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IMPACT ANALYSIS OF SPENT FUEL DRY CASKS UNDER ACCIDENTAL DROP SCENARIOS

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ABSTRACT

A series of analyses were performed to assess the structural response of spent nuclear fuel dry casks subjected to various handling and on-site transfer events. The results of these analyses are being used by the Nuclear Regulatory Commission (NRC) to perform a probabilistic risk assessment (PRA). Although the PRA study is being performed for a specific nuclear plant, the PRA study is also intended to provide a framework for a general methodology that could also be applied to other dry cask systems at other nuclear plants.

The dry cask system consists of a transfer cask, used for handling and moving the multi-purpose canister (MPC) that contains the fuel, and a storage cask, used to store the MPC and fuel on a concrete pad at the site. This paper describes the analyses of the casks for two loading events. The first loading consists of dropping the transfer cask while it is lowered by a crane to a concrete floor at ground elevation. The second loading consists of dropping the storage cask while it is being transferred to the concrete storage pad outdoors.

Three dimensional finite element models of the transfer cask and storage cask, containing the MPC and fuel, were utilized to perform the drop analyses. These models were combined with finite element models of the target structures being impacted. The transfer cask drop analyses considered various drop heights for the cask impacting the reinforced concrete floor at ground level. The finite element model of the target included a section of the concrete floor and concrete wall supporting the floor. The storage cask drop analyses evaluated a 30.5 cm (12 in.) drop of the cask impacting three different surfaces: reinforced concrete, asphalt, and gravel.

KEY WORDS: impact analysis, drop analysis, spent fuel, dry cask, finite element model, nonlinear, dynamic, transfer cask, storage cask.

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) is currently performing a probabilistic risk assessment (PRA) for storing spent nuclear fuel in dry casks at nuclear power plants. Input to the PRA study was needed regarding the structural response of a dry cask storage system subjected to various mechanical loads. Evaluations of the casks were required for accidental loading events resulting from the handling, on-site transfer, and on-site storage of the cask system, and the effects of natural phenomena such as wind, flood, and earthquake. Initially simplified analyses were performed for all of these loading events. On the basis of these prior analyses, it was determined that more detailed analyses were warranted for certain loading events in order to obtain more realistic results. This paper describes the analyses performed on a spent nuclear fuel transfer cask and storage cask subjected to two loading events identified as requiring more detailed evaluation.

2 PURPOSE

The purpose of this study is to perform nonlinear impact analyses of a spent nuclear fuel cask system. The specific loading events analyzed were (1) a drop of the HI-TRAC transfer cask from various heights up to 30.5 m (100 ft) onto a concrete floor and (2) a 30.5 cm (1 ft) drop of the HI-STORM storage cask onto a concrete pad, asphalt surface, and gravel surface.

3 APPROACH

Existing computer models of the HI-TRAC transfer cask and HI-STORM storage cask, containing the sealed multi-purpose canister (MPC) and fuel, were utilized to perform the various drop analyses. These models were obtained from Holtec International (cask vendor) and were combined with newly developed finite element models of the various targets. A number of different load cases were analyzed for the transfer cask drop and the storage cask drop accidents. For the transfer cask drop case, a vertical drop and horizontal drop of the HI-TRAC cask onto the concrete floor were evaluated. For the storage cask drop case, a vertical drop of the HI-STORM cask onto three types of surfaces (concrete, asphalt, and gravel) were evaluated.

The LS-DYNA [1] computer code was used to perform the nonlinear impact analyses. LS-DYNA is a general purpose finite element code for analyzing the large deformation dynamic response of structures. The main solution methodology is based on explicit time integration. The program is particularly suited to analyze complex impact type problems. LS-DYNA is the same program utilized by Holtec in developing the HI-TRAC and HI-STORM cask models and used by Holtec to obtain NRC certification of the HI-STORM Cask System.

4 ANALYTICAL MODELS

4.1 HI-TRAC Transfer Cask Drop on a Concrete Floor

The HI-TRAC model used in this analytical study is the 125 ton HI-TRAC transfer cask, loaded with the MPC-68 full of fuel, and with the bottom transfer lid in place. The transfer cask outside diameter is 2.39 m (94 in.) and the height is 5.12 m (201 1/2 in.). The transfer cask, fully loaded with the MPC and fuel, weighs approximately 110,200 kg (243,000 lb). The cask is constructed using inner and outer cylindrical stainless steel shells, filled with lead shielding material in the annular space between the shells. The target that the cask impacts is a reinforced concrete floor supported by a wall beneath the floor. Due to symmetry in a vertical plane, a half model representation of the HI-TRAC cask containing the MPC and fuel, concrete floor, and concrete wall beneath the floor was developed. The concrete floor model dimensions are 3.96 m x 17.2 m x 0.61 m thick (156 in. x 678 in. x 24 in.). The concrete wall model is 13.1 m x 17.2 m x 0.381 m thick (516 in. x 678 in. x 15 in.). The concrete compressive strength is 29.0 MPa (4,200 psi). Appropriate boundary conditions were applied to the concrete floor and wall to represent the support provided by the adjacent shear walls and foundation mat.

The HI-TRAC transfer cask model received from Holtec represented the MPC and fuel as a single region which was modeled using equivalent solid elements. The model does not include a separate shell for the MPC. Therefore, for the vertical end drop case, a series of vertical "truss elements" were added to represent the MPC shell. This provided a means of obtaining the vertical response of the MPC directly from the LS-DYNA analysis. Some additional modifications were made to the transfer cask model to improve the accuracy for the type of impact problem being analyzed.

The LS-DYNA model of the HI-TRAC cask and concrete floor/wall used for the vertical end drop case is shown in Figures 1 and 2. For the horizontal drop case, the same HI-TRAC cask model was utilized; however, the cask model was rotated ninety degrees.

The LS-DYNA model considered the various nonlinear effects important to this type of impact problem. In addition to large deformation capability, the analytical model included many contact surfaces between the various components, such as the fuel region to MPC bottom plate and the bottom transfer lid plate to the concrete floor surface. Material nonlinear behavior was represented using an elasto-plastic material with nonlinear stress-strain curve for the steel elements. For the solid brick concrete elements, a constitutive model with concrete damage and failure capability was used.

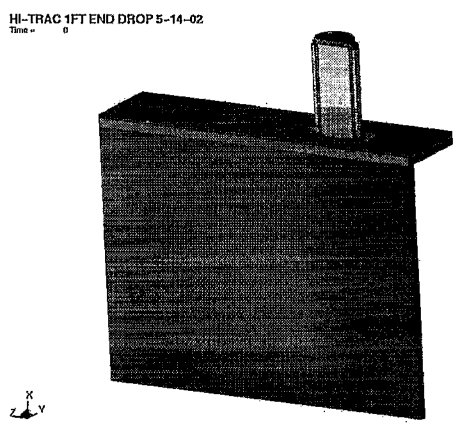

Figure 1 HI-TRAC Vertical End Drop Model With Concrete Floor/Wall

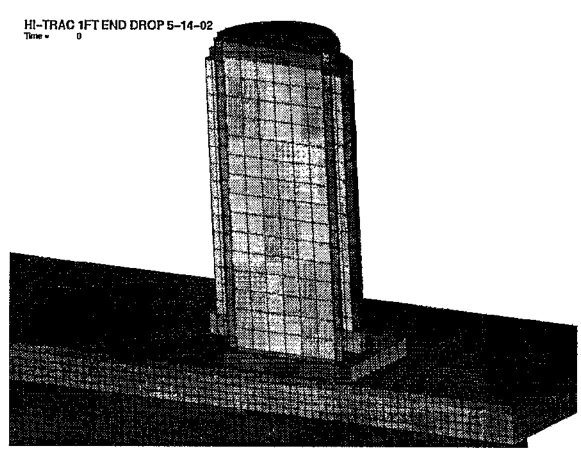

Figure 2 HI-TRAC Finite Element Model

4.2 HI-STORM Storage Cask Drop on Concrete Pad, Asphalt, and Gravel

The HI-STORM model used in this analytical study is the HI-STORM 100 storage cask loaded with the MPC-68 full of fuel. The storage cask outside diameter is 3.37 m (132 1/2 in.) and the height is 5.87 m (231 in.). The storage cask, fully loaded with the MPC and fuel, weighs approximately 163,300 kg (360,000 lb). The cask is constructed using inner and outer cylindrical stainless steel shells, filled with concrete in the annular space between the shells. The three impact surfaces that are modeled for the drop analyses are concrete, asphalt, and gravel. All of the surfaces rest on a soil sublayer. Due to symmetry in a vertical plane, a half model representation of the HI-STORM cask containing the MPC and fuel, impact surface, and underlying soil was developed.

The LS-DYNA model of the HI-STORM cask, concrete pad, and soil used for the vertical drop case is shown in Figures 3 and 4. This model was also used for the other two cases: the vertical drop onto the asphalt layer and the vertical drop onto the gravel layer. However, the thickness of the pad, material constitutive model, and material properties were modified to represent the asphalt and gravel materials at the subject facility.

The LS-DYNA model for the HI-STORM storage cask drop analyses included nonlinear effects described above for the HI-TRAC transfer drop model. However, to obtain bounding rigid body accelerations, the HI-STORM model was conservatively made rigid, making the impact target and soil the primary energy absorbing media. The Mohr-Coulomb material model was utilized for asphalt and gravel, which are defined by a friction angle and cohesion value.

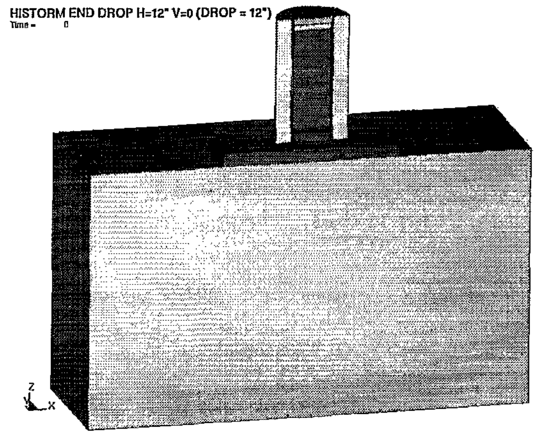

Figure 3 HI-STORM Model With Concrete Pad And Soil

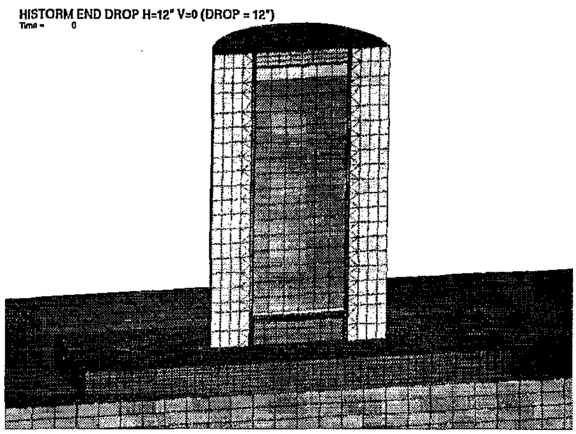

Figure 4 HI-STORM Finite Element Model

5 CASES ANALYZED

5.1 Drop of HI-TRAC Transfer Cask

This case considers the drop of the HI-TRAC cask in the reactor building while it is lowered by the crane to the concrete floor at ground elevation. Various drop heights of the cask were considered up to 30.5 m (100 ft). The drop heights selected for analysis were 0.305 m, 7.62 m, 24.4 m, and 30.5 m (1, 25, 80, and 100 ft), which permits interpolation of the results at any other drop height. Two drop orientations were analyzed for the cask impact on the concrete floor; the cask in an upright position (vertical end drop) and the cask in a horizontal orientation.

5.2 HI-STORM Storage Cask Drop on Concrete Pad, Asphalt, and Gravel

The HI-STORM storage cask is transported from the reactor building to a reinforced concrete storage pad outdoors. Therefore, three accidental drop cases of the storage cask are analyzed corresponding to the three different surfaces that the transport vehicle travels over. A drop of the storage cask onto concrete, asphalt, and gravel surfaces is analyzed. For all three cases a drop height equal to 30.5 cm (12 in.) was utilized, which corresponds to the height the storage cask is held above the ground while it is being transported from the reactor building to the reinforced concrete storage pad.

Drop Onto Reinforced Concrete Storage Pad

For this case, a 30.5 cm (12 in.) vertical end drop of the storage cask impacting a 61 cm (24 in.) thick reinforced concrete pad, resting on soil was analyzed. Three analyses were performed corresponding to the lower bound, best estimate, and upper bound elastic soil moduli, which are equal to 324 MPa, 641 MPa, and 1,579 MPa (47 ksi, 93 ksi, and 229 ksi), respectively. Poison's ratio is equal to 0.4 and the soil density is 2,003 kg/m3 (125 lbs/cubic ft).

Drop Onto Asphalt Surface

For this case, a 30.5 cm (12 in.) vertical end drop of the storage cask impacting a 30.5 cm (12 in.) thick layer of asphalt resting on soil was analyzed. Because asphalt material properties are sensitive to temperature, three loading cases were considered. The three cases correspond to material properties of asphalt at 4.4° C, 23.9° C, and 43.3° C (40° F, 75° F, and 110° F). This approximates the expected average temperature at the subject facility corresponding to winter, spring/fall, and summer. The best estimate values for the elastic modulus of asphalt are 10,342 MPa at 4.4° C (1,500 ksi at 40° F), 4,482 MPa at 23.9° C (650 ksi at 75° F), and 1,379 MPa at 43.3° C (200 ksi at 110° F).

Drop Onto Gravel Surface

Two cases were evaluated for the storage cask drop on a gravel surface: a 30.5 cm (12 in.) thick gravel layer and a 61 cm (24 in.) thick gravel layer, both resting on soil. The 61 cm (24 in.) layer corresponds to the gravel region surrounding the concrete pad where the storage casks are stored, while the 30.5 cm (12 in.) layer corresponds to the gravel region away from the concrete pad where the gravel layer tapers to smaller thicknesses.

Since precise information for the gravel material at the subject plant was not known, the properties for the gravel layer were determined from a literature review of available information on "well graded" crushed stone aggregate. A value of 345 MPa (50 ksi) for the elastic modulus was selected as the best estimate value. To gauge the effect of varying the modulus of the gravel material, an analysis was performed for the best estimate value (345 MPa (50 ksi)) and for the upper bound estimate (689 MPa (100 ksi)) for the 30.5 cm (12 in.) thick gravel layer case. The upper bound value of elastic modulus is considered to be conservative because a higher modulus would result in higher impact forces and accelerations.

6 ANALYTICAL RESULTS

The primary results of interest for the various drop cases analyzed are the maximum accelerations of the MPC and fuel, the maximum stresses/strains in the MPC, and relative deformations between the MPC and the HI-TRAC or the HI-STORM cask. It is acceptable for the MPC, HI-TRAC or HI-STORM casks to undergo permanent deformation, provided that the MPC maintains leaktight integrity.

6.1 Drop of HI-TRAC Transfer Cask

Vertical End Drop Onto Concrete Floor

The structural response of the MPC for the vertical end drop of the HI-TRAC transfer cask onto the concrete floor is summarized in Table 1. For each drop height, the MPC maximum acceleration corresponding to the top of the MPC is presented. The maximum axial stress in the MPC is shown in the next column followed by the maximum axial strain. The maximum acceleration of the fuel is also provided.

Table 1. HI-TRAC Drop Analyses

HI-TRAC Drop Orientation	Drop Height (ft)	Multi- Purpose Canister (MPC)			Fuel
		Max Acceleration (g)	[1] Max Stress (ksi)	[1] Max Strain (%)	[2] Max Acceleration (g)
Vertical End Drop	1	56.9	7.47	0.03	38.8 x DLF[3]
	25	170	20.7	0.7	149 x DLF[3]
	80	177.8	21.8	1.6	190 x DLF[3]
	100	178.2	22.2	2.0	198 x DLF[3]
Horizontal Drop	1	37	> yield	0.47	37
	25	122	> yield	3	122
	80	230	> yield	3	230
	100	264	> yield	3	264

Note: 1 ft = 30.48 cm; 1 ksi = 6.895 MPa

1. Maximum stresses & strains:
   End drop case - are based on maximum axial forces at the bottom of the MPC.
   Horizontal case - stresses are principal stresses and strains are effective plastic strain based on HI-TRAC inner shell.
2. Accelerations are based on combined MPC/fuel model.
3. All fuel accelerations must be multiplied by the appropriate dynamic load factor (a maximum of 1.52).

The maximum acceleration of the MPC is 56.9 g, 170 g, 177.8 g, and 178.2 g, corresponding to the 0.305 m, 7.62 m, 24.4 m, and 30.5 m (1, 25, 80, and 100 ft) drop heights. A representative plot of the MPC maximum acceleration time history for the 7.62 m (25 ft) drop height is presented in Figure 5. As expected, with increasing drop heights the acceleration increases; however, the relationship is nonlinear. This occurs because the structural properties of the MPC and other HI-TRAC members are nonlinear and some of these members deform into the plastic region. The MPC shell deformed into the plastic region at approximately the 7.62 m (25 ft) drop height. Once the MPC deforms into the plastic region, its acceleration will not increase significantly as the drop height is increased; however, the plastic strain will continue to grow.

The maximum axial stress in the MPC for the 0.305 m (1 ft) drop is 51.5 MPa (7.47 ksi). For this drop height the MPC remains in the elastic range of the material property. For drop heights of 7.62 m (25 ft) and greater, the stress exceeds the yield stress of the MPC shell (139 MPa (20.1 ksi) at 232° C (450° F)). However, the stress is well below the ultimate stress value of 441 MPa (64.0 ksi) for the type of stainless steel material used for the MPC shell. A plot of the force time history for the 7.62 m (25 ft) drop height is presented in Figure 6.

The maximum total strain in the MPC shell is 0.03% for the 0.305 m (1 ft) drop and rises to 2.0% strain for the 30.5 m (100 ft) drop. The maximum strain of 2.0% is well below the 40% ultimate strain limit typical for the MPC stainless steel material.

The relative deformation between the HI-TRAC top lid and the top of the MPC was reviewed to ensure that there is no contact/impact between the HI-TRAC and the MPC. A review of the relative displacement, throughout the time history for the 30.5 m (100 ft) drop (worst) case, demonstrated that a gap is maintained, and therefore, the HI-TRAC top lid does not impact the top of the MPC.

For the vertical drop case, Table 1 provides the maximum vertical acceleration of the fuel corresponding to various drop heights of the cask. Because the fuel was modeled as a rigid region (i.e., with no flexibility), there is the possibility of dynamic amplification. If elastic response is assumed, an upper bound estimate of the DLF, to be applied to the tabulated fuel accelerations in Table 1, is 1.52. This is based on the maximum DLF for a one degree-of-freedom system subjected to a triangular load pulse, as documented in standard texts on structural dynamics [2]. If the fuel region is modeled more realistically in a future model refinement, the maximum acceleration can be obtained directly from the fuel finite elements. This would be expected to significantly reduce the maximum acceleration response of the fuel.

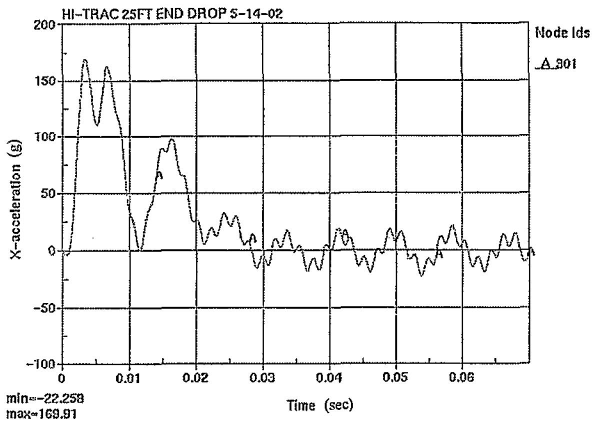

Figure 5 MPC Acceleration Time History
7.62 m (25 Ft) Vertical Drop On Concrete Floor

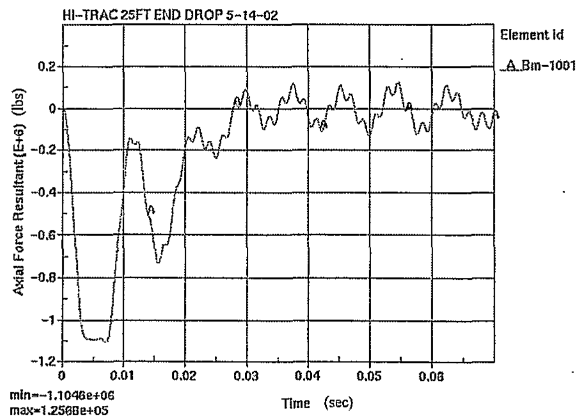

Figure 6 MPC Force Time History
7.62 m (25 Ft) Vertical Drop On Concrete Floor

<u>Horizontal Drop Onto the Concrete Floor</u>

The structural response of the MPC for the horizontal drop of the HI-TRAC cask onto the concrete floor is also summarized in Table 1. For each drop height, the MPC/fuel maximum acceleration from the time history is presented. This acceleration corresponds to the maximum predicted acceleration obtained from the bottom, middle, or top of the MPC/fuel region.

As indicated in Table 1, the maximum acceleration of the MPC/fuel is 37 g, 122 g, 230 g, and 264 g, corresponding to the 0.305 m, 7.62 m, 24.4 m, and 30.5 m (1, 25, 80, and 100 ft) drop heights. Unlike the vertical drop case, a DLF is not required for the horizontal drop because the MPC/fuel region was modeled using equivalent solid elements (i.e., were not modeled as a rigid region). As expected, with increasing drop heights the acceleration increases; however, the relationship is nonlinear. As in the vertical end drop case, this occurs because the structural properties of the HI-TRAC members are nonlinear and some of these members deform into the plastic region.

As described earlier, the HI-TRAC model obtained from the cask vendor does not include the MPC as a separate discrete shell. To obtain an estimate of the stresses/strains in the MPC shell, the stresses and strains calculated in the HI-TRAC inner shell were utilized. This assumes that the maximum deformation of the MPC shell would correspond to the deformation of the HI-TRAC inner shell that supports the MPC.

From the LS-DYNA analysis, the maximum principal stress in the HI-TRAC inner shell was calculated to be somewhat higher than the yield point, indicating that some plastic deformation occurs. From the computer analysis, the maximum effective plastic strain in the HI-TRAC inner shell was calculated to be less than 3% for the worst case, which is well below ~40% strain limit for the HI-TRAC stainless steel material.

The deformation of the HI-TRAC inner shell relative to the MPC shell was reviewed. The maximum change in the diametrical dimension was determined at the top, bottom, and mid point along the height of the HI-TRAC inner shell. The maximum change in diametrical dimension is less than the nominal available gap. Thus, there is no permanent deformation that would cause the HI-TRAC inner shell to impinge the MPC shell.

6.2 HI-STORM Drop on Three Different Surfaces

Drop on Concrete Pad

The maximum acceleration values for the 30.5 cm (12 in.) drop of the HI-STORM cask system onto the 61 cm (24 in.) concrete pad resting on soil are shown in Table 2. The maximum acceleration at the bottom center of the HI-STORM cask is 41.2 g's for the best estimate soil property. The acceleration time history at this location is shown in Figure 7. The acceleration time history plot is initially flat at 1.0 g for a period of time because the HI-STORM cask was dropped from a height of 30.5 cm (12 in.) above the concrete pad and then impacted the pad at about 0.248 seconds. As shown in Table 2, the variation in soil property does not have a significant effect on the maximum acceleration of the cask for the configuration and parameters defined for this load case.

Since the MPC shell was not discretely modeled, the stresses in the MPC were calculated using the stresses determined by the cask vendor from previous calculations [3] and scaling the results in proportion to the new calculated g values. Using this approach and the appropriate dynamic load factor (because the HI-STORM model was made rigid), the stresses in the MPC shell were calculated to be - 53.3 MPa (- 7,732 psi). This stress value is well below the elastic buckling stress and yield for the MPC stainless steel material.

Table 2. HI-STORM Drop Analyses

Impact Surface	Thickness of Target Layer (in.)	Elastic Soil Modulus* (ksi)	Max Acceleration (g)	Comment
Concrete	24	47	40.4	Lower bound soil property
		93	41.2	Best estimate soil property
		229	44.5	Upper bound soil property
Asphalt	12	93	25.4	Best estimate asphalt property at 4.4 °C (40 °F) and best estimate soil property
		93	23.2	Best estimate asphalt property at 23.9 °C (75 °F) and best estimate soil property
		93	Bounded by 23.9 °C (75 °F) Case	Best estimate asphalt property at 43.3 °C (110 °F) and best estimate soil property
Gravel	24	93	21.9	Best estimate gravel property and soil property
	12	93	15.8	Best estimate gravel property and soil property
			19.0	Upper bound gravel property and best estimate soil property

Note: 1 in. = 2.54 cm; 1 ksi = 6.895 MPa

* Elastic soil modulus was based on the shear modulus calculated from the shear wave velocity of the free field

Drop on Asphalt Layer

Three basic cases were evaluated corresponding to material properties of asphalt at 4.4° C, 23.9° C, and 43.3° C (40° F, 75° F, and 110° F), which approximates the expected average temperature at the subject facility corresponding to winter, spring/fall, and summer. The maximum acceleration values for a 30.5 cm (12 in.) drop of the HI-STORM cask for the 4.4° C and 23.9° C (40° F and 75° F) are shown in Table 2. The 43.3° C (110° F) drop case was not analyzed because at this high temperature, the acceleration would be lower than the 23.9° C (75° F) case.

The maximum accelerations at the bottom center of the HI-STORM cask, for the best estimate asphalt property are 25.4 g's and 23.2 g's for the 4.4° C and 23.9° C (40° F and 75° F) cases, respectively. The acceleration time history for the 4.4° C (40° F) case is shown in Figure 8.

Using the same approach described for the HI-STORM drop on concrete and the appropriate dynamic load factor, the vertical stresses in the MPC shell were calculated to be - 50.0 MPa (- 7,245 psi) and - 45.6 MPa (- 6,618 psi) for the 4.4° C and 23.9° C (40° F and 75° F) cases, respectively. Both of these stress values are well below the elastic buckling stress and yield for the MPC stainless steel material.

Drop on Gravel Layer

Two cases were analyzed corresponding to a 61 cm (24 in.) layer of gravel and a 30.5 cm (12 in.) layer of gravel. The maximum acceleration values for these two drop cases are shown in Table 2. The maximum accelerations at the bottom center of the HI-STORM cask, for the best estimate gravel property are 21.9 g's and 15.8 g's for the 61 cm and 30.5 cm (24 in. and 12 in.) gravel layer cases, respectively. As a measure of the sensitivity of the gravel material property, an upper bound case for the gravel property was performed for the 30.5 cm (12 in.) gravel layer. The maximum acceleration for this upper bound gravel property was 19.0 g's. The acceleration time history for this case (30.5 cm (12 in.), upper bound gravel property) is shown in Figure 9. This represents a 20% increase in acceleration from the best estimate gravel property.

Using the same approach described for the HI-STORM drop on concrete and the appropriate dynamic load factor, the vertical stresses in the MPC shell for the 30.5 cm (12 in.) drop case were calculated to be - 39.7 MPa (- 5,754 psi) and - 28.6 MPa (- 4,151 psi) for the 61 cm (24 in.) and 30.5 cm. (12 in.) gravel layers, respectively. Both of these stress values are well below the elastic buckling stress and yield for the MPC stainless steel material.

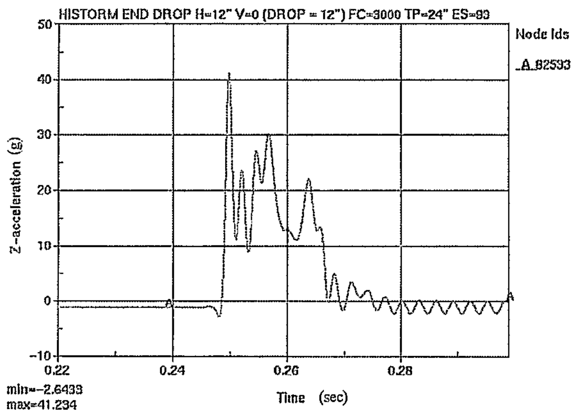

Figure 7 HI-STORM Acceleration Time History
30.5 cm (12 in.) Vertical Drop On Concrete Pad

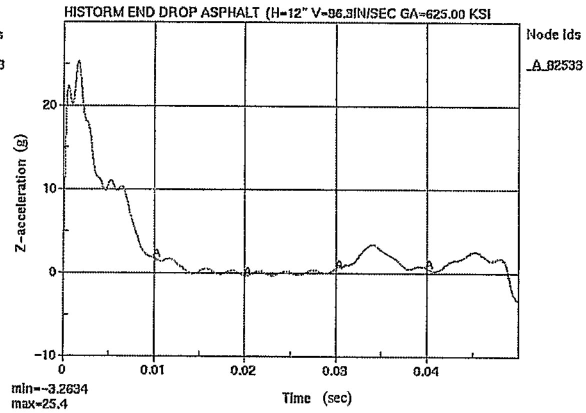

Figure 8 HI-STORM Acceleration Time History
30.5 cm (12 in.) Vertical Drop On Asphalt at 4.4° C (40° F)

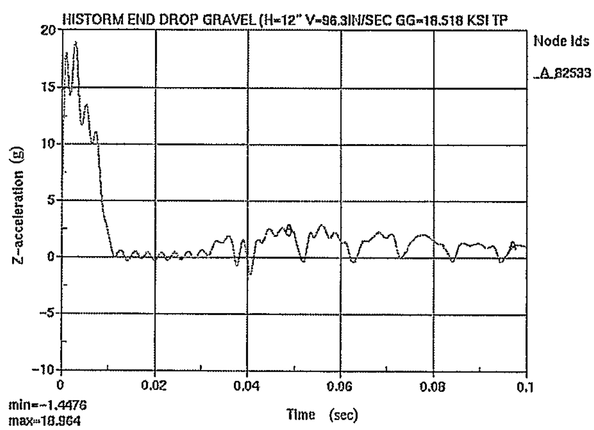

Figure 9 HI-STORM Acceleration Time History
30.5 cm (12 in.) Vertical Drop On 30.5 cm (12 in.) Gravel Layer

7 CONCLUSIONS

This study evaluated the structural response of the HI-TRAC fuel transfer cask and the HI-STORM storage cask to various drop scenarios. The analyses for the HI-TRAC transfer cask considered vertical and horizontal drop cases onto a reinforced concrete floor due to drops from various heights. For the HI-STORM storage cask drop scenarios, analyses were performed for a 30.5 cm (12 in.) drop of the cask onto three different surfaces (concrete, gravel, and asphalt). The LS-DYNA analyses and the evaluations reported herein focused on the structural adequacy of the MPC shell. In addition, the fuel response in terms of maximum acceleration was determined.

These analyses were used as input for a PRA performed by the NRC. More information on the analyses described in this paper and the entire PRA study performed by the NRC will be presented in a NUREG report that will be published later this year.

7.1 HI-TRAC Drop Cases

The analyses for the HI-TRAC end drop determined that maximum accelerations increased from 57 g's for the 0.305 m (1 ft) drop height to 178.2 g's for the 30.5 m (100 ft) drop height. The results of the vertical drop analyses demonstrate that for the 0.305 m (1 ft) drop, the vertical stresses in the MPC shell are in the elastic range (below yield) of the material. For the 7.62 m (25 ft) up to 30.5 m (100 ft) drop cases, the stresses in the MPC shell exceed yield but the strains are well below the ultimate strain value, and therefore, the materials will not rupture. In addition, the deformations between the HI-TRAC top lid and the MPC top lid remain within the available nominal gaps.

For the horizontal drop cases the MPC acceleration values are lower than the vertical drop case up to 7.62 m (25 ft). For drop heights of 24.4 m (80 ft) and higher, the acceleration values for the horizontal drop are greater than those for the vertical drop cases. For the horizontal drop cases, the stresses exceeded yield; however, the strains were well below the ultimate strain value of the MPC shell.

Although the MPC ultimate stress or strain values were not reached for any of these cases, a check on the buckling strength is recommended to determine whether it would govern the capacity of the MPC shell. Resistance to buckling is provided by the close proximity of the HI-TRAC inner shell, the fuel basket supports attached vertically to the MPC shell wall, and the fuel basket grid structure.

7.2 HI-STORM Drop Cases

The analyses for the 30.5 cm (12 in.) drop of the HI-STORM cask onto concrete, asphalt, and gravel surfaces demonstrated that the maximum acceleration occurs for the drop onto the concrete pad. The maximum acceleration for the drop on the concrete pad was 41.2 g's. The maximum compressive stress in the MPC shell due to this drop case was calculated to be - 53.3 MPa (- 7,732 psi). For the HI-STORM drop onto the asphalt layer, three temperature conditions for the asphalt were considered. The maximum vertical stress in the MPC shell was calculated to be - 50.0 MPa for the 4.4° C (- 7,245 psi for the 40° F) governing case. The results for the HI-STORM drop onto gravel show that the maximum stresses are - 39.7 MPa (- 5,754 psi) and - 28.6 MPa (- 4,151 psi) for the 61 cm (24 in.) and 30.5 cm (12 in.) gravel layers, respectively. All of the calculated stresses are well below yield and below the elastic buckling stress. Therefore, it can be concluded that the MPC shell would not fail or rupture during the 30.5 cm (12 in.) drop onto all three surfaces.

8 REFERENCES

1. LS-DYNA Computer Code and associated manuals, Version 960, March 2001, Livermore Software Technology Corporation.
2. Biggs, J.M., "Introduction to Structural Dynamics," McGraw Hill Book, Company, New York, 1964.
3. Topical Safety Analysis Report for the Holtec International Storage and Transfer Operation Reinforced Concrete Module Cask System (HI-STORM 100 Cask System), NRC Docket No. 72-1014, Holtec Report HI-951312, Volumes I and II, Revision 8, June 25, 1999.

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