VALIDATION OF ELASTIC-PLASTIC COMPUTER ANALYSES
FOR USE IN NUCLEAR WASTE SHIPPING CASK DESIGN

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ABSTRACT

GA Technologies designed the Defense High Level Waste (DHLW) Truck Shipping Cask (1) using state-of-the-art analytical techniques verified by model testing performed by Sandia National Laboratories (SNL). The DHLW cask has a thick-walled stainless steel body and incorporates integral stainless steel impact limiters that protect the two ends of the cask during the hypothetical accident condition 30-ft free drop. These integral impact limiters absorb the drop energy through gross plastic deformations. GA used elastic-plastic computer codes developed at Los Alamos and Lawrence Livermore Laboratories, HONDOII and DYNA3D, to analyze for this nonlinear behavior. In order to evaluate the analyses, GA developed elastic-plastic stress criteria that were adapted from the ASME Boiler and Pressure Vessel Code, Division I, Section III. This innovative design and analytical approach required test verification. Therefore, SNL performed 30-ft drop and puncture tests on a half-scale model of the DHLW cask. The testing confirmed that the analytical approach works and results in a safe, conservative design.

DISCUSSION

The DHLW design and analytical approach differs from traditional cask designs with "soft" impact limiters. These traditional casks are designed using simplified equivalent static loading of the cask due to the impact loading and are evaluated against the elastic analysis allowables defined in NRC Regulatory Guide 7.6.

For hypothetical accident conditions, the design criteria developed for the DHLW cask were adapted from Appendix F of the ASME B&PV Code for the design and analysis of Class 1, safety related nuclear components. These criteria were originally developed for the safe operation and survival of pressure vessels and components under the most severe static and dynamic loadings. They are most often applied to the analysis of nuclear power plant components under the most severe or, what are commonly called faulted plant conditions, such as the maximum credible earthquake and loss-of-cooling accident. These criteria assure that the structural integrity of the pressure boundary is maintained during such events while allowing gross general plastic deformations and damage requiring repair. The application of such criteria to the hypothetical accident conditions for cask design is identical in the need to maintain cask integrity and leak tightness during a severe event producing such deformations. The DHLW criteria further restrict deflections in the area of the closure seals and bolt stresses to assure the leak rate allowables are met. These latter aspects of the criteria will not be discussed in this paper.

The following stress criteria apply to containment boundary components when elastic-plastic finite element analysis is used:

Primary membrane stress intensity
(maximum average effective stress
through a section)

$$P_M < S_y + 1/3\ (S_{uT} - S_y)$$

Local primary membrane plus bending stress intensity

(maximum effective stress in the cask)

$$P_L + P_b < \text{greater of } .7\ S_{uT} \text{ or } S_y + 1/3\ (S_{uT} - S_y)$$

where: S_y = yield stress
S_{uT} = ultimate true stress

It should be recognized that the above criteria are conservative for dynamic impact since they are based on load-controlled principles in which there is a large margin between the allowable stresses and the maximum load-carrying capacity of the material (P_{max}) as shown in Fig. 1. The cask drop conditions are energy-controlled events where the structure must absorb the kinetic energy of impact. The above limits on stress severely restrict the allowable strain energy absorbed by the cask material to a small fraction of the energy which it is capable of absorbing. The total energy that can be absorbed by the material is the complete area under the curve up to fracture (see Fig. 1).

The above stress criteria were used to evaluate the DHLW cask design based on large deformation, elastic-plastic analysis. A half-scale model of this design was built and tested at Sandia National Laboratories as described in Refs. 2 and 4. Figure 2 shows a cutaway drawing of the cask. The results were used to correlate test and analytical results to establish the validity of using nonlinear computer analysis to demonstrate compliance with regulations. The following test sequence was performed:

1) 30-ft bottom-end drop
2) 30-ft closure-end drop
3) 40-in. gas sample-port-puncture drop
4) 30-ft side-slap-down drop

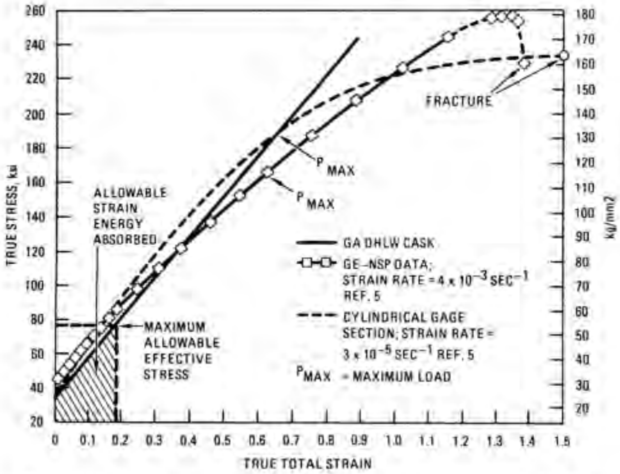
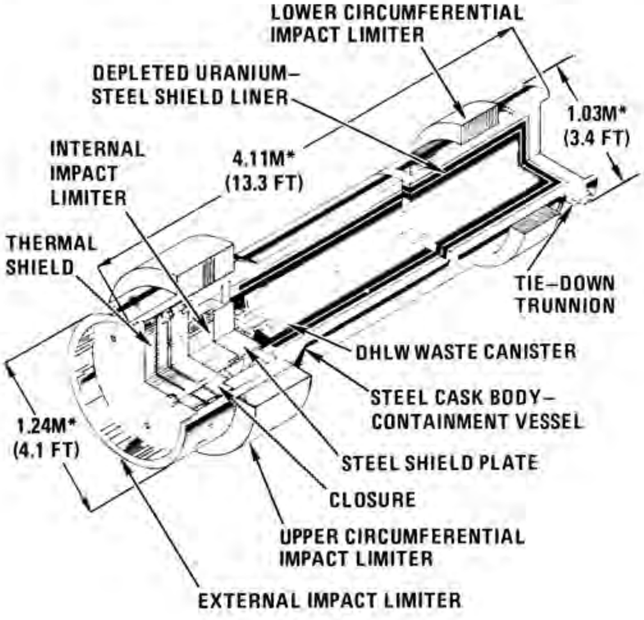


Fig. 1. True-stress versus true-strain data for annealed 304 stainless steel.



***DIMENSIONS SHOWN ARE FULL SCALE. TESTS WERE PERFORMED ON HALF SCALE MODEL**

Fig. 2. DHLW truck cask.

5) 40-in. closure-puncture drop

6) 30-ft center-of-gravity over-bottom-corner drop

7) 30-ft side-slap-down drop

All tests were completed successfully and verified that the analytical design approach is conservative. The cask maintained its integrity for all drops. There was no change in leakage throughout the test sequence.

Permanent deformations in the seal area were nearly nil, as predicted by analysis. Deformations in other regions were consistently less than predicted by analysis. Decelerations correlated very well and were typically lower than predicted by analysis.

This paper presents detailed comparisons of the 30-ft bottom-end and closure-end drop test results with analytical predictions. These are the most critical events that the cask must withstand. The bottom-end drop event imparts the highest accelerations in the cask of any drop orientation. The closure-end drop causes the highest loadings on the closure.

The two end-drop analyses are axisymmetrical and were performed using HONDOII (6). Figures 3 and 4 show the models used for the analyses. Several simplifying modeling assumptions that affect the comparison to test results are as follows:

1) Waste Contents: The contents were conservatively modeled as a solid homogeneous elastic material for the entire canister, including the pintle. In reality, the stainless steel canister is not normally filled to the top. By modeling the contents in this way, the canister will not absorb energy by deforming plastically; the energy is conservatively transferred through the honeycomb internal impact limiter to the closure. However, for the test, the canister was filled with 80% simulated glass waste and several layers of lead in order to increase the canister weight to the maximum design weight.

2) The modeling of the shear ring and the shield liner is simplified for both analyses while still maintaining the correct loading onto the containment boundary.

3) No friction or damping was modeled. For a one-degree-of-freedom system, the equation of motion can be written as follows:

$$M\ddot{x} = F_{int} + F_{ext} + F_{fric} \qquad \text{Eq. (1)}$$

$$F_{int} = Kx + C\dot{x} \qquad \text{Eq. (2)}$$

where

M = mass
$\ddot{x}$ = acceleration
F_{int}, F_{ext}, F_{fric} = Internal, external and frictional force, respectively
K = spring constant
x = displacement
C = damping coefficient
$\dot{x}$ = velocity

The finite element codes used in the analysis do not include F_{fric} and $C\dot{x}$; therefore all the energy has to be absorbed by deformation. In cases like the 30-ft drop events where the normal force is very high, friction between two stainless steel surfaces can have a significant effect on the cask behavior, and ignoring it is very conservative. Lack of damping becomes more significant and conservative as the duration of the events increases.

4) Strain Rate Effects: No strain rate effects are modeled in the analysis. The following properties are used for stainless steel:

Yield stress = 35,000 psi
Strain Hardening Modulus = 234,400 psi
Elastic Modulus = 28.3 x 10^6 psi

RESULTS

The analysis must simulate the behavior of the cask to be valid and must provide conservative analyt-

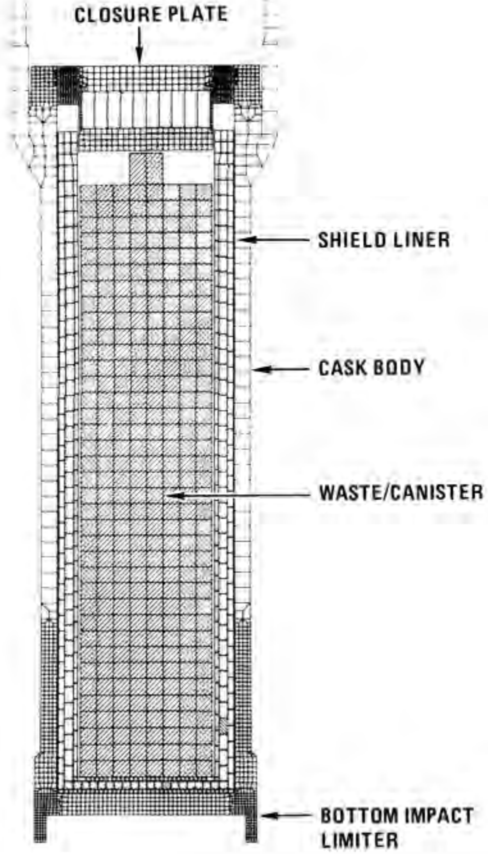


Fig. 3. DHLW bottom-end drop, finite element model.

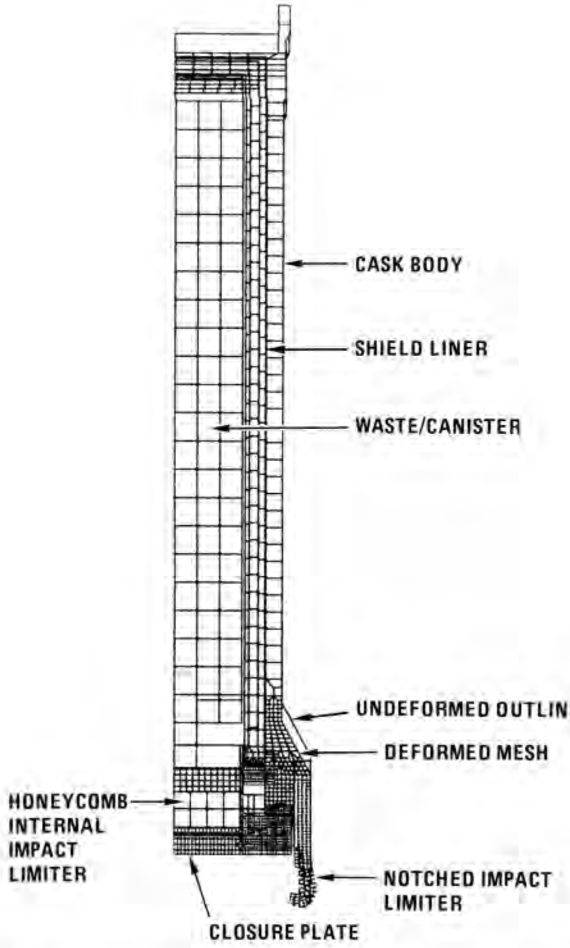


Fig. 4. DHLW closure-end drop finite element model showing deformed shape.

ical cask design data. In order to show that the finite element analyses performed on the cask correctly model the dynamic event, and provide conservative results that can be used to show the cask design is conservative, the following comparisons are made with half-scale test results:

- Accelerations
- Duration of primary impact
- Deformations

The following sections summarize the comparisons.

Accelerations

In order to make a valid comparison between test data and analytical results, both were filtered at the same frequency level. The half-scale test results were filtered with a low-pass filter at 2 KHZ. The analytical results were filtered at an equivalent 1 KHZ full-scale level using the Cooley-Tukey Fourier transform program developed by Brenner (3). This frequency level is high enough to assure that the dynamic response of the cask is included in the numerical data.

Table I presents the results of the acceleration comparisons. The comparisons show that the analyses are conservative as the analytical accelerations are consistently the same or greater than the test accelerations. The discrepancy between the closure and contents values during the closure-end drop is due to the fact that the contents was conservatively modeled as a solid homogeneous elastic material, as discussed earlier. During the drop, the canister pintle buckled and, therefore, absorbed much of the contents' energy, not loading the closure as much as the analysis conservatively predicted.

Duration of Main Event

In order to show that the analyses model the actual dynamic behavior, it is essential that duration of the primary impact compares closely. Table I shows a comparison of the time before the cask body rebounds. In spite of differences in time definition, as explained in Note C, Table I, the times correlate within 6% on both tests. This agreement indicates that both the analysis and the test measured the same dynamic behavior.

Displacements

Results show that analytical displacements are consistently larger than the test measurements. During all the tests, most of the deformation occurred in the area of the impact limiters. The cask body deformations were minimal, and there was negligible deformation in the closure seal area.

Figure 5 shows the deformed shape of the bottom of the cask after the 30-ft bottom-end drop. The deformations of the impact limiter are much larger in the analysis than resulted from the test.

The deformation on the notched impact limiter due to the closure-end drop also shows that the analysis is very conservative. During this drop, the analysis

TABLE I

Comparison of Acceleration and Duration Data

Accelerometer Number	Location	Bottom-End Drop			Closure-End Drop		
		Test(a)	Analysis	Analysis/Test Ratio	Test(a)	Analysis	Analysis/Test Ratio
1 and 2	Cask body	530 g	773 g	1.46	275 g	334 g	1.21
3	Closure	(b)	1822 g	--	490 g	1410 g	2.97(d)
4	Shield sleeve	940 g	928 g	0.99	288 g	460 g	1.6
5	Contents	890 g	838 g	0.94	93 g	242 g	2.6(d)
1 and 2 average	Time before cask body rebounds(c)	4.65 msec	4.8 msec	1.03	9.4 msec	10 msec	1.06

(a) Test acceleration values have been divided by two to transform to full-scale equivalent. Test time values have been multiplied by two to transform to full-scale equivalent.

(b) Suspect data.

(c) Test times were measured to the point of zero velocity (or minimum velocity) using integrated velocity history. Analysis times were measured to the point of minimum kinetic energy of the complete cask.

(d) For analysis, contents were conservatively modeled as a solid homogenous elastic material. See discussion in text.

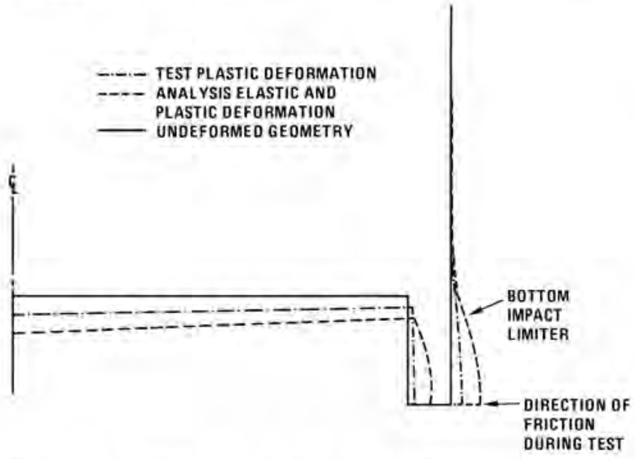


Fig. 5. Bottom end of cask after 30-ft bottom-end drop.

indicates that the notched impact limiter bent inwards much more than occurred during the test. During the analysis, four teeth in the impact limiter were effective, as shown in Fig. 6. In the test, only two teeth closed up while the third tooth deformed in some areas and not in others.

The results of both tests confirm that the drop energy is not only absorbed by plastic deformation, as modeled, but also by other mechanisms, such as friction, damping and heat generation.

CONCLUSIONS

The half-scale tests performed on the DHLW cask by SNL confirm that the DHLW cask design is capable of withstanding all the required regulatory drop environments and that the analytical approach used to design it is conservative and results in a safe cask. The conservative analytical results can be attributed to several conservative assumptions made for the analyses. Examples of these assumptions are as follows:

- Strain rate effects were not included
- Contents were treated elastically
- Friction between interfaces was not included
- Material damping terms were not included.

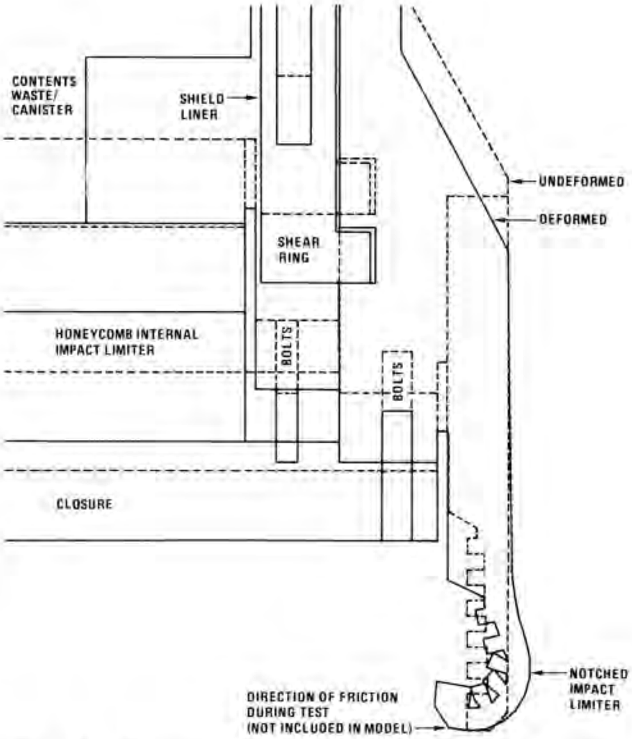


Fig. 6. Closure end of cask after 30-ft closure-end drop (analytical results).

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