

Sensitivity Analysis of SPACE Code Parameters for the NEPTUN Boil-Off Tests

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1. Introduction

An intermediate-break loss of coolant accident (IB LOCA) is being considered as a new design basis accident to replace the conventional large-break LOCA [1]. For this purpose, phenomena identification and ranking table (PIRT) was developed for the IB LOCA. For the licensing of the new design basis accident, validation of the SPACE code is required against the key IB LOCA phenomena identified through the PIRT. As part of this effort, the SPACE code was validated against the NEPTUN boil-off tests, which address the boil-off behavior identified as one of the key phenomena for the IB LOCA [1].

In the present study, uncertainty analysis was also performed to account for the propagation of uncertainties in physical models, empirical correlations, and input parameters to the predicted results. Quantifying these uncertainties provides confidence bounds for the predictions and supports a reliable assessment of the code's predictive capability.

2. NEPTUN Boil-Off Tests

NEPTUN boil-off tests were performed to investigate the decrease in mixture level and the resulting heat-up of the fuel rods under small-break and intermediate-break LOCA conditions. The test parameters included bundle power, system pressure, and initial coolant subcooling [2].

NEPTUN boil-off tests were used to validate and improve interfacial friction and steam cooling heat transfer models in various system analysis codes such as TRAC-BD1/MOD1 and RELAP5/MOD2 [3].

The test bundle of the NEPTUN facility consisted of 33 electrically heated rods and four unheated guide-tubes as shown in Fig. 1. The heater rods, with a heated length of 1,680 mm, had a chopped cosine axial power profile. Three experimental cases from the NEPTUN boil-off test series were simulated using the SPACE code, and their test conditions are summarized in Table I.

Table I: Test conditions for the selected boil-off tests

Experimental number	5006	5007	5008
Bundle power (kW)	42.1	24.6	10.5
Pressure (MPa)	0.5	0.5	0.5
Initial coolant temperature (°C)	140	140	140

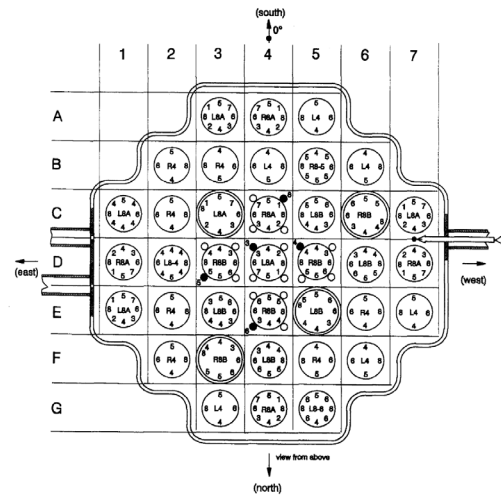


Fig. 1. Cross-sectional diagram of the NEPTUN test facility [2]

3. SPACE Code Modeling

Figure 2 shows the SPACE nodalization and heat-structure models developed to simulate the NEPTUN test facility, including the electrically heated rods, guide tubes, and spacer grids. The heater rods and guide tubes were modeled as a rod bundle consisting of 21 axial cells. Owing to insufficient information on the facility geometry and the corresponding experimental data, the heat structure of the test-section housing and heat losses from the test section to the environment were neglected in the SPACE model. The measured wall temperature distributions of the heated rods, guide tubes, and steam inside the test section at the onset of boil-off, together with the fluid temperature at the test-section inlet and the system pressure, were specified as the initial conditions for the SPACE calculations.

4. Sensitivity Analysis of Uncertainty Parameters

To quantify the model uncertainty of the SPACE code for the boil-off phenomenon under IBLOCA conditions, inverse uncertainty quantification (inverse UQ) should be performed for all SPACE model parameters associated with the phenomenon. However, when a large number of relevant parameters are considered, inverse UQ can become computationally prohibitive. It is therefore desirable to first identify the parameters that significantly affect the boil-off

phenomenon through sensitivity analysis, reduce the number of parameters, and then perform inverse UQ.

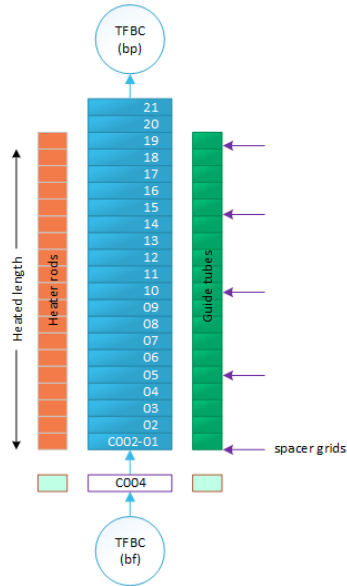


Fig. 2. SPACE model of the NEPTUN test facility

The sensitivities of the parameters affecting the boil-off phenomenon were evaluated using the Morris method [4]. Compared with variance-based methods that evaluate combinations of input parameters, the Morris method can screen a large number of parameters with substantially fewer model evaluations. It can also provide indirect information on nonlinear effects and interactions among the parameters. Parameters with negligible influence can be eliminated based on the Morris analysis, and the model uncertainty of the SPACE code will subsequently be estimated through inverse UQ using the identified influential parameters.

The Morris method is a global sensitivity analysis technique that efficiently screens influential model parameters for computationally expensive system analysis codes [4]. It discretizes the input-parameter space and repeatedly generates one-at-a-time (OAT) trajectories, in which only one parameter is varied at each step. Consequently, it can capture nonlinear effects and parameter interactions across a broader region of the input space than local sensitivity analysis conducted at a single reference point.

By rapidly screening out parameters with negligible influence using relatively few model evaluations, the Morris method reduces the dimensionality and computational cost of subsequent detailed uncertainty analyses, such as Monte Carlo or Sobol analyses.

A total of 36 uncertainty parameters were selected for the sensitivity analysis of the SPACE code for the boil-off phenomenon. Existing uncertainty values were used for parameters with available uncertainty information. For the remaining parameters, whose uncertainties were unknown, a uniform distribution ranging from 0.5 to 1.5 was assumed for the sensitivity analysis.

In the Morris sensitivity analysis, the modified mean, μ^* , represents the overall influence of an input variable on the model output, irrespective of the direction of its effect. The standard deviation, σ , indicates the variability of the elementary effects and is commonly interpreted as evidence of nonlinear behavior and/or interactions with other input variables. Thus, a large μ^* identifies an influential input, whereas a large σ suggests that its effect varies across the input space.

The Morris sensitivity analysis was performed using the in-house sensitivity analysis code Ourovoros, version 0.24.2 [5]. The influential uncertainty parameters identified through the Morris sensitivity analysis are listed in Table II. Figure 3 shows the importance ranking of the uncertainty parameters, whereas Fig. 4 presents their modified means and standard deviation for the heater-rod wall temperature at an elevation of 0.978 m above the bottom of the heated section in the NEPTUN boil-off Test 5007.

The vertical dashed line in Fig. 3 indicates a value corresponding to 1% of the maximum mean absolute elementary effect. Although the sensitivity rankings varied slightly depending on the collapsed liquid level and wall-temperature measurement location, the parameters listed in Table II were generally identified as influential in predicting the NEPTUN boil-off tests.

The sensitivity analysis identified the Bestion drift-flux model as the most influential parameter, while the other influential parameters were primarily associated with nucleate-boiling heat transfer.

Figure 5 shows the 95% confidence band for the predicted wall temperature at an elevation of 0.978 m. The median SPACE code prediction overestimated the measured wall temperature.

Inverse uncertainty quantification will be performed for the influential parameters identified through the Morris sensitivity analysis and listed in Table II. The analysis will be conducted using the PAPIRUS code [6] to quantify the uncertainties in the key parameters of the SPACE code for the NEPTUN boil-off tests.

Table II: Influential uncertainty parameters

Name	Parameter description
dbliq	Dittus-Boelter heat-transfer coefficient for the liquid phase
dbvap	Dittus-Boelter heat-transfer coefficient for the vapor phase
chenmac	Convective component of the Chen nucleate-boiling heat-transfer correlation
chenmic	Boiling component of the Chen nucleate-boiling heat-transfer correlation
pumpf	Pumping factor
Hcrit	Critical enthalpy
Ncmix	Natural convection
best	Bestion drift-flux model

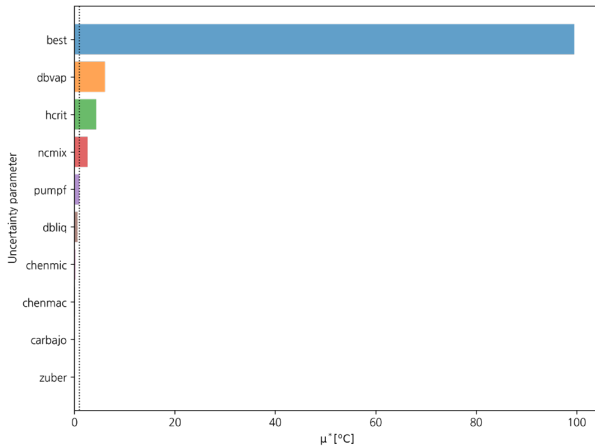


Fig. 3. Importance ranking of the uncertainty parameters

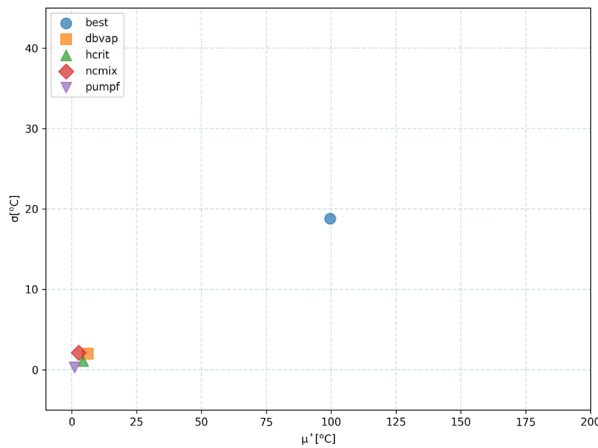


Fig. 4. Modified means and standard deviations of the uncertainty parameters

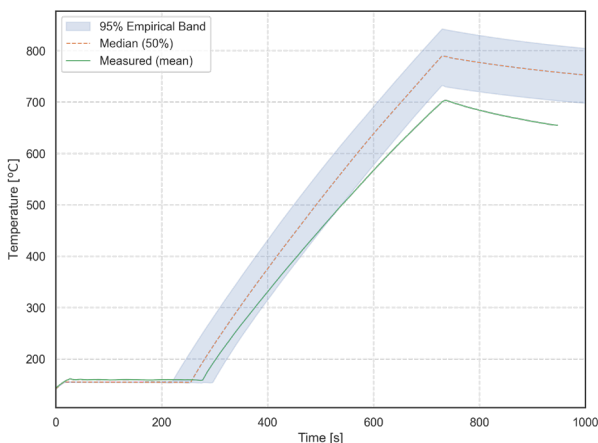


Fig. 5. 95% confidence band for the predicted wall temperature

5. Conclusions and Further Work

A sensitivity analysis of the uncertainty parameters using the SPACE code was carried out for the NEPTUN boil-off tests under IB LOCA conditions. The Bestion drift-flux model was identified as one of

the most influential parameter. The parameters related to nucleate-boiling heat transfer were also identified as influential for the boil-off phenomena.

Inverse uncertainty quantification will be performed for the influential parameters identified through the Morris sensitivity analysis. The PAPIRUS code will be used to quantify the uncertainties of the key parameters of the SPACE code for the NEPTUN boil-off tests.

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