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SUMMARY AND EVALUATION OF STEEL BILLET TESTING*

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ABSTRACT

Tests were performed at Sandia National Laboratories (SNL) and Lawrence Livermore National Laboratory (LLNL) to assess loading conditions on a spent fuel storage cask for end drops, side drops and tipover events. The tests were performed with a 1/3-scale model billet and a 1/3-scale model concrete pad, and included a variety of substrate materials. A NUREG/CR report was prepared for the Nuclear Regulatory Commission (NRC) and provides a summary and an evaluation of all the billet testing conducted. This paper provides a description of the testing and analysis method, and a summary of the results.

A “generic” or representative cask was modeled with the benchmarked finite element analysis approach and evaluated for ISFSI end and side drops and tipover events. The analytical method can be applied to similar casks to estimate deceleration loads on storage casks resulting from low-velocity drop or tipover impacts onto concrete storage pads.

1. INTRODUCTION

The Nuclear Regulatory Commission (NRC) has conducted several series of drop-test studies to develop data suitable for benchmarking impact analyses. The drop tests involved the use of a solid steel billet, roughly a 1/3-scale model of a spent fuel storage cask (the linear dimension was scaled). The billet was dropped in various orientations onto a variety of surfaces. Data were collected, a summary of the testing and of the results is provided in Reference 1.

The first series, performed in March 1993 by Sandia National Laboratories (SNL), involved five end-drops of a solid steel billet, nominally 50.8 cm (20 inches) in diameter and 1.83 m (72 inches) long, onto pads of various stiffnesses from a height of 45.7 cm (18 inches). The second series of tests, performed between July and October 1993, involved four end-drops of a near-full-scale empty Excellox 3A cask onto a full-scale concrete pad and foundation, and onto an essentially unyielding surface, from heights ranging from

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45.7 cm (18 inches) to 1.52 m (60 inches). These tests were conducted by British Nuclear Fuels Limited in Winfrith, England. (Two of the drops in the second series were sponsored jointly by Electric Power Research Institute and several storage cask user groups, vendors, and utilities.)[*] The third test series, performed in September 1993 by SNL, involved eight additional end-drop tests of the billet onto concrete pads. These pads were cast either on engineered fill or on undisturbed soil; the billet was dropped from heights ranging from 45.7 cm (18 inches) to 1.83 m (6 feet). The first three series of tests are described in Reference 2.

The fourth test series included twelve drops onto reinforced concrete pads resting on undisturbed soil. This series was conducted by Lawrence Livermore National Laboratory (LLNL) in February 1996. Results and a preliminary evaluation of the side and tipover results from the fourth test series are provided in two reports[3,4] published by LLNL.

The purpose of these tests was, in part, to characterize the effect of various foundation stiffnesses on the deceleration of the billet. In addition, the effects of side drops, end drops, and tipover events on the deceleration of the billet were characterized. The tests also provided data for benchmarking finite element models.

2. EVALUATION OF TEST DATA

One characteristic of impact testing is the presence of vibratory motions or stress waves within the test article which are superimposed upon the rigid body deceleration, giving a high indication of the peak rigid body deceleration. To remove this vibratory component of the data, the raw accelerometer data described above were filtered at an appropriate frequency such that the remaining deceleration represented the rigid body motion of the billet.

Figures 1 and 2 depict the location of the accelerometers for each drop configuration. The tests and mean acceleration results are summarized in Tables 1 through 5.

3. GENERAL DESCRIPTION OF THE FINITE ELEMENT MODEL REPRESENTATION OF BILLET DROP TESTING

A finite element model of the steel billet, concrete pad, and the subgrade soil was constructed using the TrueGrid[5] mesh generator. The billet end and side impacts were simulated by imposing a uniform initial velocity on the billet; the tipover is simulated by applying an initial angular velocity to the billet.

3.1 Steel Billet Material Representation

The material of the test billet was ASTM 576 Grade 1045 steel, with a tensile strength of 6.69×10^5 kPa (97 ksi) and a yield strength of 4.14×10^5 kPa to 4.62×10^5 kPa (60 to 67 ksi), as specified by the supplier. The material can be represented by a perfectly elastic model with

$E = 2.0685 \times 10^8$ kPa (30.0×10^6 psi). Young's modulus
$\upsilon = 0.29$, Poisson's ratio
density = 7819 kg/m^3 (488 lb/ft^3)

3.2 Subgrade Soil Representation

Soil properties vary widely from site to site; therefore, selecting a soil model to cover most situations is difficult. In light of this uncertainty, a simple elastic model was chosen to represent the subgrade soil.

A perfectly elastic soil model with

$E = 4.1 \times 10^4$ kPa (6 ksi)
$\upsilon = 0.45$
$\rho = 2179$ kg/m^3 (136 lb/ft^3)

was selected as most representative of the properties of the Livermore drop test site due to the saturated nature of the sandy clay ground during the testing in Livermore.

3.3 Concrete Representation

The concrete pad is modeled using a constitutive model based on a concrete which was developed by LLNL for the Shippingport Station Decommissioning Project in 1988.[6] The model was developed for the concrete fill in the reactor pressure vessel/neutron shield tank. At the time that the model was developed, Stanford Research Institute was contracted to measure the required properties of samples of the particular concrete grout used in the Shippingport project. Because the average compressive strengths of the Shippingport concrete grout and the concrete pads for this drop test study were similar, a modification to the Shippingport concrete model was used for the drop test concrete pad. In the present simulation, no steel reinforcement has been explicitly modeled even though the pads did in fact contain reinforcing steel. The model was judged to behave satisfactorily.

3.4 Steel Billet Impact Finite Element Simulation Results

The analysis results for the steel billet impact simulation include the response calculated by the finite element code at each calculational time step (3.7×10^{-6} seconds). The analysis results were filtered using the same filtering technique used for the test results, an eighth-order Butterworth low-pass filter with a cutoff frequency of 450 Hz. Both analysis data and test data were processed using DADiSP 4.0.[7] A comparison of the test and analysis results is depicted graphically in Figure 3 for the side drops.

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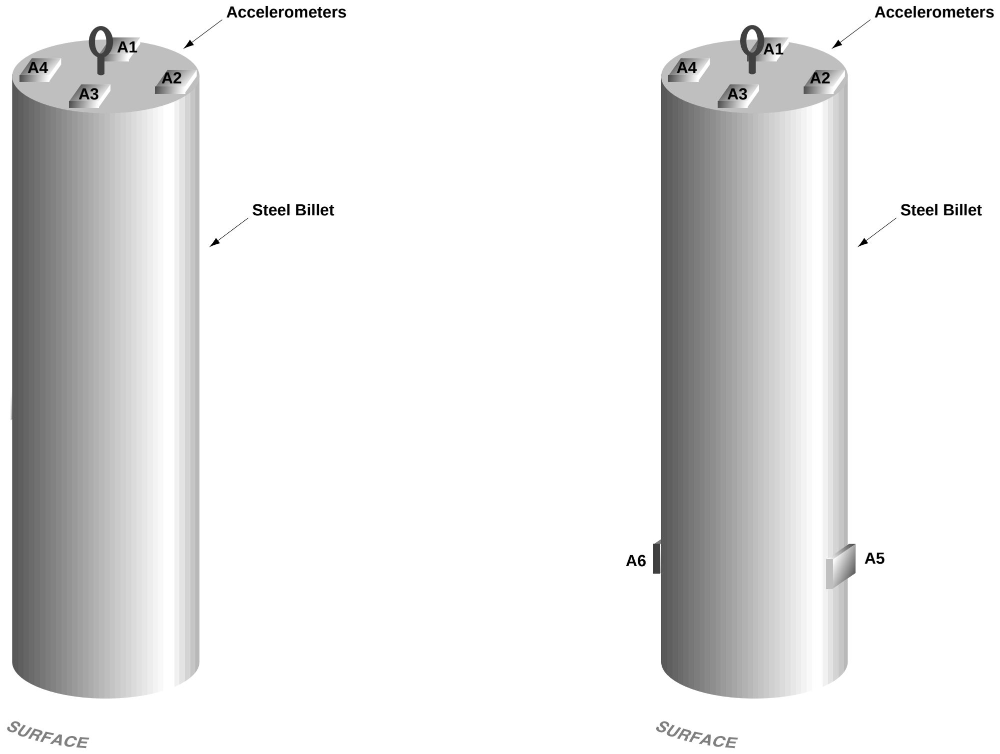
[*] Note: The second series of tests is not discussed in this report.

Table 1. Series 1 SNL Billet Drop Tests

Test Location/ Date	Test ID	Pad Dimensions	Soil/ engineered fill	Rebar	Drop Height	Mean Acceleration* (g's)
SNL/ March 1993	#166	N/A	unyielding surface	N/A	45.7 cm (18")	226.8
SNL/ March 1993	#167	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	pad on unyielding surface	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	191.7
SNL/ March 1993	#168	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	pad on 0.3m (1') fill on unyielding surface	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	207.4
SNL/ March 1993	#169	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	unknown soil A / 0.3m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	116.3
SNL/ March 1993	#170	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1') (reused the pad from test #169)	unknown soil A / 0.3m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	117.7

* Calculated for those accelerometers located on billet upper end.



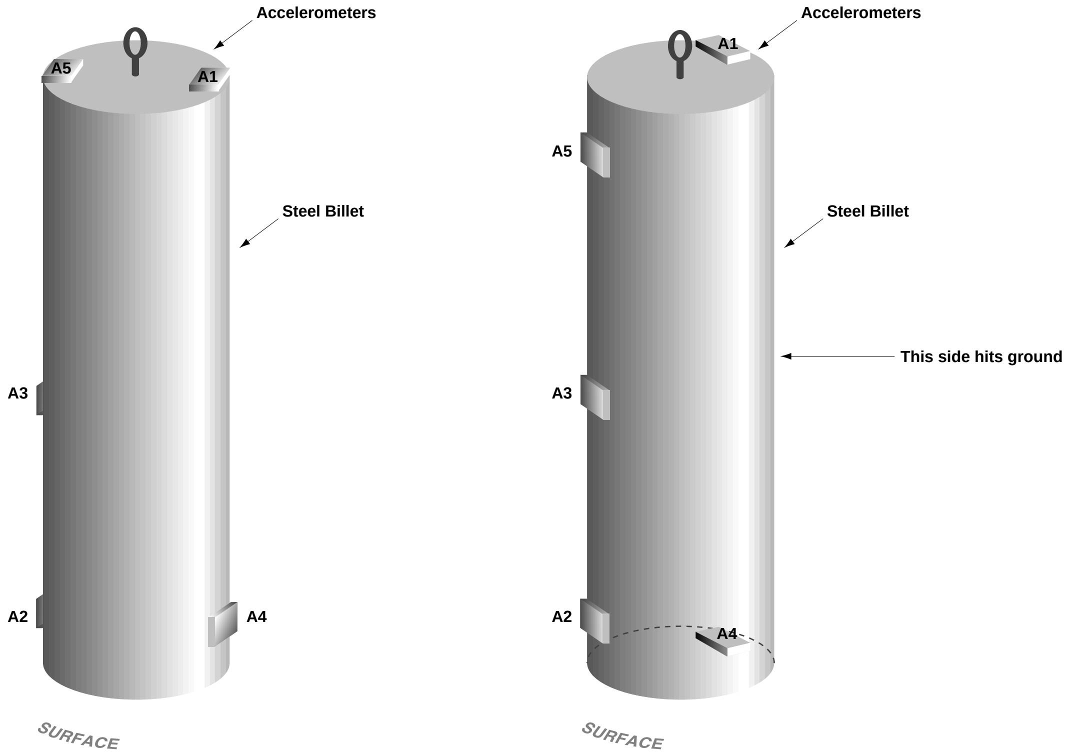
(a) SNL Series 1 End Drop Tests **(b) SNL Series 3 End Drop Tests**

Figure 1. Accelerometer Locations for SNL End Drop Tests

Table 2. Series 3 SNL Billet Drop Tests

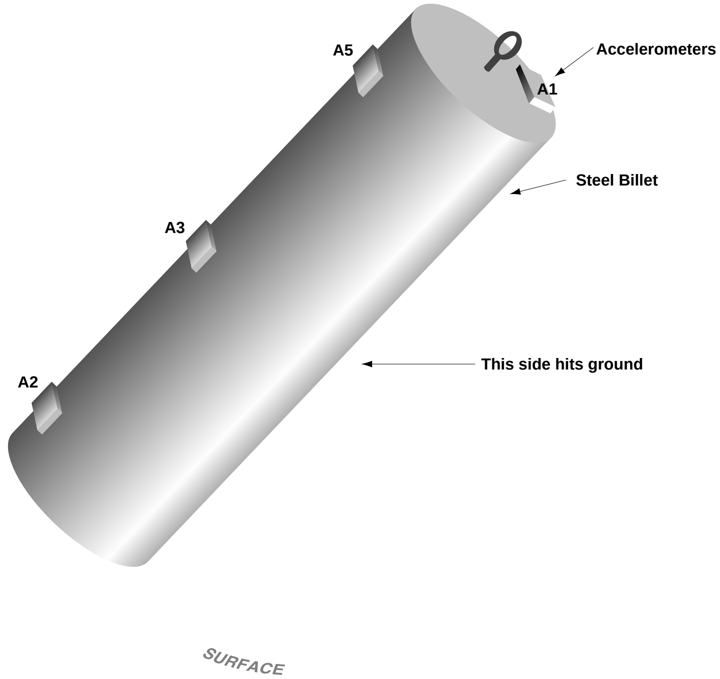
Test Location / Date	Test ID	Pad Dimensions	Soil / engineered fill	Rebar	Drop Height	Mean Acceleration* (g's)
SNL / Sept. 1993	#226, 1-A	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	unknown soil B / 0.3 m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	118.4
SNL / Sept. 1993	#228, 2-B	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	unknown soil B / 0.3 m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	135.3
SNL / Sept. 1993	#229, 3-C	1.83 m × 1.83 m × 0.23 m (6' × 6' × 9”)	unknown soil B / 0.3 m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	112.4
SNL / Sept. 1993	#230, 4-D	1.83 m × 1.83 m × 45.7 cm (6' × 6' × 18”)	unknown soil B / 0.3 m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	160.7
SNL / Sept. 1993	#231, 5-E	3 m × 3 m × 0.3 m (10' × 10' × 1')	unknown soil B / 0.3 m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	128.7
SNL / Sept. 1993	#232, 6-A	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	unknown soil B, (pad on grade)	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	45.7 cm (18")	88.7
SNL / Sept. 1993	#233, 8-A	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	unknown soil B / 0.3 m (1') fill	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	1.83 m (72")	205.9
SNL / Sept. 1993	#234, 9-A	1.83 m × 1.83 m × 0.3 m (6' × 6' × 1')	unknown soil B, (pad on grade)	#3 on 45.7 cm (18") centers (yield strength = 4.14×10^5 kPa (60 ksi))	1.83 m (72")	134.7

* Calculated for those accelerometers located on billet upper end.



(a) LLNL End Drop Tests

(b) LLNL Side Drop Tests



(c) LLNL Tipover Tests

Figure 2. Accelerometer Locations for LLNL Tests

Table 3. LLNL End Drop Billet Tests

Test Location / Date	Test ID	Pad Dimensions	Soil / engineered fill	Rebar	Drop Height	Mean Acceleration * (g's)
LLNL / Feb. 1996	#1	3m × 3m × 0.3m (10' × 10' × 1')	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	45.7 cm (18")	87.8
LLNL / Feb. 1996	#2	3m × 3m × 0.3m (10' × 10' × 1') (reused the pad from test #1)	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	45.7 cm (18")	83.3

* Calculated for those accelerometers located on billet upper end.

Table 4. LLNL Side Drop Billet Tests

Test Location / Date	Test ID	Pad Dimensions	Soil / engineered fill	Rebar	Drop Height	Acceleration at A3 (g's)
LLNL / Feb. 1996	#3	3 m × 3 m × 0.3 m (10' × 10' × 1')	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	45.7 cm (18")	108.2
LLNL / Feb. 1996	#5	3 m × 3 m × 0.3 m (10' × 10' × 1')	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	45.7 cm (18")	110.0
LLNL / Feb. 1996	#10	3 m × 3 m × 0.3 m (10' × 10' × 1') (reused the pad from test #9)	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	45.7 cm (18")	86.0
LLNL / Feb. 1996	#4	3 m × 3 m × 0.3 m (10' × 10' × 1') (reused the pad from test #3)	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	91.4 cm (36")	206.7
LLNL / Feb. 1996	#7	3 m × 3 m × 0.3 m (10' × 10' × 1')	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	91.4 cm (36")	accelerometer did not function
LLNL / Feb. 1996	#9	3 m × 3 m × 0.3 m (10' × 10' × 1')	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	91.4 cm (36")	197.0
LLNL / Feb. 1996	#6	3 m × 3 m × 0.3 m (10' × 10' × 1') (reused the pad from test #5)	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	1.83 m (72")	125.2
LLNL / Feb. 1996	#8	3 m × 3 m × 0.3 m (10' × 10' × 1') (reused the pad from test #7)	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	1.83 m (72")	125.5

Table 5. LLNL Billet Tipover Tests

Test Location / Date	Test ID	Pad Dimensions	Soil / engineered fill	Rebar	Drop Height	Acceleration at A5 (g's)
LLNL / Feb. 1996	#11	3 m × 3 m × 0.3 m (10' × 10' × 1')	approximately known soil C	#3 on 45.7 cm (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	tip	231.5
LLNL / Feb. 1996	#12	3 m × 3 m × 0.3 m (10' × 10' × 1') (reused the pad from test #11)	approximately known soil C	#3 on 45.7 (18") centers (yield strength = 4.14 × 10^5 kPa (60 ksi))	tip	213.0

It can be seen from SNL tests #226, 229, and 230 that the concrete pad thickness affects the deceleration, as expected.

The SNL tests included a variety of substrate materials, including an unyielding surface and soil with or without engineered fill above it. Details on the engineered fill are limited. The effect of the thirty centimeters of fill was to increase the deceleration of the cask by roughly 33 and 53 percent in two cases.

Again, limited test data are available to measure the effect of the drop height on the deceleration results for the end drop cases, since only two drop heights were tested. Nevertheless, the trend of the results is the expected one—as the drop height is increased, the deceleration increases.

Although no tests had identical configurations at SNL and LLNL, one SNL end drop test is similar to the two LLNL end drop tests. This is SNL test #232, an 45.7-m (18-inch) end drop onto a 1.83 m × 1.83 m × 0.3 m (6' × 6' × 1') thick concrete pad, without fill. The only differences between this test and LLNL tests #1 and #2 are that the SNL concrete pad is smaller than the LLNL pad, which was 3 m × 3 m × 0.3 m (10' × 10' × 1') thick, and the test was conducted in a different location with therefore different soil. Nevertheless, the decelerations are very comparable, with the SNL average for test #232 at 88.7 g's, and the LLNL averages at 87.8 g's and 83.3 g's for LLNL tests #1 and #2, respectively.

4. FULL SIZE "GENERIC" STORAGE CASK FINITE ELEMENT SIMULATIONS

4.1 Selection and Modeling of "Generic" Cask

A storage cask using representative dimensions, material properties, and cask weight was selected for this study. The cask selected is referred to in this report as a "generic" cask; the finite element model for this cask is shown in Figure 4.

The "generic" storage cask end and side drops and tipover were simulated with the DYNA3D[8] finite element code using the concrete and soil material property representations described for the billet model above. Only the essential structural members of the cask are included in the model. Components such as trunions and an external neutron shield are neglected. The basket structure and fuel assemblies are modeled as a solid cylinder in the region within the cask cavity occupied by fuel. The weight distribution of the cylinder representing the basket structure is representative of a typical basket with fuel assemblies. The stiffness of the cylinder is set at E = 1.9 × 10^7 kPa (2.8 × 10^6 psi) to reflect the flexible nature of the basket structure. As can be seen in Figure 4, the basket is modeled in sections to facilitate data reduction at various locations along the basket length.

The cask tipover impact is simulated with DYNA3D by imposing an angular velocity of 1.729 radians/sec (the angular velocity associated with a center-of-gravity over corner tip condition) to the entire cask body. The center of rotation is set at the edge of the cask bottom. DYNA3D calculates the initial velocity components associated with each node for this rotational motion.

4.2 Finite Element End Drop, Side Drop, and Tipover Simulation Results

The maximum rigid body decelerations are obtained from the simulations for end and side drops and tipover of the "generic" cask. The analysis results from these simulations have been filtered in a manner similar to the billet data filtering process, and are provided in Table 6. The cutoff frequency for filtering the generic cask analysis results was set at 350 Hz based on a review of the significant vibration response in the Fourier spectrum.

5. APPLICATION OF METHODOLOGY

In order to use the test data provided in References 2 and 3 to evaluate impact loads for a full-size storage cask, a series of steps needs to be taken. A brief summary is given here.

Step 1: Rigid Body Motion of Billet Tests. The accelerometer data collected and reported in References 2 and 3 include unfiltered data for 25 tests. The data must be filtered at an appropriate frequency to remove the vibratory components in the data such that the remaining deceleration represents the rigid body motion of the billet. A filter frequency of 450 Hz was used.

Step 2: Finite Element Model Representation of Billet Tests. The data collected and filtered in Step 1 are then used to determine the response characteristics of the billet-pad-soil interaction system during impact in order to develop a material model of the concrete pad for analysis of low-velocity impact conditions. This task involves developing a finite element model of the billet and pad to be used in a series of dynamic analyses simulating the billet test conditions. Based on the series of simulations, a model of the test condition is developed which characterizes the parameter of primary interest, that is, the rigid body g-loads corresponding to those determined in Step 1.

Step 3: Full-Size Storage Cask End Drop, Side Drop, and Tipover Finite Element Simulations. The constitutive model of the concrete pad and soil system developed for the finite element analysis in Step 2 is then utilized in a finite element simulation of a full-scale "generic" cask dropping onto a typical concrete storage pad.

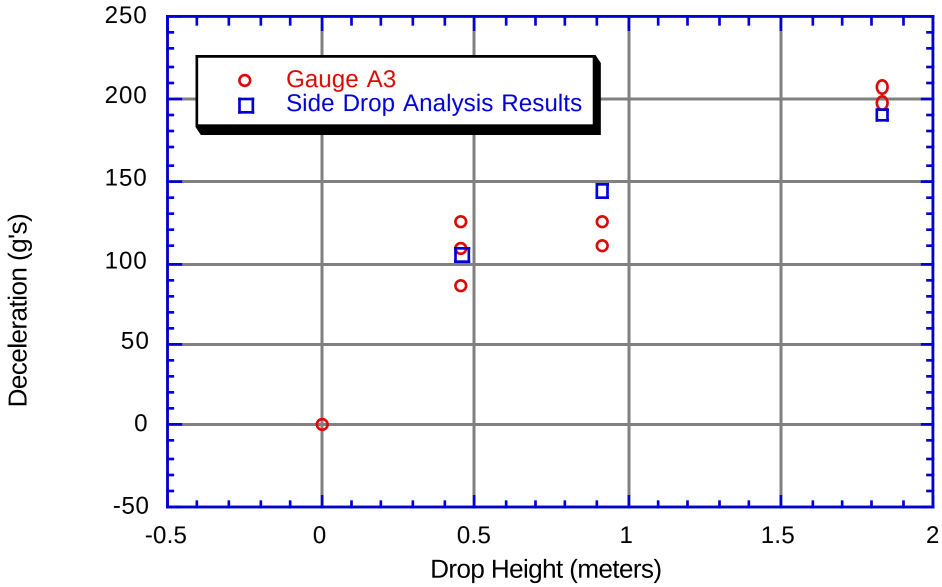


Figure 3. Comparison of Analysis and Test Results for Billet Side Drops

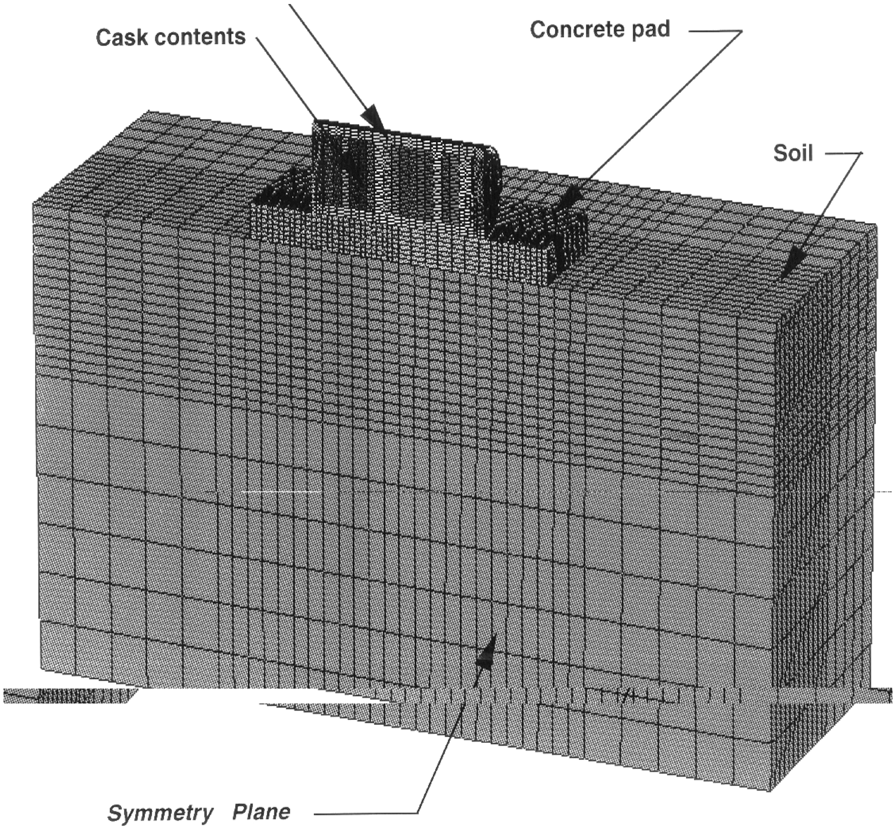


Figure 4. Finite Element Model of "Generic" Storage Cask, Side Drop and Tipover Onto Concrete Pad and Soil

Table 6. ISFSI Generic Cask End Drop, Side Drop, and Tipover Analysis Results

	Finite element analysis simulation, filtered at 350 Hz	Location of reported g's
45.7 cm (18") End Drop	47.3	Averaged through the cask wall
45.7 cm (18") Side Drop	23.2	Averaged through the cask wall
91.4 cm (36") Side Drop	36.5	Averaged through the cask wall
1.83 m (72") Side Drop	54.8	Averaged through the cask wall
3.66 m (144") Side Drop*	65.3	Averaged through the cask wall
	75.8	Averaged through the cask lid
Tipover	73.2	Averaged through the cask lid

6. SUMMARY AND CONCLUSIONS

Tests were performed at SNL and LLNL to assess loading conditions on a spent fuel storage cask for end drops, side drops and tipover events. The tests were performed with a 1/3-scale model billet and a 1/3-scale model concrete pad, and included a variety of substrate materials. A NUREG/CR report (Reference 1) was prepared for the NRC and provides a summary and an evaluation of all of the billet testing conducted. This paper provides a description of the testing and analysis, and a summary of the results.

A "generic" or representative cask was modeled with the benchmarked finite element analysis approach and evaluated for ISFSI end and side drops and tipover events. The analytical method can be applied to similar casks to estimate deceleration loads on storage casks resulting from low-velocity drop or tipover impacts onto concrete storage pads.

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