Comparison of Structural Integrity of Ductile Iron and Lead-Shielded Stainless Steel Casks for Transportation and Storage of High-Level Waste

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INTRODUCTION

Nine-meter (30-foot) drop simulations of three different types of transportation casks, a monolithic ductile iron (DI), a monolithic stainless steel (SS), and a lead-shielded stainless steel (SS/Pb) sandwich, were simulated using DYNA3D. The results show that the monolithic casks are much stiffer than the stainless steel/lead sandwich cask. The largest difference was observed between the DI cask and the SS/Pb sandwich cask. Although the SS/Pb cask experiences considerable plastic deformation, none of them experiences failure by rupture, and they all perform within the requirements of Regulatory Guide 7.6, Revision 1 (1978) and 10CFR71 (1988). To better compare the results, stress- and strain-based factors of safety were calculated for all of the simulations. These calculations show that the DI cask has a larger margin of safety than the SS/Pb sandwich cask, while the monolithic SS cask has a larger margin of safety than the monolithic DI cask. Finally, to address the concern over the brittleness of the DI casks, critical flaw sizes were calculated. All flaws required for crack propagation were larger than the detectable flaws by current inspection techniques. Overall, the results of this study indicate that DI has sufficient strength, ductility, and fracture toughness to be considered as a structural material for transport casks.

TEST-SETUP

A drop test for high impact was designed for a direct comparison between two different casks. The test-procedure consisted of the following four steps:

- the target cask lies flat on an unyielding horizontal surface;
- another cask is positioned 9 meters (30 feet) above the top surface of the target cask;
- both casks are aligned so that their center lines form a 90-degree angle when projected onto the horizontal surface, which creates the most severe loading condition by the point contact between the two casks; and

- the suspended cask free falls, impacting the target cask; the target cask is kept stationary during the free fall period, after which it is subject to motion due to the impact.

The test criteria were chosen to create severe loading conditions, beyond those prescribed by the regulations. These severe loading conditions would allow for the investigation of the introduction of any plastic deformation and the subsequent effects on the structure. Four different configurations of DI and SS cask combinations were considered:

- a monolithic DI cask was dropped on top of a monolithic SS cask;
- a monolithic SS cask was dropped on top of a monolithic DI cask;
- a monolithic DI cask was dropped on top of a SS/Pb sandwich cask; and
- a SS/Pb sandwich cask was dropped on top of a monolithic DI cask.

All casks are generic and simple and are based on designs from Sandia National Laboratories (SNL) (Sorenson 1986) for a cost-comparison study. The casks were designed for transportation by rail of 10 year-old spent fuel (Buchholz 1983). The lids were identical on all three casks, so they did not influence the outcome of the economic analysis, and therefore were not included in the original design. For this analysis, however, lids had to be added which resulted in slightly different cask weights than the original design. The casks were assumed to be empty with no impact limiters.

FINITE ELEMENT ANALYSIS

For the analysis, DYNA3D, a nonlinear, explicit, three-dimensional finite element code for solid and structural mechanics, was used. The models simulated drop tests consisting of two casks; one cask resting on a rigid surface, and the other falling freely from a 9-meter (30-feet) height on the other cask. The initial condition of the analysis positioned the falling cask in contact with the target cask with an initial speed of 13.4 m/s (527 in/sec), which corresponds to the speed of the cask just before the dynamics of the collision take place.

Prior to this drop test analysis, benchmarking was performed to assess the accuracy of the model and different features of DYNA3D in the analysis. Simulations were performed of an end drop of an aluminum annulus cylinder onto an unyielding surface. This experiment included data on plastic deformation of the structural material which was important in the benchmarking process. The results from DYNA3D were then compared to experimental results and those from other finite element codes (Glass 1989; Glass et. al. 1985). It was found that the results were in good agreement with the experimental data and within the range of the results from the other finite element codes. In addition, these experiments were used to verify different boundary conditions and some of the features of DYNA3D such as different material models.

To reduce CPU-time and disk-space requirements, quarter-symmetry was used in all models. This is only possible when the actual physical model has two planes of symmetry, therefore; the lid was assumed to be rigidly connected to the cask body which made the top and bottom of the cask identical. This assumption was feasible since the simulated test did not result in stresses near the lid area that would be capable of causing it to fail. For the same reasons, the lid of the DI cask was assumed to be ductile iron.

A "stonewall" was used to model the rigid surface underneath the bottom cask, and a "sliding interface" without friction was specified between the two casks (Stillman 1992, page 188). To model the friction between the stainless steel and lead layers, DYNA3D has the option to specify static and kinetic friction within the plane of movement. Due to lack of data, however, only two extreme cases were considered:

- rigidly connected nodes between the layers, i.e., 100% friction, thus no relative movement between the layers was allowed; and
- sliding surfaces with no friction between the layers, i.e., the layers were allowed to move freely with respect to each other. Thick shell elements were used to model the SS layers.

For the comparative analysis, the former case represents the most favorable condition for the sandwich cask.

Material Models

In all the models, an isotropic elastic-plastic material model was used for the materials, which represents both the linear elastic and the plastic domain of the stress-strain curve with straight lines. The material properties for DI and SS were obtained from ASTM Standard A 874 and A 473, respectively. These standards prescribe minimum allowable values of yield and ultimate strength along with failure strain, which results in the weakest possible casks that would be acceptable. Values used for lead were taken from a report by Adams et al. (1981). Fracture toughness data were obtained from a report by Salzbrenner and Crenshaw (1990). These values are summarized in Table 1.

Failure Criteria

When considered for cask structure applications, DI may be limited more by considerations of ductility and fracture toughness rather than by strength. The U.S. Nuclear Regulatory Commission design guidelines for transport casks (NRC 1978) implies that the cask should be able to elastically withstand all loads applied during normal use or hypothetical accident conditions (McConnell 1993). Specifically, it is generally assumed that application of such loads will not cause through-wall plasticity. If this condition is applied, the necessity of having a material capable of undergoing extreme plastic deformation is greatly diminished. Theoretically, only a limited tensile

Table 1 Material Properties for DI, SS, and Pb.

Material	DI	SS	Pb
Young's Modulus E (105MPa)	1.72	1.93	1.91
Poisson's Ratio ν	0.27	0.27	0.42
Yield Strength σ_y (MPa)	30 207	30 207	30
Ultimate Strength (MPa)	45 310	75 517	-
Tangent Modulus slope (i.e., of the inelastic part of a uniaxial stress vs. strain curve (Whirley 1991, page 73)) E_T (10^3MPa)	0.71	1.53	0.03
Total Elongation (%)	12	40	-
Density ρ (g/cm^3)	7.2	8.02	11.3
Fracture Toughness, K_{JC} ($\text{MPa}\cdot\sqrt{\text{m}}$) @-29ºC	73.8	-	-

ductility might be required to withstand local plastic deformation. As a practical matter, however, it is prudent to require sufficiently high ductility as a means of demonstrating a margin of safety against tearing failure.

Six models were analyzed for the four drop test experiments. In the first model a DI cask was allowed to free fall onto a monolithic SS cask. The second model was the reverse situation of the first; a monolithic SS cask was dropped on top of the monolithic DI cask. In the third model, a DI cask was dropped onto a SS/Pb sandwich cask. The fourth analysis was the reverse setup of the previous case. The interface between the SS and Pb layers were "tied" and no relative displacement across the interface was allowed. The fifth model was similar to the third, but instead of merging the nodes between the two materials, they were kept separate and allowed to slide without friction and separate. The sixth model was similar to the fourth but allowed for sliding interface between SS and Pb. In all of these models, the mechanical response of the DI and SS was assessed in terms of three different failure criteria to compare their performance under the loading conditions.

First, the *maximum tensile stress* in the casks was calculated and compared with the NRC Regulatory Guide 7.6 (1978) allowable stress values. For the loading condition of the experiments, the allowable stress in a cask is the lesser of $2.4S_m$ or $0.7S_u$. The value of S_m is based on the American Society of Mechanical Engineers (ASME) design stress intensity and is, for ferritic steels, the smaller of two-thirds of the yield strength (S_y) or one fourth of the ultimate strength (S_u). The regulatory allowable stress $(= 2.4S_m)$ is, therefore, 223 MPa (32,400 psi) for DI and 309 MPa (44,880 psi) for SS. The stress-based failure criterion, therefore, occurs when:

$$\mathrm{FS}_\sigma = 2.4\frac{S_m}{S_a} < 1 \Rightarrow \text{failure},$$

where S_a is the maximum applied tensile stress and FS_σ is the factor of safety in terms of stress.

A second failure criterion is based on the *strain to failure*. This deformation-based failure criterion presents a more rational basis for determining the actual physical response of a structure than the NRC/ASME stress-based method (McConnell 1993). The strain-based failure criterion compares the maximum true strain in a structure (ε_a) to the true strain at failure (ε_f) for the respective material. Hence, the failure criterion based on strain becomes:

$$FS_\varepsilon = \frac{\varepsilon_f}{\varepsilon_a} < 1 \Rightarrow \mathit{failure}.$$

For DI as a ferritic material, the possibility exists, that, under certain circumstances, the material may fail in a brittle manner at stresses below the yield stress. Therefore, a third failure analysis, *fracture mechanics analysis*, was performed to determine the minimum flaw size that would cause crack initiation in the structure under the given loading condition. To this end, the driving force for the initiation of brittle fracture was compared with the material's inherent resistance to fracture, the fracture toughness (McConnell 1993). The critical flaw size (a_c) for crack propagation, and in turn brittle failure, can be calculated from the following relationship:

$$a_c = \frac{1}{\pi}\left[\frac{K_{Jc}}{S_a C}\right]^2,$$

where K_{Jc} is fracture toughness, S_a is axial tensile stress, and C is a geometry factor, generally equal to 1.1 to 1.2. Thus, the largest flaw that can be tolerated by the cask at a specified stress level can be computed. This equation is valid only for the elastic regime, and was used despite the fact that some plastic deformation occurred during the impact.

DISCUSSION OF RESULTS

The general results from these analyses indicate that DI has sufficient strength, ductility, and fracture toughness to be considered for structural applications in transport casks. The data from these analyses are summarized in Table 2.

In the first model, a DI cask was allowed to free fall onto a monolithic SS cask. During the impact, both casks underwent plastic deformation. The permanent vertical deformation at the center of the SS cask was more than two and a half times as big as at the same location in the DI cask. The second model was the reverse situation of the first; a monolithic SS cask was dropped on top of the monolithic DI cask. Qualitatively, the results were identical to those in the first case. Quantitatively, the deformations were somewhat smaller, due to the slightly smaller mass of the falling cask.

In the third model, a DI cask was dropped onto a SS/Pb sandwich cask. In this analysis, the deformation in the SS/Pb cask was significantly higher than in the previous analyses. The cask wall penetrated the cavity of the cask by more than 35.6 cm (14 in). After the

Table 2 Summary of Drop-Test Data.

Models	DI onto SS	SS onto DI	DI onto SS/Pb (tied interface)	SS/Pb onto DI (tied interface)	DI onto SS/Pb (sliding interface)	SS/Pb onto DI (sliding interface)
Impact duration (sec)	0.021	0.017	0.0825	0.075	0.110	0.090
Rebound sp (m/sec)	2.9	3.7	5.0	5.2	2.7	2.8
Perm plastic def (cm)	2.06 (DI)	2.97 (DI)	0.00 (DI)	0.00 (DI)	0.00 (DI)	0.00 (DI)
	5.46 (SS)	5.46 (SS)	22.0 (SS/Pb)	19.7 (SS/Pb)	43.4 (SS/Pb)	41.1 (SS/Pb)
Max eff plastic st (%)	4.60 (DI)	5.39 (DI)	0.00 (DI)	0.00 (DI)	0.00 (DI)	0.00 (DI)
	9.50 (SS)	9.06 (SS)	5.74 (SS)	5.55 (SS)	5.12 (SS)	5.10 (SS)
	-	-	43.7 (Pb)	43.8 (Pb)	12.92 (Pb)	8.51 (Pb)
Max K.E. (kJ)	1245	1258	1245	1190	1245	1190
Final K.E. (kJ)	54	103	175	175	54	52

top cask had bounced back and the elastic strains were released, the permanent plastic deformation was still 22.0 cm (8.7 in). Since most of the kinetic energy was converted into plastic deformation of the SS/Pb cask, the deformation in the DI cask was negligible. The fourth analysis was the reverse setup of the previous case. Once more, the deformations were somewhat smaller as expected, since the lighter SS/Pb cask was the impacting cask. The deformations in the DI cask were again negligible.

The fifth model was the same situation as the third case, but instead of merging the nodes between the two materials, they were allowed to slide without friction and separate. This model resulted in even higher plastic deformation in the sandwich cask, whereas the plastic deformations in the DI cask were again negligible. The permanent deformation at the center of the cask was 43.4 cm (17.1 in) after the impact, which is about half the diameter of the cavity that would hold the payload. Case six gave results similar to that of case five. With the SS/Pb cask on top, the impact energy was lower than in the previous case which, again, resulted in smaller deformation.

With the values obtained from the finite element calculations, factors of safety were calculated for the DI casks under the given loading conditions. The factor of safety shows how close a structure is to failure under given conditions. With that information, the calculated results can be more easily interpreted. To calculate the factors of safety, the maximum values for effective plastic strain and von Mises stress were taken from the simulations at various time steps and factors of safety were calculated. The minimum values of factors of safety over the impact duration are given in Table 3.

Although the stress-based criterion predicts failure in the DI cask for the impact between the two monolithic casks, it is unlikely that failure would occur in a real drop test. The criterion uses a conservative value for the allowable stress, which is considerably below the ultimate strength of the material where failure by rupture occurs. The criterion also does not consider that a large amount of energy is converted into permanent plastic deformation by performing work on the structure before failure occurs. This "buffer" does not show in this criterion. The strain-based criterion, which yields a higher factor of safety, is a more realistic criterion since it takes the deformation into account. Also, the stresses used in the stress-based criterion are maximum values that occur locally and are not through-wall stresses.

Table 3 Factors of Safety for Finite Element Analyses.

	FS_σ **(ASME Design Stress Intensity)**		FS_ε **(True Strain Failure Criterion)**	
	DI	**SS**	**DI**	**SS**
DI onto SS	0.76	1.12	2.61	4.21
SS onto DI	0.74	1.12	2.23	4.41
DI onto SS/Pb (merged)	1.44	1.24	-	6.97
SS/Pb onto DI (merged)	1.29	1.25	-	7.21
DI onto SS/Pb (sliding)	1.42	1.26	-	7.82
SS/Pb onto DI (sliding)	1.42	1.26	-	7.84

The critical crack size was calculated for the DI casks in the simulated drop tests. The smallest critical flaws for each case are given in Table 4. The highest stresses occurred in the case which involved the two monolithic casks. Since both casks are very stiff and strong, a smaller amount of energy was absorbed by plastic deformation. This results in a very short and intense impact with high peak stresses. No brittle failure should occur since an existing flaw of size 1.59 cm can be easily detected by current inspection methods. Since the stresses change very rapidly during the impact, it is possible that some of the maximum values of stress were not caught if they occurred between two time steps.

CONCLUSIONS

In all the cases considered in this work, plastic deformation after the impact was observed due to the impact, but not large enough to cause failure by rupture. The initial point contact between the two casks causes high interface stresses and because of different material properties, the casks behave differently. The data acquired to this point shows better structural integrity of monolithic DI casks over sandwich SS/Pb casks, but a slight advantage of the monolithic SS cask over a DI cask.

Since no experimental data exist for this test-setup, the results have to be interpreted carefully. The models of the SS/Pb cask with nodes merged between different materials and then with sliding interfaces yield much different results. These cases are the two extremes of the model, so the anticipated transport scenarios will be somewhere in between. This shows, that there are a number of unknown parameters that cannot be determined without experimental results. The best model of the material interface will most likely have a sliding interface with a coefficient of friction in the plane of contact.

The results obtained from these analyses suggest that DI can be assigned a structural role in transport cask designs. The most obvious benefit of qualifying DI for use in transport casks results in reduction of the use of expensive containment material such as stainless steel. The ability to partially or completely eliminate such material may lead to substantial economic gains through lower material and fabrication costs.

ACKNOWLEDGMENTS

The funding for the research project was provided by Sandia National Laboratories. The authors wish to acknowledge continued technical support from Mr. Ken Golliher formerly with the Department of Energy.

Table 4 Minimum Critical Flaws Calculated From the Finite Element Results.

Casks	DI-SS	SS-DI	DI-SS/Pb (nodes merged)	SS/Pb-DI (nodes merged)	DI-SS/Pb (sliding interfaces)	SS/Pb-DI (sliding interfaces)
Crit flaw (cm)	1.59	1.93	7.31	5.83	7.14	7.12

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