly distributed velocity is modeled by dividing the cask model into 30 velocity zones along the axial direction. All nodes within a zone have the same velocity, which is linearly calculated from the velocities of the top and the bottom plates. The horizontal velocity of the entire cask is assumed to be a constant that is equal to the higher of the top plate and the bottom plate horizontal velocities.

7.5.1.4.1 Flap Down Drop – Maximum Vertical Velocity (Cases FDP11 and FDP12)

The FDP1 analyses are performed with two initial conditions for thermal load cases T1 and T3, and pressures of 20 psi and –3 psi as described in 10 CFR 71. Preliminary analyses indicate that at approximately 0.024 second a failure occurs in the elements located at the top plate ligament between the RV flange and the top plate rim. A total of six elements within a 22.5 degree arc of the top plate rim near the impact location of the cask half model, are then removed and the analysis continues until the top plate has reached the maximum displacement. Stress at locations E1, E2, E3 and E4 of Figures 7.5.1.4.1c and 7.5.1.4.1d are the stresses for selected nodes of the failed elements.

Figures 7.5.1.4.1a and 7.5.1.4.1b show the time histories of the vertical and horizontal displacements of the top plate center, the bottom plate center and the top of the RV bottom head up to the maximum impact duration of 0.028 second. Both vertical and horizontal displacements reach the maximum values within the given duration.

The top plate CG reaches its maximum vertical displacement of -7.225 inches at time 0.01979 second in the FDP12 drop case. The top plate center reaches its maximum horizontal displacement of -2.545 inches at time 0.02665 second in the FDP11 drop case.

As shown in Figures 7.5.1.4.1c and Figure 7.5.1.4.1d, the maximum principal stress at locations E1, E2, E3 and E4 reach the material tensile strength Su=70 ksi at approximately 0.024 second. The element stiffness at these locations is removed, thus the element stresses reduce to zero after 0.024 second. The adjacent elements at locations E5 and E6 continue to take load until the end of impact duration without additional failures. The cask gross structure remains intact after the impact. The maximum bolt stress intensity is 97.73 ksi, which is less than Su =100 ksi. Typical results at the

time when the top plate center reaches peak vertical/horizontal displacements are shown in the following figures:

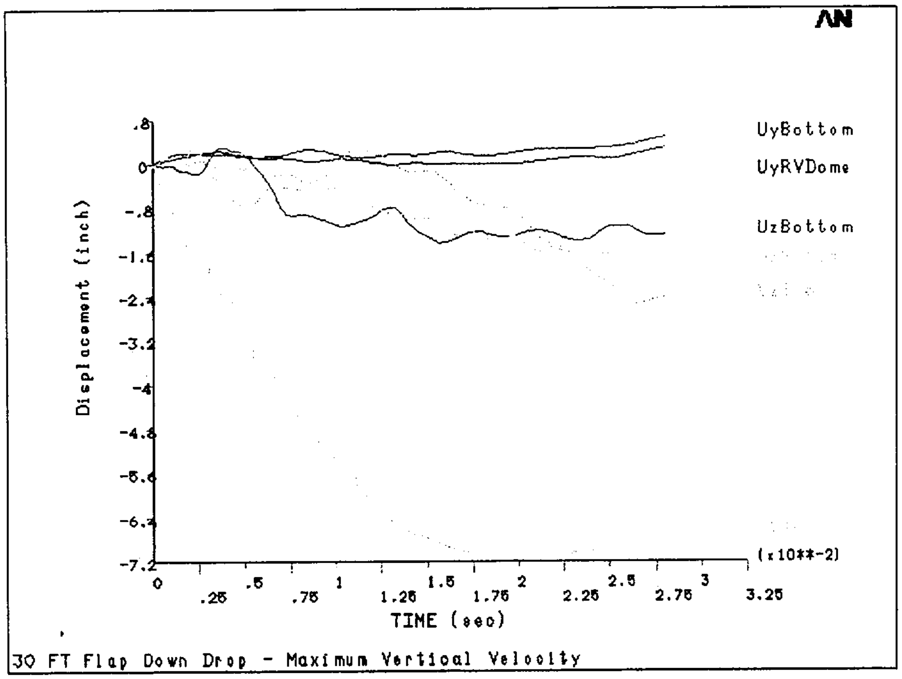


Figure 7.5.1.4.1a: FDP11 Vertical Displacement Time History

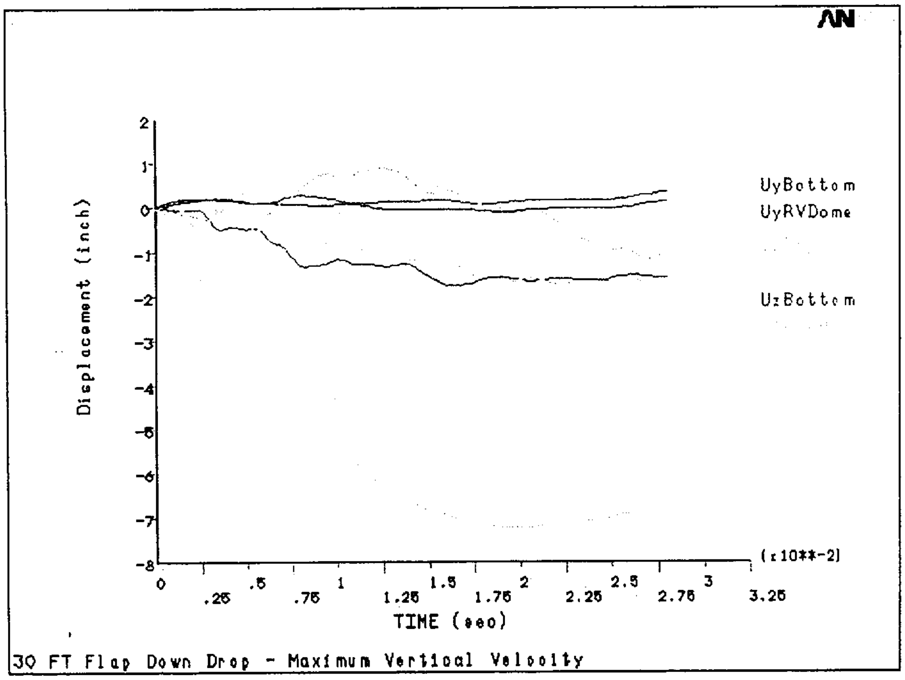


Figure 7.5.1.4.1b: FDP12 Vertical Displacement Time History

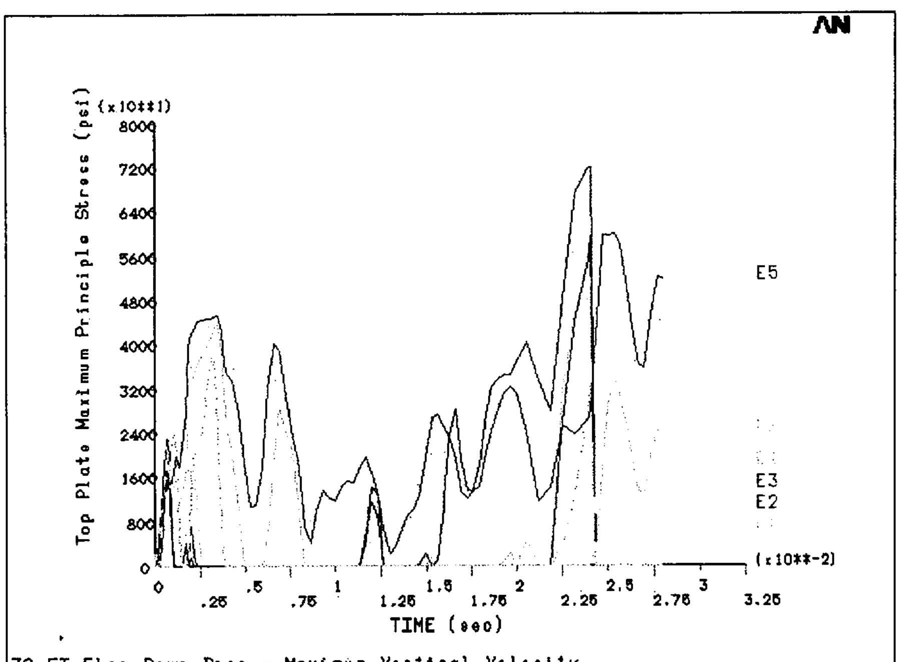


Figure 7.5.1.4.1c: FDP11 Maximum Principal Stress Time History

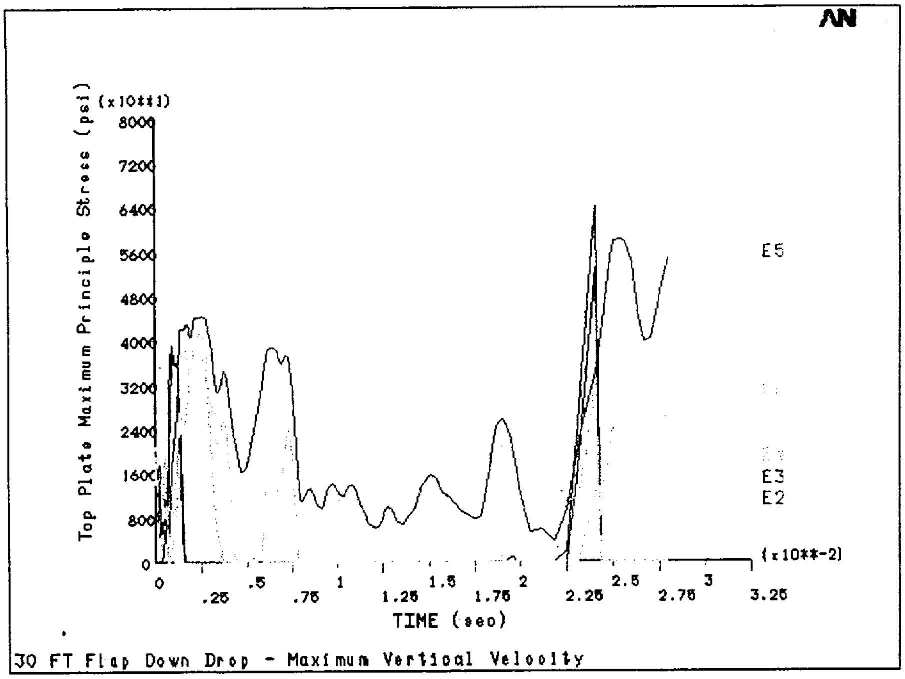


Figure 7.5.1.4.1d: FDP12 Maximum Principal Stress Time History

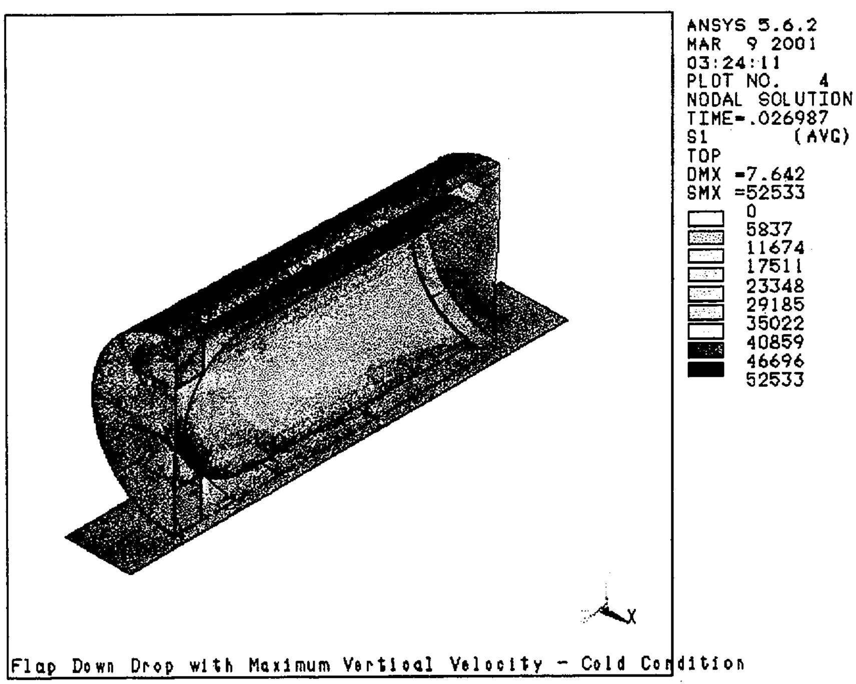


Figure 7.5.1.4.1e: FDP12 Maximum Principal Stress Contours

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No. S-10525-020-012
		Rev. 0 / Date:
● Important to Safety Category A	Non-Safety-Related	Page 82

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

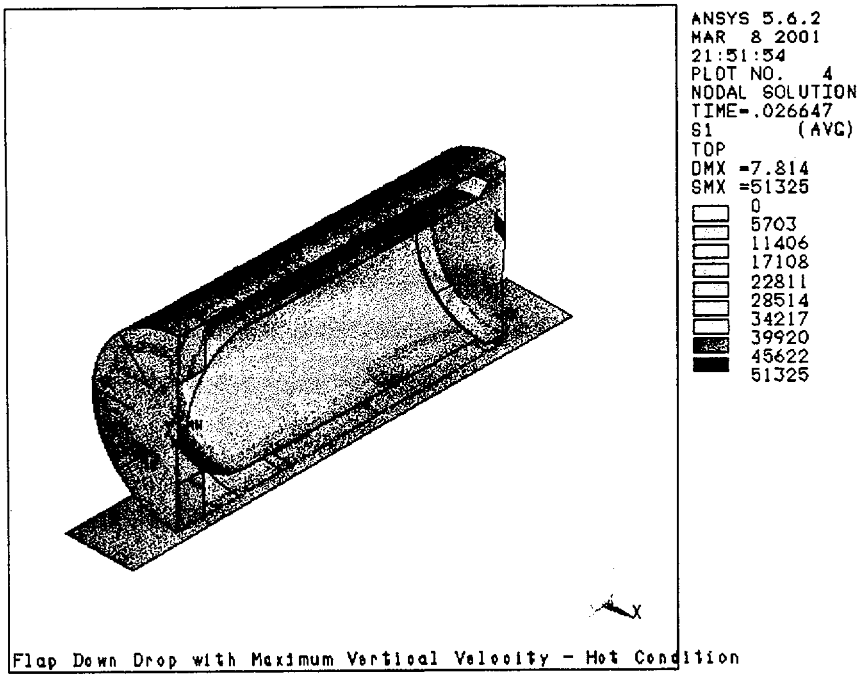


Figure 7.5.1.4.1f: FDP11 Maximum Principal Stress Contours

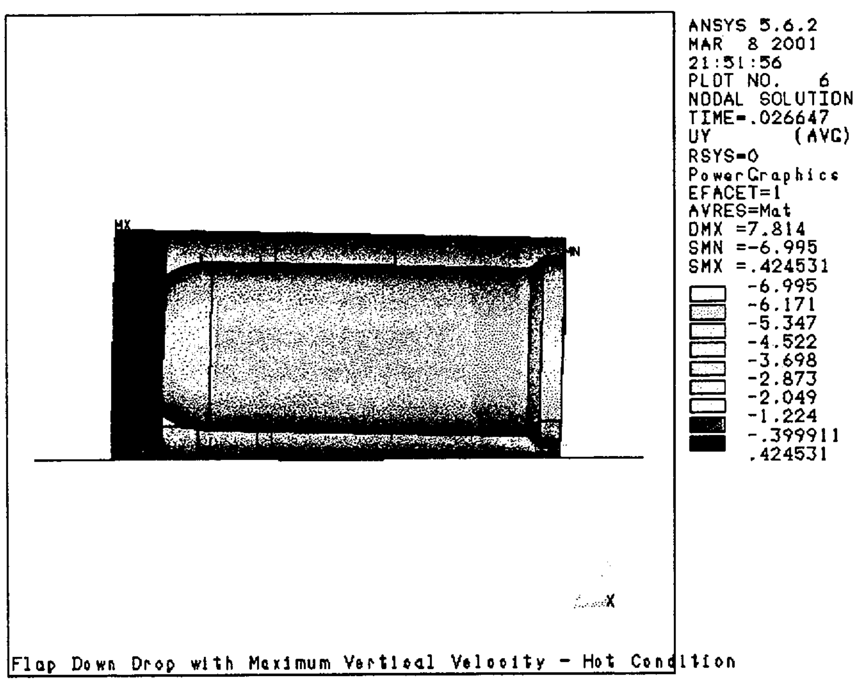


Figure 7.5.1.4.1g: FDP12 Vertical Displacement Contours

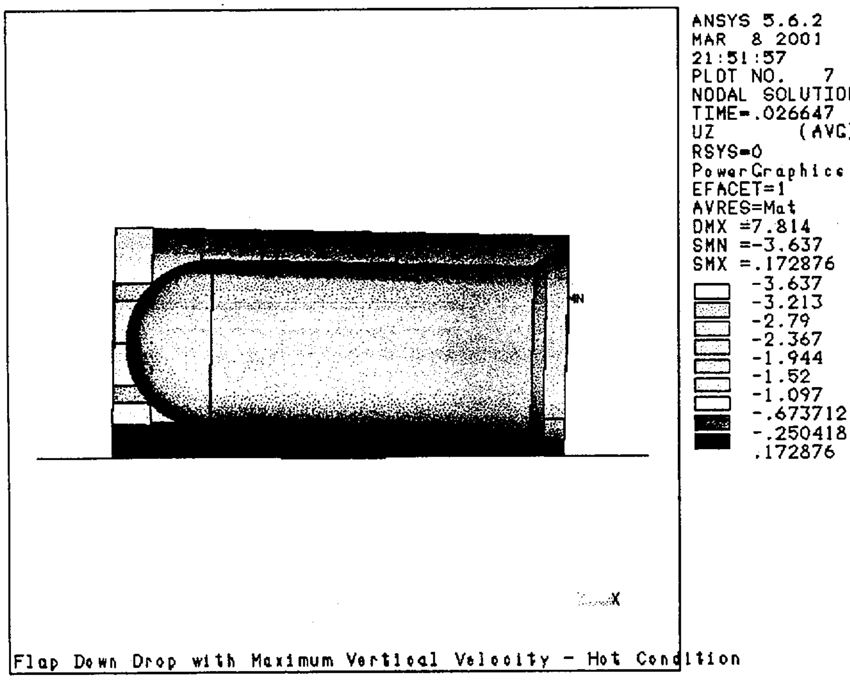


Figure 7.5.1.4.1h: FDP11 Horizontal Displacement Contours

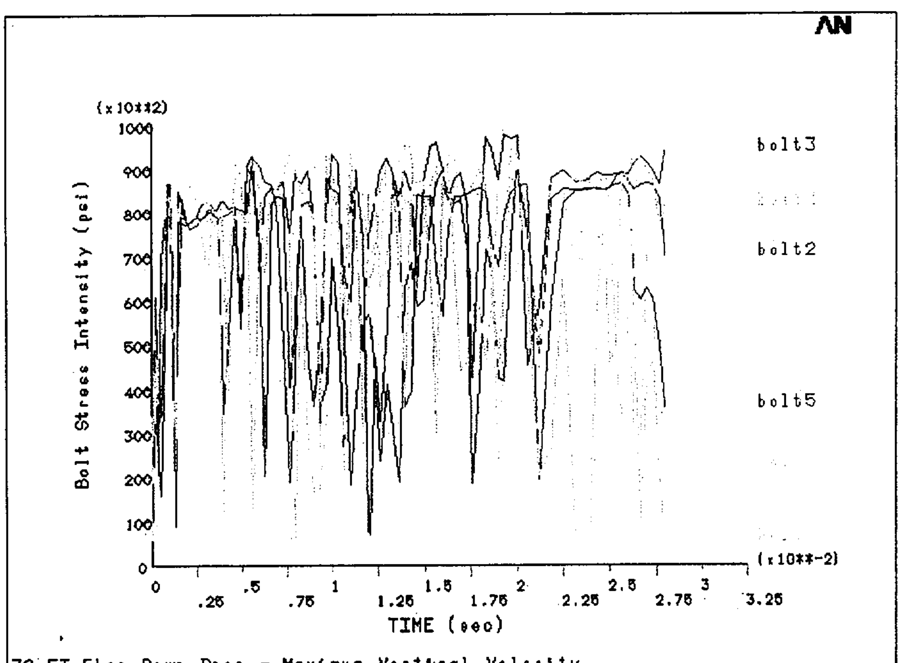


Figure 7.5.1.4.1k: FDP11 Bolt Stress Intensity Time History

7.5.1.4.2 Flap Down Drop – Maximum Horizontal Velocity (Cases FDP21 and FDP22)

The initial conditions for the FDP2 analyses include nodal temperatures from thermal load cases T1 and T3, pressures of 20 psi and –3 psi as described in 10 CFR 71, and the linear distributed initial vertical impact velocity and horizontal velocity listed in Table 7.5.1.4b for FDP2. Contacts between the cask shell and the essential unyielding, horizontal surface is modeled along with the contact between the RV flange and the cask shell.

At time 0.012 second a failure occurs in elements located at the top plate ligament between the RV flange and the impact corner. Four elements that extend over an arc of 15 degrees of the cask half model (Locations E1, E2 and E3 of Figures 7.5.1.4.2c and 7.5.1.4.2d) are then removed and the interactive analysis continues until the top plate has reached the maximum vertical and horizontal displacements without additional failures.

The top plate CG reaches its maximum vertical displacement of -7.740 inches at time 0.02562 second in the FDP22 drop case. The top plate center reaches its maximum horizontal displacement of -9.207 inches at time 0.02595 second in the FDP21 drop case.

As shown in Figures 7.5.1.4.2c and 7.5.1.4.2d, the maximum principal stress at location E1 approaches the material tensile strength, Su, at approximately 0.012 second. The element stiffness at this location is removed, thus the element stress reduces to zero after 0.012 second. The adjacent elements at locations E4, E5 and E6 continue to take load through the end of impact duration without failure. The cask gross structure remains intact after the impact. The maximum bolt stress intensity is 96.37 ksi, which is less than Su =100 ksi. Typical results at the time when the top plate center reaches peak vertical/horizontal displacements are shown in the following figures:

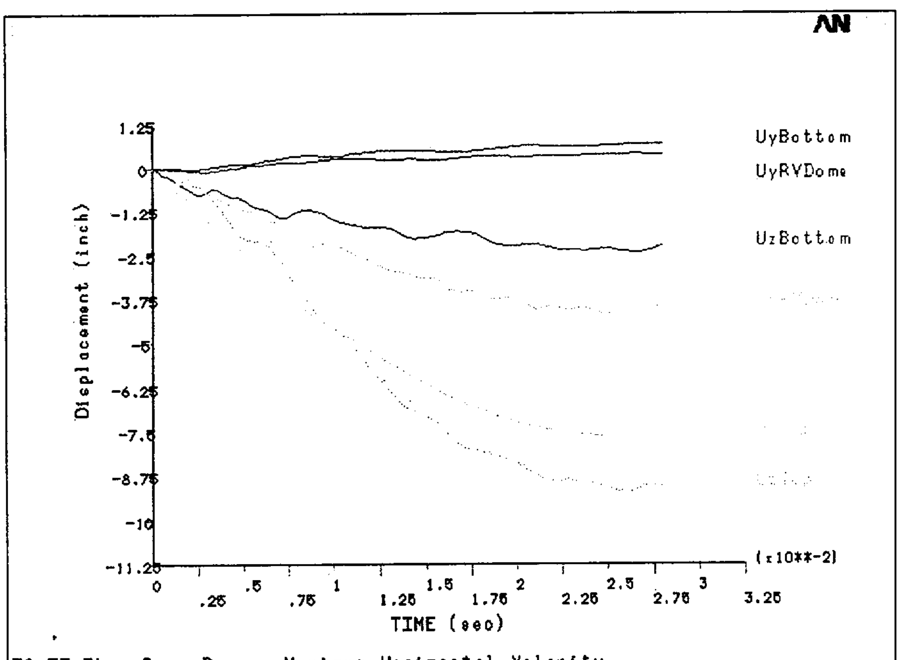


Figure 7.5.1.4.2a: FDP21 Vertical Displacement Time History

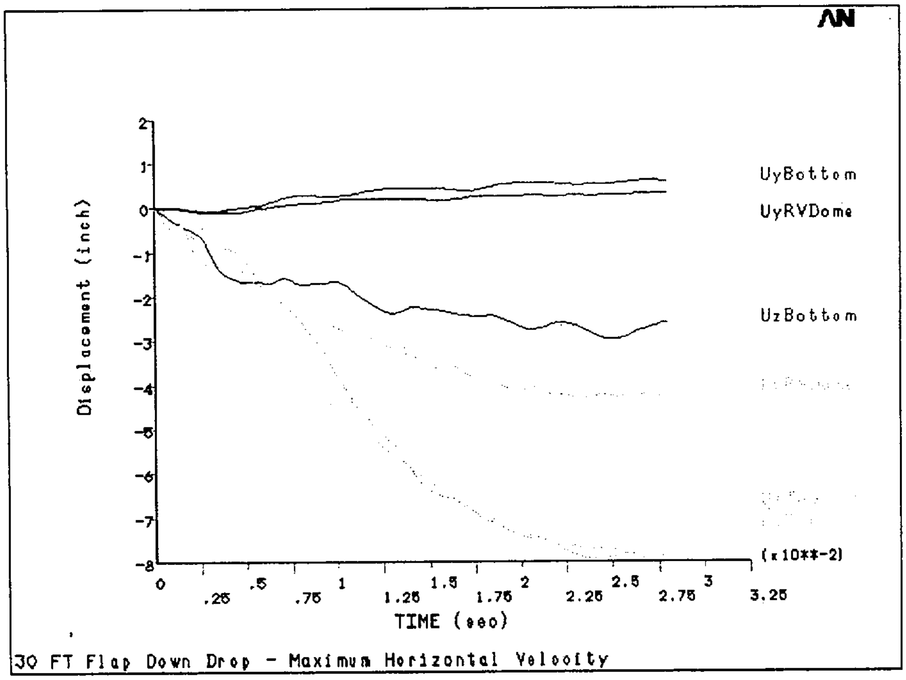


Figure 7.5.1.4.2b: FDP22 Vertical Displacement Time History

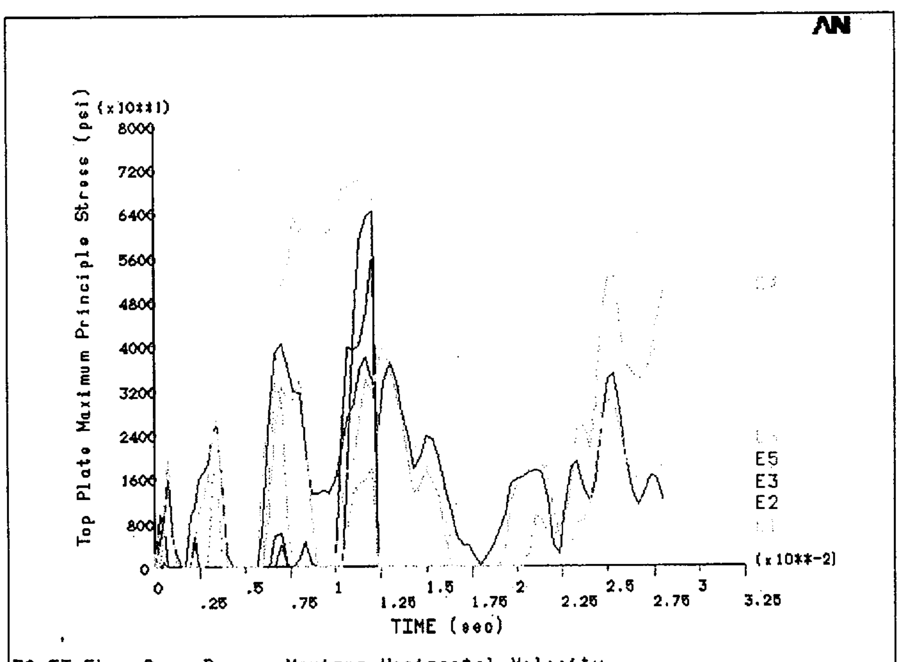


Figure 7.5.1.4.2c: FDP21 Maximum Principal Stress Time History

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
● Important to Safety Category A	Non-Safety-Related	Rev. 0	Date:
		Page	86

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

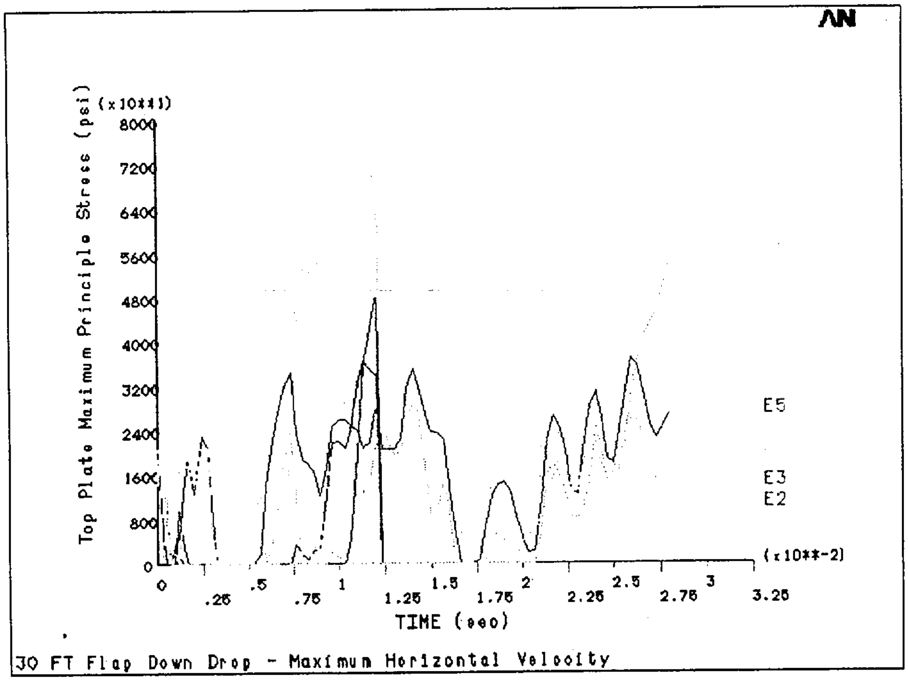


Figure 7.5.1.4.2d: FDP22 Maximum Principal Stress Time History

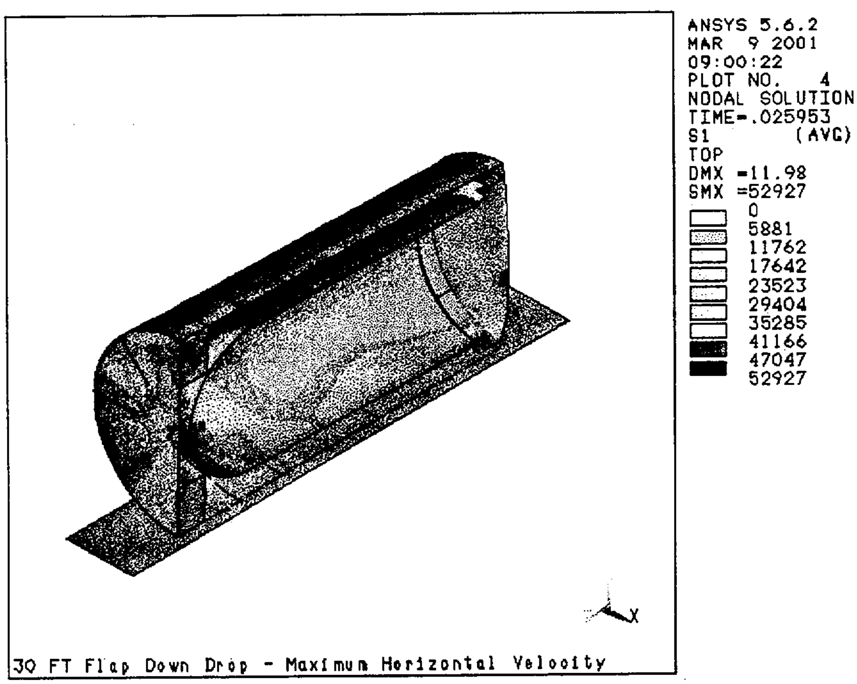


Figure 7.5.1.4.2e: FDP21 Maximum Principal Stress Contours

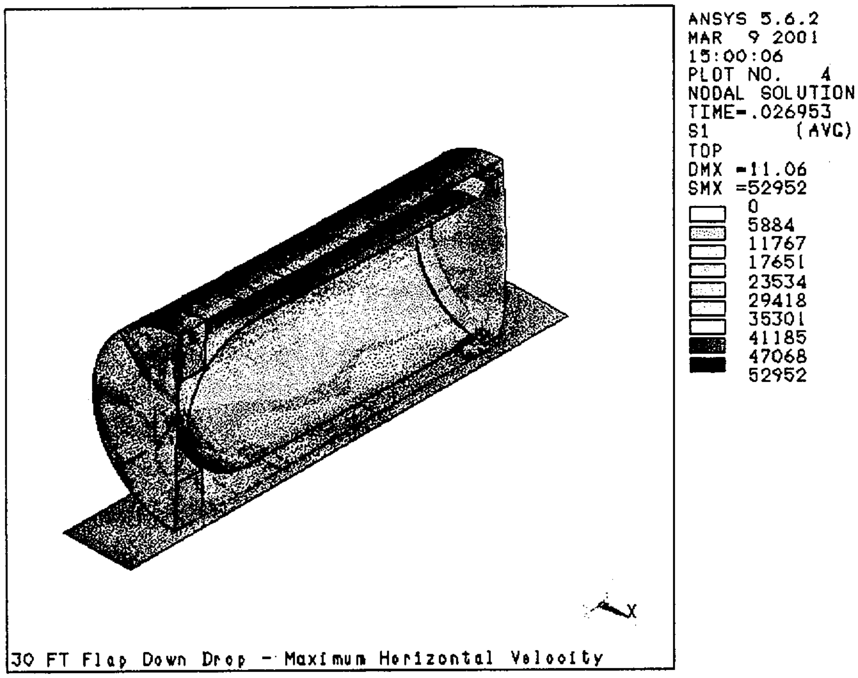


Figure 7.5.1.4.2f: FDP22 Maximum Principal Stress Contours

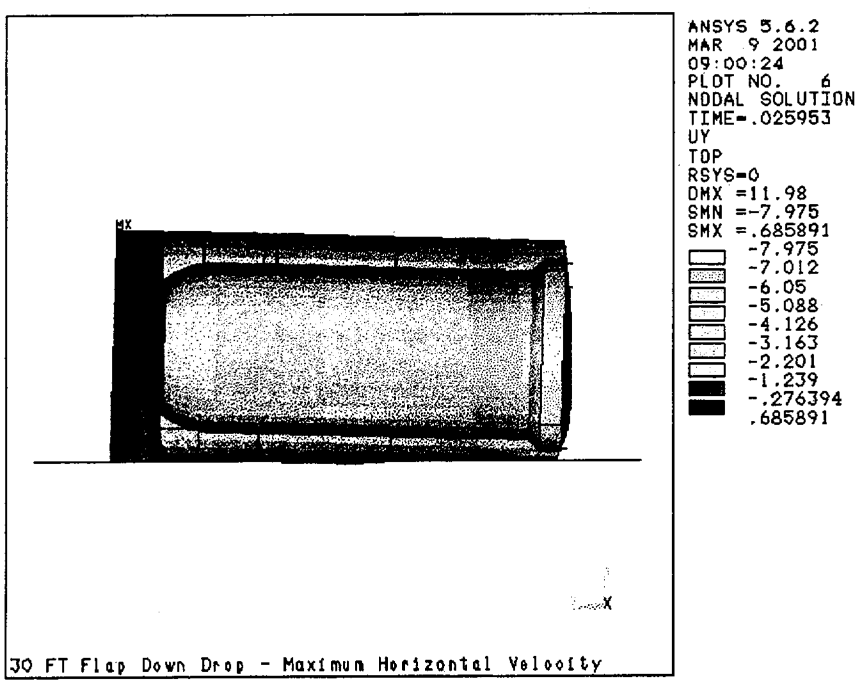


Figure 7.5.1.4.2g: FDP21 Vertical Displacement Contours

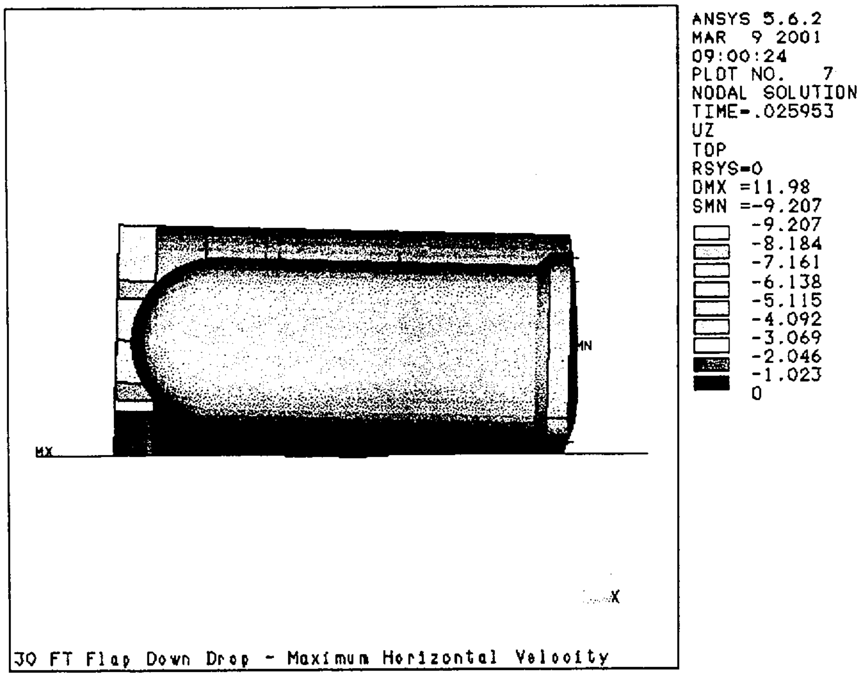


Figure 7.5.1.4.2h: FDP22 Horizontal Displacement Contours

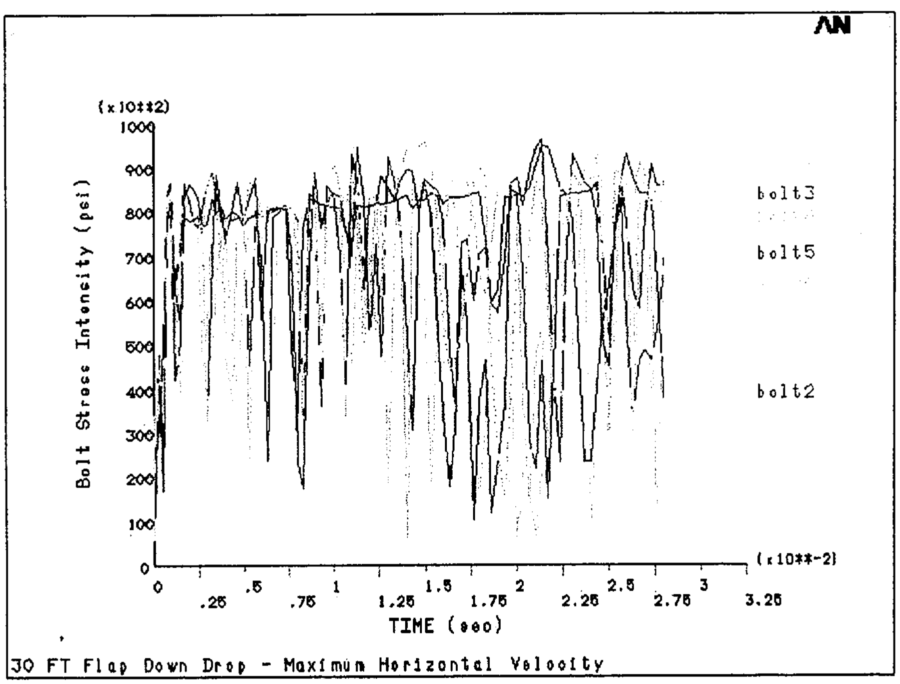


Figure 7.5.1.4.2k: FDP21 Bolt Stress Intensity Time History

7.5.2 Result Verification for 30-foot Drop Analyses

7.5.2.1 Energy Conservation Check

The results of the 30-foot drop dynamic impact analyses are verified using the principal of energy conservation. The total instantaneous strain energy, kinetic energy and the cumulative plastic work should be approximately equal to the initial impact energy, KE = ½ mv^2, where m is the total RVTS mass and v = 527.4 in/s is the impact velocity of a 30-foot drop. A horizontal 30' drop analysis is performed without the initial thermal and pressure conditions for the purpose of checking the principal of conservative energy. The analysis RUNID is HDEnergy.

The calculated mass of the model (half of the RVTS), per Section 7.3, is 730.38 lbf-sec^2/in.

$$KE = \frac{1}{2} mv^2 = .5*(730.38)*(527.4)^2 = 101.58E+06 \text{ in-lbf}$$

The ANSYS results include the instantaneous strain energy (StrainE), cumulative plastic work (PlastE) and kinetic energy (KinE). These energy values are calculated and integrated over the model volume from the element data tables for all output load steps. The plots of the instantaneous strain energy, cumulative plastic work and kinetic energy are shown in Figure 7.5.2.1. At the end of the first load step, the FEA calculated initial kinetic energy is 101.298E+06 in-lbf, and the strain energy is 0.4025E+6 in-lbf. Thus the total initial energy calculated by ANSYS is 101.7E+06 in-lbf, which is essentially the same as the input impact energy KE. At the end of the impact period, the instantaneous strain energy (StrainE) and kinetic energy (KinE) are diminishing, and the cumulative plastic work (PlastE) reaches a plateau value of 118.382E+06 in-lbf. The FEA calculated plastic work is conservatively over-estimated by about 18% of the total impact energy.

The ANSYS calculated plastic work for the element type VISCO106 is documented in the ANSYS Theory Manual. The usage of the ANSYS calculated plastic work for the element type SHELL181 is justified by the benchmark analyses documented in Section 7.5.2.3. The calculated cumulative plastic work for both elements is essentially the same as the input kinetic energy.

Based on the result of the verification problem, it is concluded that the calculated damages of the thirty-foot drop calculations are reasonably conservative, and are suitable for estimating an upper-bound damage of a potential HAC breach of containment of the RVTS cask.

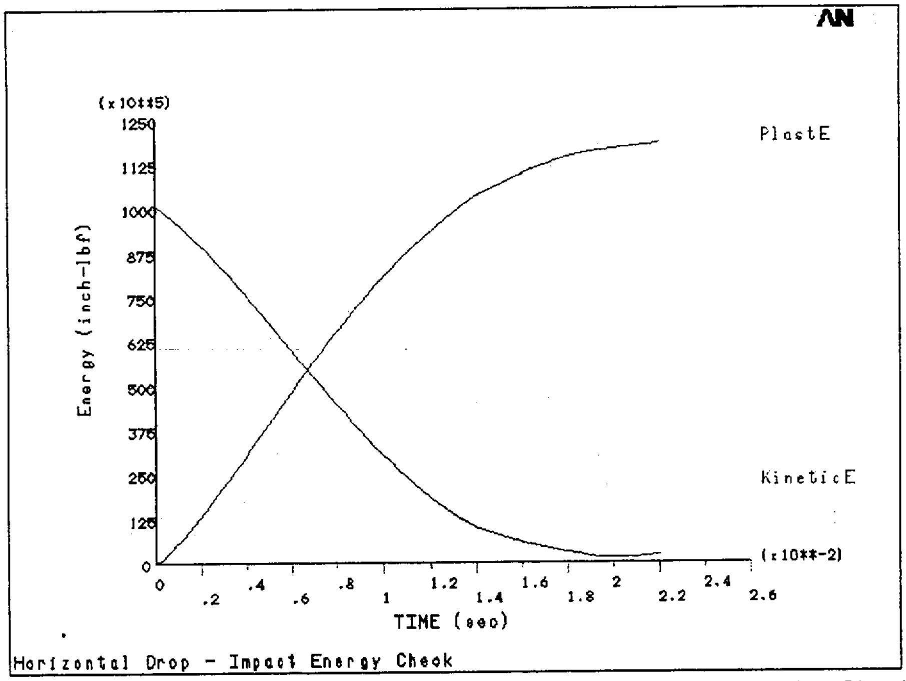


Figure 7.5.2.1 Cask Drop Verification Problem – Energy Conservation Check

7.5.2.2 Effect of the PCG Solver Convergence Tolerance

The purpose of the analysis FDP11a is to investigate the effect of the PCG solver convergence tolerance. A convergence tolerance of 1E-08 is used in FDP11a in lieu of 1E-03 in FDP11. As shown in Tables 7.5.2.2a and 7.5.2.2b, the differences in the peak S1 values and displacements of the two analyses are less than 0.1%. Therefore, the PCG solver convergence tolerance value has no significant effect on the results of the 30-Foot drop analyses.

Table 7.5.2.2a: Extreme Values of FDP11 Analysis with PCG Convergence Value of 1E-3.

VARI	TYPE	NODE	IDENTIFIERS	NAME	MINIMUM	AT TIME	MAXIMUM	AT TIME
2	ESOL	4732	S1	E1	0	2.00E-05	5.04E+04	2.40E-02
3	ESOL	4731	S1	E2	0	2.00E-05	7.18E+04	2.40E-02
4	ESOL	4735	S1	E3	0	2.00E-05	5.92E+04	2.40E-02
5	ESOL	4739	S1	E4	0	2.00E-05	3.83E+04	3.17E-03
6	ESOL	4743	S1	E5	0	2.00E-05	5.99E+04	2.53E-02
7	ESOL	4747	S1	E6	0	2.00E-05	4.38E+04	3.50E-03
8	NSOL	1106	UY	UyTop	-7.17	1.96E-02	-1.62E-02	2.00E-05
9	NSOL	3315	UY	UyBottom	3.88E-03	2.00E-05	0.4857	2.80E-02
10	NSOL	50	UY	UyRVDome	-1.41E-02	1.33E-02	0.2857	2.80E-02
11	NSOL	1106	UZ	UzTop	-2.545	2.67E-02	0.2565	1.13E-02
12	NSOL	3315	UZ	UzBottom	-1.424	1.56E-02	0.2951	3.83E-03
13	NSOL	50	UZ	UzRVDome	-1.636	2.67E-02	0.3788	2.33E-03

Table 7.5.2.2b: Extreme Values of FDP11a Analysis with PCG Convergence Value of 1E-8.

VARI	TYPE	NODE	IDENTIFIERS	NAME	MINIMUM	AT TIME	MAXIMUM	AT TIME
2	ESOL	4732	S1	E1	0	2.00E-05	5.02E+04	2.40E-02
3	ESOL	4731	S1	E2	0	2.00E-05	7.18E+04	2.40E-02
4	ESOL	4735	S1	E3	0	2.00E-05	5.90E+04	2.40E-02
5	ESOL	4739	S1	E4	0	2.00E-05	3.83E+04	3.17E-03
6	ESOL	4743	S1	E5	0	2.00E-05	5.98E+04	2.53E-02
7	ESOL	4747	S1	E6	0	2.00E-05	4.38E+04	3.50E-03
8	NSOL	1106	UY	UyTop	-7.169	1.96E-02	-1.62E-02	2.00E-05
9	NSOL	3315	UY	UyBottom	3.88E-03	2.00E-05	0.4852	2.80E-02
10	NSOL	50	UY	UyRVDome	-1.41E-02	1.33E-02	0.2856	2.80E-02
11	NSOL	1106	UZ	UzTop	-2.562	2.67E-02	0.2565	1.13E-02
12	NSOL	3315	UZ	UzBottom	-1.425	1.56E-02	0.2952	3.83E-03
13	NSOL	50	UZ	UzRVDome	-1.639	2.67E-02	0.3788	2.33E-03

7.5.2.3 Performance Benchmark Analysis of SHELL181 Element

Problem C8, a benchmark problem in ANSYS Verification Manual, tests the performance of various 3-D solid elements in dynamic impact analysis. The test compares the final deformed length of a cylindrical aluminum bar impacting on a rigid wall with an experimental result.

The same benchmark problem is performed using SHELL181 element to test the performance of this element due to an in-plane impact loading. Since the cylindrical bar cannot be modeled using a shell element, the benchmark model is a square bar, which has a side equal to the diameter of the cylindrical test bar. The bar length, the impact velocity and the material properties are the same as the test case. The benchmark analysis uses the ANSYS PCG solver with a convergence tolerance of 1e-03. The input and output files are documented Appendix J. For a purpose of testing the ANSYS's cumulative plastic work calculation for SHELL181 element, a benchmark problem is also analyzed using VISCO106 element, a time dependent plasticity 2D plate element. The cumulative plastic work calculation for VISCO106 element is documented in the ANSYS Theory Manual.

The comparison of the final deformed bar length resulted from benchmark analyses using various 3-D solid elements as in ANSYS Verification Manual and SHELL181 element in this calculation is shown in Table 7.5.2.3.

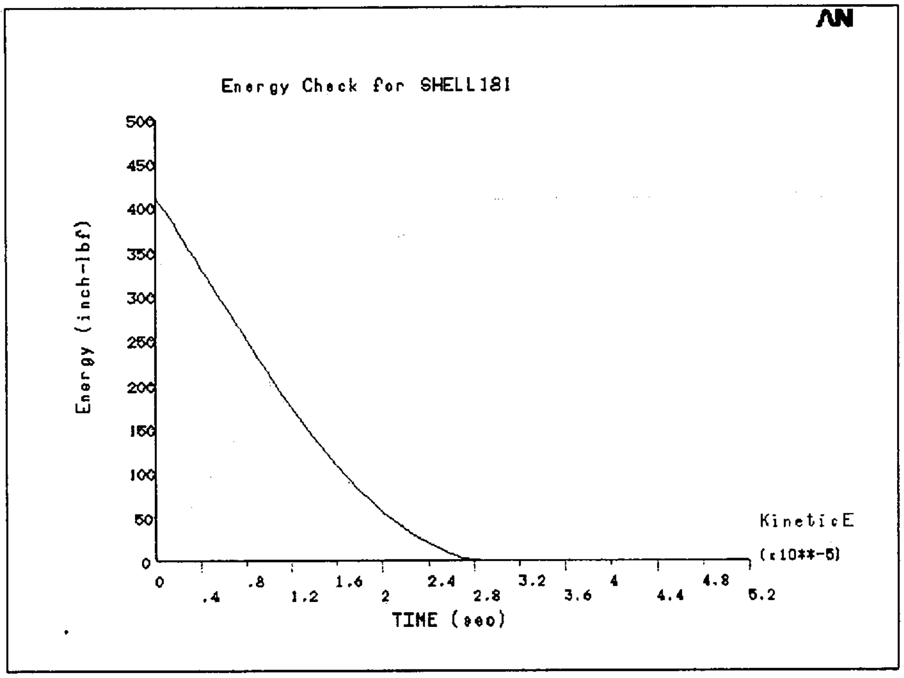
Table 7.5.2.3: Benchmark Results

Test	Deformed Length (cm)	Ratio
Experiment	1.319	1
SHELL181	1.392	1.055
VISCO106	1.398	1.060
SOLID45	1.397	1.059
SOLID95	1.408	1.067
VISCO107	1.406	1.066

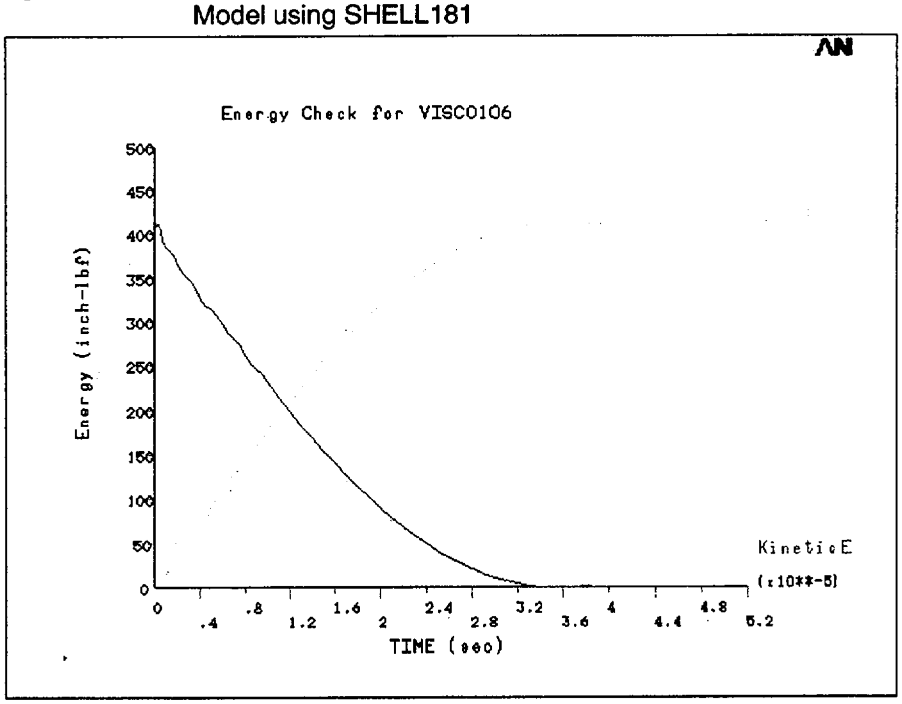
The deformed bar length from the benchmark analysis using SHELL181 is within 5.5% of the experimental value. The performance of SHELL181 is excellent in comparison with the other ANSYS solid elements. Thus SHELL181 is suitable for nonlinear dynamic impact analysis.

Figures 7.5.2.3a and 7.5.2.3b show the time history of the kinetic energy and the cumulative plastic work in the impacting bar model using SHELL181 element and VISCO106 element. The calculated

cumulative plastic work for both elements is essentially the same as the input kinetic energy. Therefore, the ANSYS cumulative plastic work calculation for SHELL181 is justified.



Figures 7.5.2.3a: Kinetic Energy and the Cumulative Plastic Work in an Impacting Bar Model using SHELL181



Figures 7.5.2.3b: Kinetic Energy and the Cumulative Plastic Work in an Impacting Bar Model using VISCO106

7.5.3 Puncture Stress Analyses

The RVTS cask shell is analyzed for a 40" puncture drop on a 6" OD steel rod. The 8-inch long steel rod is standing vertically on an essentially unyielding, horizontal surface. The rod is conservatively assumed to be rigid and remains in the vertical position. Local punching shear damage creating a 6-inch diameter hole is within the limitation of the design criteria in Section 5.0. However, the effect of the puncture drop on the existing damage from the 30-foot drop is the main concern of the puncture drop analysis. Since local puncture stress is not analyzed, refining the local mesh at the puncture location is not necessary. The most limiting damage to the cask from the 30-ft drop analyses occurs at the top rim. The total damage in a 45-degree arc of the top plate rim is considered for the subsequent HAC evaluation. The damaged elements are removed prior to the beginning of the puncture drop. Two puncture locations are considered. One location is near the mid-shell between the top plate and the shield plate. The second location is on the top shell next to the damaged top plate rim.

7.5.3.1 Puncture Drop near Mid Shell (Load Cases PMD1 and PMD2)

The initial conditions for the PMD analyses include nodal temperatures from thermal load cases T1 and T3, pressures of 20 psi and –3 psi as described in 10 CFR 71, and an initial vertical impact velocity of 176 in/sec from a 40" free fall. Contact between the cask shell and the essentially unyielding, horizontal surface is modeled along with the contact between the RV flange and the cask shell.

After an impact duration of 0.080 second, the rims of the top plate and the bottom plate have reached the ground. The mid-shell has deformed and could be penetrated by the steel rod but the maximum principal stress, S1, around the damaged 45-degree arc rim remains within the material tensile strength. As shown in Figures 7.5.3.1c and 7.5.3.1.d, S1 at locations "TopPl1", "TopPl2", "TopShl1" and "TopShl2" located near the end of the damaged rim, remains less than 45 ksi. Therefore, a 40" puncture drop on a steel rod near the mid-shell will not increase the existing damage from the 30' drop.

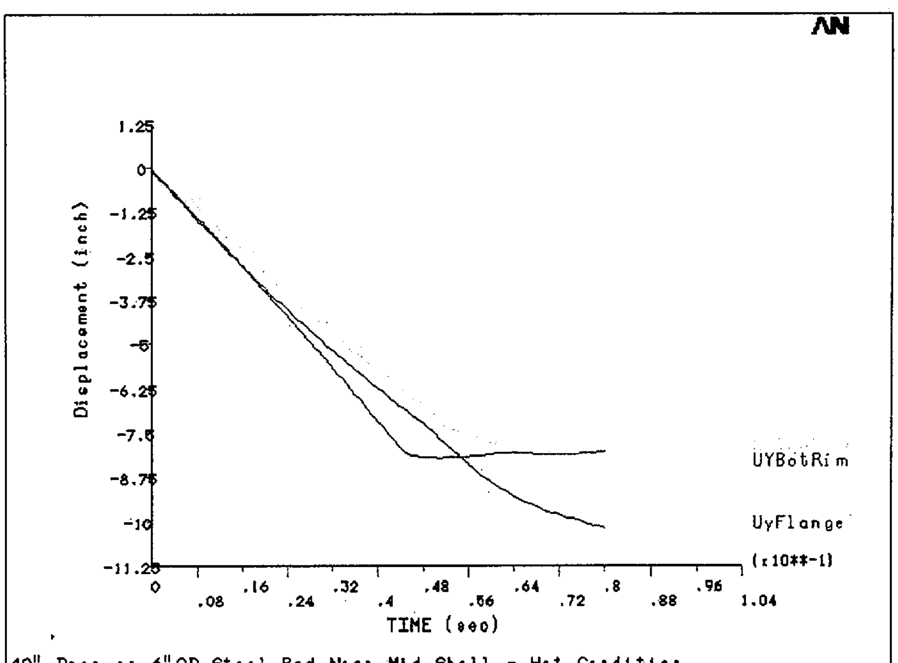


Figure 7.5.3.1a: PMD1 Vertical Displacement Time History

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
		Rev. 0	Date:
● Important to Safety Category A	Non-Safety-Related	Page	94

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Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

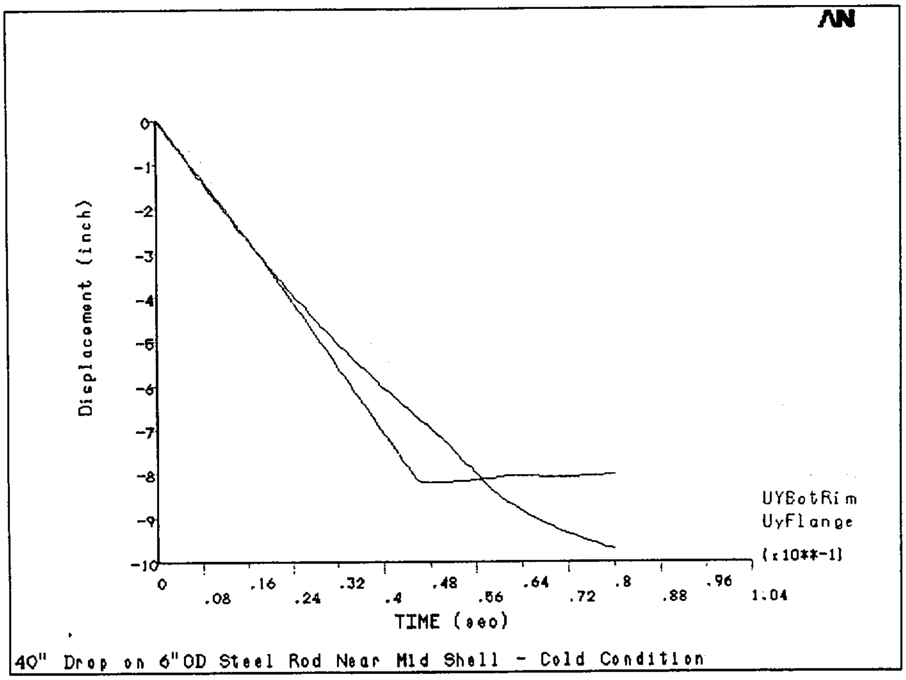


Figure 7.5.3.1b: PMD2 Vertical Displacement Time History

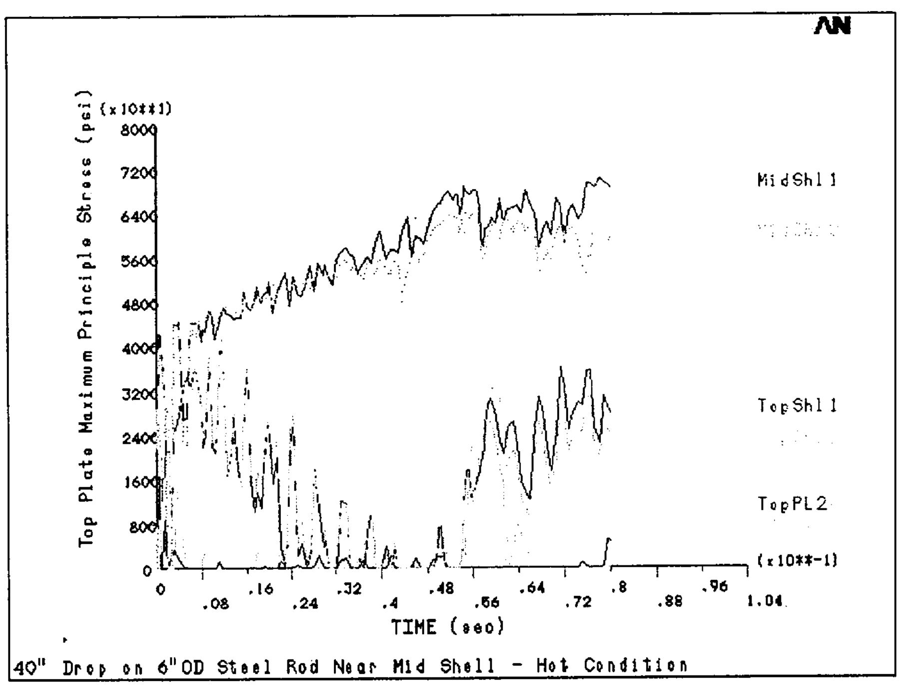


Figure 7.5.3.1c: PMD1 Maximum Principal Stress Time History

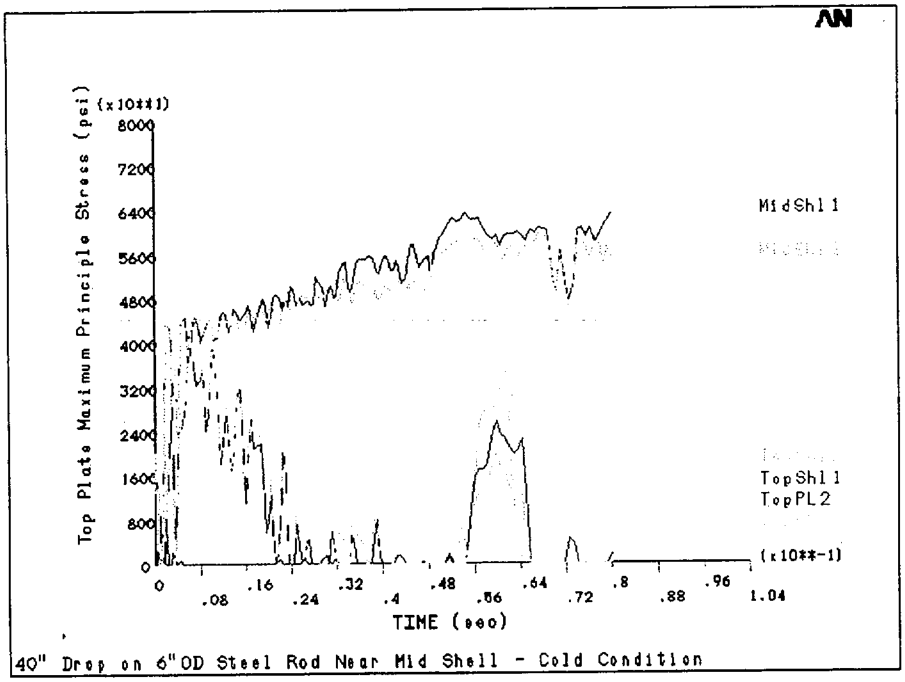


Figure 7.5.3.1d: PMD2 Maximum Principal Stress Time History

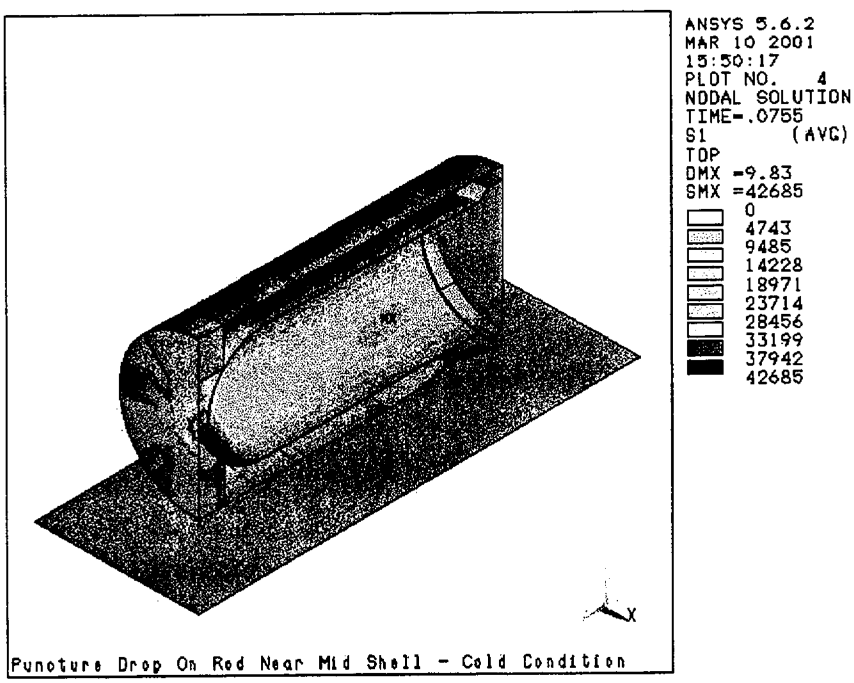


Figure 7.5.3.1e: PMD2 Maximum Principal Stress Contours

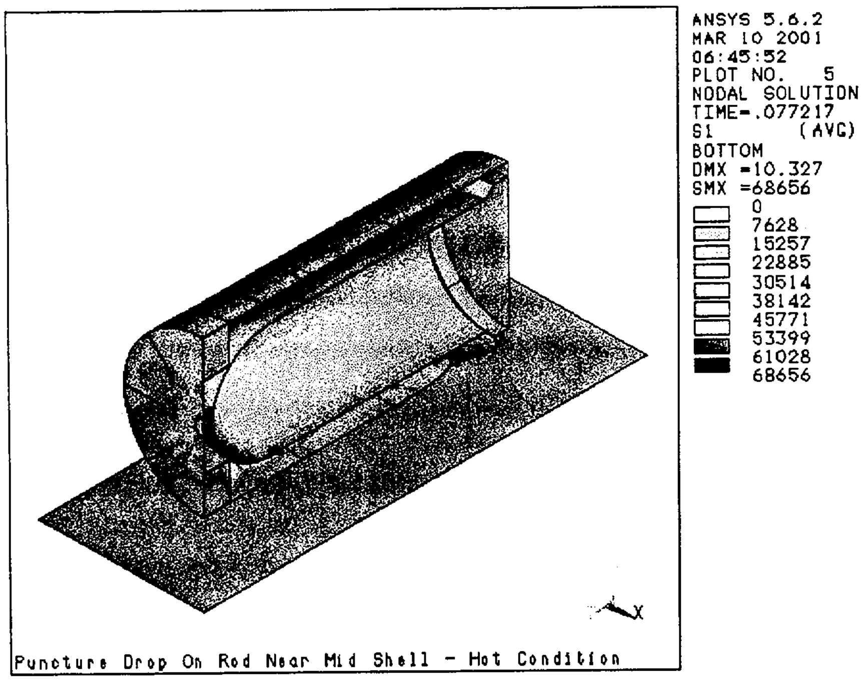


Figure 7.5.3.1f: PMD1 Maximum Principal Stress Near the Puncture Location

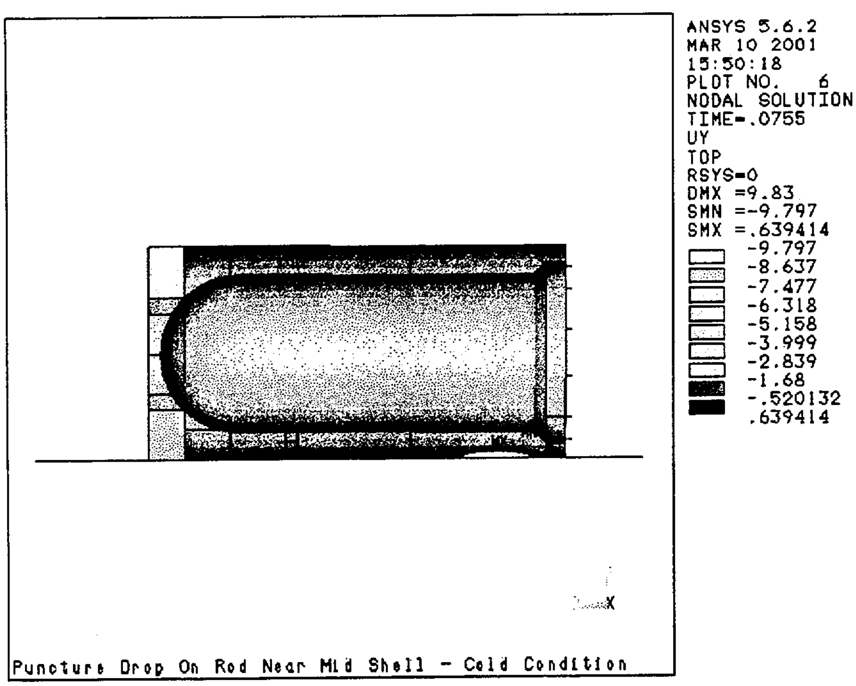


Figure 7.5.3.1g: PMD2 Vertical Displacement Contours

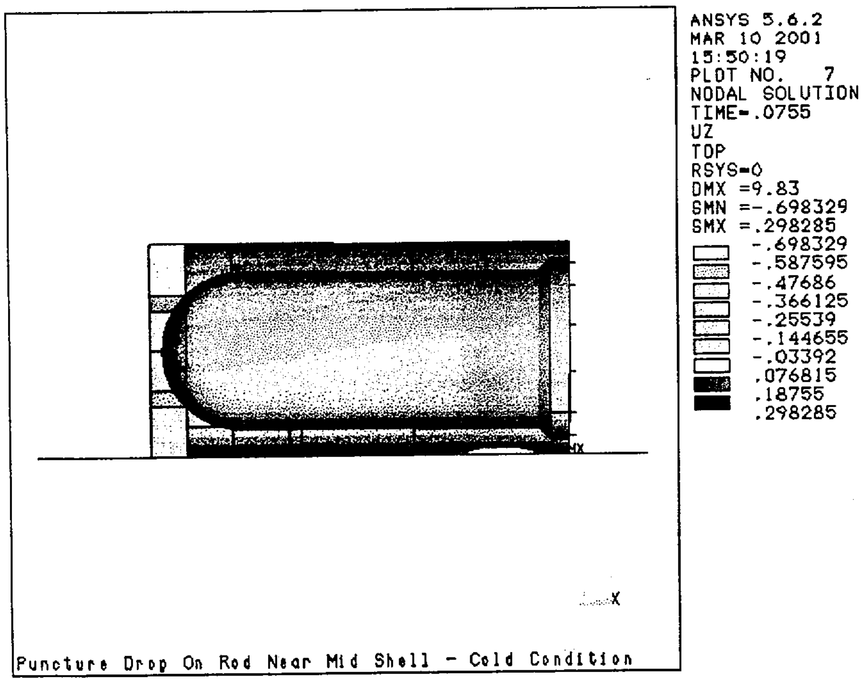


Figure 7.5.3.1h: PMD2 Horizontal Displacement Contours

7.5.3.2 Puncture Drop near Top Shell (Load Cases PTD1 and PTD2)

The initial conditions for the PTD analyses include nodal temperatures from thermal load cases T1 and T3, pressures of 20 psi and –3 psi as described in 10 CFR 71, and an initial vertical impact velocity of 176 in/sec from a 40" free fall. Contact between the cask shell and the essentially unyielding, horizontal surface is modeled between the RV flange and the cask shell.

After an impact duration of 0.060 second, the RV flange has reached the cask shell at the damaged rim. The puncture location at the top-shell has deformed and could be penetrated by the steel rod but the maximum principal stress, S1 at anywhere else remain less than the material tensile strength. As shown in Figures 7.5.3.1c and 7.5.3.1.d, S1 at locations "TopPl1", "TopPl2", "MidShl1" and "MidShl2" located near the end of the damaged rim, remains less than 45 ksi. Therefore, a 40" puncture drop on a steel rod near the top shell will not increase the existing damage from the 30' drop.

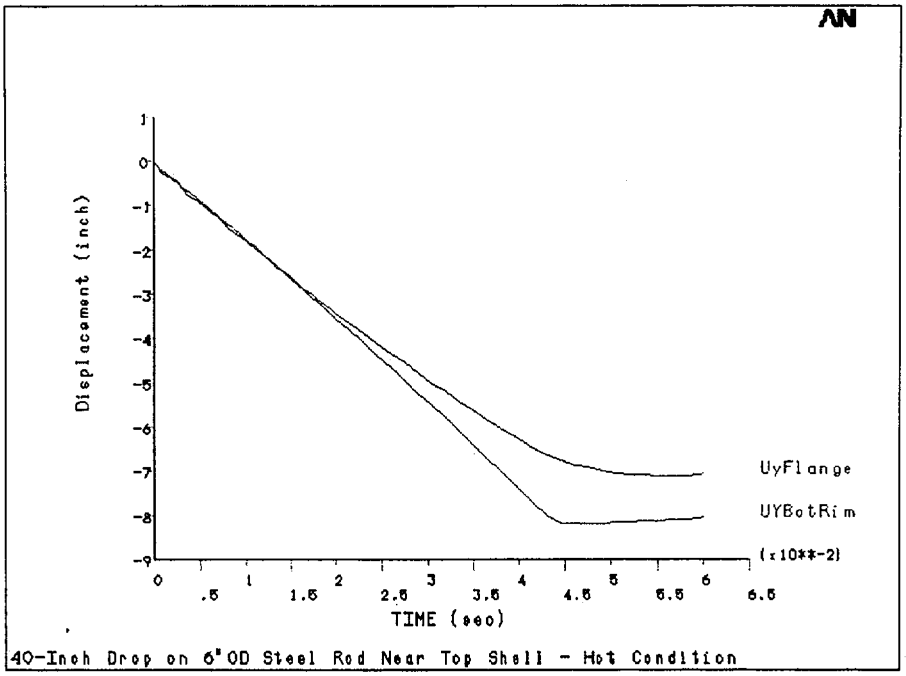


Figure 7.5.3.2a: PTD1 Vertical Displacement Time History

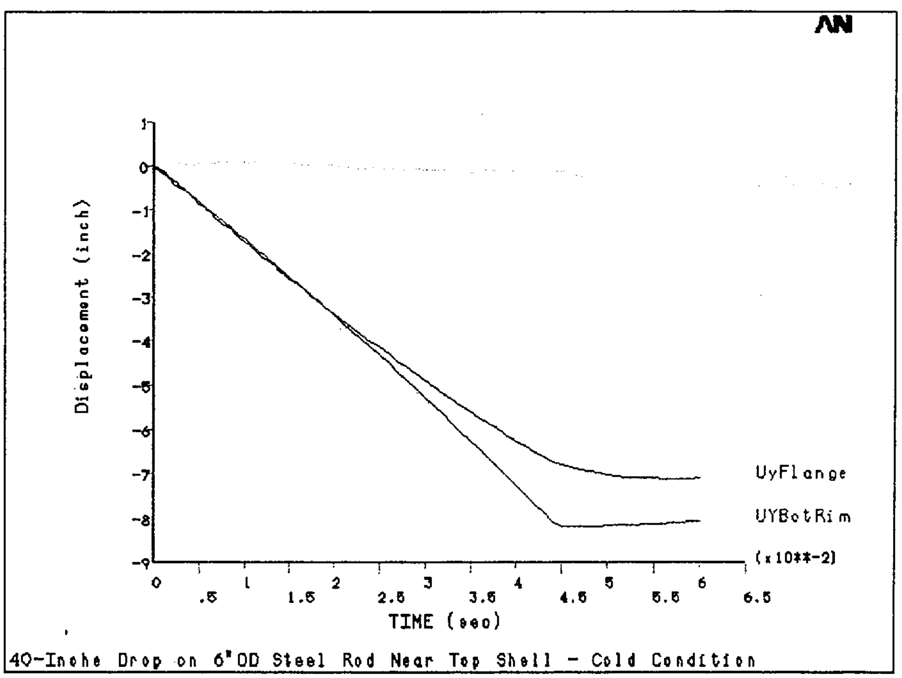
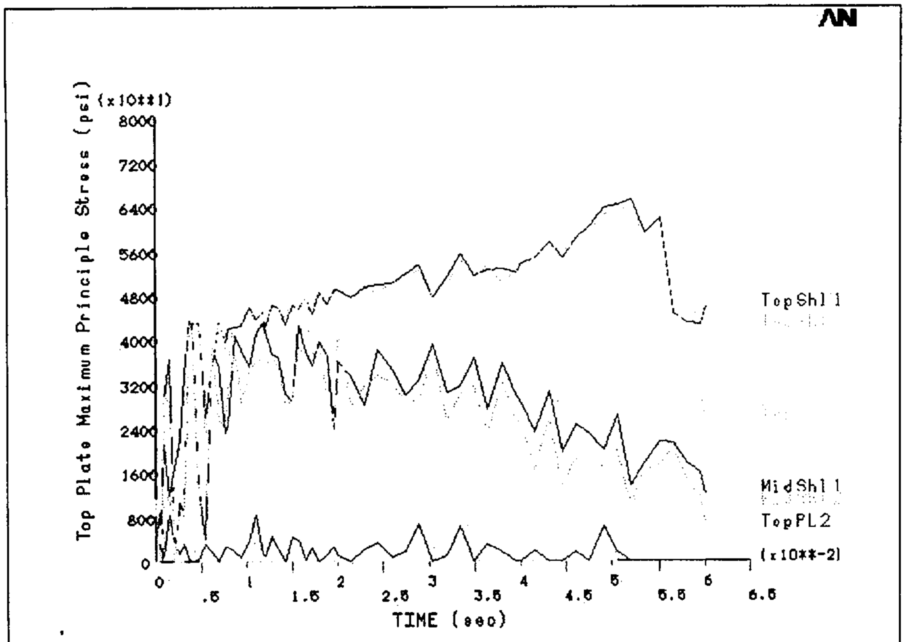
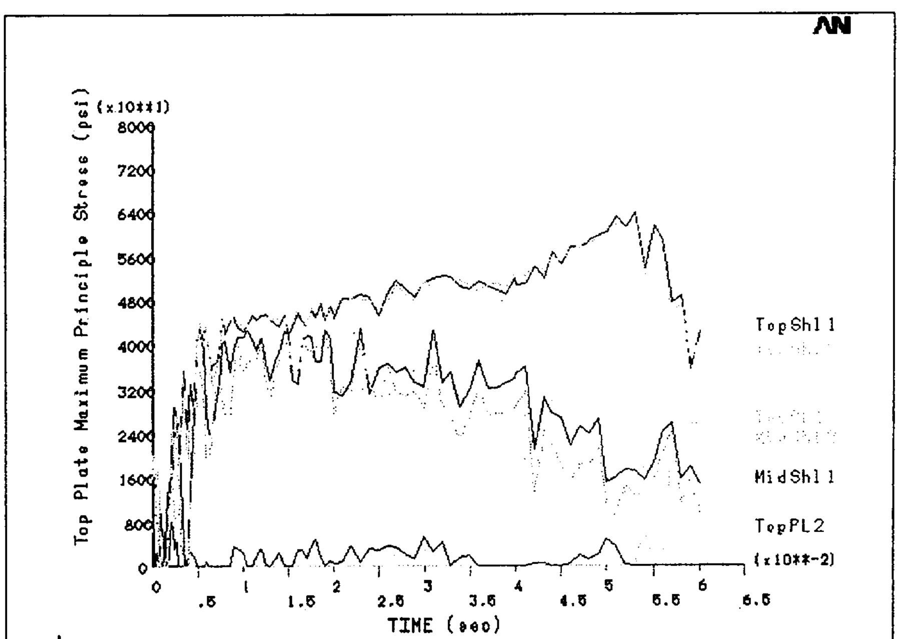


Figure 7.5.3.2b: PTD2 Vertical Displacement Time History



40-Inch Drop on 6" OD Steel Rod Near Top Shell - Hot Condition

Figure 7.5.3.2c: PTD1 Maximum Principal Stress Time History



40-Inchs Drop on 6" OD Steel Rod Near Top Shell - Cold Condition

Figure 7.5.3.2d: PTD2 Maximum Principal Stress Time History

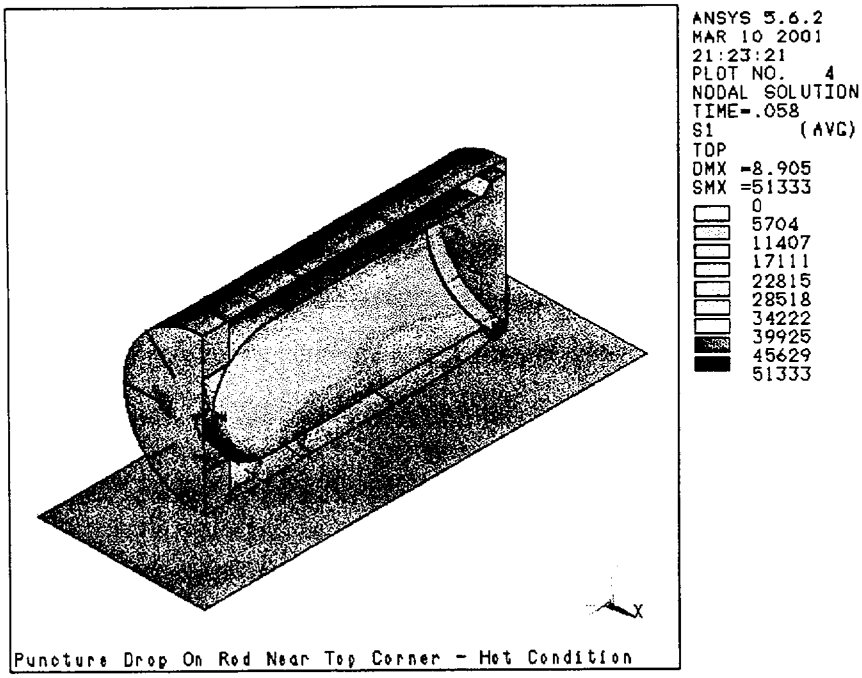


Figure 7.5.3.2e: PTD1 Maximum Principal Stress Contours

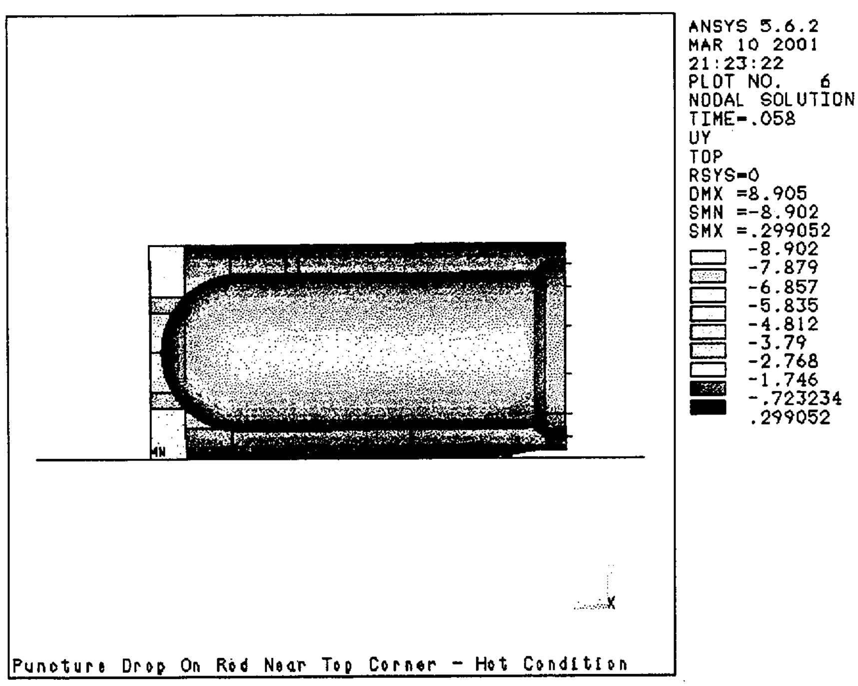


Figure 7.5.3.2f: PTD1 Vertical Displacement Contours

7.5.4 Thermal Fire Accident

During the 30-minute hypothetical fire accident, differential thermal expansion occurs between the RVTS cask and the RV in both longitudinal and radial directions. This differential thermal expansion may cause a gap between the base of the RV and the internal donut ring support. Therefore, the RV could potentially become a cantilevered beam supported only by the cask top closure plate through the RV flange bolts. Although the LDCC between the annulus of the RVTS cask could provide compressive support during this scenario, the effect of the LDCC is conservatively neglected in the structural analysis to ensure that the RV flange bolts and the cask top closure plate can adequately support the weight of the RV during and after the 30-minute thermal exposure.

A nonlinear weight analysis is performed without support on the RV hemispherical bottom at the donut plate. The analysis includes the maximum HAC pressure of 95 psi along with the fire accidents considering with two initial thermal conditions. These two thermal load cases, T4 and T5 analyzed in Section 7.2, are:

- T4 = Fire condition, Initial 100°F Ambient, Zero Decay Heat and Zero Insolation.
- T5 = Fire condition, Initial -20°F Ambient, Zero Decay Heat and Zero Insolation.

Nodal temperatures of load cases T4 and T5 are shown in Figures 7.5.4a and Figure 7.5.4b, respectively. These temperature distributions are the limiting temperature gradient that the RVTS would experience during a 30-minute fire. Temperature dependent material properties listed in Attachment A are modeled. All loads are gradually increased in multiple sub-steps. Note that the time variable in the graphs is the sub-step and not the actual time duration.

Figure 7.5.4c shows the THACC1 vertical displacement of the top plate center and the RV bottom head with respect to the load steps. The RV bottom head moves up to about 0.298" and then drops down to about 0.1" due to weight load and reduced strength as the temperature rises.

Bolt stress intensity increases to 40 ksi as the temperature rises to 950°F. The load is then redistributed to the other bolts. At the highest bolt temperature of 1250°F, the stress intensity in all studs is 31.7 ksi, which is less than the bolt tensile strength of 46 ksi at 1250°F

The maximum stress intensity in the cask reaches 31.5 ksi at a location near the damaged top cover plate rim as the temperature rises to about 450 °F. The maximum stress intensity is less than the material tensile strength of 70 ksi at temperature not greater than 700°F. The maximum stress intensity is then reduced to 18 ksi at the highest temperature of 1400 °F, which is less than the material tensile strength of 23 ksi for the cask material at a temperature of 1400°F.

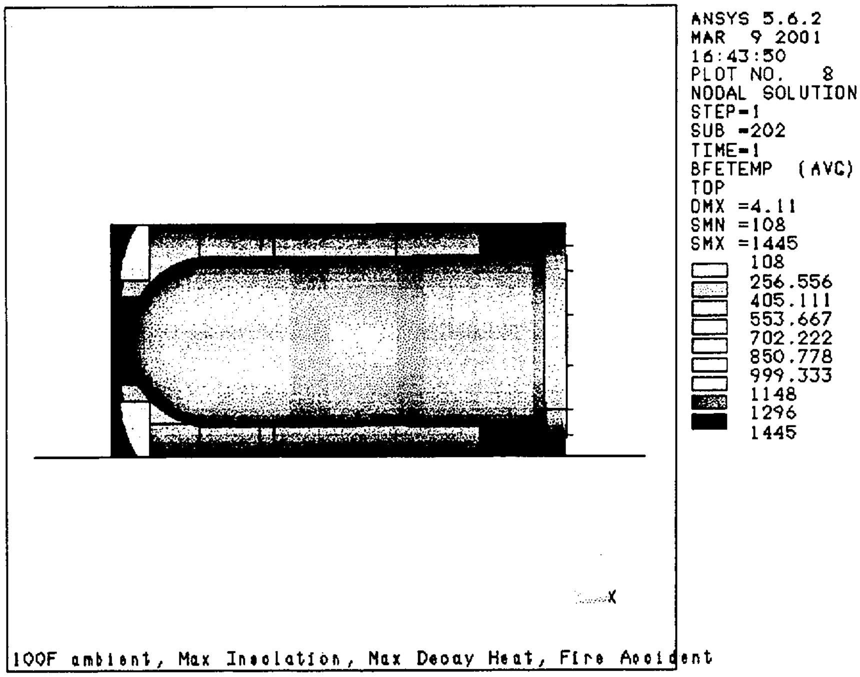


Figure 7.5.4a: THACC1 – Temperature Distribution After 30 Minutes

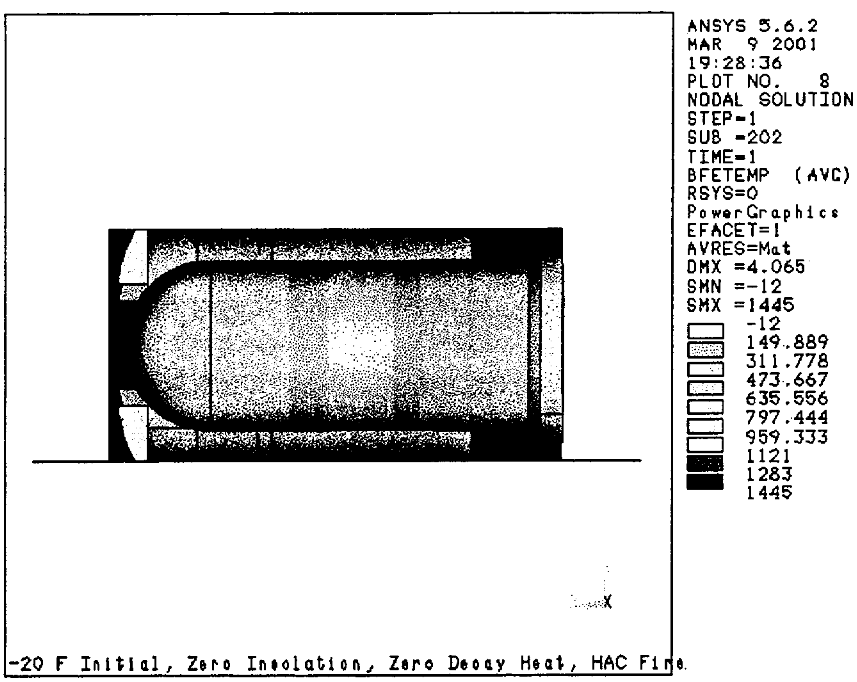


Figure 7.5.4b: THACC2 – Temperature Distribution After 30 Minutes

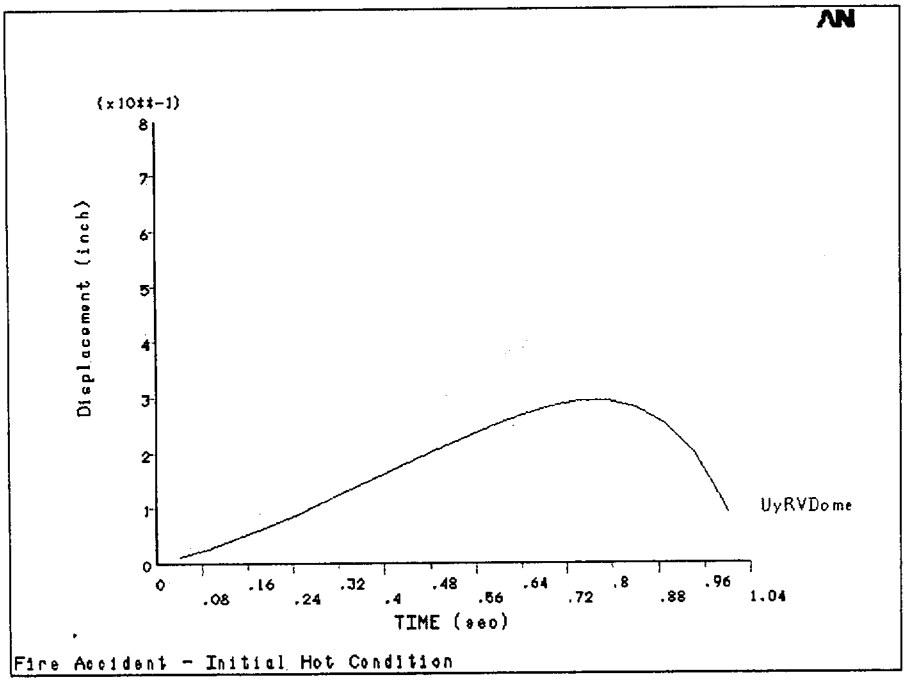


Figure 7.5.4c: THACC1 – Vertical Displacement During Fire Accident

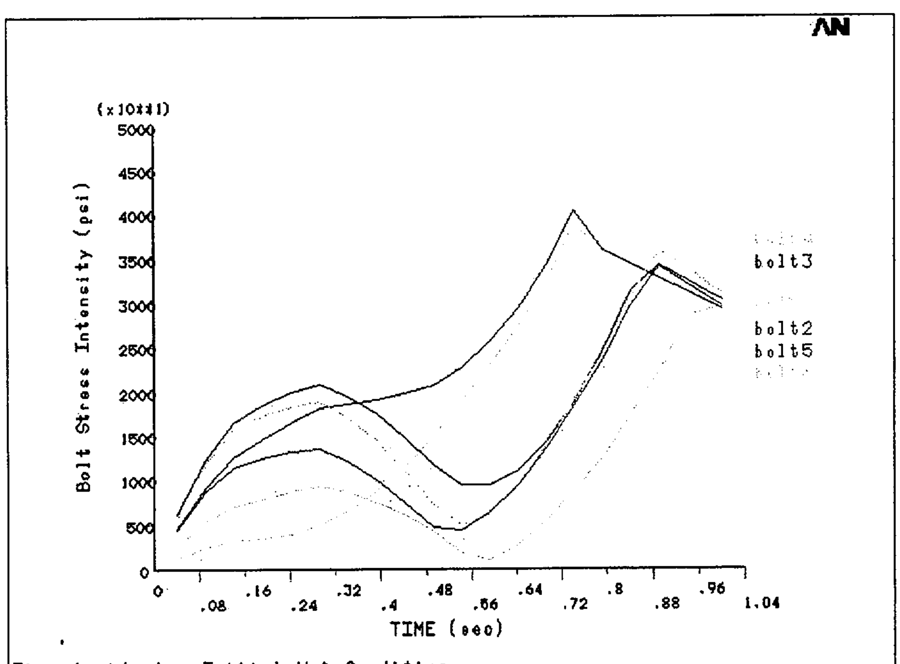


Figure 7.5.4d: THACC1 – Bolt Stress Intensity During Fire Accident

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Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
		Rev. 0	Date:
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Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

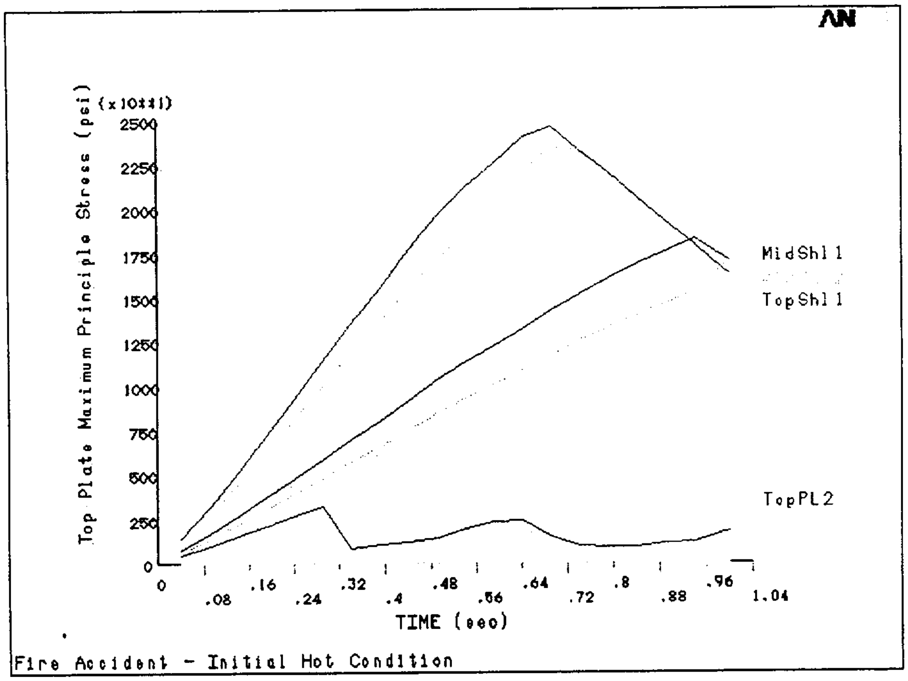


Figure 7.5.4e: THACC2 –Maximum Principal Stress During Fire Accident

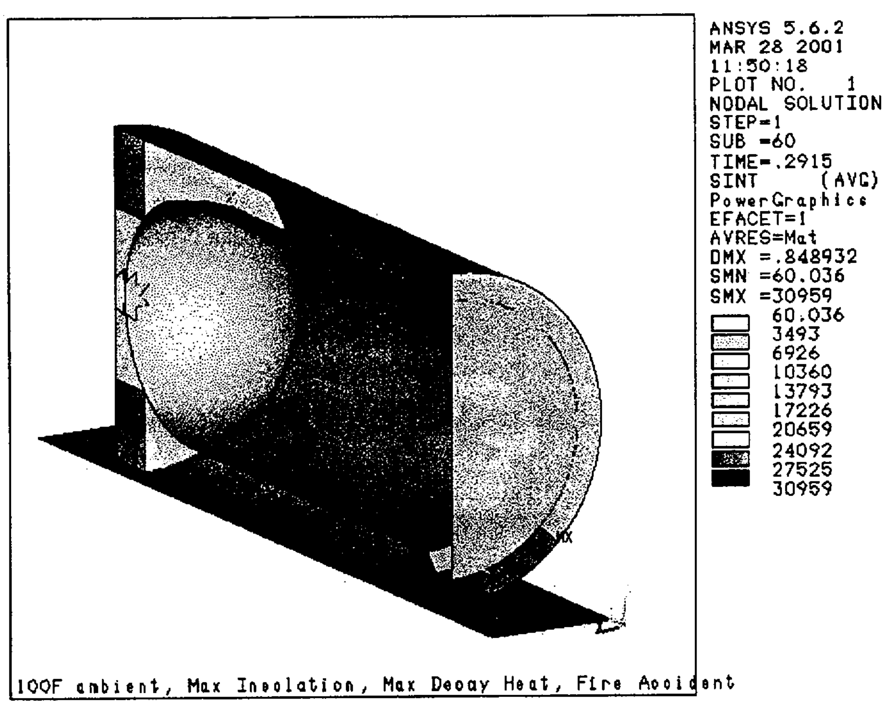


Figure 7.5.4f: THACC1 – Stress Intensity Contours

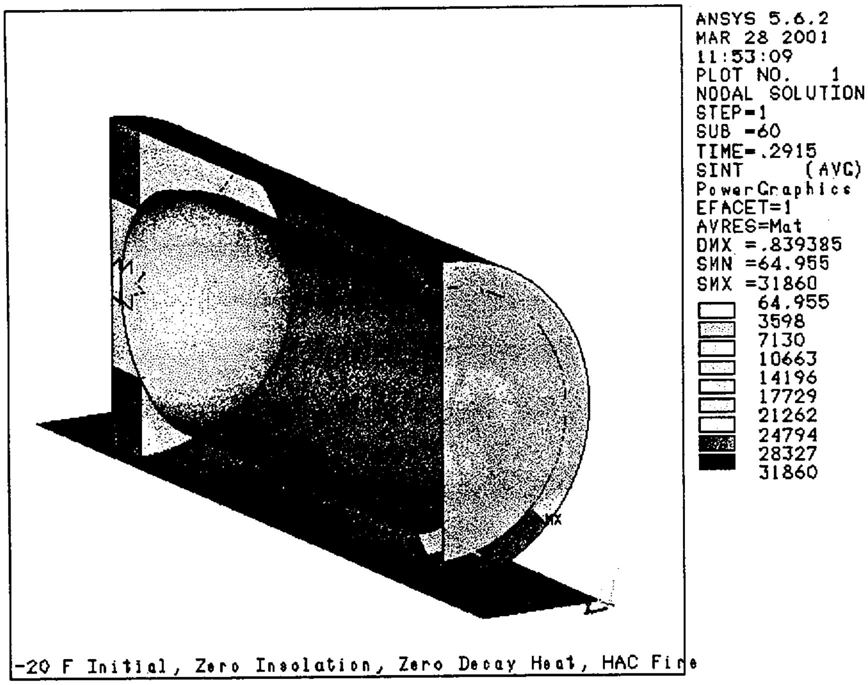


Figure 7.5.4g: THACC2 – Stress Intensity Contours

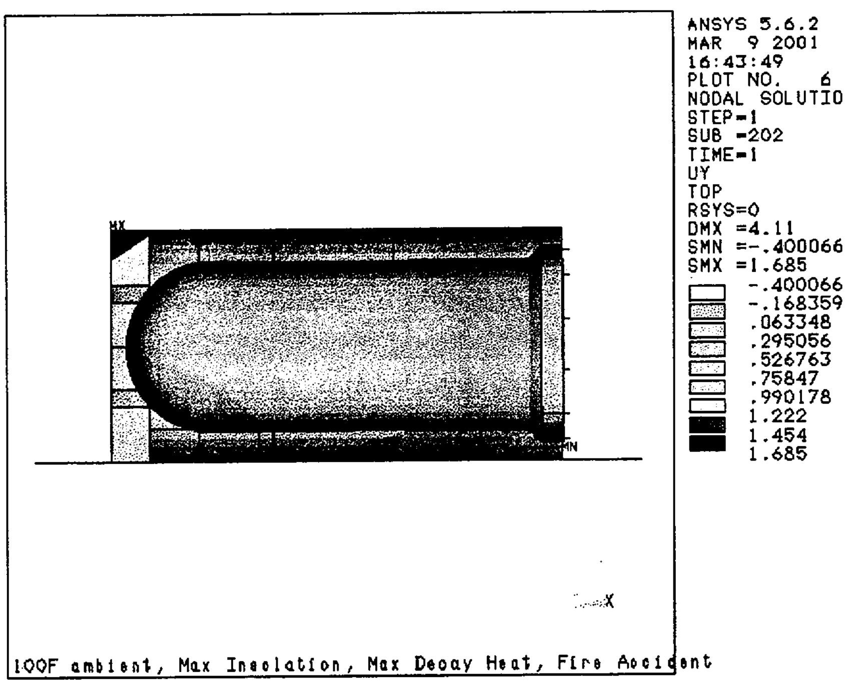


Figure 7.5.4h: THACC1 – Vertical Displacement Contours

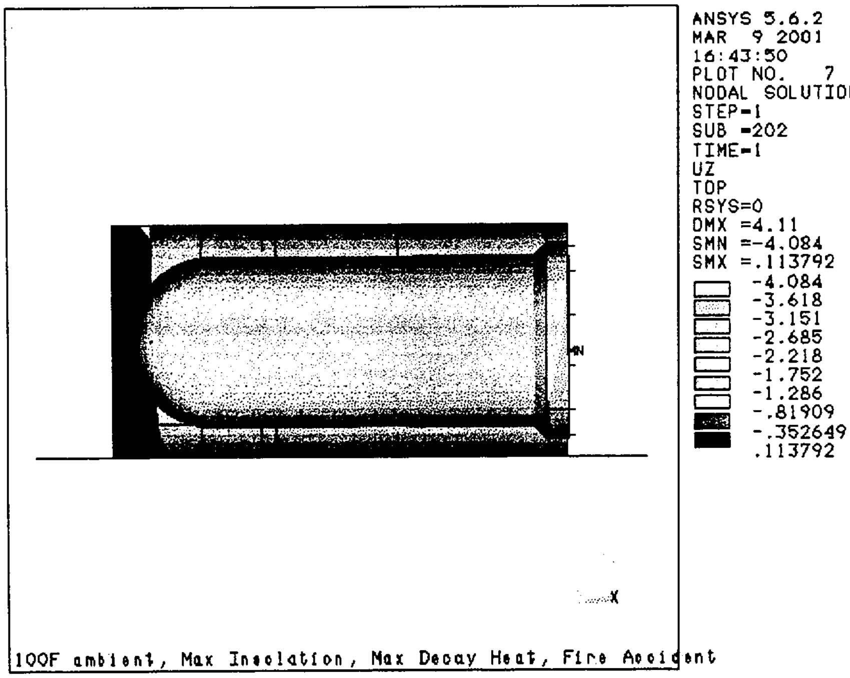


Figure 7.5.4i: THACC2 – Horizontal Displacement

7.5.5 Water Immersion

The RVTS cask is subjected to an external pressure equivalent to immersion under 50 feet of water (21.7 psig) per 10 CFR 71.73 (c)(6). The vessel buckling effects are checked by combining the minimum internal pressure –3 psig (resulting from the initial temperature condition of -20° F) with the above immersion pressure to maximize the total pressure effect. Therefore, an equivalent external pressure of 21.7+3 = 24.7 psig will be used for the water immersion analysis. The maximum allowable external pressure determined using ASME Section III, Reference 3.1, Article NB-3133.3 is calculated as follows:

$$\frac{L}{D_o} = 2$$ Cask length L =300 inches and Do =156 inches

$$\frac{D_o}{T} = 52$$ Cask thickness T = 3 inches

From Figure G, ASME Section II, Part D, Subpart 3, the A factor for the above parameter is

$$A = 0.002$$

From Figure CS-2, ASME Section II, Part D, Subpart 3, for carbon steel with a yield strength between 30 ksi to 38 ksi and at a temperature less than 300 °F, factor B for the external pressure calculation is

$$B = 15000\,\text{psi}$$

The allowable external pressure Pa per NB-3133.3 is

$$P_a = \frac{4}{3}\frac{B}{D_o/T} \qquad P_a = 385\text{psi}$$

Water immersion external pressure is 24.7 psig This is less than the allowable external pressure, Pa. Therefore, the RVTS Cask meets the 10 CFR 71.73(c)(6) requirements for the water immersion condition. The safety margin is 15.

7.5.6 Shield Plate and Ring Plate Weld Check

The shield plate and the ring plate are welded continuously around the circumference of cask cylindrical shell interior surface. The fillet welds are designed to support the shield plate and the ring plate from axial sliding. The vertical drop load case is expected to be the worst loading case for the fillet welds because of the direction and the duration of the impact. The impact direction of the vertical drop is the same as the axial direction of the cask. The vertical drop case has the smallest impact duration. The smaller impact duration, the higher impact acceleration would be resulted. As shown in Table 7.5.6, the VD1 load case has the highest the axial load on the fillet weld at the time of the peak vertical or horizontal displacements of the selected key locations. Therefore, the VD1 load case is selected for weld stress calculation.

Table 7.5.6 Axial Loads on Shield Plate and Ring Plate Fillet Welds under HAC Conditions

Load Case	Post 1 Output File	Weld Location	Axial Force On Half Model (lbs)
VD1	VDP1Weld.out	Shield Plate	3397700
	VDP1Weld.out	Ring Plate	2677900
VD2	VDP2Weld.out	Shield Plate	2229300
	VDP2Weld.out	Ring Plate	1832300
HD1	HDP1Weld.out	Shield Plate	724370
	HDP1Weld.out	Ring Plate	347480
HD2	HDP2Weld.out	Shield Plate	1419600
	HDP2Weld.out	Ring Plate	248480
CD1	CDP1Weld.out	Shield Plate	1340900
	CDP1Weld.out	Ring Plate	12574
CD2	CDP2Weld.out	Shield Plate	1293800
	CDP2Weld.out	Ring Plate	155270
FDP11	FDP11Weld.out	Shield Plate	1653500
	FDP11Weld.out	Ring Plate	208510
FDP12	FDP12Weld.out	Shield Plate	808960
	FDP12Weld.out	Ring Plate	183170
FDP21	FDP21Weld.out	Shield Plate	387780
	FDP21Weld.out	Ring Plate	631060
FDP22	FDP22Weld.out	Shield Plate	1459200
	FDP22Weld.out	Ring Plate	333450

The displacement time histories of the shield plate and the ring plate in Figure 7.5.6 show that the time it takes the initial velocity of 527.4 in/sec to reduce to zero is 0.00625 seconds. Thus the impact acceleration is:

G = 527.4 / (0.00625* 386.4) = 218 g

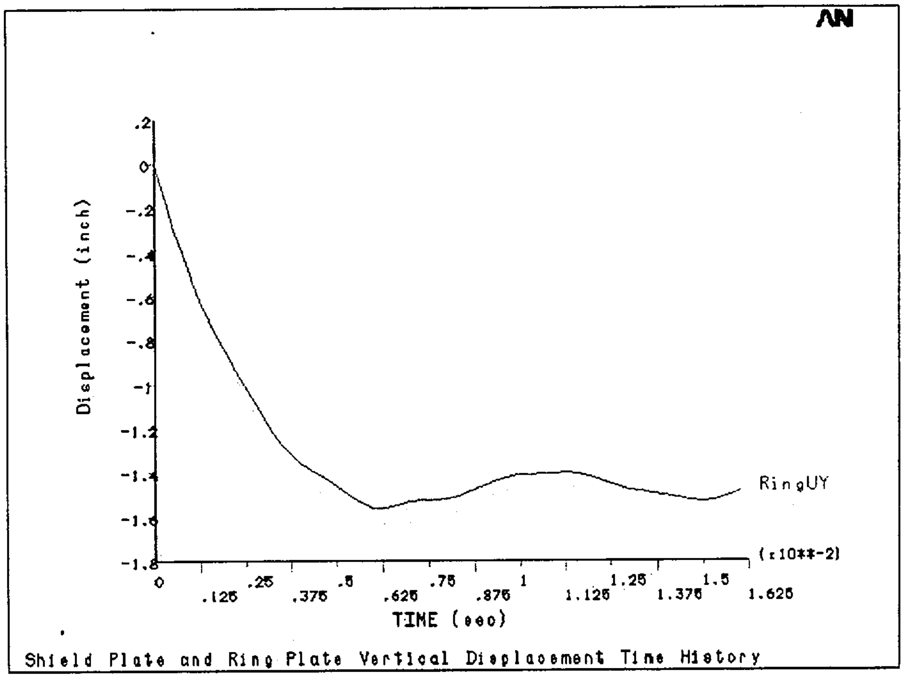


Figure 7.5.6: VD1 Vertical Displacement Time Histories of the Shield Plate and the Ring Plate

The weight of the shield plate is SPWT = 0.284 * (3.14*75*2) * 4 * 96 = 51, 370 lbs
The weight of the ring plate is RPWT = 0.284 * (3.14*75*2) * 3 * 40 = 16, 050 lbs

The axial force on the shield plate is Fs = SPWT * G = 51,370 * 218 = 11.22 E+6 lbs
The axial force on the ring plate is Fr = RPWT * G = 16,050 * 218 = 3.05E+6 lbs

Shear area of the shield plate 1" fillet welds As = 2 * (3.14*75*2) * 1 * 0.707 = 666 in^2
Shear area of the ring plate 0.5" fillet welds Ar = 2 * (3.14*75*2) * 0.5* 0.707 = 333 in^2

Shear stress in the shield plate weld = Fs /As = 11.22E+6 / 666 = 16,680 psi
Shear stress in the ring plate weld = Fr /Ar = 3.05E+6 / 333 = 10,530 psi

The allowable shear stress on the effective area per NF-3226.2 is 0.45 times nominal tensile strength (70 ksi) of the weld material or 31,500 psi

Therefore, the shield plate and the ring plate remain intact in HAC events.

7.6 Burial Condition

Once the RVTS reaches Barnwell, SC, its final destination, it will be moved in a horizontal position and placed in a burial trench. The cask will then be buried under a 40 feet deep column of soil with a density of 120 pcf, per Reference 3.17. Therefore, the RVTS is designed to withstand the constant pressure of 33 psig resulting from these burial conditions. Per the calculation in 7.5.5, the cask allowable external pressure is 385 psi. Therefore, the RVTS Cask has a safety factor of 11 under the final burial condition.

7.7 Brittle Fracture Protection Evaluation

10 CFR Part 71 requires that casks used to transport radioactive material be designed with consideration of NCT and HAC that might occur at –20°F, the lowest service temperature (LST = –20°F). The provisions of Regulatory Guide 7.11, " Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels With a Maximum Wall Thickness of Four Inches" and NUREG/CR-1815, "Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick", are used in the measurement and determination of NDT (Nil Ductility Transition) temperature for the RVTS plate material to meet the above 10 CFR 71 requirements.

The Big Rock Point RVTS is a Type B, Category II cask. Therefore, the required NDT temperature is determined by using a value of β=0.6 in accordance with the methodology provided in Section 5.2 of NUREG/CR-1815.

For a cask shell thickness of 3 inches, SA-516 Grade 70 carbon steel plate with a yield strength less than 60 ksi, the NDT temperature requirement determined from Section 5.2.1, Figure 6 of NUREG/CR-1815 is:
LST- A°F = -20 °F - 0°F = -20 °F.

For the end plate, fabricated from 4-inch SA-516 Grade 70 carbon steel plate with a yield strength less than 60 ksi, the shifted temperature, A°F, from Figure 6 of NUREG/CR-1815 is 15 °F. Therefore, the required NDT temperature is:
LST- A°F = -20 °F - 15°F = -35 °F.

Therefore, the specified NDT temperature is -35 °F for the RVTS cask material to meet the 10 CFR 71 requirement (LST=-20°F) for shipping of a Type B, Category II cask.

Alternatively, a NDT temperature of -20 °F is acceptable to protect the RVTS from brittle fracture, provided that the lowest service temperature, LST, is limited to:

LST=NDT+ A°F = -20 °F+15 °F = -5 °F

8.0 Conclusion

The structural evaluation of the Big Rock Point RVTS demonstrates that the RVTS design meets the criteria in 10 CFR 71.35, "Package Evaluation", which requires casks used to transport radioactive materials to demonstrate adequacy for the NCT and HAC specified in Subparts E and F of 10 CFR Part 71. The evaluation complies with Regulatory Guide 7.6, "Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels" for linear elastic analyses. Load combinations of the structural evaluation are in accordance with Regulatory Guide 7.8, "Load Combinations for the Structural Analysis of Shipping Casks for Radioactive Material". Material toughness requirements and the lowest service temperature, LST, determination are per Regulatory Guide 7.11, "Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches". In addition, the RVTS cask also meets the design vibration and shock accelerations given by both the guidelines of the Association of American Railroads (AAR) and the ANSI N14.2 (Draft). Finally, the RVTS cask meets the design requirements of the burial conditions given by the disposal facility at Barnwell, SC.

The minimum stress margin factors for the NCT is 1.2, which is the minimum margin for 1-foot drop load. For shock and vibration loads during transport, the minimum load margin is 1.9. A minimum margin of 4.6 is present for all other NCT loads. The NCT fatigue usage factor is 0.109. Since the fatigue usage factor is several times less than the allowable of 1, the shipping distance can be extended to at least twice of the assumed value of 1500 miles if needed. The 5-foot drop linear elastic analyses indicate a minimum stress margin of 1.04 for handling accident conditions. The extreme stress range that envelops all NCT and Handling Accident Condition meets the Reg. Guide 7.6, Position 7 criteria with a stress margin factor of 2.38.

Among the 30-foot drop analyses for HAC, the most limiting load case is the secondary flap down drop resulting from a 10 degree oblique corner drop. The nonlinear dynamic impact analysis results show potential for local damage that extends over a 45-degree arc along the cask top plate rim. Local damage is also expected for the other flap down drops, especially the 50-degree oblique drop, which has the maximum horizontal velocity. This flap down drop causes local damage on a 30-degree arc of the top plate rim. No local failure is predicted in the vertical drop, horizontal drop and the corner drop on the cask CG. In all 30-foot drops, the RVTS cask remains a stable structure and sustains no structural failure that exceeds the damage limits set forth in Reference 3.6.10, Calculation N-10525-041-001, "Breach of Containment". The fillet welds of the shield plate and ring plate are well within the weld shear stress allowable per Section 5.0. Bolt stress intensity remains less than the Code minimum specified material tensile strength. No bolt failure is predicted. However, even if all bolts fail, the RV flange would drop down and come into contact with the cask shell, which is directly supported by the essentially unyielding, horizontal surface. Thus, bolt failure would not result in a significant contribution to the cask 30-foot drop damages. Based on the results of the 30-foot drop analyses, it is concluded that the maximum damage would not extend more than a quarter of the top plate circumference.

In the subsequent HAC analyses, failure in a quarter of the RVTS top plate circumference is assumed prior to the 40-inch puncture drop and fire accident analyses. The puncture drop on a 6-inch OD steel rod would punch a hole on the cask shell but would not extend the existing cask damage. The fire accident analysis demonstrates that the damaged cask remains a stable structure under the weight load and HAC fire accident pressure at the elevated temperature.

The required NDT temperature is -35 °F for the RVTS cask material to meet the 10 CFR 71 requirement for shipping a Type B, Category II cask at the lowest service temperature of -20°F. However, a NDT temperature of -20 °F is acceptable to protect the RVTS from brittle fracture, provided that the lowest service temperature, LST, is limited to –5°F.

A total weight of 800 lbs for the 0.5" thick steel plates with rounded edge can be welded on the RVTS exterior surface to provide local shielding if required.

ATTACHMENT A

MATERIAL PROPERTIES

Sargent & Lundy	Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No.	S-10525-020-012
	●	Important to Safety Category A	Non-Safety-Related	Rev. 0 Date:
				Page A2

Client	BNFL, Inc	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

The following thermal properties are obtained from ASME Code, 1995 Edition, Section II, Part D, Subpart 2, Tables TE-1 and TCD:

Temperature °F	Mean Coefficient of Thermal Expansion, α X10^{-6} (in/in/°F)		Nominal Coefficient of Thermal Conductivity, Tc Btu/(hr-ft-°F)	
	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo
70	5.42	7.02	23.6	23.3
100	5.53	7.06	23.9	23 6
150	5.71	7.16	24.2	24.1
200	5.89	7.25	24.4	24.4
250	6.09	7.34	24.4	24.6
300	6.26	7.43	24 4	24.7
350	6.43	7.50	24.3	24.7
400	6.61	7.58	24.2	24.6
450	6.77	7.63	23.9	24.4
500	6.91	7.70	23.7	24.2
550	7.06	7.77	23.4	23.9
600	7.17	7.83	23.1	23.5
650	7.30	7.90	22.7	23.2
700	7.41	7.94	22.4	22.8
750	7.50	8.00	22.0	22.4
800	7.59	8.05	21.7	22.0
850	7.9	8.1	21 2	21.6
900	7.9	8.1	20.9	21.2
950	8.0	8.2	20.5	20.8
1000	8.1	8.2	20 0	20.4
1050	8.1	8.3	19.6	19.9
1100	8.2	8.3	19.2	19.5
1150	8.3	8.3	18.7	19.0
1200	8.3	8.4	18.2	18.6
1250	8.4	8.4	17.5	18.1
1300	8.4	8.4	16.7	17.6
1350	--	8.5	15.8	17.0
1400	--	8 5	15.3	16 1
1450	--	8.5	15.1	15.3
1500	--	8.5	15.1	15.5

Sargent & Lundy

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No. S-10525-020-012
		Rev. 0 / Date:
● Important to Safety Category A	Non-Safety-Related	Page A3

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date

The following mechanical properties are obtained from ASME Code, 1995 Edition, Section II, Part D, Subpart 1, Table 2A and Subpart 2, Table TM-1:

Temperature °F	Modulus of Elasticity, E $X10^6$ (psi)		Design Stress Intensity, Sm $X10^3$ (psi)	
	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo	SA-516 Gr 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo
-100	30 2	29.9	--	--
-20	--	--	23.3	26 7
70	29.5	29.2	23.3	26.7
100	29.34*	29.0*	23.3	26.7
200	28.8	28.5	23.1	26 7
300	28.3	28.0	22.5	26.7
400	27.7	27.4	21.7	26.7
500	27.3	27.0	20.5	26.7
600	26.7	26.4	18.7	26.7
650	--	--	18.4	26 7
700	25.5	25.3	18.3	26.7
800	24.2	23.9	--	--
900	22.4	22.2	--	--

* Per Interpolation

The following mechanical properties are obtained from ASME Code, 1995 Edition, Section II, Part D, Subpart 1, Tables U and Y-1:

Temperature °F	Tensile Strength, Su X10^3 (psi)		Yield Strength, Sy X10^3 (psi)	
	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo
70	70.0	80.0	38.0	50.0
100	70.0	80.0	38.0	50.0
150	--	--	35.7	48.6
200	70.0	80.0	34.6	47.2
250	--	--	34.2	46.2
300	70.0	80.0	33.7	45.3
400	70.0	80.0	32.6	44.5
500	70.0	80.0	30.7	43.2
600	70.0	80.0	28.1	42.0
650	70.0	80.0	27.6	41.4
700	70.0	80.0	27.4	40.6
750	69.3	80.0	26.5	40.0
800	64.3	80.0	25.3	38.8
850	58.6	76.6	24.4	37.2
900	52.0	72.7	24.1	34.9
950	46.2	67.3	23.2	31.9
1000	40.3	62.2	21.1	28.4

Per Reference 3.8, the typical concrete compressive strength at 28 days is between 2500 and 4000 psi

The following mechanical properties are obtained from ASME Code, 1995 Edition, Section II, Part D, Subpart 1, Tables 4 and Y-3 for SA-193 B7 (1Cr-1/5Mo) with bolt diameter > 4". It should be noted that only the minimum tensile strength Su of 102,000 psi is available from the above Reference.

Temperature °F	Design Stress Intensity, Sm X10^3 (psi)	Yield Strength, Sy X10^3 (psi)	Remark
-20 to 100	25.0	75.0	Sy/Sm = 3
200	23.3	69.9	Sy/Sm = 3
300	22.4	67.2	Sy/Sm = 3
400	21.8	65.4	Sy/Sm = 3
500	21.0	63.2	Sy/Sm = 3
600	20.3	60.9	Sy/Sm = 3
650	19.7	59.2	Sy/Sm = 3
700	19.2	57.5	Sy/Sm = 3
750	18.5	55.4	Sy/Sm = 3
800	17.5	52.7	Sy/Sm = 3

For HAC fire accident analyses, the material yield strength at elevated temperature is calculated from the temperature trend curve (European Convention for Constructional Steelwork), given in Ref. 3.20, ASCE Manual No. 78, "Structural Fire Protection", page 22, as follows

Sy = Syo*(1+C/(767*ln(C/1750))) for $0\,^{\circ}C < C \le 600\,^{\circ}C$ (A1)

Sy = Syo*(108 –C/1000)/(C-440) for $600\,^{\circ}C < C \le 1000\,^{\circ}C$ (A2)

Where, Syo is the material yield strength at room temperature
C is the material temperature in °C. The same temperature trend curve is assumed for the material tensile strength.

Yield Strength, and Tensile Strength, At Elevated Temperatures						
Temperature °F	SA-516 Gr. 70 C-Mn-Si		SA-302 Gr. B Mn-½Mo		SA-193 B7 (1Cr-1/5Mo)	
	Sy (ksi)	Su (ksi)	Sy (ksi)	Su (ksi)	Sy (ksi)	Su (ksi)
1200	19.529	35.974	25.696	41.113	38.544	52.419
1250	17.232	31.744	22.674	36.278	34.011	46.255
1300	15.418	28.402	20.287	32.459	30.430	41.385
1350	13.949	25.695	18.354	29.366	27.531	37.442
1400	12.735	23.459	16.756	26.810	25.134	34.183
1450	11.715	21.579	15.414	24.662	23.121	31.444

The same temperature trend curve is assumed for the material plastic modulus. This assumption is based on the plastic slopes of the stress strain curves of ASTM A36 material at various temperatures as shown in Figure 2.8 of Ref. 3.20.

Material plastic modulus Ep, the slope of stress strain curve between Sy and Su, can be calculated from the material Sy, Su and elongation as follows:

Ep = (Su - Sy) / Elongation

The tangent modulus Et per Eq. 4-1-48 of the ANSYS Theory Manual is:

Et = Ep * E /(Ep + E)

At room temperature, the material tangent modulus is:

	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo	SA-193 B7 (1Cr-1/5Mo)
Elongation	0.20	0.20	0.18
Elastic Modulus (psi)	29.5E+06	29.2E+06	29.7E+06
Tangent Modulus (psi)	160E+03	166E+03	139E+03

At temperature, the material tangent modulus (psi) is calculated using Equations A1 and A2 as follows:

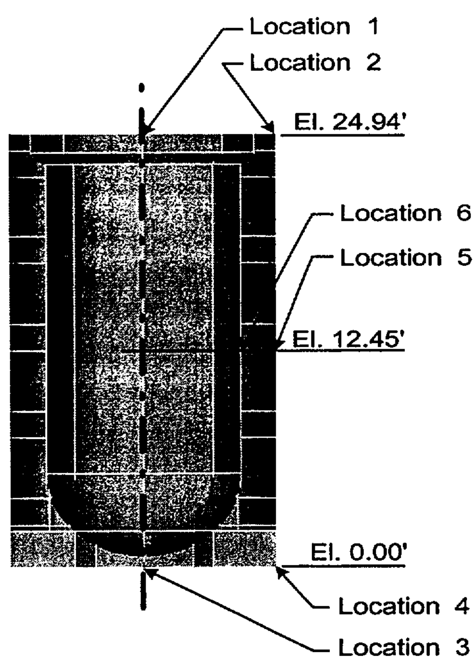
Temperature °F	SA-516 Gr. 70 C-Mn-Si	SA-302 Gr. B Mn-½Mo	SA-193 B7 (1Cr-1/5Mo)
400	140 E+03	145 E+03	122 E+03
600	121 E+03	126 E+03	106 E+03
800	97E+03	100E+03	84E+03
1000	65E+03	67E+03	56E+03
1450	49E+03	51E+03	43E+03

ATTACHMENT B

TEMPERATURE DISTRIBUTION

Based on the RVTS Cask temperature distribution for Normal Conditions of Transport and the Hypothetical Accident Conditions calculated in reference 3.6.1, the following temperature at the selected locations will be used as the boundary conditions for thermal heat transfer analysis.

Location		Temperature (°F)				
		Case 2a	Case 3a	Case 3b	Case 4a	Case 4b
		100 °F with Insolation	-40 °F without Insolation	-20 °F without Insolation	100 °F without Insolation	-20 °F without Insolation
1	Top Plate Center	156	-39	-19	1405	1404
2	Top Plate Circumference	175	-39	-19	1418	1417
3	Bottom Plate Center	157	-39	-19	1414	1413
4	Bottom Plate Circumference	172	-39	-19	1445	1445
5	Cask Shell Wall @ El. 12.45'	191	-39	-19	1162	1147
6	RV Wall @ El. 12.45'	181	-32	-12	108	-12



Case 2a: Steady-State Temperature Distribution

Elev. (ft) \ Radius (feet)	0	0.92	1.83	2.75	3.67	4.17	4.29	4.42	4.43	4.87	5.12	5.32	5.52	5.72	5.92	6.08	6.25	6.38	6.5
24.94	156.09	156.41	157.42	159.22	162.04	164.12	164.67	165.2	165.25	166.26	167.29	168.25	169.33	170.51	171.79	172.9	173.95	174.45	174.69
24.6	156.18	156.51	157.52	159.34	162.2	164.39	165.08	165.88	165.91	166.33	167.49	168.48	169.58	170.81	172.2	173.53	175.11	175.3	175.45
22.57	165.74	165.96	166.55	167.5	168.76	169.51	169.7	169.89	169.89	169.91	178.76	179.87	181	182.17	183.36	184.38	185.42	185.44	185.48
20.53	171.5	171.64	171.94	172.39	172.92	173.22	173.29	173.36	173.36	173.37	182.85	184	185.13	186.24	187.33	188.24	189.13	189.14	189.16
18.49	175.51	175.65	175.87	176.14	176.38	176.47	176.49	176.51	176.51	176.52	185.1	186.13	187.13	188.09	189.02	189.78	190.51	190.52	190.52
16.45	178.7	178.97	179.39	179.95	180.37	179.93	179.72	179.44	179.44	179.45	187.28	188.23	189.17	190.09	191	191.03	191.04	191.04	191.04
16.11	179.15	179.44	179.94	180.79	182.24	181.9	181.88	179.92	179.92	179.91	187.49	188.41	189.31	190.19	191.05	191.05	191.06	191.06	191.07
15.45	179.96	180.29	180.96	182.54	190.48	183.64	183.22	180.84	180.84	180.8	187.82	188.67	189.5	190.31	191.09	191.1	191.1	191.11	191.11
15.36	180.05	180.39	181.06	182.67	190.35	183.38	183.09	180.93	180.93	180.89	187.85	188.7	189.52	190.32	191.1	191.1	191.11	191.11	191.12
13.64	181.21	181.38	181.59	181.82	181.91	181.53	181.53	181.37	181.37	181.37	188.08	188.89	189.67	190.43	191.17	191.17	191.17	191.18	191.18
11.91	181.48	181.56	181.61	181.63	181.56	181.51	181.51	181.4	181.4	181.41	188.1	188.91	189.69	190.44	191.17	191.18	191.18	191.18	191.19
10.18	181.07	181.11	181.14	181.15	181.12	181.12	181.12	181.01	181.01	181.01	187.94	188.78	189.58	190.37	191.12	191.13	191.13	191.14	191.14
8.45	179.91	179.95	180	180.07	180.16	180.28	180.28	180.13	180.13	180.13	187.53	188.43	189.3	190.16	191	191.01	191.02	191.02	191.03
6	177.52	177.56	177.64	177.76	177.92	178.01	178.03	178.06	178.06	178.06	185.5	186.4	187.27	188.12	188.94	189.61	190.27	190.27	190.28
3.55	174.49	174.55	174.71	174.96	175.27	175.46	175.51	175.56	175.56	175.56	182.74	183.62	184.51	185.4	186.29	187.05	187.81	187.82	187.85
1.1	170.02	170.14	170.47	171.02	171.78	172.28	172.43	172.61	172.62	172.67	175.2	175.63	176.23	177	177.91	178.77	179.71	179.74	179.82
0.67	169.97	170.08	170.42	170.97	171.72	172.19	172.29	172.38	172.39	172.47	170.62	171.02	171.74	172.7	173.87	175	176.29	176.34	176.45
0.33	156.58	156.78	157.41	158.54	160.34	161.72	162.12	162.56	162.6	164.28	165.39	166.38	167.46	168.65	169.99	171.27	172.81	173.33	173.59
0	156.45	156.65	157.26	158.39	160.17	161.54	161.94	162.37	162.42	164.07	165.18	166.16	167.22	168.37	169.6	170.64	171.59	172.07	172.33

Case 2b: Steady-State Temperature Distribution (Sensitivity Test)

Elev. (ft) \ Radius (feet)	0	0.92	1.83	2.75	3.67	4.17	4.29	4.42	4.43	4.87	5.12	5.32	5.52	5.72	5.92	6.08	6.25	6.38	6.5
24.94	156.45	156.79	157.83	159.7	162.64	164.81	165.37	165.92	165.97	166.96	167.89	168.79	169.8	170.93	172.16	173.24	174.26	174.74	174.99
24.6	156.55	156.89	157.94	159.84	162.81	165.09	165.81	166.65	166.68	167.1	168.1	169.02	170.06	171.23	172.57	173.85	175.39	175.58	175.73
22.57	167.29	167.51	168.15	169.17	170.53	171.36	171.56	171.77	171.77	171.79	174.39	176.39	178.34	180.26	182.17	183.76	185.35	185.37	185.41
20.53	173.94	174.09	174.43	174.93	175.54	175.9	175.98	176.08	176.08	176.09	178.63	180.57	182.45	184.27	186.05	187.51	188.95	188.96	188.98
18.49	178.6	178.75	178.99	179.3	179.6	179.74	179.77	179.8	179.8	179.81	181.93	183.54	185.09	186.59	188.03	189.19	190.33	190.33	190.34
16.45	182.24	182.51	182.95	183.55	184.02	183.6	183.39	183.12	183.12	183.13	185.06	186.55	188	189.42	190.82	190.85	190.87	190.87	190.88
16.11	182.74	183.03	183.55	184.44	185.95	185.69	185.67	183.65	183.65	183.64	185.47	186.88	188.24	189.57	190.87	190.88	190.89	190.9	190.9
15.45	183.65	183.98	184.67	186.28	194.27	187.45	187.03	184.64	184.64	184.61	186.19	187.42	188.62	189.79	190.93	190.94	190.94	190.95	190.96
15.36	183.75	184.09	184.78	186.43	194.14	187.19	186.9	184.74	184.74	184.7	186.26	187.48	188.66	189.82	190.94	190.94	190.95	190.96	190.96
13.64	185.07	185.24	185.46	185.71	185.83	185.47	185.46	185.31	185.31	185.31	186.77	187.88	188.96	190.01	191.02	191.03	191.03	191.04	191.04
11.91	185.41	185.48	185.55	185.58	185.54	185.51	185.51	185.41	185.41	185.41	186.85	187.95	189.01	190.04	191.04	191.04	191.05	191.05	191.06
10.18	184.98	185.03	185.07	185.09	185.1	185.12	185.12	185.01	185.01	185.02	186.55	187.71	188.84	189.93	190.99	190.99	191	191	191.01
8.45	183.73	183.77	183.84	183.94	184.07	184.23	184.23	184.07	184.07	184.07	185.79	187.11	188.39	189.64	190.86	190.87	190.88	190.89	190.89
6	181.04	181.09	181.19	181.35	181.55	181.67	181.7	181.73	181.73	181.74	183.42	184.7	185.94	187.13	188.29	189.23	190.15	190.15	190.16
3.55	177.51	177.58	177.77	178.06	178.44	178.67	178.73	178.79	178.79	178.8	180.52	181.84	183.13	184.39	185.65	186.69	187.73	187.74	187.77
1.1	172.24	172.37	172.75	173.37	174.23	174.82	175	175.21	175.21	175.27	175.57	175.95	176.49	177.19	178.05	178.87	179.77	179.8	179.87
0.67	172.17	172.3	172.69	173.31	174.17	174.7	174.82	174.92	174.93	175.01	172.45	172.01	172.31	173.05	174.09	175.15	176.38	176.43	176.54
0.33	157.01	157.21	157.82	158.93	160.7	162.05	162.44	162.87	162.91	164.54	165.63	166.59	167.65	168.82	170.14	171.4	172.93	173.44	173.7
0	156.87	157.06	157.67	158.77	160.52	161.86	162.24	162.67	162.71	164.33	165.41	166.36	167.4	168.54	169.74	170.78	171.72	172.19	172.45

Project No. 10525-020
Calc. No. S-10525-020-012
Rev. 0
Page B3

Case 3a: Steady-State Temperature Distribution (-40)

Elev. (ft) \ Radius (feet)	0	0.92	1.83	2.75	3.67	4.17	4.29	4.42	4.43	4.87	5.12	5.32	5.52	5.72	5.92	6.08	6.25	6.38	6.5
24.94	-38.66	-38.64	-38.58	-38.48	-38.35	-38.25	-38.23	-38.22	-38.22	-38.24	-38.34	-38.41	-38.48	-38.55	-38.6	-38.65	-38.68	-38.69	-38.7
24.6	-38.66	-38.63	-38.57	-38.48	-38.34	-38.24	-38.21	-38.17	-38.17	-38.18	-38.32	-38.4	-38.47	-38.54	-38.6	-38.65	-38.71	-38.71	-38.72
22.57	-37.2	-37.17	-37.13	-37.08	-37.03	-37	-36.99	-36.98	-36.98	-36.99	-38.25	-38.41	-38.56	-38.71	-38.85	-38.98	-39.09	-39.1	-39.1
20.53	-35.86	-35.82	-35.77	-35.75	-35.74	-35.74	-35.74	-35.74	-35.74	-35.75	-37.89	-38.15	-38.4	-38.64	-38.88	-39.07	-39.26	-39.26	-39.26
18.49	-34.47	-34.37	-34.29	-34.24	-34.27	-34.34	-34.37	-34.39	-34.39	-34.39	-37.43	-37.8	-38.15	-38.49	-38.8	-39.06	-39.31	-39.31	-39.31
16.45	-32.93	-32.69	-32.36	-31.94	-31.73	-32.29	-32.52	-32.8	-32.8	-32.81	-37.21	-37.74	-38.26	-38.77	-39.26	-39.27	-39.29	-39.29	-39.29
16.11	-32.69	-32.42	-32	-31.29	-30.04	-30.7	-30.72	-32.49	-32.49	-32.51	-37.14	-37.7	-38.24	-38.76	-39.27	-39.27	-39.28	-39.28	-39.28
15.45	-32.24	-31.92	-31.32	-29.82	-21.72	-28.94	-29.39	-31.87	-31.88	-31.92	-36.98	-37.59	-38.17	-38.73	-39.27	-39.27	-39.28	-39.28	-39.28
15.36	-32.18	-31.86	-31.25	-29.72	-21.87	-29.23	-29.53	-31.81	-31.82	-31.87	-36.97	-37.58	-38.17	-38.73	-39.27	-39.27	-39.28	-39.28	-39.28
13.64	-31.64	-31.48	-31.33	-31.2	-31.25	-31.73	-31.73	-31.92	-31.92	-31.93	-36.97	-37.57	-38.16	-38.72	-39.27	-39.27	-39.27	-39.28	-39.28
11.91	-31.65	-31.59	-31.59	-31.68	-31.89	-32.02	-32.02	-32.15	-32.15	-32.16	-37.04	-37.63	-38.2	-38.75	-39.28	-39.28	-39.28	-39.28	-39.28
10.18	-32.04	-32.02	-32.05	-32.16	-32.33	-32.42	-32.42	-32.54	-32.54	-32.55	-37.17	-37.73	-38.27	-38.79	-39.29	-39.29	-39.29	-39.29	-39.3
8.45	-32.87	-32.86	-32.88	-32.93	-33.01	-33.01	-33.01	-33.16	-33.16	-33.17	-37.36	-37.87	-38.36	-38.84	-39.3	-39.31	-39.31	-39.31	-39.31
6	-34.19	-34.18	-34.18	-34.2	-34.23	-34.25	-34.26	-34.26	-34.26	-34.27	-37.41	-37.79	-38.16	-38.51	-38.84	-39.11	-39.37	-39.37	-39.38
3.55	-35.31	-35.3	-35.28	-35.25	-35.22	-35.21	-35.21	-35.21	-35.21	-35.21	-37.76	-38.07	-38.36	-38.65	-38.93	-39.16	-39.38	-39.38	-39.38
1.1	-36.55	-36.52	-36.46	-36.36	-36.22	-36.11	-36.08	-36.04	-36.04	-36.03	-38.07	-38.32	-38.56	-38.78	-38.98	-39.14	-39.3	-39.3	-39.3
0.67	-36.56	-36.53	-36.47	-36.37	-36.23	-36.14	-36.12	-36.1	-36.1	-36.09	-38.05	-38.48	-38.75	-38.93	-39.07	-39.17	-39.27	-39.27	-39.27
0.33	-38.71	-38.72	-38.74	-38.79	-38.86	-38.91	-38.93	-38.95	-38.95	-39.02	-39.06	-39.1	-39.13	-39.16	-39.19	-39.21	-39.23	-39.24	-39.24
0	-38.72	-38.73	-38.75	-38.8	-38.87	-38.93	-38.94	-38.96	-38.96	-39.03	-39.07	-39.1	-39.13	-39.16	-39.19	-39.21	-39.22	-39.23	-39.23

Case 3b: Steady-State Temperature Distribution (-20)

Elev. (ft) \ Radius (feet)	0	0.92	1.83	2.75	3.67	4.17	4.29	4.42	4.43	4.87	5.12	5.32	5.52	5.72	5.92	6.08	6.25	6.38	6.5
24.94	-18.77	-18.74	-18.69	-18.59	-18.45	-18.36	-18.34	-18.32	-18.32	-18.35	-18.44	-18.51	-18.58	-18.65	-18.71	-18.75	-18.78	-18.79	-18.8
24.6	-18.76	-18.74	-18.68	-18.58	-18.45	-18.35	-18.31	-18.27	-18.27	-18.28	-18.42	-18.5	-18.58	-18.64	-18.71	-18.76	-18.81	-18.81	-18.82
22.57	-17.3	-17.27	-17.23	-17.18	-17.13	-17.1	-17.09	-17.08	-17.08	-17.09	-18.34	-18.5	-18.65	-18.8	-18.95	-19.07	-19.19	-19.19	-19.19
20.53	-15.96	-15.91	-15.87	-15.84	-15.83	-15.84	-15.84	-15.84	-15.84	-15.84	-17.97	-18.23	-18.49	-18.73	-18.96	-19.16	-19.34	-19.34	-19.35
18.49	-14.56	-14.46	-14.38	-14.33	-14.36	-14.44	-14.46	-14.48	-14.48	-14.48	-17.51	-17.88	-18.23	-18.56	-18.88	-19.14	-19.39	-19.39	-19.39
16.45	-13.02	-12.78	-12.45	-12.03	-11.82	-12.38	-12.61	-12.89	-12.89	-12.9	-17.29	-17.82	-18.34	-18.84	-19.33	-19.35	-19.36	-19.36	-19.36
16.11	-12.78	-12.51	-12.09	-11.38	-10.13	-10.79	-10.81	-12.58	-12.58	-12.6	-17.22	-17.77	-18.32	-18.84	-19.34	-19.35	-19.35	-19.35	-19.36
15.45	-12.32	-12.01	-11.4	-9.91	-1.81	-9.03	-9.48	-11.96	-11.96	-12.01	-17.06	-17.67	-18.25	-18.81	-19.34	-19.35	-19.35	-19.35	-19.35
15.36	-12.27	-11.95	-11.34	-9.81	-1.96	-9.32	-9.62	-11.9	-11.9	-11.96	-17.05	-17.66	-18.24	-18.8	-19.34	-19.35	-19.35	-19.35	-19.35
13.64	-11.72	-11.57	-11.42	-11.29	-11.34	-11.82	-11.82	-12	-12	-12.02	-17.04	-17.65	-18.23	-18.8	-19.34	-19.34	-19.35	-19.35	-19.35
11.91	-11.73	-11.68	-11.68	-11.77	-11.97	-12.1	-12.1	-12.23	-12.23	-12.24	-17.11	-17.7	-18.27	-18.82	-19.35	-19.35	-19.35	-19.35	-19.36
10.18	-12.13	-12.1	-12.14	-12.24	-12.41	-12.5	-12.5	-12.63	-12.63	-12.64	-17.24	-17.8	-18.34	-18.86	-19.36	-19.36	-19.36	-19.37	-19.37
8.45	-12.95	-12.94	-12.96	-13.02	-13.1	-13.09	-13.09	-13.24	-13.25	-13.25	-17.43	-17.94	-18.43	-18.91	-19.37	-19.38	-19.38	-19.38	-19.38
6	-14.27	-14.26	-14.26	-14.28	-14.31	-14.33	-14.34	-14.34	-14.34	-14.35	-17.49	-17.87	-18.23	-18.58	-18.91	-19.18	-19.44	-19.44	-19.44
3.55	-15.39	-15.38	-15.36	-15.33	-15.31	-15.29	-15.29	-15.29	-15.29	-15.29	-17.83	-18.14	-18.44	-18.72	-19	-19.23	-19.45	-19.45	-19.45
1.1	-16.63	-16.6	-16.54	-16.44	-16.3	-16.19	-16.16	-16.12	-16.12	-16.11	-18.15	-18.4	-18.63	-18.85	-19.05	-19.22	-19.37	-19.37	-19.37
0.67	-16.64	-16.61	-16.55	-16.45	-16.31	-16.22	-16.2	-16.18	-16.18	-16.17	-18.13	-18.56	-18.82	-19	-19.14	-19.24	-19.34	-19.34	-19.34
0.33	-18.8	-18.8	-18.83	-18.87	-18.94	-18.99	-19.01	-19.03	-19.03	-19.09	-19.14	-19.17	-19.21	-19.23	-19.26	-19.28	-19.3	-19.31	-19.31
0	-18.81	-18.81	-18.84	-18.88	-18.95	-19.01	-19.02	-19.04	-19.04	-19.11	-19.15	-19.18	-19.21	-19.24	-19.26	-19.28	-19.3	-19.3	-19.31

Case 4a: **Transient Temperature Distribution at Time Equal 0.50 Hours**

Elev. (ft) \ Radius (feet)	0	0.92	1.83	2.75	3.67	4.17	4.29	4.42	4.43	4.87	5.12	5.32	5.52	5.72	5.92	6.08	6.25	6.38	6.5
24.94	1405.43	1405.43	1405.43	1405.38	1403.95	1389.9	1376.83	1360.62	1359.5	1360.13	1385.27	1393.83	1397.85	1401.18	1406.81	1414.55	1418.15	1418.14	1443.99
24.6	1136.76	1136.77	1136.76	1136.43	1125.75	1012.83	889.04	701.18	695.54	705.04	971.08	1043.46	1075.33	1100.89	1144.68	1215.49	1336.03	1368.82	1427.19
22.57	103.89	103.92	103.96	104.01	104.06	104.11	106.49	120.45	120.51	120.94	102.94	102.54	102.51	104.45	133.54	359.21	1354.91	1379.53	1430.51
20.53	103.58	103.63	103.67	103.7	103.71	103.71	103.75	104.04	104.04	104.05	101.65	101.4	101.26	103.08	132.06	357.92	1355.02	1379.62	1430.54
18.49	104.99	105.09	105.17	105.22	105.19	105.11	105.09	105.08	105.08	105.07	102.12	101.77	101.55	103.36	132.85	358.53	1354.19	1378.98	1430.32
16.45	106.54	106.77	107.1	107.51	107.71	107.16	106.94	106.67	106.67	106.66	102.38	102.1	106.23	171.05	783.1	916.82	1231.01	1302.06	1408.04
16.11	106.78	107.04	107.45	108.16	109.38	108.74	108.73	106.98	106.97	106.96	102.46	102.21	107.13	179.61	821.26	881.67	1033.12	1187.92	1380.94
15.45	107.23	107.55	108.14	109.6	117.54	110.46	110.02	107.59	107.59	107.54	102.62	102.32	107.12	178.14	803.15	856.92	999.68	1163.69	1375.49
15.36	107.29	107.6	108.2	109.7	117.4	110.18	109.88	107.65	107.65	107.59	102.63	102.32	107.11	177.99	801.51	855.09	997.72	1162.29	1375.18
13.64	107.84	108	108.14	108.27	108.22	107.74	107.74	107.56	107.56	107.55	102.64	102.34	107.12	177.89	800.18	853.78	996.62	1161.57	1375.02
11.91	107.85	107.9	107.9	107.81	107.6	107.47	107.47	107.35	107.35	107.34	102.58	102.29	107.09	177.87	800.2	853.8	996.64	1161.58	1375.02
10.18	107.47	107.49	107.45	107.35	107.18	107.09	107.09	106.97	106.96	106.95	102.45	102.2	107.04	178.08	802.71	856.34	998.96	1163.13	1375.36
8.45	106.65	106.67	106.65	106.59	106.51	106.51	106.51	106.36	106.36	106.35	102.27	102.09	107.44	185.3	871.29	952.99	1152.84	1255.24	1396.27
6	105.35	105.36	105.36	105.35	105.32	105.29	105.29	105.28	105.28	105.28	102.2	101.83	101.59	103.38	132.74	358.32	1354	1378.83	1430.27
3.55	104.24	104.26	104.28	104.31	104.33	104.35	104.35	104.37	104.37	104.37	101.86	101.56	101.38	103.15	132.09	357.92	1355.02	1379.62	1430.54
1.1	106.88	106.91	106.97	107.07	107.16	106.77	106.21	105.26	105.22	105.11	101.95	101.63	101.5	103.34	132.35	358.2	1355.07	1379.66	1430.55
0.67	111.32	111.34	111.4	111.5	111.61	111.54	111.52	111.55	111.57	113.4	170.05	157.09	155.99	158.29	187.37	403.98	1354.46	1379.41	1430.49
0.33	1202.15	1202.15	1202.15	1202.15	1202.14	1202.14	1202.15	1202.16	1202.16	1202.35	1203.15	1204.93	1209.47	1220.28	1243.91	1281.5	1341.28	1377.93	1430.65
0	1414.13	1414.13	1414.13	1414.13	1414.13	1414.13	1414.13	1414.13	1414.13	1414.16	1414.27	1414.53	1415.2	1416.82	1420.46	1426.48	1436.37	1445.36	1457.55

Radius (feet)

Case 4a: **Transient Temperature Distribution at Time Equal 0.75 Hours**

Elev. (ft) \ Radius (feet)	0	0.92	1.83	2.75	3.67	4.17	4.29	4.42	4.43	4.87	5.12	5.32	5.52	5.72	5.92	6.08	6.25	6.38	6.5
24.94	1161.2	1161.2	1161.17	1160.53	1146.69	1051.27	998.76	946.01	942.09	940.16	1037.39	1092.19	1125.52	1150.48	1179.02	1209.7	1244.56	1247.03	1202.79
24.6	1187.6	1187.6	1187.57	1186.68	1166.91	1023.47	926.37	806.51	803.63	807.27	998.48	1085.21	1133.21	1168.42	1209.58	1250.49	1274.29	1256.46	1206.13
22.57	105.21	105.23	105.28	105.32	105.36	105.81	112.2	137.09	137.17	137.64	104.57	103.77	104.19	110.82	172.49	475.49	1280.33	1264.39	1213.38
20.53	103.59	103.63	103.67	103.7	103.71	103.73	103.89	104.72	104.72	104.74	101.67	101.43	101.75	108.24	169.87	473.49	1280.46	1264.52	1213.5
18.49	104.99	105.09	105.17	105.22	105.19	105.11	105.1	105.09	105.09	105.09	102.13	101.81	102.06	108.73	171.36	474.48	1279	1263.12	1212.29
16.45	106.54	106.77	107.1	107.51	107.71	107.16	106.94	106.67	106.67	106.66	102.51	103.17	117.25	244.67	964.15	1039.95	1162.29	1159.54	1123.69
16.11	106.78	107.04	107.45	108.16	109.38	108.74	108.73	106.98	106.97	106.96	102.61	103.41	118.98	254.22	977.03	1001.1	1038.69	1044.87	1022.18
15.45	107.23	107.55	108.14	109.6	117.54	110.46	110.02	107.59	107.59	107.54	102.76	103.5	118.75	250.88	949.52	966.76	993.34	997.84	978.17
15.36	107.29	107.6	108.2	109.7	117.4	110.18	109.88	107.65	107.65	107.59	102.78	103.51	118.72	250.55	947.11	964.04	990.12	994.53	975.06
13.64	107.84	108	108.14	108.27	108.22	107.74	107.74	107.56	107.56	107.55	102.79	103.52	118.71	250.25	944.6	961.45	987.48	991.98	972.69
11.91	107.85	107.9	107.9	107.81	107.6	107.47	107.47	107.35	107.35	107.34	102.72	103.47	118.68	250.24	944.64	961.49	987.52	992.01	972.73
10.18	107.47	107.49	107.45	107.35	107.18	107.09	107.09	106.97	106.96	106.95	102.6	103.38	118.67	250.75	948.33	965.32	991.44	995.78	976.2
8.45	106.65	106.67	106.65	106.59	106.51	106.51	106.51	106.36	106.36	106.35	102.43	103.38	120.16	264.74	1031.53	1066.83	1118.17	1116.27	1085.07
6	105.35	105.36	105.36	105.35	105.32	105.29	105.29	105.28	105.28	105.28	102.2	101.87	102.1	108.7	171.07	474.13	1278.82	1262.95	1212.14
3.55	104.25	104.26	104.28	104.31	104.34	104.35	104.36	104.42	104.42	104.41	101.86	101.6	101.87	108.31	169.9	473.49	1280.47	1264.53	1213.51
1.1	110.85	110.88	110.93	111.02	110.96	109.83	108.85	107.32	107.25	107	102.64	102.26	102.55	109.07	170.7	474.14	1280.45	1264.51	1213.49
0.67	115.94	115.96	116.02	116.11	116.08	115.53	115.34	115.24	115.24	117.28	213.8	196.64	194.88	201.65	260.35	541.29	1279.21	1262.81	1211.85
0.33	1229.65	1229.65	1229.65	1229.65	1229.65	1229.66	1229.68	1229.73	1229.74	1230.24	1231.85	1234.6	1240.27	1250.8	1266.75	1278.74	1275.04	1252.41	1201.28
0	1189.55	1189.55	1189.55	1189.55	1189.55	1189.56	1189.58	1189.6	1189.61	1189.93	1190.89	1192.68	1196.32	1202.81	1211.72	1216.01	1206.64	1181.26	1136.86

Radius (feet)

Case 4b: **Transient Temperature Distribution at Time Equal 0.50 Hours**

Elev. (ft)																			
24.94	1403.57	1403.57	1403.57	1403.52	1401.98	1387.18	1373.55	1356.59	1355.43	1356.1	1382.36	1391.3	1395.55	1399.08	1404.99	1413.06	1416.84	1416.74	1443.41
24.6	1122.94	1122.94	1122.94	1122.56	1110.87	989.81	858.92	660.39	654.31	664.41	945.7	1022.77	1057.08	1084.63	1131.13	1205.44	1331.37	1365.48	1426.12
22.57	-15.44	-15.41	-15.37	-15.32	-15.28	-15.21	-12.38	4.06	4.14	4.64	-16.44	-16.88	-16.89	-14.72	17.56	266.02	1351	1376.71	1429.57
20.53	-15.96	-15.91	-15.87	-15.84	-15.83	-15.83	-15.78	-15.44	-15.44	-15.43	-17.97	-18.23	-18.35	-16.31	15.86	264.55	1351.12	1376.81	1429.6
18.49	-14.56	-14.46	-14.38	-14.33	-14.36	-14.44	-14.46	-14.47	-14.47	-14.48	-17.51	-17.87	-18.09	-16.04	16.71	265.22	1350.22	1376.12	1429.37
16.45	-13.02	-12.78	-12.45	-12.03	-11.82	-12.38	-12.61	-12.89	-12.89	-12.9	-17.27	-17.52	-12.72	61.07	746.96	888.82	1219.69	1294.45	1406.02
16.11	-12.78	-12.51	-12.09	-11.38	-10.13	-10.79	-10.81	-12.58	-12.58	-12.6	-17.19	-17.4	-11.66	71.03	789.76	853.5	1012.26	1174.74	1378.02
15.45	-12.32	-12.01	-11.4	-9.91	-1.81	-9.03	-9.48	-11.96	-11.96	-12.01	-17.03	-17.3	-11.67	69.51	770.78	827.54	977.07	1149.22	1372.36
15.36	-12.27	-11.95	-11.34	-9.81	-1.96	-9.32	-9.62	-11.9	-11.9	-11.96	-17.02	-17.29	-11.68	69.35	769.05	825.6	975	1147.74	1372.04
13.64	-11.72	-11.57	-11.42	-11.29	-11.34	-11.82	-11.82	-12	-12	-12.02	-17.02	-17.28	-11.68	69.23	767.57	824.15	973.79	1146.95	1371.87
11.91	-11.73	-11.68	-11.68	-11.77	-11.97	-12.1	-12.1	-12.23	-12.23	-12.24	-17.09	-17.34	-11.71	69.21	767.6	824.18	973.82	1146.96	1371.87
10.18	-12.13	-12.1	-12.14	-12.24	-12.41	-12.5	-12.5	-12.63	-12.63	-12.64	-17.22	-17.43	-11.76	69.45	770.36	826.96	976.34	1148.63	1372.23
8.45	-12.95	-12.94	-12.96	-13.02	-13.1	-13.09	-13.09	-13.24	-13.25	-13.25	-17.4	-17.55	-11.34	77.17	843.52	929.33	1138.43	1245.7	1393.94
6	-14.27	-14.26	-14.26	-14.28	-14.31	-14.33	-14.34	-14.34	-14.34	-14.35	-17.49	-17.86	-18.09	-16.07	16.54	264.95	1350.02	1375.96	1429.32
3.55	-15.39	-15.38	-15.36	-15.33	-15.3	-15.29	-15.29	-15.26	-15.26	-15.27	-17.83	-18.13	-18.31	-16.3	15.82	264.5	1351.11	1376.81	1429.6
1.1	-12.21	-12.19	-12.13	-12.03	-11.94	-12.41	-13.04	-14.12	-14.17	-14.3	-17.67	-18.01	-18.13	-16.05	16.15	264.83	1351.16	1376.85	1429.61
0.67	-7.22	-7.19	-7.13	-7.04	-6.93	-7.02	-7.06	-7.02	-7.01	-4.95	58.28	43.73	42.5	45.06	77.25	315.51	1350.51	1376.55	1429.54
0.33	1192.54	1192.54	1192.54	1192.54	1192.53	1192.53	1192.54	1192.55	1192.55	1192.76	1193.65	1195.57	1200.37	1211.65	1236.15	1275.09	1337.06	1375.05	1429.7
0	1412.73	1412.73	1412.73	1412.73	1412.73	1412.73	1412.73	1412.73	1412.74	1412.76	1412.89	1413.17	1413.87	1415.55	1419.28	1425.44	1435.57	1444.76	1457.26
	0	**0.92**	**1.83**	**2.75**	**3.67**	**4.17**	**4.29**	**4.42**	**4.43**	**4.87**	**5.12**	**5.32**	**5.52**	**5.72**	**5.92**	**6.08**	**6.25**	**6.38**	**6.5**
Radius (feet)																			

Case 4b: **Transient Temperature Distribution at Time Equal 0.75 Hours**

Elev. (ft)																			
24.94	1152.14	1152.15	1152.12	1151.41	1136.31	1033.28	977.11	920.83	916.65	914.55	1018.56	1077.55	1113.54	1140.33	1170.59	1202.88	1239.34	1242.52	1198.29
24.6	1177.47	1177.47	1177.44	1176.46	1155.06	1001.93	899.34	772.9	769.79	773.61	975.68	1067.87	1119.16	1156.67	1200.09	1243.27	1269.65	1251.98	1201.52
22.57	-14	-13.97	-13.93	-13.88	-13.85	-13.29	-5.72	23.73	23.82	24.4	-14.59	-15.51	-15.04	-7.69	60.29	392.7	1275.77	1260.09	1208.97
20.53	-15.95	-15.91	-15.87	-15.84	-15.83	-15.81	-15.61	-14.64	-14.64	-14.61	-17.94	-18.18	-17.81	-10.6	57.34	390.45	1275.9	1260.23	1209.1
18.49	-14.56	-14.46	-14.38	-14.33	-14.36	-14.44	-14.45	-14.45	-14.45	-14.46	-17.51	-17.83	-17.52	-10.11	58.98	391.55	1274.34	1258.74	1207.81
16.45	-13.02	-12.78	-12.45	-12.03	-11.82	-12.38	-12.61	-12.89	-12.89	-12.9	-17.12	-16.3	-0.29	142.85	940.26	1020.59	1150.45	1148.65	1113.44
16.11	-12.78	-12.51	-12.09	-11.38	-10.13	-10.79	-10.81	-12.58	-12.58	-12.6	-17.02	-16.03	1.73	153.87	955.37	980.62	1020.19	1027.69	1006.03
15.45	-12.32	-12.01	-11.4	-9.91	-1.81	-9.03	-9.48	-11.96	-11.96	-12.01	-16.87	-15.94	1.49	150.43	926.7	944.66	972.37	977.89	959.22
15.36	-12.27	-11.95	-11.34	-9.81	-1.96	-9.32	-9.62	-11.9	-11.9	-11.96	-16.85	-15.93	1.46	150.08	924.18	941.8	968.97	974.38	955.9
13.64	-11.72	-11.57	-11.42	-11.29	-11.34	-11.82	-11.82	-12	-12	-12.02	-16.85	-15.93	1.44	149.75	921.46	938.99	966.11	971.59	953.32
11.91	-11.73	-11.68	-11.68	-11.77	-11.97	-12.1	-12.1	-12.23	-12.23	-12.24	-16.92	-15.98	1.4	149.74	921.51	939.04	966.15	971.63	953.36
10.18	-12.13	-12.1	-12.14	-12.24	-12.41	-12.5	-12.5	-12.63	-12.63	-12.64	-17.05	-16.08	1.4	150.3	925.49	943.17	970.39	975.72	957.13
8.45	-12.95	-12.94	-12.96	-13.02	-13.1	-13.09	-13.09	-13.24	-13.24	-13.25	-17.22	-16.07	2.98	165.12	1012.9	1050.11	1104.42	1103.48	1073
6	-14.27	-14.26	-14.26	-14.28	-14.31	-14.33	-14.34	-14.34	-14.34	-14.35	-17.48	-17.82	-17.53	-10.18	58.61	391.13	1274.16	1258.56	1207.65
3.55	-15.39	-15.37	-15.35	-15.33	-15.3	-15.28	-15.27	-15.21	-15.21	-15.21	-17.82	-18.09	-17.77	-10.6	57.31	390.41	1275.91	1260.24	1209.1
1.1	-7.73	-7.71	-7.65	-7.57	-7.66	-8.95	-10.07	-11.79	-11.86	-12.15	-16.9	-17.31	-16.96	-9.72	58.23	391.15	1275.89	1260.22	1209.08
0.67	-2.03	-2.01	-1.95	-1.87	-1.92	-2.57	-2.78	-2.91	-2.9	-0.64	106.43	87.16	85.16	92.62	157.21	465.15	1274.69	1258.52	1207.43
0.33	1221.84	1221.84	1221.84	1221.84	1221.84	1221.85	1221.88	1221.93	1221.93	1222.49	1224.2	1227.09	1233.01	1243.98	1260.61	1273.39	1270.53	1248.03	1196.75
0	1182.33	1182.33	1182.33	1182.33	1182.33	1182.34	1182.35	1182.39	1182.39	1182.74	1183.77	1185.66	1189.48	1196.28	1205.62	1210.31	1201.24	1175.83	1131.24
	0	**0.92**	**1.83**	**2.75**	**3.67**	**4.17**	**4.29**	**4.42**	**4.43**	**4.87**	**5.12**	**5.32**	**5.52**	**5.72**	**5.92**	**6.08**	**6.25**	**6.38**	**6.5**
Radius (feet)																			

ATTACHMENT C

Contact Stiffness Calculation

Purpose:

To determine the the force-displacement relationship at contact between the RVTC and a flat, semi-finite concrete block.

Reference:

1. Roark R. J., 'Formulas for Stress and Strain", 5th Edition. Table 33, Case 4 Formulas for stress and strain due to pressure on or between elastic bodies
2. Ferguson, P.M., "Reinforced Concrete Fundamentals", John Willey and Son, NY, 1965.
3. Baumeister T. 'Marks' Standard Handbook for Mechanical Engineers'. Eighth Edition, McGraw-Hill

Assumption:

A compressive strength of 4000 psi for the concrete is conservatively used since a high crushing strength provides a conservative load-displacement curve for impact analysis.

Methodology:

Stress and strain due to contact pressure between two elastic bodies from Case 4, Table 33, Roark's Handbook, Reference 1 are used to calculate the force-displacement relationship at contact between the RVTC and a flat, semi-finite concrete block.

Applied force and the total compressive contact pressure between the two bodies are in equilibrium. As contact stress exceeds the crushing strength of the concrete, the concrete strength decreases and the contact area increases to maintain the equilibrium. Therefore, a strength reduction factor k is included in the concrete elastic modulus to model the crushing effect. The strength reduction factor k is determined such that the maximum compressive stress in concrete remains to be less than the crushing strength.

Typical concrete compressive strength at 28 day is in the range of 2650 psi to 4000 psi (Page 6-188, Mark's Handbook, Ref. 3). In this calculation, a compressive strength of 4000 psi is conservatively used since a high crushing strength provides a conservative load-displacement curve for impact analysis.

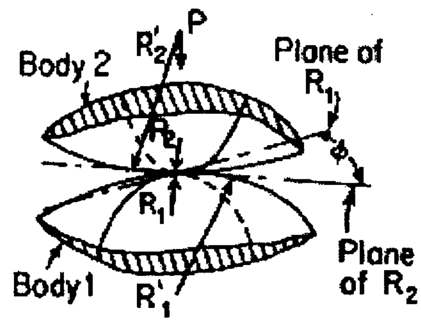
$$f_{cr} := 4000 \quad \text{psi}$$

The elastic modulus of concrete, per Ref. 2, is:

$$E_c := 57400 \cdot \sqrt{f_{cr}} \qquad E_c = 3.63 \cdot 10^6 \qquad \text{psi}$$

Calculation:

General case of two bodies in contact



Notation file Provides an explanation of Table 33 in Reference 1 and the notation used.

At point of contact, minimum and maximum radii of curvature are R_1 and R'_1 for body 1, and R_2 and R'_2 for body 2. Then $1/R_1$ and $1/R'_1$ are principal curvatures of body 1, and $1/R_2$ and $1/R'_2$ of body 2; and in each body the principal curvatures are mutually perpendicular. The radii are positive if the center of curvature lies within the given body, i.e., the surface is convex, and negative otherwise. The plane containing curvature $1/R_1$ in body 1 makes the angle ϕ with the plane containing curvature $1/R_2$ in body 2.

Input dimensions, properties and loading for horizontal drop position:

All units are in lbf, in and psi

Minimum radius of curvature for body 1, the radius of the cask: $R_1 := 13 \cdot 6$

Maximum radius of curvature for body 1, a large number for straight line: $R'_1 := 1000 \cdot R_1$

Poisson's ratio for body 1, steel cask: $\nu_1 := .3$

Modulus of elasticity for body 1, steel cask: $E_1 := \left(28 \cdot 10^6\right)$

Angle between planes: $\phi := 0\cdot deg$

Minimum radius of curvature for body 2, flat conrete foundation: $R_2 := 1000\cdot R_1$

Maximum radius of curvature for body 2, flat surface: $R'_2 := 1000\cdot R_1$

Poisson's ratio for body 2, concrete: $\nu_2 := 0.2$

Modulus of elasticity for body 2, concrete: $E_2 := E_c$

Set initial value of acceleration to g=1 $g := 1$

Total loading as a function of g: $P(g) := 540000\cdot g$

Constants:

$$K_D := \frac{1.5}{\left(\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R'_1}+\frac{1}{R'_2}\right)} \qquad K_D = 116.65$$

The elastic modulus of crushed concrete is reduced by a factor k. The factor k will be deterenined such that the compressive stress is less than or equal to f_c

$$C_E(k) := \frac{1-\nu_1^{\,2}}{E_1}+\frac{1-\nu_2^{\,2}}{E_2\cdot k}$$

$$\theta := acos\left[\frac{K_D}{1.5}\cdot\sqrt{\left(\frac{1}{R_1}-\frac{1}{R'_1}\right)^2+\left(\frac{1}{R_2}-\frac{1}{R'_2}\right)^2+2\cdot\left(\frac{1}{R_1}-\frac{1}{R'_1}\right)\cdot\left(\frac{1}{R_2}-\frac{1}{R'_2}\right)\cdot\cos(2\cdot\phi)}\right]$$

$$r := \cos(\theta)$$

$$r = 0.996$$

Table values:

a, b, and l are given by the following table:

v holds table values for cos(q)

$$v := (0\ \ .10\ \ .20\ \ .30\ \ .40\ \ .50\ \ .60\ \ .70\ \ .75\ \ .80\ \ .85\ \ .90\ \ .92\ \ .94\ \ .96\ \ .98\ \ .99)^T$$

$$\alpha := (1\ \ 1.07\ \ 1.15\ \ 1.242\ \ 1.351\ \ 1.486\ \ 1.661\ \ 1.905\ \ 2.072\ \ 2.292\ \ 2.6\ \ 3.093\ \ 3.396\ \ 3.824\ \ 4.508\ \ 5.937\ \ 7.774)^T$$

$$\beta := (1\ \ .936\ \ .878\ \ .822\ \ .769\ \ .717\ \ .664\ \ .608\ \ .578\ \ .544\ \ .507\ \ .461\ \ .438\ \ .412\ \ .378\ \ .328\ \ .287)^T$$

$$\lambda := (.750\ \ .748\ \ .743\ \ .734\ \ .721\ \ .703\ \ .678\ \ .644\ \ .622\ \ .594\ \ .559\ \ .510\ \ .484\ \ .452\ \ .410\ \ .345\ \ .288)^T$$

$\alpha := \mathrm{linterp}(v, \alpha, r)$ $\alpha = 8.878$

$\beta := \mathrm{linterp}(v, \beta, r)$ $\beta = 0.262$

$\lambda := \mathrm{linterp}(v, \lambda, r)$ $\lambda = 0.254$

Length of contact area for horizontal drop is the cask length: $L1 := 300$

Half width of the contact area, Ref. 1, as a function of g and k:

$$d(g,k) := \beta \cdot \left(P(g) \cdot K_D \cdot C_E(k)\right)^{\frac{1}{3}}$$

Relative displacement along the axis of loading, Ref. 1, as a function of g and k: :

$$y(g,k) := \lambda \cdot \left(\frac{P(g)^2 \cdot C_E(k)^2}{K_D}\right)^{\frac{1}{3}}$$

Compression Stress

$$\sigma_c(g,k) := \frac{1.5 \cdot P(g)}{2 \cdot L1 \cdot d(g,k)}$$

Concrete Crushing strength: $f_{cr} = 4 \cdot 10^3$ psi

Crushing occurs as stress reaches f_{cr}

At a given acceleration g, the reduced factor k for crushed concrete is determined by solving the following equation:

Guess value of k is $x := 0.1$

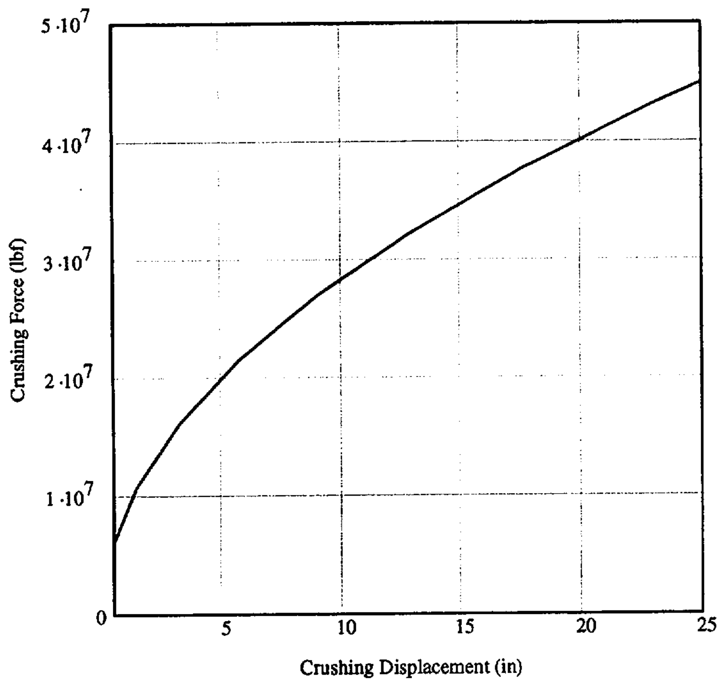
$k(g) := \text{root}\left[\left(\sigma_c(g,x) - f_{cr}\right), x\right]$ $k(2) = 2.575$

The crushing depth cr(g) as a function of g is

$$cr(g) := \left| \begin{array}{l} x \leftarrow 0.001 \\ k \leftarrow \text{root}\left[\left(\sigma_c(g,x) - f_{cr}\right), x\right] \\ k \leftarrow \text{if}(k > 1, 1, k) \\ y(g,k) \end{array} \right.$$

Therefore, for acceleration in the range of: $g := 10, 20 .. 120$

The force-displacement curve of the contact are:



P(g) =	cr(g) =
$5.4\cdot10^{6}$	0.36
$1.08\cdot10^{7}$	1.44
$1.62\cdot10^{7}$	3.24
$2.16\cdot10^{7}$	5.76
$2.7\cdot10^{7}$	8.999
$3.24\cdot10^{7}$	12.959
$3.78\cdot10^{7}$	17.639
$4.32\cdot10^{7}$	23.038
$4.86\cdot10^{7}$	29.158
$5.4\cdot10^{7}$	35.997
$5.94\cdot10^{7}$	43.557
$6.48\cdot10^{7}$	51.836

Conclusion:

The above calculated force-displacement relationship at contact between the RVTC and a flat, semi-finite concrete block will be used in the Finite Element Analysis for the drop cases.

ATTACHMENT D

Beam Model Properties Calculation

Purpose:

To determine the properties of Beam Model for Lumped Parameter Dynamic Impact Analysis.

Reference:

1. United States Nuclear Regulatory Commission Rules and Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Materials", January 30, 1998.
2. S&L Calculation No.: S-10525-020-002, "Volume and Weight of Reactor Vessel Transport System", Rev. 2.
3. NUREG/CR-3966.

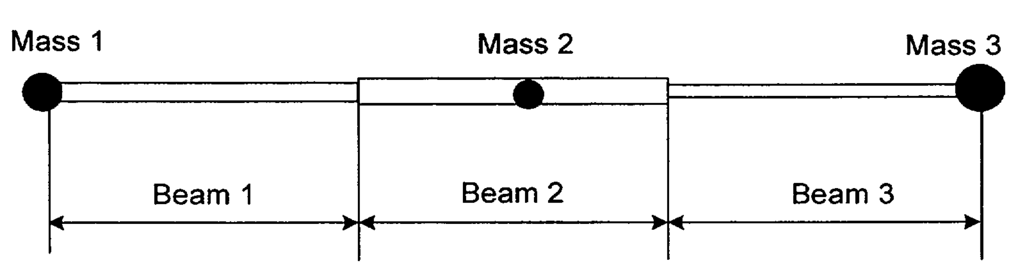
Assumption:

The weight of the stiffener plate and plate support will be uniformly distributed as beam model. This will not significantly affect the stiffness of the beam model.

Methodology:

Lumped Parameter Dynamic Analysis is an acceptable methodology for RV transport cask (RVTC) drop analyses per NUREG/CR-3966, Reference 3. In this approach, the RV transport cask is modeled as a beam with distributed mass and concentrated masses. Dynamic impact analysis is then performed per the requirements of 10 CFR 71.73(c)(1). The beam responses to the drop analyses are then input into the detailed RVTC model for stress calculation and buckling check. The purpose of this attachment is to calculate the beam and mass properties of the lumped parameter model of the RVTC.

Per the cask geometry, dimensions and component weights from Calc. S-10525-020-002, Ref.2, the cask can be model as 3 equal length beams and 3 lump masses as described below:



Concentrated Mass:

Mass 1: Bottom Cask Plate+Donut Plate + Internals (Core Plate, Baffes)

Mass 2: RV Thermal Shield+ Top Guide Plate +Retainer and Seals

Mass 3: Top Cask Plate + RV Flange +Steam Baffes and Sparger

Distributed Mass:

Beam 1: 3" cask shell + 3" (Trunion Ring + Stiffening Plates)+ 5.25" RV Shell + concrete/insulation

Beam 2: 3" cask shell + 4" Cask Shield Plates+ 5.25" RV Shell + concrete/insulation

Beam 3: 3" cask shell + 5.25" RV Shell + concrete/insulation

Calculation:

Data from S-10525-020-002, Reference 2:

Steel density

$$\gamma_{st} := 490 \frac{lbf}{ft^3}$$

M1 Calculation

Cask Base Plate Volume $V_{base} := 44.2 \cdot ft^3$

Donut Ring Volume $V_{ring} := 27.2 \cdot ft^3$

WT(Core Plate + Baffles + Diffusers) $WT_{int} := 5100 \cdot lbf$

$$M_1 := \gamma_{st} \cdot \left(V_{ring} + V_{base}\right) + WT_{int}$$

$$M_1 = 4.009 \cdot 10^4 \cdot lbf$$

M2 Calculation

RV Thermal Shield+ Top Guide Plate +Retainer and Seals

$$M_2 := (1.07 + 5.08 + 13 + .55 + .813) \cdot 1000 \cdot lbf$$

$$M_2 = 2.051 \cdot 10^4 \cdot lbf$$

M3 Calculation

Cask Top Plate: $V_{top} := 44.2 \cdot ft^3$

RV Flange: $V_{flg} := 48.1 \cdot ft^3$

Steam Baffes and Sparger $WT_{SBS} := (1.64 + .13) \cdot 1000 \cdot lbf$

$M_3 := (V_{top} + V_{flg}) \cdot \gamma_{st} + WT_{SBS}$

$M_3 = 4.7 \cdot 10^4 \cdot lbf$

Cask Shell Thickness: $t := 3 \cdot in$

Cask Shell Mean Radius $R := \frac{13 \cdot 12 \cdot in}{2} - \frac{t}{2}$

Cask Length (excludes top and bottom plates) $L := in \cdot (24 \cdot 12 + 11.5 - 4 \cdot 2)$

Cross Section Area $A_{cask} := \pi \cdot 2 \cdot R \cdot t$ $A_{cask} = 1.442 \cdot 10^3 \cdot in^2$

Cross Section Moment of Inertia $I_{cask} := \pi \cdot R^3 \cdot t$ $I_{cask} = 4.219 \cdot 10^6 \cdot in^4$

Total WT $WT_{cask} := A_{cask} \cdot L \cdot \gamma_{st}$ $WT_{cask} = 1.192 \cdot 10^5 \cdot lbf$

RV Thickness: $t_{rv} := \left(5 + \frac{1}{4} + \frac{5}{32}\right) \cdot in$

RV Mean Radius: $R_{rv} := 53.1 \cdot in + \frac{t_{rv}}{2}$

RV Length (exclude top flange) $L_{rv} := (215.2 + 53.1) \cdot in + t_{rv}$ $L_{rv} = 273.706 \cdot in$

Cross Section Area $A_{rv} := \pi \cdot 2 \cdot R_{rv} \cdot t_{rv}$ $A_{rv} = 1.896 \cdot 10^3 \cdot in^2$

Cross Section Moment of Inertia $I_{rv} := \pi \cdot R_{rv}^{\ 3} \cdot t_{rv}$ $I_{rv} = 2.951 \cdot 10^6 \cdot in^4$

Total RV WT (exclude top flange) $WT_{rv} := (61.2 + 235.9) \cdot ft^3 \cdot \gamma_{st}$ $WT_{rv} = 1.456 \cdot 10^5 \cdot lbf$

Cask Shield Plate thickness $t_{ts} := 4 \cdot in$

Cask Shield Plate Mean Radius $R_{ts} := R - \dfrac{(t + t_{ts})}{2}$ $R_{ts} = 73 \circ in$

Cask Shield Plate Length $L_{ts} := 96 \cdot in$

Cross Section Area $A_{ts} := \pi \cdot 2 \cdot R_{ts} \cdot t_{ts}$ $A_{ts} = 1.835 \cdot 10^{3} \circ in^{2}$

Cross Section Moment of Inertia $I_{ts} := \pi \cdot R_{ts}^{3} \cdot t_{ts}$ $I_{ts} = 4.889 \cdot 10^{6} \circ in^{4}$

Total WT $WT_{ts} := A_{ts} \cdot L_{ts} \cdot \gamma_{st}$ $WT_{ts} = 4.994 \cdot 10^{4} \circ lbf$

Trunion Reinforced Ring Thickness $t_{tr} := 3 \cdot in$

Trunion Reinforced Ring Mean Radius $R_{tr} := R - \dfrac{(t + t_{tr})}{2}$ $R_{tr} = 73.5 \circ in$

Trunion Reinforced Ring Length $L_{tr} := 40 \cdot in$

Cross Section Area $A_{tr} := \pi \cdot 2 \cdot R_{tr} \cdot t_{tr}$ $A_{tr} = 1.385 \cdot 10^{3} \circ in^{2}$

Cross Section Moment of Inertia $I_{tr} := \pi \cdot R_{tr}^{3} \cdot t_{tr}$ $I_{tr} = 3.742 \cdot 10^{6} \circ in^{4}$

Ring WT $WT_{tr} := A_{tr} \cdot L_{tr} \cdot \gamma_{st}$ $WT_{tr} = 1.571 \cdot 10^{4} \circ lbf$

WT of 8 Donut Stiffening Plates $WT_{dp} := 6.4 \cdot ft^{3} \cdot \gamma_{st}$ $WT_{dp} = 3.136 \cdot 10^{3} \circ lbf$

WT of the above components

$$WT := M_1 + M_2 + M_3 + WT_{cask} + WT_{rv} + WT_{ts} + WT_{tr} + WT_{dp}$$

$$WT = 4.412 \cdot 10^{5} \circ lbf$$

The total RVTC WT is 564300 lbf per Reference 2, therefore, the balanced WT which consists of filled concrete, insulation and others, can be approximated as

$WT_{conc} := 564300 \cdot lbf - WT$ $WT_{conc} = 1.231 \cdot 10^{5} \circ lbf$

Properties of Beam Models for lumped parameter dynamic analysis:

The method of composite beam per NUREG/CR-3966 is used in the following beam properties calculation:

Total beam length: $L_{cask} := (24 \cdot 12 + 11.5) \cdot in$

Beam 1: 3" cask shell + 3" (Trunion Ring + Stiffening Plates)+ 5.25" RV Shell + concrete/insulation

Combined Area $A_1 := A_{cask} + A_{rv} + A_{tr}$ $A_1 = 4.723 \cdot 10^3 \, in^2$

Combined Moment of Inertia $I_1 := I_{cask} + I_{rv} + I_{tr}$ $I_1 = 1.091 \cdot 10^7 \, in^4$

Beam 1 length $L_1 := \frac{L_{cask}}{3}$ $L_1 = 99.833 \, in$

Distributed WT per unit length

$$w_1 := \frac{(WT_{tr} + WT_{dp})}{L_1} + \frac{WT_{cask}}{L_{cask}} + \frac{WT_{rv}}{L_{cask}} + \frac{WT_{conc}}{L_{cask}} \qquad w_1 = 1.484 \cdot 10^3 \, \frac{lbf}{in}$$

$w_1 \cdot L_1 = 1.482 \cdot 10^5 \, lbf$

Beam 2: 3" cask shell + 4" Cask Shield Plates+ 5.25" RV Shell + concrete/insulation

Combined Area $A_2 := A_{cask} + A_{rv} + A_{ts}$ $A_2 = 5.172 \cdot 10^3 \, in^2$

Combined Moment of Inertia $I_2 := I_{cask} + I_{rv} + I_{ts}$ $I_2 = 1.206 \cdot 10^7 \, in^4$

Beam 2 length $L_2 := \frac{L_{cask}}{3}$ $L_2 = 99.833 \, in$

Distributed WT per unit length

$$w_2 := \frac{(WT_{ts})}{L_2} + \frac{WT_{cask}}{L_{cask}} + \frac{WT_{rv}}{L_{cask}} + \frac{WT_{conc}}{L_{cask}} \qquad w_2 = 1.795 \cdot 10^3 \, \frac{lbf}{in}$$

Beam 3: 3" cask shell + 5.25" RV Shell + concrete/insulation

Combined Area $A_3 := A_{cask} + A_{rv}$ $A_3 = 3.338 \cdot 10^3 \, in^2$

Combined Moment of Inertia $I_3 := I_{cask} + I_{rv}$ $I_3 = 7.171 \cdot 10^6 \, in^4$

Beam 2 length $L_3 := \frac{L_{cask}}{3}$ $L_3 = 99.833 \, in$

Distributed WT per unit length

$$w_3 := \frac{WT_{cask}}{L_{cask}} + \frac{WT_{rv}}{L_{cask}} + \frac{WT_{conc}}{L_{cask}} \qquad w_3 = 1.295 \cdot 10^3 \, \frac{lbf}{in}$$

Check: $TotalWT := M_1 + M_2 + M_3 + w_1 \cdot L_1 + w_2 \cdot L_2 + w_3 \cdot L_3$

$TotalWT = 5.643 \cdot 10^5 \, lbf$ OK

Conclusion:

The above calculated weight and geometric properties, namely M_1, M_2, M_3, A_1, A_2, A_3, I_1,I_2, I_3, w_1, w_2 and w_3, will be used in the Beam Model Finite Element Analysis.

ATTACHMENT E

Penetration Load Evaluation

Purpose:

To determine the adequacy of the cask thickness due to the loading from puncture event specified in 10CFR71.71(c)10, Reference 1. During this event, a vertical hemispherical-end steel cylinder of 1.25" diameter and 13 lbs is dropped from a height of 40" onto the exposed surface of the RVTS cask.

Reference:

1. United States Nuclear Regulatory Commission Rules and Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Materials", January 30, 1998.

2. ASCE Manual, "Structural Analysis and Design of Nuclear Plant Facilities", 1980 Edition.

3. Design Sketch Drawing No. SD-10525-020-001, Rev. 0.
   SD-10525-020-002, Rev. 0.

4. "Bounding Normal Operating Pressure for RVTS", Calc. No. M-10525-020-002, Rev. 0.

Assumption:

The cask is transported under normal condition with internal pressure range of -3 psig to 20 psig and temperature range of -20 ^oF to 195 ^oF and it is well supported by 5 equally spaced saddles. Although the existing bilateral tensile stresses in the target shell under this condition are considered negligible compared to the ultimate strength of 70000 psi while the projectile dropping on the cask, it will be assumed to be 10000 psi for conservatism.

Methodology:

The following Ballistic Research Laboratory Formula from ASCE Manual, Reference 2, will be utilized to determine the perforation thickness , e, of the steel target caused by an impacting non-deformable steel projectile.

$$(e/d)^{3/2} = D*Vo^2/(1.12*10^6*Ks^2)$$

Alternately, the Modified Stanford Formula as shown below from the same reference will be used for comparing the result.

$$(e/d)^2 + 3*F/128*(e/d) = 0.0452*D*Vo^2/Ss$$

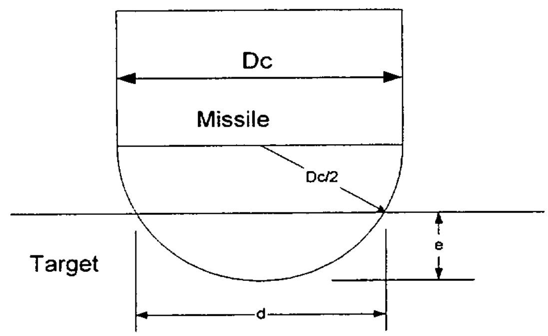
The miminum required design thickness per reference 2 will be 1.25 times the calculated perforation thickness. This thickness will be compared with the actual thickness to determine its adequacy.

Calc For	Reactor Vessel Transport Cask Stress Analysis		Calc. No. S-10525-020-012	
			Rev. 0	Date:
● Important to Safety Category A		Non-Safety-Related	Page E3	

Client	BNFL, Inc.		Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal		Reviewed by: C. W. Mak	Date
Proj. No.	10525-020	Equip. No.	Approved by:	Date

Calculation:

$Dc := 1.25$	in	Projectile Diameter, Ref. 1
$w := 13$	lbs	Projectile Weight, Ref. 1
$h := 40$	in	Drop Height, Ref. 1
$g := 386$	in/s^2	Gravitational Constant
$Ks := 1$		Steel penetrability constant, Ref. 2
$B := 5.625$	in	Minimum width of plate between rigid supports, Ref. 3
$Su := 70000$	psi	Ultimate tensile stress of target plate, SA 516 Gr. 70, Ref. 3.
$St := 10000$	psi	Existing bilateral tensile stresses, see assumption section.



Impact velocity: $Vo := \sqrt{2 \cdot g \cdot h}$ $\quad Vo = 176$ in/s

Diameter of Contact Area: $d(e) := 2 \cdot \sqrt{\left[\left(\frac{Dc}{2}\right)^2 - \left(\frac{Dc}{2} - e\right)^2\right]}$

Density: $D(e) := \frac{w}{d(e)^3}$

Per Ballistic Research Laboratory Formula·

Perforation thickness: $f(e) := \left(\frac{D(e) \cdot Vo^2}{1.12 \cdot 10^6 \cdot Ks^2}\right)^{\frac{2}{3}} \cdot d(e)$

Initially set e to be a small value: $e := .001$

Therefore, perforation thickness: $e := root(f(e) - e, e)$ $\quad e = 0.426$ in

minimum design thickness: $td := 1.25 \cdot e$

$td = 0.53$ in < Minimum cask shell plate thickness of 3" per Ref. 3

Per Modified Stanford Formula:

$(e/d)^2 + 3*F/128*(e/d) = 0.0452*D*Vo^2/Ss$

where $Ss := Su - St$

F = B/d, except F ≤ 8, and F ≤ 100*(e/d), whichever is lower.
Therefore the following two cases will be investigated.

Case 1: $F1(e) := \frac{B}{d(e)}$ $\quad r1(e) := \left(\frac{e}{d(e)}\right)^2 + \left(\frac{3 \cdot F1(e)}{128} \cdot \frac{e}{d(e)}\right) - \frac{0.0452 \cdot D(e) \cdot Vo^2}{Ss}$

Case 2: $F2(e) := \frac{100 \cdot e}{d(e)}$ $\quad r2(e) := \left(\frac{e}{d(e)}\right)^2 + \left(\frac{3 \cdot F2(e)}{128} \cdot \frac{e}{d(e)}\right) - \frac{0.0452 \cdot D(e) \cdot Vo^2}{Ss}$

Initially set e to be a small value: $e := .001$

Therefore, for case 1, perforation thickness: $e := root(r1(e), e)$ $\quad e = 0.441$ in $\quad F1(e) = 4.708$

minimum design thickness: $td := 1.25 \cdot e$

$td = 0.55$ in < Minimum cask shell plate thickness of 3" per Ref. 3

Initially set e to be a small value: $e := .001$

Therefore, for case 2, perforation thickness: $e := root(r2(e), e)$ $\quad e = 0.292$ in $\quad F2(e) = 27.615$

Since F1(e) < F2(e), case 1 is applicable.

Conclusion:

Based on the above evaluation, it can be concluded that the minimum design thicknesses calculated using two different approach are similar and well smaller than the actual minimum cask plate thickness. Therefore the cask shell thickness of 3" per Reference 3 is adequate for the purpose of taking the punching load during puncture event specified in 10CFR71.71(c)10, Reference 1.

ATTACHMENT F

RV FLANGE BOLT LOAD EVALUATION

Purpose:

The purpose of the attachment is to evaluate the RV Flange Bolts and Nuts for NCT and HAC loading. The evaluation is based on the following design options of bolt and nut:

Option 1: New SA-193, Grade B7, 4.75" OD bolts with the existing high strength nuts.
Option 2: Modified existing high strength bolts with new designed low strength nuts.

Reference:

1. ANSYS Analysis Output: Bolt.out 3/06/01
2. ASME B&PV, Section III, Subsection NB, NF and Appendices, 1995 Edition
3. Combustion Engineering Drawing E-201-805-5, "Stud, Nut, Washers & O-Ring Details" for Reactor Vessel – General Electric Co. – BWR- Consumers Power, 8/15/1960.
4. Oberg E., Jones D.F. and Horton L.H., "Machinery's Handbook", 23rd Edition, Industrial Press Inc.
5. ASME B1.1, 1989 Edition.

Input:

Description	Option 1	Option 2
Bolt nominal OD (inch)	4.75	4.5
Bolt Material	SA-193 grade B7	A-193 special order
Bolt Yield Strength (ksi)	70	120
Bolt Tensile Strength (ksi)	100	140
Nut Material	A-194 special order	SA-105 or SA-266 Class 2
Nut Yield Strength (ksi)	(*)	36
Nut Tensile Strength (ksi)	(*)	70

(*) see Assumption 1

Assumption:

1. Per Ref. 3, the nut and stud bolts material chemical composition conforms to AISI-4340 steel, a high strength carbon steel alloy. Therefore, the nut material yield strength and tensile strength are assumed to be the same as the strengths of the stud bolts.

Methodology:

1. Since the strength of the bolt material in Option 1 is bounded by the strength of bolts in Option 2, the bolt evaluation will be based on Option 1. The new designed nuts in Option 2 have lower strengths than the existing nuts; therefore; the evaluation of nuts is based on Option 2.

2. The existing bolt material specification is A-193 with a minimum yield strength of 120 ksi and a minimum tensile strength of 140 ksi as specified in Ref. 3. The existing bolts will be cut and rethreaded. The nominal bolt diameter would be reduced to 4.5", which is a ¼ inch less than the OD of bolts in Option 1. The reduced bolt size will be used in this calculation.

3. Bolts were modeled as coupling nodes in the linear elastic FEA performed for NCT and handling accident condition. The bolt-axial force is the Fz force and the shear forces are the Fx and Fy in the ANSYS FEA output in the local cylindrical coordinate (Reference 1). The maximum axial load and the average shear load will be used to calculate the bolt stresses for the NTC and handling accident condition.

4. Bolts were modeled explicitly in the nonlinear impact FEA for HAC drops and fire accident. Bolt stress intensity time histories are plotted in the main report and the extreme values are listed in the ANSYS output. No hand calculation is required for bolts in HAC. Option 1 was used in the HAC analyses. Tensile strength of bolt material in Option 2 is twice as that of Option 1. Therefore, a small change in bolt OD will not reduce the structural capacity of the bolts.

5. The nut minimum engagement length is determined such that the threads are sufficient to carry the full load necessary to break the bolt without stripping the threads. The method of minimum engagement length calculation is given in Ref. 4.

Acceptance Criteria:

For A193 Gr. B7 material, Reference 2:

at 200 ^{o}F: Design Stress Intensity, Sm = 23,300 psi
Yield Strength, Sy = 70,000 psi
Tensile Strength, Su = 100,000 psi

For NCT:

Per NB-3232, Reference 2, bolt stress allowable Fb is:
Fb = 2*Sm = 46,600 psi

For the Handling Accident Condition:

Per Appendix F, F-1335.1, Reference 2, the allowable are:
1. Allowable Tensile Stress: Ftb = smaller of 0.7 Su or Sy = 70,000 psi
2. Allowable Shear Stress: Fvb = smaller of 0.42 Su or 0.6 Sy = 42,000 psi
3. Interaction Ratio: $IR = ((Ft/Ftb)^2 + (Fv/Fvb)^2) < 1$

Calculation:

Dimensions for 4½"-8N-2A bolt :

Reference: ASME B1.1-1989	Diameter (in)	Pitch Diameter (in)
Bolt	Major: Dsmin = 4.4822	Esmin = 4.4066
Nut	Minor: Knmax = 4.39	Enmax = 4.4310

For steels of over 100 ksi tensile strength, the bolt tensile area is

$$At = 3.1416\left(\frac{Esmin}{2} - \frac{0.16238}{n}\right)^2$$

At = 15 in^2

Bolt Stress Area, Ab = 16.8 in^2 for 4¾" OD bolt was used in the "Bolt Stress Detailed Calculation" section, therefore, a factor of (16.8 / 15) = 1.12 will be used to adjust the stress in 4½" OD bolt.

NCT and Handling Accident Condition Bolt Stresses:

Shear Force Fs= $(Fx^2 + Fy^2)^{1/2}$

Tensile Stress, Ft = Maximum Axial Force / Ab

Shear Stress Fv = Sum of Shear Force / (7 * Ab)

Based on the result summary at the end of the "Bolt Stress Detailed Calculation" section, the bolt tensile and shear stresses are calculated for each NCT and Handling Accident loading case, adjusted for reduced bolt OD, and compared with the allowable as shown as below:

Condition	Load Case (*)	Criteria	Stress (psi) or IR	Allowable Stress (psi) or IR
NTC	N9	Tensile Stress	11,320	46,600
	N11	Shear Stress	11,510	46,600
Handling Accident Condition	A3a	Tensile Stress	39,580	70,000
	A3a	Shear Stress	28,920	42,000
	A3a	Interaction Ratio	0.79	1

(*) See the main report for load case definition.

Minimum engagement length:

Adjustment factor for relative strength of bolt and nut: (Ref. 4)

$$J = \frac{\pi \cdot n \cdot Knmax \cdot \left[\frac{1}{2 \cdot n} + 0.57735(Esmin - Knmax)\right]}{\pi \cdot n \cdot Dsmin \cdot \left[\frac{1}{2 \cdot n} + 0.57735(Dsmin - Enmax)\right]} \cdot \frac{\sigma ext}{\sigma int}$$

Where n = 8, number of thread per inch

σ ext and σ int are the tensile strengths of bolt and nut respectively.

J = 1.58

The required engagement length Le:

$$Le = \frac{2 \cdot At}{\pi \cdot Knmax \cdot \left[\frac{1}{2} + 0.57735 n \cdot (Esmin - Knmax)\right]} \cdot J$$

Le = 5.8 inches or rounded of to 6 inches

Conclusion:

All bolt stresses are within the allowable. The minimum engagement for the new design low strength nut is 6 inches.

Bolt Stress Detailed Calculations:

Load Case 31, N1= P1 + T1, Hot Environment, Max P.

NODE	FX	FY	FZ	FS
10315	139870	-10010	-963	140227
10317	141900	-19412	-10	143221
10339	138180	-2775	1733	138207
10425	143210	-8635	-12612	143470
10427	148340	-877	12177	148342
10446	141590	-24838	-327	143752

Tensile Stress = 751 psi < 46,600 psi
Shear Stress = 7,289 psi < 46,600 psi

Load Case 32, N2= P2 + T2, Cold Environment, Min P.

NODE	FX	FY	FZ	FS
10315	-125860	-10479	-478	126295
10317	-122700	-19151	3140	124185
10339	-127810	-2819	-351	127841
10425	-122210	-7699	-15179	122452
10427	-116530	-1504	11289	116539
10446	-122990	-23593	1577	125232

Tensile Stress = 904 psi < 46,600 psi
Shear Stress = 6,314 psi < 46,600 psi

Load Case 33, N3= P3 + T3, Increased External Pressure

NODE	FX	FY	FZ	FS
10315	-106410	-10434	-393	106920
10317	-103170	-18971	3128	104899
10339	-108290	-2849	-125	108327
10425	-102710	-7594	-15724	102990
10427	-96767	-1571	11777	96779
10446	-103470	-23522	1336	106109

Tensile Stress = 936 psi < 46,600 psi
Shear Stress = 5,323 psi < 46,600 psi

Load Case 34, N4= P4 + T1, Minimum External Pressure

NODE	FX	FY	FZ	FS
10315	148700	-10062	-1216	149040
10317	150400	-19860	-482	151705
10339	146970	-2733	1665	146995
10425	151880	-8792	-11343	152134
10427	156570	-565	11556	156571
10446	150080	-25162	-183	152174

Tensile Stress = 688 psi < 46,600 psi
Shear Stress = 7,726 psi < 46,600 psi

Load Case 35, N5= V1 + T1, Vertical Shock, Hot Environment.

NODE	FX	FY	FZ	FS
10315	132820	-21026	-14548	134473
10317	135980	-38865	-12551	141425
10339	131960	-6679	-4294	132128
10425	152410	-15925	43478	153239
10427	147810	7311	3793	147990
10446	136750	-57091	-15879	148188

Tensile Stress = 2,588 psi < 46,600 psi
Shear Stress = 7,291 psi < 46,600 psi

Load Case 36, N6= V2 + T3, Vertical Shock, Cold Environment.

NODE	FX	FY	FZ	FS
10315	-101490	-22906	2680	104042
10317	-95803	-38862	7244	103385
10339	-101860	-7388	12599	102127
10425	-99226	-18629	-53530	100959
10427	-84457	-8474	24365	84880
10446	-95635	-42216	6641	104538

Tensile Stress = 3,186 psi < 46,600 psi
Shear Stress = 5,101 psi < 46,600 psi

Load Case 37, N7= V3 + T1, Lateral Shock, Hot Environment.

NODE	FX	FY	FZ	FS
10315	149730	-33354	-7708	153400
10317	148110	-42724	-2284	154148
10339	140430	-24670	-3918	142580
10425	155220	35207	100940	159162
10427	143270	75021	-2093	161723
10446	134530	-60487	-29890	147502

Tensile Stress = 6,008 psi < 46,600 psi
Shear Stress = 7,811 psi < 46,600 psi

Load Case 38, N8= V4 + T3, Lateral Shock, Cold Environment.

NODE	FX	FY	FZ	FS
10315	-88296	-36803	3567	95659
10317	-86127	-45041	12695	97193
10339	-95893	-25248	6923	99161
10425	-104820	34553	-54785	110368
10427	-90896	55293	14528	106392
10446	-98597	-39312	-8109	106145

Tensile Stress = 3,261 psi < 46,600 psi
Shear Stress = 5,229 psi < 46,600 psi

Load Case 39, N9= V5 + T1, Longitudinal Shock, Hot Environment.

NODE	FX	FY	FZ	FS
10315	166650	-6145	53344	166763
10317	173230	-17642	60938	174126
10339	160270	-875	52879	160272
10425	168470	-2244	-157	168484
10427	195980	-3022	169770	196003
10446	167860	-27941	53281	170169

Tensile Stress = 10,105 psi < 46,600 psi
Shear Stress = 8,808 psi < 46,600 psi

Load Case 40, N10= V6 + T3, Longitudinal Shock, Cold Environment.

NODE	FX	FY	FZ	FS
10315	-73092	-5474	58411	73296
10317	-65822	-16975	67818	67975
10339	-79418	-375	55953	79418
10425	-70113	700	6340	70116
10427	-46736	-217	142030	46736
10446	-70478	-27359	59505	75602

Tensile Stress = 8,454 psi < 46,600 psi
Shear Stress = 3,513 psi < 46,600 psi

Load Case 41, N11= I1*0.45 + T1, 1' Horizontal Drop, Hot Environment.

NODE	FX	FY	FZ	FS
10315	57746	-94219	-36215	110507
10317	121820	-126660	-15473	175735
10339	20985	-36259	-40949	41893
10425	226500	-122370	22965	257442
10427	266800	-279930	69128	386707
10446	189690	-140690	194	236169

Tensile Stress = 4,115 psi < 46,600 psi
Shear Stress = 10,276 psi < 46,600 psi

Load Case 42, N12= I2*0.45 + T3, 1' Horizontal Drop, Cold Environment.

NODE	FX	FY	FZ	FS
10315	-169730	-94561	-36213	194293
10317	-105060	-126910	-13516	164753
10339	-206720	-36214	-42634	209868
10425	-363	-121230	23543	121230
10427	39664	-280370	66552	283161
10446	-36937	-139750	2269	144548

Tensile Stress = 3,961 psi < 46,600 psi
Shear Stress = 9,506 psi < 46,600 psi

Load Case 51, A1= I1 + T1, 5' Horizontal Drop, Hot Environment.

NODE	FX	FY	FZ	FS
10315	-23965	-209840	-80466	211204
10317	118740	-281900	-32804	305886
10339	-106010	-80539	-92579	133133
10425	351040	-271460	51043	443756
10427	440240	-622100	152050	762115
10446	269570	-312210	1985	412484

Tensile Stress = 9,051 < 70,000 psi
Shear Stress = 19,291 < 42,000 psi
Bolt Stress Interaction Ratio = .23 < 1

Load Case 52, A2= I2 + T3, 5' Horizontal Drop, Cold Environment.

NODE	FX	FY	FZ	FS
10315	-255730	-210020	-80475	330917
10317	-112210	-281800	-30851	303318
10339	-337870	-80496	-93934	347326
10425	120640	-269510	52320	295278
10427	209650	-623020	148690	657348
10446	39176	-310790	4249	313249

Tensile Stress = 8,851 < 70,000 psi
Shear Stress = 19,111 < 42,000 psi
Bolt Stress Interaction Ratio = .22 < 1

Load Case 53, A3a= I3a + T1, 5' Oblique First Drop, Hot Environment.

NODE	FX	FY	FZ	FS
10315	-41126	-259660	-24081	262896
10317	170910	-311650	67534	355437
10339	-169890	-101200	-85996	197747
10425	552360	-193860	215140	585391
10427	866830	-727170	593630	1131446
10446	412670	-288420	144760	503470

Tensile Stress = 35,335 < 70,000 psi
Shear Stress = 25,820 < 42,000 psi
Bolt Stress Interaction Ratio = .63 < 1

Load Case 54, A4a= I4a + T3, 5' Oblique First Drop, Cold Environment.

NODE	FX	FY	FZ	FS
10315	-284170	-260230	-24496	385320
10317	-71471	-312380	69808	320451
10339	-412950	-101180	-88801	425164
10425	309510	-193330	216750	364928
10427	623160	-727040	589940	957557
10446	170430	-288170	147760	334795

Tensile Stress = 35,115 < 70,000 psi
Shear Stress = 23,709 < 42,000 psi
Bolt Stress Interaction Ratio = .57 < 1

```
Load Case 55, A3b= I3b + T1, 5' Oblique Second Drop, Hot Environment.
 NODE          FX           FY           FZ           FS
10315        -61594      -138890      -288260       151935
10317         14672      -194910      -250990       195461
10339       -107230       -49687      -310800       118182
10425        150190      -159310      -183340       218944
10427        198530      -282510      -198570       345291
10446        102340      -208130      -213570       231930
                          Tensile Stress =  18,500 <  70,000  psi
                           Shear  Stress =  10,729 <  42,000  psi
                        Bolt Stress Interaction Ratio =  .14 < 1

Load Case 56, A4b= I4b + T3, 5' Oblique Second Drop, Cold Environment.
 NODE          FX           FY           FZ           FS
10315       -303600      -139430      -288060       334086
10317       -226600      -195540      -248490       299304
10339       -349300       -49666      -312740       352813
10425        -91510      -158950      -182150       183409
10427        -43900      -282910      -201170       286295
10446       -138750      -207780      -210760       249848
                          Tensile Stress =  18,615 <  70,000  psi
                           Shear  Stress =  14,505 <  42,000  psi
                        Bolt Stress Interaction Ratio =  .19 < 1
```

Result summary

Condition	Load Case	Criteria	Stress (psi) or IR	Allowable Stress (psi) or IR
NTC	39 (N9)	Tensile Stress	10,105	46,600
	41 (N11)	Shear Stress	10,276	46,600
Handling Accident Condition	53 (A3a)	Tensile Stress	35,335	70,000
	53 (A3a)	Shear Stress	25,820	42,000
	53 (A3a)	IR	0.63	1

CALCULATION S-10525-020-012

REVISION 0

ATTACHMENTS “G” AND “H” NOT INCLUDED

ATTACHMENT I

Corner Drop Local Stiffness Calculation

Purpose:

To determine the local force-displacement relationship at contact between the RVTC and an unyield flat surface block during a 30 ft corner drop event.

Reference:

1. ANSYS analysis Output: CD2-disp.out dated 3/07/01
2. ANSYS analysis Input: obqbeam-7.txt dated 3/07/01

Methodology:

Based on the analytical result of the 30 ft corner drop analysis(Reference 1), simple log curve fitting technique is used to determine the local force-displacement relationship at contact between the RVTC and an unyield flat surface. This stiffness is then used in the Finite Element beam model (Reference 2) to stimulate the rigid body motion for determining the impact velocity.

Calculation:

The force-displacement data from Reference 1 are read into a matrix array called "data". The force data Y is multiplied by a factor of 2 since only half model is used in the 30 ft corner drop analysis.

data := READPRN("CD2-disp.out")

Displacement: $X := (-data)^{\langle 0 \rangle}$

Force: $Y := data^{\langle 1 \rangle} \cdot 2$

This data is then fit to a simple log curve model function $Y = a \cdot \ln(x) + b$, where a and b are unknown.

$$F(x) := \begin{bmatrix} \ln(x) \\ 1 \end{bmatrix}$$

Let $S := \text{linfit}(X, Y, F)$

The following function is defined such that it uses these newly found parameter values in the logarithmic model. Also, a range variable is defined over which to graph the function.

$$p(x) := S_0 \cdot \ln(x) + S_1$$

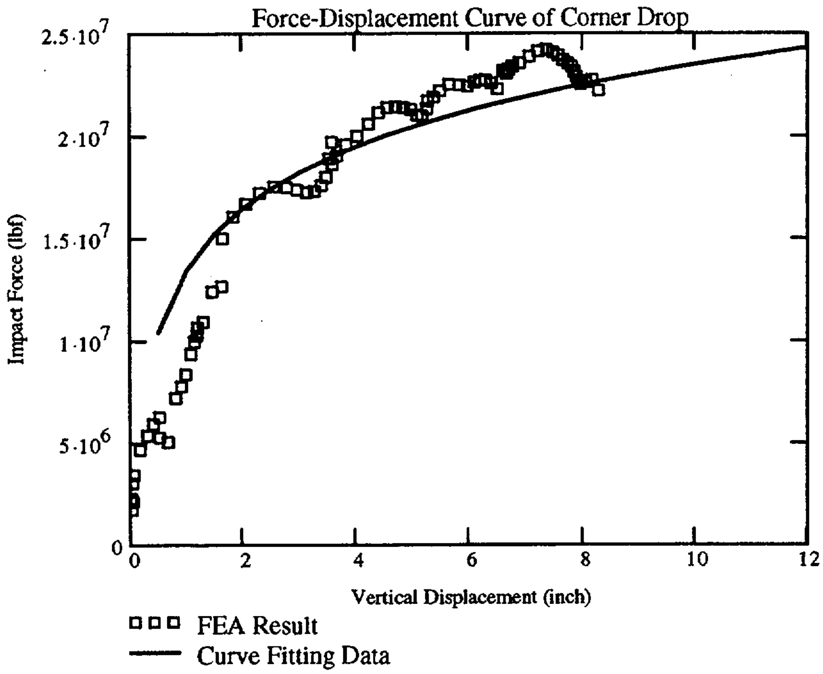
$$f(x) := F(x) \cdot S$$

$$z := .5, 1 .. 12$$

A graph of the model function with the newly found parameter values and the original data points reveals a good fit and is shown as follows:

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No. S-10525-020-012
● Important to Safety Category A	Non-Safety-Related	Rev. 0 Date:
		Page I3 / Final

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date



z =	p(z) =
0.5	$1.044 \cdot 10^7$
1	$1.347 \cdot 10^7$
1.5	$1.524 \cdot 10^7$
2	$1.649 \cdot 10^7$
2.5	$1.747 \cdot 10^7$
3	$1.826 \cdot 10^7$
3.5	$1.894 \cdot 10^7$
4	$1.952 \cdot 10^7$
4.5	$2.003 \cdot 10^7$
5	$2.049 \cdot 10^7$
5.5	$2.091 \cdot 10^7$
6	$2.129 \cdot 10^7$
6.5	$2.164 \cdot 10^7$
7	$2.196 \cdot 10^7$
7.5	$2.226 \cdot 10^7$
8	$2.255 \cdot 10^7$
8.5	$2.281 \cdot 10^7$
9	$2.306 \cdot 10^7$
9.5	$2.33 \cdot 10^7$
10	$2.352 \cdot 10^7$
10.5	$2.373 \cdot 10^7$
11	$2.394 \cdot 10^7$
11.5	$2.413 \cdot 10^7$
12	$2.432 \cdot 10^7$

Conclusion:

The above calculated force-displacement relationship , p(z), at contact between the RVTC and an unyield surface concrete block will be used in the Finite Element Beam Model Analysis (Reference 2) for the 30 ft oblique drop cases.

ATTACHMENT J

ELEMENT PERFORMANCE

BENCHMARK ANALYSIS INPUT AND OUTPUT FILES

Input Filename: ib.txt dated 03-02-01

```
/BATCH
/COM,ANSYS RELEASE  5.4    UP19971021
09:24:37    02/28/2001
/input,menust,tmp      ,,,,,,,,,,,,,,,,,1
/GRA,POWER
/GST,ON
/PREP7
!*
ET,1,SHELL181
!*
KEYOPT,1,3,2
KEYOPT,1,4,0
KEYOPT,1,5,0
KEYOPT,1,9,0
KEYOPT,1,10,0
!*
!*
R,1,.762e-2, , , , ,
!R,1,.1e-2, , , , ,

RMORE, , , , , , ,
!*
L=2.347e-2
d=.762e-2
e=70e9
et=100e6
sy=420e6
dens=2700
g=9.81
RECTNG,0,1,0,d,
!*
UIMP,1,EX, , ,e,
UIMP,1,DENS, , ,dens,
UIMP,1,ALPX, , , ,
UIMP,1,REFT, , , ,
UIMP,1,NUXY, , ,.3,

!*
TB,BISO,1,1, , ,
!*
TBMODIF,2,1,Sy
TBMODIF,3,1,ET
TYPE,   1
MAT,       1
REAL,       1
ESYS,       0
!*

LESIZE,ALL, , ,12, ,1, , ,1,
CM,_Y,AREA
ASEL, , , ,        1
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
MSHKEY,1
AMESH,_Y1
MSHKEY,0
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*

!*
FINISH
/SOLU
!*
ANTYPE,4
NLGEOM,1

OUTRES,ALL,50
EQSLV,PCG,1E-3
!RESCONTRL,DEFINE,ALL,LAST,3
CUTCONTROL,PLSLIMIT,.15
!EQSLV,FRONT
RESCONTRL,DEFINE,ALL,5,1

NROPT,FULL
DL,       4, ,SYMM
FLST,2,2,1,ORDE,2
FITEM,2,20
FITEM,2,164
!*
/GO
D,P51X, , , , , ,UY,UZ, , , ,

IC,ALL,UX, ,-478,
SAVE
TIMINT,ON
OUTPR,ALL,50
TIME,1e-8
AUTOTS,ON
KBC,1
NSUBST,100,100 ,50 ,ON
SOLVE
TIMINT,ON

TIME,1e-6
AUTOTS,ON
KBC,0
NSUBST,2500,2500 ,250 ,ON
SOLVE
TIME,5e-6
AUTOTS,ON
KBC,0
NSUBST,2500,2500 ,500 ,ON
SOLVE
TIME,1e-5
SOLVE
TIME,2e-5
SOLVE
TIME,3e-5
SOLVE
TIME,4e-5
SOLVE
TIME,5e-5
SOLVE

FINISH
/POST26
!*
!*
!*
NSOL,2,20,U,X,
!*
PLVAR,2, , , , , , , , , ,
!*
```

Input Filename: energy.txt dated 03-13-01

```
/POST1
*DIM,energy,ARRAY,100,4,1,

SET,FIRST
!IRLIST
ETABLE, ,SENE,
!*
ETABLE, ,KENE,
ETABLE, ,NL,PLWK
ETABLE,vol,VOLU,
!*
!*
!SSUM
*DO,i,1,76,1
!SET, , ,1, ,.001*i, ,
SET, , ,1, , , ,i,

ETABLE,REFL
SMULT,PlasticE,NLPLWK,VOL,1,1,

SSUM
*GET,tse,SSUM, ,ITEM,SENE
*GET,tke,SSUM, ,ITEM,KENE
*GET,tpe,SSUM, ,ITEM,PlasticE

energy(i,1)=tse
energy(i,2)=tpe
energy(i,3)=tke
!energy(i,4)=tse+tke
*enddo

*CREATE,ansuitmp
*CFOPEN,enlist-ib,txt,
*VWRITE,energy(1,1),energy(1,2),energy(1,3),, , ,
, , , ,
(f15.1,f15.1,f15.1)
*CFCLOS
*END
/INPUT,ansuitmp
!*
FINISH
/POST26
!*
!*
!*
NSOL,2,20,U,Y,uy
!*
VPUT,energy(1,1),3, ,
VPUT,energy(1,2),4, ,
VPUT,energy(1,3),5, ,
VARNAM,3,StrainE
VARNAM,4,PlastE

!*
VARNAM,5,KineticE
VARNAM,6,TotalE
!*


!*
/SHOW,JPEG
JPEG,QUAL,100,
JPEG,ORIENT,HORIZ
JPEG,COLOR,2
JPEG,TMOD,0
/GFILE,500,
/dev,font,1,Courier*New,400,,-15,0,0,,,
!/dev,font,1,Times*New*Roman,400,,-15,0,1,,,
/ANNO,TMOD,0
/GTHK,AXIS,1
/ANUM ,0, 1,-0.75 ,-0.55   !Annotation Start
Location
/TSPEC, 15, 1.0, 1, 90,  0

/RGB,INDEX,100,100,100, 0
/RGB,INDEX, 80, 80, 80,13
/RGB,INDEX, 60, 60, 60,14
/RGB,INDEX,  0,  0,  0,15

/AXLAB,X,TIME (sec)
/AXLAB,Y,
/TLAB,-0.75,-0.60,          Energy (inch-lbf)

/TSPEC, 15, 1.0, 1, 0,  0
/ANUM ,0,     1, 0.065, 0.75
/TLAB,-0.35, 0.75,Energy Check for SHELL181

PLVAR,4,5, , , , , , , ,
/ANNO,DELE
/RESET

/SHOW,file,grph,
/SHOW,term
/RESET

FINISH
/POST1
/OUTPUT, ib-disp,out
!*
Set,Last
*GET,Dx20,NODE,20,U,X
DL=L+Dx20    !negative disp
*MSG,INFO,L
Original Length L = %G
*MSG,INFO,DL
Deformed Length DL = %G
/OUTPUT,TERM
```

Output Filename: ib-disp.out dated 03-13-01 for SHELL181 element model

```
USE LAST SUBSTEP ON RESULT FILE  FOR LOAD CASE 0

 SET COMMAND GOT LOAD STEP=     8  SUBSTEP=    501  CUMULATIVE ITERATION=  8743
   TIME/FREQUENCY= 0.50000E-04
 TITLE=

 *GET  Dx20      FROM  NODE     20  ITEM=U     X      VALUE=-0.954708256E-02

 PARAMETER DL        =    0.1392292E-01
 Original Length L = 2.347E-02.
 Deformed Length DL = 1.392291744E-02.
```

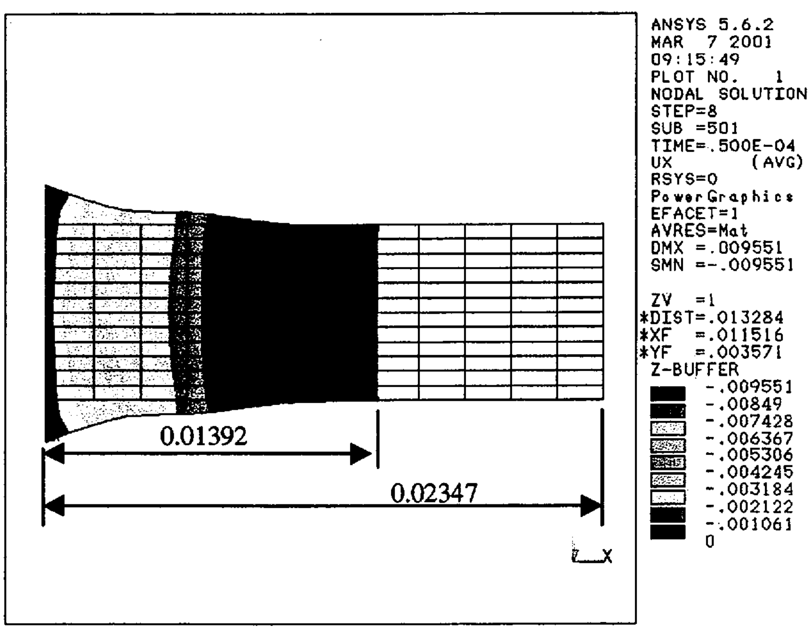
Output Filename: ibv-disp.out dated 03-13-01 for VISCO106 element model

```
USE LAST SUBSTEP ON RESULT FILE  FOR LOAD CASE 0

 SET COMMAND GOT LOAD STEP=     8  SUBSTEP=    501  CUMULATIVE ITERATION=  6663
   TIME/FREQUENCY= 0.50000E-04
 TITLE=

 *GET  Dx20      FROM  NODE     20  ITEM=U     X      VALUE=-0.948646419E-02

 PARAMETER DL        =    0.1398354E-01
 Original Length L = 2.347E-02.
 Deformed Length DL = 1.398353581E-02.
```



Deflected Shape of the Impact Bar modeled with SHELL181 element.

Calc For	Reactor Vessel Transport Cask Stress Analysis	Calc. No. S-10525-020-012
● Important to Safety Category A	Non-Safety-Related	Rev. 0 Date:
		Page J5 / Final

Sargent & Lundy

Client	BNFL, Inc.	Prepared by: P. H. Hoang	Date
Project	Big Rock Point Major Component Removal	Reviewed by: C. W. Mak	Date
Proj. No. 10525-020	Equip. No.	Approved by:	Date