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Development of Aircraft Impact Scenario on a Concrete Cask in Interim Storage Facility

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1. Introduction

The interim storage facility (ISF) is designed and constructed for storing pre-cooled spent nuclear fuel (SNF) for a few decades before recycling or permanent disposal. Korea Radioactive Waste Agency (KORAD) and Korea Atomic Energy Research Institute (KAERI) have been developing various dry storage cask models to be used in a near future. A concrete cask design concept is an option for SNF storage, which widely used in many countries.

IAEA safety guide No. SSG-15 [1] mentions the hypothetical initiating events of SNF storage. Among the external initiating events, the aircraft strike on a storage cask is considered one of the dominant contributions to the risk during storage phase [2]. Although the probability of aircraft crash on ISF is extremely small, it is important to develop the accident scenario caused by an intentional malicious acts launched towards the storage facility in terms to improve inherent security. Thus, the probabilistic approach to develop aircraft impact scenarios on a storage cask is needed.

This paper provides a method for determining the failure criteria in global and local damage responses for the concrete cask under extreme mechanical impact condition.

2. Impact condition analysis

2.1 Description of ISF

As assumed in the EPRI NP-3365 report [3], the spent-fuel storage facility would serve for 1000MWe PWR during 40 years operating period. Around 60 fuel assemblies discharge from the reactor per year. The canister in the concrete cask accommodates 24 spent fuel assemblies. At the end of active storage phase, about 2400 PWR fuel assemblies would be stored in 100 concrete casks, which is the maximum inventory over the storage facility lifetime. The storage cask layout model is 10 x 10 square array freestanding casks on a concrete pad covered by confinement building as illustrated in Fig.1.

The typical concrete storage cask mainly consists of a heavy reinforced concrete body closed by double upper lids as a containment shield, and an inner steel canister provides a leak-tight confinement of the spent fuel.

2.2 Missile design

The Boeing 747-400 is considered as a typical impacting aircraft. However, the size of a dry storage cask is much smaller than B747. Therefore, it is not possible for the entire mass of the aircraft to strike the cask. We assume that the most severe impact condition is the direct impact of aircraft jet engine on the cask that may cause a release of radioactive materials, regardless of other stiff elements. The turbofan engine type (CF6-80C2), used for B747-400, was chosen. The engine weighs about 4.4 tons (9670 Ib), the effective impact diameter is about 1.5 m, the length is 4.3 m, and has a blunt nose shape [4].

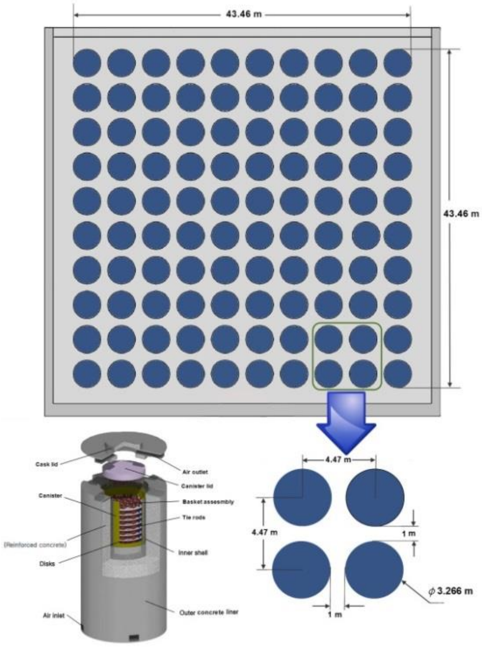

Fig.1. Schematic layout of ISF and concrete cask model.

Although the specification of B747 is known, accurate method to predict the aircraft impact velocity on any building is not possible; because it depends on many factors such as the size of the target, topography around the site, weather, payload, pilot skills, etc. Thus, the assumed impact velocity values of the jet engine were based on the reduced velocity after penetrating 15 cm (6 inches) thickness of the exterior normal concrete (concrete strength 2200 psi) wall without bars. The minimum required impact velocity to penetrate 15 cm of normal concrete can be calculated by using Modified NDRC (National Defense Research Committee) formula for large diameter missiles [5], which equals 158 km/h. Thus, the aircraft impact velocity is approximately reduced to 27% before impacts the storage casks. Fig.2 shows the measured velocity of B747 before and after collapse the building wall of storage facility.

$$V_r = 1000D.^{1.8}\sqrt{\frac{x_c^{\,2}}{KNWD}} \tag{1}$$

Where:

- x_c is the crushed casing penetration depth (in.);
- V_r:Engine velocity (ft/sec);
- D is the average outer diameter of the engine casing (in.);
- W: Total engine weight (lbs);
- $K = 180/(f_c')^{1/2}$;
- N=0.84 (blunt-nose missile);
- f_c': Concrete strength (psi).

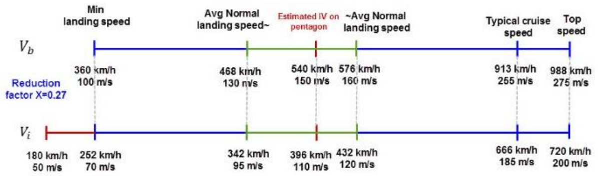

Fig.2. Description of measured velocity of B747 before and after collapse the storage-building wall.

The most probable value of impact velocity would be around the average normal landing speed (130~160 m/s) for B747. Nevertheless, we should also take into account the possible impact velocity values during abnormal landing caused by a malfunction or an attention attack. Therefore, we selected the minimum and maximum possible impact velocities on the storage cask (50~200) m/s as a conservative assumption.

2.3 Impact scenario

The accident scenario of a targeted B747 engine impact into the storage cask is set from a literature survey, and the impact conditions are derived from the scenario. The aircraft impact orientation is an important factor to be determined in an aircraft crash scenario. During normal landing for fixed-wing aircraft, it usually rests on the ground in a distinctly nose-up attitude to become parallel to the ground. On the other hand, the biggest impact load can happen during horizontal impact on the cask. Therefore, this study only covers the perpendicular impact on the center of the sidewall as shown in Fig. 3, because it is considered the most logical impact orientation and the largest vulnerable area of impact into casks.

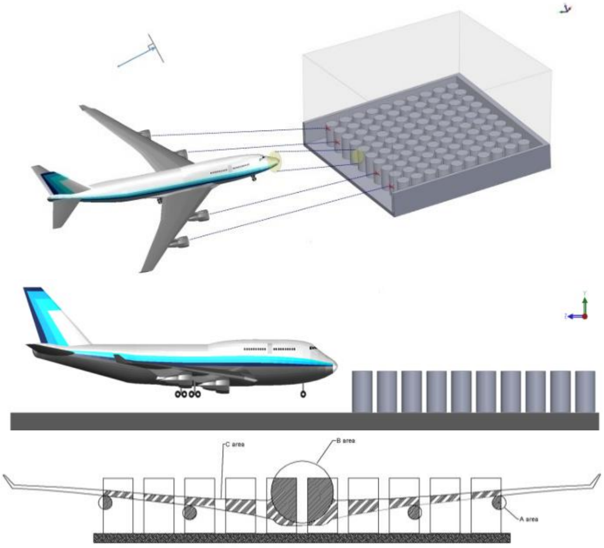

Fig.3. Schematic representation of impact scenario.

3. Assessment methodology of damage response for concrete cask due to aircraft engine impact

The storage casks may experience structural damage in several modes as a result of an aircraft crash. Further, depending upon various parameters involved, the critical mode of damage may vary for different casks models. In the aircraft impact scenario on a storage cask, two mechanical modes of damage could be delineated: global structural damage mode, and local structural damage mode. In this section, some of the empirical formulas are recommended for determining the criteria of failure for local damage response. In addition, new formulas are derived to determine the probability of tipping and slipping in global damage response.

3.1 Global structural damage assessment

Global structural damage is a response of the overall target structure, as measured by its state of strain or displacement [5]. Two initial exclusive response modes were selected in this study, tip-over and sliding. In this analysis, the missile and storage cask are assumed to be rigid. The free-body diagram (FBD) for storage cask is described in Fig. 4.

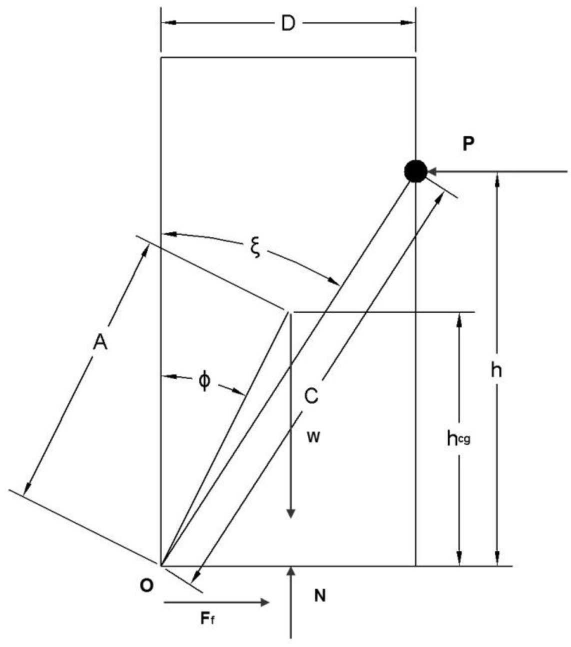

Fig.4. Free-body diagram (FBD) for storage cask.

In the static condition, the cask does not move vertically, thus the sum of vertical forces is equal to zero:

$$\sum F_y = 0$$
$$F_y = -W + N = 0,$$
$$N = W = m_c g \tag{2}$$

The equation for friction force is $F_f = \mu N$, where μ is the coefficient of friction (static fraction) between the cask and the ground surface:

$$F_f = \mu N$$
$$F_f = \mu m_c g \tag{3}$$

The critical pushing force on the cask, which will cause the cask to tip-over, can be derived using the moment equation at point O that presents the maximum resisting moment:

$$\sum \mathrm{M} = 0$$

$$-P_{cr} h + W.\frac{D}{2} = 0$$

$$P_{cr} = \frac{D\ g\ m_c}{2\ h}, \qquad h \neq 0 \tag{4}$$

Then, the force analysis for x-axis in a static equilibrium:

$$\sum F_x = 0$$

$$F_x = P_{cr} - F_f = 0$$

From Eqs. (3) and (4), the critical impact height is given by:

$$h_{cr} = \frac{D}{2\mu} \tag{5}$$

If the force is applied at a point above the base of the cask and higher than h_{cr}, the cask will pitch forward and tip over, rather than slides along the floor. In addition, we note that as P grows very large, h becomes quite small. However, a very strong applied force delivered very low on the cask could still topple it. On the other hand, since the force cannot be applied any higher above the floor than h = $\frac{D}{2\mu}$, we find that:

$$h = \frac{m_c g}{2P_{cr}} D \leq h_{cr} = \frac{D}{2\mu} \rightarrow \frac{m_c g}{2P_{cr}} \leq \frac{1}{2\mu} \rightarrow P_{cr} \geq \mu m_c g$$

This tells us that a force less than $\mu m_c g$ applied anywhere cannot cause the cask to tip over since the hit location above the floor and less than the h_{cr}. Thus, the cask cannot slide across the surface as long as the value of P is less than F_f. For the cask to slide across the floor without tipping, P must lie in the range.

$$\mu N < P < P_{cr}$$

It can be rewritten for impact velocity as:

$$V_{s0} < V < V_T$$

Where V_T is the required impact velocity to tip over the cask at the critical height impact h_{cr}, and V_{s0} is the minimum required velocity to initiate sliding. The V_T can be calculated by applying and combining the conservation of angular momentum at point O of the cask and the conservation of energy when the center of gravity is directly over the point of the rotational O, as described in NUREG-1864 [2]:

$$V_T{}^2 = \frac{2[\,m_m\, g\, C(1 - \cos\xi) + W\, A(1 - \cos\,\phi)]\left(m_m\, C^2 + \frac{W}{g} A^2\right)}{(m_m\ \ C\ \cos\,\xi)^2} \tag{6}$$

Moreover, the V_s can be calculated by applying the conservation of momentum and the equation of motion for the storage cask after impact, then the velocity and sliding displacement equation as:

$$x = \left(\frac{m_m V_s}{m_m + \frac{W}{g}}\right) t - \frac{\mu g t^2}{2} \tag{7}$$

The minimum required velocity to slip the cask about 50 cm, which is the distance from the edge of the storage cask to the edge of the pad, can be calculated by using the following equation that also described in NUREG-1864 [2]:

$$V_s = \frac{\left(\mathrm{m_m} + \frac{\mathrm{W}}{\mathrm{g}}\right)\sqrt{2\mathrm{x_{max}} \times \mu \times \mathrm{g}}}{\mathrm{m_m}} \tag{8}$$

From the above analysis, we can define the criteria of tipping and slipping modes. For instance, Eq (6) finds the minimum and critical required velocities for tipping, Eq. (5) finds the critical height impact location and Eq. (8) finds the minimum required impact velocity to cause a relative displacement by sliding the cask. Table 1 lists the values of the parameters as an example for this study.

Table 1.The required calculations to find the probability for tipping and slipping response.

Parameters	**Values**
Cask mass, m_c	144000 kg
Missile mass, m_m	4400 kg
Fraction coefficient, μ [6]	0.55
Cask diameter D (m)	3.266 m
Cask height H (m)	6.03 m
A	3.43 m
C at the top of cask C at h_{cr}	6.85 m 4.41 m
V_{min} for tipping	204.3 km/h
h_{cr}	2.97 m
V_{cr} *(Critical)*	414.7 km/h
V_s	327.5 km/h
h_s, when $V_T = V_s$	4.74 m
h_{min} *when* $V_{max} = 720$ km/s	1.81 m

Through the previous data and equations, the probability of either tip-over or sliding based on the vulnerable area of the cask and the impact velocity can be estimated by using the probability estimation method. All the possible impact height locations on the storage cask has been fitted and plotted in a normal distribution [1.745, 3.015] also the proposed B747 impact velocity has been plotted and fitted in a log-Gamma distribution [143.98, 0.04136] as a best fit shown in Fig.5.

Figure 5 shows the relation between the impact velocities with the impact locations on the cask described in two distribution curves and divided into four areas based on the previous calculations in Table 1 as a separation boundary between sliding and tip-over modes, as follows:

1-The impact velocity in **A** domain: $180 \le V_i < 200$

$V_i < V_{min}$, No Tip-over

$V_i < V_s$, Sliding less than 50 cm

2-The impact velocity in **B** domain: $200 \le V_i < 327.5$

$V_s > V_i \ge V_{\min}$ **&** $h > h_s$ (E area), Tip-over

$V_i < V_s$, Sliding less than 50 cm

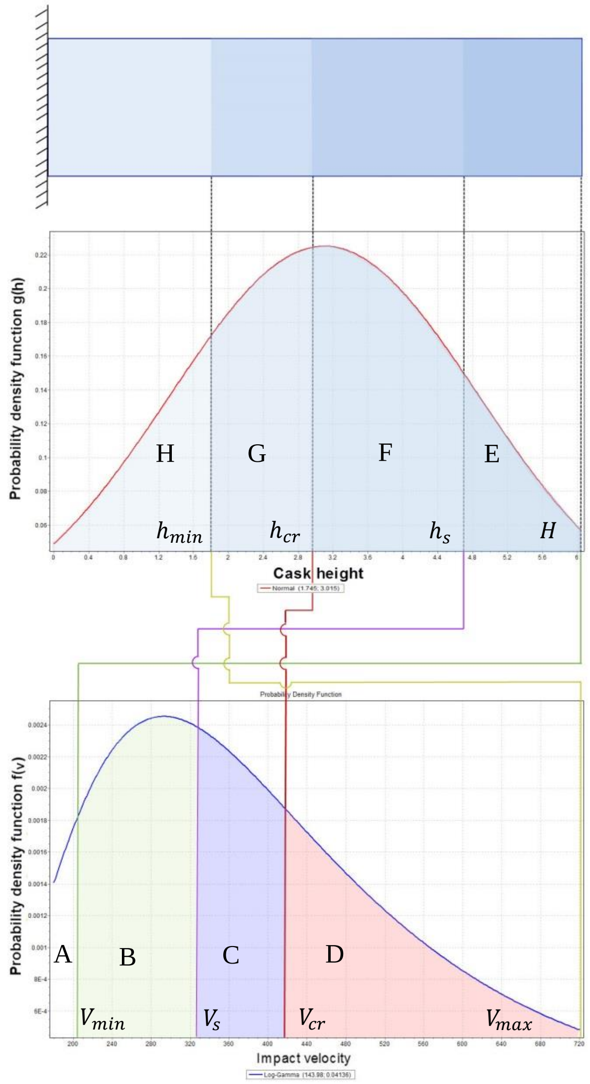

Fig.5. Schematic diagram of failure probability estimation method for global response damage.

3-The impact velocity in **C** domain: $327.5 \le V_i < 414.7$

$V_{cr} > V_i \ge V_s$ **&** $h > h_{cr}$ (E & F area), Tip-over

$V_i \ge V_s$ **&** $0 > h > h_{cr}$ (H & G area), Sliding over than 50 cm

4-The impact velocity in **D** domain: $414.7 \le V_i < 720$

$V_{max} > V_i \ge V_{cr}$ & $h > h_{\min}$ (E & F & G area), Tip-over

$V_i \ge V_{cr}$ & $0 > h > h_{\min}$ (H area), Sliding over than 50 cm

From the above, we can calculate the failure probability for tip over and sliding as follows:

$$P_{tip-over} = \int_{V_{min}}^{V_s} f(v).dv. \int_{h_s}^{H} g(h).dh + \int_{V_s}^{V_{cr}} f(v).dv. \int_{h_{cr}}^{H} g(h).dh + \int_{V_{cr}}^{V_{max}} f(v).dv. \int_{h_{min}}^{H} g(h).dh \quad (9)$$

$$P_{sliding} = \int_{V_s}^{V_{cr}} f(v).dv. \int_{0}^{h_{cr}} g(h).dh + \int_{V_{cr}}^{V_{max}} f(v).dv. \int_{0}^{h\,min} g(h).dh \quad (10)$$

Where:

– *f(x)* is the probability density function for impact velocity.

$$f(v) = \frac{(\ln(v))^{\alpha-1}}{v\beta^{\alpha}\Gamma(\alpha)}\exp(-\ln(v)/\beta)$$

– *g(x)* is the probability density function for cask height.

$$g(h) = \frac{\exp\left(-\frac{1}{2}\left(\frac{h-\mu}{\sigma}\right)^2\right)}{\sigma\sqrt{2\pi}}$$

The above equations calculate the probability of occurrence the tip-over and sliding more than 50 cm based on criteria of the four possible conditions. By utilizing both of height and impact velocity distribution curves in Fig. 5 and using equation (9) and (10), we can find the initial response probability where the cask will tip-over or slide more than 50 cm due to missile impact.

Global Damage response (Initial predicted response)	
$P_{tip-over}$	$P_{sliding}$
0.353	0.150

The results showed that the probability of tipping over during missile impact is higher than sliding. Therefore, it is important to analyze the consequence of tipping over because various impact loadings can happen in different locations on the cask. Regarding the sliding mode, it is less significant than tipping over because most of impact load will only generate on a local area of the cask body.

3.2 Local damage assessment

In this study, the primary local damage effect of interest is the potential perforation of the outer reinforced concrete wall and inner steel liner. Two applicable empirical formulas have been selected to define the concrete wall thickness criteria to prevent perforation due to missile impact. Modified NDRC eq. (1) calculates the penetration depth and reduced Degen eq. (11) calculates wall thickness required to prevent perforation. To evaluate the steel liner target, Ballistic Research laboratory (BRL) eq. (12), which is widely accepted formula for predicting penetration of steel targets, was selected [5].

$$t_p = \alpha_p D\left\{2.2\left(\frac{x_c}{\alpha_c D}\right) - 0.3(x_c/(\alpha_c D)^2\right\}, \text{for } \frac{x}{\text{D}} \le 1.52 \quad (11)$$

$$T^{1.5} = \frac{0.5MV_i^2}{17400K_s D^{1.5}} \quad (12)$$

Where:

- t_p: wall thickness to prevent perforation (inches);
- x_c : crushed casing penetration depth (inches);
- K_s : Constant depending on the grade of the steel (=1);
- The recommended reduction factors for penetration and perforation are α_p =0.60, $\alpha_c = 0.5$. [7]
- D : average outer diameter of the engine casing (inches);
- T : predicted thickness to just perforate a steel plate (in.);
- M : missile mass (lb-sec /ft);
- V_i : missile impact velocity (ft/sec).

The steel liner plate will damage when the missile velocity in excess of those required to perforate a given wall thickness, the residual velocity of the engine missile can be estimated by using the following equation: [8]

$$V_R = \left[\frac{V_i^2 - V_p^2}{1 + \frac{w_{cp}}{w}}\right]^{0.5} \qquad (13)$$

Where:

- V_R : Residual velocity (ft/sec);
- V_P: Missile velocity that just initiates perforation.
- W_{cp}:Weight of the concrete plug ejected by the perforating missile with weight, W.(lbs);
  $W_{cp} = \pi \rho_c (t_w/3)(r_1{}^2 + r_1 r_2 + r_2{}^2)$
  $r_1 = D/2$, minor radius of cone (inches).
  $r_2 = r_1 + t_0(tan\theta)$, major radius of cone (inches).
  $\theta = 45°/(t_w/\mathrm{D})^{1/3}$
- t_0: Wall thickness (inches).
- ρ_c: is the weight density of concrete.

By using the above equations, we can estimate the wall thickness criteria to prevent perforation. Then, we can plot the probability distribution of wall thickness criteria with respect to the variation of the impact velocity (V_i) to find the damage probability for the concrete outer body and inner steel with canister. The probability of canister damage depends on the probability of concrete damage as described below.

The probability of canister damage = probability of concrete full perforation × probability of steel liner damage.

It should be noted that the probability of full perforations of concrete cask is extremely low because the typical concrete wall thickness around 70~80 cm. Moreover, although the impact velocity is very high and the shape of missile nose is very sharp, the cask will move by sliding or tip-over during collision which causes a part of local impact energy on the cask body transfer to motion energy. Therefore, local damage response should be considered not only for perforation but also for other effects such as cracking, scabbing, spalling, and penetration as a part of global damage response.

4. Conclusions

In this study, the response scenario due extreme mechanical impact conditions on storage cask and a method to estimate the failure criteria for global and local damage responses were developed and introduced. However, there are many factors neglected in this study such as cylindrical cask body shape, interaction between the global response and local response, hit angles and impact areas, seal tightness, bolts damage, and so on. In addition, the suggested Ballistic Research laboratory (BRL) formula is more suitable to use for small rigid missiles and thin targets. Therefore, further work to verify the failure criteria is needed. Moreover, the fire effect due to aircraft fuel explosion is also needed to complete the aircraft impact scenario on interim storage facility (ISF) to use it in the probabilistic approach. The most suitable method to well predict and develop this accident scenario is by using an analytical simulation.

REFERENCES

[1]. IAEA safety guides, “Storage of Spent Nuclear Fuel”, SSG-15, pp 99, 2012.

[2]. US-NRC,“A Pilot Probabilistic Risk Assessment of a Dry Cask Storage System at a Nuclear Power Plant”, NUREG-1864, 2006.

[3]. NUS corporation, “Review of Proposed Dry-storage Concepts Using Probabilistic Risk Assessment”, EPRI NP-3365, 1984.

[4]. Corgi Shirai, et al., “Safety analysis of DPMC subjected to impulsive loads due to aircraft engine crash”, 2008.

[5]. US-DOE Standards, “Accident Analysis For Aircraft Crash Into Hazardous Facilities”, DOE-STD-3014, 2006.

[6]. US-NRC, “Parametric Evaluation of Seismic Behavior of Freestanding Spent Fuel Dry Cask Storage Systems”, NUREG/CR-6865, pp 47-48, 2005.

[7]. Sugano, et al., “Local Damage to Reinforced Concrete Structures Caused by Impact of Aircraft Engine Missiles part 2. Evaluation of the Test Results”, Nuclear engineering and design, volume 40, pp. 407-423, 1993.

[8]. Anil K. Kar, “Residual Velocity for Projectiles”, Nuclear engineering and design, volume 53, pp. 87-95, 1978.