ANALYSIS OF A HYPOTHETICALLY DROPPED SPENT NUCLEAR FUEL SHIPPING CASK IMPACTING A FLOOR MOUNTED CRUSH PAD[1]

Brian D. Hawkes
Evert D. Uldrich
Lockheed Martin Idaho Technologies Company, Inc.
Specialty Engineering & Sciences Department
Post Office Box 1625
Idaho Falls, Idaho 83415-3760
United States of America
(208) 526-2870, (208) 526-0425, BDH@inel.gov

ABSTRACT

A crush pad has been designed and analyzed to absorb the kinetic energy of a hypothetically dropped spent nuclear fuel shipping cask into a 44-ft. deep cask unloading pool at the Idaho Chemical Processing Plant. This facility, located at the Idaho National Engineering and Environmental Laboratory, is an U. S. Department of Energy Site.

The 110-ton Large Cell Cask was assumed to be accidentally dropped onto the parapet of the unloading pool, causing the cask to tumble through the pool water and impact the floor mounted crush pad with the cask's top corner. The crush pad contains rigid polyurethane foam, which was modeled in a separate computer analysis to simulate the manufacturer's testing of the foam and to determine the foam's stress and strain characteristics. This computer analysis verified that the foam was accurately represented in the analysis to follow. A detailed non-linear, dynamic finite element analysis was then performed on the crush pad and adjacent pool structure to assure that a drop of this massive cask does not result in unacceptable damage to the storage facility. Additionally, verification was made that the crush pad adequately protects the cask from severe impact loading. At impact, the cask has significant vertical, horizontal and rotational velocities. The crush pad absorbs much of the energy of the cask through plastic deformation during primary and secondary impacts. After the primary impact with the crush pad, the cask still has sufficient energy to rebound and rotate until it impacts the pool wall. An assessment is made of the damage to the crush pad and pool wall and of the impact loading on the cask.

INTRODUCTION

A crush pad has been designed and analyzed to absorb the kinetic energy of a hypothetically dropped spent nuclear fuel shipping cask into a 44-ft. deep cask unloading pool (Fig. 1) at the Fluorinel and Storage Facility (FAST). This facility, located at the Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering and Environmental Laboratory (INEEL), is an U. S. Department of Energy site. The basis for this study is an analysis by Uldrich and Hawkes (1997).

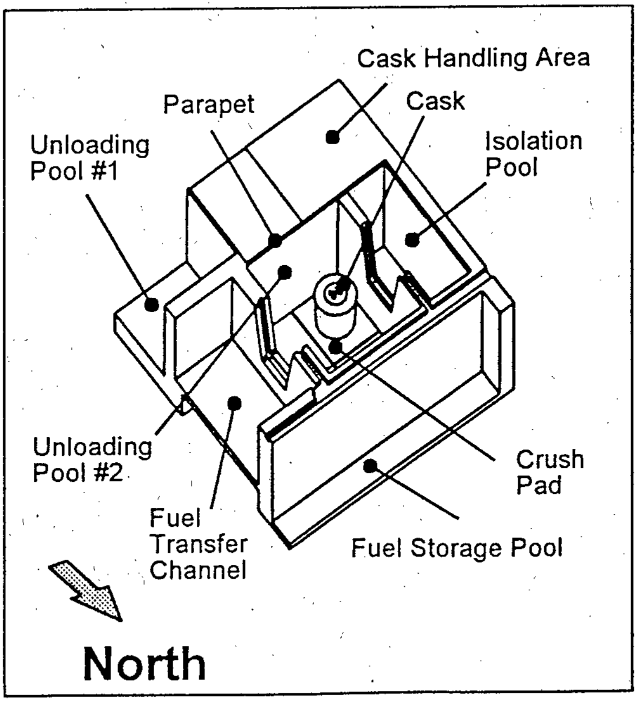

Figure 1. Overall View of the Cask Unloading Pool, the Cask and the Crush Pads

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DISCLAIMER

The purpose of this analysis was to evaluate various hypothetical cask drop scenarios to determine that: (1) the crush pad design was adequate, (2) the cask deceleration at impact was less than 100 g, and (3) the rebound of the cask into the unloading pool wall was acceptable. This analysis demonstrates that a large spent fuel, shipping cask, when dropped onto a foam crush pad, bounces and continues to rotate. The cask has sufficient energy after the initial impact with the crush pad to subsequently impact the pool wall.

ANALYTICAL PROCEDURE

The kinematics of the potential drop scenarios were evaluated using the computer code "Working Model 2D" (Knowledge Revolution, 1996). It was determined that the cask dropping onto the parapet of the unloading pool, causing the cask to tumble through the pool water and impact the floor mounted crush pad with the cask's top corner, was the most severe scenario (Fig. 2). In this portion of the analysis the cask and the parapet of the unloading pool were treated as rigid. This results in an upper bound solution. (The absorbed energy of the cask impacting the parapet is neglected.) The output from the "Working Model" analysis consisted of the vertical, horizontal and rotational velocities of the cask, the cask orientation, and the cask location at impact.

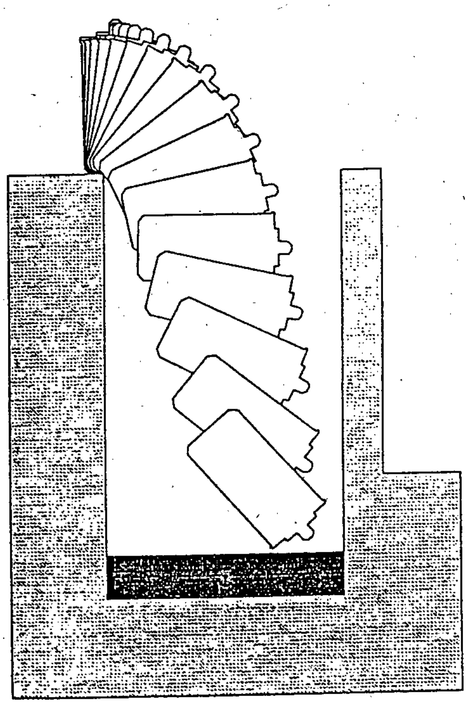

Figure 2. The Working Model sequence of the cask dropping to the parapet, tumbling into the unloading pool, and impacting the crush pad with its upper corner.

These parameters became input for dynamic analysis using the ABAQUS/Explicit (Hibbitt, Karlsson, and Sorensen, 1996) program. This analysis traced the impact of the cask into the foam crush pad, the deformation of the crush pad, the rebound of the cask upward in the pool, the continued rotation of the cask, and eventual impact of the cask into the pool wall.

DESCRIPTION OF THE POOL, CASK, AND CRUSH PAD

The cask is transported by an overhead crane at a maximum height of two feet above the concrete deck at FAST. The unloading pool is 44 ft. deep with a water depth of 42.5 ft. The foam crush pad was assumed to be 4.5 ft. thick. Therefore, the cask dropped approximately 3.5 ft. through air and 38 ft. through water. The water effect of buoyancy was included in the ABAQUS analysis. The weight of the cask was decreased by the weight of the displaced volume of water. The additional water effect of drag was neglected. Since, the cask was rotating as it passed through the water, the drag effect would have been difficult to quantify accurately. In addition, it was conservative (resulting in higher cask velocities) to neglect the drag effect.

The cask is the 110-ton Large Cell Cask (LCC). Upper and lower bound weights used in the analysis were 220,000 and 160,000 lbs. respectively. The cask has a tapered body with the diameter varying from 81.5 in. at the bottom to 83.5 in. at the top. Consequently, a cylinder with a nominal body diameter of 82.5 in. was used in the analyses along with a nominal body length of 165.5-in. (Fig. 3). The cask has a top mounted lifting lug, which protrudes 22.25 in. above the body and has a width of about 15 in. The cask also has a 7.5-in. chamfer at the bottom corner. The geometric effects of the lug and the chamfer were neglected in these analyses and the cask was always treated as a rigid body. Treating the cask as rigid was done for two reasons. First, the cask is very rigid compared to the foam crush pad and to the concrete parapet and pool wall. It is felt that the energy absorbed by a non-rigid cask would be relatively small. Secondly, by neglecting the energy absorbing capability of the cask, the resulting solution represents an upper bound for damage to the crush pad and surrounding concrete structure. A computational benefit was also realized in shorter computer run times due to faster solution convergence.

The crush pads are constructed of 48-in. of 20 pounds per cubic foot (pcf) foam (General Plastics, 1996), a ¼-in. stainless steel (SST) top cover plate, a 1-in. SST bottom plate, ½-in. side plates, and two 2 ½-in. SST ballast plates. The two crush pads are 11 ft.-10 in. wide by 18ft.-2 in. long. The safety factor against floating is 1.27, which is greater than the allowable of 1.1. A lower bound foam density of about 9.0 pcf would produce a safety factor against floating of 1.1.

Since the cask does impact the pool wall, it is noted that the pool wall is constructed of reinforced concrete. The wall is four foot thick with #9 reinforcing steel on 12-in. centers on both faces and in both the horizontal and vertical directions. The wall is 44-ft. tall by about 24-ft. wide (between the north-south gate walls). The bottom of the wall and the two ends were assumed fixed and the top of the wall was free. The concrete was modeled using continuum elements with plasticity and with the ABAQUS concrete reinforcing steel (rebar) elements. An ACI 318-95 Code capacity calculation for a point load in mid-span resulted in a wall capacity of 504,000 lbs. in shear and 593,000 lbs. in flexure (Uldrich and Hawkes, 1997).

FOAM MODEL VERIFICATION

One object of the foam model verification was to verify that the ABAQUS representation of the foam model accurately represented the foam behavior as was tested by the manufacturer. The manufacturer tests the foam by fixing a cube, 1.5-in. on a side, to a wall and then impacting it with a pendulum at various velocities. This dynamic impact data is then translated into uniaxial stress-strain data.

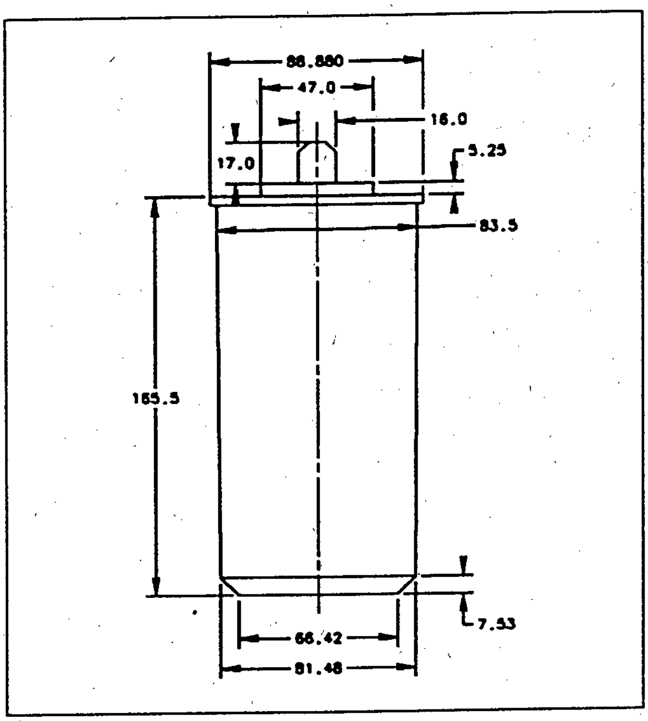

Figure 3. Large Cell Cask Dimensions (in.)

The manufacturer's stress-strain data was used to generate an ABAQUS foam-hardening model. The ABAQUS verification model is a cube of foam, 1.5 in. on an edge. This foam is restrained on the bottom and is compressed, at a velocity consistent with the manufacturer's test velocity, by a rigid surface on the top (Fig. 4). The displacement of the top surface and the reaction force on the bottom surface were calculated and converted to stress and strain. These were compared to the manufacturer's data to verify that the ABAQUS foam-hardening model produces appropriate results (Fig. 5). The comparison shows that the results from the ABAQUS foam model compare very closely with the original foam data from the manufacturer.

The crushable foam plasticity model, an integral feature of the ABAQUS/Explicit code, was used to represent the foam. It was developed for the analysis of crushable foams that are typically used for energy absorption. The foam plasticity model is used to represent the ability of the foam to deform volumetrically in compression due to cell wall buckling processes. The model therefore works in terms of volumetric stress and strain. This foam model also accounts for the difference between a foam material's compressive strength and its much smaller tensile capacity resulting from cell wall breakage in tension. The strain in the foam was purposely kept to less than 60%, to ensure that there would be no failure within the foam.

THE WORKING MODEL ANALYSIS

The kinematics of the potential drop scenarios were evaluated using the computer code "Working Model 2D" (Knowledge Revolution, 1996). When the LCC is hypothetically dropped, it falls about two feet before impacting the pool wall parapet, at which time its starts to tumble, rotating about 166° and impacting the crush pad with a top corner of the cask. The cask velocities at impact were 60 in./sec. horizontally towards the north wall, 460 in./sec. vertically downward, and 85°/sec. rotationally (about the cask's center-of-gravity) with the upper portion of the cask rotating towards the north wall. The impact of the corner of the cask was 139 in. from the north wall. The cask diameter in this analysis was 82.5 in.; thus, the north side of the cask was only about 56.5 in. from the north wall (Fig. 6).

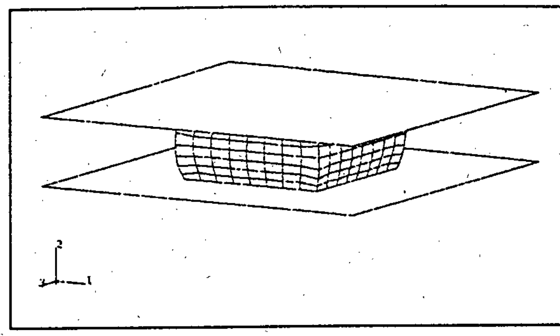

Figure 4. ABAQUS finite element model of crushed foam.

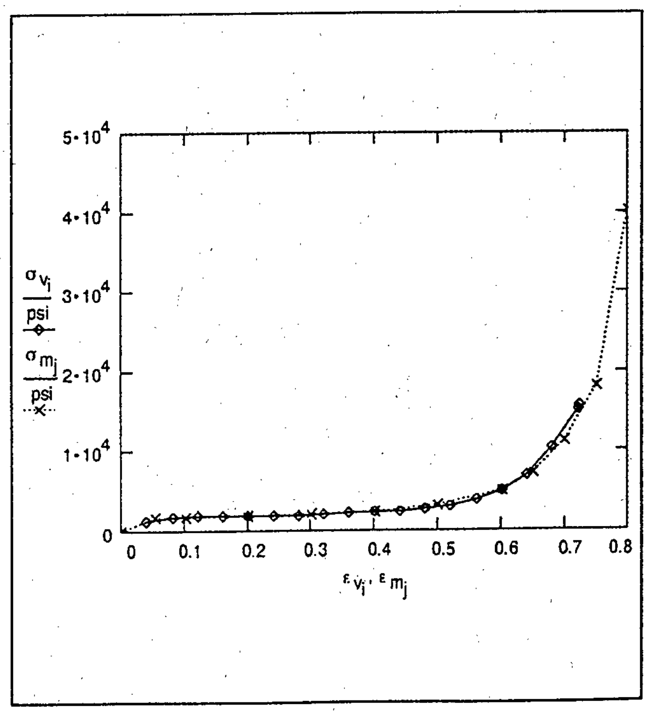

Figure 5. Comparison of the ABAQUS foam model verification (subscript v) results and the manufacturer's (subscript m) test data (σ is stress in psi and ε is strain in in./in.)

THE ABAQUS ANALYSIS

The ABAQUS/Explicit analysis was started using the above velocities as initial conditions. The ABAQUS computer model is shown in Fig. 7. The crushing of the crush pad is shown in Fig. 8. The deep indentation to the right is the initial impact area of the cask. The cask continues to rotate after the initial impact, producing the second lesser indentation to the left.

After the cask rebounds from the crush pad, it impacts the north wall. A computer plot of the cask impacting the north wall is shown in Fig. 9.

THE ABAQUS RESULTS

The results from the dynamic analysis are presented in graphical form in several plots (Fig's. 10 through 15). It should be noted that the start time for the plots is 0.04 sec. Initial contact of the cask with the crush pad occurred just slightly after 0.00 sec. Therefore, the initial conditions as stated above are not shown on these plots. From these result plots, it is evident that the cask reaches maximum crush depth at about 0.06 sec. and then rebounds from the crush pad at about 0.08 sec. The cask then travels upward through the pool water until about 0.56 sec., when it descends and rotates until it initially contacts the wall at about 0.96 sec. The cask reaches maximum contact with the wall at 0.97 sec., and rebounds from the wall at 1.00 sec. At about 1.04 sec. the cask again contacts the crush pad and starts decelerating. The cask reaches its maximum penetration into the crush pad for this impact at 1.08 sec. It again rebounds from the crush pad at 1.12 sec. and travels through pool water until the end of the plot at 1.20 sec.

The first results plot, shown in Fig. 10, is of one-half the total kinetic energy of the cask (as only one-half of the cask was modeled). The next result plots show histories of the three velocities (Figs. 11, 12, and 13). It should be noted that the horizontal energy at impact was about 1.02×10^6 in.-lbs., the vertical energy was 60.24×10^6 in.-lbs., and the rotational energy (based on a rotational mass moment of inertia of 1.668×10^6 lbs.-in.-sec.^{2}) was 1.84×10^6 in.-lbs. Based on these values, which were calculated using the velocities at impact, the total cask energy was 63.10×10^6 in.-lbs.

The energy at rebound (as the cask clears the crush pad, t = 0.08 sec.) was 1.39×10^6 in.-lbs. horizontal, 10.28×10^6 in.-lbs. vertical, and 0.12×10^6 in.-lbs. for the rotational energy. The total energy at cask rebound then was 11.79×10^6 in.-lbs. The difference in energy (from impact to rebound) of 51.31×10^6 in.-lbs. has to be absorbed (strain energy) by the crush pad. The energy absorbed by the crush pad during primary impact was about 81% of the initial cask energy.

As can be seen in Fig's. 11 and 13, as the cask moves through the pool between impacts there is no change in the horizontal and rotational velocities. The vertical velocity however, changes from 190 in./sec. vertically upward to about 150 in./sec. downward (Fig. 12). The cask then impacts the pool wall with nearly the amount of energy it had when it left the crush pad. As the cask impacts the wall, its vertical velocity decreases slightly as it drags along the wall. When it releases, the vertical downward velocity increases until the cask has a second impact with the crush pad.

The cask's energy at its second impact with the crush pad is 0.26×10^6 in.-lbs. horizontal, 7.42×10^6 in.-lbs. vertical, and 1.20×10^6 in.-lbs. rotational. This gives a total cask energy, based on cask velocities, of 8.87×10^6 in.-lbs. This is only 25% less than the 11.79×10^6 in.-lbs. when the cask first rebounded from the crush pad. After this second impact, the total cask energy is 4.83×10^6 in.-lbs. From the initial impact to the end of the second impact with the crush pad, then, the cask has lost 92% of its energy.

The depth of penetration into the crush pads is shown in Fig. 8. This represents the maximum penetration of 15.1 in. in the vertical direction from the primary cask impact. This equates to 31.5% strain, which is acceptable. The foam manufacturer (General Plastics, 1996) recommends that the strains be limited to about 60%. The second cask impact with the crush pad produced a 10.0-in. deep penetration. The penetrations in Fig. 8 do not show these maximum penetrations. Figure 8 shows the penetrations at 1.2 sec., after elastic rebound had occurred.

Considering the energy absorption capacity of the crush pad and the depth of penetration of the cask (strain less than 60%), the crush pad has an acceptable design.

Based on a separate evaluation of the cask, its limiting design deceleration was established to be 100 g. Figure 14 shows the horizontal and vertical accelerations of the cask. The vector sum of these accelerations produces a maximum cask deceleration of 47.9 g during the primary impact with the crush pad, 16.6 g during impact with the wall, and 31.1 g during the second impact with the crush pad. As expected, the primary impact produced the greatest deceleration, which is of an acceptable magnitude.

When the cask impacts the wall, the cask's vertical velocity is about 150 in./sec. (Fig. 12) and the horizontal velocity is about 70 in./sec. (Fig. 11). The vertical velocity decreases slightly on impact indicating some wall crushing/deformation. This means that the cask was momentarily hung up by the wall. Obviously, the horizontal velocity of the center of gravity (c. g.) of the cask slowed substantially, but did not reverse directions immediately. The rotational velocity (Fig. 13) shows an almost immediate change in direction of rotation at impact with the wall. This allows for a continued horizontal velocity (of the c. g.) towards the wall. The cask then changes horizontal directions and rebounds from the wall. The horizontal velocity of 70 in./sec. has been shown by analysis to be less than an expected concrete cone cracking velocity of 128 in./sec. for a four-foot-thick concrete wall (Hawkes, 1996). This indicates that there will not be a local failure of the wall.

The wall node on the opposite (north) side of the wall from the cask, as shown in Fig. 15, had about –0.05-in. displacement (in the direction the cask is moving). This nodal displacement represents the true generalized behavior of the wall. A crater will develop at the point where the cask impacts the wall. Surrounding this crater will be localized bulging. The node on the cask side of the wall is located in this region of bulging, which initially displaces 0.07 in. out from the wall and eventually displaces up to about 0.18 in. Since the concrete wall is 4-ft. thick, this localized bulging is insignificant. In addition, the ABAQUS model of the wall used continuum elements rather than brittle cracking elements and so to some extent this localized behavior may be due to the modeling methods rather than representing actual behavior. After the instant of impact, the displacement histories for these nodes are characteristic of ringing. A nodal time displacement

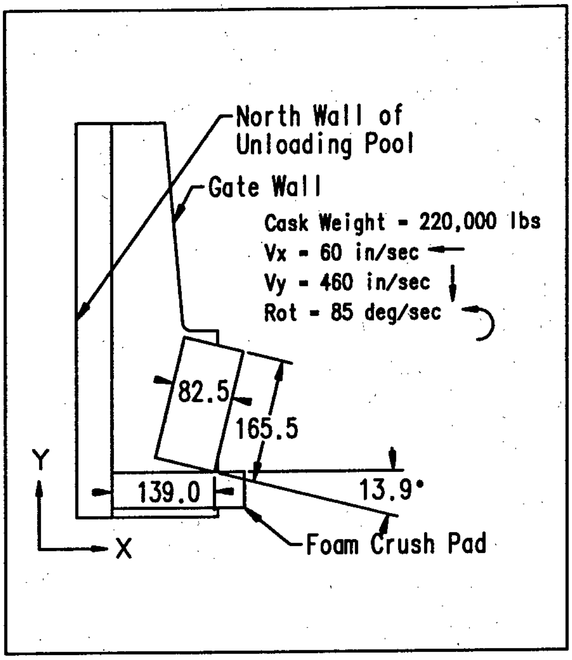

Figure 6. Initial conditions for cask/foam impact (dimensions in in.).

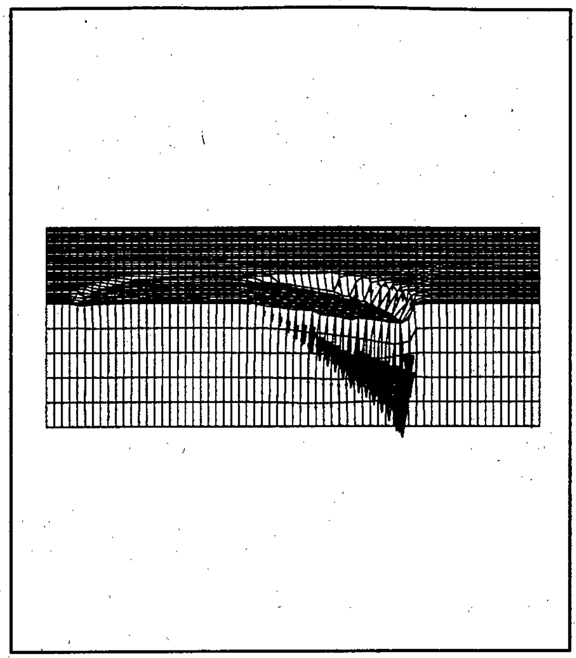

Figure 8. Plastic deformation of foam after cask impact (at time=1.20 sec.).

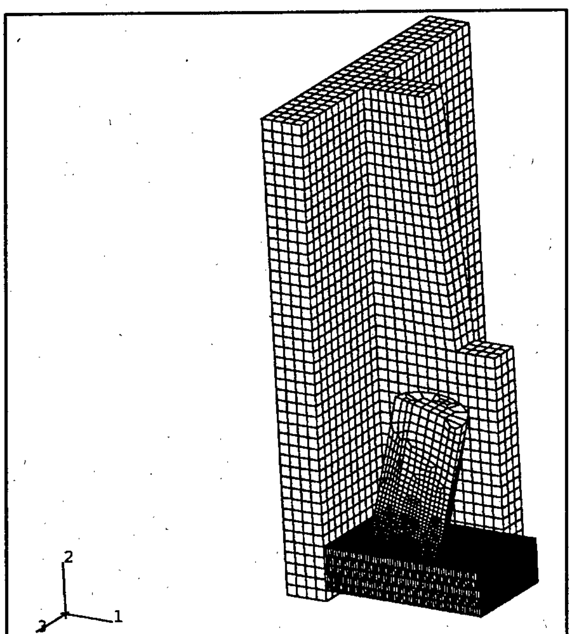

Figure 7. ABAQUS finite element model showing cask, crush pad and wall just before impact.

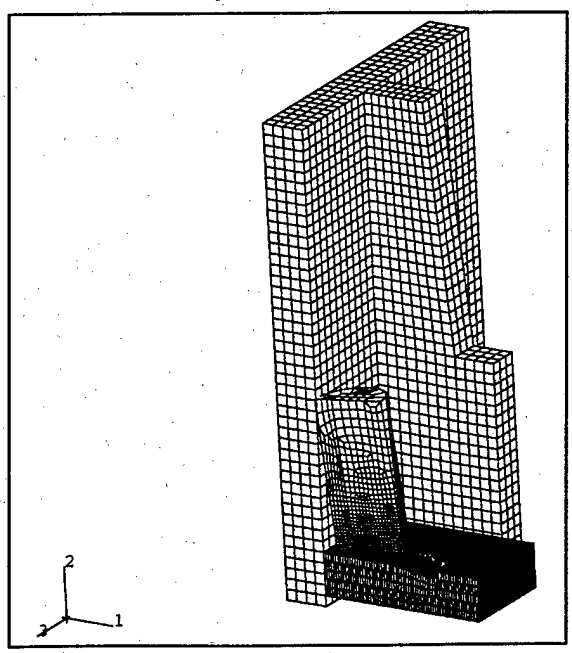

Figure 9. ABAQUS finite element model of cask impacting the wall after rebounding from foam impact.

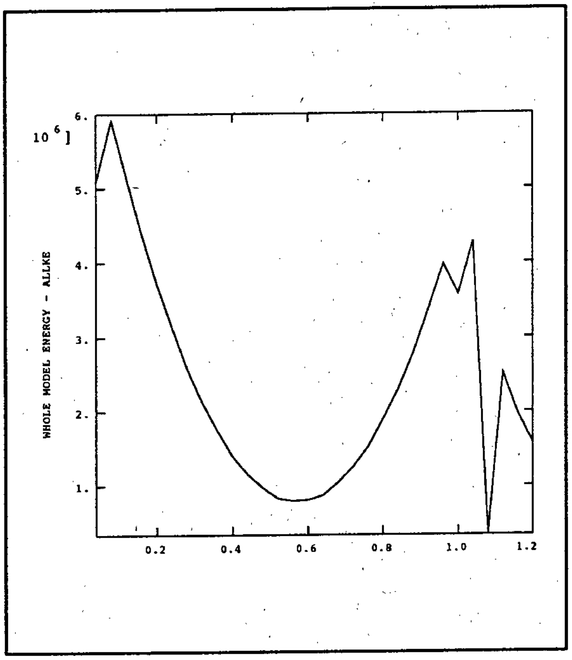

Figure 10. Kinetic energy of the cask's center of gravity (in.–lbs. and sec.).

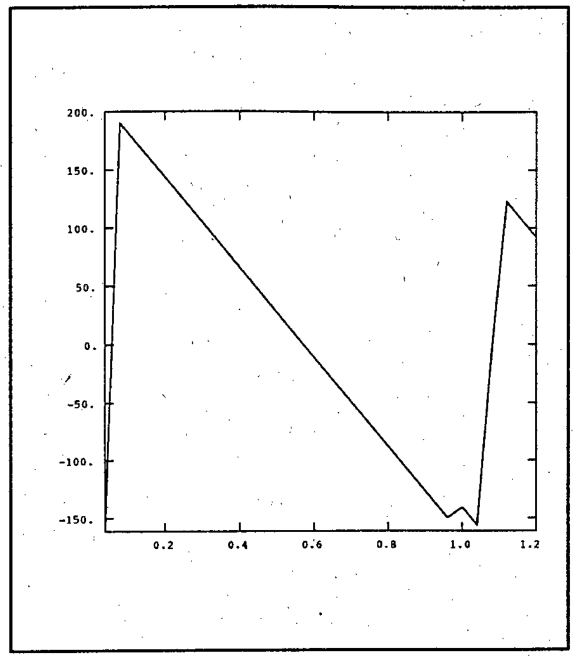

Figure 12. Velocity of the cask's center of gravity in the vertical direction (in./sec. and sec.).

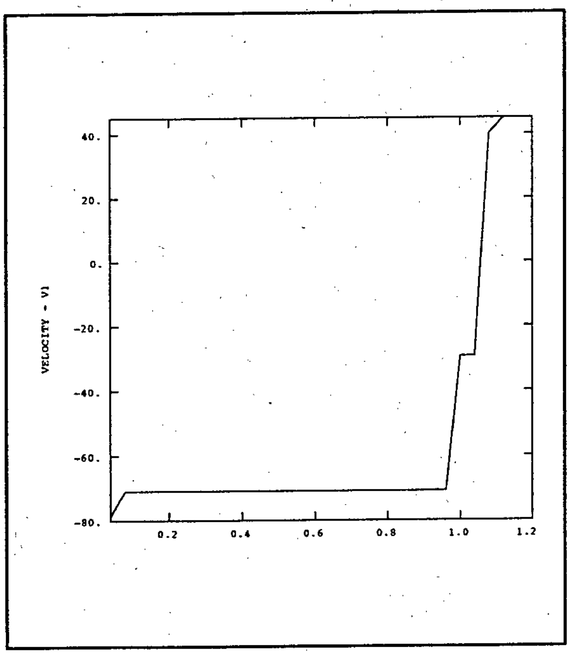

Figure 11. Velocity of the cask's center of gravity in the horizontal direction (in./sec. and sec.).

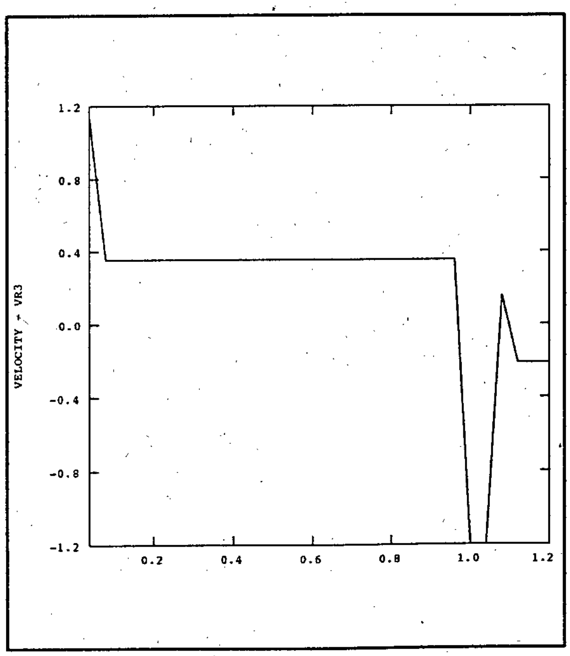

Figure 13. Velocity of the cask's center of gravity in rotation (rad./sec. and sec.).

profile of the wall (Fig. 15) shows that there is little general flexure (about 0.05-in.), which indicates that the impact force is within the wall capacity (Uldrich and Hawkes, 1997).

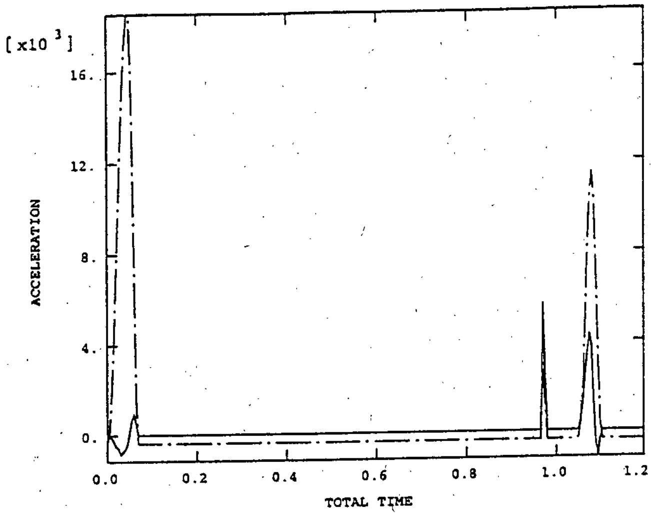

Figure 14. Horizontal (solid line) and vertical (dash-dot line) accelerations of the cask's center of gravity (in./sec^2. and sec.).

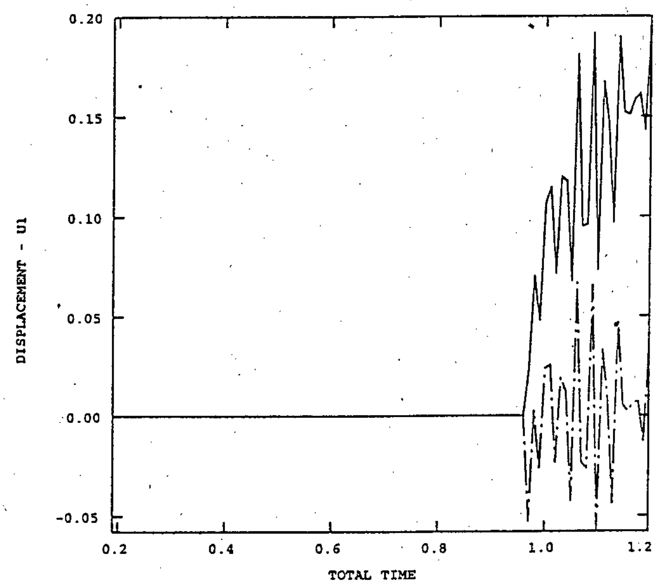

Figure 15. Time history displacement for the wall at cask impact (in. and sec.). (Node on cask side of wall, solid line; node on opposite side of wall, dash-dot line.)

ANALYSIS CONCLUSIONS

The analysis, which represents an upper bound, has shown that the design of the crush pad was adequate. Two impacts with the crush pad and one impact with the wall captured 92% of the cask's energy. It was shown that the stress and strain characteristics of the foam were accurately represented by the ABAQUS/Explicit foam model. The maximum strain in the foam for this hypothetical drop accident was 31.5%, which is acceptable. The cask deceleration was 47.9 g, which is within the acceptable limit of 100 g. Rebound of the cask into the pool wall does no significant damage to the wall. When the cask is dropped and it impacts the crush pad, it rebounds from the pad resulting in subsequent impacts with the pool wall and crush pad.

CONCLUSIONS OF THIS STUDY

When a large spent fuel cask (such as the 110-ton LCC) is accidentally dropped onto a foam crush pad; it may rebound with sufficient horizontal or rotational energy as to have a second impact with a pool wall or some other object. This happens because of the relatively large elastic strain attained in the foam material (about 5%) before the foam actually crushes. Hand analyses of cask drops in the past have been reasonably accurate in estimating cask decelerations and in predicting penetration depth of a cask into a crush pad. These methods are generally not sufficient, however, in treating the dynamics of these secondary impacts.

NOTICE

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