Preliminary Assessment of the Probabilistic Risk of Nuclear Power Plant against to the Aircraft Impact Loading

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Abstract: In Korea, a research to develop the aircraft impact risk quantification technology was initiated in 2012 by Korea Atomic Energy Research Institute. This paper presents the purpose and objectives of that research project and introduces the interim results during the first two years. In the first year, aircraft impact accident scenario was developed and the reference parameter of the aircraft impact accident was determined. To determine the reference loading parameter, we performed repetitive simulations for many analysis cases with considering the variations of loading parameters such as mass, velocity, angle of crash, etc. A revised version of Riera's analysis method, which is appropriate for a simplified impact analysis was applied to the simulation procedure. The target nuclear power plant is one of typical PWR type NPPs. In the second year, the floor response spectra for the locations of important components were evaluated for the estimation of the failure probabilities and fragility functions of structures and equipments. Some representative floor response spectra for containment building and primary auxiliary building were presented in this paper. A conceptual technical procedure to assess the aircraft impact risk of NPP by using the previous results was proposed. It is expect that the aircraft impact risk onto the NPPs will be estimated in near future.

Keywords: Aircraft Impact, Aircraft Impact Risk, Reference Parameter, Floor Response Spectra, Core Damage Probability.

1. INTRODUCTION

Research on aircraft impacts (AI) has grown gradually in a theoretical and experimental way since the Riera method was first introduced [1]. Most of these studies have been mainly focused on global and local damage of the structures subjected to an aircraft impact [2-6]. In addition, these studies have been aimed to verify and ensure the safety of the targeted walls and structures especially in the viewpoint of the deterministic approach.

However, recently, the regulation and the assessment of the safety of the nuclear power plants (NPPs) against to an aircraft impact are strongly encouraged to adopt a probabilistic approach, i.e., the probabilistic risk assessment of an aircraft impact [7-9]. In Korea, research to develop aircraft impact risk quantification technology was initiated in 2012 by Korea Atomic Energy Research Institute (KAERI). In this paper, the total technical roadmap of that research project and its interim results during the first two years will be presented.

In the first year, 2012, we developed aircraft impact accident scenario and performed preliminary fragility analysis of the local failure of the targeted wall by aircraft impact. An aircraft impact event can be characterized by the appropriate load parameters (i.e., aircraft type, mass, velocity, angle of crash, etc.). Therefore, the reference parameter should be selected to represent each load effect in order to evaluate the capacity/fragility of SSCs using deterministic or probabilistic methods. This is similar to the use of the peak ground acceleration (PGA) to represent the ground motion spectrum of the earthquake in the seismic probabilistic risk assessment (SPRA) approach. We developed the methodology to decide on the reference parameter for the aircraft impact risk quantification among some reasonable candidates, which can represent many uncertain loading parameters.

To detect the response and the damage of the target structure, missile-target interaction and Riera's time-history analysis method have been used primarily in the aircraft impact research area. To define the reference loading parameter, we need to perform repetitive simulations for many analysis cases.

Thus, we applied a revised version of Riera's method, which is appropriate for a simplified impact simulation. The target NPP to determine the reference parameter and evaluate the preliminary assessment of aircraft impact risk was selected among the typical Korean PWR NPPs. The response has been calculated for pre-stressed concrete containment buildings subjected to aircraft impact loading, and the responses according to each reference parameter have been analyzed.

In 2013, the second year, we evaluated the floor response spectra for the locations of important components for the estimation of the failure probabilities and fragility functions of structures and equipments. Some representative floor response spectra for containment building and primary auxiliary building were presented in this paper. With the conceptual technical roadmap proposed in this paper to assess the aircraft impact risk of NPP and the previous results of the project in KAERI, we expect that the aircraft impact risk of the NPPs can be estimated in terms of the core damage probability (CDP) in near future.

2. AIRCRAFT IMPACT RISK ASSESSMENT METHODOLOGY

Figure 1 is a schematic diagram for the assessment procedure of the aircraft impact event induced risk of NPPs. The total procedure composed by three stages; structural analysis to obtain structural responses and evaluate the structural safety, fragility assessment to estimate the aircraft impact fragility functions of safety-related equipments, and system level probabilistic safety assessment (PSA) to quantify the aircraft impact induced risk.

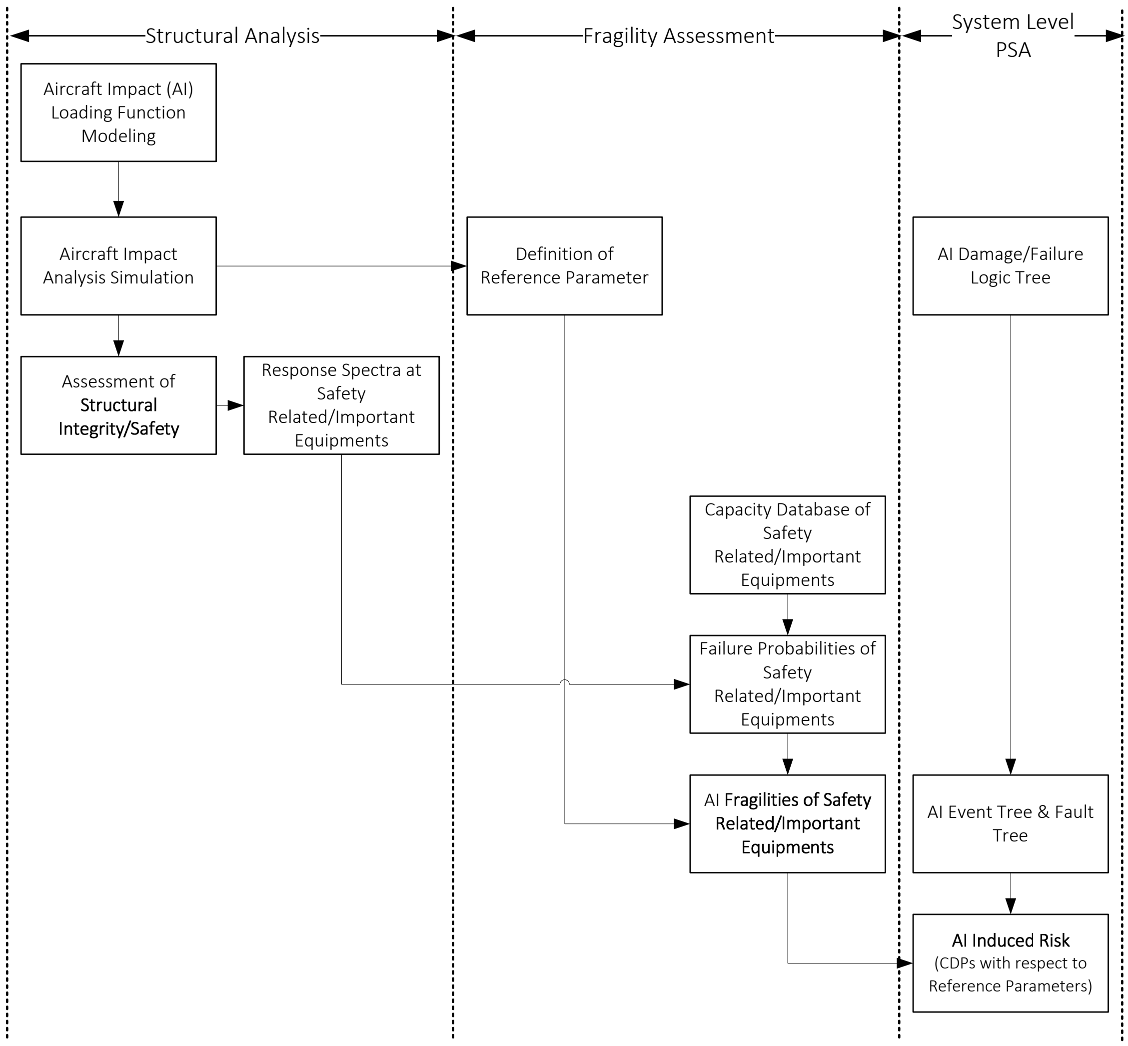


Figure 1: Technical Roadmap to Assess the Risk of NPP against to Aircraft Impact Events

The previous studies on the aircraft impact analysis of NPPs were mainly focused on the structural analysis stage, i.e., the numerical and experimental studies to assess the structural integrity/safety of protecting barrier structures (such as walls, roof, and other barriers). To evaluate the fragilities and the risk induced by aircraft impact, further studies including probabilistic analysis and plant level system analysis are should be performed.

In seismic PSA approach, the seismic failure probability and seismic capacity (in another word, fragility) can be described by one of the reference parameters, peak ground acceleration (PGA). To assess the aircraft impact induced risk, the reference parameter which takes similar roll of PGA in seismic PSA should be selected.

For the fragility assessment stage, on the other hand, the structural response spectrum in specific location point of each safety related equipment should be evaluated from the aircraft impact simulations. Then the failure probability of each equipment can be estimated from the relationship between the response spectrum and capacity data of each equipment. The fragility, i.e., the median capacity and uncertainty parameters, can be evaluated with respect to the reference parameter.

From the research project in KAERI during the first two year, preliminary studies for each stage were performed. Response spectra at the location points of safety related equipments and important SSCs were estimated in structural analysis stage. A method to select the reference parameter of aircraft impact loading was developed for the fragility assessment. Logic trees of damage/failure sequences for important SSCs under aircraft impact event were also developed to perform the plant level system analysis. In chapter 3 to 5, each result of the studies will be introduced briefly.

3. DETERMINATION OF REFERENCE LOADING PARAMETER

The most important reasons that the PGA is preferred for the reference parameter in seismic PSA approach, can be found in its simplicity, intuitiveness and close correlation with structural responses. For the aircraft impact risk assessment, the impact velocity is commonly proposed for the reference parameter because the structural response showed a close relationship with the impact velocity. However, in the preliminary aircraft impact simulation in our institute, we found that the structural response can be differed significantly with respect to the variation of another important parameter, the mass of fuel, even though the impact velocity is same. Figure 2 shows one of the structural response at the containment wall with respect to the variation of impact velocity. It can be seen that the responses increase rapidly as the mass of remained fuel increases especially for the case of high impact velocity (≧150 m/s). Therefore, another reference parameter which is able to describe the effects of important loading parameters should be introduced. In this study, we proposed four candidates of reference parameter, and evaluated the correlations between structural response and each candidate parameter.

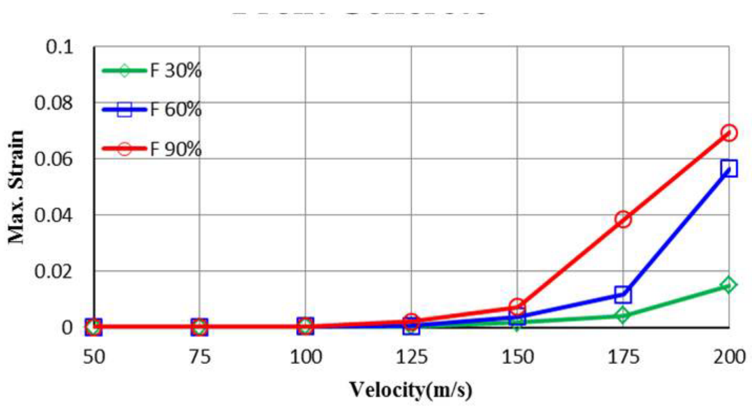


Figure 2: Structural Responses with respect to the Variation of Fuel Masses & Impact Velocities

3.1. Modeling of Structure and Loading Function

The target structure to develop the method of reference parameter selection, is one of the typical Korean PWR containment building. We developed three-dimensional finite element model of the containment building (Figure 3). The concrete damaged plasticity model [10, 11] was used for the concrete material model (Table 1). The steels in tendon, rebar and liner were modeled by using the piecewise-linear stress-strain curves.

(a) Wall **(b) Rebar** **(c) Tendon** **(d) Internal Structure**

Figure 3: Three-Dimensional Finite Element Model of the Target Containment Building

Table 1: Material Properties of Concrete

Concrete Properties					
Young's Modulus (kg/cm^2)		Poisson's Ratio	Density (kg/cm^3)	f_{cu}(kg/cm^2)	f_{ct}(kg/cm^2)
3.10E5		0.17	2.403E-6	425	42
Plasticity Parameters					
Dilation Angle	Eccentricity	f_{b0}/f_{c0}	K	Viscosity Parameter	
38	0	0	0	0	

To evaluate the correlations between structural response and each candidate parameter, we developed the Riera's aircraft impact force-time history function with respect to the variation of loading parameters, i.e., impact velocity and mass of remained fuel. For each force-time history, the type of aircraft is assumed as Boeing767 model. The variation ranges of impact velocity and remained fuel percentage are 50 to 200 m/s, and 30 to 90%, respectively.

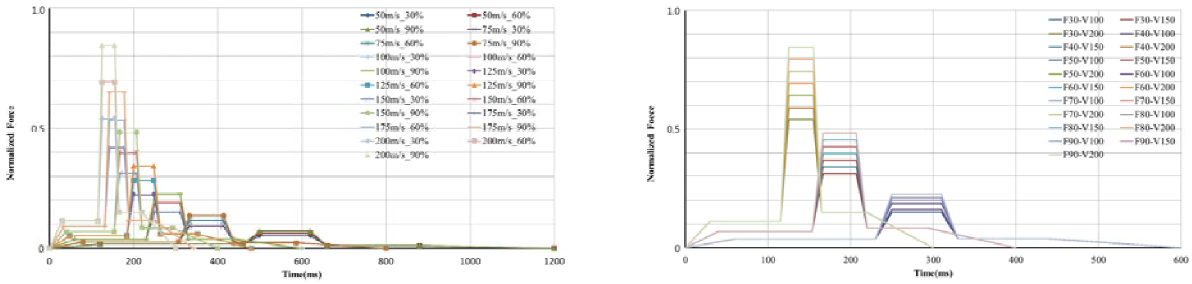


Figure 4: Aircraft Impact Force-Time Histories with respect to the Variation of Mass & Velocity

3.2. Determination of the Reference Parameter

We proposed four candidates of reference parameter, i.e., kinetic energy, total impulse, maximum impulse, and maximum force. The definition of each parameter can be illustrated by using the impact force-time history curve (Figure 5). Each candidate parameter is able to represent the effect of the most important loading parameters, mass and velocity. The wellness of correlation between the reference parameter and structural responses can be formulated by using the coefficient of determination, i.e., R^2. It can be stated that the higher value of the coefficient of determination (R^2) means the smaller error in monotonically increase linear relationship. R^2 values of each candidate parameter for each structural response in material were summarized in Table 2. From the results in Table 2, we can found that the maximum force shows the highest R^2 value in most responses in materials. The simplicity and intuitiveness of the maximum force parameter is also remarkable compared to other candidate parameters. Therefore, we concluded that the maximum force is the most proper candidate for the reference parameter of aircraft impact loading.

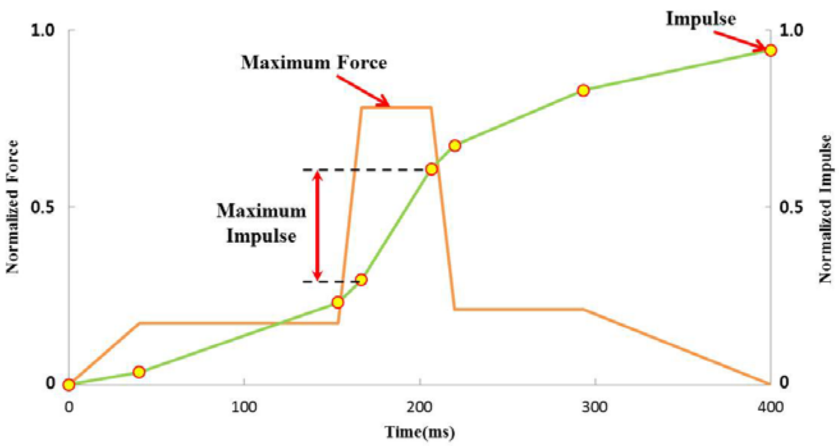


Figure 5: The Definition of Each Candidate Parameter in Force-Time History

Table 2: R2 Value of Each Candidate Parameter for Each Response in Materials

Parameters	Concrete	Rebar	Tendon
Kinetic E.	0.930	0.937	0.911
Impulse	0.939	0.919	0.927
Max. Impulse	0.854	0.750	0.776
Max. Force	0.923	0.939	0.944

4. FLOOR RESPONSE SPECTRA AGAINST TO AIRCRAFT IMPACT LOADING

For the fragility assessment, the structural response spectrum in specific location point of each safety related equipment should be evaluated from the aircraft impact simulations. Therefore, we estimated the response spectra at the location points of safety related and important equipments in containment building and primary auxiliary building. Some of the results were demonstrated in this chapter.

4.1. Floor Response Spectra of Containment Building

To evaluate the structural response spectra in specific location points of equipments in containment building, we used the three-dimensional finite element model introduced in chapter 3. The force-time history method was selected for the many times of repetitive numerical simulations. The impacting area of the containment building was a lower part of equipment hatch where produced the most significant response in preliminary impact analysis. The loading areas for fuselage and wing & engine were illustrated in Figure 6. Figure 7 shows the results of the structural response spectra at the location of the base of the important equipments. The specific category of each equipment is concealed for the safeguard information.

(a) Fuselage **(b) Wing & Engine**

Figure 6: Aircraft Impact Loading Area in Containment

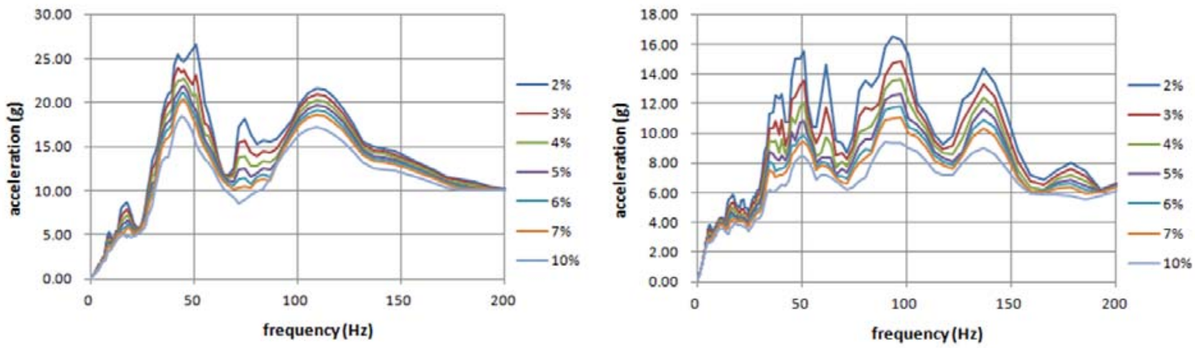


Figure 7: Response Spectra in Internal Structure of Containment Building

4.2. Floor Response Spectra of Primary Auxiliary Building

To evaluate the structural response spectra in specific location points of equipments in primary auxiliary building, we developed the three-dimensional finite element model of primary auxiliary building. The force-time history method was also selected for the many times of repetitive numerical simulations, and the method was verified by using the more complicated missile-target interaction method. Figure 8 depicts the finite element model of primary auxiliary building and the verification analysis using missile-target interaction method. The impacting area of the primary auxiliary building was a center part of the eastern wall which is the most critical area of the building. Figure 9 and 10 show the results of the structural response spectra at the location of the base of the emergency diesel generator (EDG) and the essential water chiller (EWC), respectively. The EDG is located at 100 ft floor level, and ECW is located at 77 ft floor level. It can be found that the magnitude of response increases abruptly as the impact velocity increases from 125 to 150 m/s while the responses are relatively similar at the velocity of 125 m/s and 150 m/s. We could also found that the responses at higher frequency range are quite larger than those of the seismic floor response spectra.

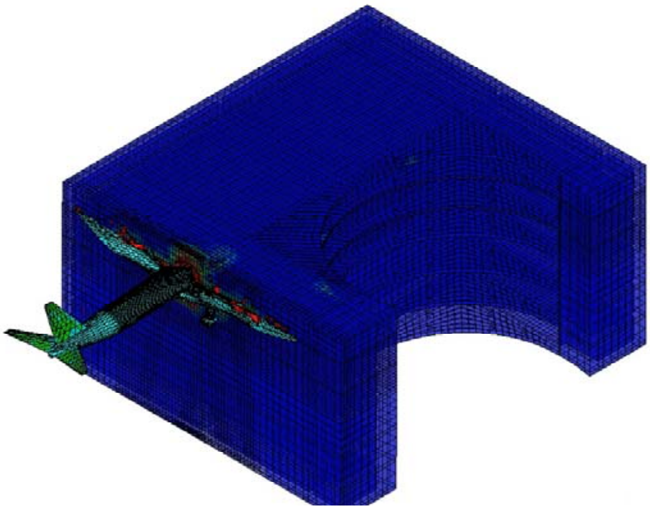


Figure 8: Finite Element Model of Primary Auxiliary Building & Verification Analysis

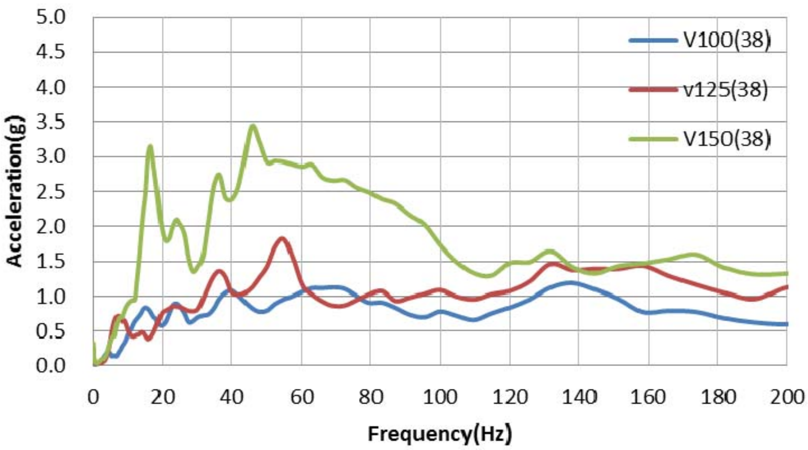


Figure 9: Response Spectra at the Location of the Base of EDG

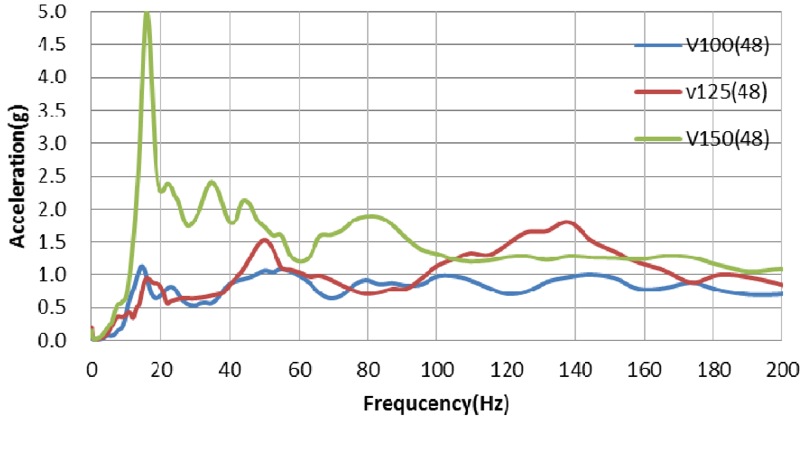


Figure 10: Response Spectra at the Location of the Base of EWC

5. DAMAGE/FRAILURE LOGIC TREE OF AIRCRAFT IMPACT EVENT

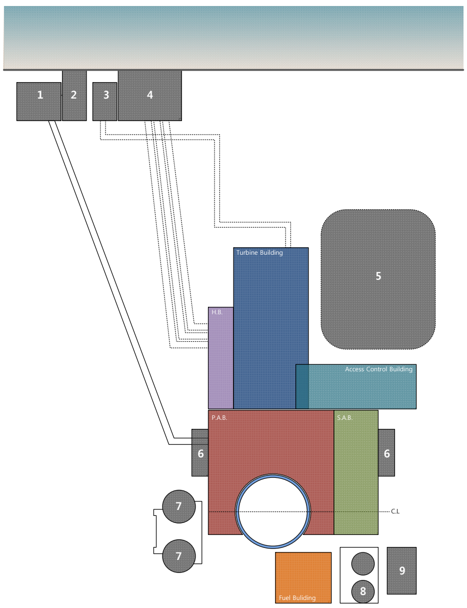
To perform the plant level system analysis, the logic trees of damage/failure sequences for important SSCs under aircraft impact event were developed. These logic trees are required in the development of the plant level event tree (ET) and fault tree (FT) of the aircraft impact induced accidents. With the fragility database of safety related equipments and critical SSCs, we can estimate the plant level aircraft impact risk by solving the Boolean equations in ET & FT.

From the plant level risk information, it is expected that the efficient way to reduce the aircraft impact threat and enhance the plant capacity against to the aircraft impact can be proposed. In this chapter, a procedure to develop the logic trees of damage/failure sequences for important SSCs will be introduced and an example of the logic tree will be demonstrated.

To develop the logic trees of damage/failure sequences for important SSCs under aircraft impact event, firstly, we select a target NPP. The target NPP is one of typical Korean PWR NPP. Figure 11 shows the placements of safety-related important SSCs of the target NPP. Then, we performed screening out procedure based on intervening structures and near field topography. With these results, we only considered the survived possible directions and SSCs in the development of logic tree.

The scattered particles of aircraft and structures after impact can cause the secondary damages on the SSCs which are opened in the yard. The effects of the secondary damages are also included in the logic tree. Figure 12 depicts an example of the damage/failure sequence logic tree for impact on the turbine building.

We developed also five another logic trees for important SSCs such as containment building, primary auxiliary building, secondary auxiliary building, access control building, and intake building. These logic trees will be used in the development of the plant level event tree (ET) and fault tree (FT) for the aircraft impact induced accidents.



1. CCW HX Bldg.
2. ESW Intake Structure
3. TBCCW HX Room
4. CW Intake Structure
5. Offsite Power
6. Diesel Oil Storage Tank
7. Condensate Storage Tank
8. Reactor Make-up Water Storage Tank
9. AAC Diesel Generator Bldg.

Figure 11: Placements of Safety-Related Important SSCs in the Target NPP

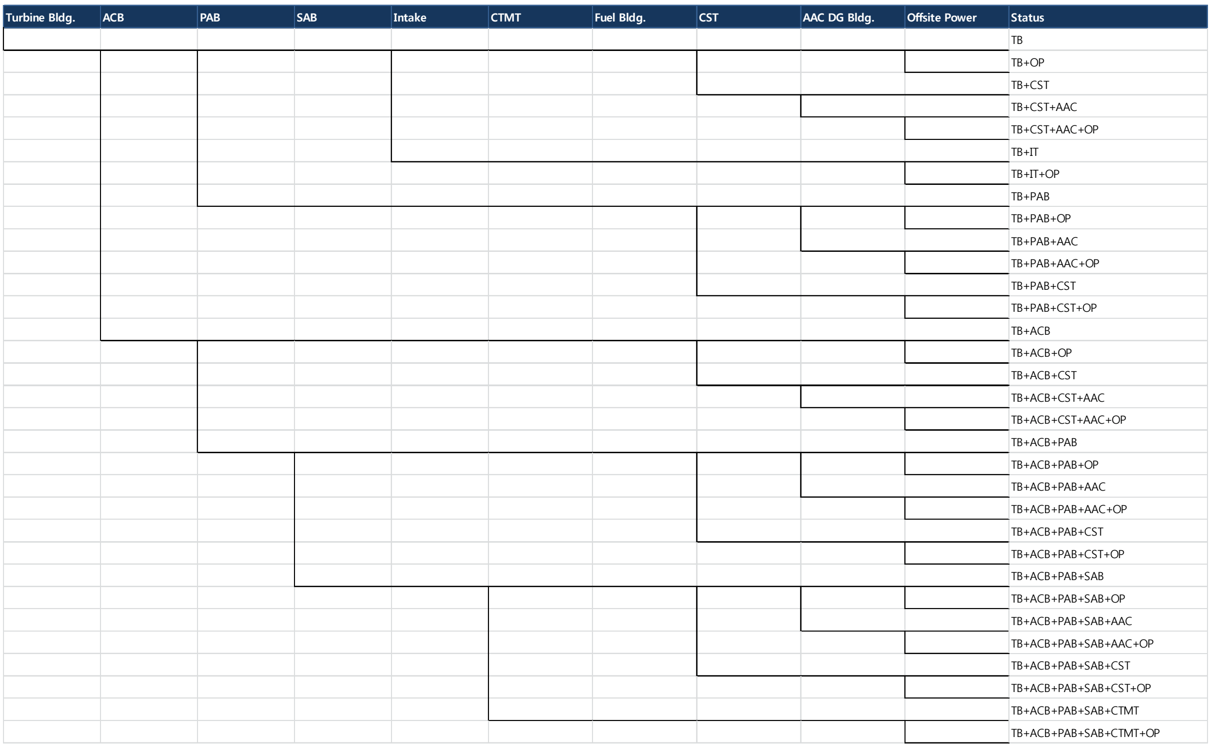


Figure 12: Example of Damage/Failure Sequence Logic Tree (Turbine Building Case)

6. CONCLUSIONS

The interim results of the on-going project in KAERI to assess the risk of NPPs against aircraft impact events were presented. First, the procedure to assess the aircraft impact induced risk was proposed. The total procedure composed by three stages; structural analysis to obtain structural responses, fragility assessment to estimate the aircraft impact fragility functions, and system level probabilistic safety assessment (PSA) to quantify the aircraft impact induced risk.

A method to select the reference parameter of aircraft impact loading was also presented. Four candidates of reference parameter were proposed, and the correlations between structural response and each candidate parameter were evaluated. From the results, we concluded that the maximum force is the most proper candidate for the reference parameter of aircraft impact loading.

Response spectra at the location points of safety related equipments and important SSCs were estimated. By combining the response spectra results and the capacity database of equipment & SSCs, the aircraft impact fragility can be estimated in terms of the reference parameter.

A procedure to develop the logic trees of damage/failure sequences for important SSCs was introduced and an example of the logic tree was demonstrated. These logic trees will be used for the development of the plant level ET & FT, and also for the evaluation of plant level aircraft impact risk. From the plant level risk information, it is expected that the efficient way to reduce the aircraft impact threat can be proposed. Also, the enhancement of the plant capacity against to the aircraft impact will be possible.

Acknowledgements

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