Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Reassessment of Wind-borne Missile Fragility Incorporating Site-Specific Local Wind Field and CFD-FSI-Based Impact Velocity

Jae-Wook Jung [a*], Daegi Hahm [a]
[a] *Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, South Korea, 34057*
**Corresponding author: jaewook1987@kaeri.re.kr*

Keywords : high-wind PRA, wind-borne missile, local wind amplification, CFD, FSI, fragility reassessment

1. Introduction

Extreme and combined external hazards have become important safety issues for nuclear power plants (NPPs) since the Fukushima accident in 2011. Among them, high-wind events can cause direct wind load effects and indirect damage driven by wind-borne missiles. Wind borne-missile refers to debris propelled by high winds into safety significant structures, systems, and components (SSCs). Because screening out all high-wind scenarios may not be applicable for all sites, a probabilistic high-wind risk assessment (HW PRA) can be required for site-specific SSCs.

In previous assessment [1], a wind-borne missile fragility evaluation framework was demonstrated for condensate storage tank (CST) by combining a generic wind-borne missile hazard with an impact simulation, where a representative 6-inch pipe missile and a design-basis impact velocity were adopted. However, this previous approach did not account for two sources of uncertainty that can significantly affect the resulting risk estimate:

(1) the assumption of uniform “open-field” wind velocity across the plant site (ignoring local velocity amplification due to buildings and layout), and

(2) the use of a highly conservative design-basis missile impact velocity [2].

This research presents an enhanced fragility reassessment that explicitly incorporates a CFD-based evaluation of local wind velocity amplification within a plant site and a CFD–FSI (fluid–structure interaction) re-estimation of the missile impact velocity for a representative pipe-type missile. The updated demand characterization is then propagated into the CST wind-borne missile fragility, providing a more realistic and site-specific fragility estimate.

2. Methods and Results

2.1 Baseline wind-borne missile fragility framework

The high-wind fragility of an SSC is defined as the conditional probability of failure as a function of a wind-related damage parameter (e.g., wind velocity). A lognormal fragility form consistent with seismic fragility practice is used [3]:

$$f(v) = \Phi(\frac{\ln v/v_m + \beta_u \Phi^{-1}(Q)}{\beta_r})$$

where Φis the standard normal cumulative distribution function, v is wind speed, v_m is the median wind speed capacity, β_r represents aleatory variability (randomness), β_u represents epistemic uncertainty, and Q is the confidence level.

For wind-borne missiles, the overall conditional failure probability depends on both the probability of missile impact (missile impact hazard) and the conditional probability of failure given an impact [3]. A target hit probability model can be expressed as:

$$P_{hit} = \Psi \times \mathrm{SA_T} \times N$$

where Ψ is the normalized impact probability (based on wind intensity category and equipment shielding/elevation conditions), $\mathrm{SA_T}$ is the exposed target area, and N is the missile population within the relevant walkdown region.

2.2 CFD-based evaluation of local wind velocity within a plant site

To reflect site layout effects, a computational fluid dynamics (CFD) model of the plant site was developed using the LS-DYNA ICFD solver. The model explicitly represents major buildings/structures and applies boundary conditions suitable for high-wind inflow: prescribed velocity at inlet boundaries, pressure outlet boundaries, free-slip on far-field boundaries, and non-slip on the ground and structure surfaces.

A set of simulations was performed for eight wind directions (E, W, N, S, NE, SE, NW, SW). The design wind velocity condition (40 m/s) was applied. The simulation results show that local wind velocity can deviate substantially from inflow wind velocity due to building-wind effects such as channeling between structures and flow separation around sharp corners. In particular, for NW and SW wind directions, local peak speeds around 75–80 m/s (approximately twice the inlet velocity) can occur near rectangular building corners and inter-building passages, indicating that local wind amplification can be a contributor to debris generation and missile transport near exposed SSCs.

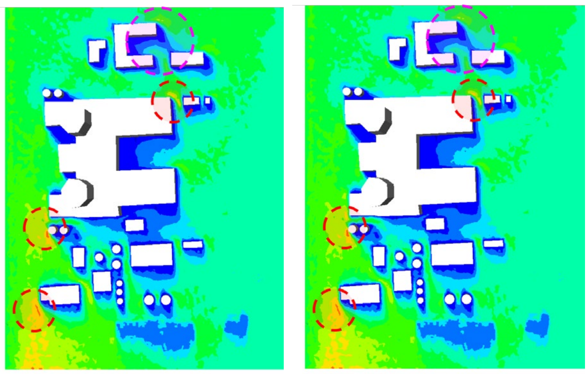

Fig. 1. CFD-based local wind field distribution over the plant site for NW (left) and SW (right) wind directions.

The computed local wind field was used to define a worst local wind velocity envelope for fragility reassessment, enabling a site-specific demand characterization rather than assuming spatially uniform wind velocity.

2.3 *CFD–FSI-based re-estimation of missile impact velocity*

In addition to local wind amplification, realistic missile impact velocity is a critical input to wind-borne missile fragility. Design-basis impact velocities can be conservative because they may not fully account for actual debris aerodynamics, tumbling, and drag effects.

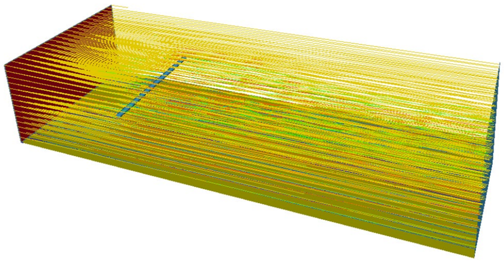

Fig. 2. CFD–FSI simulation of a 6-inch pipe missile under high-wind condition.

A CFD–FSI missile simulation model was developed using LS-DYNA CFD capabilities coupled with structural motion (FSI) to reproduce wind-driven debris motion. The model was validated against wind tunnel test data [4], demonstrating that the impact velocity (the important response parameter for fragility) can be predicted with high accuracy. After validation, the method was applied to the representative 6-inch pipe missile to compute its translational velocity history and impact velocity under various wind speeds.

The re-estimated impact velocity for the 6-inch pipe missile at the design wind speed (40 m/s) was below 10 m/s, which is significantly smaller than the conservative design-basis value. This result implies that impact demand used in previous fragility assessments may be overly conservative, and that an integrated CFD–FSI approach can provide a more realistic demand for wind-borne missile fragility evaluations.

2.4 *Reassessment of CST wind-borne missile fragility*

Using the site-specific worst local wind velocity envelope derived from the plant site CFD analysis and the CFD-FSI derived realistic missile impact velocity, the CST wind-borne missile fragility is reassessed.

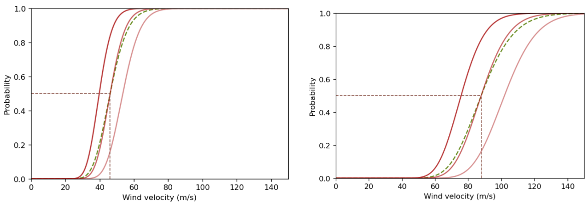

Fig. 3. Reassessment results of wind-borne missile fragility: (left) baseline case, (right) reassessment.

The updated fragility results show a substantial right-shift of the fragility curve, indicating improved performance margin when realistic missile impact velocity is used, even if local wind velocity amplification is conservatively considered.

3. Conclusions

This study reassessed wind-borne missile fragility for a CST by incorporating CFD-based local wind amplification and CFD–FSI-based missile impact velocity estimation. The plant-site CFD analysis shows that building-wind interactions can nearly double the local wind velocity relative to inflow conditions, while the CFD–FSI simulation, validated against wind tunnel data, yields a substantially lower impact velocity than the conventional design-basis value. Incorporating both refinements shifts the median capacity and nearly doubles the 1% failure wind velocity, confirming that design-basis missile velocities govern fragility conservatism more than site wind assumptions.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Climate, Energy & Environment(MCEE) of the Republic of Korea (No. RS-2022-KP002850).

REFERENCES

[1] J.W. Jung and D. Hahm, Wind-borne Missile Fragility Assessment for Nuclear Power Plant Equipment to External Hazard due to High-wind, Korean Nuclear Society Spring Meeting, 2024.
[2] KHNP, Shin Kori Units 1 and 2 Final Safety Analysis Report (for public use), 2018.
[3] EPRI, High Wind Risk Assessment Guidelines, TR-3002003107, Electric Power Research Institute, 2015.
[4] H. Jeong, S. Lee, J. Park, and S.D. Kwon, A Study on the Flight Initiation Wind Speed of Wind-Borne Debris. KSCE Journal of Civil and Environmental Engineering Research, Vol. 40, No. 1, pp. 105-110, 2020.