A Simplified Analysis of the Regulatory Puncture Test*

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INTRODUCTION

Among the prescribed tests in the Nuclear Regulatory Commission safety standards in Title 10 of the Code of Federal Regulations, Part 71, Subpart F (10 CFR 71.73) for packagings of radioactive materials is a puncture test, which must follow a 9-m (30-ft) drop event and precede an 800°C thermal event in the hypothetical-accident test sequence. The specific conditions of the puncture test involve a free drop of the specimen through a distance of 1 m (40 in.) in a position for which maximum damage is expected, onto the upper end of a solid, vertical, cylindrical, mild-steel bar mounted on an essentially unyielding, horizontal surface. The bar must be 15 cm (6 in.) in diameter, with the top horizontal and its edge rounded to a radius of not more than 6 mm (1/4 in.) and of a length as to cause maximum damage to the package, but not less than 20 cm (8 in.) long. The long axis of the bar must be vertical. A packaging user must demonstrate in the Safety Analysis Report for Packaging, either by test or analysis, that the packaging can withstand the puncture test without loss or dispersal of radioactive contents, with no significant increase in external radiation levels, and no substantial reduction in the effectiveness of the packaging, including the assurance of subcriticality.

Figure 1 is a schematic diagram of a hypothetical puncture test that involves a typical rectangular package containing an inner box of radioactive materials. It is a rectangular package like the one shown in Figure 1 that motivated the development of a simplified method for predicting damage in shipping packages subjected to the 10 CFR 71 regulatory puncture test. (For a drum-type package, depending on its radius of curvature relative to that of the puncture bar, the simplified method may be applicable to a side drop of the drum onto the puncture bar.) The method is applicable to packages that have composite exterior walls consisting of an outer skin resting on an inner backing. The skin isolates the backing and contents of the package from the external environment, but provides little structural protection for the contents during the puncture test. The structural protection is furnished by the backing, which is made of an impact-absorbing, crushable material. The following sections present the overall analytical approach, the skin strain and energy absorption, the energy absorption of the backing, and a comparison of calculated and experimental results obtained from five puncture tests.

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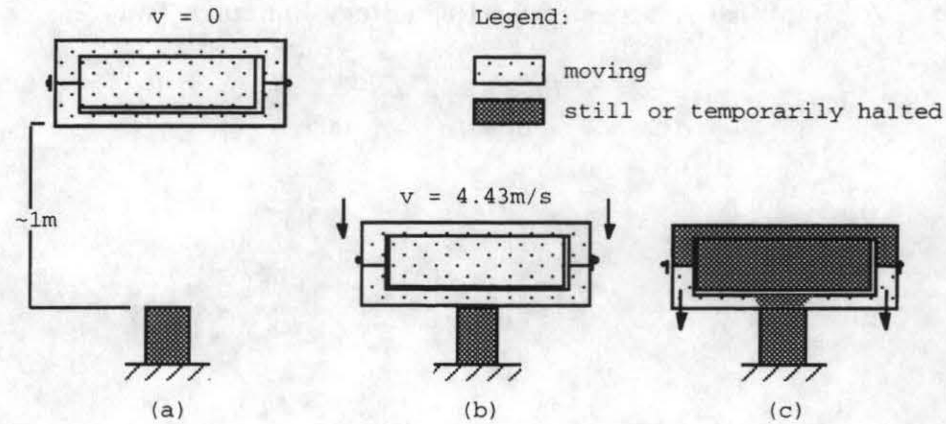

Figure 1. Schematic diagram of a rectangular package during the regulatory puncture test

ANALYTICAL APPROACH

The overall approach in the simplified method is to express the energy absorption during the puncture event as a function of the depth of the dent made by the puncture bar in the exterior wall of the package. The depth of the dent is then increased incrementally until the energy absorption equals the drop energy. Two analytical models, a cone model and a cylinder model, shown in Figure 2, are used to bracket the possible dent shapes and thus potentially the energy absorption of a dent of any depth. The cone model assumes that the dent is shaped like a truncated cone, with the shorter radius equal to that of the puncture bar. The larger radius of the cone is equal to one-half of the shortest dimension of the package side under study. The cylinder model assumes that the dent shape is cylindrical, with a constant radius equal to that of the puncture bar. Thus, for any given dent depth during a puncture event, the cone model would calculate more energy absorption from the crushing of the impact-absorbing material (backing), less energy absorption from plastic deformation of the skin, and a greater chance of bending fracture and less chance of shear fracture of the backing than the cylinder model.

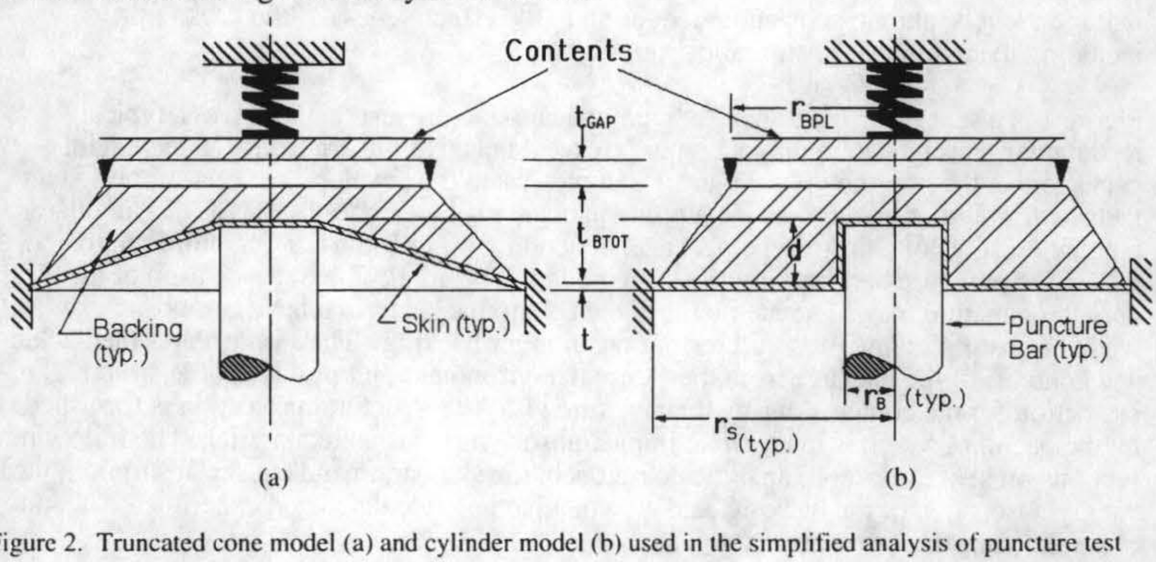

Figure 2. Truncated cone model (a) and cylinder model (b) used in the simplified analysis of puncture test

The calculations for either model commence with a determination of whether the loading necessary to crush the backing is sufficient to bend or cause shear fracture of the backing, as indicated by exceeding the allowable stress values for the backing. If fracture occurs, the configuration is assumed to adopt a postfracture geometry, as illustrated in Figure 3 for the bending fracture. In the figure, the solid lines show the package geometry before fracture for both models, and the dashed lines show the geometry after bending fracture, with L_2 and L_4 corresponding to the cone model and the cylinder model, respectively. The dent depth at fracture, d_F in Figure 3, is equal to zero for this situation. The fracture energy of the backing and the strain energy of the plastic deformation of the skin (with the end of the puncture bar moving into contact with the package contents) are summed and compared with the drop energy, and the calculations are concluded. Shear fracture of the backing is considered only for the cylinder model with the geometry illustrated in Figure 1(c). Stress and deflection of the backing are calculated using formulae for cases 9a (for the cylinder model) and 9b (for the cone model) in Roark and Young (1982); these cases are applicable to a flat circular plate of constant thickness.

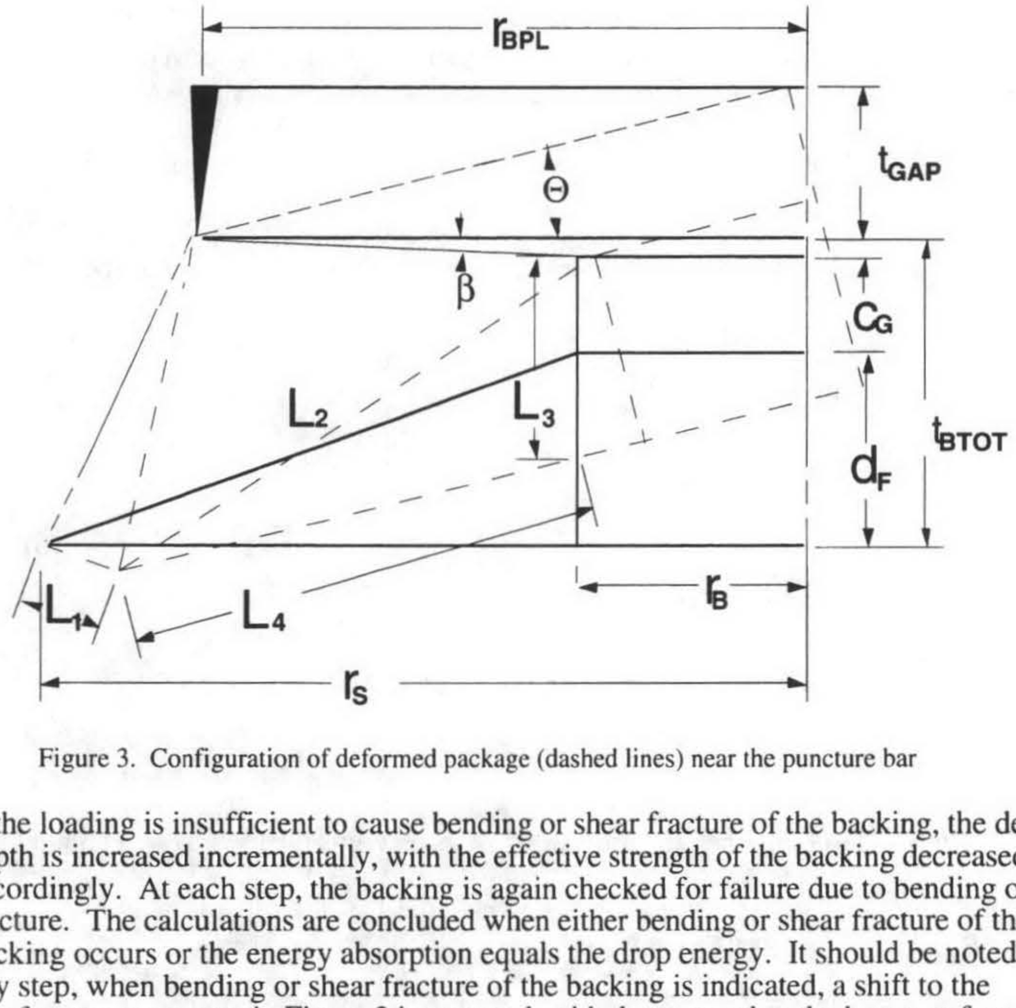

Figure 3. Configuration of deformed package (dashed lines) near the puncture bar

If the loading is insufficient to cause bending or shear fracture of the backing, the dent depth is increased incrementally, with the effective strength of the backing decreased accordingly. At each step, the backing is again checked for failure due to bending or shear fracture. The calculations are concluded when either bending or shear fracture of the backing occurs or the energy absorption equals the drop energy. It should be noted that, at any step, when bending or shear fracture of the backing is indicated, a shift to the postfracture geometry in Figure 3 is assumed, with d_F set equal to the latest prefracture value. At this point the calculations would proceed as previously described for fracture with $d_F = 0$.

SKIN STRAIN AND ENERGY ABSORPTION

Uniform radial strain ε_r is assumed, so that the tangential strain ε_t at any radius r on the end of the bar is

$$\varepsilon_t = \frac{2\pi\left[r(1 + \varepsilon_r) - r\right]}{2\pi r} = \varepsilon_r. \tag{1}$$

Conservation of volume in deformation,

$$0 = \varepsilon_r + \varepsilon_t + \varepsilon_z, \tag{2}$$

gives the axial strain ε_z as

$$\varepsilon_z = -\varepsilon_r - \varepsilon_t = -2\varepsilon_r. \tag{3}$$

For a given dent depth d, let L represent the "radial" length of the skin between the rim of the bar and the edge of the skin. Then

$$\varepsilon_r = \frac{L + r_B - r_S}{r_S}, \tag{4}$$

where r_B and r_S are defined in Figure 2. For the cone model before fracture of the backing,

$$L_{CONE} = \left[d^2 + \left(r_S - r_B\right)^2\right]^{1/2}. \tag{5}$$

For the cylinder model before fracture of the backing,

$$L_{CYL} = r_S - r_B + d. \tag{6}$$

Select an initial radial position r_l,

$$r_l = \frac{r_B r_S}{r_B + L} \tag{7}$$

that will be stretched to r_B by the puncture bar; then the energy absorbed by that stretching is

$$E_{INN} = \int_0^{r_S - r_l} \sigma_y 2\pi \left(r_l + s\right) t_S \, ds$$

$$= 2\pi t \int_0^{r_B - r_l} \left(\sigma_y + \frac{Hs}{r_l}\right)\left(r_l + s\right)\left(1 - 2\frac{s}{r_l}\right) ds, \tag{8}$$

where t is the original skin thickness, σ_y is the skin yield stress, H is the skin strain hardening coefficient, s is the distance that the skin is stretched beyond r_1, and t_s is the skin thickness for any value of s.

The force required to stretch the skin inside r_l is exactly the same at any s as the force necessary to stretch the skin outside r_l. However, the amount of stretch for the outside skin is equal to $(r_S - r_l)/r_l$ times the amount of stretch s for the skin inside r_l. Therefore, the total amount of energy absorbed by the skin is

$$E_{SKIN} = E_{INN}\left(1 + \frac{r_S - r_l}{r_l}\right). \tag{9}$$

After bending fracture of the backing, the skin shape in Fig. 3 can be found approximately as follows:

$$\theta = \sin^{-1}\frac{t_{GAP}}{r_{BPL}}, \tag{10}$$

$$\beta \approx \tan^{-1}\frac{t_{BTOT} - d_F}{r_{BPL} - r_B} - \theta, \tag{11}$$

$$C_G \approx \left(r_{BPL} - r_B\right)\tan\beta, \tag{12}$$

$$L_l = 2\sqrt{t_{BTOT}^2 + \left(r_s - r_{BPL}\right)^2}\,\sin\frac{\theta}{2}, \tag{13}$$

$$L_2 \approx \sqrt{\left(r_s - r_B - L_l\right)^2 + \left(t_{BTOT}^2 - C_G\right)^2}, \tag{14}$$

$$L_3 \approx \frac{d_F}{\cos\theta}, \tag{15}$$

and

$$L_4 \approx r_S - r_B - L_3\sin\theta. \tag{16}$$

For the cone model, the value of L to use in Eqs. 4 and 7 is

$$L_{CONE,PF} = L_l + L_2 + t_{GAP} + C_G. \tag{17}$$

For the cylinder model, the value of L to use in Eqs. 4 and 7 is

$$L_{CYL,PFB} = L_l + L_3 + L_4 + t_{GAP} + C_G. \tag{18}$$

After shear fracture of the backing in the cylinder model, the value of L to use in Eqs. 4 and 7 is

$$L_{CYL,PFS} = r_S - r_B + t_{BTOT} + t_{GAP}. \tag{19}$$

ENERGY ABSORPTION OF THE BACKING

For the cone model, the energy absorbed by crushing of the backing before fracture is (using the equation for the volume of a truncated cone)

$$E_{BCR,CONE} = \sigma_{CR}\pi\frac{d}{3}\left[r_S^2 + r_S(r_B + t) + (r_B + t)^2\right]. \quad (20)$$

For the cylinder model, the energy absorbed by crushing of the backing before fracture is

$$E_{BCR,CYL} = \sigma_{CR}\pi d(r_B + t)^2. \quad (21)$$

The elastic deformation of the backing and the gap between the backing and the package contents are taken into account in determining whether bending or shear fracture of the backing would occur. When the gap closes, it is assumed that crushing of the backing occurs at the point of contact with the contents and that energy is absorbed until the contact area is large enough to provide static equilibrium consistent with the spring constant assigned to the contents.

RESULTS AND CONCLUSIONS

Calculations were performed with the cone and cylinder models for five puncture tests with the package parameters listed in Table 1. The packages are identified as A1, A2, B1, B2, and PAT-1. The first four packages were tested under the auspices of the U.S. Department of Energy, but the tests have not been reported previously. The A1 and A2 packages are nominally identical, except that the wood used for A1 was hemlock fir, which is a stiffer backing material than the poplar that was used for A2. Both A1 and A2 were 1/2-scale models; therefore, the diameter of the puncture bar was 7.5 cm instead of 15 cm. The prototype B1 and B2 packages were also nearly identical, except that the skin of B1 was thinner than that of B2.

Table 1. Parameters of Packages Used in the Simplified Analyses of the Puncture Tests

Parameter	A1 and A2	B1 and B2	PAT-1[a]
Weight, N	4900	197,600 (206,500[b])	2220
Skin thickness, cm	0.15	0.94 (1.24[b])	0.17
Skin radius, cm	10.6	34.7	15.2
Backing plate thickness, cm	1.90	3.81	15.2
Number of backing plates	3	5	1
Backing plate radius, cm	8.3	26.8	10.2
Backing/content gap thickness, cm	0.64	1.27	0.76
Backing material	Hemlock fir (Poplar[b])	Poplar	Redwood

[a]Anon. (1978)

[b]Parameters for A2 and B2

Table 2 shows calculated and measured (or experimentally observed) results for the five puncture tests. Three observable effects of the tests, dent depth on the package outer wall, skin rupture, and damage to package contents, are used to evaluate the results, even though only the dent depth is quantitatively measurable. Skin rupture is important because it can result in unfavorable exposure of the backing and contents to the 800^{0}C hypothetical thermal event that follows.

Table 2. Experimental and Calculated Results for the Five Puncture Tests

Package and Parameters	Experimental	Calculated (Cone Model)	Calculated (Cylinder Model)
A1, 1/2-scale Model 1: Hemlock-fir backing			
Dent depth, cm	"Shallow"	3.0+	3.0+
Skin ruptured	No	Yes	Yes
Content damaged	Dented	17,400 N load	17,400 N load
A2, 1/2-scale Model 2: Poplar backing (less stiff than that of A1)			
Dent depth, cm	"Shallow"	3.8+	3.8+
Skin ruptured	No	Yes	Yes
Content damaged	Dented	15,600 N load	15,600 N load
B1, Prototype 1: 197,600 N, 0.94-cm-thick skin			
Dent depth, cm	20	8.1+	14.7+
Skin ruptured	Yes	No	Yes
Content damaged	Dented	57,800 N load	57,800 N load
B2, Prototype 1: 206,500 N, 1.24-cm-thick skin			
Dent depth, cm	9.4	8.1+	14.7+
Skin ruptured	Yes	No	Yes
Content damaged	No	57,800 N load	57,800 N load
PAT-1 (cylindrical surface)			
Dent depth, cm	"Minor imprint"	< 0.25	< 0.51
Skin ruptured	No	No	No
Content damaged	No	No	No

If backing fracture does not occur, the calculated dent depths in Table 2 were determined as the value when the total energy absorption was equal to the drop energy. The total energy absorption is the sum of the skin strain energy, Eq. 9, the crushing energy of the backing, Eqs. 20 and 21, and the elastic strain energy of the backing, which can be found in Roark and Young (1982). When backing fracture is indicated, the dent depth is equal to t_{BTOT} + t_{GAP}. Skin rupture is assumed to occur when the calculated skin radial strain, given in Eq. 4, reaches 25%. When the gap between the backing and contents is closed because the backing is bent, the calculated load on the contents is taken to be equal to the product of the crushing strength of the backing and the frontal area of the puncture bar. The calculated loads on the contents are listed in Table 2, mainly to indicate the expected contacts between the backing and the contents.

Examination of the calculated dent depths in Table 2 shows that the values obtained for the A2 package are greater than those for the A1 package, because poplar, the backing material for A2, is less stiff than hemlock-fir, the backing material of A1. More poplar, therefore, must be crushed to a greater depth to absorb the drop energy than with the hemlock-fir. Even though the B2 package has a thicker skin than the B1 package, the difference in thickness is apparently too small to effect a noticeable change in the dent depth that was calculated incrementally in the iterative procedure. Both the cone and cylinder models predicted skin rupture (based on a 25% skin strain criterion) for the A1 and A2 packages, contrary to experimental observation. For the B1 and B2 packages, skin ruptures were observed experimentally; the cylinder model predicted its occurrence, but the cone model did not. Some of these discrepancies could be due to the strain criterion assumed for skin rupture. As for damage to package contents incurred in the puncture tests, neither of the two models predicted how contact between backing and contents, and hence potential damage to the contents, would be prevented by increasing the skin thickness by one-third for the B2 package. For the PAT-1 package that had a cylindrical surface, both models calculated results that are in qualitative agreement with the data. Additional effort is needed to investigate model sensitivities to parameters such as the crushing strength of the backing, its dependence on the degree of compression of the backing that accompanies the crushing, and the thickness of backing that remains between the puncture bar and the package contents after fracture of the backing.

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REFERENCES

Anon., *Safety Analysis Report for the Plutonium Air Transportation Package, Model PAT–1*, U.S. Nuclear Regulatory Commission report NUREG-0361 (1978).

Roark, R. J. and Young, W. C. *Formulas for Stress and Strain*, McGraw-Hill, New York, NY., 5th Ed., p. 362 (1982).