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Development of an Evaluation Methodology for Loss of Large Area induced from Extreme Events with malicious origin

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ABSTRACT

Event of loss of large area (LOLA) induced from extreme external event at multi-units nuclear installation has been emerged a new challenges in the realm of nuclear safety and regulation after Fukushima Dai-Ichi accident. The relevant information and experience on evaluation methodology and regulatory requirements are rarely available and negative to share due to the security sensitivity. Most of countries has been prepared their own regulatory requirements and methodologies to evaluate impact of LOLA at nuclear power plant. In Korea, newly amended the Nuclear Safety Acts requires to assess LOLA in terms of EDMG (Extended Damage Mitigation Guideline). Korea Institute of Nuclear Safety (KINS) has performed a pilot research project to develop the methodology and regulatory review guidance on LOLA at multi-units nuclear power plant since 2014. Through this research, we proposed a methodology to identify the strategies for preventive and mitigation of the consequences of LOLA utilizing PSA techniques or its results. The proposed methodology is comprised of 8 steps including policy consideration, threat evaluation, identification of damage path sets, SSCs capacity evaluation and identification of mitigation measures and strategies. The consequence of LOLA due to malevolent aircraft crash may significantly susceptible with analysis assumptions including type of aircraft, amount of residual fuel, and hittable angle and so on, which cannot be shared overtly. This paper introduces a evaluation methodology for LOLA using PSA technique and its results. Also we provide a case study to evaluate hittable access angle using flight simulator for two types of aircrafts and to identify potential path sets leading to core damage by affected SSCs within damaged area.

Keywords: *BDBEEE, LOLA, EDMG*

1 INTRODUCTION

After September 11 event in 2001 and Fukushima nuclear disaster in 2011, the landscape of nuclear safety paradigm has been changed drastically. Before September 11 event, malevolent man-made hazards have rarely taken into consideration for safety design of nuclear installations. Fukushima catastrophic disaster gave us a wakeup call for re-consideration of robustness of current accident management framework against the event of loss of large area induced from beyond design basis extreme external events (BDBEEE). USNRC announced several regulatory requirements and guidance documents regarding the event of loss of large area including 10CFR 50.54(hh)[1], Regulatory Guide 1.214[2] and SRP 19.4[3]. In Korea, the consideration of loss of large area has been limitedly taken into account for newly constructing NPPs as a voluntary basis. In general, it is hardly possible to find available information on methodology and key assumptions for the assessment of LOLA due to “need to know based approach”. Urgent needs exists for developing country specific regulatory requirements, guidance and evaluation methodology by themselves with the consideration of their own geographical and nuclear safety and security environments. Korea Hydro and Nuclear Power Company (KHNP) has prepared an Extended Damage Mitigation Guideline for APR-1400 as a near-term post-Fukushima action plan. However, accident management during the event of loss of large area at multi-unit site requires cross-cutting and interdisciplinary coordination and cooperating among in-house organizations or inter-organizations. The submittal guidance NEI 06-12[4] related to B.5.b Phase 2&3 focused on unit-wise mitigation strategy instead of site level mitigation or response strategy. Phase I mitigating strategy and guideline for LOLA provides emphasis on site level arrangement including cooperative networking outside organizations and agile command and control system. Korea Institute of Nuclear Safety has carried out a pilot in-house research project to develop the methodology and guideline for evaluation of loss of large area since 2014. This paper introduces the summary of the results and outcomes of the aforementioned research project [5].

2 METHODOLOGY

The main purpose of LOLA evaluation is to delineate potential mitigation strategies amd measures through identifying vulnerability and anticipated offsite consequences induced from the chosen hazards or threats scenarios. Figure 1 provides an overall outlook of a methodology for the LOLA assessment.

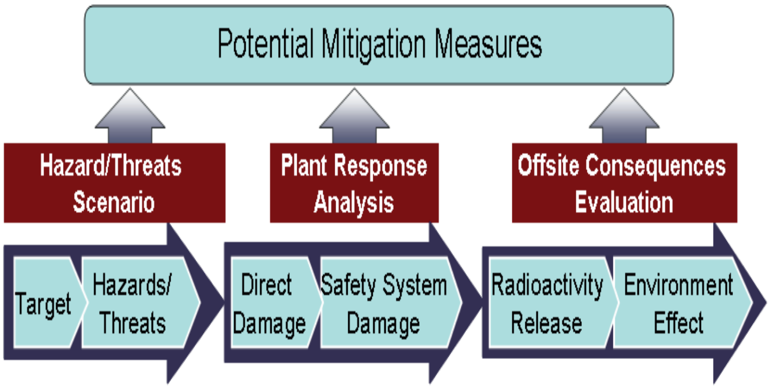

Figure 1: The framework of LOLA assessment

In case of LOLA events induced from fire and explosion with malicious origin, most of countries have dealt the selection of target scenarios and major analysis assumptions as “need to know” basis or safeguard information approach. The detailed information on the aforementioned should be dealt as sensitive information in terms of nuclear security due to the possibility of misuse to identify vulnerability of being targeted facilities for malicious acts such as radiological sabotage.

Figure 2: A methodology for LOLA Assessment

Figure 2 provides an evaluation methodology for the event of LOLA induced from explosion or fire with malicious origin. The approach of need-to-know requires policy consideration step to select the target scenarios and assumptions for the analysis reflecting following aspects:

- Type and size of aircraft being crashed
- Hitting point and angle
- Terminal velocity to crash
- Amount of residual fuel

Target scenarios and analysis assumptions affect significantly to characterize the scope of analysis and potential mitigation strategies and measures.

The characterization of target scenarios and major assumptions based on the policy consideration are followed by specifying damage area print as shown in Figure 2. Damage area footprint provides visualization of damaged area and list of affected rooms and structures, system and components (SSCs). Figure 3 gives an example of visualization of affected area. Magnitude of damage area varies with hitting point and size of fireball generated by fire and explosion. The size of fireball specifies the number of SSCs to be considered for the assessment. Identification of damage area can be made by computational fluid dynamics, fire analysis and empirical correlation of damage functions considering following aspects:

- Fireball overpressure
- Cable fragility
- Fire propagation effect
- Available firefighting assets
- Fire-induced failure of SSCs
- Burning liquid fuel spread in multi-level structures

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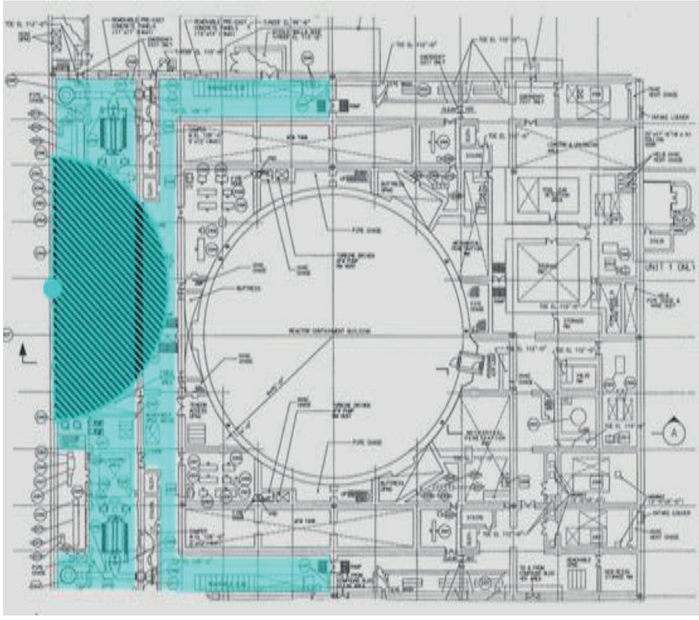

Figure 3: Example of damage footprint

We can utilize various mechanistic models as a function of amount of fuel and duration time of fireball to calculate maximum diameter of fireball [6] [7].

Identified damage area footprint and list of affected SSCs make possible to specify the path sets to core damage using PSA(Probabilistic Safety Assessment) models and existing PSA result. For the conservative approach, a conservative assumption with entire failure of SSCs included in fireball diameter can be made. Through the site walk-down and detailed evaluation of survivability of SSCs, unnecessarily pessimistic sequences of events or SSCs can be screened out from the list of target analysis. Based on finalized path sets to core damage and listed SSCs, consequence analysis should be made by utilization of existing severe accident analysis codes such as MELCOR or MAAP.

However, when we utilize existing PSA and severe accident analysis results, careful attention should be given due to the possible alien mechanism of containment failure, which is screened out in existing PSA framework.

Final outcomes of LOLA evaluation is identification of candidate strategies for EDMG (Extended Damage Mitigation Guides). Through this pilot research, we proposed a draft EDMG guideline for domestic nuclear power plants with emphasis on following aspects at the strategical point of view:

- Firefighting response strategy
- Response strategies for mitigating core damage
- Response strategies for mitigating fuel damage at spent fuel pool

3 CASE STUDY

As a case study, a comparative assessment for identify hittable angle to bring most significant consequence for two types of aircrafts, which are fighter plane and carrier plane, was carried out with empirical evaluation utilizing full-scoped real flight simulator and quantification model. The simulations are aimed to investigate the hittable angles depends on velocity and size of physical dimensions. The case of fighter plane gives us insights the impacts of high terminal velocity with small physical dimension in terms of mass. Detailed information related to simulation and target aircrafts are given to Table 1.

Table 1 Physical characteristics of aircrafts used for the simulation

	Engine	Physical Dimension(m)	Max Velocity	Termin. Velocity
Fighter	Single Jet	15m(L) x 10m(W) x 5m(H)	2500km/h	900-1200km/h
Carrier	Double Turbo-Prop Jet	21m(L) x 26m(W) x 8m(H)	509km/h	300-400km/h

As the target facility for the simulation, an imaginary nuclear power plant with two units of 1000Mwe PWR located in seashore. To identify the access angle giving significant impact to the facility, 9 representative angles as shown in Table 2. For each representative angles, 20 times simulations by real military pilots has been done with real flight simulator. Figure 4 and 5 provide sketches of simulated inside view and outside view during the access.

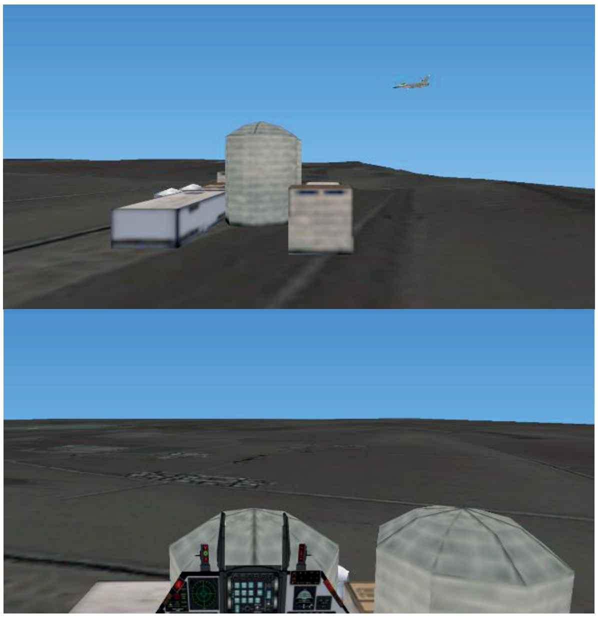

Figure 4: Inside and outside sketch view of simulation for fighter plane

Figure 5: Inside and outside sketch view of simulation for carrier

Table 2 summarizes the empirical results of flight simulator for identifying hittable angles.

Ang / Prob.	0 °	5°	10°	15°	20°	30°	45°	60°	90°
Fighter	≥85 %	≤95%	≥95%	100%	100%	≤95%	≤75%	≤25%	0%
Carrier	≥90%	≤95%	≥95%	100%	100%	≤75%	0%	0%	0%

The samples of simulated flight profiles including access angles of aircrafts provided from Figure 6 to 8.

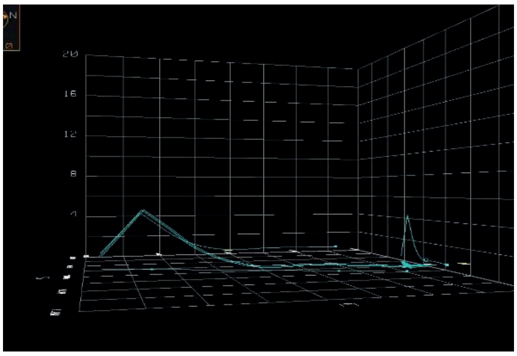

Figure 6: Flight profiles and access angle (0°)

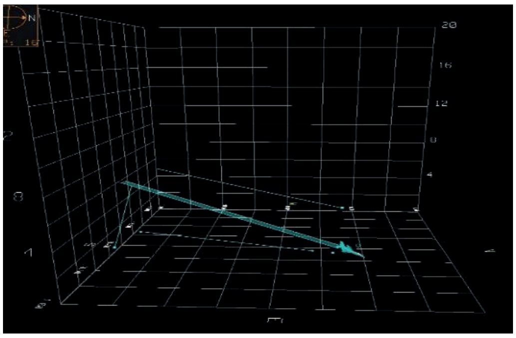

Figure 7: Flight profiles and access angle (30°)

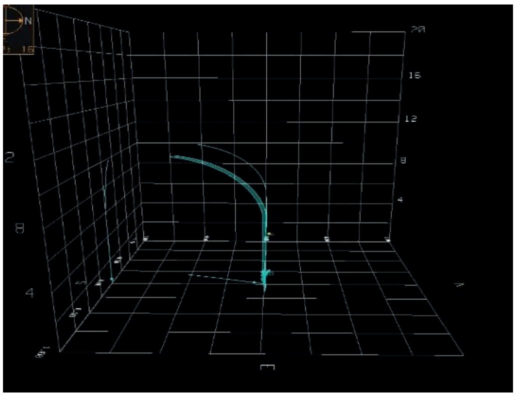

Figure 8: Flight profiles and access angle (90°)

Simulation results demonstrated that fighter plane make possible drastic changing access angle even higher angles than 60°, while the carrier was not possible to change access angle abruptly higher than 60° as shown in Table 2. However, both types of aircraft is not possible to access perpendicular direction to the facility due to the difficulties of posturing the planes. For identification of optimal angle for the evaluation, we quantified impact momentum depending on access angle using following equation 1[8]:

$$F_R = \sqrt{\left(\frac{4k}{\pi}\right)\left(\frac{M+\frac{k\pi\rho_c d^3}{4}}{\frac{4d^3 f_c^{0.456}}{82.6V^2 cos^2(k\pi sin\beta)+\rho_c d^3}}\right)} \times \frac{121.7\rho_c d^3\sqrt{f_c}}{2M}\left(\frac{V}{1000d}\right)^{0.2} \times cos\beta \qquad (1)$$

Where,

M: Mass of aircraft
K: dimensionless constant for
ρ_c: Density of concrete structure
d: diameter of projectile (Aircraft's head)
V: Access Velocity

Quantification result of impact momentum demonstrate that high impact momentum appears at the range of 0° to 30° of access angle as shown in Figure 9. Considering piloting difficulties and impact momentum, access angle to be taking into account for the assessment would be zero to 30° depending on terminal velocity and mass of target aircraft.

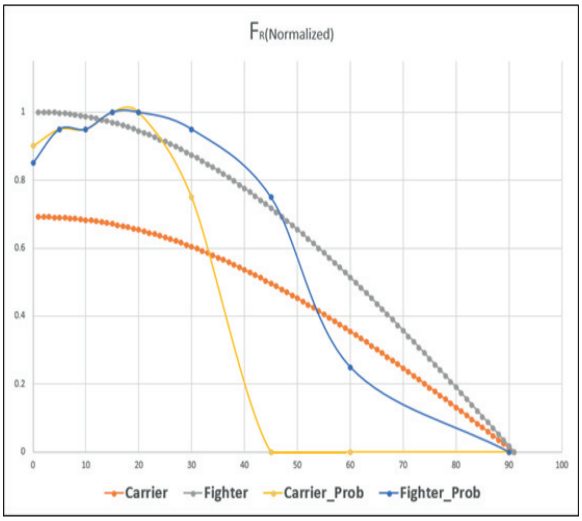

Figure 9: Impact momentum and hitting probability depending on access angle (normalized)

Identification of impact momentum and target access angle call for estimating fireball size characterized by the amount of residual fuel inventory of aircrafts to be assessed. The residual fuel inventory on the verge of crashing are a critical factor to estimate the fireball size which gives significant influence to damaged area footprint. We assumed 82% of residual fuel inventory conservatively, which is same inventory at the beginning of cruising altitude. We estimated fireball size for those of two aircrafts based on the assumed amount of residual fuel and using Abassi's equation 2[9].

$$D = 5.8(m_{feul})^{\frac{1}{3}} \qquad (2)$$

We got fireball size of around 20m for fighter and around 50m for carrier from the calculation.

Fighter plane case was screened out from the list of target scenario for identification damaged area footprint due to that carrier case having 2.5 times higher fireball size can encompass fighter plane's impact.

Damaged area footprint and identification of affected SSCs within damaged area can be made by reviewing the general arrangement drawing and walk-down of target facility to be assessed.

Based on the affected SSCs, the path sets leading to core damage can be identified using existing PSA model and Quantification tools. In this study, quantification was made by VIPEX/FTREX[1]® code.

Through the quantification of path sets using the aforementioned code and PSA model, we identified that 1448 sets out of 112,466 sets are exposure as susceptible sets leading to core damage. Figure 10 gives a sample of results of automatic identification of basic event including safety critical functions related to target sets with VIPEX.

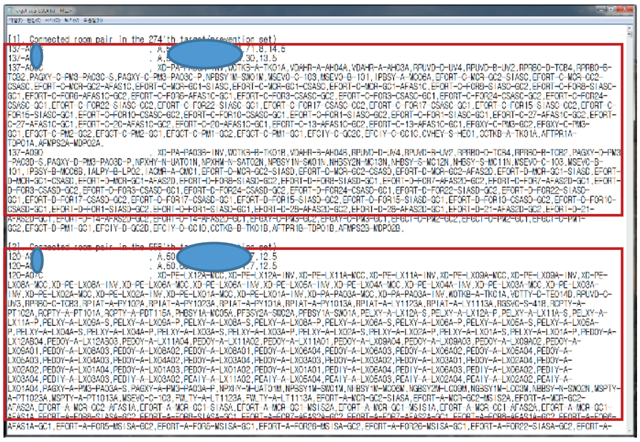

Figure 10: List of basic events affected by SSCs within fireball (example)

The results of case study demonstrated that containment structure secures robustness against target scenarios and SSCs located with damaged area at auxiliary building may be susceptible with breaching primary heat removal and RCS inventory control.

The result of case study demonstrated that the proposed methodology secure enough technical feasibility and applicability for the evaluation of beyond design basis extreme events in regard with preparing strategies of EDMG.

4 CONCLUSION AND REMARKS

After Fukushima Dai-Ichi accident, the awareness on countering the event of loss of large area induced from extreme man-made hazards or extreme beyond design basis external event at nuclear installations. Urgent need exists to develop regulatory guidance for coping with this undesirable situation, which has been out of consideration at existing nuclear safety regulatory framework due to the expectation of rare possibility of occurrence. This paper introduces a methodology and consideration to be given for evaluating the event of loss of large area at nuclear power plant with regard to prepare extended damage mitigation guide (EDMG). As a case study, empirical evaluation for identifying access angle related to analysis assumption with real flight simulator and pilots. Based on identified access angle, type of aircraft and the amount of residual fuel, damage area which is characterized by fireball size and path sets leading to core damage was quantified using PSA tools and results. Analysis results demonstrated that significant impact took a place at the around 20 degree of access angle and 1448 basic events are closely tied with affected SSCs within fireball. This paper proposed a systematic approach for evaluating loss of large area induced from beyond design basis external event with malicious origin. The refining the proposed methodology and its demonstration of the feasibility will be continued through the consecutive research work.

[1] VIPEX :Vital area Identification Package Expert
FTREX: Fault Tree Reliability Evaluation eXpert

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