Probabilistic Risk Assessment of Cask Drop Accident during On-site Spent Nuclear Fuel Transportation

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1. Introduction

In Republic of Korea, a handling method of Spent Nuclear Fuel (SNF) is not determined yet, SNFs stacked in Spent Fuel Pool (SFP) on Nuclear Power Plant (NPP) site. But within several years, some SFPs will be full of SNFs. If alternative is determined such as installing a cask storage on NPP site before SFPs are filled with SNFS, that will be the best situation. However, it's not easy to determine the handling method because it is sensitive issue to public. The best way to handle this situation for a while is transferring the SNF from relatively placeless SNP to other SNPs. There are two ways to transfer the SNF from a site to other site, one is land transportation and the other is maritime transportation. Maritime transportation might be used because this way uses more safe route which is far from populated area. The whole transportation process can be divided in two parts: transferring the SNF between SNP and wharf in-Nuclear Power Plant (NPP) site by truck, and transferring the SNF from the wharf to the other wharf by ship. In this research, on-site SNF transportation between SNP and wharf was considered.

Two kinds of single accident can occur during this type of SNF transportation, impact and fire, caused by internal events and external events. Among these, Probabilistic Risk Assessment (PRA) was done for impact accident on cask caused by drop only because it was analyzed as almost the whole risk of cask storage system by PRA reports about cask storage system which has similar process with that of on-site SNF transportation.

2. Methods

2.1 Process of On-site SNF transportation

When the SNF is moving, it should be inside of the SNF cask which can prevent the leakage of radioactive materials. Bolted metal cask is selected as a target cask, for example KN-12. Figure 1 shows the example of bolted metal cask, KN-12. It is composed of four parts: 21 fuel assemblies, cask body, 2 cask lids, and 2 impact limiters which made of wood to absorb the impact energy.

The detailed process of on-site SNF transportation will be almost similar to the process of cask storage system which transfer the SNF from SNP to cask storage system. Because detailed operation sequence of on-site SNF transportation is not determined yet, modified process of cask storage system which is from NUREG-1864 report was used. Table I shows the modified process. Based on the modified process, drop accident scenarios were invented. There are two variables for each scenario, height and state of cask. During the whole process, SNF assemblies can be existed in three states: only SNF assemblies, SNF assemblies inside the cask without impact limiter, and SNF assemblies inside the cask with impact limiter. Every stages can be divided in two kinds of operation: horizontal and vertical operation of crane. By each stage, a specific height range is determined.

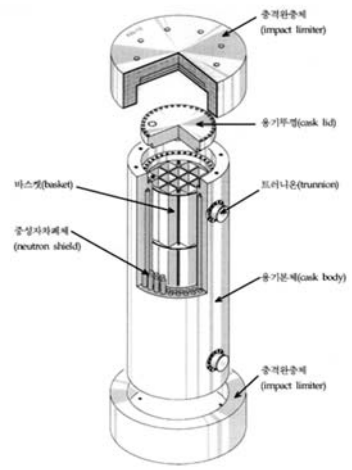

Fig. 1. Overview of KN-12 cask

Table I: Modified process of in-site transportation

Stages	Contents	Height (m)		State
		Before	After	
1	Loading fuel assemblies into the cask	4.8	0	SNF assemblies
2	Lifting the cask out of the cask pit	0	13	SNF assemblies + Cask
3	Moving the cask to the railing area	0	13	
4	Lowering the cask over a railing of the spent fuel pool	13	0.3	
5	Moving the cask to the preparation area	0.3	0.3	
6	Lowering the cask onto the preparation area	0.3	0	
7	Preparing the cask (draining, drying, inerting, and sealing)	0	0	
8	Lifting the cask	0	0.6	
9	Moving the cask to the equipment hatch	0.6	0.6	
10	Inspection and maintaining the cask	0.6	0.6	
11	Lowering the cask onto the equipment hatch	0.6	0	
12	Equipping the impact limiter to cask body	0	0	
13	Lifting the cask	0	0.6	SNF assemblies + Cask + Impact limiter
14	Moving the cask to the shipment area	0.6	0.6	
15	Inspection and maintaining the cask	0.6	0.6	
16	Lifting the cask	0.6	3	
17	Moving the cask to the truck	3	3	
18	Lowering the cask on the truck	3	1	
19	Transferring the cask to wharf by truck	1	1	
20	Inspection and maintaining the cask	1	1	
21	Lifting the cask	1	5	
22	Moving the cask to the ship	5	5	
23	Lowering the cask onto ship	5	0	

2.2 Risk Analysis Method

Risk can be calculated by multiplying frequency and consequence.

$$\text{Risk} = \text{Frequency} \times \text{Consequence} \quad (1)$$

The frequencies of each scenario for drop accident are used as a same data from U.S.NRC and EPRI reports. Details are discussed in chapter 2.3.

To get the consequence, the same approach which is used for level 3 PSA of NPP was used. With wind history data and source term, the consequence by person (mSV/person) can be calculated. Hotspot code was used to calculate the consequence based on source term, using the simple Gaussian plume model. Source term can be calculated by multiplying the Material-at-risk (MAR), Release Fraction (RF), and Leak Path Factor (LPF).

$$\text{Source term} = \text{MAR} \times \text{RF} \times \text{LPF} \quad (2)$$

MAR is the initial amount of interested radiation, which can be calculated by Origen code. Under the impact accident situation, only gas materials under room temperature can be released to the environment. So Kr and Cs are considered as target radioactive materials in this research. There are two barriers to prevent the radioactive materials in SNF are released to environment: fuel rod and the cask. So, RF which means released fraction of radioactive materials from fuel rod to environment, can be calculated by multiplying FDR, $RF_{r\text{-}c}$, $RF_{c\text{-}e}$.

$$\text{RF} = \text{FDR} \times \text{RF}_{r-c} \times \text{RF}_{c-e} \quad (3)$$

Fuel Damage Ratio (FDR) is ratio of damaged claddings of fuel rod by impact. $RF_{r\text{-}c}$ is released fraction of radioactive material from rod to cask, and $RF_{c\text{-}e}$ is released fraction of radioactive material from cask to environment. Details are discussed in chapter 2.4, 2.5, and 2.6. Leak Path Factor (LPF) is attenuation coefficient in the environment, it was considered as 1 conservatively in this research.

2.3 Frequency

There are three states for SNF assemblies. For each state, different frequency was used. 3.2E-05 was used for fuel assembly drop during loading. It is a state before SNF assemblies are put into the cask. 5.6E-05 was used for cask drop during a single crane action. Whether the impact limiter is installed or not, this frequency was used if the SNF assemblies are located inside of cask. 3.3E-08 was used for cask drop during transferring by truck. All frequency data were referred from NUREG-1864 and EPRI-1009691.

2.4 Fuel Damage Ratio

In this research, 21 assemblies are assumed to be inside of the cask. Figure 3 shows the FEM model of 21 fuel assemblies. Each fuel assembly is expressed in a simple dummy model, which has same weight with real fuel assembly.

The method of calculating fuel damage ratio is used as the same method in NUREG-6672. Table II shows the peak strains in fuel rods resulting from a 100G impact. Strains of fuel cladding are assumed to increase linearly with decreasing fuel burnup. From 55 to 60 GWDt/ MTU spent fuel is assumed to fail at 1 percent strain, from 40 to 45 GWDt/ MTU spent fuel fails at 4 percent strain, and from 0 to 25 GWDt/ MTU spent fuel fails at 8 per cent strain. Based on the accelerations of each fuel assembly dummy, fuel damage ratio can be calculated by linear interpolation.

Fig. 2. FEM model of 21 fuel assemblies inside the cask

Table II: Peak strains in fuel rods resulting from a 100 G impact (NUREG-6672)

Fraction of PWR Rods	Peak Strain, %
1/15	3.3
2/15	2.9
3/15	2.2
4/15	2
5/15	1.7
6/15	1.5
7/15	1.4
8/15	1.4
9/15	1.4
10/15	1.3
11/15	1.3
12/15	1.2
13/15	1.2
14/15	1.1
15/15	1.1

2.5 RFr-c

The cask is sealed with lid, and the lid is fastened by bolts. By the impact, the impacted part is deformed like in figure 3. Although the lid is still fastened on cask body, leak area on lid can be made because of deformation. Four node pairs which are point of contact between lid and cask body around the lid bolts are selected as reference pairs. Average value of displacements in the same direction with cask body between nodes in each pair is considered as lid gap. By multiplying the lid gap and circumference of lid, total leak area can be calculated.

In this research, recovery of lid gap by o-ring seal is not considered on lid gap analysis conservatively.

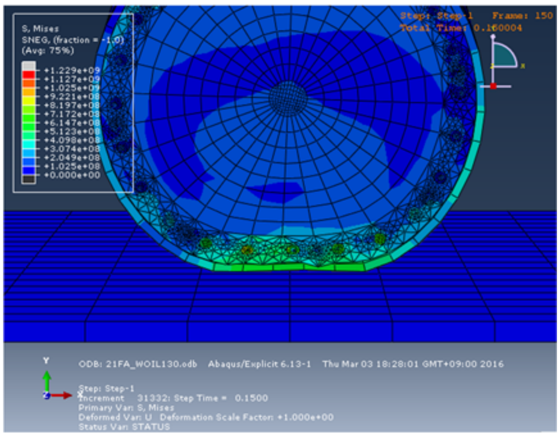

Fig. 3. Stress distribution on impacted part

2.6 RFc-e

Same method from NUREG-6672 was used to calculate the released fraction of radioactive material from cask to environment. Cask-to-environment release fractions can be calculated based on leak area. After pressurization due to the failure of SNF cladding, cask depressurization times decrease as cask leak areas increase. Thus, a large leak area means a short depressurization time, little time for fission product deposition to cask interior surfaces, and consequently large cask-to-environment release fractions.

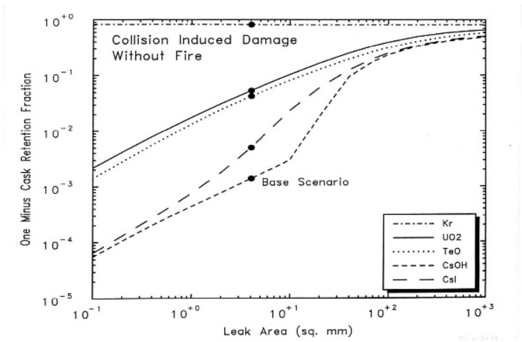

Fig. 4. Dependence of Cask-to-Environment release fractions (1.0-Rention) on the size of the cask failure (leak area) (NUREG-6672)

2.7 FEM simulation

To calculate the impact energy from drop accident, ABAQUS which is Finite Element Method (FEM) software was used. By the reference [1], [2], and [3], the most conservative drop condition for the SNF cask was considered as 20° oblique drop on all scenarios. Total time of drop accident was considered to cover the subsequent impact. Floor was considered as a rigid body for conservation. 1, 3, 5 m drop cases of SNF assemblies only and the cask with impact limiter, 1, 4, 7, 10, 13 m drop cases of the cask without impact limiter were done in FEM simulation. Linear interpolation was used to get the risk in other scenarios with other heights.

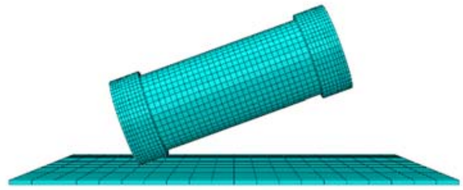

Fig. 5. FEM model for drop accident simulation

3. Results

There are 5 conditions to calculate the risk from on-site SNF transportation: burn-up, enrichment, cooling year, wind data with direction, and distance from accident place. Specific conditions were used in this research. Burn-up and enrichment of SNF were used as 45,000 MWD/MTU, and 4.5wt% each. Cooling year of SNF was assumed to 10 years. With these condition, MAR was obtained from Origen code. Total 5 kinds of radioactive isotopes were considered, Cs-134, Cs-135, Cs-137, Kr-81, and Kr-85. Initial amount of radiation from radioactive isotopes are 3.91E+03, 1.72E-01, 5.24E+04, 1.37E-07, and 3.35E+03 Curie each. Wind history data of 2012 near Kori-site was used to calculate the consequence based on source term. 16 directions were considered, and the risk was calculated as an average value of all directions. Figure 6 shows the 16 directions for wind effect. 5.7 km was considered for the result, the Low Population Zone (LPZ). The total risk for these conditions is calculated as 6.139E-001 mSv/person, with 1.095E-003 total failure probability. Figure 7 shows the event tree of on-site SNF transportation.

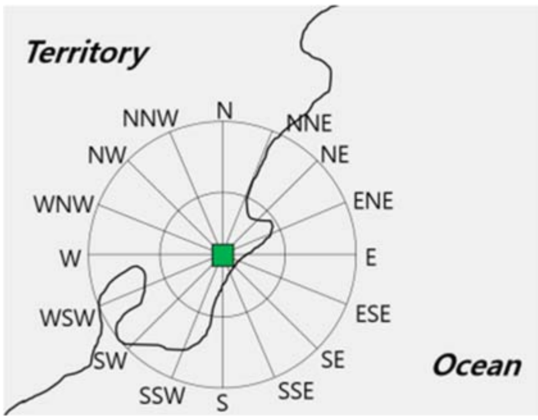

Fig. 6. 16 directions for wind effect

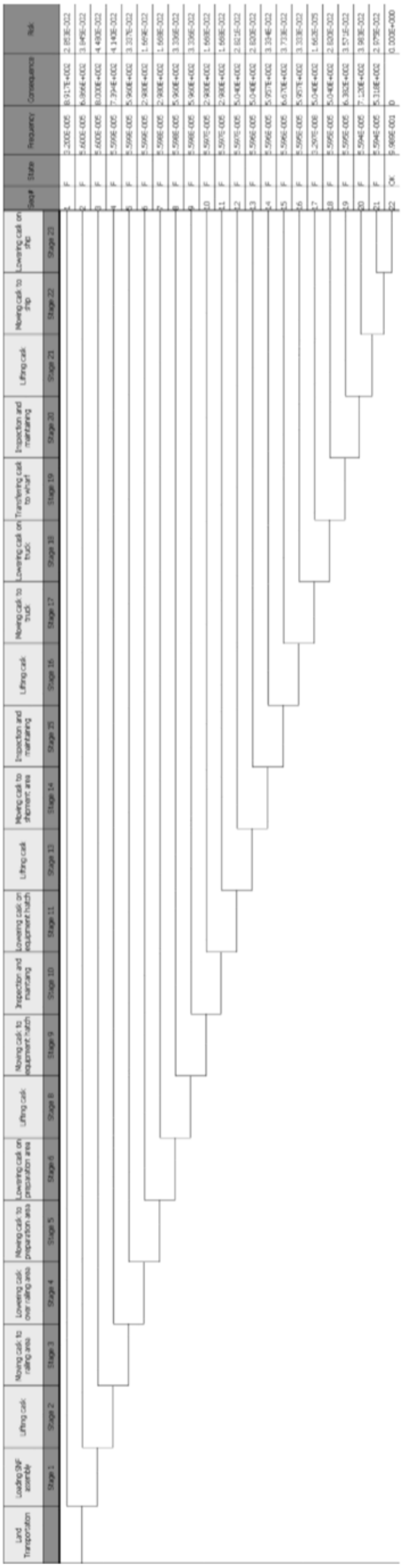

Fig. 7. Event tree of on-site SNF transportation

3. Conclusions

In this research, PRA of cask drop accident during on-site SNF transportation was done, risk to a person (mSv/person) from a case with specific conditions was calculated. In every 11 FEM simulation drop cases, FDR is 1 even the fuel assemblies are located inside of the cask. It is a quite larger value for all cases than the results with similar drop condition from the reports which covers the PRA on cask storage system. Because different from previous reports, subsequent impact was considered. Like in figure 8, accelerations which are used to calculate the FDR has extremely higher values in subsequent impact than the first impact for all SNF assemblies. So, cases with larger leak area shows larger risk. To get more accurate risk, more accurate FDR and wind data should be used. It can be possible with detailed model of inside cask structure and material properties for FEM model, and wind history data for many years.

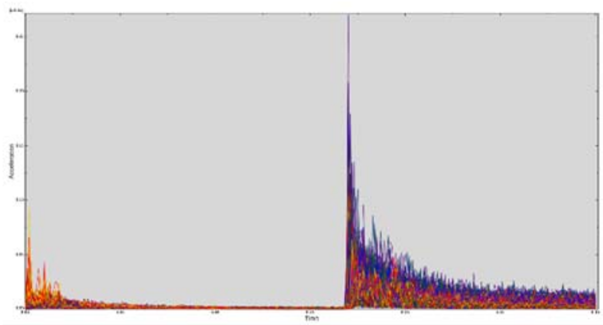

Fig. 8. Accelerations of all SNF assemblies during drop accident

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