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SEISMIC TIPPING ANALYSIS OF A SPENT NUCLEAR FUEL SHIPPING CASK SITTING ON A CRUSH PAD¹

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ABSTRACT

A crush pad has been designed and analyzed to absorb the kinetic energy of an accidentally 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 a U. S. Department of Energy Site.

Conventional analysis techniques available for evaluating a cask for tipping due to lateral seismic forces assume that the cask rests on a rigid surface. In this analysis, the cask (110 tons) sits on a stainless steel encased (0.25-in. top plate), polyurethane foam (4-ft. thick) crush pad. As the cask tends to rock due to horizontal seismic forces, the contact area between the cask and the crush pad is reduced, increasing the bearing stress, and causing the pivoting corner of the cask to depress into the crush pad. As the crush pad depresses under the cask corner, the pivot point shifts from the corner toward the cask center, which facilitates rocking and potential tipping of the cask. Subsequent rocking of the cask may deepen the depression, further contributing to the likelihood of cask tip-over. However, as the depression is created, the crush pad is absorbing energy from the rocking cask. Potential tip-over of the cask was evaluated by performing a non-linear, dynamic, finite element analysis with acceleration-time history input. This time history analysis captured the effect of a deforming crush pad, and also eliminated conservatisms of the conventional approaches. For comparison purposes, this analysis was also performed with the cask sitting on a solid stainless steel crush pad. Results indicate that the conventional methods are quite conservative relative to the more exacting time history analysis. They also indicate that the rocking motion is less on the foam crush pad than on the solid stainless steel pad.

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). During normal operation, the spent fuel cask will sit on the crush pad while it is being unloaded

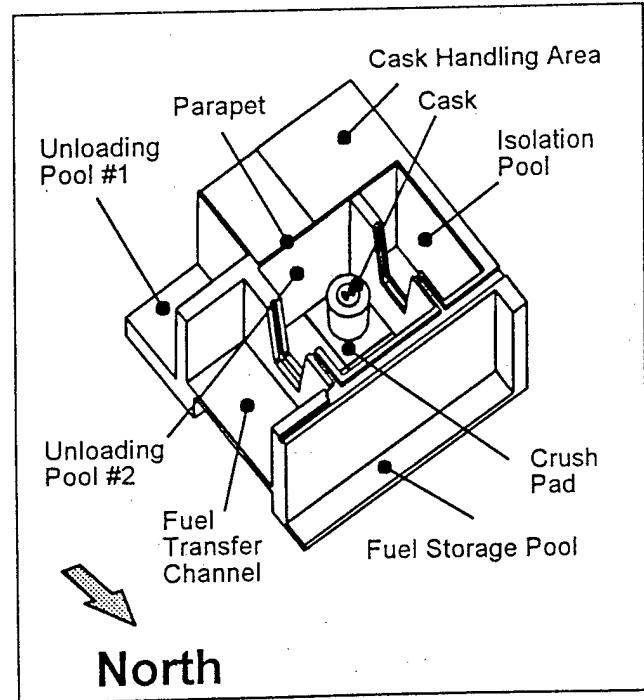


Figure 1. Overall View of the Cask Unloading Pool, the Cask and the Crush Pads
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and may be subjected to a seismic event. This facility, located at the Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering and Environmental Laboratory (INEEL), is a U. S. Department of Energy site.

The purpose of this analysis was to evaluate the seismic tipping resistance of the Large Cell Cask (LCC), while sitting on a crush pad at the bottom of the cask unloading pool. As the cask tends to rock during a seismic event, the pad may crush due to the cask bearing pressure. Consequently, a seismic tipping analysis of a cask, while sitting on a crush pad, has different analytical considerations than while sitting on a rigid surface. For comparison purposes, an additional analysis was performed with the cask sitting on a solid stainless steel pad.

ANALYTICAL PROCEDURE

A response spectrum analysis of a cask sitting on a crush pad will not predict the crushing under the corner of the cask during seismic rocking. Therefore, a seismic acceleration-time history analysis is required so that this non-linear effect (the crush pad deflecting under the corner of the cask) can be considered. The time history approach also accurately captures the rocking motion of the cask. The acceleration-time histories used in this analysis were from a recent seismic analysis for a reracking project in the adjacent storage pools (Malik and Bolourchi, 1994). The seismic acceleration histories are 5-sec. segments of the original time histories and are shown in Figures 2 and 3. The peak accelerations were maintained in the 1.5 to 3.5-sec. time period; otherwise the curves are gradually increasing or decreasing to facilitate convergence in the computer program.

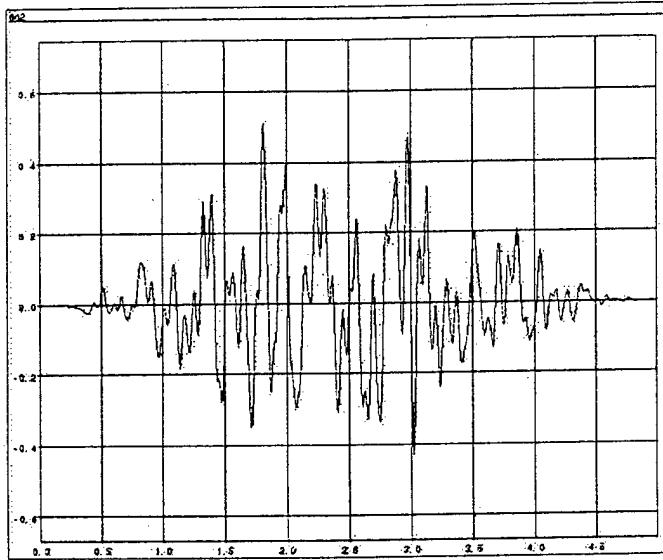


Figure 2. Acceleration-time history in the vertical direction (g. and sec.).

These acceleration-time histories became input for an ABAQUS/Explicit (Hibbit, Karlsson, and Sorensen, 1996) analysis.

This analysis traced the rocking of the cask and its subsequent corner crushing into the foam crush pad.

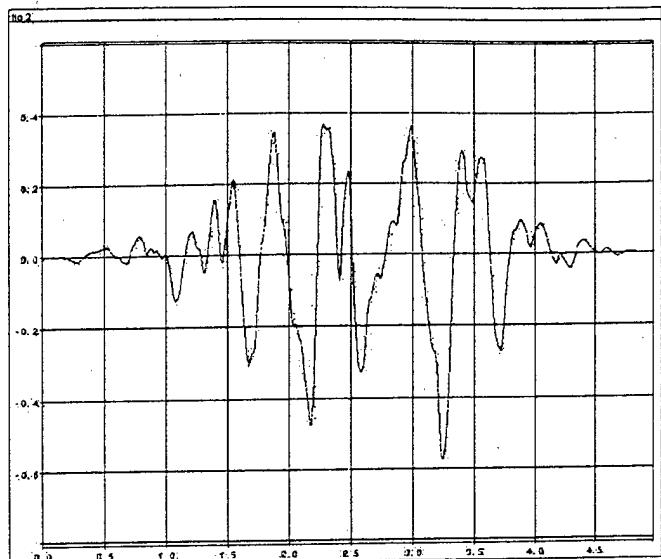


Figure 3. Acceleration-time history in the horizontal direction (g. and sec.).

DESCRIPTION OF THE POOL, CASK, AND CRUSH PAD

The unloading pool is 44 ft. deep with a water depth of 42.5 ft. The foam crush pad was assumed to be 4.0 ft. thick (Fig. 1).

The cask is the 110-ton Large Cell Cask (LCC). Upper bound weight used in this analysis was 220,000 lbs. The cask has a tapered body. The diameter varies from 81.5 in. at the bottom to 83.5 in. at the top. Consequently, a nominal body diameter of 82.5 in. was used in the analyses along with a nominal body length of 165.5 in. (Fig. 4). The cask has a 7.5-in. chamfer at the bottom corner, which results in a bottom diameter of 66.42 in. This is an important consideration in determining the dimension to the rocking corner of the cask and the likelihood of the cask tipping. In this analysis, the cask was treated as a rigid body.

The crush pads are constructed of a 48-in. thickness of 20-pcf-density foam, a 1/4-in. stainless steel (SST) top cover plate, a 1-in. SST bottom plate, 1/2-in. side plates, and two 2 1/2-in. SST ballast plates at the bottom. The two crush pads are 11 ft.-10 in. wide by 18 ft.-2 in. long. Two pads cover the entire floor of the unloading pool. The safety factor against floating is 1.27, which is greater than the allowable of 1.1. A foam density of about 9.0 pcf would produce a safety factor of 1.1.

FOAM MODEL VERIFICATION

One object of 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.

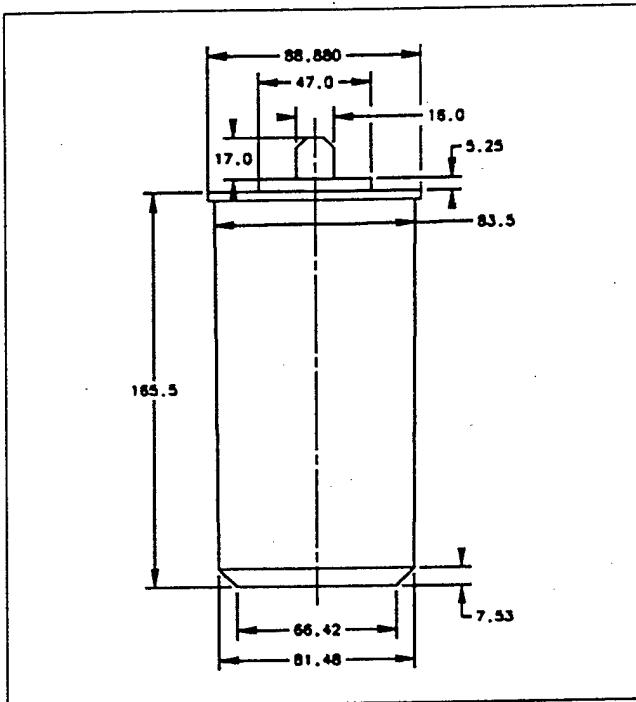


Figure 4. Large Cell Cask Dimensions (in.)

This dynamic impact data is then translated into uniaxial stress-strain data.

The manufacturer's stress-strain data was used to generate an ABAQUS foam-hardening model. The ABAQUS verification model simulated a cube of foam, 1.5 in. on an edge. This foam was restrained on the bottom and was compressed by a rigid surface on the top (Fig. 5). 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. 6). The comparison shows that the results from the ABAQUS foam model compare very closely with the original foam data from the manufacturer.

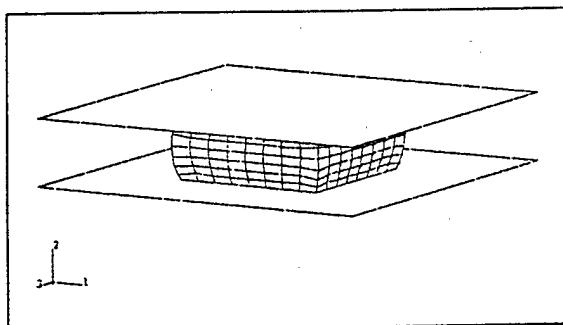


Figure 5. ABAQUS finite element model of crushed foam in verification analysis.

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. It can be used when rate-dependent effects are important, such as in a cask impact situation.

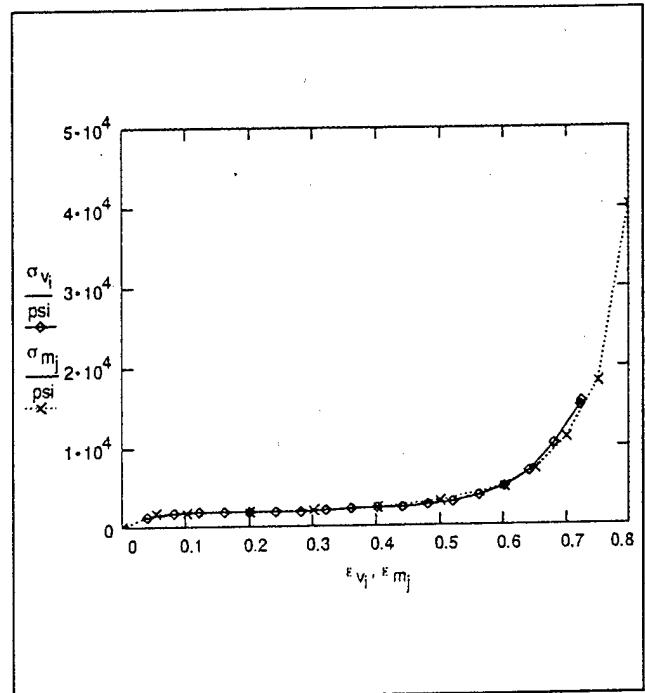


Figure 6. Comparison of the ABAQUS foam model verification (subscript v) results and the manufacturer's (subscript m) test data (σ is stress in psi and ϵ is strain in in./in.).

THE ABAQUS ANALYSIS

The ABAQUS/Explicit analysis used vertical and horizontal 5-sec. acceleration-time histories (Fig's. 2 and 3). The vertical and horizontal time-histories were applied simultaneously to the bottom surface of the crush pad. The crush pad model included the stainless steel cover plates and those plates had elastic/plastic properties. A wet friction value of 0.5 was used between the cask and the crush pad. The ABAQUS computer model is shown in Fig. 7. In addition, a second analysis was completed with the cask sitting on a solid stainless steel pad. This second computer model is identical to the previous model, only the foam material in the crush pad was replaced with a solid stainless steel material.

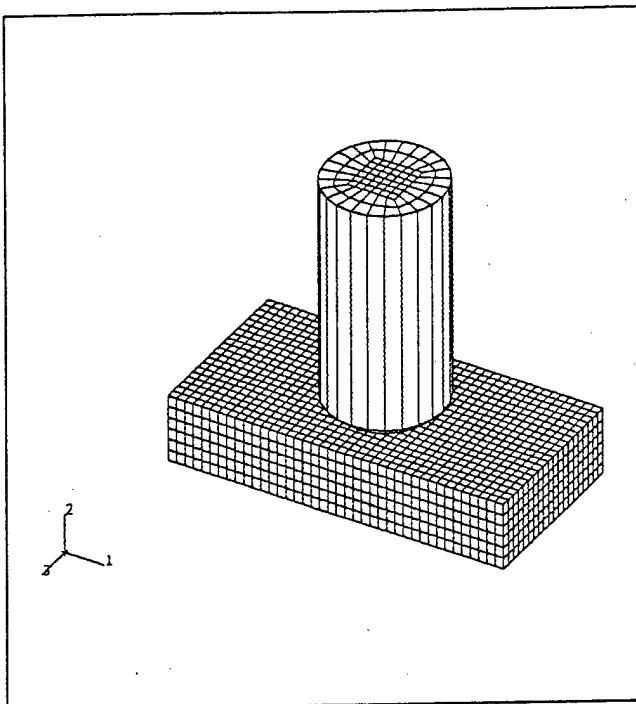


Figure 7. ABAQUS Finite Element Model Showing the Cask and Crush Pad

THE ABAQUS RESULTS

The results are presented in graphical form in several plots. It should be noted that the start time for the plots is 10.0 seconds. This initial 10-sec. time period allowed for the cask and crush pad to analytically reach equilibrium from the static vertical weight of the cask. The input time histories were initialized at a time of 10 sec. in the analysis. Figure 8 shows the vertical displacement of the center of gravity of the cask. The horizontal displacement and angular rotation are shown in Fig's. 9 and 10 respectively.

Figures 11, 12, and 13 show the vertical and horizontal displacements and the rotation of the center of gravity of the cask when it is on the solid stainless steel pad.

The maximum displacements and tipping of the cask on the foam crush pad occur at about 13.5 sec. At that time the vertical and horizontal displacements are about 0.56 and 2.51 in., respectively. The rotation is about 0.029 radians, or 1.67°. The cask and crush pad are shown in a displaced plot (with no magnification of the displacements) in Fig. 14. Comparing to the cask on the solid stainless crush pad, the maximum displacements and tipping occur at 13.25 sec. The maximum vertical and horizontal displacements are about 1.08 and 2.93 in., respectively. The cask rotation is about 0.037 radians or 2.13°. Obviously, the cask's displacements and rotation, during this seismic event, are greater, when the cask is sitting on the solid stainless pad compared to the foam crush pad. This is attributed to the energy absorbing capabilities of the foam.

By calculating the horizontal displacement of the cask's center of gravity due to the angular rotation and comparing that to the

calculated horizontal displacement, it can be determined that the cask may slide about 0.133 in. (from the cask's original position) on the foam crush pad during cask rocking. The cask on the solid stainless pad may slide about 0.132 in. during cask rocking.

A similar calculation and comparison for vertical displacement indicates that the cask penetrates the crush pad about 0.44 in. A vertical displacement of 0.44 in. represents about 1% strain in the foam, which is below the 5% limit for elastic strain for this foam material (Fig. 6). It is concluded therefore, that for this cask/crush pad combination with these seismic acceleration time histories, the crush pad foam material remains elastic during cask rocking. A similar calculation for the cask on the solid stainless pad indicates that the cask penetrates the pad about 0.11 in., which would be expected. This is a localized dimpling effect of the relatively sharp bottom corner of the cask bearing on the flat surface of the pad.

The angular rotation that the cask would have to experience to tip over is slightly less than 22°. At the small displacements and the small angular rotation experienced by this cask at its peak rocking on either the foam crush pad or the solid stainless steel pad, it is in no danger of tipping. Hand analyses by R. L. Bratton (Uldrich and Hawkes, 1997) reports a 4% margin against tipping using an energy approach and a 2% margin against cask lift using a static equivalent force and moment approach. These analyses were completed using the crush pad as a rigid surface and using a zero period ground acceleration of 0.2625 g. Results from the time history analyses indicate that the conventional hand analysis methods were conservative.

A study of time-sequenced stress plots of the foam crush pad's $\frac{1}{4}$ -in. stainless steel cover plate indicate that, during severe cask rocking, the stress in the plate exceeds the yield stress for 304L stainless steel by less than 20%. The corresponding elastic strain is 0.104% and the maximum plastic strain is 0.056%. The plastic strain is a residual strain that occurs in the cover plate under the cask corners when the cask rocks. This may mean that this cover plate will show some permanent marks (dimples or indentations) from the cask rocking.

Another interesting observation, from the time-sequenced displacement plots of the cask sitting on the foam crush pad, indicates that the cask actually separates from the crush pad at a time of about 11.75-sec. (Fig. 15). The closest corner of the cask to the crush pad separates from the crush pad by about 0.043-in. The displacement and rotation shown in this figure are magnified (100x) to more clearly show the separation. At the time of 11.75 sec., which is 1.75 sec. in Fig. 2, a vertical seismic acceleration of over 0.4 g occurs. A similar study of the time-sequenced displacement plots of the cask sitting on the solid stainless steel pad indicates no separation between the cask and the pad.

ANALYSIS CONCLUSIONS

This seismic time history analysis has shown that the cask, while sitting on a foam crush pad, will not tip over when subjected to this specific event. This seismic event has peak accelerations of slightly over 0.4 g in the three orthogonal directions. Actually the cask has a large margin of safety against tipping. The analysis also shows that

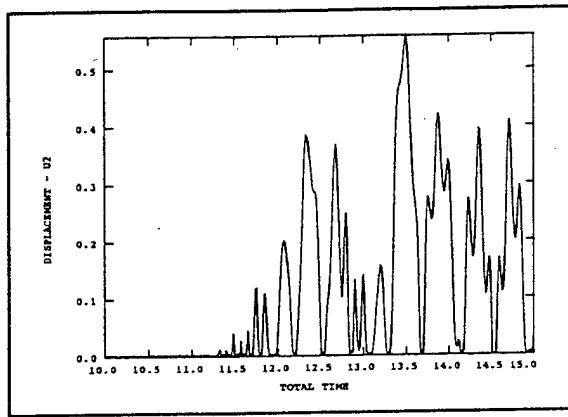


Figure 8. Vertical displacement of the cask's center of gravity (in. and sec.) for the foam crush pad.

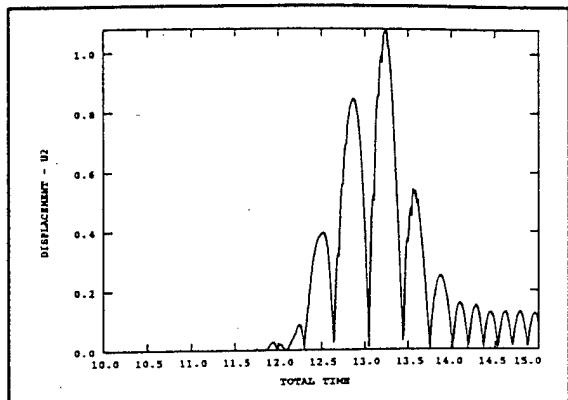


Figure 11. Vertical displacement of the cask's center of gravity (in. and sec.) for the solid stainless steel pad.

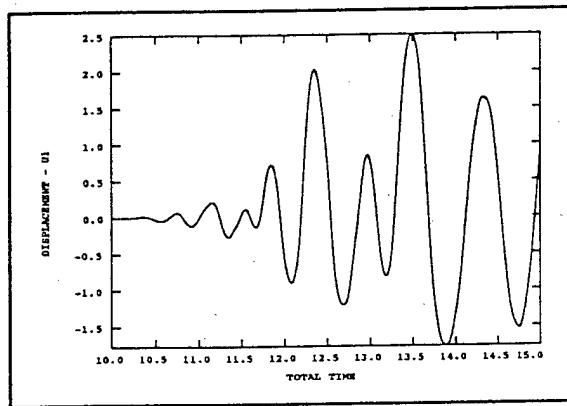


Figure 9. Horizontal displacement of the cask's center of gravity (in. and sec.) for the foam crush pad.

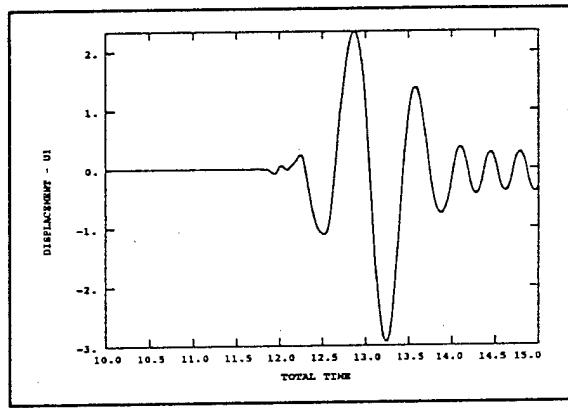


Figure 12. Horizontal displacement of the cask's center of gravity (in. and sec.) for the solid stainless steel pad.

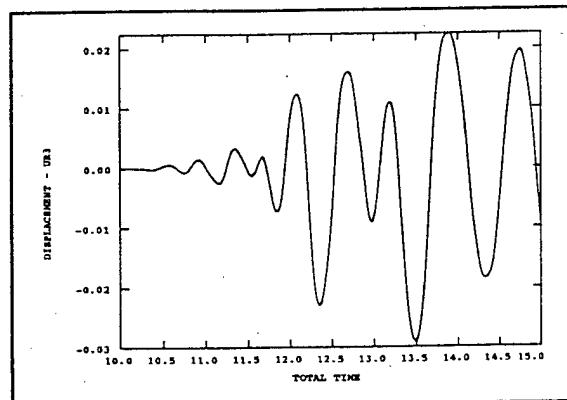


Figure 10. Angular rotation of the cask about its center of gravity (radians and sec.) for the foam crush pad.

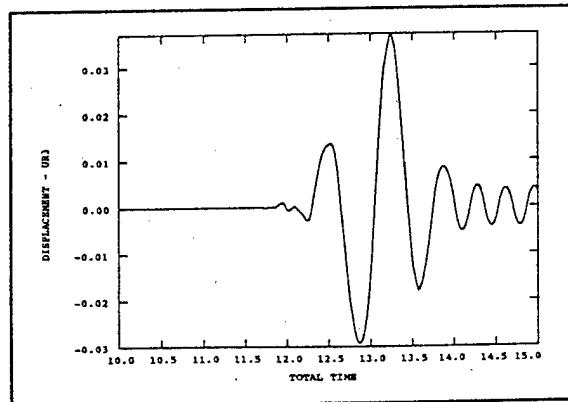


Figure 13. Angular rotation of the cask about its center of gravity (radians and sec.) for the solid stainless steel pad.

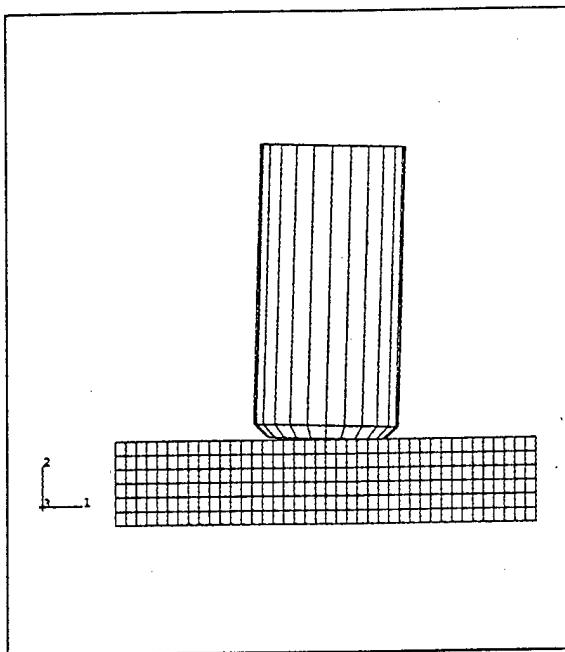


Figure 14. Position of the cask on the foam crush pad at time of 13.5 sec. Displacements and rotations not magnified.

the foam in the crush pad remains elastic while the stainless steel cover plate does experience some minor plasticity. It also shows that the cask goes through about two cycles of rocking in 1.1 sec. of seismic duration. During rocking the cask slides slightly. As a point of interest, the analysis shows that the cask bounced off the crush pad at least once during the seismic event.

A similar analysis of the same cask sitting on a solid stainless steel pad yielded similar results. Although the cask rotates slightly more, it still is in no danger of tipping. In this case, the cask rocks slightly slower (two cycles in 1.3 sec.) but with greater displacement magnitudes. The cask does not bounce off the solid stainless steel pad.

CONCLUSIONS OF THIS STUDY

A large spent fuel cask, such as this LCC (110 tons), sitting on a foam crush pad during a seismic event will rock and be subjected to tipping as would a cask sitting on a rigid surface. A non-linear, dynamic finite element analysis is valuable in determining the precise rocking motions of the cask, the damage to the crush pad and whether the cask will tip. In this case the magnitude of rocking was slightly less for the cask sitting on the foam crush pad than for a cask on a rigid surface. Performing such an analysis does require that a seismic acceleration-time history be developed for input.

Hand analyses of a cask subjected to seismic forces can be analyzed by several different methods. These methods are

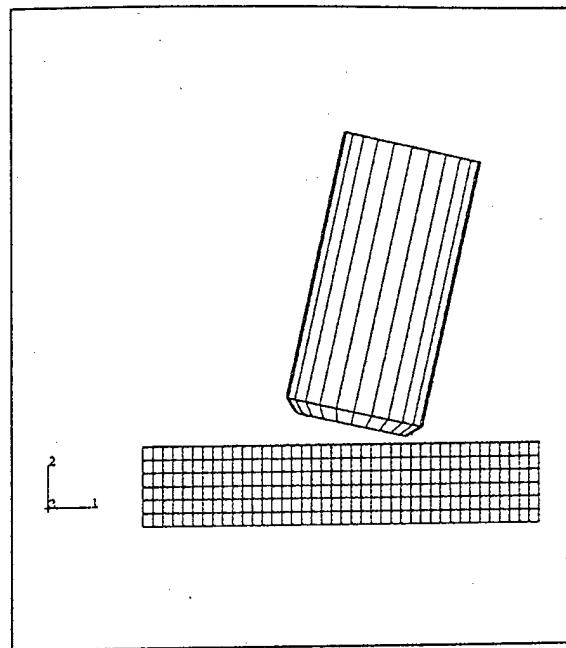


Figure 15. Cask shown separating from the foam crush pad at time of 11.75 sec. Displacements and rotation are magnified (100 x) to show the separation.

necessarily conservative. This computer analysis eliminates many of these conservative assumptions and procedures.

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