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A CFD-Based Framework for Near-Field Atmospheric Dispersion Modeling of Radioactive Nuclides in Realistic Accident Scenarios

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1. Introduction

Nuclear facilities are vital energy sources but can inflict severe radiological and non-radiological harm during accidents, as evidenced by TMI-2, Chernobyl, and Fukushima. In Korea, coastal plants near dense cities (e.g., Busan, Ulsan, Gwangju) elevate population exposure risks and wider socio-economic, environmental, and trust impacts. Effective emergency response is hindered by complex urban forms and local meteorology, making near-field dispersion prediction difficult. Gaussian plume tools (e.g., MACCS) aid consequence and probabilistic assessments but lack near-field resolution for complex buildings and EAB-scale flows. Research on radionuclide dispersion using CFD is currently underway.[1][2] To bridge this gap, this study proposes a Computational Fluid Dynamics(CFD)-based framework for realistic accident scenarios that resolves near-field plume behavior and rigorously assesses emergency-worker radiological and non-radiological exposures, providing actionable inputs for mitigation and response planning.

2. Framework

The framework consists of two main stages:
(1) Derivation of representative nuclear accident scenarios and analysis of radiological source terms,
(2) CFD-based Radioactive Nuclides atmospheric dispersion analysis.

2.1 Derivation of representative nuclear accident scenarios and analysis of radiological source terms

Nuclear facilities include nuclear fuel fabrication plants, nuclear power plants, research reactors, and waste management facilities, and the proposed framework is applicable to all such facilities. Next, PSA-based accident scenarios are derived for the selected nuclear facility, representative scenario is then chosen to analyze the Mechanical Source Term(MST).

Next, analyze the MST for the PSA-selected accident scenarios at the chosen nuclear facility. Through the MST analysis, obtain data such as the time series of radioactive nuclide releases, the particle size distribution of radioactive materials, and the release pressure from the release surface to the atmosphere.

2.2 CFD-based Radioactive Nuclides atmospheric dispersion analysis

CFD analysis can incorporate building geometry, terrain conditions, and finely resolved wind and turbulence fields in three-dimensional high resolution, enabling more accurate modeling of complex atmospheric flows and the dispersion of radioactive materials around nuclear facility exteriors. In particular, it can effectively simulate local vortices, turbulence, and lower atmospheric dynamics, which are essential considerations for near-field dispersion assessments.

For the CFD analysis, the selected nuclear facility is modeled in 3D. Near-field atmospheric dispersion requires detailed modeling to capture building-induced vortices and local terrain features. Modeling must include leakage/breach locations, which should be represented as surfaces and configured to serve as boundary conditions. Considering the site-specific meteorological data for the nuclear facility, the inlet wind speed profile is set as a boundary condition, and the analysis is performed.

Unlike lumped codes such as MACCS, CFD can analyze the following phenomena more realistically:
(1) Resuspension of radioactive materials due to decay heat
(2) Dry and wet deposition

Whereas MACCS computes these using correlations, CFD solves the governing equations. Resuspension can be modeled by incorporating the heat generated from radioactive decay as a decay-heat source term in the Navier–Stokes governing equations, and wet deposition can be analyzed by applying particle–particle interactions between raindrops and radioactive aerosols and/or probabilistic attenuation effects. Through transient atmospheric dispersion analysis that reflects realistic accident scenarios at nuclear facilities, the final outputs provide the spatial and temporal distribution of radioactive materials.

3. Case Study

3.1 Derivation of representative nuclear accident scenarios and analysis of radiological source terms

Saeul Nuclear Power Plant Units 1 and 2 were selected as the case study. Saeul 1 and 2 are APR1400 reactors, and the site lies in a region densely clustered with the Kori and Shin-Kori plants, presenting a multi-unit issues. By analyzing high-resolution distributions of radioactive materials within the Exclusion Area Boundary(EAB)—the working environment for plant personnel during a nuclear incident—future studies can derive stepwise movement routes and dwell points.

Accident scenarios were derived based on PSA. Table I presents the Fussell–Vesely(FV) values of the sequences calculated using Aims-PSA, up to a cumulative 95%. From SBOR-08 sequence, showing the highest value, was selected as the representative case-study scenario. Selected accident scenario corresponds to a sequence where, following a station blackout(EDG fail to run), the Alternative-AC generator operates for 24 hours and secondary heat removal from auxiliary feedwater, but delayed restoration of AC power leads to core damage. Event tree for selected scenario is shown in Figure 1.

Table I. Fussell–Vesely value by sequence

Event	FV	Cumulative
#GIE-SBOR-08	0.2672	0.2672
#GIE-TLOCCW-2	0.1166	0.3838
#GIE-MLOCA-3	0.0984	0.4822
#GIE-DVI-LOCA-3	0.0824	0.5646
#GIE-SBOR-28	0.0677	0.6323
#GIE-SGTR-12	0.0621	0.6944
#GIE-SGTR-23	0.0315	0.7259
#GIE-SBOS-08	0.0309	0.7568
#GIE-SLOCA-20	0.0233	0.7800
#GIE-LOOP-17	0.0213	0.8013
#GIE-SGTR-09	0.0213	0.8226
#GIE-SBOS-28	0.0210	0.8436
#GIE-LOOP-12	0.0209	0.8645
#GIE-TLOCCW-4	0.0156	0.8802
#GIE-MLOCA-2	0.0141	0.8942
#GIE-GTRN-06	0.0115	0.9058
#GIE-SGTR-11	0.0109	0.9167
#GIE-SLOCA-04	0.0097	0.9264
#GIE-GTRN-05	0.0091	0.9355
#GIE-RVR-1	0.0078	0.9433
#GIE-GTRN-07	0.0064	0.9497
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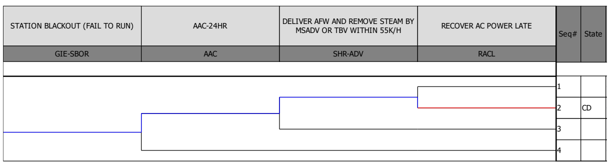


Fig. 1. Simplified Event Tree of SBOR-08

MST analysis for the SBOR-08 scenario was performed using the MELCOR 2.2 code, and the containment pressure and radioactive nuclide release were analyzed and presented in Fig. 2 and Fig. 3, respectively. The post containment failure time-series data were applied as boundary conditions at the release surface.

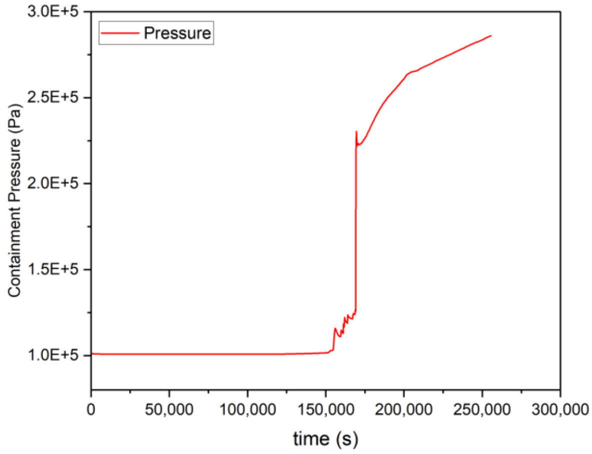


Fig. 2. Containment Pressure of SBOR-08

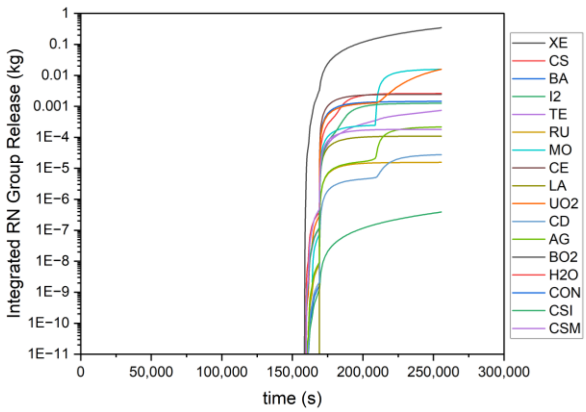


Fig. 3. Integrated RN group Release of SBOR-08

3.2 CFD-based Radioactive Nuclides atmospheric dispersion analysis

ANSYS Fluent was used for the CFD analysis. The modeled APR1400 and the containment breach(release surface) model are shown in Fig. 3 and Fig. 4. The containment failure modeling followed the ultimate internal pressure capacity study, with the breach located along the dome's hoop direction at 30°–45°, and a failure area of 2.121 m² was represented.[3] To reduce computing resources, a finer mesh was generated near the plant and coarser meshes farther away, the resulting 7.4M volume mesh as shown in Fig. 5.

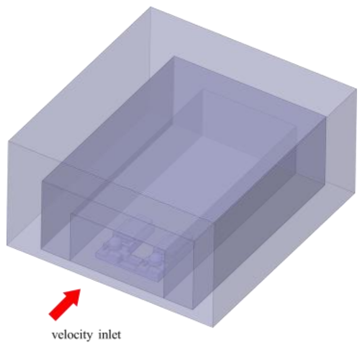


Fig. 4. 3D Modeling of APR1400

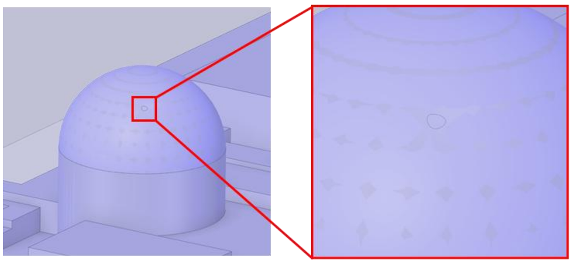


Fig. 5. Breach modeling

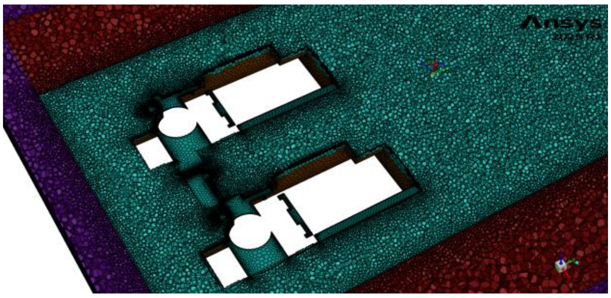
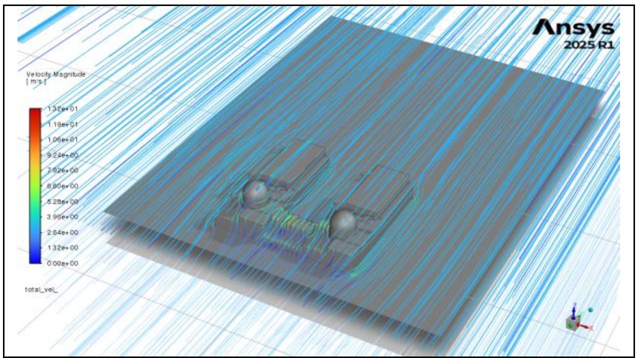


Fig. 6. Volume mesh of APR1400

A boundary condition was set so that a 3.0 m/s wind flows normal to the inlet surface, and a transient analysis was performed using the Large Eddy Simulation(LES) WALE model as the solution approach. The LES transient results before containment failure are shown in Fig. 6.



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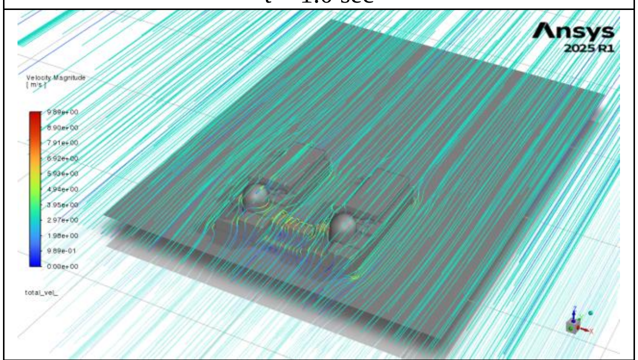

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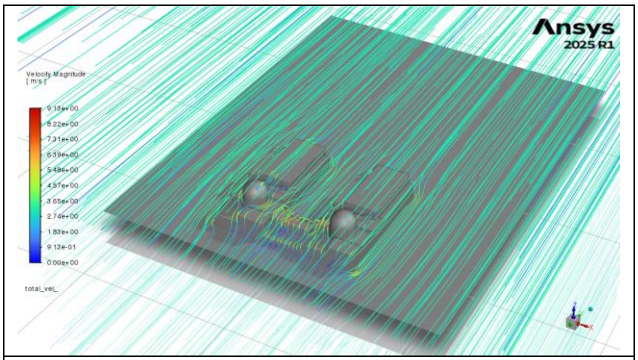

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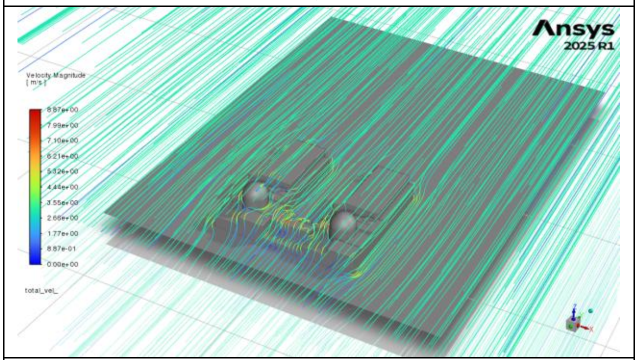

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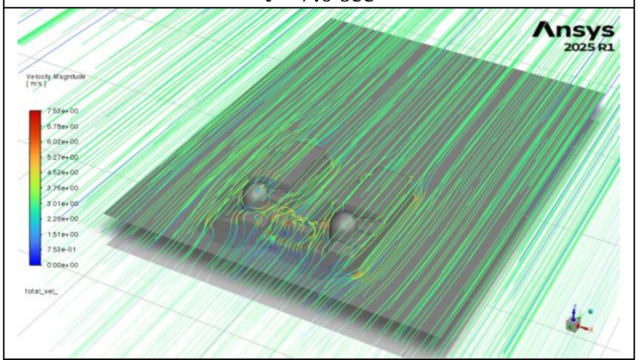

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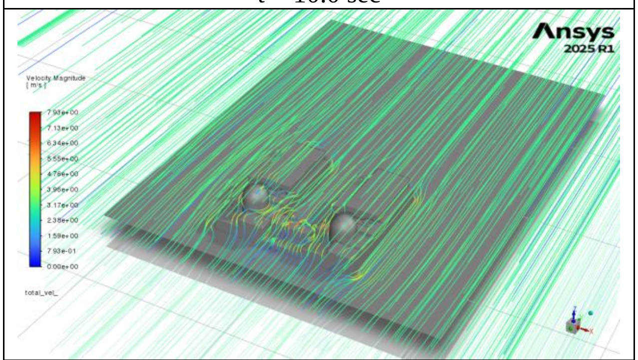

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Fig. 7. Transient analysis of Before-rupture in 3.0m/s velocity inlet condition

Before-rupture analysis is currently being performed until the wind field stabilizes, after which the pressure at the breach and the time-series data of radioactive nuclide releases obtained in the MST stage will be applied as boundary conditions at the release surface for the analysis. Resuspension and dry/wet deposition of radioactive nuclides will also be incorporated into the case study.

3. Conclusions

Accidents at nuclear facilities can cause severe radiological and non-radiological impacts, as seen at TMI-2, Chernobyl, and Fukushima. Conventional Gaussian plume analysis code aid risk assessment but lack EAB-scale fidelity for complex building aerodynamics. To address this, we propose an integrated framework linking PSA-based scenario selection, MST quantification, and CFD-based near-field dispersion. We then demonstrate the framework through a case study at Saeul NPP Units 1 and 2(APR1400) within a dense multi-unit cluster with Kori and Shin-Kori, transferring source terms as boundary conditions and resolving near-field plume behavior with explicit consideration of resuspension and dry/wet deposition to inform site-specific emergency planning. Ongoing work will continue the transient analyses to capture stabilized wind fields and time-evolving releases.

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