Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Calculating radionuclide release rates from deep-sea submerged spent fuel casks: a surrogate model approach

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***Keywords :** SNF, CFD, metamodeling, risk assessment, maritime transportation

1. Introduction

In South Korea, due to the saturation of SNF storage at pressurized water reactors and the coastal locations of nuclear power plants, maritime transportation of SNF is considered essential. This paper discusses the development of a surrogate model for a CFD-based Barrier Effect Model, which assesses radionuclide dispersion from damaged SNF casks submerged at sea. The model performs risk assessment by not assuming immediate dispersion, but by considering the barrier effect, which delays the release of radionuclides. To support efficient training data generation, a comprehensive factor effect analysis was conducted. This analysis identified key factors that significantly influence the release rates of radioactive nuclides and the temperature changes when SNF casks are lost at sea.

2. CFD-based release rate assessment model

In this section, the CFD techniques used to evaluate the release rate and temperature of radionuclides from submerged transport containers in deep sea are described. The CFD model employs sub-modeling techniques and includes brief results.

2.1 CFD Model Outline

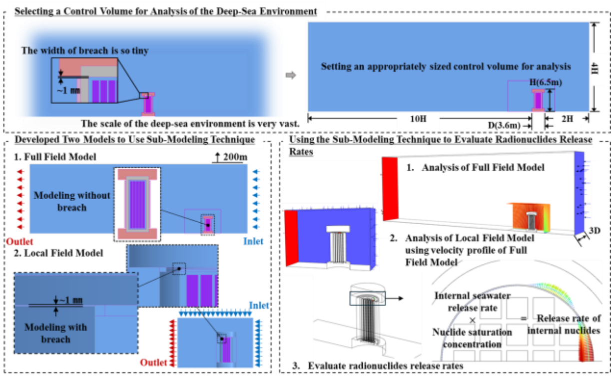

Fig. 1. Schematic of the seawater release rate assessment model using CFD model.

The size of the external control volume to evaluate the flow around the B-type cask and the size of the breach where the barrier effect is believed to apply are more than three orders of magnitude apart, showing a clear scale difference. To address this scale difference, a sub-modeling technique was used. An overview of the analysis is shown in Figure 1. This technique has the advantage of allowing detailed analysis of specific areas after analyzing the full field model and is particularly useful for solving problems with large scale differences. The full field model consists of the cask and the control volume around the cask itself. The local field model consists of the transport cask, which accurately models the gap in the lid stopper, and the local seawater volume around the gap. The focus of the local field model is to accurately calculate the mass flow rate of seawater through the gap in the lid stopper. The two models are coupled with a one-way (full field → local field) coupling based on the velocity profile.

2.2 CFD Model Results

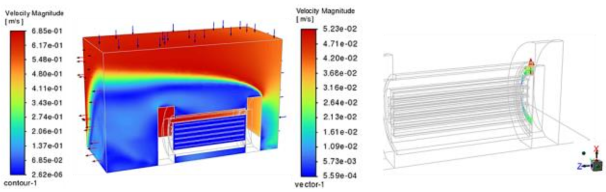

Fig. 2. Local Field Model Result Visualization: Velocity (Left: Around cask / Right: Through the breach).

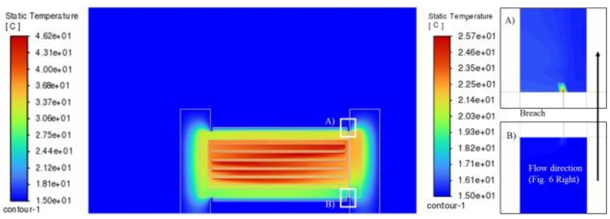

Fig. 3. Local Field Model Result Visualization: Temperature (Left: Overall / Right: Detail).

The results of the developed CFD-based release rate assessment model are shown in Figure 2 and 3. The analysis conditions are an external temperature of 15 degrees Celsius, an external flow velocity of 0.5 m/s, an internal decay heat of 16.8 kW, and a gap size of 1 mm. Figure 2 allows for the evaluation of internal seawater outflow through the gap During this process, temperature changes also occur, as shown in Figure 3. The mass flow rate of the expelled seawater, quantified using MATLAB, is measured at 7.42 g/s.

2.3 Compared to traditional models

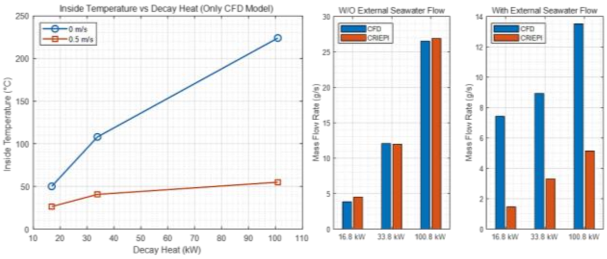

Fig. 4. Comparison of CFD and barrier effect model – with and without external seawater flow under varying decay heat.

In this section, we compare it to the Barrier Effect Model. which was formulated under the assumption of natural convection conditions. The comparative analysis focuses on the seawater outflow rates under two scenarios: natural convection and external flow. In the case of natural convection, we find similar trends to the existing model, while in the case of external flow, the developed model has a larger seawater outflow rate.

3. Preliminary Research for Developing a Surrogate Model

This section outlines the metamodeling process for a mass release rate assessment model that has been developed through deterministic simulation, intended for integration into a Spent Nuclear Fuel (SNF) maritime transportation risk assessment code. The objective of this study is to gather preliminary data necessary for actual sampling efforts.

3.1 Set the surrogate model valid range

Table 1: Key input parameters and their ranges

	Breach size [mm]	External temp [℃]	Flow velocity [m/s]	Decay heat [kW]
Min	0.3	3	0.09	3.665
Max	1.0	26.8	1.37	47.050

The accuracy of the surrogate model is assessed through sampling. To this end, we identified four critical factors: ocean-related factors, accident probability factors, and seafarer port-related factors, and established the appropriate input space as illustrated in Table 1.

3.2 Factor Effect Analysis

ANOVA analysis was conducted to determine the validity of the selected factors' effects on mass release rate and release temperature. This analysis utilized the Taguchi Method, a form of Fractional Factorial Design. We employed a two-level, four-factor factorial design, specifically using model T8. The outcomes of this analysis are detailed in Tables 2 and 3.

Table 2: Results of a factor effect analysis on release rate [Analysis of Variance; ANOVA].

Source	DOF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Decay heat	1	1087.53	33.38%	412.44	412.44	108.17	0.061
Temperature	1	36.72	1.13%	276.77	276.77	72.59	0.074
Velocity	1	0.1	0.00%	374.56	374.56	98.23	0.064
Breach size	1	1236.16	37.94%	1236.16	1236.16	324.2	0.035
Decay heat*Velocity	1	18.12	0.56%	18.12	18.12	4.75	0.274
Temperature*Velocity	1	875.4	26.87%	875.4	875.4	229.59	0.042
Error	1	3.81	0.12%	3.81	3.81		
Total	7	3257.85	100.00 %				

Table 3: Results of a factor effect analysis on release temperature [Analysis of Variance; ANOVA].

Source	DOF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Temperature	1	1060.72	21.41%	950.14	950.14	1198.86	0.018
Velocity	1	43.97	0.89%	62.31	62.31	78.62	0.071
Breach size	1	306.85	6.19%	104.99	104.99	132.47	0.055
Decay heat	1	3216.98	64.92%	3216.98	3216.98	4059.08	0.01
Temperature *Velocity	1	316.64	6.39%	316.64	316.64	399.52	0.032
Temperature *Breach size	1	9.16	0.18%	9.16	9.16	11.56	0.182
Error	1	0.79	0.02%	0.79	0.79		
Total	7	4955.11	100.0%				

4. Conclusions

In this study, preliminary information was obtained for metamodeling as part of the initial phase to develop a surrogate model based on a CFD-based release rate assessment model. Input factors were selected, the valid range for the model was established, and data for sampling were gathered through ANOVA analysis of the selected factors. This process is expected to contribute significantly to the development of a SNF maritime transportation assessment code in the future.

REFERENCES

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