Effect of Lead Shielding on Cask Pin Puncture[1]

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INTRODUCTION

The overall weight of a spent-fuel transport cask is minimized when its gamma shield consists of depleted uranium only; however, because of its high modulus of elasticity, a gamma shield of depleted uranium only, may not meet the 10 CFR 71 puncture requirements. The hypothetical accident puncture load is that load which is sustained by the cask when it drops from a 40-inch height onto a 6-inch diameter mild steel bar. This concern prompted investigation of hybrid gamma shields consisting of an outer layer of lead with an inner layer of depleted uranium; these gamma shield were assumed to be sandwiched between two stainless steel shells. The outer steel shell is permitted to plastically deform during a puncture event; however, if only depleted uranium is present, the puncture forces are transmitted through the depleted uranium and a permanent dimple in the inner containment shell may result. A shell of lead outside the depleted uranium shell acts as a shock absorber, diffusing the concentrated load of the pin. The purpose of this study was to determine the optimum thickness combination of a multiwall, depleted uranium/lead gamma shield for a spent-fuel transportation cask. Since depleted uranium is a more effective gamma shield than lead, the optimum gamma shield design will be composed primarily of depleted uranium with a minimum thickness of lead backing the outer shell. The lead thickness must be sufficient to alleviate regulatory concerns associated with the assumed strength of the depleted uranium shell.

ANALYSIS METHODS

The analysis was performed by the finite element method utilizing the ANSYS computer program and by use of the Nelm's empirical equation. In order to determine the proper boundary for the simulated quasi-static analysis, a simple stress wave propagation scheme was applied. Based on

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specified rail/barge cask dimensions and using austenitic stainless steel, the support locations can justifiably be considered at each end of the cask. To determine the effect of different thickness combinations of a depleted uranium and lead gamma shield, a series of 18 structural analyses were performed. The corresponding cask weight and the equivalent acceleration were calculated for each case so as to balance the puncture load, which is represented as a quasi-static, uniformly distributed pressure of 51,300 psi, over the area of the puncture pin surface.

The pin puncture analyses are classically performed by the use of Nelm's equation, an empirical relationship between the weight of the cask and ultimate tensile strength of the outer shell, which determines the necessary thickness of the outer shell. However, Nelm's equation only applies to outer steel shells with a lead gamma shield, and does not specify the minimum thickness of lead needed to protect the inner shell.

A finite element model was developed to permit the calculation of the inner containment wall stresses as a function of lead layer thickness, with the depleted uranium layer adjusted to maintain a constant gamma shield effectiveness; thus, the depleted uranium layer was thickened as the lead layer was thinned. The cask includes a 1.0-inch thick inner stainless steel shell and a 2.2-inch thick outer stainless steel shell, which were sized by a previous computer analysis of a 100-ton rail/barge cask for a 30-foot horizontal drop onto an unyielding surface.

GEOMETRIC CONFIGURATION

This study considers the cask with a specified inner diameter of 64.79 inches, a constant inner shell thickness of 1.0 inch, a varied gamma shield thickness, and a constant outer shell thickness of 2.2 inches. A three-dimensional finite element model was constructed for the analysis, as shown below.

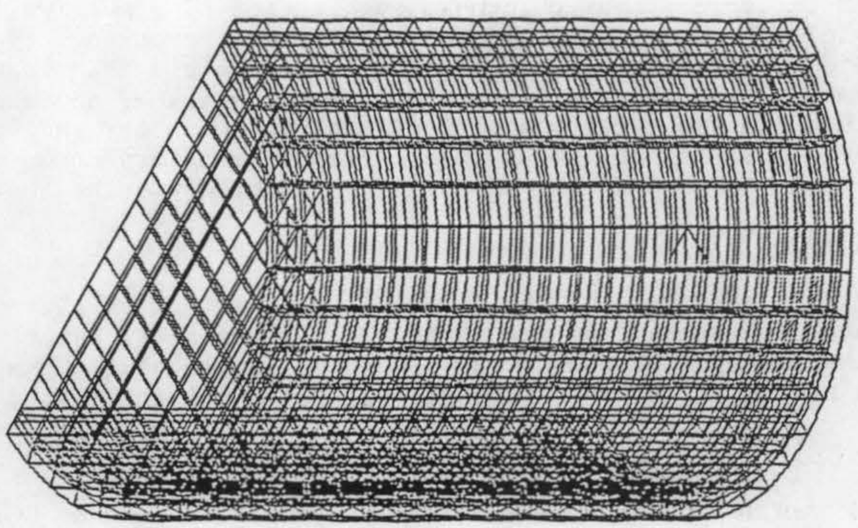

Figure 1 Three-Dimensional ANSYS Finite Element Model

The following considerations were incorporated into the modeling:

1. The cask is considered as a four-shell (steel-depleted uranium-lead-steel) cylindrical tube. The inner shell is modeled using a thin shell element (ANSYS STIF63). The other three shells are modeled as an assembly of three-dimensional brick elements (ANSYS STIF45).
2. The solid end is represented by a very stiff grid assembly. The ANSYS STIF4 element is used.
3. Only a quarter model is required to evaluate the structural response of a cask for the pin puncture condition, because the critical puncture location is at the midpoint of the cask body.

DETERMINATION OF BOUNDARY LOCATION

To consider a steel object, with dimensions appropriate for a rail/barge cask, dropping from a 40-inch height, the propagation length of the stress wave must be investigated in order to determine the proper boundary location of the cask for the puncture accident.

The material properties of austenitic stainless steel at 70°F are:

Young's Modulus = $E = 28.3 \times 10^6$ psi

Poisson's Ratio = $\nu = 0.275$

Mass Density = $\rho = 0.000741352\ \mathrm{lb/in^3}$

The wave propagation speeds are:

C1 = the speed of the dilatation wave

$$= \left(\frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)\rho}\right)^{0.5} = 219{,}628 \text{ in/sec}$$

C2 = the speed of the distortion wave

$$= C1 \left(\frac{1 - 2\nu}{2(1 - \nu)}\right)^{0.5} = 122{,}352 \text{ in/sec}$$

The average of C1 and C2 is taken as the average speed of the stress wave; that is, 171,000 inches/second.

The impact speed of a 40-inch drop is calculated as:

$$V = (2\ G\ h)^{0.5} = (2 \times 386.4 \times 40)^{0.5}$$
$$= 175.82 \text{ in/sec}$$

The average speed after impact is estimated as two-thirds of the impact speed.

$$\text{ave } V = 2/3 \times V = 117.21 \text{ in/sec}$$

Denoting "D" as the maximum deflected distance of the cask body due to the puncture load, the required time to travel "D" distance is $t = D/\text{ave } V$. The stress wave propagation distance is $s = 0.5 \times (C1 + C2) \times t$.

Therefore, if D = 0.1 inch, then:

$$t = 0.1/117.21 \text{ (in/sec)}$$
$$s = 145.89 \text{ in}$$

The effective distance from the center of the cask body, where the puncture load is applied, to any location of the cask is estimated as:

$$L = (18)(4.54) + 64.79 + (2) \times (1.0 + 3.2 + 2.2)$$
$$= 159.3 \text{ in}$$

Thus, the required displacement to assure the appropriate cask response for a simulated quasi-static approach should be:

$$d = 0.1 \times 159.3/145.89 = 0.1092 \text{ in}$$

If the maximum displacement of the analysis is less than d, then the boundary locations should be adjusted accordingly.

LOADING CONDITIONS

Two loadings were considered: (1) the cask dropping from a 40-inch height onto a 6-inch diameter mild steel bar, and (2) the associated acceleration during the impact to maintain the force equilibrium condition of the structural system. The cask contents impact load is neglected because it is not significant for the puncture condition.

The dynamic impact loading resulting from the cask dropping 40 inches onto a mild steel bar is represented as 51,300 psi as previously discussed. The equivalent puncture force is:

$$F = \text{Area} \times \text{Dynamic Impact Stress}$$
$$= 0.25\,\pi\,(6)^2 \times 51{,}300$$
$$= 1{,}450{,}473 \text{ lb}$$

$(1/4)F = 362{,}620$ lb (dynamic impact load applied to a quarter model)

The associated acceleration is calculated as:

$$a = (362{,}620/W)\ (386.4)$$

where

W = the associated cask weight of a quarter model

EMPIRICAL APPROACH

Pin puncture analyses are commonly performed by the use of Nelm's Equation, an empirical equation to determine the minimum thickness of a shell required to resist puncture. However, Nelm's Equation only addresses a steel shell backed by a lead shell and does not discuss the minimum thickness of lead required to protect an inner shell from a pin puncture event.

Nelm's Equation is used to calculate the minimum required outer shell thickness for Type 304 stainless steel and for Type XM-19 stainless steel.

$$t = \text{thickness of outer shell} = (W/Su)^{0.71} \quad \text{(Nelm's Equation)}$$

where

	XM-19	Type 304	
S_u @ 70°F	100	75	ksi
S_u @ 300°F	94.3	66	ksi
W = Estimated Cask Weight	205	205	kip

then

t @ 70°F	1.665	2.023	in
t @ 300°F	1.736	2.236	in

CONCLUSION

Table 1 documents the maximum displacement and stress intensity (SI) values for the cask obtained from the ANSYS analysis results. All of the outer shell displacements are greater than 0.1092 inch as required for the boundary conditions specified in the finite element model. The stress intensities in the four shells (the inner shell, uranium, lead, and outer shell) are taken at the cask middle plane where the puncture load is applied. As previously described, the inner shell is modeled using thin shell elements. The ANSYS analysis results provide the top, middle, and bottom stresses for the thin shell elements. The bottom stress is selected because it is the most critical and gives the maximum primary membrane plus primary bending ($P_m + P_b$) stress. The depleted uranium, lead and outer shell layers are modeled using brick elements. The ANSYS analysis results provide only the average element stresses for the brick elements.

Table 1
Analysis Parameters and Results for Gamma Shield Selection

(1) Outer Shell Thickness (in)	(2) Lead Shell Thickness (in)	(3) Depleted Uranium Shell Thickness (in)	(4) Displacement at Location of Puncture (in)	(5) Estimated Cask Weight (lb)	Stress Intensity (6) Shell	Stress Intensity (7) Stress (psi)
2.2	3.20	0.00	0.1365	212,564	1-Inner	35,343*
					2-Lead	6,296
					3-Lead	7,256
					4-Outer	43,132
2.2	2.75	0.27	0.1321	211,076	1-Inner	34,447*
					2-dU	15,818
					3-Lead	6,998
					4-Outer	42,256
2.2	2.50	0.42	0.1303	210,276	1-Inner	34,230*
					2-dU	15,598
					3-Lead	7,120
					4-Outer	41,832
2.2	2.25	0.56	0.1290	208,980	1-Inner	34,337*
					2-dU	15,660
					3-Lead	7,277
					4-Outer	41,481
2.2	2.00	0.71	0.1274	208,224	1-Inner	34,539*
					2-dU	15,832
					3-Lead	7,454
					4-Outer	41,033
2.2	1.75	0.86	0.1259	207,488	1-Inner	34,873*
					2-dU	16,120
					3-Lead	7,670
					4-Outer	40,559
2.2	1.50	1.00	0.1247	206,252	1-Inner	35,365*
					2-Uranium	16,529
					3-Lead	7,949
					4-Outer	40,131
2.2	1.25	1.16	0.1227	206,080	1-Inner	35,790*
					2-dU	16,950
					3-Lead	8,282
					4-Outer	39,501

Table 1 (cont)
Analyses Parameters and Results for Gamma Shield Selection

(1) Outer Shell Thickness (in)	(2) Lead Shell Thickness (in)	(3) Depleted Uranium Shell Thickness (in)	(4) Displacement at Location of Puncture (in)	(5) Estimated Cask Weight (lb)	Stress Intensity (6) Shell	(7) Stress (psi)
2.2	1.00	1.306	0.1212	205,200	1-Inner	36,352*
					2-dU	17,505
					3-Lead	8,747
					4-Outer	38,937
2.2	0.75	1.45	0.1195	204,236	1-Inner	36,950*
					2-dU	18,188
					3-Lead	9,411
					4-Outer	38,340
2.2	0.50	1.60	0.1173	203,604	1-Inner	37,486*
					2-dU	19,043
					3-Lead	10,430
					4-Outer	37,647
2.2	0.25	1.75	0.1145	202,996	1-Inner	37,890*
					2-dU	20,271
					3-Lead	12,293
					4-Outer	36,939

* The stress limit is the material yield strength at normal operating temperature (300°F assumed):

(a) For Type 304 stainless steel, $S_y = 22{,}500$ psi

(b) For Type XM-19 stainless steel, $S_y = 39{,}300$ psi.

The analysis results tabulated in Table 1 indicate that plastic deformation occurs in an inner shell of Type 304 stainless steel. This does not occur for an inner shell of Type XM-19 stainless steel, due to its higher yield strength.

Table 2 presents the finite element analysis results for cask geometries based on the outer shell thicknesses calculated using Nelm's Equation. As noted, the Nelm's Equation does not define a required minimum lead shell thickness. Based on the calculated stress intensities tabulated in Table 2, use of an outer shell thickness that satisfies or exceeds the requirements of Nelm's Equation does not ensure that the inner shell stress limits will be satisfied.

Table 2
Comparison Study of Outer Shell Thickness Calculations
(Nelm's empirical equation vs. finite element approach)

(1) ** Outer Shell Thickness (in)	(2) Lead Shell Thickness (in)	(3) Depleted Uranium Shell Thickness (in)	(4) Displacement at Location of Puncture (in)	(5) Estimated Cask Weight (lb)	Stress Intensity (6) Shell	Stress Intensity (7) Stress (psi)
1.7	3.2	0.0	0.1688	199,896	1-Inner	43,858*
					2-Lead	7,975
					3-Lead	8,879
					4-Outer	54,724
2.0	3.2	0.0	0.1482	207,478	1-Inner	38,445*
					2-Lead	6,903
					3-Lead	7,854
					4-Outer	47,181
2.2	3.2	0.0	0.1365	212,564	1-Inner	35,343*
					2-Lead	6,296
					3-Lead	7,256
					4-Outer	43,132
2.2	2.0	0.0	0.1672	171,618	1-Inner	42,339*
					2-Lead	7,693
					3-Lead	8,404
					4-Outer	47,717

* The stress limit is the material yield strength at normal operating temperature (300°F assumed):

(a) For Type 304 stainless steel, $S_y = 22,500$ psi

(b) For Type XM-19 stainless steel, $S_y = 39,300$ psi.

** Reference Nelm's Equation.

FINDINGS

The ANSYS analysis showed that a relatively thin layer of lead, 0.25-inch to 0.50-inch thick, effectively cushions the inner steel wall, as the pin only penetrates 0.15 inch or less into the outer wall. The analysis further showed that the use of high-strength stainless steel can prevent plastic deformation in the inner wall, which would occur if Type 304 stainless steel were used. Adjustments to the thickness of the outer shell can also be made to reduce the puncture loads on the inner shell, guided by the ANSYS calculations. Thus, this analysis demonstrated that the required thicknesses of the lead shock-absorbing layer and the outer steel shell may be determined by finite element analysis.