Design, Analysis, and Testing of Wood Filled Impact Limiters

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INTRODUCTION

In current practice, Type B packagings are generally provided with protective covers or impact limiters designed to protect the cask body during impact after the 30 foot free drop regulatory accident. Both the target and the typical shielded cask are essentially rigid. Therefore, the impact limiters must deform or crush in a precisely controlled manner to absorb the kinetic energy without producing excessive inertial loadings or contact forces on the cask body.

Transnuclear has found wood to be an ideal energy absorption material for use in impact limiters. Wood has many properties that give it a distinct advantage over other materials. These advantages include:

- High energy absorption can be achieved per pound of material.
- Large strain can be accomodated before material "lockup."
- A wide selection of material properties is available in different woods .
- Anisotropic behavior (i.e. the crush strength variation with load orientation relative to grain direction) can be used to advantage in local areas of the limiter.
- Properties of wood can be verified before asssembly into the limiter (rather than determined afterward as in the case of foam).

This paper describes the design, analysis and testing approaches used to develop and verify the performance of wood filled impact limiters for several recent Transnuclear packagings.

DESIGN

A spent fuel cask, complete with impact limiters on both ends, is shown in Figure 1. The configuration of a typical Transnuclear wood filled impact limiter is shown in Figure 2. Wood has excellent compressive stress-strain behavior for the intended purpose as shown by a typical redwood test curve in Figure 3. However, wood has low tensile and shear strength so that large rings of wood (even if they were available in the proper size with the desired grain orientation) would crack and split and move out of position as they crush.

Therefore our approach is to utilize the wood only as a crush medium and to protect it, confine it and hold it in place with a thin metal structure. The structure, which also provides attachment locations, consists of inner and outer steel shells joined by radial gussets which divide the interior into compartments. The shell is thin and is easily buckled and smashed and absorbs very little energy as the limiter is crushed from the side or corner. The gussets may provide some added stiffness for the end drop where they are all loaded simultaneously. Carefully designed wedge shaped wood blocks are assembled into the interior compartments of the limiter between the gussets.

Each region of the limiter is filled with a particular type of wood which is selected and oriented (with respect to grain direction) to absorb the proper energy for a particular impact orientation without applying excessive force to the cask body. Typical design crush properties for balsa and redwood are listed below:

TYPICAL WOOD COMPRESSIVE STRENGTH

	BALSA	REDWOOD
*Parallel Crush Stress	1560-2010 psi	5000-6500 psi
*Perpendicular Crush Stress	300-420 psi	750-975 psi
Locking Strain	80%	60%

*relative to grain direction

Note in Figure 2 that a redwood section with the grain oriented radially is provided around the side of the cask body for the side impact where the crush footprint is small. Balsa wood is provided in the center of the limiter adjacent to the end of the cask since the footprint involves the whole limiter and a softer material is required. Both balsa and redwood are used in series in the corner of the limiter where the available crush distance is greater but the wood is oriented in a weaker direction.

METHOD OF ANALYSIS

A computer code, ADOC (<u>A</u>cceleration due to <u>D</u>rop <u>O</u>n <u>C</u>overs), has been written to determine the packaging response during impact after a free drop. The code was developed to analyze the general problem involving primary impact followed by rotation and secondary impact. The ADOC dynamic model of a typical packaging is shown in Figure 4. The cask body is assumed to be rigid and axisymmetric. All of the energy absorption occurs in the impact limiters, also assumed to be axisymmetric. The two dimensional motion of the packaging is completely described by the vertical, u, horizontal, w, and rotational, ρ, components of motion of its center of gravity as shown in Figure 5. The external forces applied to the packaging include both the vertical and horizontal (friction) forces at the primary impact end and the vertical force at the secondary end.

A standard numerical integration is performed to increment the solution from time (t_i) to time (t_{i+1}). Note that at time (t_i) the displacements and velocities of the three degrees of freedom describing the motion of the CG are known. The following procedure is applied at each time step:

1) The deformation of each of the limiters is calculated based on the geometry and initial displacements.

2) The forces and moments that the limiters exert on the packaging are determined using the above limiter deformations and their stress-strain characteristics (described below).

3) The component accelerations are determined from:

$$Mu'' + F_{v1} + F_{v2} - W = 0$$
$$Mw'' - F_h = 0$$
$$J\rho'' - F_{v1} x_{v1} + F_{v2} x_{v2} + F_h y_h = 0$$

4) The integrations are performed and the displacements and velocities are obtained at time (t_{i+1}).

The process is then repeated for increasing time until the secondary impact ends.

The key to the analysis is the program logic used in the determination of the impact limiter force in step 2. The wood is idealized as an elastic, perfectly plastic material up to a specified locking strain. The stress-strain input to ADOC for each region of the limiter is shown in Figure 6. The step in the curve is built into the stress strain law so that two crushable materials in series can be properly modeled.

The code first determines the crushing mode (shape and orientation of crush footprint relative to original undeformed limiter). Elements are then projected vertically from the footprint to the cask body or to the opposite boundary of the limiter. The strain in each element is calculated from the deformation of the end of the element on the target (footprint) divided by the undeformed length. The force in the element is then determined from the stress-strain curve for the material in that part of the limiter at this strain. If the element projection does not intersect the cask body, the element is in the portion of the limiter not backed up by the body. The effectiveness of the non backed up material is usually less than 100%; therefore this is an input parameter. The total vertical force applied to the packaging at a particular time is the sum of all of the element forces (and the moment due to the vertical force is the sum of the element moments). The horizontal friction force is also considered at the primary impact end.

Output from the code includes the complete history of displacements, accelerations and impact forces and the final impact limiter crush deformations.

TESTING

Both static and dynamic tests have been performed this past year on models of the TN-BRP and TN-Gemini Limiters. The models were 1/3 scale for the BRP and 1/2 scale for the Gemini. The static crush tests were performed to provide carefully measured force-deflection curves for the limiters for incorporation into the corresponding cask Safety Analysis Reports. The impact limiter models for the BRP cask were crushed on the end, side and two intermediate angles (30° and 60°). The impact limiter models for the Gemini cask were tested on the end, side and CG over corner (45°).

The static test limiter models were mounted on rigid fixtures that simulated the ends of the respective casks. The outside of the limiters were crushed by a large plate attached to the platen of the test machine. The BRP models were crushed in a large machine at the National Bureau of Standards and the Gemini models in a similar privately owned facility. Figure 7 shows the 30° test of the BRP limiter model in progress. Figure 8 shows a typical crushed limiter (TN-Gemini) after a corner test. Note that the crushing is quite local and the footprint is very much like that assumed in the analysis (the surface formed by the intersection of the target plane with the undeformed limiter).

The test results generally agreed quite well with the predictions made using the ADOC computer code described above. Two bounding analyses were performed -- one based on minimum wood strength and nil effectiveness of unbacked material, the other based on maximum wood strength and maximum likely effectiveness of unbacked material. The upper bound prediction assumed that all of the wood has the maximum strength and even the unbacked material is almost completely effective. This prediction is sufficiently conservative to envelope any possible effects cf shell and gusset buckling. This procedure produced upper and lower bound performance predictions with the actual behavior expected to be somewhere between these extremes.

The numerical results (listed below) from the BRP static tests correlate well with the ADOC predictions using the bounding analysis procedure.

COMPARISON OF BRP ONE-THIRD SCALE MODEL STATIC CRUSH TEST RESULTS WITH PREDICTIONS

TEST	ANGLE BETWEEN AXIS AND PLATEN (DEGREES)	MAXIMUM MEASURED FORCE (POUNDS)	PREDICTED FORCE RANGE (POUNDS)	MEASURED DEFLECTION (INCHES)	PREDICTED DEFLECTION RANGE (INCHES)
1	0 (side)	$.620 \times 10^6$	$.630$ to $.68 \times 10^6$	4.75	4.00 to 4.20
2	30	$.640 \times 10^6$	1.52 to 1.55×10^6	9.75	8.90 to 9.23
3	60	$.680 \times 10^6$	1.23 to 1.37×10^6	10.5	8.06 to 8.42
4	90 (end)	1.01×10^6	$.750$ to 1.20×10^6	3.85	2.90 to 4.35

Figure 9 shows a typical force deflection curve. This curve, the corner crush curve for the TN-Gemini model, shows the upper and lower bound predicted curves as well as the measured data. The experimental curve shows some irregularities, probably caused by both metal and wood instabilities (buckling and cracking). The agreement between the test curve and predictions is excellent in this case. In other cases the measured curve shifts from approximately the upper bound prediction to the lower bound prediction as the limiter is crushed due to tearing of the portion of the limiter structure that supports the unbacked material.

The dynamic tests were actual 30 foot free drop tests performed using models of the BRP and Gemini cask bodies with model limiters attached to each end. The BRP body was a rigid cylinder representing only the size and mass of the cask whereas the Gemini body was a complete model with inner and outer containers and simulated contents. The BRP tests were performed at the Sandia National Laboratories and the Gemini tests at Southwest Research Institute. End and shallow angle side drops were performed on the BRP model while the Gemini was dropped on the corner and side as well as on the top and at the shallow angle orientation. Figure 10 shows the BRP model after the end and side drop tests.

The impact limiters performed essentially as predicted in all cases. It should be noted that it is difficult to obtain accurate measurements of the cask rigid body deceleration during the end impact where the crush footprint equals the entire end area of the limiter, even at initial contact. The suddenly applied deceleration force results in a deceleration curve with a very short rise time, and in addition, an axial stress wave is generated in the cask body. Accelerometer data, when filtered below the axial natural frequency of the test body, correlates well with the ADOC bounding predictions. Figure 11 shows the filtered acceleration-time curve for the BRP end impact compared with the ADOC bounding predictions. Figure 12 shows the acceleration-time curve at the CG for the shallow angle side drop compared with the ADOC predictions. The predicted performance of the impact limiters in terms of accelerations, crush depth and duration agrees very well with the measured data.

A more complete discussion of the test results for the TN-Gemini models is presented in another paper.

CONCLUSIONS

It has been concluded from these studies that:

- Wood filled impact limiters are practical, and their performance is predictable using the ADOC computer program.

- The wood filled limiters absorb the required energy with only a slight elastic springback (a very slight bounce was observed in the dynamic tests).

- The dynamic loads and forces are difficult to measure, especially for the end impact. Accelerometer data, when properly filtered, correlates well with predictions.

- Crush deformations from the dynamic tests are less than static deformations for the same energy. In part this is due to the fact that less than 100% of the kinetic energy is dissipated by crushing of the limiter.

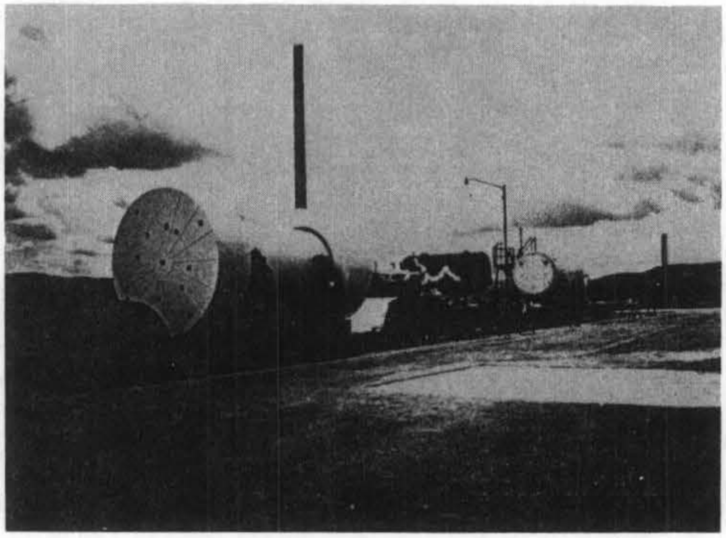

FIGURE 1 TN-BRP CASK COMPLETE WITH IMPACT LIMITERS

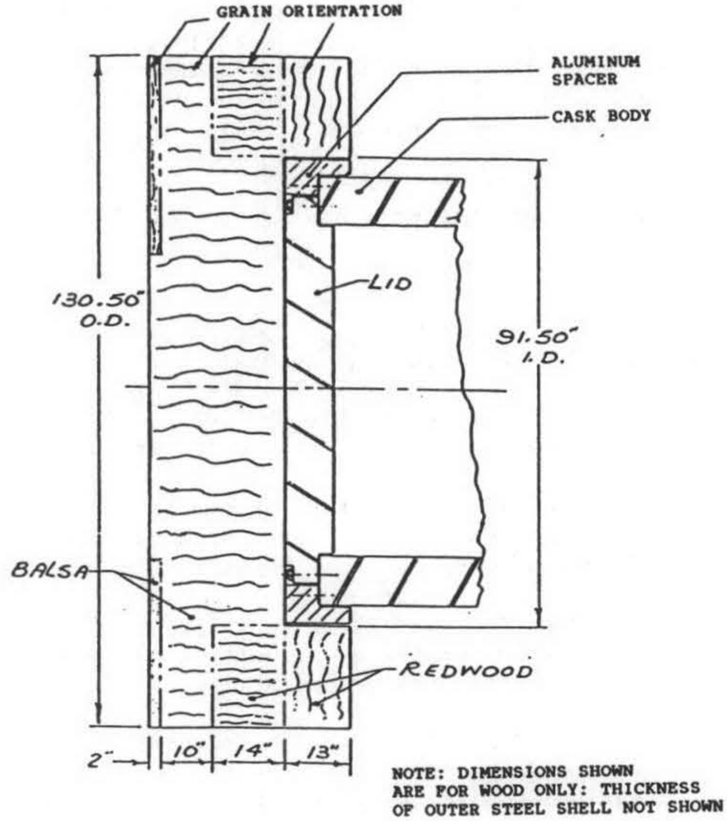

FIGURE 2 FRONT IMPACT LIMITER FOR BRP CASK

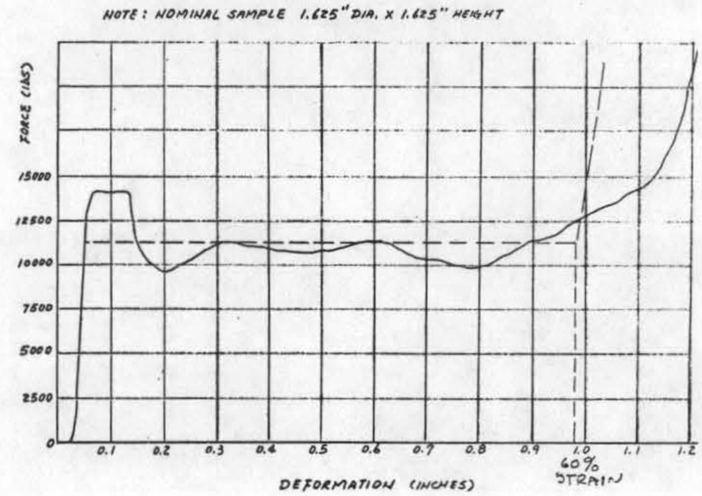

FIGURE 3 TYPICAL FORCE-DEFLECTION CURVE FOR REDWOOD

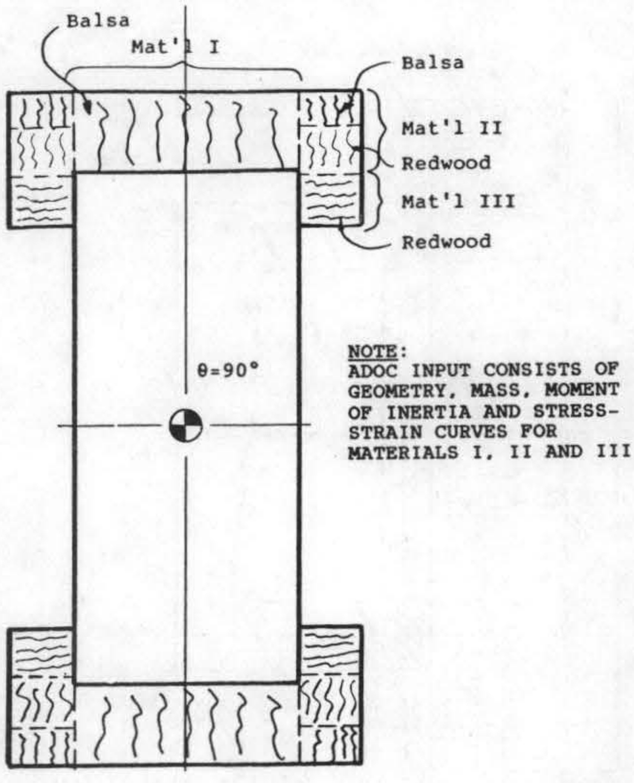

FIGURE 4 TYPICAL ADOC COMPUTER MODEL

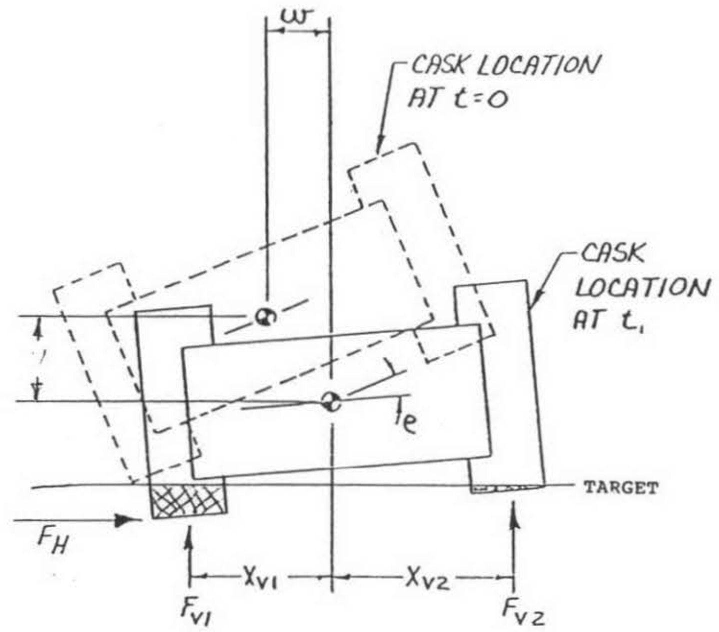

FIGURE 5 ADOC MODEL DISPLACEMENT AND FORCES

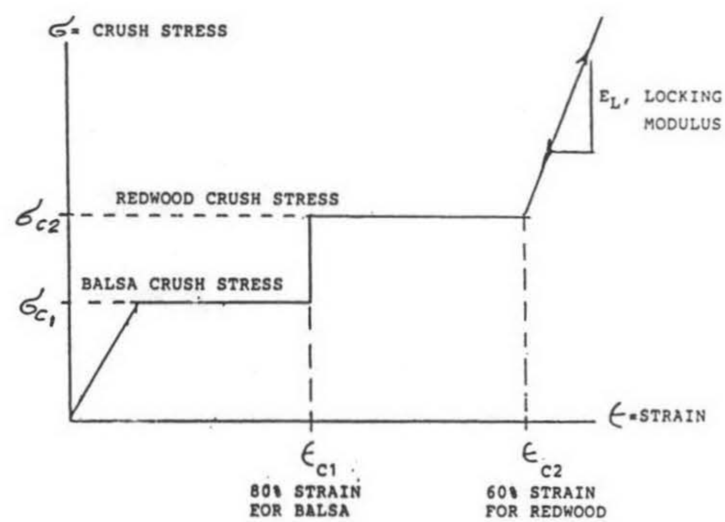

FIGURE 6 STRESS-STRAIN RELATIONSHIP OF CRUSHABLE MATERIALS

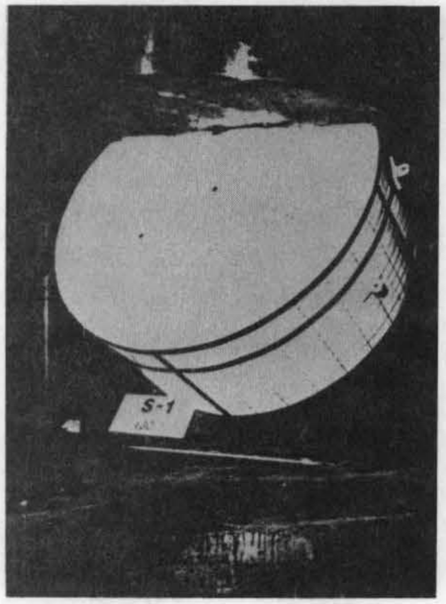

FIGURE 7 STATIC CRUSH TEST OF BRP MODEL LIMITER AT NBS

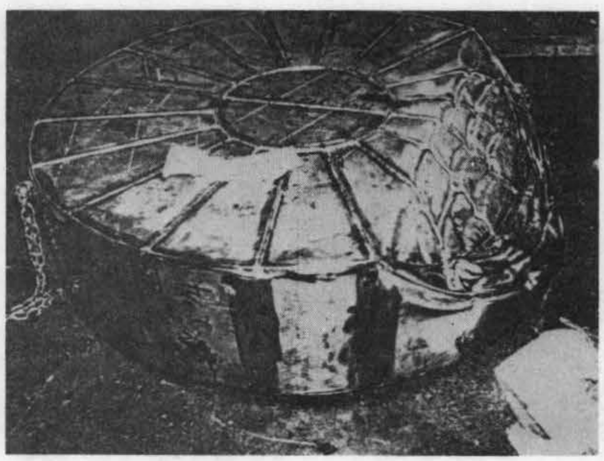

FIGURE 8 GEMINI MODEL LIMITER AFTER CORNER CRUSH TEST

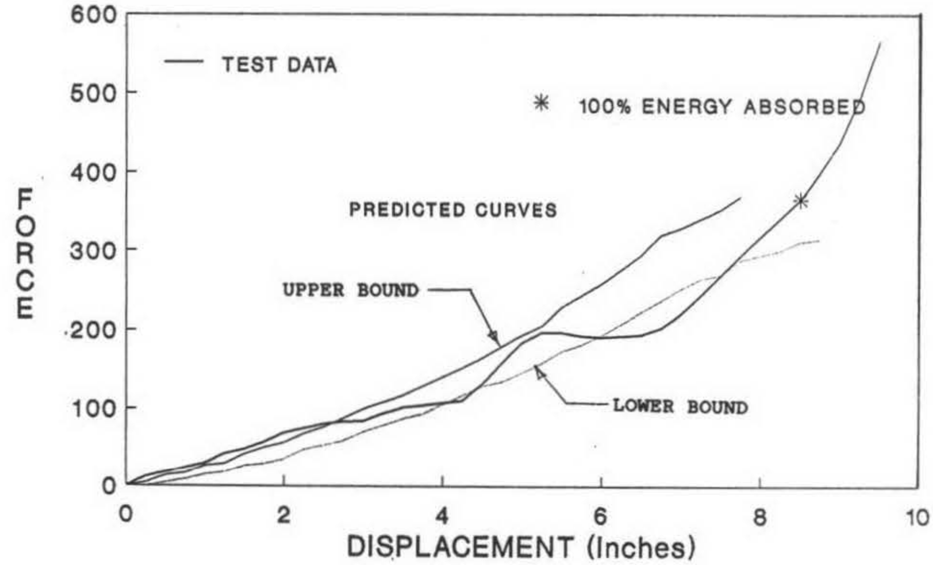

FIGURE 9 TN-GEMINI MODEL
TEST DATA AND PREDICTED FORCE-DISPLACEMENT CURVES
FOR CORNER CRUSH TEST

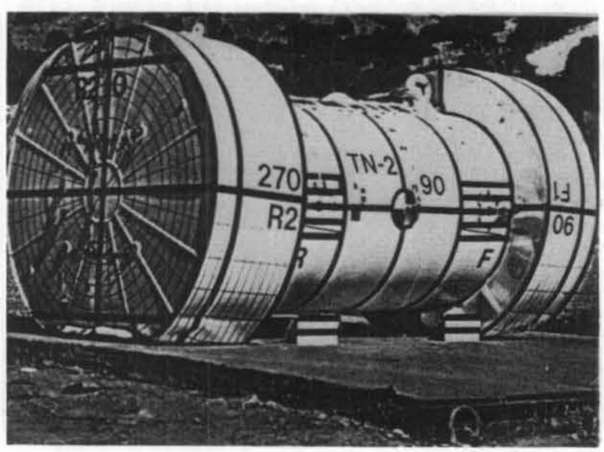

FIGURE 10 BRP MODEL AFTER SIDE DROP TEST

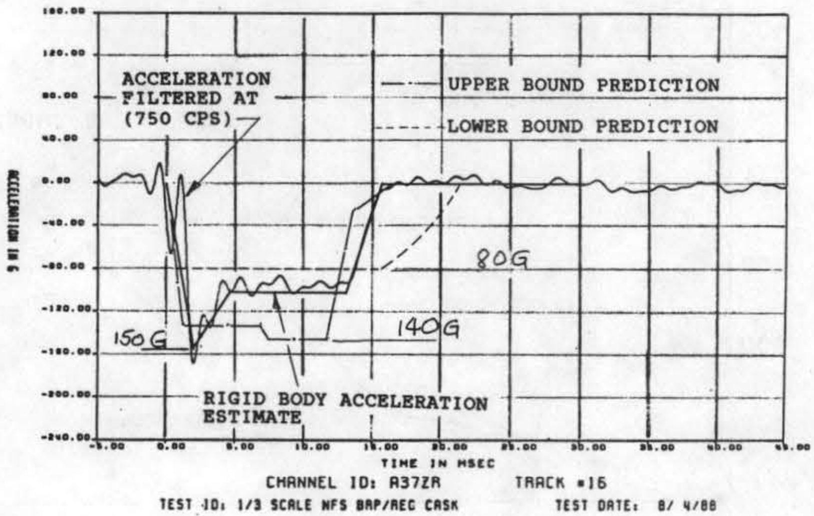

FIGURE 11 TN-BRP MODEL
COMPARISON OF MEASURED AND PREDICTED ACCELERATIONS, END DROP

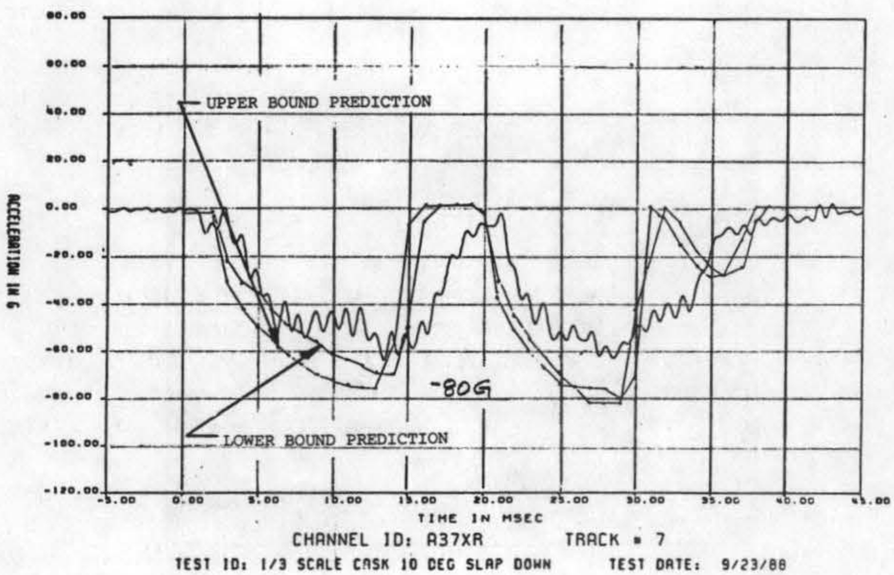

FIGURE 12 TN-BRP MODEL ACCELERATION TIME-TRACE
COMPARISON OF MEASURED AND PREDICTED ACCELERATIONS,
C.G. LOCATION, SHALLOW ANGLE SIDE DROP