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		QA							
		Safety							
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Scott Edwards

Interim Structural Evaluation of the MCO Cask

S. S. Shiraga

Rust Federal Services Inc., Northwest Operations, Richland, WA 99352
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Abstract: The purpose of this interim report is to verify that the structural performance of the current Multiple Canister Overpack (MCO) cask design meets the structural performance requirements.

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LIST OF TERMS

2-D	two-dimensional
3-D	three-dimensional
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel (Code)
BNFL	British Nuclear Fuels Limited
CSB	Canister Storage Building
CVD	Cold Vacuum Drying (Facility)
EPRI	Electric Power Research Institute
FEA	Finite Element Analysis
MCO	Multiple Canister Overpack
NCT	normal conditions of transport
SARP	Safety Analysis Report for Packaging
SNL	Sandia National Laboratory
SST	stainless steel
TN	Transnuclear, Incorporated
WHC	Westinghouse Hanford Company

INTERIM STRUCTURAL EVALUATION OF THE MCO CASK

1.0 INTRODUCTION

1.1 OBJECTIVE

The objective of this interim report is to verify that the structural performance of the current Multiple Canister Overpack (MCO) cask design meets the structural performance requirements of the Westinghouse Hanford Company (WHC) Specification (WHC 1995). Structural analysis of this package is performed via a refined finite element model generated for computation by ABAQUS/Explicit (1995). This numerical model provides a representative simulation of cask impacts onto a concrete surface. The refined impact simulation models are developed by calibration of the ABAQUS/Explicit Finite Element Analysis (FEA) structural impact model with actual tests of cask impacts onto concrete surfaces.

The MCO transport cask (MCO cask), currently being designed by Transnuclear (TN), is used on the Hanford Site to transport spent nuclear fuel. Spent nuclear fuel will be transported from the K-Basins Loadout Facility in the 100 Area to the Cold Vacuum Drying (CVD) Facility in 100 Area for processing, and then to the Canister Storage Building (CSB) in the 200 Area for storage. Design and fabrication of the MCO cask is being performed by TN to the requirements of the *Specification for SNF Path Forward Cask and Transportation System* (WHC 1995). The cask is required to maintain the primary level of containment during the normal conditions of transport and under accident conditions.

In April 1996, the preliminary MCO cask design performance was evaluated in the *Preliminary Safety Analysis Report for Packaging (Onsite) Multiple Canister Overpack Cask* (WHC 1996a) using highly conservative and idealized analytical concrete surface impact models developed with the ABAQUS/Explicit (ABAQUS 1995) general purpose finite elements program. Since this time, the cask design has evolved and the analytical numerical simulation models of the concrete surface have been refined. Subsequently, an interim reevaluation of the cask performance is presented.

It was shown in the preliminary Safety Analysis Report for Packaging (SARP) that the most severe loadings specified for this cask are the 9 m (30 ft) drop for accident conditions, and 0.3 m (1 ft) drop for normal conditions of transport (NCT) onto a 20 cm (8 in.) thick reinforced concrete surface. Consequently, three conditions are evaluated in this document to demonstrate the structural integrity and performance of this evolution in cask configuration. The three worst case loading conditions evaluated are the 9 m (30 ft) bottom end flat drop, the 0.3 m (1 ft) bottom end oblique drop, and the impact velocity failure threshold for 60 mph top end oblique impact. For conservatism, it is assumed that the cask is fully loaded and at maximum design pressure and temperature.

1.2 EVALUATION/DESIGN CRITERIA

The cask is designed to the *Specification for SNF Path Forward Cask and Transportation System* (WHC 1995). Design and fabrication criteria outlined in the specification are derived from requirements for packaging and transportation within the Hanford Site boundary. These requirements are specific to the NCT and accident conditions within the Site. The criteria for evaluation of the cask loadings are based on the requirements of the American Society of Mechanical Engineers (ASME) (1995), Subsection NB for Safety Class 1 components. Guidance for application of the ASME Code and load combinations for evaluation are taken from Regulatory Guide 7.6 (NRC 1978) and Regulatory Guide 7.8 (NRC 1977). As specified in Regulatory Guide 7.6, the NCT loads are evaluated to Service Level A requirements and accident conditions are evaluated to Service Level D requirements.

The ASME Code stress intensity used for comparison to ASME allowables is defined as the largest difference among the principal stresses. For example, if σ_1 , σ_2 , and σ_3 are the three principal stresses and $\sigma_1 > \sigma_2 > \sigma_3$, then the ASME Code stress intensity is $(\sigma_1 - \sigma_3)$. In all evaluation cases the results of the ABAQUS runs are retrieved and processed to obtain the ASME Code stress intensities. Comparison of the ASME Code stress intensities versus the ASME Code allowables are used to demonstrate the structural integrity and containment performance of the cask except in critical areas where plastic deformation is a primary factor. For impact velocity failure threshold evaluations, where material rupture is the limiting parameter, the plastic strain at ultimate elongation is used to assess the performance of the cask.

Although peak accelerations are determined, they are not used in evaluation of the stresses. As determined from British Nuclear Fuels Limited (BNFL) impact tests on concrete (Stokley and Williamson 1996), the use of peak acceleration for quasi-static evaluations is overly conservative. The integrity of the cask is a function of total impulse of the impact scenario. Consequently, for this evaluation, the equivalent average stress over the total impulse is used to determine the ASME Code stress intensity.

2.0 SUMMARY OF RESULTS

2.1 PACKAGE EVALUATION

2.1.1 Accident Conditions-9 m (30 ft) Flat Bottom End Drop

In this numerical simulation, the MCO cask is given an initial velocity of 13.4 m/s (44 ft/s) and impacts with the flat bottom end into the concrete target. This is to simulate the cask dropping 9 m (30 ft) onto a concrete pad, flat onto its bottom end. In this case, the impact was simulated for a period of 20 ms.

The resulting peak impact acceleration for this case is 57.7gs, and the average acceleration over impact period is determined as 29gs. The largest stress intensity magnitude within the containment boundary is found to be 88.6 MPa (12.85 ksi) at element 21310. Location of the elements is shown on Figures 2-1, 2-2, and 2-3. On the exterior surface, the largest stress intensity magnitude is found to be 89.01 MPa (12.91 ksi) at element 21346. For the closure lid bolts, the highest stress intensity magnitude calculated is 519.51 MPa (75.35 ksi) for bolts at element locations 9906 and 9907 (Figure 2-4). Based on these stress intensities and the ASME Code primary stress allowables in Tables 4-1 and 4-3, it is concluded that the cask will maintain structural integrity and containment of the contents.

In this drop scenario, only localized minor plastic deformations occur around the bottom drain port area. The maximum strain values in these areas are approximately 0.5%, which are only slightly over the elastic limit of 0.2% strain. Consequently, at these locations, there are only localized minor deformations. Since the ASTM rupture strain for 304 stainless steel shell is 35%, no breach of containment will occur at these locations. Also, since only localized minor dimensional changes occur, the cover plate will remain secured to the bottom drain port, thereby maintaining containment.

2.1.2 NCT-0.3 m (1 ft) Center of Gravity over Corner Bottom End Oblique Drop

For this numerical cask impact simulation, the MCO cask is given an initial velocity of 2.4 m/s (96.3 in/s) and then impacted into the concrete target at some angle. The angle of impact is defined as the center of gravity over the bottom end corner. This is to simulate a 0.3 m (1 ft) free fall of the cask onto the concrete pad. In this case, the impact was simulated for a total period of 35 ms.

The peak acceleration for a bottom end oblique drop is calculated as 5.4gs at the bottom corner of impact. The average acceleration of the entire impulse is 4gs based on the velocity change.

High stresses are only found at the point of impact. In this orientation, the initial peak contact stress intensity is 313.29 MPa (45.44 ksi) at the point of impact (bottom corner), element 21336. The resulting average stress intensity at the corner is 156.65 MPa (22.72 ksi). Location of the element is shown on Figures 2-1, 2-2, and 2-3. Although this

Figure 2-1. Cask Model for Bottom End Drop.

Figure 2-2. Cask Bottom Section Element Numbers.

Figure 2-3. Cask Drain Port Section Element Numbers.

stress intensity is above the allowable listed in Table 4-1, it is very localized and concentrated, causing only localized deformation of the cask. The stress intensities rapidly reduce toward the interior of the cask. This is demonstrated by the lower stress intensity values on the interior surface, which is defined as the containment boundary. The maximum average stress intensity at the interior surface is 23.51 MPa (3.41 ksi) at element 20695, which is much lower than the allowable listed in Table 4-1 at 392 °C (200 °F). Stress intensities produced by this impact on the closure lid bolts have a maximum of only 7.72 MPa (1.12 ksi) at element 9907 (Figure 2-4), which is well below the allowables listed in Table 4-3. Based on these stress intensities, and the ASME Code primary stress allowables, it is concluded that the cask will maintain structural integrity and containment of the contents.

The analysis shows the axial force in the bottom drain port cover has a peak value of 29,802 N (6,700 lb) and an average value of 14,901 N (3,350 lb) over the entire impact scenario. These relatively low force values indicate that the stresses on the $\frac{1}{2}$ in. closure bolts will not exceed allowable values. Consequently, it is concluded that the cask will experience only localized exterior deformation at the bottom corner, and will maintain structural integrity and containment of the contents after an NCT bottom end oblique drop.

2.1.3 96.6 kph (60 mph) Failure Threshold Evaluation

This case is used to evaluate the impact velocity change failure threshold performance of the MCO cask for the radiological risk evaluation (WHC 1996b). The impact velocity change failure threshold is numerically simulated by a 96.6 kph (60 mph) top end impact of the cask onto the concrete surface. The cask impact orientation is 78.4° off of vertical, relative to the concrete surface.

Figure 2-4. Lid and Lid Bolts Model.

The resultant peak acceleration determined from the impacted forces for a 20 ms impact duration is 5.9gs. The average acceleration computed is 5.3gs, based the velocity change for the duration. The estimated average stress intensities on the exterior and interior surfaces of the cask are well below the ASME stress intensity allowable of 172 MPa (25 ksi) at 93 °C (200 °F) (Table 4-1). The maximum average stress intensity on the interior surface (defined as the containment boundary) is 86.53 MPa (12.55 ksi) at element 5650 and 80.12 MPa (11.62 ksi) on the exterior surface at element 5664. The location of the elements are depicted in Figures 2-5, 2-6, 2-7, 2-8, and 2-9. Evaluation of the lid bolts show the average stress intensities on the bolt are negligible with a maximum bolt stress intensity of 77.5 MPa (11.24 ksi) at element 9907 (Figure 2-4). This low bolt loading is due to transference of the impact loading from the closure lid to the cask body in a compressive mode. In all cases the stress intensities are shown to be below the stresses required to produce a 35% plastic strain on the cask body/lid 304 stainless steel (SST) material. Bolt material strains are less than the defined 9.3% plastic strain required to produce rupture. Consequently, it is demonstrated that the cask closure lid, body, or closure bolts will not rupture in a 96.6 kph (60 mph) impact with the specified concrete surface.

For this impact scenario, a majority of the impact energy is absorbed by the extensive deformation of the trunnion and brackets, as well as the trunnion penetration into the concrete surface. The von Mises stresses of the lifting bracket and trunnion for this impact are well above material yield strength and the plastic strain of the material. This loading renders the lifting system unusable, but provides protection against rupture failure of the closure bolts and closure lid, thereby maintaining the containment boundary.

2.2 STRUCTURAL MODEL CALIBRATION

Data for calibration of the analytical impact models was obtained from cask drop tests onto various concrete and soil surfaces which were conducted by Sandia National Laboratory (SNL) in 1986. Actual cask impact test data is summarized in an SNL report (Gonzales 1987) and pertinent data is presented in Table 2-1 of this document.

Figure 2-5. Cask Model for Top End Drop.

Figure 2-8. Cask Lid Flange Element Numbers.

Figure 2-9. Top of Cask Lid Element Numbers.

NOT FOR CONSTRUCTION

Table 2-1. SNL Target Hardness Test Results.¹

Test		Maximum recorded acceleration (gs)	Penetration cm (in.)
Concrete runway	13 m/s (44 ft/s)	480	0.64 (0.25)
	20 m/s (66 ft/s)	900	10 (4)
	27 m/s (88 ft/s)	1000	20 (8)
Concrete highway	13 m/s (44 ft/s)	350	10 (4)
	20 m/s (66 ft/s)	----	10 (4)
	27 m/s (88 ft/s)	7500	48 (19)

¹SNL = Sandia National Laboratory
 Gonzales, A., 1987, Target Effects on Package Response: An Experimental and Analytical Evaluation, SAND86-2275, Sandia National Laboratory, Albuquerque, New Mexico.

This test data is used to develop and calibrate realistic two-dimensional (2-D) and three-dimensional (3-D) models simulating cask impacts onto concrete surfaces with the ABAQUS/Explicit (ABAQUS 1995) general purpose finite element program. The resulting computer simulations are used to determine concrete/soil target behavior and simulation parameters.

Comparisons from three 2-D calibrated simulations to test data are presented in Table 2-2 to demonstrate the validity of the ABAQUS/Explicit FEA modeling methods for cask impact evaluation. The 2-D model used both the runway concrete and highway concrete cask impact tests data to study material behavior and develop simulation parameters for target models. In the 2-D model the concrete is modelled as a uniform isotropic material and the soil was modeled as nonlinear spring elements. A preliminary report for the 2-D simulation model is provided in Section 7.1.

Results comparing 3-D calibrated simulations to actual test data are presented in Table 2-3 to demonstrate the accuracy and realistic representation of the ABAQUS/Explicit FEA modeling methods used in the evaluation of casks. The 3-D model differs from 2-D model in that the soil and concrete are represented by 8-node brick elements. These changes were made for a more accurate representation of the concrete and soil behavior. Comparison of the 2-D and 3-D modeling results with actual test data demonstrates the 3-D model substantially improves simulation accuracy of cask impacts onto concrete surfaces.

Table 2-2. 2-D Model Comparison of Highway and Runway Concrete Impact.

Impact Velocity m/s (ft/s)	Target	Calculated Peak <i>g</i> load	Measured Peak <i>g</i> load	Calculated Penetration cm (in.)	Measured Penetration cm (in.)
13.4 (44.0)	Concrete highway	583	350	9.4 (3.7)	10.2 (4.0)
13.4 (44.0)	Concrete runway	814	480	0.8 (0.3)	0.64 (0.25)
26.8 (88.0)	Concrete runway	1128	1000	13.5 (5.3)	20.3 (8.0)

2-D = two-dimensional

Table 2-3. 3-D Model Comparison of Runway Concrete Impact.

Impact velocity m/s (ft/s)	Calculated peak <i>g</i> load	Measured peak <i>g</i> load	Calculated penetration cm (in.)	Measured penetration cm (in.)
20.1 (66.0)	894	900	11.9 (4.7)	10.2 (4.0)
26.8 (88.0)	1343	1000	22.1 (8.7)	20.3 (8.0)

3-D = three-dimensional

3.0 COMPUTER MODEL DESCRIPTION

3.1 FINITE ELEMENT MODELS

Each finite element model consists of two parts--the projectile and the target. The projectile includes the cask body, the lid, lid bolts, lifting brackets, and payloads. The target includes the reinforced concrete pad and soil models. ABAQUS/Explicit (1995) finite element computer code is used for this analysis.

Several contact pairs are defined in each drop case depending on drop orientations. There is always a contact pair between the cask (projectile) and the concrete pad (target). The concrete pad contact surface includes a large central portion of the concrete pad through its entire depth. Because the concrete and the smeared rebars in this study are allowed to undergo large deformations, the lower layers of the concrete can become contact surfaces. The other contact surface (or surfaces) for this pair is the cask impact surface. For example, in the bottom end oblique drop the cask impact surfaces include the bottom surface of the cask, the lower portion of the cask outside wall, and the outside surface of the drain port cover plate. The contact surfaces form contact pairs from which the total reaction force can be obtained.

The lid's bottom surface and the cask's top surface form another contact pair. These two surfaces are allowed to move apart, but do not penetrate one another. Relative movement of the lid to the cask body is restrained by the 12 closure bolts. The shear key on the cask body takes up the shear loads subjecting the lid bolts to only tensile loads.

The payload inside the cask cavity is modelled by two separate contact pairs. The first pair is the exterior surface of the payload and the interior surface of the cask body; the second pair is the exterior surface of the payload and the interior surface of the lid. Assuming the payload initially rests in the cask when the cask is dropped in the top down orientation, the payload is free to slide and impact the lid. This results in additional load effects on the cask.

In addition, the bottom end drop cases are modeled with the drain port at the bottom corner of the cask. The drain port is fitted with a cover plate and fastened to the cask body with four 1.3 cm (0.5 in.) bolts. A contact pair is defined between the cover plate and the drain port hole which allows them to move independently without penetrating each other. Movement is restrained by four bolts or a threaded cover plate.

Three different models are constructed to address different drop conditions--the bottom end flat drop, the bottom end oblique drop, and the top end oblique drop. All these models use a half (180°) section for both projectile and target. The lid, lifting brackets, and payload remain the same for all cases while the cask body's meshes are modified to have finer meshes around the impact point. The orientation of the cask/lid is kept unchanged for all cases (i.e., Z for the vertical coordinate, and X and Y for two horizontal coordinates).

The target model remains the same in all cases, only the orientation is changed. The initial impact velocity in each case is modified in X, Y, and Z axis components to reflect the impact orientation. These techniques minimize the modelling efforts.

3.2 BOTTOM END FLAT DROP MODEL

The finite element model of bottom end flat drop is shown in Figure 3-1, which is a half (180°) section of the MCO cask and concrete pad. In this model, the drain port is also included.

The cask model uses finer meshes at the bottom section and the outer cylindrical wall of the cask. Coarser meshes are on the top section and the inner cylindrical wall (Figure 3-2). The 180° section of the cask is divided into four 7.5° sectors and ten 15°. Finer meshes are used around the drain port (Figure 3-3). The lid is modeled separately from the cask body. The lid, shear key, and lid bolts are modelled with moderate detail (Figures 3-4 and 3-5). The lid bolts are modelled by using ABAQUS tensile truss element (T3D2). These truss elements can only withstand tensile loads, but provide better simulation bolt behavior during the impact. Included in this model are the lifting brackets as shown in Figure 3-6.

The payloads are modelled with a small number of elements to conserve the computing resources (Figure 3-7). The main function of the payloads is to generate a total weight of 27,215 kg (60,000 lb) of the entire cask/transportation assembly (13,607 kg [30,000 lb] in this half section model) by modifying its density. In this analysis, the payloads can slide inside the cask cavity.

The concrete model used is a half-section of a square block of 6 m (20 ft x 20 ft) by 20 cm (8 in.) thick concrete pad with reinforcing steel bars. However, an equivalent circular concrete pad is used for easier incorporation of the reinforcing steels (Figure 3-8). The reinforcing steels are smeared into the concrete elements with the ABAQUS *REBAR command. The nonlinear soil springs are modelled by using ABAQUS SPRING4 elements. Soil masses are lumped at the concrete bottom nodes to simulate the effective inertia of the soil mass during the impact.

As a half-section model, the appropriate symmetric boundaries are specified at the symmetric surface (Y-plane). The soil nodes are fixed in all three transnational directions.

For the 9 m (30 ft) drop, an initial velocity of 1340 cm/s (527.5 in/s) is given at all nodes of the cask assembly including the payloads. The total run time of the analysis is 20 ms. The ABAQUS computer code selects the initial time step based on the model element dimension and automatically adjusts the step size for efficiently carrying out the computation.

Figure 3-1. MCO Cask Bottom End Flat Drop Finite Element Model.

Figure 3-2. MCO Cask Bottom End Flat Drop-Cask Assembly.

Figure 3-3. MCO Cask Bottom End Flat Drop-Cask Bottom Detail.

Figure 3-4. MCO Cask Bottom End Flat Drop-Cask Top/Shear Key Detail.

Figure 3-5. MCO Cask Bottom End Flat Drop-Lid Model.

Figure 3-6. MCO Cask Bottom End Flat Drop-Lid and Lifting Bracket Model.

Figure 3-7. MCO Cask Impact Evaluation Payload Model.

Figure 3-8. MCO Cask Impact Evaluation Concrete/Soil Model.

3.3 BOTTOM END OBLIQUE DROP MODEL

The finite element model of the bottom end oblique drop is similar to the bottom end flat drop model (Figure 3-9). The main difference is a rotation of the concrete pad by 13.16° such that the vector of initial velocity passes through the bottom edge of the cask, near the drain port. In other words, the axis of the cask and the concrete surface form an angle of 76.04° , not a 90° for the bottom end flat drop. Also, the pad is shifted such that the impact point is at the center of the concrete pad. The impact is in both X and Z directions in this model. This case will cause the maximum impact force around the drain port, which is a weak point on the cask body. The models of lid, lid bolt, and lifting brackets are unchanged. Similarly, the payload model remains the same as that in the bottom end flat drop.

To simulate the bottom end oblique drop, the initial velocity is applied in both X and Z directions. For the 9 m (30 ft) drop, an initial total velocity of 1340 cm/s (527.5 in/s) is given at all nodes of the cask assembly, including the payloads. The component velocity is 305 cm/s (120.09 in/s) in the X direction and 1304.7 cm/s (513.65 in/s) in the Z direction. For the 0.3 m (1 ft) drop case, the initial velocity is 244.6 cm/s (96.3 in/s), and the component velocity is changed to 55.68 cm/s (21.92 in/s) in the X direction and 238.18 cm/s (93.77 in/s) in the Z direction.

Figure 3-9. MCO Cask Bottom End Oblique Drop Finite Element Model.

As a half-section model, the appropriate symmetric boundary conditions are specified at the symmetric surface. The soil nodes are fixed in all three directions.

3.4 TOP END OBLIQUE DROP MODEL

The top end oblique drop model is shown in Figure 3-10. The drain port is not included in this model to save computing resources. The impact location is at the tip of one lifting bracket.

The cask model has finer meshes in the top section of the cask (Figure 3-11). In order to simulate the worst top end oblique impact, the cask body is tilted 78.4° off vertical from the concrete surface. Because the cask model is set up in the vertical direction, and the concrete/soil model is rotated into the proper orientation, the initial velocity in this model is in both X and Z directions.

Due to the bracket height (53 cm [21 in.] over the top of lid), the top of lid and the flange of the lid cannot have a normal impact with the concrete pad. Therefore, the impact force from the direct lid impact or the direct flange of lid impact is much lower than that of the direct bracket impact. The 78.4° impact is determined after an examination of data from several impact orientations.

For the 9 m (30 ft) drop, an initial total velocity of 1340 cm/s (527.5 in/s) is given at all nodes of the cask assembly, including the payloads. The component velocity of the 78.4° top end oblique drop is 539.2 cm/s (212.3 in/s) in the X direction and 2627.4 cm/s (1034.4 in/s) in the Z direction.

As a half-section model, the appropriate symmetric boundary conditions are specified at the symmetric surface. The soil nodes are fixed in all three directions.

Figure 3-10. Top End Oblique Drop Finite Element Model.

Figure 3-11. Lid and Lifting Bracket Model.

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4.0 COMPONENT OR SYSTEM DESCRIPTION

The materials and cask configuration used in this analysis are based on the material specifications given in the TN's technical proposal and drawing (TN 1995, TN 1996a).

4.1 MCO CASK DESCRIPTION

4.1.1 Cask Dimensions

The dimensions of MCO cask used in this analysis are based on the drawings, TN drawing 3035-3, as of June 10, 1996 (TN 1996a). The cask is 432.44 cm (170.25 in.) height from the bottom to the top of the lid. The outer diameter of cask is 101.12 cm (39.81 in.) and the wall thickness is 18.57 cm (7.31 in.), which results in an 63.98 cm (25.19 in.) inner diameter of cask cavity. The bottom plate is 15.57 cm (6.13 in.) thick.

The lid is a stepped cap approximately 28 cm (11 in.) in height, 8.9 cm (3.5 in.) top thickness, 8 cm (3 in.) cylindrical wall, and 8.9 cm (3.5 in.) flange thickness. The lifting brackets extend 53 cm (21 in.) above the top of the lid.

4.1.2 Cask Body and Lid

The material of fabrication for the MCO cask body and lid is SA-336, Type 304 SST. Material properties are obtained from ASME Boiler and Pressure Vessel (B&PV) Code (ASME 1992).

The mechanical properties are as follows:

- $E = 197,185 \text{ MPa}$ ($28.3 \times 10^6 \text{ psi}$) at 21°C (70°F)
- Poisson's Ratio = 0.3
- Density = $8,009 \text{ kg/m}^3$ (500 lbf/ft^3)

The ASME, Section III, Class 1 component material minimum ultimate strength (S_u), minimum yield strength (S_y), and stress allowables (S_m) from ASME (1992), Tables U, Y-1, and 2A are shown in Table 4-1.

Table 4-1. Mechanical Properties of Cask Body and Closure Lid.

SA-336, Type 304 SST			
Temperature °C (°F)	MPa S_u (ksi)	MPa S_y (ksi)	MPa S_t (ksi)
up to 38 (100)	482.6 (70.0)	206.8 (30.0)	137.9 (20.0)
93 (200)	456.4 (66.2)	172.4 (25.0)	137.9 (20.0)
149 (300)	424.0 (61.5)	155.1 (22.5)	137.9 (20.0)
204 (400)	413.7 (60.0)	142.7 (20.7)	128.9 (18.7)
260 (500)	408.9 (59.3)	133.8 (19.4)	120.7 (17.5)

SST = stainless steel

The plasticity of Type 304 SST is represented in Table 4-2.

Table 4-2. Plastic Strain Properties of 304 SST.

Stress MPa (psi)	Plastic strain	Stress MPa (psi)	Plastic strain
150.8 (21,870.0)	0.0	316.7 (45,930.0)	0.070
172.4 (25,000.0)	0.002	329.6 (47,800.0)	0.080
189.7 (27,510.0)	0.004	341.8 (49,570.0)	0.090
198.8 (28,830.0)	0.006	353.1 (51,210.0)	0.100
205.5 (29,810.0)	0.008	379.1 (54,980.0)	0.125
210.9 (30,590.0)	0.010	402.0 (58,300.0)	0.150
233.3 (33,840.0)	0.020	420.4 (60,970.0)	0.175
252.9 (36,680.0)	0.030	436.6 (63,320.0)	0.200
271.0 (39,310.0)	0.040	459.2 (66,600.0)	0.250
287.1 (41,640.0)	0.050	475.7 (69,000.0)	0.300
302.5 (43,870.0)	0.060	482.6 (70,000.0)	0.350

SST = stainless steel

The failure plastic strain of Type 304 SST used in this ABAQUS/Explicit analysis is assumed to be 35% based on the ductility of the material given in the ASME Code (1992).

4.1.3 Lid Bolts

There are twelve 3.8 cm (1.5 in.) diameter high-strength steel bolts uniformly spaced on the flange of lid. The twelve 3.8 cm (1.5 in.) diameter

high-strength lid bolts made of SA-540, Grade B24, Class 1 steel. The material properties are obtained from ASME B&PV Code (ASME 1992).

The mechanical properties are:

- $E = 199,943 \text{ MPa } (29.0 \times 10^6 \text{ psi})$
- Poisson's Ratio = 0.3
- Density = $7,849 \text{ kg/m}^3 \text{ (490 lbf/ft}^3\text{)}$

The ASME, Section III, Class 1 bolting material minimum ultimate strength (S_u), minimum yield strength (S_y), and stress allowables (S_m) from ASME (1992), Table 4 are shown in Table 4-3.

Table 4-3. Mechanical Properties of Closure Lid Bolts.

SA-540, Grade B24, Class 1 Bolting Steel			
Temperature °C (°F)	S_u MPa (ksi)	S_y MPa (ksi)	S_m MPa (ksi)
up to 38 (100)	1,137.6 (165.0)	1,034.2 (150.0)	344.7 (50.0)
93 (200)	1,085.2 (157.4)*	988.7 (143.4)*	329.6 (47.8)
149 (300)	1,051.4 (152.5)*	955.6 (138.6)*	318.5 (46.2)
204 (400)	1,019.0 (147.8)*	926.6 (134.4)*	308.9 (44.8)
260 (500)	987.3 (143.2)*	897.7 (130.2)*	299.2 (43.4)

* = Assume strength is proportional to the S_m value at temperature.

The plasticity of SA-540, Grade B24, Class 1 bolting steel is represented in Table 4-4.

Table 4-4. Plastic Strain Properties of Closure Bolts.

Stress MPa (psi)	Plastic strain
1,036.3 (150,300.0)	0.0
1,251.4 (181,500.0)	0.0933

The failure criteria of the bolt material is based on the material's minimum elongation data of 10% (ASME 1992). The plastic failure strain of the bolt material used in ABAQUS/Explicit analysis is assumed to be 9.33%.

4.2 MCO CASK CONCRETE AND SOIL TARGET DESCRIPTION

4.2.1 Reinforced Concrete Pad Dimensions

As specified in the cask performance specification (WHC 1995), the thickness of the target concrete pad is 20 cm (8 in.). The reinforcement steels are No. 7 rebars installed in two orthogonal directions with 30 cm (12 in.) spacing on both top and bottom surfaces, and 5 cm (2 in.) concrete cover.

4.2.2 Reinforced Concrete

The reinforced concrete pad is assumed to be much larger than the impact area of the MCO cask projectile. A 711 cm (280 in.) diameter and 20 cm (8 in.) thick circular concrete pad is used in this study; this is the equivalent circular pad of a 6 m by 6 m (20 ft x 20 ft) square pad. The use of the circular section is for easier incorporation of smeared rebars in the model. Other concrete properties are as follows:

- Compressive strength: 28 MPa (4000 psi)
- Elastic modulus: 24,820.6 MPa (3.6×10^6 psi)
- Poisson's ratio: 0.15
- Density: 2,403 kg/m³ (150 lb/ft³)

The concrete is represented by a Drucker-Prager plasticity model which has the same angle of friction and dilation angle of 35.1°. The yield surface is assumed as a von Mises circle in a derived differential principal stress plane. The hardening parameter of concrete is reduced from the Electric Power Research Institute (EPRI) (1986) and is represented by:

Table 4-5. Plastic Strain Properties Concrete.

Stress MPa (psi)	Plastic strain
15.5 (2250.0)	0.0
26.9 (3900.0)	0.0013
20.7 (3000.0)	0.0024
16.6 (2400.0)	0.0034
12.3 (1790.0)	0.0044
8.1 (1180.0)	0.0054
5.5 (800.0)	0.0060
0.7 (100.0)	0.0061

4.2.3 Rebars

The concrete pad is reinforced by 2.2 cm (7/8 in.) diameter steel rebars with 30 cm (12 in.) spacing and 5 cm (2 in.) concrete cover on both surfaces. However, the rebar material is not specified in the vendor's documentation (TN 1995 and 1996). The following material properties are used in the analysis which correspond to the A615, Grade 60 steel, a commonly used rebar material (ASTM 1993).

- Elastic modulus: 203,390.6 MPa (29.5×10^6 psi)
- Poisson's Ratio: 0.30
- Density: 7849 kg/m³ (490 lbf/ft³)

The plasticity of A615, Grade 60 steel is represented by a relationship shown in the following table:

Table 4-6. Plastic Strain Properties of Rebar.

Stress MPa (psi)	Plastic strain
490.7 (71,170.0)	0.0
493.8 (71,626.0)	0.004985
573.2 (83,130.0)	0.017098
665.1 (96,460.0)	0.036202
722.1 (104,728.0)	0.055113
752.1 (109,080.0)	0.073795

The rebars are smeared into the concrete as steel layers by using the ABAQUS *REBAR command.

4.2.4 Soil

The density of soil is assumed to be 1922 kg/m³ (120 lb/ft³). In this analysis, the typical soil properties at the Hanford Site 200 Area (Atalay 1993) are used.

- Elastic modulus: 39.3 MPa (5,700.0 psi)
- Poisson's Ratio: 0.35
- Density: 1,762 kg/m³ (110 lbf/ft³)

The soil is represented by a Drucker-Prager plasticity model with the same angle for friction and dilation of 35.2°. The ratio of the yield stress in triaxial tension to the yield stress in triaxial compression is 0.82. The hardening rule of the soil is shown below.

Table 4-7. Plastic Strain Properties
of Soil.

Stress Pa (psi)	Plastic strain
13,798.2 (2.0)	0.0
45,090.7 (6.54)	0.0055
59,569.3 (8.64)	0.0156
68,670.2 (9.96)	0.0259
73,634.3 (10.68)	0.0362
75,702.7 (10.98)	0.0467
76,530.0 (11.1)	0.0573
76,116.3 (11.04)	0.068
74,461.6 (10.8)	0.0788
71,979.6 (10.44)	0.0897
68,256.5 (9.9)	0.1
62,051.4 (9.0)	0.112

5.0 STRUCTURAL ANALYSIS

5.1 STRUCTURAL EVALUATION OF CASK

5.1.1 9 m (30-ft) Bottom End Flat Drop

This case is to simulate the MCO cask having a 9 m (30 ft) drop on the concrete pad with its flat end. The total run time of this case is 20 ms. Results for this case are filled with "ringing" noise in the impact force history as shown in Figure 5-1, resulting in an impact period which cannot be readily defined. Since the total reaction force is the summation of all nodes at the cask contact area with concrete, by filtering frequencies higher than 1000 Hz, the reaction force history has a clear impact of about 1.5 ms (Figure 5-2). Consequently, the total reaction force is determined by averaging the forces over the impact period. This time averaged total reaction force over the impact period is more realistic in predicting the cask acceleration. Based on Figure 5-2, the peak acceleration is found to be 57.7 g (7.7×10^6 N [1.732×10^6 lb] divided by the 133,444 N [30,000 lb] of model weight). The maximum reaction force of the whole cask is twice of the force shown in Figure 5-2 since a half-section model is being used. The average acceleration over the impact period is estimated as 29g, conservatively assuming as half of the peak acceleration.

An alternative way to estimate the acceleration is to use the nodal velocity data. Figures 5-3 through 5-5 indicate velocities at some nodes of the cask at the bottom surface, center of gravity level, and lid level, respectively. All data show the initial velocities of 13.4 m/s (528 in/s) are decreased to 8.1 m/s (320 in/s) at 20 ms. This gives an average acceleration of 26.9g. The agreement of two estimated average accelerations is excellent; consequently, either method can be applied to determine average acceleration. In this case, the average acceleration determined by force is used.

5.1.1.1 Stress Intensity. The ASME Code stress intensity is defined as the largest difference among the principal stresses. If P_1 , P_2 , and P_3 are the three principal stresses and $P_1 > P_2 > P_3$, then the ASME Code stress intensity is $(P_1 - P_3)$. Results of the principal stresses at the most critical elements/locations of the cask body are retrieved from the ABAQUS run and processed to obtain the ASME Code stress intensities. Similarly, the ASME Code stress intensities of the lid bolts are obtained. The stress intensity also contains high frequency noise. For simplicity and conservative consideration, the estimated average ASME stress intensity is obtained as the half of the maximum peak stress intensity. The estimated average ASME Code stress intensities are summarized in Table 5-1 at the most critical exterior shell and confinement boundary locations, and at all lid bolts. The most critical stress intensity plots are shown in Figures 5-6 and 5-7. The stress intensity plots of bolts are shown in Figures 5-8 through 5-14.

Figure 5-1. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Total Reaction Force History at Bottom of Cask.

Figure 5-2. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Time Filtered Total Reaction History.

Figure 5-3. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete: Velocity at Cask Bottom Surface.

Figure 5-4. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete: Velocity at Cask Center of Gravity Level.

Figure 5-5. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Velocity at Cask Lid Level.

Table 5-1. Estimated Average ASME Code Stress Intensity at Critical Locations for the 9 m (30 ft) Bottom End Drop.

Cask body/Lid				Lid bolt	
Exterior		Confinement boundary			
Element	Stress intensity MPa (ksi)	Element	Stress intensity MPa (ksi)	Element	Stress intensity MPa (ksi)
21336	32.60 (4.73)	614	83.60 (12.13)	9901	463.7 (67.25)
21337	45.71 (6.63)	615	51.43 (7.46)	9902	519.2 (75.30)
21338	53.23 (7.72)	616	69.01 (10.01)	9903	518.8 (75.25)
21339	40.75 (5.91)	21310	88.60 (12.85)	9904	518.5 (75.20)
21340	46.06 (6.68)	21305	87.84 (12.74)	9905	518.8 (75.25)
21341	55.85 (8.10)	21300	86.94 (12.61)	9906	519.5 (75.35)
21342	61.43 (8.91)	21295	91.35 (13.25)	9907	519.5 (75.35)
21343	69.36 (10.06)	21290	78.94 (11.45)		
21344	79.36 (11.51)	21285	87.29 (12.66)		
21345	63.71 (9.24)	21280	80.94 (11.74)		
21311	60.95 (8.84)	21275	85.70 (12.43)		
21316	68.04 (9.87)	21270	71.15 (10.32)		
21346	89.01 (12.91)	20720	65.22 (9.46)		
		20715	81.43 (11.81)		
		20710	87.35 (12.67)		
		20705	71.36 (10.35)		
		20695	81.98 (11.89)		
		20690	84.11 (12.20)		
		20685	79.29 (11.50)		
		20680	61.78 (8.96)		
		20160	74.53 (10.81)		
		20159	81.84 (11.87)		
		20158	84.53 (12.26)		
		20157	77.50 (11.24)		
		20110	66.10 (9.587)		
		20109	71.50 (10.37)		
		20108	61.29 (8.89)		
		20107	61.16 (8.87)		
		20106	55.16 (8.00)		

Figure 5-6. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
ASME Stress Intensity at EL 21311.

Figure 5-7. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
ASME Stress Intensity at EL 21295.

Figure 5-8. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #1.

Figure 5-9. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #2.

Figure 5-10. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #3.

Figure 5-11. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #4.

Figure 5-12. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #5.

Figure 5-13. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #6.

Figure 5-14. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Axial Stress at Bolt #7.

The resulting maximum force at the drain port cover plate screw area is found to be in the range of 88,962 N (20,000 lb) (Figure 5-15). The estimated average force is in the range of 44,481 N (10,000 lb).

5.1.1.2 Deformation Results. The deformation in this drop scenario only occurs around the drain port area. Figure 5-16 shows the von Mises stress at the bottom of the cask at the 20 ms instant. Figure 5-17 shows the plastic strain of the cask bottom at 20 ms. As shown, only the vicinity of the drain port is subjected to any plastic strain. The maximum plastic strain is approximately only 0.5% and can be considered negligible. Figures 5-18 and 5-19 show the concrete von Mises stress plot and plastic strain plot, respectively.

5.1.2 0.3 m (1-ft) Bottom End Oblique Drop

This case simulates the MCO cask free fall of 0.3 m (1 ft) before the cask impacts the concrete surface on its bottom corner. To provide the most severe impact loading the around the drain port, the cask is positioned such that the center of gravity passes through the bottom corner nearest the drain port.

There are two consecutive runs for this case. The first run has a run time of 20 ms, the second one restarts from the end of first run and has a run time of another 15 ms, until it stopped due to system errors. The total run time for this case is 35 ms. Figures 5-20 and 5-21 depict the reaction force

Figure 5-15. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Drain Plate Screw Total Axial Force History.

Figure 5-16. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
Mises Stress at Bottom of Cask at 20 ms.

Figure 5-17. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete: PEEQ Strain at Bottom of Cask at 20 ms.

Figure 5-18. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete: Mises Stress at 8 in. Concrete at 20 ms.

Figure 5-19. MCO Cask 30 ft Bottom End Flat Drop on 8 in. Concrete:
PEEQ Strain at 8 in. Concrete at 20 ms.

Figure 5-20. MCO Cask 1 ft Bottom End Corner Drop on 8 in. Concrete:
Time Smoothed Total Reaction History.

Figure 5-21. MCO Cask 1 ft Bottom End Corner Drop on 8 in. Concrete:
Time Smoothed Total Reaction History.

history of the bottom corner impact. It is seen that the maximum peak has been reached at about 721,039.9 N (162.1×10^3 lb) for the half-section model. This gives a peak acceleration of 5.4gs (721,039.9 N [162.1×10^3 lb] divided by 133,444 N [30,000 lb] of the model weight). The average acceleration of the impact cannot be calculated from the force history. However, the average acceleration can be calculated from the velocity data as shown in Figures 5-22 through 5-27 (the cask nodes at the bottom surface, center gravity level and the lid level, respectively). The initial velocity of the 1 ft drop is 2.4 m/s (96.3 in/s). The velocity profiles for all three components indicate an instant velocity of about 1.1 m/s (42.0 in/s) at 35 ms. Since the velocity reduction is linear the average acceleration is found as 4gs.

5.1.2.1 Stress Intensity. High stress is only found at the exterior of the cask bottom corner. Figure 5-28 shows the stress intensity plot at the bottom corner element. The peak stress intensity value (313.29 MPa [45.44 ksi]) at this corner is higher than that of the 30 ft bottom end flat drop. However, this high local stress concentration rapidly falls off towards the interior. A typical stress intensity profile at the interior is shown in Figure 5-29. The estimated average ASME stress intensity is assumed to be half of the peak value. The average stress intensities at the most critical location are tabulated in Table 5-2.

Figure 5-22. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Bottom of Cask.

Figure 5-23. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Bottom of Cask.

Figure 5-24. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Center of Gravity Level of Cask.

Figure 5-25. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Center of Gravity Level of Cask.

Figure 5-26. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Top Level of Cask.

Figure 5-27. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Top Level of Cask.

Figure 5-28. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
ASME Stress Intensity at EL 21336.

Figure 5-29. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
ASME Stress Intensity at EL 21295.

Table 5-2. Estimated Average ASME Code Stress Intensity at Critical Locations from the 1 ft Bottom Oblique Drop.

Cask body/lid				Lid bolt	
Exterior		Confinement boundary			
Element	Stress intensity MPa (ksi)	Element	Stress intensity MPa (ksi)	Element	Stress intensity MPa (ksi)
21336	156.65 (22.72)	614	8.55 (1.24)	9901	5.93 (0.86)
21337	70.32 (10.20)	615	7.17 (1.04)	9902	6.14 (0.89)
21338	40.82 (5.92)	616	13.10 (1.90)	9903	3.52 (0.51)
21339	23.86 (3.46)	20695	23.51 (3.41)	9904	4.21 (0.61)
21340	18.89 (2.74)	20690	15.65 (2.27)	9905	5.10 (0.74)
21341	95.28 (13.82)	20685	10.89 (1.58)	9906	6.96 (1.01)
21342	41.44 (6.01)	20680	7.03 (1.02)	9907	7.72 (1.12)
21343	27.92 (4.05)	20160	11.58 (1.68)		
21344	18.34 (2.66)	20159	8.55 (1.24)		
21345	15.58 (2.26)	20158	8.41 (1.22)		
21311	125.76 (18.24)	20157	8.41 (1.22)		
21316	92.39 (13.40)	20110	13.44 (1.95)		
21346	38.33 (5.56)	20109	12.41 (1.80)		
		20108	12.76 (1.85)		
		20107	10.07 (1.46)		
		20106	9.79 (1.42)		

The lid bolts stresses are minimal in the 1 ft bottom end corner drop. In this case, the drain port cover plate is assumed to be screwed into the cask. The average and peak axial forces in this region are 6,700 lb and 3,350 lb, respectively (Figure 5-30).

5.1.2.2 Deformation Results. The deformation from a 1 ft bottom corner drop is highly localized (Figure 5-31) for von Mises stress and for plastic strain at the bottom of the cask (Figure 5-32). The von Mises stress and plastic strain of concrete at 20 ms are shown in Figures 5-33 and 5-34, respectively.

5.1.3 96.6 kph (60 mph) Top End Oblique Drop

This case is used to evaluate cask impact velocity failure threshold performance for the MCO cask radiological risk evaluation (WHC 1996b). Cask performance is evaluated by numerically simulating the cask impacting the concrete pad at one of its lifting brackets and trunnions at a velocity of 96.6 kph (60 mph). The impact orientation of the cask is an angle of 78.4° with the surface of concrete pad, which is approximately the cask center of gravity over the impact point.

Figure 5-30. MCO Cask 1 ft Bottom End Oblique Drop:
Drain Port Plate Screw Total Axial Force.

Figure 5-31. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Mises Stress at Bottom of Cask at 20 ms.

Figure 5-32. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete: PEEQ Strain at Bottom of Cask at 20 ms.

Figure 5-33. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete: Mises Stress at 8 in. Concrete at 20 ms.

Figure 5-34. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
PEEQ Strain at 8 in. Concrete at 20 ms.

The total run time is 20 ms. The analysis is not carried long enough to determine a well defined impact cycle (Figures 5-35 and 5-36). The peak, however, may have been reached as shown in Figure 5-36, which indicates that the peak acceleration is about 5.9gs (789,540.9 N [177.5 x10³ lb] divided by 133,444 N [30,000 lb] of the half-section cask weight). The average impact acceleration is determined from the velocity data as shown in Figures 5-37 through 5-39. The initial velocity is 26.8 m/s (1056 in/s) and the average velocity of the cask at the center of gravity level is about 25.8 m/s (1015 in/s) at 20 ms. Consequently, the average stress acceleration can be calculated as $(26.8 \text{ m/s} - 25.8 \text{ m/s}) / (0.020 \text{ s} \times 9.81 \text{ m/s}^2) [(1056 \text{ in/s} - 1015 \text{ in/s}) / (0.020 \text{ s} \times 386.4 \text{ in/s}^2)] = 5.3\text{gs}$.

Results of the principal stresses at the most critical elements/locations of the lid and top cask body at the exterior and confinement boundary are retrieved from the ABAQUS run and processed to obtain the ASME Code stress intensities. Similarly, the ASME Code stress intensities (tensile stresses) of all lid bolts are obtained. The estimated average ASME Code stress intensities are assumed as half of the peak stress intensities and summarized in Table 5-3 at the most critical locations. The most critical stress intensity plots are shown in Figure 5-40 for an exterior element and Figure 5-41 for an interior element. The lid bolt stress intensity plots are shown in Figures 5-42 through 5-48. As shown in the results, the lid bolt stresses are negligible since the majority of impact load is transferred from the lid to the cask body in a compression.

Figure 5-35. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: Total Reaction History (Unfiltered).

Figure 5-36. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: Filtered Total Reaction History at 1000 Hz.

Figure 5-37. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Bottom of Cask.

Figure 5-38. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Center of Gravity Level of Cask.

Figure 5-39. MCO Cask 1 ft Bottom Corner Drop on 8 in. Concrete:
Velocity at Top Level of Cask.

Table 5-3. Estimated Average ASME Code Stress Intensity
at Critical Locations from the 96.6 kph (60 mph) Top End Oblique Drop.

Cask body/lid				Lid bolt	
Exterior		Confinement boundary			
Element	Stress intensity MPa (ksi)	Element	Stress intensity MPa (ksi)	Element	Stress intensity MPa (ksi)
5664	80.12 (11.62)	5650	86.53 (12.55)	9901	77.50 (11.24)
5678	34.54 (5.01)	5050	55.57 (8.06)	9902	60.74 (8.81)
5064	25.65 (3.72)	3650	38.33 (5.56)	9903	25.37 (3.68)
5078	30.13 (4.37)	3651	38.40 (5.57)	9904	8.76 (1.27)
4078	65.22 (9.64)	3652	37.09 (5.38)	9905	16.48 (2.39)
4079	60.19 (8.73)	3450	22.20 (3.22)	9906	15.86 (2.30)
4080	61.16 (8.87)	3250	13.58 (1.97)	9907	21.17 (3.07)
		3050	10.82 (1.57)		

ASME = American Society of Mechanical Engineers

Figure 5-40. MCO Cask 88 fps Top End Oblique Drop on 8 in. Concrete:
ASME Stress Intensity at EL 5664.

Figure 5-41. MCO Cask 88 fps Top End Oblique Drop on 8 in. Concrete:
ASME Stress Intensity at EL 5650.

Figure 5-42. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #1.

Figure 5-43. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #2.

Figure 5-44. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #3.

Figure 5-45. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #4.

Figure 5-46. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #5.

Figure 5-47. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #6.

Figure 5-48. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
Axial Stress at Bolt #7.

5.1.3.1 Deformation Results. The deformation in this drop case occurs during the 20 ms period, primarily at the trunnion. As shown in Figure 5-49, the trunnion and bracket penetrate into the concrete pad. The von Mises stresses of the lifting bracket and trunnion are well above yield strength of the Type 304 SST (Figure 5-50) and the plastic strain is 35% (Figure 5-51), which is the ultimate elongation defined for this material. However, the peak stress and strain at the lid are only slightly above yield on the exterior surface as shown in Figures 5-52 and 5-53. The interior surface stress intensities are below yield. Therefore, no containment boundary rupture is predicted during this 20 ms period yet. The behavior of concrete is shown in Figures 5-54 and 5-55.

5.2 STRUCTURAL MODEL DEVELOPMENT AND CALIBRATION

The preliminary reports in Sections 7.1 and 7.2, show the development and bench marking of the numerical modeling method applied for analysis of the MCO cask impacts onto the concrete pad. Both use ABAQUS/Explicit to develop numerical simulation models from SNL data for cask impacts onto a concrete surface (Gonzales 1987). The modeling results are then compared with actual cask impact data. The two numerical models take different approaches to numerically simulating the concrete impact surface. In Section 7.1, the simulation was performed based on a 2-D numerical model, which models the soil as nonlinear springs and the concrete as a uniform isotropic material using its compressive stress-strain relationships. This numerical model, as shown in Section 7.1 provides a conservative estimate of the peak acceleration loads

Figure 5-49. MCO Cask 88 fps Top Lifting Bracket on 8 in. Concrete:
PEEQ Strain at Concrete at 20 ms.

Figure 5-50. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: Mises Stress at Lifting Bracket at 20 ms.

Figure 5-51. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: PEEQ Strain at Lifting Bracket at 20 ms.

Figure 5-52. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: Mises Stress at Lid.

Figure 5-53. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: PEEQ Strain at Lid.

Figure 5-54. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete: Mises Stress at 8 in. Concrete.

Figure 5-55. MCO Cask 88 fps Top Lifting Bracket Drop on 8 in. Concrete:
PEEQ Strain at 8 in. Concrete.

from an impact onto a concrete surface. The numerical simulation calibration described in Section 7.2 is a 3-D model which models the soil and concrete as finite-element models composed of 8-noded brick elements. Both the soil and concrete constitutive models are Drucker-Prager plasticity models. This 3-D numerical simulation model provides a more realistic representation of the behavior of cask impacts onto concrete surfaces. The results of this model show that the accelerations and concrete penetrations from the numerical simulations compare very well to the measured values. Consequently, the numerical modeling method of the concrete surface developed by this 3-D model is used for evaluation of the MCO cask impact.

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7.0 APPENDICES

7.1 TWO DIMENSIONAL MODEL

CALIBRATION OF ABAQUS MCO CASK MODELS WITH SANDIA TEST DATA

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CALIBRATION OF ABAQUS MCO CASK MODELS WITH SANDIA TEST DATA

1.0 INTRODUCTION

Sandia National Laboratories (SNL) had conducted drop testing around 1986 to obtain experimental data of a scaled transportation package with two types of concretes and several types of soils. The testing data were summarized in an SNL report (Gonzales 1987) and some pertinent data are presented here in Table 1. SNL had also performed some analysis intending to validate the analytical models and computer programs, some of which are presented here in Table 2. The Sandia's analytical results don't correlate completely with its test data.

The objective of this study is to use the ABAQUS/Explicit (ABAQUS 1995) general purpose finite element program to develop analytical impact models of the SNL cask on runway and highway concrete and then to calibrate the concrete material properties used in these models with the test data reported in the SNL report.

The ABAQUS/Explicit computer program has been used at Hanford to predict the accelerations, deformations, and stresses of the Transnuclear transportation cask under normal and accidental drop conditions, (Shiraga 1996). The ABAQUS/Explicit computer program is not designed specifically for the impact problems of transportation cask drops. Some important ingredients that are available in the more specific impact analysis programs are not available in ABAQUS/Explicit. Users have to simulate the drop problems with properly developed models using very general ABAQUS capabilities, procedures, and methodologies.

The response of a cask impacting a yielding concrete/soil target involves many factors and testing is usually performed to quantify these factors. However, testing is relatively costly and time consuming. On the other hand, computer simulation is relatively simple and can be used to examine a vast amount of parameters with reasonable time and cost.

To use the computer simulation to determine the best combinations of concrete and soil material properties during the impact condition, and to calibrate the computer models with available testing data, is a cost effective way to ensure the proper usage of the computer modeling in solving impact problems. This is what provides motivation for the current calibration runs of the cask impact problem. The lessons learned in these calibration runs can then be applied to the Transnuclear transportation cask drop evaluation.

However, some precaution should be given here. The Sandia testing data is limited and not always consistent. The current study is only trying to correlate the analytical results and test data on the cask overall acceleration, and the concrete penetration depth for a few cases that are reasonably consistent. In addition, the effect of concrete reinforcement in the dynamic setting can not be studied here because Sandia's concrete target consists no steel reinforcement (highway concrete case) or a very small amount of reinforcement. (runway concrete case).

Table 1 Sandia Target Hardness Test Results (Gonzales 1987)

TEST		MAXIMUM RECORDED ACCELERATION (g's)	PENETRATION (in)
CONCRETE RUNWAY	44 ft/s	480	0.25
	66 ft/s	900	4
	88 ft/s	1000	8
CONCRETE HIGHWAY	44 ft/s	350	4
	66 ft/s	-	4
	88 ft/s	7500	19

Table 2 Comparison of Experimental versus Analytical Results (Gonzales 1987)

TEST		ACCELERATIONS (g's)		PENETRATION (inches)	
		Experimental	Analytical	Experimental	Analytical
CONCRETE HIGHWAY	44 ft/s	350	300	4	8
	88 ft/s	7500	600	8	14

2.0 ANALYTICAL MODELS

Two analytical concrete/soil models have been developed and used in the study—the runway concrete/soil and the highway concrete/soil. Because of the axisymmetric conditions, only the axisymmetrical models of the cask and concrete/soil are developed and used here.

2.1 Runway Concrete/Soil Model

The runway concrete/soil model consists of a 20' X 20' X 18" thick pad made of 5000 psi compressive strength concrete, 3/4" aggregate, and 5-in. square steel mesh. This reinforced concrete was constructed in 1976 for another program and was not used until the 1986 cask drop testing. As a result, the reinforced concrete had been aged for 10 years. The specified compressive strength is 5000 psi; however, the actual compressive strength for the 10-year old concrete can be much higher. The concrete compressive strength is found to have an increase of 35% after one year in comparison with the 28 days' strength, and to have an increase of 10% tensile strength after one year over the 28 days' tensile strength, (Johnson 1967, p. 29).

2.1.1 Concrete model

The concrete is a brittle material with fairly high compressive strength but relatively low tensile strength (about one tenth of compressive strength). The concrete behaves differently with compressive and tensile loadings and also with static and dynamic loadings. The static concrete properties are usually available in the literature; but this is not so for the dynamic concrete properties.

The concrete in this study is assumed to be a uniform isotropic material. For the runway concrete, the modulus of elasticity $E = 57000 \sqrt{f'_c} = 4.0 \times 10^6$ psi (ACI 318-89, para. 8.5) and Poisson ratio = 0.18 (Gonzales 1987, Appendix B) are used to describe its elastic behavior. The plastic portion of the stress-strain relationship of a 5000 psi concrete is adopted from an EPRI report (1986) and is shown in Table 3.

Table 3 The Plasticity of Runway Concrete

Plastic Stress (psi)	Plastic Strain
3002.	0.0
4005.	0.0002
5009.	0.00055
5010.	0.00075

The plastic stress is assumed to peak at 5000 psi. The failure mechanism after reaching the design strength is modelled with the ABAQUS FAILURE

command. Some range of initial damages (offset strains) and final failure strains are investigated in this study to obtain the best calibrated model of the runway concrete.

The reinforcement has been simply specified as 5" square steel mesh in the SNL report (Gonzales 1987). The reinforcement steel has about an area of 0.21 in^2 at 5" spacing (Ryerson 1980) and assumed to have 3" concrete cover on both faces. The material is assumed to be ASTM A36 steel. The modulus of elasticity is 29×10^6 psi, Poisson ratio is 0.3, and yield strength is 36 ksi.

The treatment of concrete in tension and compression, and also in shear during the impact will be further discussed in Section 2.4.

2.1.2 Soil model

The prepared soil foundation is a 10-in. thick section of compacted soil with plate bearing testing data given in the SNL report. The average coefficient of vertical subgrade reaction k_s is found to be 250 lbf/in^3 (psi/in.). The testing bearing strength has to be modified to the modulus of subgrade reaction for an actual square foundation by the formula (Atalay 1993, Table 3.2),

$$k_s = k_{s1}[(B + 1)/2B]^{1/2}$$

where B is the foundation length/width dimension in feet. Given $B = 20 \text{ ft}$, the modulus of subgrade reaction is 69 psi/in. The above value is for static loading, and the dynamic modulus of subgrade is about 10 times that of the static modulus of subgrade reaction, (Atalay 1993, Table 3.2). Consequently, the dynamic modulus of subgrade reaction (k_{sd}) is 690 psi/in.

The tributary area of the foundation is determined based on a 360-degree ring for the axisymmetrical model, from which the spring constant is determined at each foundation node, which is equal to the above dynamic modulus of subgrade reaction (k_{sd}) multiplied by the tributary area.

The soil spring is nonlinear. This means that no force is transmitted if the relative displacement of the foundation to the soil is positive. When the relative displacement of foundation to soil is small in compression, the soil spring is proportional to the above 690 psi/in dynamic value. When the soil is locked up as mentioned in the SNL report, which is assumed to be 5" in this case, the compressive soil spring is proportional to a very large k_{sd} value ($690 \times 10^6 \text{ psi/in}$).

Soil mass is lumped to the foundation node in this case. The amount of soil mass is assumed to be half the thickness of the prepared soil layer, 5" in this case and with 120 lb/ft^3 density.

2.2 Highway Concrete/Soil Model

The highway concrete/soil model consists of a 10' X 10' X 9" plain Portland cement concrete pad of 3000 psi compressive strength with two layers of prepared pavement foundation. The top layer of pavement foundation is a 9"-thick Class II base used in highway construction, which is typically a compact crushed quarry stone layer sandwiched between the concrete and the compacted Class IV subbase. The Class IV subbase is a 12"-thick compact soil. There is no steel reinforcement used in the concrete.

2.2.1 Concrete model

In this study, the highway concrete is also modelled as a uniform isotropic material by using its compressive stress-strain relationship. For example, the elastic properties are modelled by the modulus of elasticity $E = 2.5 \times 10^6$ psi, and Poisson ratio = 0.18 (Gonzales 1987, Appendix B). The stress-strain relationship used in the study for the piecewise stress-strain curve (EPRI 1986) are presented in Table 4.

Table 4 The Plasticity of Highway Concrete

Plastic Stress (psi)	Plastic Strain
2753.	0.0
3005.	0.0004
3006.	0.0008

The damage starts from zero when the plastic strain reaches the offset strain and increases to one when final failure strain is reached. The elasticity modulus as well as the shear and bulk moduli are proportionally reduced according to the damage incurred. Refer to ABAQUS/Explicit User's Manual (ABAQUS 1995) for more detailed discussion of the ductile failure. The amounts of failure strain and offset strain are parameters in this study. The treatment of concrete in tension and compression, and also in shear during the impact will be further discussed in Section 2.4.

2.2.2 Soil Model

The soil properties related to the highway concrete were not specified in the SNL report. In this study, soil properties of the highway concrete are assumed to be the same as those of the runway testing because they are the most relevant SNL site-specific soil data. More specifically, the coefficient of vertical subgrade reaction (k_{s1}) of 250 psi/in is used in deriving the modulus of vertical subgrade reaction (K_s) after adjusting to the foundation size (Atalay 1993, Table 3.2),

$$K_s = k_{s1}[(B + 1)/2B]^{1/2}$$

where B is the length/width dimension of foundation in feet. Given B = 10 ft, the modulus of subgrade reaction is 76 psi/in.

The above value is for static loading, and the dynamic modulus of subgrade is about 10 times that of the static modulus of subgrade reaction, (Atalay 1993, Table 3.2). Consequently, the dynamic modulus of subgrade reaction (k_{sd}) is 760 psi/in.

The tributary area of the foundation is determined (a 360-degree ring in the axisymmetric model) and from which the spring constant is determined at each foundation node.

The soil spring is nonlinear. This means no force transmitted if the relative displacement of foundation to soil is positive. The compressive soil spring is proportional to the above 760 psi/in value when the relative displacement of foundation to soil is small. The compressive soil spring becomes a large value (proportional to 760×10^6 psi/in) when the soil is locked up, which is assumed to be 15" in this highway concrete case.

Soil mass is assumed to be generated from the 15" soil of 120 lb/ft³ density and lumped to the bottom of the foundation.

2.3 Cask Model

The overall outside dimensions of the test cask are 20" in diameter and 72" in height. The entire assembly weights about 5200 pounds. The cask is constructed with A36 steel.

The cask is a prefabricated cylindrical structure, which consists of an outer cylinder (20 in. OD and 1.5 in. thick) and an inner cylinder (17 in. OD and 2 in. thick). The top and bottom caps are 2 inches thick. The bottom cap is welded to the outer cylinder and the top cap is fastened to the outer cylinder with twelve 0.5-in. bolts. The inner cylinder is to simulate the shielding. The payload is constructed by 20 circular plates, fastened together with a rod. The circular plates and the inner cylinder are connected to the outer cylinder with steel pins in radial direction. The density of outer and inner cylinders uses A36 steel actual weight, but the density of payload disks is adjusted such that the total assembly weight matches 5200 pounds.

Some measurements of the acceleration and deformation of the cask were taken during the SNL testing. There were four accelerators, mounted at the middle of the height of the outer cylinder, and 90 degrees apart. Some tests had four additional accelerators equally mounted between the four regular accelerators. A total of 8 strain gages were mounted at two levels, 2.75" and 12" from the bottom of the cask. Similar to the accelerators, they were mounted 90 degrees apart.

The acceleration measurements were reported in the report only at one point for each test. The strain was measured and reported in a similar fashion.

2.4 ABAQUS Finite Element Computer Program

ABAQUS/Explicit general purpose finite element computer program, Version 5.5 (ABAQUS 1995) is used for this calibration study.

The cask is modelled with ABAQUS axisymmetric continuum elements (CAX4R) with finer meshes at the bottom of the cask and coarser meshes at the top. The cask model is shown in Figure 1. Similarly, the concrete pad is modelled with ABAQUS CAX4R elements. The soil springs are modelled with ABAQUS SPRINGA elements with the nonlinear option. Soil masses are modelled with ABAQUS MASS elements. Concrete and soil models are shown in Figure 2 and 3 for runway and highway concretes, respectively. The input files are included in Appendices.

For this end drop problem, a contact surface pair is defined. This pair consists of the bottom surface of cask and the top surface of concrete pad. During the contact, the total reaction force on either surface should represent the total force imparting on the cask, and from which the acceleration or deceleration can be calculated. The acceleration history obtained in this way may be different in shape from the one obtained in actual testing; however, the maximum values should be comparable. The testing acceleration data are obtained at the middle level of the cask, which may have been influenced by many high-frequency waves. The SNL reported acceleration data have been filtered. The analytical acceleration history can also be filtered by different filtering frequencies as shown in the section of results and comparisons.

The modeling of concrete targets deserves special attention here. The ABAQUS/Explicit Version 5.5 provides two types of failure models, namely, ductile failure and brittle cracking. The former is designed to allow the stable removal of elements from the finite element model as a result of tearing or ripping of the structure. The ABAQUS/Explicit will automatically delete elements from the mesh when they exceed the failure criteria. The brittle cracking is designed to predict the cracking of a brittle material, such as concrete, when the tensile strain exceeds the failure criteria.

The study conducted here has shown that results from ABAQUS brittle cracking failure don't match well enough with the Sandia's impact testing data in both cask acceleration and concrete penetration depth and shape. Instead the ductile failure works better in this case. See Figures 4 and 5 for the Mises stress plots using the brittle cracking and ductile failure models,

respectively. The deformed shape of the ductile failure model matches better with the SNL report than that of the brittle cracking failure model. The SNL report indicates that the concrete fails in shear plug mode, i.e., a 45 degree cone-shaped plug when subjected to cask end impact (Gonzales 1987, Fig. 18). However, the concrete penetration figures in the SNL report show the penetrations have parallel walls (Gonzales 1987, Fig. 23 and 27). One possible explanation is that the cone-shaped shear plug is for static type of loading (or low strain rate loading) while the parallel-wall shear plug is for high speed loading. For impact loading, the concrete failure is more likely due to local shear failure on the top surface than due to tension or compression failure. The analysis is performed to study what level of concrete strength can best compare with the SNL test data.

The shear strength of concrete is relatively large in comparison with the tensile strength. The former has been variably reported from 35% to 80% of the compressive strength, (Ferguson 1958). The range of variability is because it is relatively difficult to separate shear from other stresses in testing. ACI 318 Code (ACI 318-89, 1992) limits the shear stress of concrete by properly designing against the diagonal tension stress failures, although shear stress and diagonal tension stress are really two different things.

Before the final analysis is conducted, the analytical models of both runway concrete and highway concrete are used to perform an elastic/perfectly plastic analysis with the yield stress as the parameter. These runs are carried out without failure modeling. In the final analysis, the concrete material in the analytical models are changed to the piecewise stress-strain curve up to the design strength. The stress levels out at the design strength and then the ductile failure model is applied. The offset plastic strain and failure plastic strain are used as parameters to determine the best calibrated models.

ABAQUS

Figure 1. Sandia Runway Concrete Case-Cask Assembly.

ABAQUS

Figure 2, Sandia Runway Concrete Case-Concrete Pad and Soil Springs.

ABAQUS

Figure 3, Sandia Highway Concrete Case-Concrete Pad and Soil Springs.

3.0 RESULTS AND COMPARISONS

3.1 Elastic Perfectly Plastic Concrete Model

In the elastic perfectly plastic concrete model, the concrete stress-strain curves for runway concrete and highway concrete are similar to that shown below. The elastic and perfectly plastic stress-strain curve is used to determine the effects of concrete modulus of elasticity (a fixed value) and yield stress on the cask acceleration and concrete penetration.

Figure 6 Elastic Perfectly-Plastic Stress-Strain Curve.

3.1.1 Runway Concrete Results

Runway concrete results of acceleration and concrete penetration are shown below in Tables 5 through 7. The filtered accelerations indicate the peak g-levels when higher frequency components above the indicated frequency are filtered out. Because these accelerations are obtained from the total reaction forces at the contact surface divided by the total assembly weight, the results at higher filtering frequencies may be used to compare with the SNL test data.

There are two groups of results in this case: (1) 44 fps drop case, and (2) 66 fps and 88 fps drop cases. The first group contains a lower energy than the second group.

Based on the acceleration comparison, the yield stress used in the concrete model of the first group (low energy group) should be less than 50% of the design strength, the yield stress used in the concrete model of the second group (high energy group) should be at the full design strength. However, based on the concrete penetration data, the yield stress used in the concrete model of the first group (low energy group) should be at the high end of the design strength, while the yield stress used in the concrete model of the second group (high energy group) should be at low end of the design strength. It requires different yield stress of the concrete to match both acceleration and concrete penetration.

For a conservative prediction of acceleration, the yield stress used in the concrete model should use full design strength for the elastic and perfectly plastic model of runway concrete.

Table 5. Runway Concrete Results with Design Strength of 5000 Psi
44 fps Drop Case

(Sandia Test Data: 480 g/0.25" Concrete Penetration)						
Yield Stress (psi)	Acceleration (g)					Concrete Penetration (inch)
	Filtering Frequency					
	None	3K Hz	2K Hz	1K Hz	0.6K Hz	
500	435	245	199	162	155	3.0
1250	486	351	321	300	286	1.5
2500	568	549	545	508	432	0.7
3750	683	735	741	667	561	0.5
5000	830	880	895	804	696	0.35
5000 (Rigid Soil)	1076	1049	1025	1031	1083	0.37

NOTE: Rigid Soil = concrete is fixed at bottom surface.

Table 6. Runway Concrete Results with Design Strength of 5000 Psi
66 fps Drop Case

(Sandia Test Data: 900 g/4.0" Concrete Penetration)

Yield Stress (psi)	Acceleration (g)					Concrete Penetration (inch)
	Filtering Frequency					
	None	3K Hz	2K Hz	1K Hz	0.6K Hz	
500	638	341	274	198	193	6.7
1250	690	440	381	334	324	3.2
2500	774	631	597	561	509	1.7
3750	854	823	816	760	646	1.1
5000	946	1018	1020	926	773	0.83
5000 (Rigid soil)	1196	1164	1145	1118	1168	0.74

NOTE: Rigid Soil = concrete is fixed at bottom surface.

Table 7. Runway Concrete Results with Design Strength of 5000 Psi
88 fps Drop Case

(Sandia Test Data: 1000 g/8.0" Concrete Penetration)

Yield Stress (psi)	Acceleration (g)					Concrete Penetration (inch)
	Filtering Frequency					
	None	3K Hz	2K Hz	1K Hz	0.6K Hz	
500	838	438	349	247	228	11.4
1250	891	528	441	381	356	5.7
2500	973	708	645	599	567	3.0
3750	1050	910	872	822	725	2.0
5000	1128	1098	1087	1012	859	1.5
5000 (rigid soil)	1274	1269	1240	1178	1224	1.2

NOTE: Rigid Soil = concrete is fixed at bottom surface.

3.1.2 Highway Concrete Results

For the highway concrete cases in the SNL report, only the results of 44 fps drop case are considered to be reasonable. The analytical results of current study are presented in Table 8.

The acceleration of the 44 fps case requires the yield stress used in the concrete model to be around 1000 psi (between 25% and 50% of design strength). However, the concrete penetration requires the yield stress of the concrete model to be at an even lower level of the design strength. The optimal value of yield stress used in the concrete model is somewhere around 30% of the concrete design strength.

Table 8. Highway Concrete Results with Design Strength of 3000 Psi
44 fps Drop Case

(Sandia Test Data: 350 g/4.0" Concrete Penetration)

Yield Stress (psi)	Acceleration (g)					Concrete Penetration (inch)
	Filtering Frequency					
	None	3K Hz	2K Hz	1K Hz	0.6K Hz	
300	352	223	193	147	116	6.8
750	383	284	250	198	184	3.3
1500	428	395	360	300	257	2.1
2250	475	509	481	388	314	1.4
3000	581	609	583	453	349	1.1
3000 (Rigid Soil)	708	697	709	667	655	0.68

Note: Rigid soil = concrete is fixed at bottom surface.

3.2 Concrete Model with Failure Criteria

The piecewise stress-strain curve is used to model the concrete more closely with its given stress-strain relationship up to the concrete design strength. The stress peaks at the concrete design strength until the failure criteria kicks in. A typical stress-strain curve is shown below.

Figure 7 Piecewise Stress-Strain Curve Plus Ductile Failure Criteria.

3.2.1 Runway Concrete Results

To conservatively predict the acceleration and concrete penetration, the use of high yield stress in the concrete model seems to be justifiable. As shown in Table 9 for the 44 fps drop onto runway concrete, the modification of the stress-strain curve and the addition of ductile failure criteria seem to have no strong influence on either cask acceleration or concrete penetration. The best calibrated concrete model of the low energy group is the case with 40% failure plastic strain and 1% offset plastic strain. In this best calibrated case, the acceleration prediction is 70% higher than the SNL test data and the concrete penetration is about 20% less than the SNL test data.

Table 9. Runway Concrete Results with Design Strength of 5000 Psi
44 fps Drop Case

(Sandia Test Data: 480 g/0.25" Concrete Penetration)

Case	Failure Criteria Used		Acceleration (g)					Concrete Penetration (Inch)
			Filtering Frequency					
	Failure Plastic Strain	Offset Plastic Strain	None	3K Hz	2K Hz	1K Hz	.6K Hz	
Elastic Perfectly Plastic at 5000 psi	None	None	830	880	895	804	696	0.35
Piecewise Stress-strain Curve Peaking at 5000 psi	0.3	0.01	831	867	883	784	665	0.32
Piecewise Stress-strain Curve Peaking at 5000 psi	0.4	0.01	814	862	878	787	671	0.30

In the case of 88 fps drop onto the runway concrete, Table 10, the use of failure criteria in the elastic perfectly plastic analysis increases the concrete penetration drastically, while the accelerations remains at about the same level as before. The best calibrated case in this elastic perfectly plastic analysis has a failure plastic strain of 40% and an offset plastic strain of 10%. This best calibrated case has a conservative prediction in acceleration to the Sandia testing result and a 50% under-prediction of the concrete penetration. The final analysis incorporating the piecewise stress-strain curve and lowering the offset plastic strain to 1% improves the concrete penetration to a 30% under-prediction of the SNL test data.

Table 10. Runway Concrete Results with Design Strength of 5000 Psi
88 fps Drop Case

(Sandia Test Data: 1000 g/8.0" Concrete Penetration)

Case	Failure Criteria Used		Acceleration (g)					Concrete Penetration (inch)
			Filtering Frequency					
	Failure Plastic Strain	Offset Plastic Strain	None	3K Hz	2K Hz	1K Hz	.6K Hz	
Elastic Perfectly Plastic at 5000 psi	None	None	1128	1098	1087	1012	859	1.5
Same	1.0	0.5	1128	1097	1086	1012	859	1.5
Same	0.5	0.1	1128	1097	1086	1006	838	3.3
Same	0.4	0.1	1128	1097	1086	1004	832	4.0
Same	0.3	0.1	1128	1097	1084	998	820	4.0
Piecewise Stress-strain Curve Peaking at 5000 psi	0.4	0.01	1128	1075	1050	966	797	5.3

3.2.2 Highway Concrete Results

The use of a piecewise stress-strain curve instead of elastic perfectly plastic curve seems to have negligible effect on the acceleration and concrete penetration. The addition of failure criteria seems to have insignificant change in the acceleration but have drastic change in the concrete penetration. This is especially true when the lower offset plastic strain is used, see Table 11. In the best calibrated model, the case with a piecewise stress-strain curve and with a failure plastic strain of 20% and an offset plastic strain of 0.1%, the acceleration prediction is 70% higher than the SNL test data and the concrete penetration is 10% less than the SNL test data.

Table 11. Highway Concrete Results with Design Strength of 3000 Psi
44 fps Drop Case

(Sandia Test Data: 350 g/4.0" Concrete Penetration)

Case	Failure Criteria Used		Acceleration (g)					Concrete Penetration (inch)
			Filtering Frequency					
	Failure Plastic Strain	Offset Plastic Strain	None	3K Hz	2K Hz	1K Hz	.6K Hz	
Elastic Perfectly Plastic at 1500 psi	None	None	428	395	360	300	257	2.1
Same	1.0	0.5	429	395	360	300	257	2.1
Elastic Perfectly Plastic at 3000 psi	None	None	581	609	583	453	349	1.1
Piecewise Stress-strain Curve Peaking at 3000 psi	0.3	0.1	588	616	589	472	367	1.6
Same	0.3	0.01	588	613	585	465	356	2.0
Same	0.2	0.01	585	611	583	462	350	3.3
Same	0.2	0.001	583	599	572	454	344	3.7

4.0 DISCUSSION AND RECOMMENDATION

The maximum acceleration level seems to be governed by the modulus of elasticity and yield stress level of the concrete model. In general, the modulus of elasticity and yield stress are referred to those of concrete compressive strength. The cases investigated in this study are related to zero or very small amounts of steel reinforcement. In such circumstance, the predominant failure mode of concrete is the local shear plug type of failure. Shear strength is the governing variable in the prediction of concrete penetration and cask acceleration. Unfortunately, the shear strength of concrete is not a well defined quantity in most cases, they can be in the range from 35% to 80% of the compressive strength. Hence, the full compressive strength can be used in the concrete model and this should yield conservative predictions in accelerations.

The offset plastic strain and failure strain correlates more with the concrete penetration, sometimes the effects are quite substantial. For the cases investigated, it is found that the offset plastic strains may be as small as possible (<1%) and the failure strains may be in the range of 20% to 40%. The failure strain of concrete can be envisioned as the total accumulation of plastic strain, cracks, and other effects. EPRI report (1986, Figs 6 and 7) has indicated that a 4000 psi concrete has a maximum strain of 5% when a crack opens, and has a 12% strain in the crushed zone.

For a concrete target constructed to ACI 318 (1992) code or equivalent criteria, the dominant failure mode of concrete is probably the local tensile cracking and steel reinforcement debonding. In such cases, the concrete compressive strength, which results in the ultimate strength of concrete, can be used in the stress-strain relationship and the tensile failure strength can be used in the tensile brittle cracking criteria.

The overall reaction of cask is also related to the total energy level proposed by the cask and the concrete/soil hardness or rigidity. The EPRI (1986) formula can be used effectively in the prediction of cask maximum acceleration. However, the effect of the soils role and the total energy of the cask on the cask overall response still remains an area requiring additional study, especially for a shallow concrete pad and high cask energy. The massive rupture effect of concrete with the reinforced steel deserves further study.

Recommendations to Transnuclear Mco Cask Analysis

In the future Transnuclear MCO cask analysis, the following recommendations on the concrete model may be considered in performing the ABAQUS/Explicit analysis.

- 1) The more realistic concrete compressive stress-strain curve may be used for the concrete with reinforcement steels. The shear stress-strain curve may be used for concrete without reinforcement steels. Using the compressive stress-strain curve in the latter case is conservative for acceleration prediction.

- 2) The reinforcing steels should be modeled into the concrete. The reinforcing steels can be modelled as truss elements or can be smeared into the concrete by ABAQUS REBAR command.
- 3) The ABAQUS/Explicit ductile failure may be invoked. The reinforced concrete can be better represented by the ductile failure than the brittle cracking in ABAQUS/Explicit. Currently, ABAQUS/Explicit doesn't have the concrete element as in ABAQUS/Standard. In fact, the reinforced concrete constructed to the current standard, such as ACI 318-89 (1992) is considered as a ductile structure. The catastrophic brittle failure is prevented from happening in current concrete design.

In ABAQUS/Explicit model, the offset plastic strain of concrete can be taken at 1% for the micro-crack. The failure plastic strain of concrete can be in the 20% to 40% range.

5.0 REFERENCES

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APPENDIX A

ABAQUS MODEL FOR SANDIA TEST DATA
RUNWAY CONCRETE

- A-1 -

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*HEADING
EVALUATION OF SANDIA CASK DROP TEST/CONCRETE RUNWAY 44FPS
SOIL SPRINGS USE SPRING ELEMENTS + REBARS
+ CONCRETE PLASTIC CURVE + FAILURE
*RESTART, WRITE, NUMBER INTERVAL=20
**
** GENERATE THE NODES OF BOTTOM 2-IN THICK PLATE
** BOTTOM SECTION IS NAMED SECTA, TOP SECTION IS NAMED SECTB
**
*NODE, SYSTEM=R
*NODE, NSET=P1
1, 0.0, 0.0, 0.0
*NODE, NSET=P2
10, 6.5, 0.0, 0.0
*NFill, NSET=SECTA, BIAS=1.085
P1, P2, 9
*NODE, NSET=SECTA
11, 7.0, 0.0, 0.0
12, 7.5, 0.0, 0.0
13, 8.0, 0.0, 0.0
14, 8.5, 0.0, 0.0
15, 9.0, 0.0, 0.0
16, 9.5, 0.0, 0.0
17, 10.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=68, OLD SET=SECTA, NEW SET=SECTB
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFill, NSET=AREA1
SECTA, SECTB, 4, 17
**
** GENERATE THE NODES OF 4 LAYERS OF 0.5-IN. THICK
** BOTTOM SECTION IS NAMED SECTB, TOP SECTION IS NAMED SECTC
**
*NCOPY, SHIFT, CHANGE NU=68, OLD SET=SECTB, NEW SET=SECTC
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFill, NSET=AREA2
SECTB, SECTC, 4, 17
**
** GENERATE THE NODES OF 18 LAYERS OF 0.625 IN. THICK
** BOTTOM SECTION IS NAMED SECTC, TOP SECTION IS NAMED SECTD
**
*NCOPY, SHIFT, CHANGE NU=306, OLD SET=SECTC, NEW SET=SECTD
0.0, 11.25, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFill, NSET=AREA3
SECTC, SECTD, 18, 17
**
** GENERATE THE NODES OF 15 LAYERS OF 1.25 IN. THICK
** BOTTOM SECTION IS NAMED SECTD, TOP SECTION IS NAMED SECTE
**
*NCOPY, SHIFT, CHANGE NU=255, OLD SET=SECTD, NEW SET=SECTE

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- A-2 -

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0.0, 18.75, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA4
SECTD, SECTE, 15, 17
**
** GENERATE THE NODES OF 2 LAYERS OF 2.125 IN. THICK
** BOTTOM SECTION IS NAMED SECTE, TOP SECTION IS NAMED SECTF
**
*NCOPY, SHIFT, CHANGE NU=34, OLD SET=SECTE, NEW SET=SECTF
0.0, 4.25, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA5
SECTE, SECTF, 2, 17
**
** GENERATE THE NODES OF 7 LAYERS OF 4.25 IN. THICK
** BOTTOM SECTION IS NAMED SECTF, TOP SECTION IS NAMED SECTG
**
*NCOPY, SHIFT, CHANGE NU=119, OLD SET=SECTF, NEW SET=SECTG
0.0, 29.75, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA6
SECTF, SECTG, 7, 17
**
** GENERATE THE NODES OF 4 LAYERS OF 1.0 IN. THICK
** BOTTOM SECTION IS NAMED SECTG, TOP SECTION IS NAMED SECTH
**
*NCOPY, SHIFT, CHANGE NU=68, OLD SET=SECTG, NEW SET=SECTH
0.0, 4.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA7
SECTG, SECTH, 4, 17
*****
**
** GENERATE THE ELEMENTS OF BOTTOM PLATE
** FOUR 0.5-INCH LAYERS, PLATE1 THROUGH PLATE4
**
*ELEMENT, TYPE=CAX4R
1, 1, 2, 19, 18
*ELGEN, ELSET=PLATE1
1, 16, 1, 1
*ELCOPY, OLD SET=PLATE1, NEW SET=PLATE2, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=PLATE2, NEW SET=PLATE3, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=PLATE3, NEW SET=PLATE4, ELEMENT SHIFT=16, SHIFT NODES=17
*ELSET, ELSET=PLATE
PLATE1, PLATE2, PLATE3, PLATE4
*SOLID SECTION, ELSET=PLATE, MATERIAL=A36ST
**
** GENERATE THE ELEMENTS OF CASK WALL
** WALL1 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
78, 82, 83, 100, 99

```

```

*ELGEN, ELSET=WALL1A
78, 3, 1, 1
*ELCOPY, OLD SET=WALL1A, NEW SET=WALL1B, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=WALL1B, NEW SET=WALL1C, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=WALL1C, NEW SET=WALL1D, ELEMENT SHIFT=16, SHIFT NODES=17
*ELSET, ELSET=WALL1
WALL1A, WALL1B, WALL1C, WALL1D
*SOLID SECTION, ELSET=WALL1, MATERIAL=A36ST
**
** WALL2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
142, 150, 151, 168, 167
*ELGEN, ELSET=WALL2
142, 3, 1, 1, 18, 17, 16
*SOLID SECTION, ELSET=WALL2, MATERIAL=A36ST
**
** WALL3 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
430, 456, 457, 474, 473
*ELGEN, ELSET=WALL3
430, 3, 1, 1, 15, 17, 16
*SOLID SECTION, ELSET=WALL3, MATERIAL=A36ST
**
** WALL4 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
670, 711, 712, 729, 728
*ELGEN, ELSET=WALL4
670, 3, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=WALL4, MATERIAL=A36ST
**
** WALL5 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
702, 745, 746, 763, 762
*ELGEN, ELSET=WALL5
702, 3, 1, 1, 7, 17, 16
*SOLID SECTION, ELSET=WALL5, MATERIAL=A36ST
**
** WALL6 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
814, 864, 865, 882, 881
*ELGEN, ELSET=WALL6
814, 3, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=WALL6, MATERIAL=A36ST
**
** GENERATE THE ELEMENTS OF SHIELDING
** SHIELD1 ELEMENTS
**

```

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```
** NO SHIELD1 ELEMENTS
**
**
** SHIELD2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
138, 146, 147, 164, 163
*ELGEN, ELSET=SHIELD2
138, 4, 1, 1, 18, 17, 16
*SOLID SECTION, ELSET=SHIELD2, MATERIAL=A36ST
**
** SHIELD3 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
426, 452, 453, 470, 469
*ELGEN, ELSET=SHIELD3
426, 4, 1, 1, 15, 17, 16
*SOLID SECTION, ELSET=SHIELD3, MATERIAL=A36ST
**
** SHIELD4 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
666, 707, 708, 725, 724
*ELGEN, ELSET=SHIELD4
666, 4, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=SHIELD4, MATERIAL=A36ST
**
** SHIELD5 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
698, 741, 742, 759, 758
*ELGEN, ELSET=SHIELD5
698, 4, 1, 1, 7, 17, 16
*SOLID SECTION, ELSET=SHIELD5, MATERIAL=A36ST
**
** GENERATE THE ELEMENTS OF PAYLOADS
** PAYLD1 ELEMENTS
**
** PAYLD1 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
65, 69, 70, 87, 86
*ELGEN, ELSET=PAYLD1
65, 9, 1, 1, 4, 17, 16
*SOLID SECTION, ELSET=PAYLD1, MATERIAL=PAYLD
**
** PAYLD2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
129, 137, 138, 155, 154
*ELGEN, ELSET=PAYLD2
129, 9, 1, 1, 18, 17, 16
```

*SOLID SECTION, ELSET=PAYLD2, MATERIAL=PAYLD

**

** PAYLD3 ELEMENTS

**

*ELEMENT, TYPE=CAX4R

417, 443, 444, 461, 460

*ELGEN, ELSET=PAYLD3

417, 9, 1, 1, 15, 17, 16

*SOLID SECTION, ELSET=PAYLD3, MATERIAL=PAYLD

**

** PAYLD4 ELEMENTS

**

*ELEMENT, TYPE=CAX4R

657, 698, 699, 716, 715

*ELGEN, ELSET=PAYLD4

657, 9, 1, 1, 2, 17, 16

*SOLID SECTION, ELSET=PAYLD4, MATERIAL=PAYLD

**

** PAYLD5 ELEMENTS

**

*ELEMENT, TYPE=CAX4R

689, 732, 733, 750, 749

*ELGEN, ELSET=PAYLD5

689, 9, 1, 1, 7, 17, 16

*SOLID SECTION, ELSET=PAYLD5, MATERIAL=PAYLD

**

** GENERATE THE ELEMENTS OF LID

**

** LID1 ELEMENTS

**

*ELEMENT, TYPE=CAX4R

817, 868, 869, 886, 885

*ELGEN, ELSET=LID1

817, 13, 1, 1

*SOLID SECTION, ELSET=LID1, MATERIAL=A36ST

**

** LID2 ELEMENTS

**

*ELEMENT, TYPE=CAX4R

833, 885, 886, 903, 902

*ELGEN, ELSET=LID2

833, 16, 1, 1, 2, 17, 16

*SOLID SECTION, ELSET=LID2, MATERIAL=A36ST

*ELSET, ELSET=LID

LID1, LID2

**

** GENERATE THE ELEMENTS OF CONCRETE PAD

**

*NODE, SYSTEM=R

*NODE, NSET=C1

1000, 0.0, -18.0, 0.0

*NODE, NSET=C2


```

1020, 20.0, -18.0, 0.0
*NODE, NSET=C3
1030, 40.0, -18.0, 0.0
*NODE, NSET=C4
1040, 80.0, -18.0, 0.0
*NODE, NSET=C5
1046, 140.0, -18.0, 0.0
*NFILL, NSET=CONCRET1
C1, C2, 20
C2, C3, 10
C3, C4, 10
C4, C5, 6
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET1, NEW SET=CONCRET2
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET2, NEW SET=CONCRET3
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET3, NEW SET=CONCRET4
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET4, NEW SET=CONCRET5
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET5, NEW SET=CONCRET6
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET6, NEW SET=CONCRET7
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET7, NEW SET=CONCRET8
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET8, NEW SET=CONCRET9
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET9, NEW SET=CONCRETA
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRETA, NEW SET=CONCRETB
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRETB, NEW SET=CONCRET C
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET C, NEW SET=CONCRET D
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
**
** CONCRETE PAD ELEMENT
**
*ELEMENT, TYPE=CAX4R

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1000, 1000, 1001, 1101, 1100
*ELGEN, ELSET=CONCRET1
1000, 46, 1, 1
*ELCOPY, OLD SET=CONCRET1, NEW SET=CONCRET2, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET2, NEW SET=CONCRET3, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET3, NEW SET=CONCRET4, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET4, NEW SET=CONCRET5, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET5, NEW SET=CONCRET6, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET6, NEW SET=CONCRET7, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET7, NEW SET=CONCRET8, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET8, NEW SET=CONCRET9, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET9, NEW SET=CONCRETA, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRETA, NEW SET=CONCRETB, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRETB, NEW SET=CONCRETC, ELEMENT SHIFT=100, SHIFT NODES=100
*ELSET, ELSET=CONCRETE
CONCRET1, CONCRET2, CONCRET3, CONCRET4, CONCRET5, CONCRET6, CONCRET7, CONCRET8
CONCRET9, CONCRETA, CONCRETB, CONCRETC
*SOLID SECTION, ELSET=CONCRETE, MATERIAL=CONCRETE
**
** GENERATE REBARS
**
*REBAR, ELEMENT=CONTINUUM, MATERIAL=REBAR, NAME=BR
CONCRET3, 0.021, 5.0, 0.0, 1.0, 1,,
*REBAR, ELEMENT=CONTINUUM, MATERIAL=REBAR, NAME=BH
CONCRET3, 0.021, 5.0, 90., 1.0, 1,,
*REBAR, ELEMENT=CONTINUUM, MATERIAL=REBAR, NAME=TR
CONCRET9, 0.021, 5.0, 0.0, 1.0, 1,,
*REBAR, ELEMENT=CONTINUUM, MATERIAL=REBAR, NAME=TH
CONCRET9, 0.021, 5.0, 90., 1.0, 1,,
**
** GENERATE THE SOIL SPRINGS
**
*NCOPY, SHIFT, CHANGE NU=2000, OLD SET=CONCRET1, NEW SET=SOIL
0.0, -10.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG00
3000, 1000, 3000
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG01
3001, 1001, 3001
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG02
3002, 1002, 3002
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG03
3003, 1003, 3003
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG04
3004, 1004, 3004
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG05
3005, 1005, 3005
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG06
3006, 1006, 3006
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG07
3007, 1007, 3007
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG08

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3008, 1008, 3008
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG09
3009, 1009, 3009
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG10
3010, 1010, 3010
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG11
3011, 1011, 3011
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG12
3012, 1012, 3012
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG13
3013, 1013, 3013
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG14
3014, 1014, 3014
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG15
3015, 1015, 3015
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG16
3016, 1016, 3016
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG17
3017, 1017, 3017
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG18
3018, 1018, 3018
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG19
3019, 1019, 3019
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG20
3020, 1020, 3020
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG21
3021, 1021, 3021
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG22
3022, 1022, 3022
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG23
3023, 1023, 3023
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG24
3024, 1024, 3024
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG25
3025, 1025, 3025
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG26
3026, 1026, 3026
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG27
3027, 1027, 3027
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG28
3028, 1028, 3028
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG29
3029, 1029, 3029
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG30
3030, 1030, 3030
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG31
3031, 1031, 3031
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG32
3032, 1032, 3032
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG33
3033, 1033, 3033
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG34

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3034, 1034, 3034
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG35
3035, 1035, 3035
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG36
3036, 1036, 3036
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG37
3037, 1037, 3037
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG38
3038, 1038, 3038
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG39
3039, 1039, 3039
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG40
3040, 1040, 3040
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG41
3041, 1041, 3041
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG42
3042, 1042, 3042
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG43
3043, 1043, 3043
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG44
3044, 1044, 3044
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG45
3045, 1045, 3045
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG46
3046, 1046, 3046
*ELSET, ELSET=SLSPG, GENERATE
3000, 3046, 1
*SPRING, ELSET=SLSPG00, NONLINEAR

-2.44E10, -50.
-2710., -5.
0.0
*SPRING, ELSET=SLSPG01, NONLINEAR

-1.95E11, -50.
-21677., -5.
0.0
*SPRING, ELSET=SLSPG02, NONLINEAR

-3.90E11, -50.
-43354., -5.
0.0
*SPRING, ELSET=SLSPG03, NONLINEAR

-5.85E11, -50.
-65031., -5.
0.0
*SPRING, ELSET=SLSPG04, NONLINEAR

-7.80E11, -50.
-86708., -5.
0.0

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*SPRING,ELSET=SLSPG05,NONLINEAR

-9.75E11, -50.

-108385., -5.

0.0

*SPRING,ELSET=SLSPG06,NONLINEAR

-1.17E12, -50.

-130062., -5.

0.0

*SPRING,ELSET=SLSPG07,NONLINEAR

-1.37E12, -50.

-151739., -5.

0.0

*SPRING,ELSET=SLSPG08,NONLINEAR

-1.56E12, -50.

-173416., -5.

0.0

*SPRING,ELSET=SLSPG09,NONLINEAR

-1.76E12, -50.

-195093., -5.

0.0

*SPRING,ELSET=SLSPG10,NONLINEAR

-1.95E12, -50.

-216770., -5.

0.0

*SPRING,ELSET=SLSPG11,NONLINEAR

-2.15E12, -50.

-238447., -5.

0.0

*SPRING,ELSET=SLSPG12,NONLINEAR

-2.34E12, -50.

-260124., -5.

0.0

*SPRING,ELSET=SLSPG13,NONLINEAR

-2.54E12, -50.

-281801., -5.

0.0

*SPRING,ELSET=SLSPG14,NONLINEAR

-2.73E12, -50.

-303478., -5.

0.0

*SPRING,ELSET=SLSPG15,NONLINEAR

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-2.93E12, -50.
-325155., -5.
0.0
*SPRING, ELSET=SLSPG16, NONLINEAR

-3.12E12, -50.
-346832., -5.
0.0
*SPRING, ELSET=SLSPG17, NONLINEAR

-3.32E12, -50.
-368509., -5.
0.0
*SPRING, ELSET=SLSPG18, NONLINEAR

-3.51E12, -50.
-390186., -5.
0.0
*SPRING, ELSET=SLSPG19, NONLINEAR

-3.71E12, -50.
-411863., -5.
0.0
*SPRING, ELSET=SLSPG20, NONLINEAR

-5.85E12, -50.
-650310., -5.
0.0
*SPRING, ELSET=SLSPG21, NONLINEAR

-8.58E12, -50.
-953788., -5.
0.0
*SPRING, ELSET=SLSPG22, NONLINEAR

-9.36E12, -50.
-1040495., -5.
0.0
*SPRING, ELSET=SLSPG23, NONLINEAR

-1.01E13, -50.
-1127203., -5.
0.0
*SPRING, ELSET=SLSPG24, NONLINEAR

-1.09E13, -50.
-1213911., -5.
0.0
*SPRING, ELSET=SLSPG25, NONLINEAR

-1.17E13, -50.
-1300619., -5.

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0.0
*SPRING,ELSET=SLSPG26,NONLINEAR
-1.25E13, -50.
-1387327., -5.
0.0
*SPRING,ELSET=SLSPG27,NONLINEAR
-1.33E13, -50.
-1474035., -5.
0.0
*SPRING,ELSET=SLSPG28,NONLINEAR
-1.40E13, -50.
-1560743., -5.
0.0
*SPRING,ELSET=SLSPG29,NONLINEAR
-1.48E13, -50.
-1647451., -5.
0.0
*SPRING,ELSET=SLSPG30,NONLINEAR
-2.34E13, -50.
-2601239., -5.
0.0
*SPRING,ELSET=SLSPG31,NONLINEAR
-3.43E13, -50.
-3815150., -5.
0.0
*SPRING,ELSET=SLSPG32,NONLINEAR
-3.75E13, -50.
-4161982., -5.
0.0
*SPRING,ELSET=SLSPG33,NONLINEAR
-4.06E13, -50.
-4508814., -5.
0.0
*SPRING,ELSET=SLSPG34,NONLINEAR
-4.37E13, -50.
-4855646., -5.
0.0
*SPRING,ELSET=SLSPG35,NONLINEAR
-4.68E13, -50.
-5202477., -5.
0.0
*SPRING,ELSET=SLSPG36,NONLINEAR

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-4.99E13, -50.
-5549309., -5.
0.0
*SPRING, ELSET=SLSPG37, NONLINEAR

-5.31E13, -50.
-5896141., -5.
0.0
*SPRING, ELSET=SLSPG38, NONLINEAR

-5.62E13, -50.
-6242973., -5.
0.0
*SPRING, ELSET=SLSPG39, NONLINEAR

-5.93E13, -50.
-6589805., -5.
0.0
*SPRING, ELSET=SLSPG40, NONLINEAR

-1.09E14, -50.
-12139114., -5.
0.0
*SPRING, ELSET=SLSPG41, NONLINEAR

-1.76E14, -50.
-19509290., -5.
0.0
*SPRING, ELSET=SLSPG42, NONLINEAR

-1.95E14, -50.
-21676989., -5.
0.0
*SPRING, ELSET=SLSPG43, NONLINEAR

-2.15E14, -50.
-23844688., -5.
0.0
*SPRING, ELSET=SLSPG44, NONLINEAR

-2.34E14, -50.
-26012387., -5.
0.0
*SPRING, ELSET=SLSPG45, NONLINEAR

-2.54E14, -50.
-28180086., -5.
0.0
*SPRING, ELSET=SLSPG46, NONLINEAR

-1.34E14, -50.
-14902930., -5.

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0.0
**
** GENERATE SOIL MASS AND LUMPED ONTO CONCRETE
**
*ELEMENT, TYPE=MASS, ELSET=SM00
3100, 1000
*MASS, ELSET=SM00
7.0577E-4
*ELEMENT, TYPE=MASS, ELSET=SM01
3101, 1001
*MASS, ELSET=SM01
5.6461E-3
*ELEMENT, TYPE=MASS, ELSET=SM02
3102, 1002
*MASS, ELSET=SM02
1.1292E-2
*ELEMENT, TYPE=MASS, ELSET=SM03
3103, 1003
*MASS, ELSET=SM03
1.6938E-2
*ELEMENT, TYPE=MASS, ELSET=SM04
3104, 1004
*MASS, ELSET=SM04
2.2584E-2
*ELEMENT, TYPE=MASS, ELSET=SM05
3105, 1005
*MASS, ELSET=SM05
2.8231E-2
*ELEMENT, TYPE=MASS, ELSET=SM06
3106, 1006
*MASS, ELSET=SM06
3.3877E-2
*ELEMENT, TYPE=MASS, ELSET=SM07
3107, 1007
*MASS, ELSET=SM07
3.9523E-2
*ELEMENT, TYPE=MASS, ELSET=SM08
3108, 1008
*MASS, ELSET=SM08
4.5169E-2
*ELEMENT, TYPE=MASS, ELSET=SM09
3109, 1009
*MASS, ELSET=SM09
5.0815E-2
*ELEMENT, TYPE=MASS, ELSET=SM10
3110, 1010
*MASS, ELSET=SM10
5.6461E-2
*ELEMENT, TYPE=MASS, ELSET=SM11
3111, 1011
*MASS, ELSET=SM11
6.2107E-2

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*ELEMENT, TYPE=MASS, ELSET=SM12
3112, 1012
*MASS, ELSET=SM12
6.7753E-2
*ELEMENT, TYPE=MASS, ELSET=SM13
3113, 1013
*MASS, ELSET=SM13
7.3400E-2
*ELEMENT, TYPE=MASS, ELSET=SM14
3114, 1014
*MASS, ELSET=SM14
7.9046E-2
*ELEMENT, TYPE=MASS, ELSET=SM15
3115, 1015
*MASS, ELSET=SM15
8.4692E-2
*ELEMENT, TYPE=MASS, ELSET=SM16
3116, 1016
*MASS, ELSET=SM16
9.0338E-2
*ELEMENT, TYPE=MASS, ELSET=SM17
3117, 1017
*MASS, ELSET=SM17
9.5964E-2
*ELEMENT, TYPE=MASS, ELSET=SM18
3118, 1018
*MASS, ELSET=SM18
1.0163E-1
*ELEMENT, TYPE=MASS, ELSET=SM19
3119, 1019
*MASS, ELSET=SM19
1.0728E-1
*ELEMENT, TYPE=MASS, ELSET=SM20
3120, 1020
*MASS, ELSET=SM20
1.6938E-1
*ELEMENT, TYPE=MASS, ELSET=SM21
3121, 1021
*MASS, ELSET=SM21
2.4843E-1
*ELEMENT, TYPE=MASS, ELSET=SM22
3122, 1022
*MASS, ELSET=SM22
2.7101E-1
*ELEMENT, TYPE=MASS, ELSET=SM23
3123, 1023
*MASS, ELSET=SM23
2.9360E-1
*ELEMENT, TYPE=MASS, ELSET=SM24
3124, 1024
*MASS, ELSET=SM24
3.1618E-1

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*ELEMENT, TYPE=MASS, ELSET=SM25
3125, 1025
*MASS, ELSET=SM25
3.3877E-1
*ELEMENT, TYPE=MASS, ELSET=SM26
3126, 1026
*MASS, ELSET=SM26
3.6135E-1
*ELEMENT, TYPE=MASS, ELSET=SM27
3127, 1027
*MASS, ELSET=SM27
3.8394E-1
*ELEMENT, TYPE=MASS, ELSET=SM28
3128, 1028
*MASS, ELSET=SM28
4.0652E-1
*ELEMENT, TYPE=MASS, ELSET=SM29
3129, 1029
*MASS, ELSET=SM29
4.2911E-1
*ELEMENT, TYPE=MASS, ELSET=SM30
3130, 1030
*MASS, ELSET=SM30
6.7753E-1
*ELEMENT, TYPE=MASS, ELSET=SM31
3131, 1031
*MASS, ELSET=SM31
9.9372E-1
*ELEMENT, TYPE=MASS, ELSET=SM32
3132, 1032
*MASS, ELSET=SM32
1.0841
*ELEMENT, TYPE=MASS, ELSET=SM33
3133, 1033
*MASS, ELSET=SM33
1.1744
*ELEMENT, TYPE=MASS, ELSET=SM34
3134, 1034
*MASS, ELSET=SM34
1.2647
*ELEMENT, TYPE=MASS, ELSET=SM35
3135, 1035
*MASS, ELSET=SM35
1.3511
*ELEMENT, TYPE=MASS, ELSET=SM36
3136, 1036
*MASS, ELSET=SM36
1.4454
*ELEMENT, TYPE=MASS, ELSET=SM37
3137, 1037
*MASS, ELSET=SM37
1.5357

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*ELEMENT, TYPE=MASS, ELSET=SM38
3138, 1038
*MASS, ELSET=SM38
1.6261
*ELEMENT, TYPE=MASS, ELSET=SM39
3139, 1039
*MASS, ELSET=SM39
1.7164
*ELEMENT, TYPE=MASS, ELSET=SM40
3140, 1040
*MASS, ELSET=SM40
3.1618
*ELEMENT, TYPE=MASS, ELSET=SM41
3141, 1041
*MASS, ELSET=SM41
5.0815
*ELEMENT, TYPE=MASS, ELSET=SM42
3142, 1042
*MASS, ELSET=SM42
5.6416
*ELEMENT, TYPE=MASS, ELSET=SM43
3143, 1043
*MASS, ELSET=SM43
6.2107
*ELEMENT, TYPE=MASS, ELSET=SM44
3144, 1044
*MASS, ELSET=SM44
6.7753
*ELEMENT, TYPE=MASS, ELSET=SM45
3145, 1045
*MASS, ELSET=SM45
7.3400
*ELEMENT, TYPE=MASS, ELSET=SM46
3146, 1046
*MASS, ELSET=SM46
3.8817
**
**  NODE SET DEFINITIONS
**
*NSET, NSET=AREAIN, GENERATE
18, 85, 1
*NSET, NSET=AREA
AREA2, AREA3, AREA4, AREA5, AREA6, AREA7
*NSET, NSET=ALLNODES
**AREAIN, AREA
AREA1, AREA
*NSET, NSET=AXISYM, GENERATE
1, 919, 17
1000, 2200, 100
**
**  ELEMENT SET DEFINITIONS
**

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```
*ELSET, ELSET=WALL
WALL1, WALL2, WALL3, WALL4, WALL5, WALL6
*ELSET, ELSET=SHIELD
SHIELD2, SHIELD3, SHIELD4, SHIELD5
*ELSET, ELSET=PAYLD
PAYLD1, PAYLD2, PAYLD3, PAYLD4, PAYLD5
*ELSET, ELSET=LID
LID1, LID2
*ELSET, ELSET=ALLELEMS
PLATE, WALL, SHIELD, PAYLD, LID
**
** MATERIAL DEFINITIONS
**
** A36 STEEL
**
*MATERIAL, NAME=A36ST
*ELASTIC
29.0E6, 0.3
*PLASTIC
36045., 0.
72500., 0.222
*DENSITY
7.34E-4
**
** PAYLOAD STEEL
**
*MATERIAL, NAME=PAYLD
*ELASTIC
29.0E6, 0.3
*PLASTIC
36045., 0.
72500., 0.222
*DENSITY
4.10E-4
**
** REBAR STEEL
**
*MATERIAL, NAME=REBAR
*ELASTIC
29.0E6, 0.3
*PLASTIC
36045., 0.
72500., 0.222
*DENSITY
7.34E-4
*MATERIAL, NAME=CONCRETE
*ELASTIC
4.03E6, 0.18
*PLASTIC
3002., 0.0
4005., 0.0002
5009., 0.00055
```

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5010., 0.00075
*FAILURE
0.3, 0.01
*DENSITY
1.95E-4
**
** SOIL
**
*MATERIAL, NAME=SOIL
*ELASTIC
30000, 0.25
*PLASTIC
600., 0.
*DENSITY
1.65E-4
**
** BOUNDARY CONDITIONS
**
*BOUNDARY
AXISYM, XSYMM
SOIL, 2
*INITIAL CONDITION, TYPE=VELOCITY
ALLNODES, 2, -527.5
*STEP
  DYNAMIC IMPACT
*DYNAMIC, EXPLICIT
  2.0E-2
*DLOAD
  PLATE, GRAV, 386.4, 0., -1., 0.
  WALL, GRAV, 386.4, 0., -1., 0.
  SHIELD, GRAV, 386.4, 0., -1., 0.
  PAYLD, GRAV, 386.4, 0., -1., 0.
  LID, GRAV, 386.4, 0., -1., 0.
  CONCRETE, GRAV, 386.4, 0., -1., 0.
*SURFACE DEFINITION, NAME=TCONC
CONCRETC, S3
*SURFACE DEFINITION, NAME=BCASK
PLATE1, S1
*CONTACT PAIR
BCASK, TCONC
*MONITOR, NODE=119, DOF=2
*END STEP
```

APPENDIX B
ABAQUS MODEL FOR SANDIA TEST DATA
HIGHWAY CONCRETE

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*HEADING
EVALUATION OF SANDIA CASK DROP TEST/CONCRETE HIGHWAY 44FPS
SOIL SPRINGS USE SPRING ELEMENTS + CONCRETE PLASTIC CURVE
FAILURE COMMAND
**RESTART, WRITE, NUMBER INTERVAL=20
**
** GENERATE THE NODES OF BOTTOM 2-IN THICK PLATE
** BOTTOM SECTION IS NAMED SECTA, TOP SECTION IS NAMED SECTB
**
*NODE, SYSTEM=R
*NODE, NSET=P1
1, 0.0, 0.0, 0.0
*NODE, NSET=P2
10, 6.5, 0.0, 0.0
*NFill, NSET=SECTA, BIAS=1.085
P1, P2, 9
*NODE, NSET=SECTA
11, 7.0, 0.0, 0.0
12, 7.5, 0.0, 0.0
13, 8.0, 0.0, 0.0
14, 8.5, 0.0, 0.0
15, 9.0, 0.0, 0.0
16, 9.5, 0.0, 0.0
17, 10.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=68, OLD SET=SECTA, NEW SET=SECTB
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFill, NSET=AREA1
SECTA, SECTB, 4, 17
**
** GENERATE THE NODES OF 4 LAYERS OF 0.5-IN. THICK
** BOTTOM SECTION IS NAMED SECTB, TOP SECTION IS NAMED SECTC
**
*NCOPY, SHIFT, CHANGE NU=68, OLD SET=SECTB, NEW SET=SECTC
0.0, 2.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFill, NSET=AREA2
SECTB, SECTC, 4, 17
**
** GENERATE THE NODES OF 18 LAYERS OF 0.625 IN. THICK
** BOTTOM SECTION IS NAMED SECTC, TOP SECTION IS NAMED SECTD
**
*NCOPY, SHIFT, CHANGE NU=306, OLD SET=SECTC, NEW SET=SECTD
0.0, 11.25, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFill, NSET=AREA3
SECTC, SECTD, 18, 17
**
** GENERATE THE NODES OF 15 LAYERS OF 1.25 IN. THICK
** BOTTOM SECTION IS NAMED SECTD, TOP SECTION IS NAMED SECTE
**
*NCOPY, SHIFT, CHANGE NU=255, OLD SET=SECTD, NEW SET=SECTE

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0.0, 18.75, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA4
SECTD, SECTE, 15, 17
**
** GENERATE THE NODES OF 2 LAYERS OF 2.125 IN. THICK
** BOTTOM SECTION IS NAMED SECTE, TOP SECTION IS NAMED SECTF
**
*NCOPY, SHIFT, CHANGE NU=34, OLD SET=SECTE, NEW SET=SECTF
0.0, 4.25, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA5
SECTE, SECTF, 2, 17
**
** GENERATE THE NODES OF 7 LAYERS OF 4.25 IN. THICK
** BOTTOM SECTION IS NAMED SECTF, TOP SECTION IS NAMED SECTG
**
*NCOPY, SHIFT, CHANGE NU=119, OLD SET=SECTF, NEW SET=SECTG
0.0, 29.75, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA6
SECTF, SECTG, 7, 17
**
** GENERATE THE NODES OF 4 LAYERS OF 1.0 IN. THICK
** BOTTOM SECTION IS NAMED SECTG, TOP SECTION IS NAMED SECTH
**
*NCOPY, SHIFT, CHANGE NU=68, OLD SET=SECTG, NEW SET=SECTH
0.0, 4.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NFILL, NSET=AREA7
SECTG, SECTH, 4, 17
*****
**
** GENERATE THE ELEMENTS OF BOTTOM PLATE
** FOUR 0.5-INCH LAYERS, PLATE1 THROUGH PLATE4
**
*ELEMENT, TYPE=CAX4R
1, 1, 2, 19, 18
*ELGEN, ELSET=PLATE1
1, 16, 1, 1
*ELCOPY, OLD SET=PLATE1, NEW SET=PLATE2, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=PLATE2, NEW SET=PLATE3, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=PLATE3, NEW SET=PLATE4, ELEMENT SHIFT=16, SHIFT NODES=17
*ELSET, ELSET=PLATE
PLATE1, PLATE2, PLATE3, PLATE4
*SOLID SECTION, ELSET=PLATE, MATERIAL=A36ST
**
** GENERATE THE ELEMENTS OF CASK WALL
** WALL1 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
78, 82, 83, 100, 99

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*ELGEN, ELSET=WALL1A
78, 3, 1, 1
*ELCOPY, OLD SET=WALL1A, NEW SET=WALL1B, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=WALL1B, NEW SET=WALL1C, ELEMENT SHIFT=16, SHIFT NODES=17
*ELCOPY, OLD SET=WALL1C, NEW SET=WALL1D, ELEMENT SHIFT=16, SHIFT NODES=17
*ELSET, ELSET=WALL1
WALL1A, WALL1B, WALL1C, WALL1D
*SOLID SECTION, ELSET=WALL1, MATERIAL=A36ST
**
** WALL2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
142, 150, 151, 168, 167
*ELGEN, ELSET=WALL2
142, 3, 1, 1, 18, 17, 16
*SOLID SECTION, ELSET=WALL2, MATERIAL=A36ST
**
** WALL3 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
430, 456, 457, 474, 473
*ELGEN, ELSET=WALL3
430, 3, 1, 1, 15, 17, 16
*SOLID SECTION, ELSET=WALL3, MATERIAL=A36ST
**
** WALL4 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
670, 711, 712, 729, 728
*ELGEN, ELSET=WALL4
670, 3, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=WALL4, MATERIAL=A36ST
**
** WALL5 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
702, 745, 746, 763, 762
*ELGEN, ELSET=WALL5
702, 3, 1, 1, 7, 17, 16
*SOLID SECTION, ELSET=WALL5, MATERIAL=A36ST
**
** WALL6 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
814, 864, 865, 882, 881
*ELGEN, ELSET=WALL6
814, 3, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=WALL6, MATERIAL=A36ST
**
** GENERATE THE ELEMENTS OF SHIELDING
** SHIELD1 ELEMENTS
**

```
** NO SHIELD1 ELEMENTS
**
** SHIELD2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
138, 146, 147, 164, 163
*ELGEN, ELSET=SHIELD2
138, 4, 1, 1, 18, 17, 16
*SOLID SECTION, ELSET=SHIELD2, MATERIAL=A36ST
**
** SHIELD3 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
426, 452, 453, 470, 469
*ELGEN, ELSET=SHIELD3
426, 4, 1, 1, 15, 17, 16
*SOLID SECTION, ELSET=SHIELD3, MATERIAL=A36ST
**
** SHIELD4 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
666, 707, 708, 725, 724
*ELGEN, ELSET=SHIELD4
666, 4, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=SHIELD4, MATERIAL=A36ST
**
** SHIELD5 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
698, 741, 742, 759, 758
*ELGEN, ELSET=SHIELD5
698, 4, 1, 1, 7, 17, 16
*SOLID SECTION, ELSET=SHIELD5, MATERIAL=A36ST
**
** GENERATE THE ELEMENTS OF PAYLOADS
** PAYLD1 ELEMENTS
**
** PAYLD1 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
65, 69, 70, 87, 86
*ELGEN, ELSET=PAYLD1
65, 9, 1, 1, 4, 17, 16
*SOLID SECTION, ELSET=PAYLD1, MATERIAL=PAYLD
**
** PAYLD2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
129, 137, 138, 155, 154
*ELGEN, ELSET=PAYLD2
129, 9, 1, 1, 18, 17, 16
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**SOLID SECTION, ELSET=PAYLD2, MATERIAL=PAYLD
**
** PAYLD3 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
417, 443, 444, 461, 460
*ELGEN, ELSET=PAYLD3
417, 9, 1, 1, 15, 17, 16
*SOLID SECTION, ELSET=PAYLD3, MATERIAL=PAYLD
**
** PAYLD4 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
657, 698, 699, 716, 715
*ELGEN, ELSET=PAYLD4
657, 9, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=PAYLD4, MATERIAL=PAYLD
**
** PAYLD5 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
689, 732, 733, 750, 749
*ELGEN, ELSET=PAYLD5
689, 9, 1, 1, 7, 17, 16
*SOLID SECTION, ELSET=PAYLD5, MATERIAL=PAYLD
**
** GENERATE THE ELEMENTS OF LID
**
** LID1 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
817, 868, 869, 886, 885
*ELGEN, ELSET=LID1
817, 13, 1, 1
*SOLID SECTION, ELSET=LID1, MATERIAL=A36ST
**
** LID2 ELEMENTS
**
*ELEMENT, TYPE=CAX4R
833, 885, 886, 903, 902
*ELGEN, ELSET=LID2
833, 16, 1, 1, 2, 17, 16
*SOLID SECTION, ELSET=LID2, MATERIAL=A36ST
*ELSET, ELSET=LID
LID1, LID2
**
** GENERATE THE ELEMENTS OF CONCRETE PAD
**
*NODE, SYSTEM=R
*NODE, NSET=C1
1000, 0.0, -9.0, 0.0
*NODE, NSET=C2

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1020, 20.0, -9.0, 0.0
*NODE, NSET=C3
1030, 40.0, -9.0, 0.0
*NODE, NSET=C4
1036, 70.0, -9.0, 0.0
*NFILL, NSET=CONCRET1
C1, C2, 20
C2, C3, 10
C3, C4, 6
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET1, NEW SET=CONCRET2
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET2, NEW SET=CONCRET3
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET3, NEW SET=CONCRET4
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET4, NEW SET=CONCRET5
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET5, NEW SET=CONCRET6
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET6, NEW SET=CONCRET7
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET7, NEW SET=CONCRET8
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET8, NEW SET=CONCRET9
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*NCOPY, SHIFT, CHANGE NU=100, OLD SET=CONCRET9, NEW SET=CONCRETA
0.0, 1.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
**
** CONCRETE PAD ELEMENT
**
*ELEMENT, TYPE=CAX4R
1000, 1000, 1001, 1101, 1100
*ELGEN, ELSET=CONCRET1
1000, 36, 1, 1
*ELCOPY, OLD SET=CONCRET1, NEW SET=CONCRET2, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET2, NEW SET=CONCRET3, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET3, NEW SET=CONCRET4, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET4, NEW SET=CONCRET5, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET5, NEW SET=CONCRET6, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET6, NEW SET=CONCRET7, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET7, NEW SET=CONCRET8, ELEMENT SHIFT=100, SHIFT NODES=100
*ELCOPY, OLD SET=CONCRET8, NEW SET=CONCRET9, ELEMENT SHIFT=100, SHIFT NODES=100
*ELSET, ELSET=CONCRETE

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CONCRET1, CONCRET2, CONCRET3, CONCRET4, CONCRET5
CONCRET6, CONCRET7, CONCRET8, CONCRET9
*SOLID SECTION, ELSET=CONCRETE, MATERIAL=CONCRETE
**
** GENERATE THE SOIL SPRINGS
**
*NCOPY, SHIFT, CHANGE NU=1000, OLD SET=CONCRET1, NEW SET=SOIL
0.0, -21.0, 0.0
0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG00
2000, 1000, 2000
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG01
2001, 1001, 2001
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG02
2002, 1002, 2002
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG03
2003, 1003, 2003
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG04
2004, 1004, 2004
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG05
2005, 1005, 2005
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG06
2006, 1006, 2006
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG07
2007, 1007, 2007
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG08
2008, 1008, 2008
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG09
2009, 1009, 2009
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG10
2010, 1010, 2010
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG11
2011, 1011, 2011
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG12
2012, 1012, 2012
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG13
2013, 1013, 2013
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG14
2014, 1014, 2014
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG15
2015, 1015, 2015
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG16
2016, 1016, 2016
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG17
2017, 1017, 2017
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG18
2018, 1018, 2018
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG19
2019, 1019, 2019
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG20
2020, 1020, 2020
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG21

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2021, 1021, 2021
*ELEMENT, TYPE=SPRINGA, ELSET=SLSPG22
2022, 1022, 2022
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7.2 THREE DIMENSIONAL MODEL

Numerical Simulations of Model Cask Impacts

Randall S. Marlow
9/27/96

1.0 Introduction

This document describes numerical simulations of model cask impact tests which were conducted by Sandia National Laboratory (SNL) in the late 1980's (Gonzales 1987). In the tests, Sandia impacted a cylindrical model cask into an unyielding target, concrete targets, and soil targets. The steel cask carried accelerometers and strain gages to record the mechanical response. Figure 1.0-1 shows the test unit.

The calculations described here are simulations of the cask impacts on a concrete target that was constructed to represent an aircraft runway. The cask impacted the simulated runway at three different speeds; 44 fps, 66 fps, and 88 fps. Because the data for the 44-fps impact appears to be flawed, only the 66-fps and 88-fps impacts have been simulated. (The peak acceleration reported by Sandia for 44 fps impact seems to contradict the reported concrete penetration.) The following sections describe the analyses and compare the numerical results with the results reported in Gonzales 1987.

The main purpose of the calculations is to determine the suitability of the analytical methods in the modeling of cask impacts upon concrete. The suitability is determined by comparing selected results from the numerical calculations with corresponding quantities which were measured during the Sandia test series.

2.0 Analytical Model

2.1 Overview of Model

The analytical model is a finite-element model written for the ABAQUS/Explicit Version 5.5 code. (Appendix A contains a partial listing of the ABAQUS/Explicit input file.) ABAQUS/Explicit (HKSa 1995) is designed for transient-dynamic structural analysis. It has advanced features for the modeling of nonlinear material behavior, large deformations, and general contact. Figures 2.0-1 and 2.0-2 show the finite-element mesh. The finite-element model, which is a half-symmetry model, is comprised of three main structural components. The first is the soil region. The second is the concrete slab. The third component is the cask.

The soil region in the finite-element model is composed of 8-noded brick elements. Symmetry conditions are imposed on the nodes which are on the symmetry plane. The nodes on the bottom of the soil region are fixed. The nodes on the lateral surface have no boundary conditions. The depth of the soil region is 100 in. The soil constitutive model is a Drucker-Prager plasticity model developed originally for the analysis of underground tanks (Juryk 1994). The SNL test report describes indentation tests of the actual soil layer

(Gonzales 1987). The soil model is consistent with the data from these tests.

The concrete region in the finite-element model is composed of 8-noded brick elements. Symmetry conditions are imposed on the nodes which are on the symmetry plane. No other nodes of the concrete region are constrained. The concrete constitutive model is a Drucker-Prager plasticity model. The constitutive model captures the behavior of concrete under compression but has no cracking features.

The cask body, shield, and end caps are modeled with 4-noded shell elements. The interior of the cask contains 8-noded brick elements which represent the payload. The shell elements which represent the shield are connected to the cask body with multipoint constraints. The brick elements, which are not directly connected to any shell element, interact with the bottom end-cap via contact conditions. Nodes in the cask model which are on the symmetry plane have the appropriate symmetry conditions. The steel is modeled as an elastic-perfectly plastic material.

The only load applied in the finite-element model is the gravitational body force. Impact loads are computed by the code as the impact proceeds. At the beginning of an analysis, the cask nodes are given the appropriate initial velocity. Contact conditions are enforced between the nodes which are on the top surface of the concrete region and the elements of the cask body which are likely to come into contact with the concrete region. The motion of the cask is then computed by the finite-element code.

2.1.1 Concrete Constitutive Model

As mentioned previously, the concrete is modeled with a Drucker-Prager plasticity model. This constitutive model is part of the ABAQUS package and it is described in detail in the ABAQUS theory manual (HKSb 1995). The model is useful for materials such as concrete which exhibit pressure dependent yielding and shear failure under compression. The pre-yield behavior of the constitutive model is elastic with a modulus of $4.0\text{E}+06$ psi and a Poisson's ratio of 0.15. The weight density is assumed to be 130 lbf/ft^3 .

The failure surface in the Drucker-Prager plasticity theory (as implemented in ABAQUS) is defined by the angle of friction, the ratio of the flow stress in triaxial tension to the flow stress in triaxial compression, and the dilation angle. For technical reasons, the flow stress ratio must be between 0.778 and 1.0. The concrete model has the ABAQUS default value of 1.0. The angle of friction and the dilation angle are arbitrarily assumed to be 35.2° . (In the author's experience, the angular parameters have a second-order effect on results.)

The post-yield behavior is defined so that under uniaxial compression, the concrete first yields at a stress of 2400 psi. The strength under uniaxial compression is 4800 psi, which is the nominal strength of the concrete in the runway slab. The peak stress is reached at a plastic strain of 0.0011. The stress-strain behavior after the peak is a curve derived from information contained in Rashid 1986. After the strain reaches 0.006 in uniaxial compression, the material is assumed to fail completely.

2.1.2 Soil Constitutive Model

The Drucker-Prager plasticity model is also used for soil constitutive model. The model originates in the structural analysis described in Julyk 1994. The soil constitutive model described therein was scaled so that the force required to statically push an 8-in. circular plate 0.2 in. into the model soil region in the cask analyses is approximately 3000 lbf. Thus, the subgrade modulus of the model soil region is approximately 300 psi/in. This is slightly above the average modulus reported in Gonzales 1987. A slightly higher value was chosen for the model in order to account for strain-rate effects. The weight density of the model soil is 110 lbf/ft³.

Before yield, the soil model is elastic with a modulus of 5700 psi and a Poisson's ratio of 0.35. The soil failure surface uses the same angular parameters as the concrete failure surface described above. The flow stress ratio for the soil is 0.82. In uniaxial compression, the soil model yields first at 2 psi and then strain hardens. The peak stress is a mere 11 psi. Although these stresses seem low, the soil region does indeed have the appropriate subgrade modulus.

2.1.3 Steel Constitutive Model

The A 36 steel in the cask is modeled as an elastic-perfectly plastic material. The pre-yield behavior is elastic with a modulus of $29.E+06$ and a Poisson's ratio of 0.3. The yield stress is 36,000 psi. The weight density of the steel in the model is 0.284 lbf/in³.

3.0 Numerical Results

3.1 Impact at 66 fps

Figures 3.1-1 and 3.1-2 show the "hole" which is created in the concrete region by the impact of the cask. The square-ish shape of the depression is an effect of the rectangular concrete mesh. Figure 3.1-2 is a contour plot of the vertical deflection in the concrete at the instant in time when vertical speed of the cask is reduced to 0 by the impact. The cask impact causes a shear failure and the formation of a concrete plug under the cask. Figure 3.1-3 contains a plot of the vertical displacement of a node half-way up the lateral surface of the cask body. The node travels approximately 4.7 in. downward before the cask is brought to rest. Figure 3.1-4 contains a plot of the vertical component of the acceleration of the node described above. The acceleration component was filtered at 10,000 Hz and again at 500 Hz with a 6-pole sine-Butterworth algorithm to simulate the experimentally measured and conditioned accelerometer signal. The peak acceleration in the numerical signal is 894g.

3.2 Impact at 88 fps

Figures 3.2-1 and 3.2-2 show the "hole" which is created in the concrete region by the impact of the cask. Figure 3.2-2 is a contour plot of the vertical deflection in the concrete at the instant in time when vertical speed of the cask is reduced to 0 by the impact. Again, the plug failure of the slab is apparent. Figure 3.1-3 contains a plot of the vertical

displacement of a node half-way up the lateral surface of the cask body. The node travels approximately 8.7 in. downward before the cask is brought to rest. Figure 3.1-4 contains a plot of the vertical component of the acceleration of the node described above. The acceleration component was filtered at 10,000 Hz and again at 500 Hz with a 6-pole sine-Butterworth algorithm to simulate the recorded accelerometer signal. The peak acceleration in the numerical signal is 1343g.

4.0 Comparison of Numerical Results to Experimental Results

The primary numerical results and the corresponding quantities from the SNL drops are compared in Table 4.0-1. A comparison of strain gage data and computed cask deformations is not made at this time because of limitations in the cask finite-element mesh. The accelerations and penetrations from the numerical simulation compare favorably to the measured values.

Table 4.0-1. Cask Penetrations and Accelerations

Impact Speed	Peak Acceleration (g)		Percent Difference ^c	Penetration (in)		Percent Difference ^c
	Calculated	Measured		Calculated	Measured	
66 fps	894	900	1%	4.7	4	16%
88 fps	1343	1000	29%	8.7	8	8%

5.0 Conclusion and Recommendations

The conclusion drawn from the numerical study of the Sandia cask tests must be that the analytical methods are capable of accurately describing the acceleration of a cask impacting a concrete slab and the subsequent damage to the slab. Perhaps the most remarkable feature of the numerical model is its ability to predict the plug failure caused by the cask impact. The author recommends that the Drucker-Prager model be used when modeling cask impacts on concrete targets. He also recommends additional studies to determine the effects of concrete reinforcing and cask impact orientation and shape.

6.0 References

Gonzales, Alex, 1987, "Target Effects on Package Response: An Experimental and Analytical Evaluation", SAND86-2275, Sandia National Laboratory, Albuquerque, New Mexico.

July, L.J., 1994, "Tank 241-C-106 Structural Integrity Evaluation for In Situ Conditions", WHC-SD-W320-ANAL-001, Westinghouse Hanford Company, Richland, Washington.

HKSa, 1995, *ABAQUS/Explicit User's Manual, Version 5.5*, Hibbit, Karlsson, & Sorenson, Inc., Pawtucket, Rhode Island.

HKSb, 1995, *ABAQUS Theory Manual, Version 5.5*, Hibbit, Karlsson, & Sorenson, Inc., Pawtucket, Rhode Island.

Rashid, Y.R., 1986, *The Effects of Target Hardness on the Structural Design of Concrete Storage Pads for Spent-Fuel Casks*, NP-4830, Electric Power Research Institute, Palo Alto, California.

Appendix A. ABAQUS/Explicit Input File

(An ellipsis indicates the omission of input lines.)

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*drucker prager  
35.2,0.82,35.2  
*drucker prager hardening  
2.0,0.0  
6.54,0.0055  
8.64,0.0156  
9.96,0.0259  
10.68,0.0362  
10.98,0.0467  
11.1,0.0573  
11.04,0.068  
10.8,0.0788  
10.44,0.0897  
9.9,0.1  
9.0,0.112  
*material,name=conc  
*density  
1.95E-04  
*elastic  
4.E+06,0.15  
*drucker prager  
35.2,1.0,35.2  
**60.5,1.0,0.0  
*drucker prager hardening  
2400.,0.0  
4800.,0.0011  
3950.,0.003  
3040.,0.004  
2350.,0.005  
1920.,0.006  
100.,0.0061  
*material,name=steel  
*density
```

```

7.35E-04
*elastic
29.E+06,0.3
*plastic
36000.,0.0
*solidsection,elset=conc,material=conc
*solidsection,elset=soil,material=soil
*solidsection,elset=weight,material=steel
*shellsection,elset=caps,material=steel
2.0
*shellsection,elset=wall,material=steel
1.5
*shellsection,elset=shield,material=steel
2.0
*initial conditions,type=velocity
cnodes,2,-792.0
**cnodes,2,-1056.0
*mpc
tie,50142,50307
tie,50143,50308
tie,50144,50309
tie,50145,50310
tie,50071,50227
tie,50072,50229
tie,50073,50230
tie,50074,50231
tie,50067,50228
tie,50174,50287
tie,50175,50288
tie,50176,50289
tie,50177,50290
tie,50107,50202
tie,50109,50204
tie,50110,50205
tie,50111,50206
tie,50108,50203
*boundary
bnodes,1,3
zsymm,zsymm
*restart,write,number increment=3
*elset,elset=cask
caps,shield,wall,weight
*step
*dynamic,explicit
,2.0E-02
*elset,elset=cap1,generate

```

```
50001,50024
*elset,elset=ring,generate
50049,50052
50053,50056
50057,50060
50061,50064
50113,50116
50117,50120
50121,50124
50125,50128
*surface definition,name=asurf,no thick
cap1,sneg
ring,spos
*contact node set,name=bsurf,generate
9305,9313
9913,9917
9937,9941
9961,9965
9985,9989
10009,10013
10033,10037
10057,10061
10081,10085
10105,10109
*surface definition,name=csurf,no thick
cap1,spos
*contact node set,name=dsurf,generate
50355,50359
50410,50413
50608,50610
50487,50493
50641,50647
50564,50567
50454,50456
*contact pair
asurf,bsurf
csurf,dsurf
*history output,time=0.0
*nset,nset=cg
50087,50091,50158
*node history,nset=cg
u,v,a
*monitor,node=50087,dof=2
*end step
```

Figure 10

DRAWING PROGRAM

FIG. 1.0-1

ABAQUS

Fig 2.0-1

ABAQUS

Fig. 2.0-2

ABAQUS

Fig. 3.1-1

ABAQUS

Fig 3.1-2

Fig 3.1-3

Fig 3.1-4

ABAQUS

Fig 3.2-1

ABQUS

Fig 3.2-2