A PSA framework for an Interim Dry Storage Facility Subjected to an Aircraft Crash

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ABSTRACT

An overview of a risk evaluation framework for an aircraft crash into an interim spent fuel storage facility using a probabilistic safety assessment is presented. Damages evaluation of a detailed generic cask model in a simplified building structure under aircraft impact is discussed through a numerical structural analysis and an analytical fragility assessment. Sequences of the impact scenario are shown in a developed event tree, with uncertainties considered in the impact analysis and failure probabilities calculated. Risks are estimated for three specification levels of cask and storage facility structures to evaluate the influence of parameters relevant to design safety. The proposed assessment procedure includes the determination of loading parameters and reference impact scenario, structural response analyses of facility walls, cask containment, and fuel assemblies, and a radiological consequence analysis with dose-risk estimation. The risk results for the proposed scenario in this study are expected to be small relative to design basis accidents for best-estimated, conservative values. The importance of this framework is seen in the flexibility to evaluate facility capability to withstand aircraft impact and the expectation of potential realistic risks; the framework also provides insight into epistemic uncertainty in the available data, and into the sensitivity of design parameters for structural health management of interim dry storage facility.

1. INTRODUCTION

An intentional aircraft impact (AI) into hazardous facilities became a prominent issue after September 11, 2001. The questions then arose as to what extent an interim storage facility (ISF) can adequately protect against a large commercial AI and what momentous consequences an AI may pose to society and the environment. To answer these questions, possible damage scenarios with various AI loading conditions should be investigated to estimate the potential risks. Several safety assessment studies have considered various mechanical and thermal loadings that represent severe impact conditions in the frame of a probabilistic safety assessment with conservative assumptions, or just to evaluate the structural integrity of a cask assembly based on a deterministic approach (US NRC, 2007). However, no risk assessment with a scenario of a realistic aircraft crash into an ISF has yet been completed. Development of a comprehensive and systematic framework that comprises several elements of risk evaluation would make it possible to determine the feasibility of using such a framework to predict the expected hazard posed to the public, in addition to enhancing the reliability of facility/cask designs under possible severe impact loadings from aircraft crash. Further, this approach will enable the development of the so called risk-informed regulatory framework, which is more reasonable than conventional approaches that rely more on conservatism. Thus, under the frame of a probabilistic approach, this study attempts to integrate more elements into the development of a realistic aircraft crash scenario, including possible damage consequences and associated release of fission products to the environment. The current study covers only the first assessment stage of the accident scenario, which is a direct mechanical impact from an intended AI. The current analysis is divided into four major parts: Part 1 sets up the reference impact scenario; Part 2 provides a structural response analysis; Part 3 outlines the radiological consequence analysis; and Part 4 summarizes the event tree analysis results and the accident dose-risk estimations. Illustrative examples are presented in this paper for structures of three levels of resilience subjected to concentrated impact loadings from aircraft crash.

2. METHODOLOGY OVERVIEW

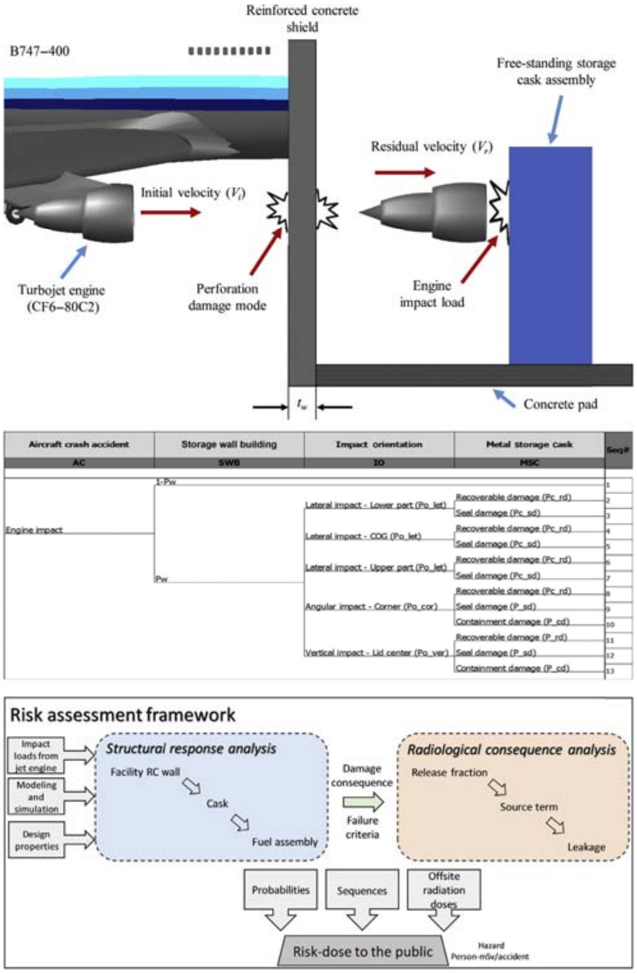

Figure 1. Framework of risk assessment for aircraft crash

The PSA framework developed in this study consists of three elements: the structural analyses of interim storage facility under aircraft crash to calculate the fuel damage ratio (FDR) and release fraction, radiological consequence analysis to calculate dose from the release, and the calculation of risk for each event tree. A simplified reference model of an interim storage facility is developed where only one free standing metal storage cask containing 24 PWR fuel assemblies are stored within a building with reinforced concrete (RC) walls. The impact scenarios were developed considering various aspects of targeted aircraft crash with different impact velocities, impact locations and impact angles. The FDR and release fraction are calculated from a sophisticated finite element analysis on the fuel assemblies and cask lid gap analysis. Three different levels of structural resilience were considered throughout the example study and three different ranges of burn-up were considered for spent nuclear fuels stored in the facility.

3. STRUCTURAL RESPONSE ANALYSES

3.1. Facility RC wall damage analysis

Since the hardest part in an aircraft is the aircraft engine, the direct impact of large size aircraft engine to the facility is considered that can possible result in the release of radioactive materials from the facility. As a best deterministic estimation, with a bias toward conservatism, as suggested in the NEI (Nuclear Energy Institute, U.S.) report (NEI, 2011), the empirical formulas employed in this study can predict the minimum RC wall thickness required to prevent local damage caused by the normal impact of an aircraft engine and its residual velocity. Impact speeds and compressive strengths of concrete are treated probabilistically as major sources of uncertainty. Utilizing the Monte-Carlo method, the cumulative distribution function for perforation thickness F(tw) is generated based on 10,000 trials. The failure probability of a given wall thickness (Pw) is calculated from the complementary cumulative distribution function. Therefore, the estimated failure probabilities for the three grades of wall are as follows: Pw(LG)=0.98, Pw(MG)=0.8, and Pw(HG)=0.27. It is noticeable that the failure probabilities of the facility wall for low- to median-resistance structures are expected to be very high compared with those for high-resistance structures.

3.2. Cask response analysis

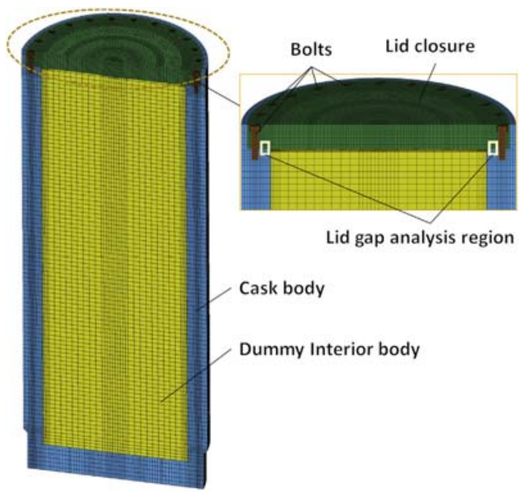

Figure 2 Cask analysis model to calculate leak path area

For the engine-cask impact analysis, the impact load-time history function and effective loading contact area for the relevant aircraft engine are needed. The details can be found in (Almomani et al, 2016). The applied impact velocities of the engine are 40 m/s, 60 m/s, 80 m/s, 100 m/s, 120 m/s, 140 m/s, and 160 m/s; these values have been selected to be within the range of the obtained residual velocities after concrete shield perforation. The finite element model for this analysis consists of a carbon steel cask body with one bolted upper lid closure without impact limiters, and a solid inner dummy weight representing the interior structure and spent fuel assemblies. The purpose of this model was to analyze the dynamic response of the lid closure system in order to calculate the leakage path area between the lid and the flange, since the lid seal plays an essential role in preventing the escape of fine particulates and radioactive gases from the cask. Therefore, unnecessary details of the cask system, such as the interior structures, were not modeled. The explicit time integration solver LS-DYNA was used to address the impact problem effectively. In the lid gap analysis, it is assumed that a closure opening greater than the pre-compression state of the metallic seal will cause leakage. The cask failure criteria, defined by Almomani et al. (2016) are as follows: recoverable damage is defined as the damage that occurs when the opening gaps are less than the elastic recovery distance ($<e_r$); seal damage is defined as the damage that occurs when the opening gaps exceed the elastic recovery distance ($>e_r$); and containment damage is defined as the damage that occurs when an irreversible deformation occurs on the cask containment.

3.3. Fuel assembly response analysis

The dynamic impact characteristics of a fuel assembly inside the cask are analyzed using the explicit nonlinear FE code ABAQUS. The interior structure of the FE model includes a fuel basket, fuel basket supports, and one fuel assembly placed at the location of engine impact. The other basket cells, which include 20 fuel assemblies, are filled with solid dummy bodies to compensate for the package weight. The purpose of this model is to analyze the dynamic response of the fuel assembly and estimate the fraction of rods that fail during the impact as an essential parameter of the radiological consequences. The impact analysis studied five impact orientations. The effect of impact angle is also studied together with the impact location and the jet engine of a B747 was chosen for this study to provide an upper bound impact load on the cask body.

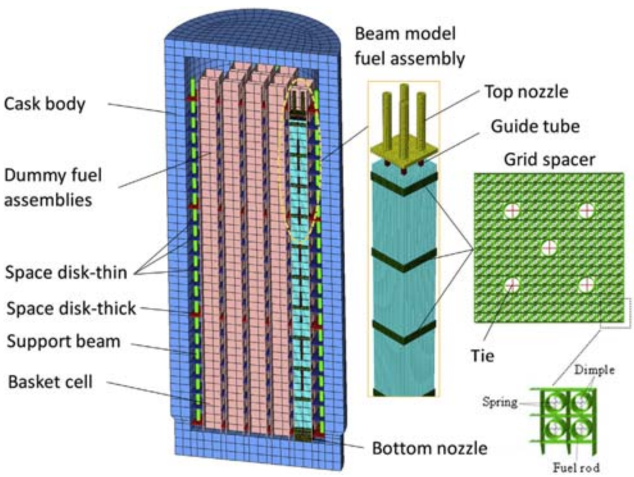

Figure 3 Detailed fuel assembly analysis model

For the fuel assembly response analysis, the cladding strain ratios have been calculated numerically. The strain failure criteria that would induce a cladding rupture with respect to burnup rate level are taken from SNL (Sandia National Laboratory) reports (SNL, 2004).

4. RADIOLOGICAL CONSEQUENCE ANALYSIS

The release fraction coefficient is used to estimate the amount of radioactive materials suspended in the air due to physical stress from an accident. A source term is used to describe the accidental airborne release of radioactive materials in atmospheric dispersion modeling. Three inventories for the radionuclides involved in the scenario that dominate the inhalation dose for all the chemical elements classes (volatiles, fission gases, and solid particles) are calculated using the ORIGEN-ARP of SCALE v.6.1.3 code (Gauld et al., 2006). The computer code HOTSPOT v.3.0.2 (Homann 2010), which was developed based on the Gaussian dispersion plume model, is used in this study to estimate the radionuclide spread from the accident. The reference person is presumed to have a breathing height of 1.5m and a breathing rate of 3.47Ee4 m^3/s. The wind speed reference height is 80 m and the release height is ground level. Hourly information from 1-year meteorological data, including wind speeds and directions, was utilized for a hypothetical site to determine the wind speed frequency groups in the scenario. In this study, three boundaries of interest surrounding the accident location are considered: an exclusion area boundary at 560 m, a low population zone at 5.7 km, and a population center distance at 7.6 km. The total effective dose equivalent at the three boundaries of interest is calculated by HOTSPOT for each event tree sequence. More details can be found in Almomani et al. (2017).

5. RISK ESTIMATION

The dose-risk elements are the product of the probabilities of the impact condition and the corresponding responses (Pw, Po, and Pc), and the fractions that lead to the release of radioactive materials that cause radiological consequences of magnitude (C). The measure of risk is given by Eq. (1), which is applied in sequence line i:

$$R_i = P_w P_o P_c \times C_i \quad (1)$$

The initiating frequency of the aircraft crash accident is assumed to be 1, representing an intentional aircraft crash. As the storage wall building is the first barrier to protect the internal spent fuel storage casks from the AI, the results of the probability of perforation (Pw) for facility walls (low, median, and high) are inserted accordingly into Column 2 of event tree. Then, the probability of each impact orientation is added in Column 3, as discussed in Section 3. Finally, the probability results of the cask response status for the three structural performance levels of metallic seal, are inserted into Column 4. All probability data are multiplied. The maximum possible radiological consequences for each sequence line, as shown in Table 1, are inserted into the Consequence column for the three rates of fuel burnup. Finally, through Eq. (1), the expected hazard to the public can be estimated in units of mSv/accident.

6. CONCLUDING REMARKS

The aim of the present article has been to confirm the flexibility of the proposed framework, which was developed in the authors' previous research via an examination of three combinations of design structures of facility and cask for a hypothetical reference facility that presents integrated damage sequences from an aircraft crash scenario. In addition, a best-estimate structural analysis, including fuel assembly damage, has been incorporated using practical FE modeling techniques to simulate accurately and efficiently the structural response under energetic loading. Subsequently, the radiological consequences for a hypothetical site were calculated, and individual risks for each possible sequence were obtained through a quantitative event tree analysis. From the probability analysis, which takes into account parameter uncertainties with assumptions for three different facility capacities, the conclusion is that an AI on a single fully loaded storage cask is not expected to cause a radiological impact that exceeds regulatory limits under the worst-case scenario for the three sets of design structures studied here. To achieve the final goal of complete risk assessment, as detailed in the Introduction, a fire scenario and a secondary mechanical impact scenario on multiple casks can be added to the proposed framework in order to evaluate accurately the overall associated radiological consequences to the public and the environment following an aircraft crash. The recommendations of this study give insight regarding the epistemic uncertainty in the available data for impact conditions and the sensitivity of the design parameters, which should be handled in a more practical manner in future research. Additional consideration of the material degradation properties of the spent fuel during the storage period should be given to control and regulate the transportation process and storage condition criteria, as well as to identify potential operating risks for enhancing safety operating procedures within different hypothetical accident conditions.

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Table 1. Calculated total effective dose equivalents (mSv)

Seq. #	Low burnup fuel			Medium burnup fuel			High burnup fuel		
	EAB	LPZ	PCD	EAB	LPZ	PCD	EAB	LPZ	PCD
2	6.00E-02	8.38E-04	5.52E-04	6.16E-02	8.60E-04	5.69E-04	9.45E-02	1.32E-03	8.73E-04
3	8.13E-02	1.14E-03	7.48E-04	4.48E-00	6.25E-02	4.12E-02	2.33E-01	3.25E-01	2.14E-01
4	6.00E-02	8.38E-04	5.52E-04	6.16E-02	8.60E-04	5.69E-04	7.04E-02	9.83E-04	6.50E-04
5	6.92E-02	9.67E-04	6.37E-04	1.18E-01	1.65E-03	1.08E-03	1.02E-01	1.42E-01	9.34E-02
6	6.00E-02	8.38E-04	5.52E-04	6.16E-02	8.60E-04	5.69E-04	7.99E-02	1.12E-03	7.37E-04
7	6.36E-02	8.88E-04	5.85E-04	1.21E-00	1.67E-02	1.10E-02	1.29E-01	1.80E-01	1.19E-01
8	6.00E-02	8.38E-04	5.52E-04	6.16E-02	8.60E-04	5.69E-04	8.11E-02	1.13E-03	7.49E-04
9	6.05E-02	8.45E-04	5.57E-04	7.49E-02	1.05E-03	6.92E-04	5.96E-00	8.32E-02	5.48E-02
10	4.56E-01	6.35E-03	4.18E-03	3.82E-01	5.33E-01	3.51E-01	7.91E-01	1.10E-00	7.26E-01
11	6.12E-02	8.55E-04	5.63E-04	8.33E-02	1.16E-03	7.69E-04	1.83E-01	2.55E-03	1.68E-03
12	1.01E-01	1.41E-03	9.32E-04	1.95E-01	2.72E-03	1.79E-03	3.19E-01	4.44E-03	2.93E-03
13	4.56E-01	6.35E-03	4.18E-03	8.22E-01	1.15E-02	7.54E-03	9.74E-01	1.36E-02	8.94E-03