Probabilistic Risk Assessment of Nuclear Power Plants against Aircraft Impact Loading

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In Korea, research to develop aircraft impact risk quantification technology was initiated in 2012 by the Korea Atomic Energy Research Institute. This paper presents the purpose and objectives of that research project and introduces the results during the last four years. Firstly, an 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 the loading parameters such as the mass, velocity, and angle of crash. 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 a typical PWR type NPP. Then, the floor response spectra for the locations of important components were evaluated for an estimation of the failure probabilities and fragility functions of the structures and equipments. Some representative floor response spectra for the containment building and primary auxiliary building are presented in this paper. A conceptual technical procedure to assess the aircraft impact risk of an NPP using the previous results was proposed. It is expect that the aircraft impact risk onto the NPPs will be estimated in the near future.

I. 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 at verifying and ensuring the safety of the targeted walls and structures especially from the viewpoint of a deterministic approach.

However, recently, the regulation and assessment of the safety of the nuclear power plants (NPPs) against 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 the Korea Atomic Energy Research Institute (KAERI). In this paper, the total technical roadmap of this research project and its results during the last four years will be presented.

First, we developed an aircraft impact accident scenario and performed a preliminary fragility analysis of the local failure of the targeted wall by an 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 a methodology to determine 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 damage of the target structure, a missile-target interaction and Riera's time-history analysis method have been primarily used in the area of aircraft impact research. 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.

We also evaluated the floor response spectra for the locations of important components for an estimation of the failure probabilities and fragility functions of the structures and equipment. Some representative floor response spectra for the 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 the near future.

II. AIRCRAFT IMPACT RISK ASSESSMENT METHODOLOGY

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

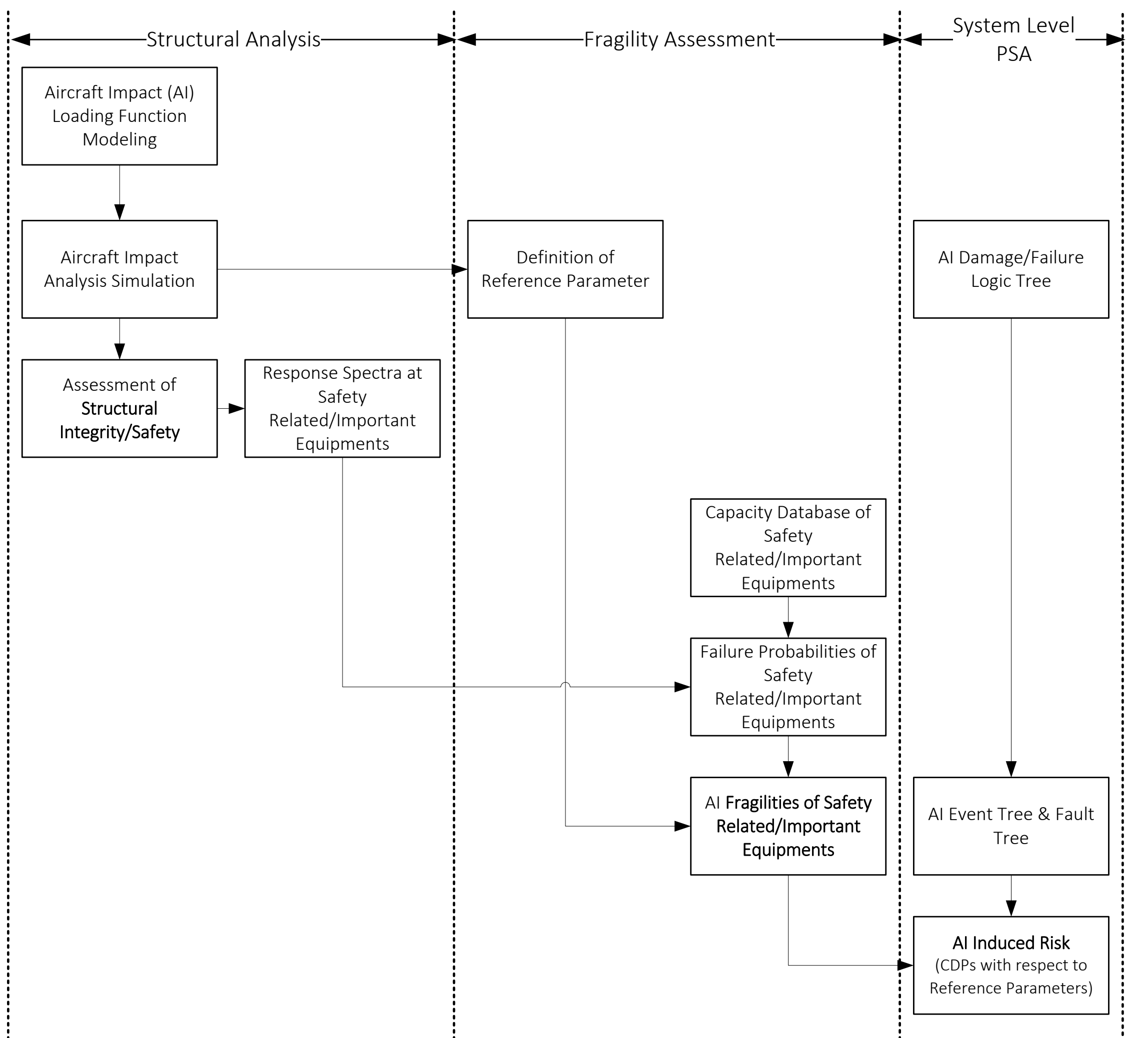


Fig. 1. Technical Roadmap to Assess the Risk of NPP against to Aircraft Impact Events

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 risk induced by an aircraft impact, further studies including a probabilistic analysis and plant level system analysis should be performed.

In a 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 a similar roll of PGA in a seismic PSA, should be selected.

For the fragility assessment stage, on the other hand, the structural response spectrum in a 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 years, preliminary studies for each stage were performed. Response spectra at the location points of safety related equipment and important SSCs were estimated in a 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 an aircraft impact event were also developed to perform a plant level system analysis. In chapters 3 through 5, each result of the studies will be introduced briefly.

Ⅲ. DETERMINATION OF REFERENCE LOADING PARAMETER

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

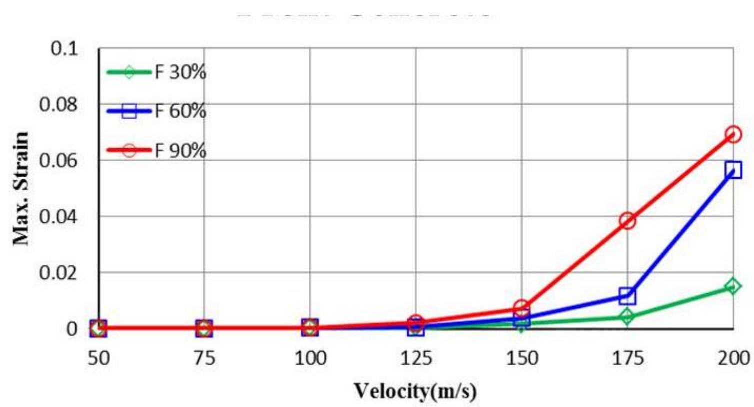


Fig. 2. Structural Responses with respect to the Variation of Fuel Masses & Impact Velocities

The target structure used to develop the method of reference parameter selection is one of the typical Korean PWR containment buildings. We developed a 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 the tendon, rebar, and liner were modeled using the piecewise-linear stress-strain curves.

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

Fig. 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 Riera's aircraft impact force-time history function with respect to the variation of the loading parameters, i.e., impact velocity and mass of the remaining fuel. For each force-time history, the type of aircraft is assumed to be a Boeing 767 model. The variation ranges of the impact velocity and remaining fuel percentage are 50 to 200 m/s, and 30 to 90%, respectively.

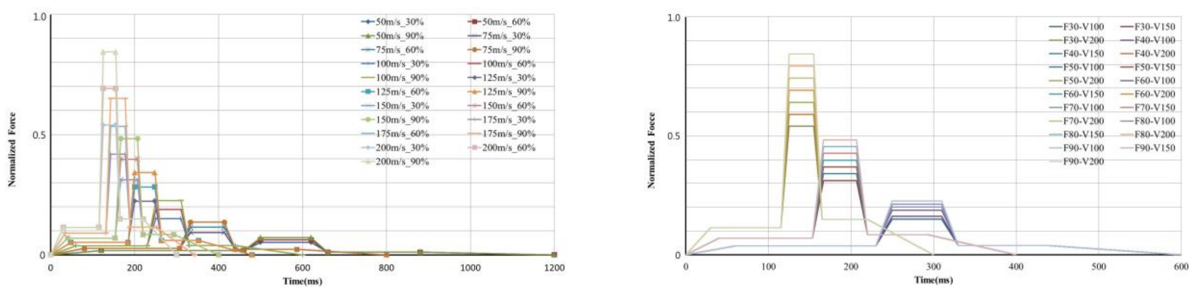


Fig. 4. Aircraft Impact Force-Time Histories with respect to the Variation of Mass & Velocity

We proposed four candidates of the reference parameter, i.e., kinetic energy, total impulse, maximum impulse, and maximum force. The definition of each parameter can be illustrated 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 the correlation between the reference parameter and structural responses can be formulated using the coefficient of determination, i.e., R2. It can be stated that the higher value of the coefficient of determination (R2) means a smaller error in a monotonically increasing linear relationship. The R2 values of each candidate parameter for each structural response in the material are summarized in Table 2. From the results in Table 2, we can see that the maximum force shows the highest R2 value in most responses in the materials. The simplicity and intuitiveness of the maximum force parameter are also remarkable compared to the other candidate parameters. Therefore, we concluded that the maximum force is the most proper candidate for the reference parameter of aircraft impact loading.

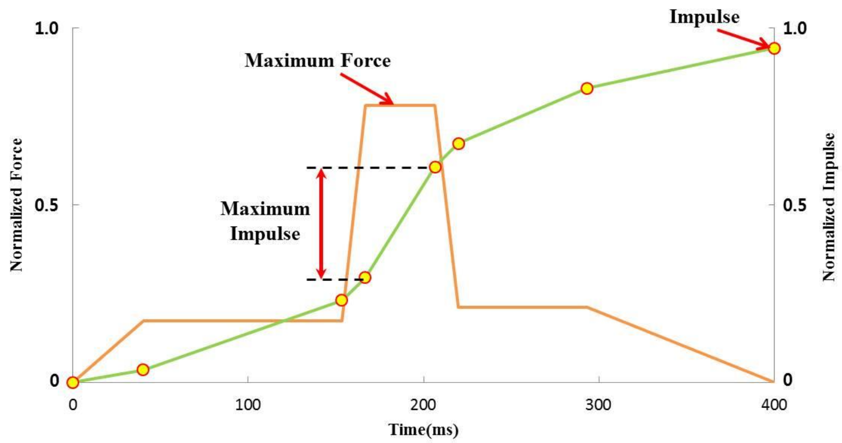


Fig. 5. The Definition of Each Candidate Parameter in Force-Time History

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

Ⅳ. FLOOR RESPONSE SPECTRA AGAINST TO AIRCRAFT IMPACT LOADING

For the fragility assessment, the structural response spectrum in the 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 equipment in the containment building and primary auxiliary building. Some of the results were demonstrated in this chapter.

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

(a) Fuselage (b) Wing & Engine

Fig. 6. Aircraft Impact Loading Area in Containment

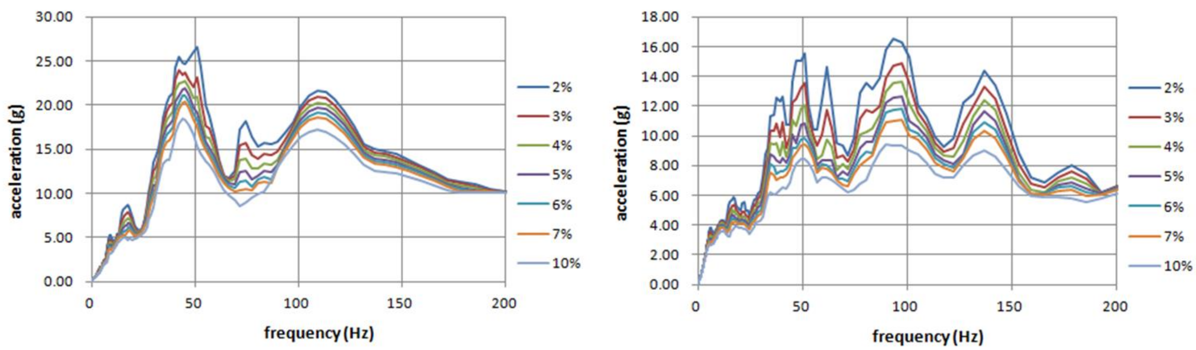


Fig. 7. Response Spectra in Internal Structure of Containment Building

To evaluate the structural response spectra in specific location points of equipment in a primary auxiliary building, we developed a three-dimensional finite element model of the primary auxiliary building. The force-time history method was also selected for the many repetitive numerical simulations, and the method was verified using a more complicated missile-target interaction method. Figure 8 depicts the finite element model of the primary auxiliary building and the verification analysis using the missile-target interaction method. The impacting area of the primary auxiliary building was the center part of the eastern wall, which is the most critical area of the building. Figures 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 a 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 a velocity of 125 m/s and 150 m/s. We also found that the responses at a higher frequency range are quite larger than those of the seismic floor response spectra.

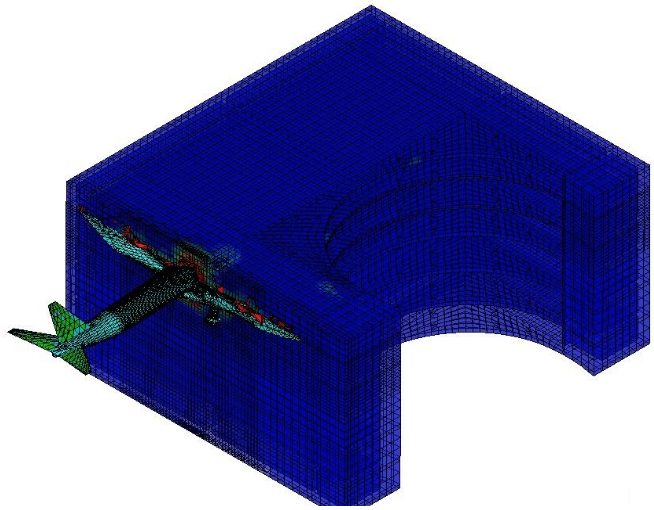


Fig. 8. Finite Element Model of Primary Auxiliary Building & Verification Analysis

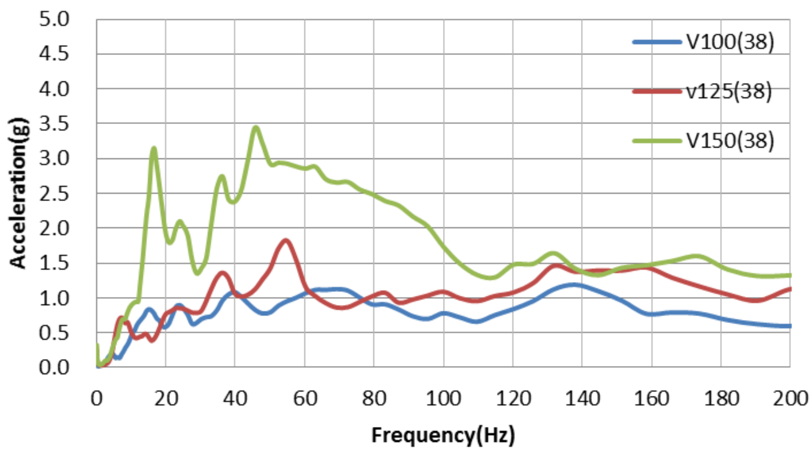


Fig. 9. Response Spectra at the Location of the Base of EDG

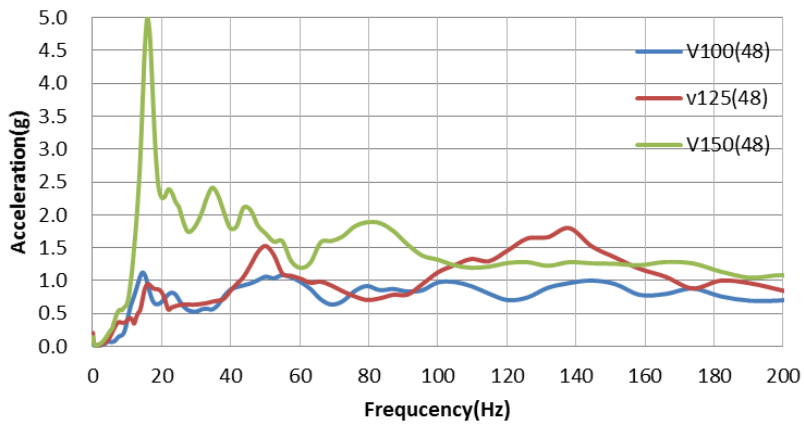


Fig. 10. Response Spectra at the Location of the Base of EWC

Ⅴ. DAMAGE/FRAILURE LOGIC TREE OF AIRCRAFT IMPACT EVENT

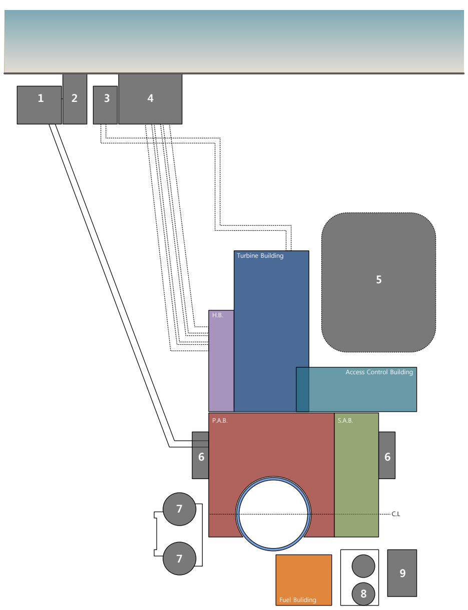
To perform the plant-level system analysis, the logic trees of the damage/failure sequences for important SSCs under an aircraft impact event were developed. These logic trees are required in the development of the plant level event tree (ET) and fault tree (FT) of the aircraft impact induced accidents. With the fragility database of the safety related equipment 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 an 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 an aircraft impact event, we first select a target NPP. The target NPP is one of the typical Korean PWR NPPs. Figure 11 shows the placements of safety-related important SSCs of the target NPP. Then, we performed a screening 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 the logic tree.

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

We also developed five other logic trees for important SSCs such as the 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 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.

Fig. 11.Placements of Safety-Related Important SSCs in the Target NPP

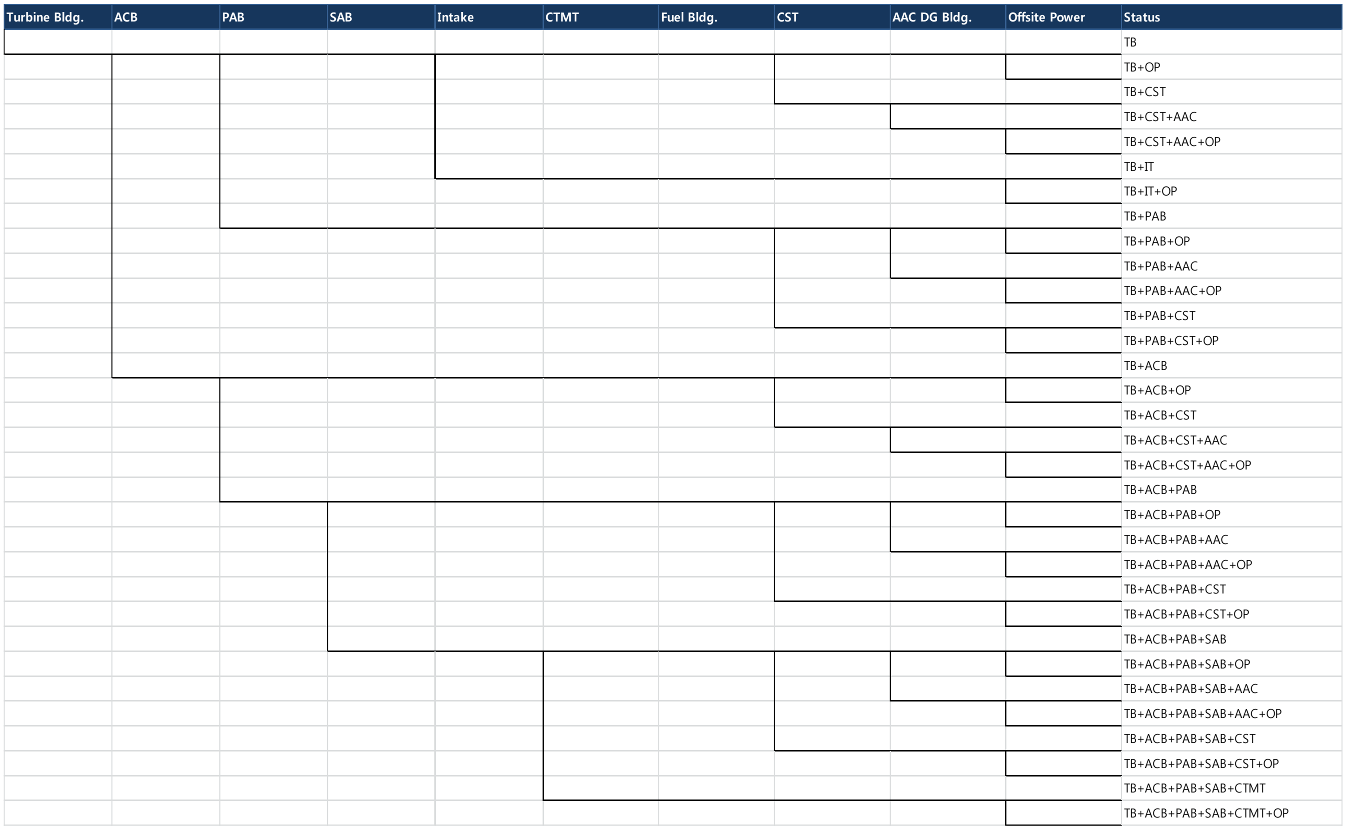


Fig. 12. Example of Damage/Failure Sequence Logic Tree (Turbine Building Case)

Ⅵ. CONCLUSIONS

The results of the on-going project in KAERI to assess the risk of NPPs against aircraft impact events were presented. First, a procedure to assess the aircraft impact induced risk was proposed. The total procedure is composed of three stages, i.e., a structural analysis to obtain the structural responses, a fragility assessment to estimate the aircraft impact fragility functions, and a 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 the reference parameter were proposed, and the correlations between the structural response and each candidate parameter were evaluated. From these results, we concluded that the maximum force is the most proper candidate for the reference parameter of aircraft impact loading.

The response spectra at the location points of the safety related equipment and important SSCs were estimated. By combining the response spectra results and 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 a 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 an efficient way to reduce the aircraft impact threat can be proposed. In addition, the enhancement of the plant capacity against an aircraft impact will be possible.

Acknowledgements

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Korean government, Ministry of Science, Ict & Future Planning (MSIP).

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