Insights from accident probability calculation for spent fuel transportation and storage

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Abstract: As capacity of onsite spent fuel storage facility meets its limitation, spent fuels needs to be transported to other space. This study aims to reveal new insights from the risk analysis of spent fuel transportation and interim storage. In consideration that spent fuels might be transported by ship rather than by train or truck due to coastal location of plant, this study focuses on three different kinds of accident: Aircraft crash on interim storage, Drop accident during onsite transportation, and Maritime transportation accidents. Accident probabilities were calculated based on probabilistic distribution, historical data, structure analysis. Risks were calculated from accident probability and consequence and cask studies for risk calculation were performed using developed software. Due to the integrity of casks, the estimated risks were reasonably small; however, it is highly dependent on accident conditions. Therefore, appropriate strategy for regulation and management for spent fuel transportation and interim storage is required to be developed based on risk analysis.

Keyword: maritime transportation; aircraft crash on an interim storage facility; drop accident during onsite transportation; level 3 PSA; spent fuel transportation

1 Introduction

Due to radioactivity hazard of spent fuels of nuclear power plants, they are required strict control. Nowadays, issues related to spent fuel are rising and spent fuel transportation problem is becoming one of the most important issues [1]. As onsite spent fuel storage facility will face its limit soon, stored spent fuels will be transported to other space [2].

In Korea, all of NPPs are located near coasts. Therefore, the most reasonable way of transportation for site-stored spent fuel is maritime transportation. When we meet onsite storage limitation, it might be the only remaining feasible option. However, there are few studies which analyzed and discussed about spent fuel transportation [3]. A study which analyzes risk of spent fuel transportation with proper scenario and proper mechanical model is important for deciding spent fuel transportation strategy. In this study, accident probability was calculated based on developed accident scenario and analysis methods.

Two accidents scenario related to spent fuel transportation, drop accident during onsite transportation and collision accident for maritime transportation, were developed for analysis. Then, risk of spent fuel transportation will be assessed combining with consequence analysis result. Especially, environmental impact which may be induced by release of radioactive material will be assessed as consequence. Aircraft crash was addressed in this study since we consider it as a typical type of accident (mechanical shock) which may happen in interim storage facility.

2 Methods

In this study, accidents during spent fuel transportation and storage are categorized into three kinds: aircraft crash on interim storage facility, drop accident during onsite transportation, and maritime transportation accident. Basically, risk is calculated by multiplying probability and consequence. Therefore, probabilities and consequences were calculated for risk assessment for three accident scenarios.

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For aircraft crash on interim storage facility accident scenario, intentional attack using airplane was assumed. Therefore, possible scenario of this accident was developed as shown in Fig.1. During development, a situation of sequential losing of internal barriers was considered.

Since risk analysis for aircraft crash on interim storage facility is assessed for randomly selected fixed location, location dependent analysis was excluded from research range. Therefore, analysis range is restricted within a storage building. For consequence calculation, 16 wind directions were used as shown in Fig.2.

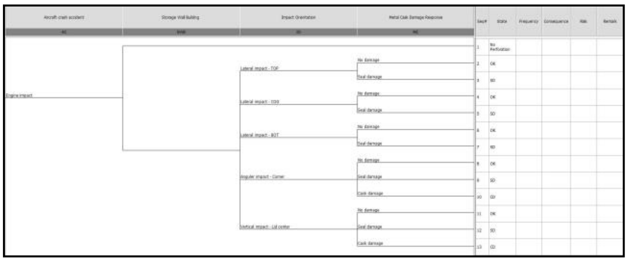

Fig.1 Event tree for an aircraft crash on interim storage facility [4].

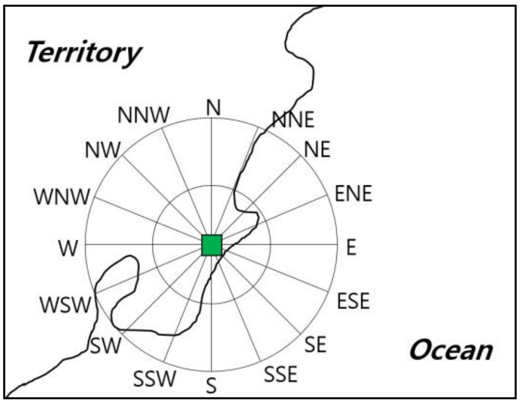

Fig.2 Direction and location of target area.

For drop accident during onsite transportation, onsite transportation from NPP to wharf was assumed for accident scenario. In addition, because casks were processed in containment building, accidents which might be happened within building were analyzed. Hence, same wind directions with aircraft crash on interim storage facility were used for consequence calculation. Event tree for this scenario is shown in Fig.3.

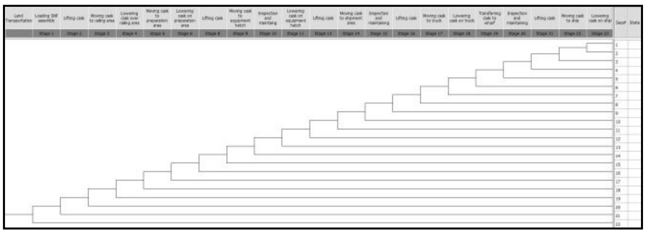

Fig.3. Event tree for onsite transportation. [5]

Maritime transportation scenario was developed assuming collision accident as shown in Fig.4. Collision accident was divided to several sub-accidents according to collision location and type. Accident analysis range is restricted to Korean ocean which is shaded in Fig.5.

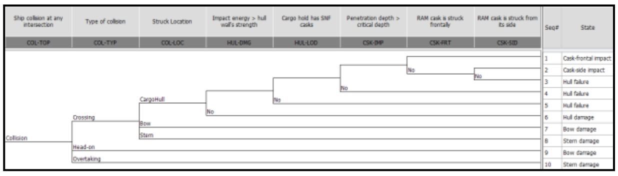

Fig. 4 Event tree for maritime transportation [6].

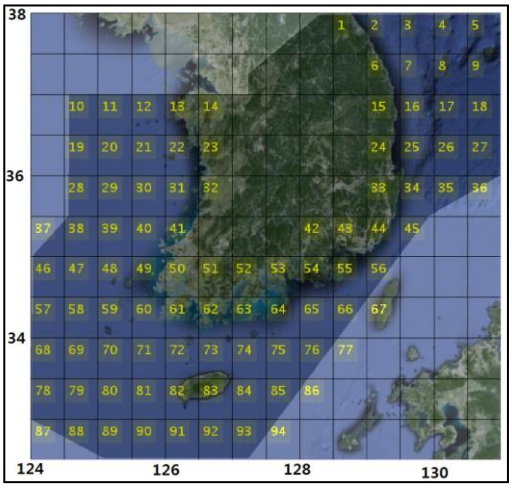

Fig. 5 Accident analysis range for maritime transportation [5].

2.1 Probability calculation for aircraft crash on interim storage facility

There were many barriers for reaching to release of radioactive material. First of all, concrete containment wall is the first and the most powerful barrier. A probability of aircraft crash on the concrete wall is assumed to 1 because this scenario is for intentional attack. Then, after crash on the concrete wall, velocity of aircraft will be reduced and this reduced velocity is 'residual velocity'. For sure, it is dependent on the initial aircraft velocity and strength of concrete wall. Figure 6 shows strength distribution of various concrete type. Perforation probability was calculated using Monte-carlo technique combining with strength distribution for different wall thicknesses.

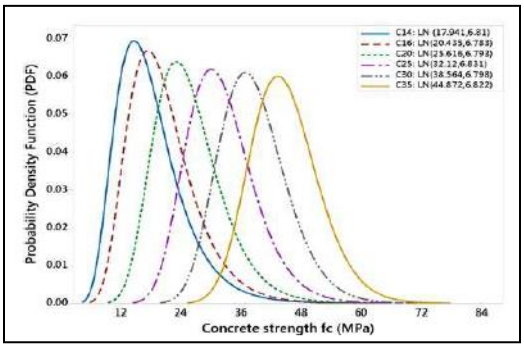

Fig.6 Strength distribution of concrete.

Then, radiological consequence can be calculated from equation (1). Five impact location for cask body were considered and leakage areas were calculated using LS-DYNA code (Livermore Software Technology Corp., www.lstc.com) constructing finite element model. Using fuel damage ratio, release fraction could be assessed using equation (1).

Other factors were taken from reference data while $ARF_{C-E} \times RF$ was calculated from cask structure-impact analysis. Ref. 4 and 5 explained well about this analysis [4, 5]. Table 1 shows analysis conditions. For consequence analysis, 5.7km of distance from NPP and average wind direction were decided.

$$\text{Release fraction} = [ARF_{C-E} \times RF] \times ARF_{R-C} \times FDR \times LRF \quad (1)$$

Table 1 Spent fuel configurations for aircraft crash on interim storage facility

Input types	Accident conditions
Spent fuel type	CE 16×16
Burn-up [MWd/MTU]	45,000
Enrichment [wt%]	4.5
Cooling time [yr]	10
Number of fuel assembly	21

2.2 Probability calculation for drop accident during onsite transportation

Probabilities for each branch in event tree were obtained from historical data and consequences were analyzed with same method as aircraft crash on interim storage facility. Detailed calculation steps are explained in Ref.5 [5]. Table 2 shows analysis conditions for onsite transportation accident. In addition, heights of each stages were set as default values. Same as consequence analysis conditions for aircraft crash on interim storage facility, 5.7km distance and average wind direction were applied.

Table 2 Spent fuel configurations for drop accident during onsite transportation

Input types	Accident conditions
Spent fuel type	CE 16×16
Burn-up [MWd/MTU]	45,000
Enrichment [wt%]	4.5
Cooling time [yr]	10
Number of fuel assembly	21

2.3 Probability calculation for maritime transportation

Automatic identification system (AIS) data was used for probability calculation. Dotted AIS data was processed to be suited for route intersection probability. Detailed calculation process is described in Fig.7 and Ref.6 [6]. If spent fuel transportation ship intersects with existing ship route, there is a collision chance. Considering serial collision chance within a route, collision probability was calculated for a route.

Then, based on collision velocity, location, and internal arrangement of spent fuel cask, cask damage probability was calculated by constructing finite element model using ABAQUS/EXPLICIT (www.3ds.com/products) code.

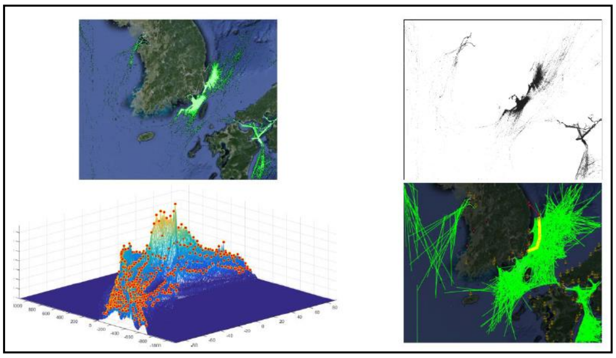

Fig.7. Traffic density and route intersections with Aframax tankers [6].

Radiological consequence for maritime transportation was calculated using MARINRAD (https://rsicc.ornl.gov/codes/ccc/ccc5/ccc-503.html). Ninety-four numbers of mesh cells were generated and coefficients for ocean dispersion and food chain were used [5]. Cask conditions are described in Table 3.

Table 3 Cask condition for consequence analysis of maritime transportation

Input types	Cask conditions
Spent fuel type	CE 16×16
Burn-up [MWd/MTU]	45,000
Enrichment [wt%]	4.5
Cooling time [yr]	10
Leach time [yr]	1,000
Leach constant [/yr]	0.1

2.4. Software application

For integrated management of risks from three accident scenarios, software named 'risk assessment program for spent fuel transportation and storage (RATS)' was developed. With this software, risks with different conditions can be managed effectively.

Using developed software, risks of several routes of maritime transportation were assessed for regulation purpose. Transportations between Korean NPPs and randomly selected imaginary storage location were assumed and shown in Fig.8. From comparing risks from these four cases, users can decide whether transport spent fuel or not. Moreover, suitable frequency of transportation or transported cask number can be decided from results.

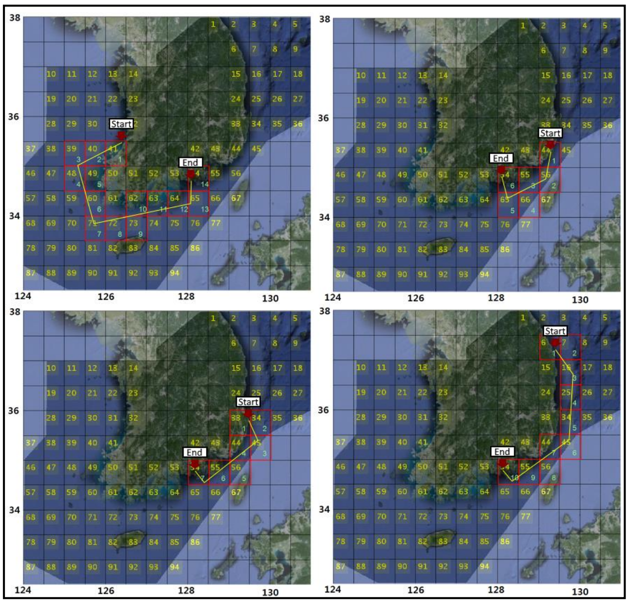

Fig.8. Imaginary transportation scenarios between NPPs and randomly selected storage facility.

3 Insights from quantification

For aircraft crash on interim storage facility, cask damage probability was calculated by considering failure probability for multiple barriers. According to concrete type and wall thickness, perforation probabilities were calculated as shown in Table 4. The stronger and thicker wall has the lower probability for perforation. Then, residual velocity distribution after perforation was obtained from Kar's equation [7]. Cask failure probability was calculated from structure analysis with residual velocity distribution.

Calculated risk is summarized in Table 5. According to this analysis result, risk of aircraft crash on interim storage facility for a person from an accident was low comparing with annual individual dose limit.

Table 4 Conditional probability of perforation according to concrete type and wall thickness

Wall conditions	70cm	80cm	90cm	100cm	110cm	120cm
C14	0.9907	0.9756	0.9435	0.8848	0.7923	0.6661
C16	0.9891	0.9707	0.9318	0.8614	0.7530	0.6108
C20	0.9851	0.9591	0.9045	0.8093	0.6711	0.5043
C25	0.9786	0.9412	0.8654	0.7404	0.5731	0.3913
C30	0.9705	0.9203	0.8228	0.6717	0.4854	0.3023
C35	0.9620	0.8987	0.7804	0.6076	0.4100	0.2333

Table 5 Result from analysis for accident of aircraft crash on interim storage facility

Analysis conditions	Results
Concrete type	C20
Wall thickness [cm]	100
Total risk [mSv/person-accident]	2.608E-005
The most risky sequence	9

Drop accident probability for onsite transportation was calculated using historical data [8, 9]. Probability of spent fuel assembly drop was 3.2E-05 while cask drop probability during processing step is 5.6E-05 and cask drop probability during transportation is 3.3E-08. Probability of each sequence in event tree was calculated based on these branch probabilities.

Consequences calculation process was same as that for aircraft crash accident. Then, finite element model was constructed and cask structure was analyzed as shown in Fig.9. From finite element model, second impact from cask drop accident was higher than first impact. It might be due to rotational energy. Rotational energy impacts on certain point combing with potential energy and it makes more serious consequence from cask failure. Risk from onsite transportation is summarized in Table 6. Concrete wall condition for this analysis was same as that for aircraft crash accident. However, risk of drop accident during onsite transportation was lower than risk of previous analysis. Individual dose from a drop accident was also lower than annual dose limit.

In addition, because the most serious risk was generated during movement of cask to railing area, process elevation for this step is required to be modified. Setting buffer for this processing step can be an alternative option.

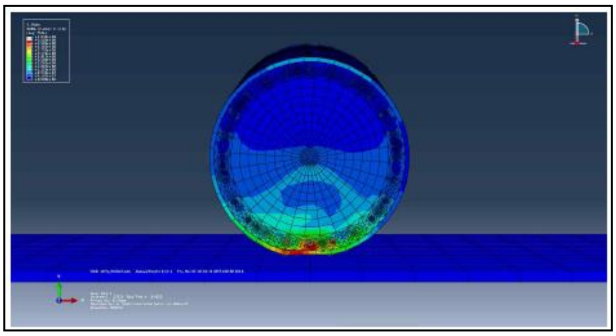

Fig.9. FEM model for spent fuel cask.

Table 6 Result from analysis for drop accident during onsite transportation

Analysis conditions	Results
Concrete type	C20
Wall thickness [cm]	100
Total risk [mSv/person-transportation]	1.151E-005
The most risky sequence	20

For accident from maritime transportation, risk is highly dependent on route length, direction, and location. Collision probability was varied according to collision type and collision direction which is linked with route direction. For head-on collision, collision probability was 0.5E-04 while 1.1E-04 for overtaking collision and 1.3E-04 for crossing collision [6]. To reduce cask damage probability with same collision condition, casks are required to be arranged segregatively [10]. In addition, bow to aft arrangement will be contributed to reduce risk.

However, consequence analysis is highly dependent on accident condition and there are many variables for accident condition. Therefore, to manage risk using software is more reasonable option. Figure 10 and Table 7 show example analysis for maritime transportation. The population and seafood consumption data along transportation route were not considered in this analysis. Based on individual dose calculation equation in Ref. 11 [11]. Hence, the risk was expressed with the unit of mSv/transportation for a person. From this analysis, dose from a transportation for a person was lower than annual dose limit. Moreover, risk can be effectively reduced by avoiding cells which have high collision probability and high consequences. Therefore, risks for different route will be analyzed in section 4 as case studies.

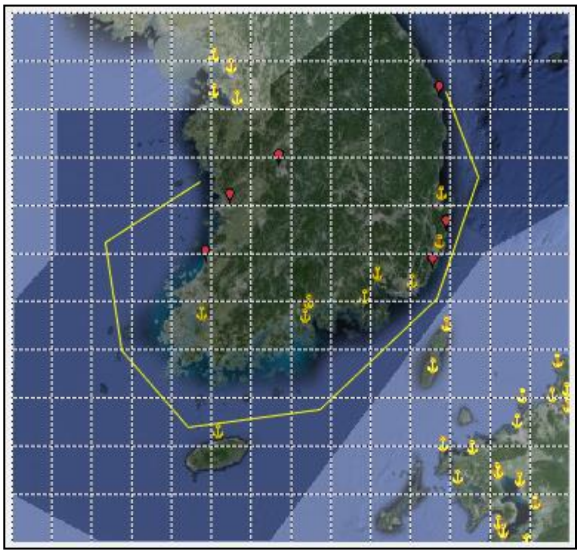

Fig.10. Example route for risk analysis of maritime transportation.

Table 7 Result from example analysis for maritime transportation

Analysis conditions	Results
The number of cells in a route	25
Total risk of a route [mSv/transportation]	2.405E-002
The number of cells that result in the most risk	55
The cell location where the probability of cask damage is the highest	34
The number of cells with the highest consequence	48

4 Case studies for risk calculations under different analysis conditions

4.1. Risk of routes under base conditions

Risks from four route cases shown in Fig. 8 were analyzed with same transportation conditions which were full (eight) casks, 7 knots speed. As shown in Table 8, risk of case 2 is the highest among four cases while risk of case 1 is the lowest. The reason of this big difference in those cases was the difference of accident probability. The accident probability of case 2 was 10 times higher than case 1. Although the consequence of case 2 was one-third of case 1, the risk of case 2 was quite higher than the risk of case 1.

Table 8 Risk analysis for four cases

Cases	Risks [mSv/transportation]
Case 1	4.856E-003
Case 2	2.182E-002
Case 3	1.502E-002
Case 4	1.963E-002

4.2. Risk comparison with different conditions

To reduce accident probability, velocity of transportation ship was changed. Analysis results are shown in Table 9. As ship velocity increased, risk of spent fuel transportation decreased. The reason of decreasing risk could be founded from Fig.11. According to increasing ship velocity, probability of collision accident decreased rapidly because of staying time in intersection points.

Therefore, to maintain the maximum velocity of ship is better to achieve relatively low risk. In addition, when the route has quite lots of intersection points with other ships like case 2, navigation with high velocity is more important than other cases because of staying time for intersection.

Table 9 Risk analysis for case 1 and 2 with different ship velocity

Cases	Risks [mSv/transportation]		
	1 knots	7 knots	13 knots
Case 1	1.328E-002	4.856E-003	4.297E-003
Case 2	5.999E-002	2.182E-002	1.934E-002

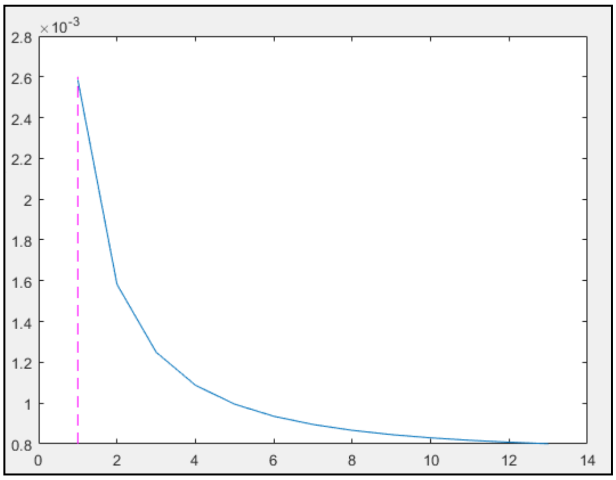

Fig.11. Collision probability [accident/transportation] according to ship velocity [knots].

5 Conclusions

The accident probability was calculated for spent fuel transportation and storage and the risk was assessed combining with consequence analysis and accident probability using developed software. There were three accidents such as aircraft crash on interim storage facility, drop accident during onsite transportation, and collision accident for maritime transportation. Probability was calculated based on characteristics of concrete wall and probabilistic distribution for accident of aircraft crash on interim storage facility. Historical probabilities were used for drop accident during onsite transportation while AIS data and structure analysis model were used for collision accident of maritime transportation. Consequences were analyzed from proper modeling codes for each accident type.

The case study results show that the risks from those accidents were reasonably small thanks to the integrity of casks. Estimated risk is, however, highly dependent on accident conditions. Thus, suitable regulation/management strategy for spent fuel transportation and interim storage is required to be developed and applied based on risk analysis.

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