Journal of the Korean Nuclear Society
Volume 30, Number 5, pp.462~469, October 1998

《Technical Note》

Structural Evaluation on the Impact of a Radioisotope Package

Sung-Hwan Chung and Heung-Young Lee
Nuclear Environment Technology Institute
150 Dukjin-dong, Young-gu, Taejon 305-353, Korea

Jeong-Hoe Ku, Ki-Seog Seo, and Hyun-Soo Han
Korea Atomic Energy Research Institute
150 Dukjin-dong, Young-gu, Taejon 305-353, Korea

(Received April 14, 1997)

Abstract

A package to transport high-level radioactive materials is required to withstand normal transport and hypothetical accident conditions pursuant to the IAEA and domestic regulations. The package should maintain the structural safety not to release radioactive material in any condition. The structural safety of the package has been evaluated by tests using proto-type or scaled-down models, however, the method by analysis is gradually utilized due to recent advancement of computers and computer codes. In this paper, to evaluate the structural safety of a radioisotope package of the KAERI, the three dimensional impact analyses under 9m free drop and 1m puncture were performed with an explicit finite-element code, the LS-DYNA3D code. The maximum stress intensity on each part was calculated and the structural safety of the package was evaluated in accordance with the regulations.

1. Introduction

A package to transport high-level radioactive materials such as nuclear spent fuel assemblies or radioisotopes should be secured to protect the public and the environment from radioactive dangers. The package is required to withstand normal transport and hypothetical accident conditions such as 9m free drop, 1m puncture, 800°C fire and 200m water immersion pursuant to the IAEA(*International Atomic Energy Agency*) and domestic regulations[1,2,3]. The package should maintain the structural safety not to release radioactive material in any condition.

As the structural safety depends on the impact of hypothetical accident conditions causing maximum damage to the package, the understanding of impact behavior and the optimization for impact-resistant properties are important. In general, the structural safety of the package has been evaluated by tests using proto-type or scaled-down models[4,5], however, the method by analysis is gradually utilized due to recent advancement of computers and computer codes such as non-linear dynamic analysis programs[6,7,8,9,10].

As the impact analysis for the package, i.e, a non-linear dynamic response problem, is not able to get an exact solution, approximate solutions are obtained using finite-element methods. Though the analysis result is not always highly credible, the accuracy is being improved by developing more effective analysis techniques.

In this paper, to evaluate the structural safety of a radioisotope package to transport high-level radioisotopes produced in the research reactor of the KAERI(*Korea Atomic Energy Research Institute*), the three dimensional impact analyses under 9m free drop and 1m puncture were performed with an explicit finite-element code, the LS-DYNA3D code[11].

The LS-DYNA3D code, which is originated from J.O. Hallquist of the LLNL(*Lawrence Livermore National Laboratories*), is a finite-element code for analyzing the large-deformable dynamic response of three dimensional structures. As an explicit code, it is appropriate for impact problems where high rate dynamics or stress wave propagation effects are important. It is based on a finite-element discretization of the three spatial dimensions and a finite discretization of time. And the code contains a robust and efficient capability for modeling the mechanical interaction for the intermittent contact of impact problems.

Through the impact analyses, the impact behavior for each load condition was understood, the maximum stress intensity on each part was calculated and the structural safety of the package was evaluated in accordance with the regulations[1,2,3].

2. Radioisotope Package

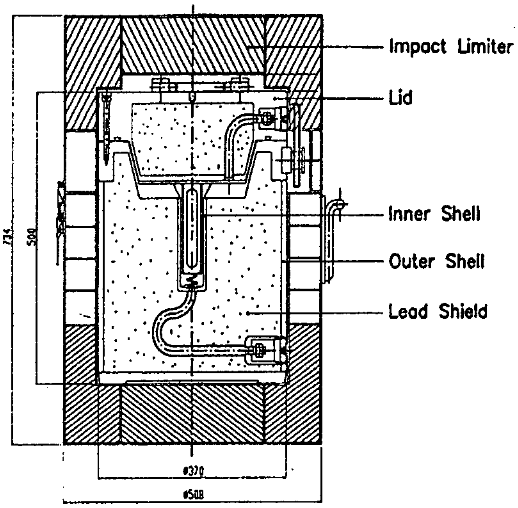

Fig. 1. Overview of a Radioisotope Package

The radioisotope package, which is classified as a type B package, is to transport safely high-level radioisotopes produced in the research reactor of the KAERI.

The package is cylindrical as shown in Fig.1. It consists of a body of inner shell, outer shell and gamma shield, a lid and upper and lower impact limiters. The lid is bolted to the top of the body for leaktightness. An aluminium capsule containing a radioisotope is loaded in the inner cavity of the body. The impact limiters to cover the externals of the package are able to withstand drop impacts and fire accidents. The annular fins of the lower impact limiter prevent heat transfer toward the inside of the body in the fire accident. The body is 370mm in outer diameter and 500mm long. The overall size of the package is 508mm in outer diameter and 734mm long. The weight of the package including the impact limiters is about 650kg.

The material of main structure is stainless steel type 304 and the gamma shield is 99% or more pure lead, which is casted between the inner shell and the outer shell. Inside of the stainless steel casing of the impact limiters is filled with balsa

Table 1. Mechanical Properties of Materials [13]

Mechanical properties	Stainless steel	Lead	Balsa wood	Red wood
Elastic modulus, MPa	186,800	98,550	678	1,563
Yield strength, MPa	258.5	6.8	13.6	45.0
Hardening modulus, MPa	1,895	19	-	-
Poisson' s ratio	0.3	0.4	0.3	0.3
Density, kg/㎥	7,913	11,070	160	314

wood and California red wood as energy absorbing materials. The woods are arrayed in the direction of each grain. The inner stainless steel shell to form a containment boundary of the package is assumed as elastic behavior in accordance with the regulations[12], and other stainless steel shells such as the outer shell, the lid and the impact limiter casing are regarded as elastic-plastic behavior of linear strain hardening. The lead shield for gamma-ray and the woods for the impact limiters are considered as elastic-fully plastic behavior. The mechanical properties of materials as shown in Table 1 are applied to the basic data of the analysis[13].

The package should maintain the structural safety pursuant to the regulations. The package should withstand a 9m free drop impact onto a target in a direction causing maximum damage. As it is difficult to define the direction of the maximum impact, the structural safety is evaluated for vertical drop, side drop and corner drop, respectively. And it is also evaluated whether the package withstand a 1m drop impact onto a mild steel round bar.

The structural safety for the impact analysis is evaluated by comparing the calculated stress intensity with the allowable stress described in the ASME(*America Society of Mechanical Engineers*) code[14]. The load condition is pursuant to the IAEA and domestic regulations. The stress evaluation criteria on hypothetical accident conditions of the package are as follows; the value of the stress intensity resulting from the primary membrane stresses(Pm) should be equal to or less than the value of 2.4Sm, and the stress intensity resulting from the sum of the primary membrane stresses and the primary bending stresses(Pb) should be equal to or less than the value of 3.6Sm, where Sm is the design stress intensity of the material and is based on the Tresca' s maximum shear stress theory. The primary membrane stress means the average normal primary stresses across the thickness of a solid section, and the primary bending stress is the component of the normal primary stress that varies linearly across the thickness of a solid section. These are self-limiting stresses that are necessary to satisfy the laws of equilibrium of forces and moments due to applied loadings, pressure loadings and body forces.

3. Impact Analysis

The impact analysis of the package is to find an approximate solution for displacements and stresses that is subjected to the history of the impact loading. The exact solution of such a problem requires that both force and moment equilibrium be maintained at all times over arbitrary volumes of the body. The finite-element method to find an approximate solution is based on approximating this equilibrium requirement by replacing it with a weaker requirement that equilibrium must be maintained in an average sense over a finite number of divisions of the volume of the body. The exact equilibrium statement is developed in the form of the virtual work statement and reduced to the approximate form of equilibrium used in a finite-element model.

The finite-element approximate equation to the load equilibrium, i.e, the non-linear governing equation of motion is written as;

$$\mathbf{M}\ddot{u}^{n} + \mathbf{I} - \mathbf{P} = \mathbf{O} \qquad (1)$$

where **M** is the consistent mass matrix, **I** is the internal force vector, **P** is the external force vector, and u^n is the nodal displacement variables.

The non-linear dynamic response is obtained by the explicit direct time integration used to all degrees of freedom of the finite-element model[15]. The central difference method is used to integrate the equations to motion in time. It is only conditionally stable, and the stability is governed by the Courant limit, $\Delta t \leq T_n/\pi$(Δt: stability time limit, T_n: the smallest period of the mesh), on time increments[16]. For solid elements, the stability limit is essentially the time required for an elastic stress wave to propagate across the smallest dimension in the element mesh.

3.1. Analysis Model

The 9m free drop analyses were performed with a three dimensional model of a half section, utilizing the symmetry of the package, with 7,295 nodes, 4,048 brick elements, 1,600 shell elements and interface elements. The symmetric boundary condition was applied to all nodes on the middle section, and only the central axis was constrained to let the other nodes of the model be freely deformed. The lid bolts to fasten the lid to the body were modeled using nodal constraints. In the middle part of the external impact limiters, the grain direction of balsa wood was axial to the package, and in the side part, the grain direction of California red wood was radial to the package. The compressive property of each wood in grain direction was considered. The casing of the impact limiters and the annular heat transfer fins were modeled using shell elements. Sliding interface elements were used for the simple contact between woods and the casing. The unyielding target surface was modeled using an infinite flat rigid wall element, and the contact of impactable parts was fully considered. The initial impact velocity of 13.3m/sec corresponding to the 9m free drop onto the target surface was applied for the loading condition[6].

The 1m puncture analysis was also performed with a three dimensional model consisted of the package excluding woods in the impact limiters and the steel round bar with 7,018 nodes, 3,760 brick elements, 1,600 shell elements and interface elements. The round bar was fixed and positioned such that it may impact the outside surface of the impact limiters. The loading condition was the initial velocity of 4.4m/sec corresponding to the 1m free drop onto the round bar[6].

3.2. 9m Free Drop Analyses

The regulations describe that the package should withstand a 9m free drop impact onto a target in a direction causing maximum damage. The free drop analyses for vertical drop, side drop and corner drop were preformed, respectively, with the impact limiters attached in the outside of the package. The impact behavior of each drop was investigated and the maximum stress intensity on each part of the package was calculated.

The **vertical drop** is that the bottom of the package is vertically dropped onto the unyielding flat target surface. The total impact time was about 7.5msec in the impact force time history as shown in Fig.2. The characteristic of the vertical drop is that the impact force is horizontally generated to the end of impact behavior due to the constant

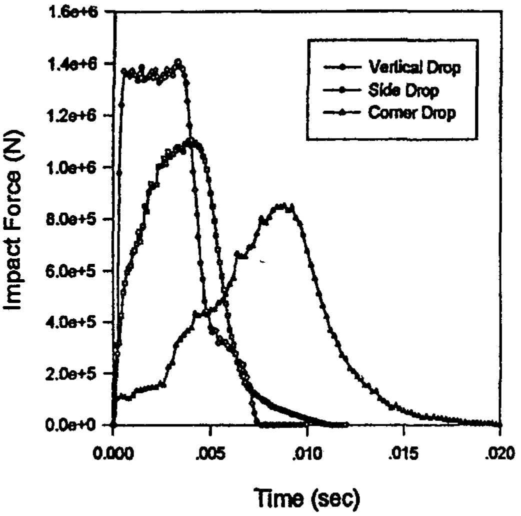

Fig. 2. Impact Force Time History for 9m Drops

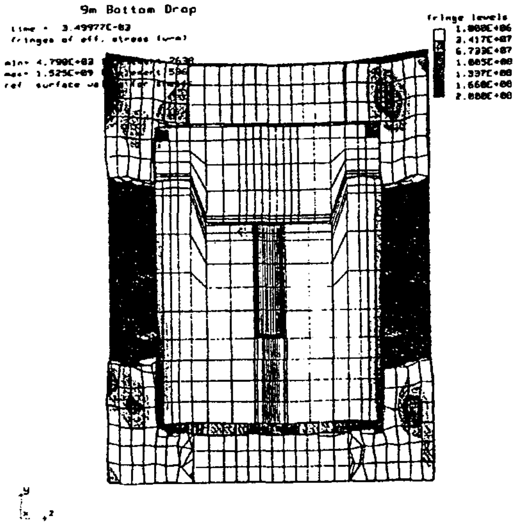

Fig. 3. Stress and Deformation Configuration for 9m Vertical Drop

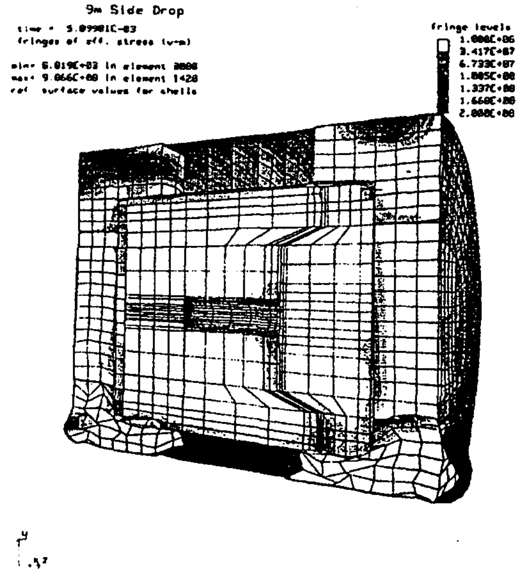

Fig. 4. Stress and Deformation Configuration for 9m Side Drop

change of impacting area. Figure 3 shows the stress and deformation configuration of the package when maximum stress was occurred. The deformation of the impact limiters was 28mm at 3.5msec after impacting. Though buckling effect by the inertia force of contents is investigated in the case of the vertical drop, it is negligible due to the light-weight aluminium capsule.

The **side drop** is that the side part of the package is horizontally dropped onto the target surface. The total impact time was about 11msec as shown in Fig.2. The side drop has a tendency that the impact force is gradually increased according to the deformation progress as the change of impacting area is increased. Figure 4 shows the stress and deformation configuration of the package when maximum stress was occurred. The deformation of the impact limiters was 37mm at 4.8msec after impacting. In general, the outer diameter of the impact limiters is determined in accordance with the energy-absorbing size for the side drop impact.

The **corner drop** is that the center of gravity of the package is vertically aligned with the impacting point and the corner of the package is dropped onto the target surface. The total impact time was about 20msec as shown in Fig.2. The corner drop, like the side drop, has also a tendency that

Table 2. Maximum Stress Intensity for Each Drop Condition

Drop conditions		Components	Maximum stress intensity, MPa		Allowable values, MPa	
			Pm	Pm+Pb	2.4Sm	3.6Sm
9m drops	Vertical	Inner shell Inner flange Lid inside	21.9 15.8 81.3	29.3 16.7 11.4	413	620
	Side	Inner shell Inner flange Lid inside	48.1 74.6 80.7	121.3 200.3 187.0		
	Corner	Inner shell Inner flange Lid inside	33.6 57.5 49.4	73.9 198.4 137.5		
1m puncture		Inner shell Inner flange Lid inside	9.2 17.6 50.4	29.2 61.8 58.1	413	620

Note) If Pm≤2.4Sm and Pm+Pb≤3.6Sm, the package is evaluated to be safe.

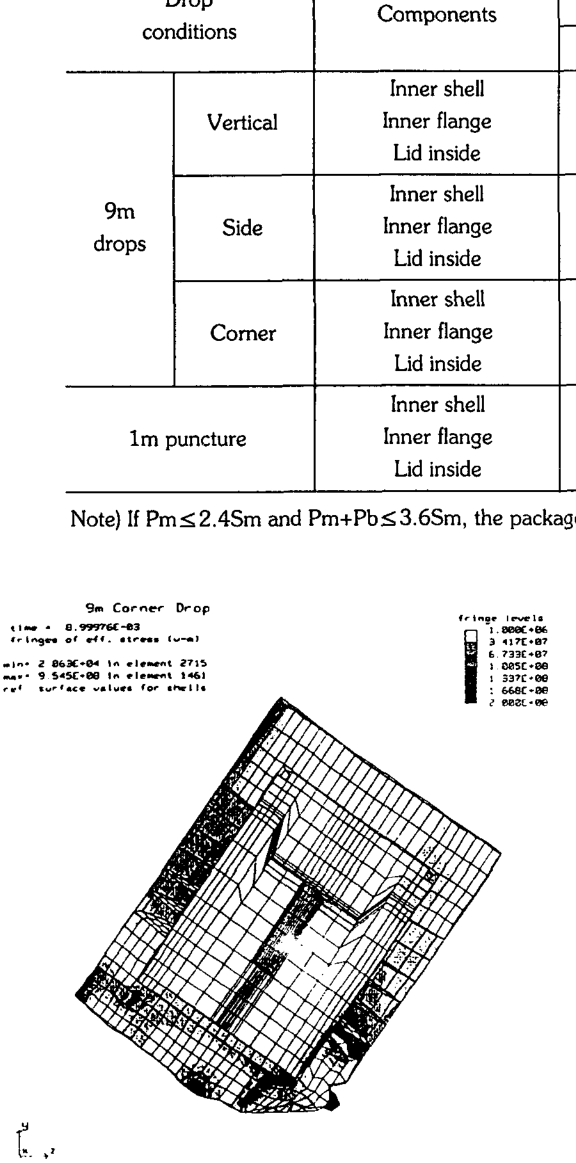

Fig. 5. Stress and Deformation Configuration for 9m Corner Drop

the impact force is gradually increased according to the deformation progress as the change of impacting area is increased. Figure 5 shows the stress and deformation configuration of the package when maximum stress was occurred. The deformation of the impact limiters was 87mm at 9.5msec after impacting. In the case of the corner drop, the deformation of the impact limiters was larger than the vertical and side drops. In general, the axial thickness of the impact limiters is determined as the energy-absorbing size for the corner drop impact.

The instant when the package impacts on the target surface, the impact reaches to maximum. The kinetic energy of the package transforms to both the crush of the impact limiters and the strain energy in the deformed body during the impact history. As shown in Fig.2, the impact forces were jumped linearly due to the crush of the impact limiters and decreased. That means the impact forces were absorbed into the crush of the impact limiters. As the impact behavior was getting longer, the impact force was decreased.

As shown in Table 2, any maximum stress intensity on the package, including the inner shell as the containment boundary of the package, does

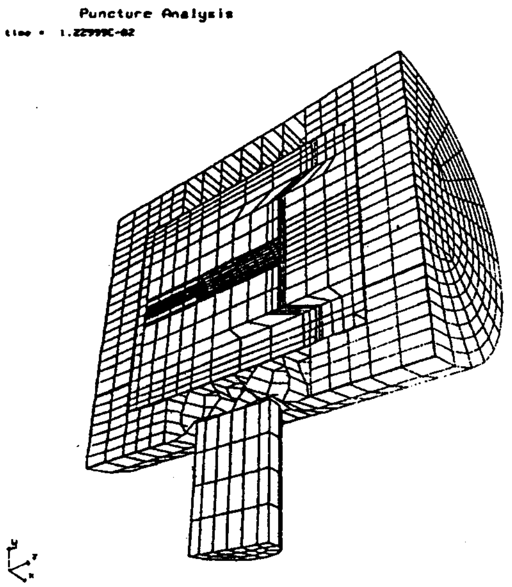

Fig. 6. Deformation Configuration for 1m Puncture

not exceed allowable values, and so the package is found to be safe structurally under the 9m free drops. It shows maximum stress intensity of the side drop is the largest among the three drops.

3.3. 1m Puncture Analysis

The regulations describe that the package should withstand a 1m drop impact onto a mild steel round bar, which is 15cm diameter and not less than 20cm long, in an orientation causing maximum damage.

While the outer casing and heat transfer fins of the impact limiters impacted on the mild steel bar were locally and largely deformed, scarcely any part of the body was notably damaged. Figure 6 shows the deformation configuration of the package. The total impact time was about 15msec and the deformation of impact limiters was 2.1cm at 9msec after impacting.

In Table 2, any maximum stress intensity on the package, to say nothing of the inner shell, does not exceed allowable values, and so the package is safe structurally under the 1m puncture.

4. Conclusions

The three dimensional impact analyses under the 9m free drops classified into vertical drop, side drop and corner drop and the 1m puncture were performed, respectively.

The impact behavior for each 9m free drop was analyzed. The impact force for each drop was gradually increased and suddenly decreased. As the impact time was getting longer, the impact force was decreased.

Any maximum stress intensity on the package under the 9m free drops and the 1m puncture does not exceed the allowable values of the regulations. Therefore, the package was evaluated to be safe structurally pursuant to the IAEA and domestic regulations.

Though there are several problems in the impact analysis such as the reduction of analysis time, the improvement of accuracy, material property at impact and analysis modeling, it is considered that the three dimensional impact analysis using the finite-element code is more useful for the optimal impact-resistant design and the structural evaluation of the packages.

References

1. IAEA Safety Series No.6, *Regulations for the Safe Transport of Radioactive Material 1985 Ed.* (1990)
2. IAEA Safety Series No.37, *Advisory Material for the IAEA Regulations for the Safe Transport Radioactive Material 3rd. Ed.* (1990)
3. MOST Bulletin No.96-38, *Regulations for the Packaging and the Transport of Radioactive Material* (1996)

4. R.A. Robinson, J.A. Hadden, and S.J. Basham, *Experimental Studies of Dynamic Impact Response with Scale Models of Lead Shielded Radioactive Material Shipping Containers*, Battelle Columbus Lab., BMI-2001 (1978)
5. H.R. Yoshimura, D.R. Bronowski, W.L. Uncapher, S.W. Attaway, V.I. Bateman, T.G., Carne, D.L. Gregory and M. Huerta, *Evaluation of Impact Limiter Performance During End-on and Slapdown Drop Tests of a One-Third Scale Model Storage/Transport Cask System*, Sandia National Lab., SAND89-1343 (1989)
6. G. Yagawa, H. Ohtsubo, H. Takeda, Y. Toi, T. Aizawa and T. Ikushima, "A Round Robin on Numerical for Impact Problems", *Nuclear Engineering and Design*, **78**, No.3, pp.377-387 (1984)
7. J.R. Friley, *Comparison of Structural Computer Programs Used for the Analysis of Spent Fuel Shipping Casks*, Battelle Pacific Northwest Lab., PNL-4161 (1984)
8. T.A. Nelson and R.C. Chun, *Methods for Impact Analysis of Shipping Containers, Lawrence Livermore National Lab.*, NUREG/CR-3966 (1987)
9. P.A. Pfeiffer and J.M. Kennedy, "Free Drop Impact Analysis of Shipping Cask", *Nuclear Engineering and Design*, **114**, No.1, pp.33-52 (1989)
10. Y.S. Lee and Y.J. Kim, "A Study on the Dynamic Behaviors of a Shipping Container under Drop Impact Loading", KSME Journal, **18**, No.11, pp.2805-2816 (1994)
11. Livermore Software Technology Corporation, *LS-DYNA3D User's Manual* (1995)
12. U.S NRC 10 CFR part 71, *Packaging and Transportation of Radioactive Materials* (1988)
13. KAERI, *Safety Analysis Report for KSC-4 Shipping Cask*, KAERI/TR-137/89, (1989)
14. ASME sec.Ⅲ, *Rules for Construction of Nuclear Power Plant Component* (1994)
15. Z.H. Zhong, *Finite Element Procedures for Contact-Impact Problems*, pp.20-76, Oxford University Press Inc., New York (1993)
16. K.J. Bathe, *Finite Element Procedures in Engineering Analysis*, pp.499~ 556, Prentice-Hall, Englewood Cliffs (1982)