Safety Analysis of Dual Purpose Metal Cask Subjected to Impulsive Loads due to Aircraft Engine Crash*

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Abstract

In Japan, the first Interim Storage Facility of spent nuclear fuel away from reactor site is being planned to start its commercial operation around 2010, in use of dual-purpose metal cask in the northern part of Main Japan Island. Business License Examination for safety design approval has started since March, 2007. To demonstrate the more scientific and rational performance of safety regulation activities on each phase for the first license procedure, CREPEI has executed demonstration tests with full scale casks, such as drop tests onto real targets without impact limiters⁽¹⁾ and seismic tests subjected to strong earthquake motions⁽²⁾. Moreover, it is important to develop the knowledge for the inherent security of metal casks under extreme mechanical-impact conditions, especially for increasing interest since the terrorist attacks from 11th September 2001⁽³⁾⁻⁽⁶⁾. This paper presents dynamic mechanical behavior of the metal cask lid closure system caused by direct aircraft engine crash and describes calculated results (especially, leak tightness based on relative dynamic displacements between metallic seals). Firstly, the local penetration damage of the interim storage facility building by a big passenger aircraft engine crash (diameter 2.7m, length 4.3m, weight 4.4ton, impact velocity 90m/s) has been examined. The reduced velocity is calculated by the local damage formula for concrete structure with its thickness of 70cm. The load vs. time function for this reduced velocity (60m/s) is estimated by the impact analysis using Finite Element code LS-DYNA with the full scale engine model onto a hypothetically rigid target. Secondly, as the most critical scenarios for the metal cask, two impact scenarios (horizontal impact hitting the cask and vertical impact onto the lid metallic seal system) are chosen. To consider the geometry of all bolts for two lids, the gasket reaction forces and the inner pressure of the cask cavity, the detailed three dimensional FEM models are developed and calculated. Main criteria for estimating the maximum leakage rate for the lid metallic seal system are no loss of the pre-stress of the lid bolts, no appearance of the plastic region between the metal seal flanges, and no large relative deformation of the lid seals. Finally, in both cases, the low leakage rate for the metal cask lid closure system under the impulsive loads due to aircraft engine crash will be proved thoroughly.

Key words: Metal Cask, Aircraft Crash, Nuclear Spent Fuel, Missile Impact, Metallic Seal, Interim Storage Facility

1. Introduction

After the terrorist attacks from 11th September 2001, accident scenarios exceeding the design requirements, such as a forced aircraft crash, were considered, and the corresponding analysis have been executed with regard to the assessment of the inherent safety in an interim nuclear spent fuel storage facility with combined transport and storage casks. In Japan, the first interim storage facility of spent nuclear fuel away from reactor site is being planned to start its commercial operation around 2010, in use of dual-purpose metal cask in the northern part of Main Japan Island. To succeed early realization of the storage facility, it is important to present whether the forced aircraft crash event might lead a considerable release of radioactive substances into the environment integrity.

In this study, firstly, a penetrating engine of a big passenger aircraft, such as Boeing 747 and Air-Bus 300, was considered, since this engine covers the wide range of possible mechanical impacts. The assumed hitting speed of this aircraft engine was based on the reduced velocity after the penetration of the engine through the building. Secondly, two mechanical impact analyses onto the fuel storage metal cask using Finite Element code LS-DYNA with the full scale engine and cask model were executed to clarify the extent of reducing the cask integrity and the leakage increase.

2. Impact analysis with the metal cask

2.1 Impact Scenarios

With the object of clarifying the movements of the lid structure of the metal cask during the extreme impact loads due to aircraft crash, two impact scenarios for aircraft engine crash onto the metal cask without impact limiters as shown in Fig.1 were considered for both, a vertical impact onto the lid structure and a horizontal impact hitting the cask.

To evaluate the lid structure behavior during the extreme impact loads, impact analyses for these scenarios have been executed with dynamic Finite Element Method analysis code LS-DYNA Ver.970.

Fig. 1 Considered scenarios for aircraft engine crash onto the metal cask without impact limiters

2.2 Impact Loading

In order to analyze the movements of the lid structure of the metal cask in case of an impact due to a big passenger aircraft engine crash, a load vs. time function and a load contact area are needed. As a relevant aircraft engine, turbo-fan engine (Type GE/CF6-80C2), which was used for big passenger planes, such as Boeing747 and Air-Bus 300, was chosen⁽⁷⁾⁻⁽⁹⁾. Fig.2 shows the outline of the relevant aircraft engine. Its length, outer diameter and weight are 2.7m, 4.3m and 4.4ton, respectively.

The local penetration damage of the interim storage facility building against a relevant aircraft engine crash has been examined. The impact velocity was set to 90m/s considering the taking-off, landing speed of the passenger aircraft, and the Type C package test conditions in the IAEA Transport Regulation⁽¹⁰⁾. The penetration depth can be calculated by the local damage formula, such as Degen formula for concrete structure⁽¹¹⁾. Fig.3 shows the relationship between the impact velocity and the penetration depth derived by Degen formula for rigid missile using the dimension of the relevant aircraft engine. For example, in case of the impact velocity 90m/s, the protection thickness for the penetration of the concrete structure should be over 96cm. According to the design concept of the storage building⁽⁵⁾, the wall thickness is set from 0.7m to 1.2m. Therefore, the reduced velocity of the engine missile after the 85cm wall thickness penetration can be estimated as about 60m/s.

The load vs. time function for the relevant aircraft engine with this reduced velocity was estimated by the impact analysis using Finite Element code LS-DYNA with the direct full scale engine model onto hypothetical rigid target as shown in Fig.4.

Fig.5 shows the loading function. Impact loads were affected by the buckling of the nose corn, the interactive force between high and low pressure turbines, and the plastic deformation of the rotor spaced in the center of the engine. In the following impact analysis, the representative diameter of the impact load contact circular area was set to 1.4m considering the stiffness distribution of the relevant aircraft engine.

Fig. 2 Outline of the relevant aircraft engine (Type GE/CF6-80C2)

Fig. 3 Relationship between the impact velocity and the penetration depth (by Degen formula)

Fig. 4 Full scale engine model

Fig. 5 Loading functions for the relevant aircraft engine

2.3 Target storage cask description

Fig.6 shows overview of a full-size metal cask model for impact analysis, and Table 1 shows main specifications of this model⁽¹²⁾. This model has been designed as metal cask for dry storage and transportation installing 21 PWR-type fuel assemblies.

This cask has double lid structure, and lid gaskets are double type metal gasket made of aluminum coating material. For primary and secondary lids, a section diameter of the gasket is 5.6 mm and 10 mm, respectively. And this cask has a gap between lid side and body. At initial condition, primary and secondary lids are placed carefully to make the gap equal. Nominal gap of primary and secondary lids at one side is 1mm and 0.5 mm, respectively.

Fig. 6 Overview of full-size metal cask model

Table 1. Specification of Metal Cask Model

Part	Material	Size (mm)	Weight (ton)
Body	Carbon steel ASTM A350LF5	Inner Dia. : 1672 Thickness : 250	84.6
Neutron Shielding	Resin	Thickness : 164	
Outer Sell	Carbon steel	Outer Dia. : 2524 Thickness : 12	
Trunnion	Stainless steel SUS F630	Diameter : 190	
Primary Lid	Carbon steel ASTM A350LF5	Outer Dia. : 1946 Thickness : 198	4.2
Secondary Lid	Carbon steel ASTM A350LF5	Outer Dia.: 2236 Thickness : 235.5	5.5
Contents	Equivalent weight	-----	24.7
Total Weight			119

2.4 Analysis model description

Fig.7 shows analysis model of a vertical impact onto the lid structure and a horizontal impact hitting the cask. This model is made as a 1/2 symmetric model considering the cask structure and the engine missile orientation. The accuracy of this analysis model was benchmarked by comparing the impact test results to simulate the impact behavior of the complicated gasketed joints⁽¹³⁾.

As to the contact condition, on every contact surface between parts of this analysis model, a slide surface condition with voids is applied. Friction coefficient of the slide surface is set to 0.14. However, only for flange surface of primary and secondary lids, these coefficient values are set to experimental value (0.6) obtained from the sliding test result with a scaled lid model⁽¹²⁾. The initial tightening force of the lid bolts, equivalent to tightening torque of 2400 N-m, is set by the equilibrium condition with the forced initial contact displacement between the lid bolt and lid flange before the impulsive loading as shown in Fig.8.

Fig. 7 Analysis model for aircraft engine crash on to the cask

Fig. 8 Initial tightening force of the lid bolts

2.5 Material properties

Metallic materials are used for the cask body, lid, lid bolts, outer shell, trunnion, and contents. These materials are simulated as isotropic elastic plastic material. Table 2 shows

material properties applied to the calculation. Strain rate effect was considered for yield stress.

Table 2. Material properties of the cask

Part	Density (kg/m ³)	Young's modulus (MPa)	Poisson's ratio (---)	Yield stress (MPa)	Hardening modulus (MPa)
Body Lid	7.85x10 ³	203460	0.3	205*	2034
Lid bolt	7.85x10 ³	202000	0.3	890*	2020
Outer shell	7.86x10 ³	203000	0.285	215	2030
Trunnion	7.86x10 ³	195000	0.3	725*	1950
Contents	7.86x10 ³	203000	0.3	215	2030

3. Containment evaluation criteria

Containment evaluation criteria for the metal gasket seal was proposed by Japan Nuclear Energy Safety Organization (JNES), based on a series of leakage tests using scale models with double type aged metal gasket made of aluminum coating material of which section diameter was 10mm⁽¹⁴⁾. Sliding or opening of the lid is defined by the relative displacement of the metallic gaskets parallel or normal to the flange, respectively as shown in Fig.9. The accumulated relative displacement $D_{S,Accumulated}$ is defined by subtracting the difference between the values of initial and residual, $D_{S,Residual} - D_{S,Initial}$ from twice the difference between maximum and minimum, $2*(D_{S,Max} - D_{S,Min})$.

The instantaneous leak rate for 60-year aged metal gasket seal subjected to the impulsive loads could be evaluated by the relationship between the leak rate and $D_{S,Accumulated}$ as shown in Fig.10, if the lid system would satisfy the following conditions.

- * There is no plastic deformation in the lid system.
- * There is no considerable opening of the lids.
- * There is no considerable loss of the torque of the lid bolts.

Fig. 9 Definition of the Sliding or Opening of the Lids

Fig. 10 Relationship between the leak rate and the accumulated relative displacement

4. Impact analysis results

4.1 Plastic deformation

Fig.11 shows the generation of the plastic deformation in each scenario. In case of the vertical impact onto the lid metallic seal system, the plastic deformation was generated in the second lid flange, therefore the leak-tightness of the secondary lid system might be lost during impact loads according to the leakage criteria described above. On the other hand, there is no plastic deformation in the lid system in case of the horizontal impact hitting the cask.

4.2 Lid Movements

Fig.12 and Fig.13 show the example of the time history of the lid movements during the vertical impact onto the lid metallic seal system and the horizontal impact hitting the cask. In case of the vertical impact, a considerable lid opening displacement was generated in the secondary lid. On the other hand, in case of the horizontal impact, the large sliding deformations of the primary and secondary lids were generated.

4.3 Evaluation of Leak-tightness

Table 3 shows the summary of the impact analysis results. According to the leakage criteria described above, it can be concluded that the leakage rate from the primary lid might be considerably low (less than 1.0×10^{-5} Pa·m³/s), and the loss of the inner pressure in the cask might be avoided during the extreme impact loading due to aircraft engine crash scenarios.

Fig. 11 Generation of plastic deformation in each scenario

Fig. 12 Time histories of the displacement of the lids for the vertical impact scenario

Fig. 13 Time histories of the displacement of the lids for the horizontal impact scenario

Table 3. Summary of the Impact Analysis

Part	Event	Vertical impact	Horizontal impact
Primary lid	Sliding*	0.23mm	1.70mm
	Opening	0.04mm	0.02mm
	Status**	None	None
Secondary lid	Sliding*	0.52mm	1.77mm
	Opening	0.07mm	0.06mm
	Status***	No plastic	No plastic
Estimated Leak Rate (Pa·m ³ /s)	Primary lid	<1.0x10 ⁻⁵	<1.0x10 ⁻⁵
	Secondary lid	Loss	<1.0x10 ⁻⁵

* Accumulated Sliding Displacement

** Generation of the plastic deformation in the lid system

5. Conclusions

The analyses of two impact scenarios for aircraft engine crash onto the metal cask without impact limiters, a vertical impact onto the lid structure and a horizontal impact hitting the cask, have been executed to clarify the extent of reducing the cask integrity and the leakage increase.

The leakage rates were calculated in connection with the determination of the accumulated relative displacements between the metallic gaskets and the flange.

After the lid behaviors in each scenario have been evaluated, it was found that although the secondary lid might lose the leak-tightness in case of the vertical impact, the leakage rate from the primary lid might be low and the loss of the inner pressure inside the cask might be avoided in the extreme impact loading conditions.

Acknowledgments

These works have been carried out under the contract from Nuclear and Industrial Safety Agency, Ministry of Economy and Trade Industry of the Japanese Government.

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