Uncertainty Quantification of the IBLOCA LSTF Test No.1 Based on the SAPIUM guideline

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ABSTRACT

This study was conducted under the OECD/NEA ATRIUM program to evaluate and improve the SAPIUM UQ guideline. Focusing on critical flow and post-CHF phenomena in an IBLOCA scenario, uncertainty quantification (UQ) was performed for LSTF Test No. 1 (IET). Following the SAPIUM Guideline, validation databases were established and classified for inverse uncertainty quantification (IUQ) and validation. Key input parameters for each phenomenon were identified, and their uncertainties were determined through IUQ and verified via validation analyses. The UQ for LSTF Test No. 1 was executed in three steps: 1) considering only the two selected phenomena; 2) adding uncertainties in initial/boundary conditions, geometry, and material properties; and 3) incorporating core radial power distribution and CCFL. Results showed that while including more contributors improved experimental data coverage, the second-step factors had a negligible impact on PCT. Instead, CCFL and power distribution were confirmed as primary contributors. This study provides a technical basis for developing future IBLOCA safety analysis methodologies based on the SAPIUM framework.

Keywords: *Uncertainty quantification, IBLOCA, LSTF, ATRIUM, SAPIUM*

1 INTRODUCTION

Over the past few decades, Best Estimate Plus Uncertainty (BEPU) methodologies have been extensively developed for nuclear power plant (NPP) safety analysis under the framework of the OECD/NEA. In this context, systematic approaches for quantifying and managing uncertainties have become increasingly important to improve the reliability and credibility of simulation results. As part of these efforts, the ATRIUM (Application Tests for Realization of Inverse Uncertainty Quantification and Validation Methodologies in Thermal-Hydraulics) project was proposed in 2022 and completed in 2025 [1]. The primary objective of the ATRIUM project is to perform a practical inverse uncertainty quantification (IUQ) exercise to demonstrate the applicability of the SAPIUM (Systematic Approach for Input Uncertainty Quantification Methodology, OECD/NEA-2020) framework. Specifically, the project aims to (i) demonstrate best practices for input uncertainty quantification, (ii) address existing open issues while identifying potential new challenges, and (iii) summarize lessons learned from participating organizations to support the refinement of current recommendations. In this framework, the SPACE code team participated using the SPACE system thermal-hydraulic code coupled with PAPIRUS, an uncertainty quantification tool.

2 ATRIUM PROJECT

In the ATRIUM project, an intermediate-break loss-of-coolant accident (IBLOCA) scenario was selected as the reference problem. Two dominant physical phenomena associated with IBLOCA—critical flow and post-critical heat flux (post-CHF) heat transfer—were identified as key contributors to the system response. To ensure a systematic and transparent analysis, each phenomenon was treated as an independent exercise using dedicated experimental databases. This stepwise and progressive approach enables the structured investigation of key thermal-hydraulic phenomena and facilitates the consistent application of best practices recommended in the SAPIUM (Systematic APproach for Input Uncertainty quantification Methodology) guideline. Ultimately, the quantified input model uncertainties are propagated to an integral effect test (IET), specifically the OECD/NEA ROSA-2 Project Large Scale Test Facility (LSTF) Intermediate-Break Hot-Leg Test IB-HL-01, thereby demonstrating the applicability of the IUQ framework in a realistic system-level analysis.1

2.1 SAPIUM Guideline

Figure 1 illustrates the SAPIUM framework [2] and its logical operational sequence, where each stage comprises structured sub-steps. Element 1 involves identifying and defining the target scenario within the activity definition scope. In Element 2, an experimental database for the selected phenomenon is established and systematically evaluated; this includes an adequacy analysis to ensure data representativeness for uncertainty quantification (UQ). This database is subsequently partitioned into two subsets for UQ (Element 4) and validation (Element 5), respectively. Simultaneously, Element 3 focuses on selecting a simulation code and assessing its capability to represent the target phenomenon, specifically considering physical models, geometric fidelity, and nodalization strategies. In Element 4, model input uncertainties are quantified via inverse UQ methodologies, such as Bayesian inference, frequentist approaches, and data assimilation. Finally, Element 5 performs forward uncertainty propagation, where the updated input uncertainties are applied to the validation database to evaluate model predictability and experimental coverage.

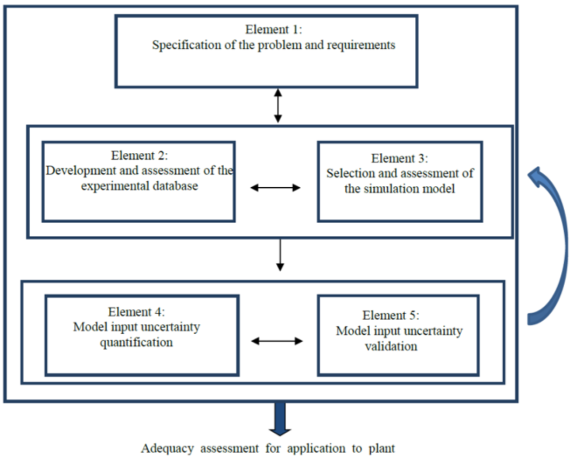


Figure 1: Major Elements of the SAPIUM Guideline [2]

2.2 Exercise 1: IUQ for Critical flow

Exercise 1 focuses on critical flow, for which the critical mass flow rate is defined as the Figure of Merit (FoM). In this study, the modified Henry–Fauske critical flow model implemented in the SPACE code was employed. Based on the SAPIUM guideline, the critical flow model in

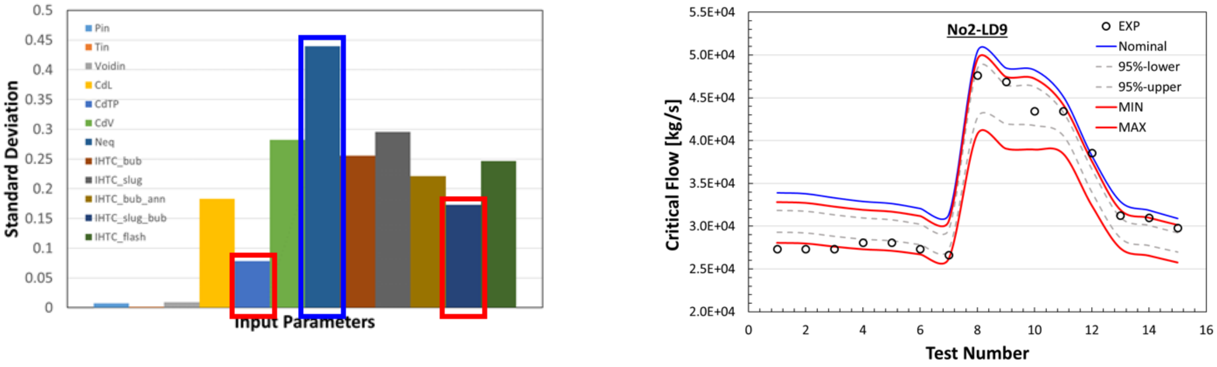
SPACE code is appropriate to evaluate discharge flow and depressurization during the IBLOCA scenario.

Table 1: Summary of the Exercise 1 Experimental Database (ED)

Experiment	Test type	D [mm]	L/D [-]	No. Tests	Pin [bar]	Xin [-]	G [kg/m^{2}s]
Sozzi-Sutherland	N2	12.7	0-140	358	56.0-71.3	-0.0044-0.00065	17528-75824
	N3	12.7	0	58	42.7-69.0	-0.0059-0.006	33161-61226
	N4	19	0	23	56.0-66.3	-0.0003-0.0099	29295-51266
SMD	Div.	20.13	18	27	20.0-120.1	< 0	15300-62200
	Exp.	20	20	12	20.0-120.1	< 0	16100-61800
Marviken	13	200	3	1	~50 (transient)	< 0	<89200
	17	300	3.7	1			<61700
	24	500	0.33	1			<59750
LSTF	**No.1**	**41**	**12**	**1-**	**10-155**	**-0.15-0.005**	**1500-46000**

The experimental database (ED) used for this exercise consists of a wide range of critical flow experiments, including the Sozzi–Sutherland tests with three different nozzles and various L/D ratios [3], the Super Moby-Dick (Super SMD) experiments with divergent and expanded nozzles [4], and the transient Marviken tests No. 13, 17, and 24 [5], as summarized in Table 1. An adequacy analysis was performed to evaluate the suitability of the data, and the database was subsequently divided into subsets for uncertainty quantification and validation.

A total of twelve input parameters were selected, including boundary conditions (outlet pressure, inlet temperature, and void fraction), three discharge coefficients, and a non-equilibrium factor. Inverse uncertainty quantification (IUQ) was performed using a Bayesian inference approach with a Markov Chain Monte Carlo (MCMC) method, generating a total of 2,000 samples [6]. Figure 2 shows the standard deviations of the input parameters, highlighting that the two-phase discharge coefficient is the most influential. Representative IUQ results are shown in Figure 3 for the Sozzi–Sutherland nozzle (L/D = 9), demonstrating reasonable agreement and coverage of the experimental data.



(a) STD of input parameters

(b) IUQ results for Sozzi-Sutherland No.2

Figure 2: Representative Results of Exercise 1

2.3 Exercise 2: IUQ for PostCHF

Exercise 2 addresses post-critical heat flux (post-CHF) heat transfer, with cladding temperature selected as the Figure of Merit (FoM). The experimental database (ED) was evaluated using the adequacy analysis methodology [7], and the selected datasets are summarized in Table 2.

The database includes the Becker tests with three different test sections [9], the Stewart tests [10], and the Thermal-Hydraulic Test Facility (THTF) uncovered-bundle and film-boiling tests [11].

Table 2: Summary of the Exercise 2 ED [7]

ED	Type	No. tests	P [bar]	G [kg/m^{2}s]	q” [W/m^2]	$T_{sub,in}$[K]
Baker T/S 1	Tube	281	30-200	500-3000	100-1250	10
Baker T/S 2	Tube	102	30-200	500-3000	90-850	10
Baker T/S 3	Tube	38	150-200	780-2475	290-940	5-10
Stewart	Tube	312	20-90	115-2833	65-460	9-56
THTF Film Boiling	Rod Bundle	22	40-130	226-806	320-940	8-46
THTF Uncovered Bundle	Rod Bundle	6	40-75	3-30	74-480	46-103
LSTF	**Rod Bundle**	**1**	**20-50**	**0-600**	**500-2000**	**0**

The Stewart tests were excluded from the adequacy analysis due to their quasi-steady-state conditions, which the SPACE code cannot accurately simulate. In contrast, the THTF experiments, characterized by rod-bundle geometries, necessitated specialized modelling approaches—specifically the integration of interfacial drag and grid-spacer models. As illustrated in Figure 3, the inclusion of grid-spacer sub-models significantly enhances prediction accuracy for THTF film-boiling tests, particularly at the locations indicated by the green lines. This underscores the critical role of grid-spacer modeling in post-CHF heat transfer analysis. Regarding the uncertainty quantification, twenty input parameters—encompassing interfacial drag, various flow regime heat transfers, and wall heat transfer coefficients—were selected. Following the same inverse uncertainty quantification (IUQ) methodology as Exercise 1, the standard deviations of these parameters were analyzed (Figure 4). The results identify the saturated film-boiling heat transfer coefficient as the primary contributor to the overall uncertainty [8].

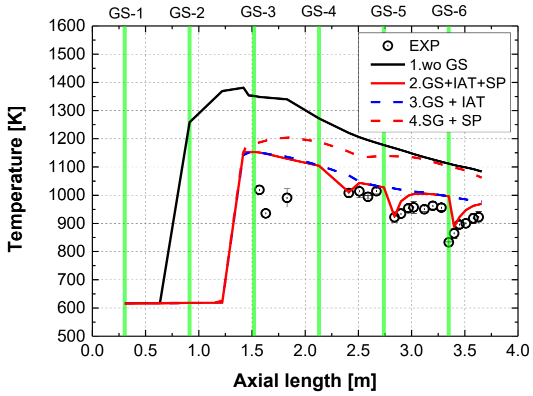
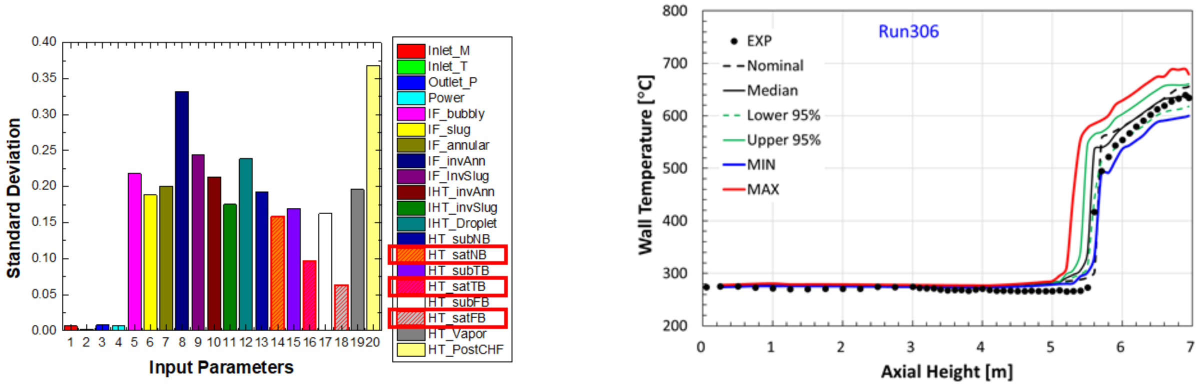


Figure 3: Clad temperature of THTF Film Boiling Test (run B) with Different Grid Spacer Model Options.



(a) STD of input parameters (b) IUQ results for Becker Test No.2 (run306)

Figure 4: Representative Results of Exercise 2

3 EXERCISE 3: UQ FOR LSTF

Exercise 3 involves validation calculations for the LSTF Test No. 1 (IB-HL-01), utilizing the updated input uncertainties derived from Exercises 1 and 2. This test simulates an intermediate-break loss-of-coolant accident (IBLOCA) initiated by a double-ended guillotine break of the pressurizer surge line connected to the hot leg. The scenario incorporates the assumed failure of both the high-pressure safety injection (HPSI) and auxiliary feedwater systems, alongside a loss of off-site power (LOOP) triggered by the reactor scram [12].

3.1 Modeling of LSTF Test No. 1 (IB-HL-01)

Figure 5 presents the nodalization scheme of the LSTF facility for the SPACE code. A total of twenty input parameters, excluding boundary conditions, were considered. To systematically investigate the impact of additional uncertainties, a stepwise approach was adopted: Step 1 includes the original twenty parameters, Step 2 incorporates additional uncertainties related to initial conditions and material properties, and Step 3 further accounts for additional phenomena such as counter-current flow limitation (CCFL) and radial power distribution. Several Figures of Merit (FoMs) were evaluated, including break mass flow rate, break density, core water level, and peak cladding temperature (PCT), as shown in Table 3.

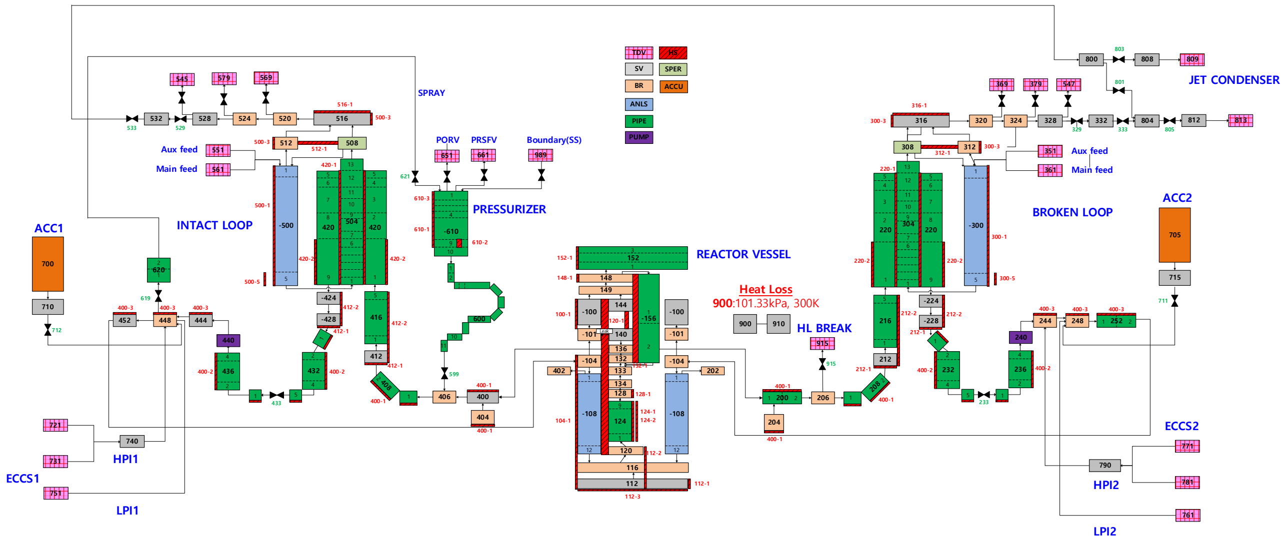
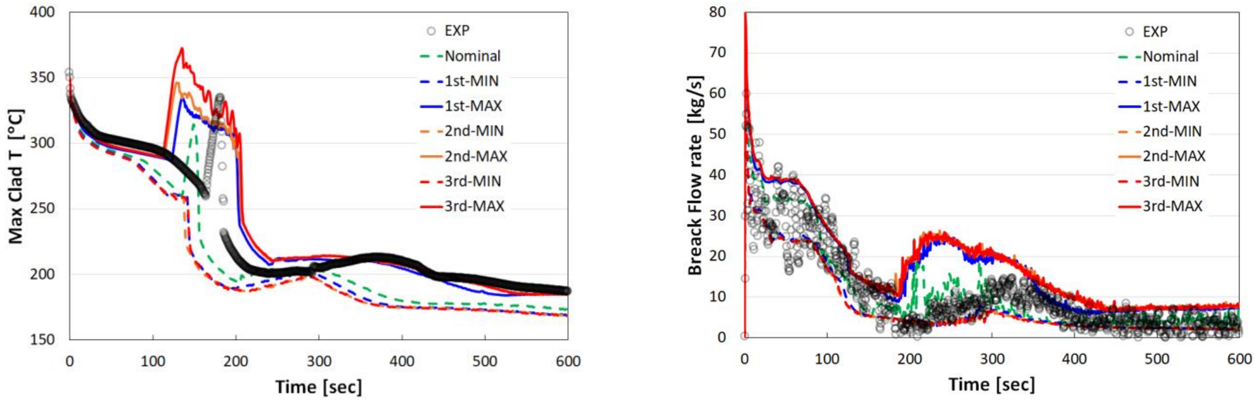


Figure 5: Nodalization of LSTF Test no.1 for SPACE code

3.2 Uncertainty Quantification with 3 Steps

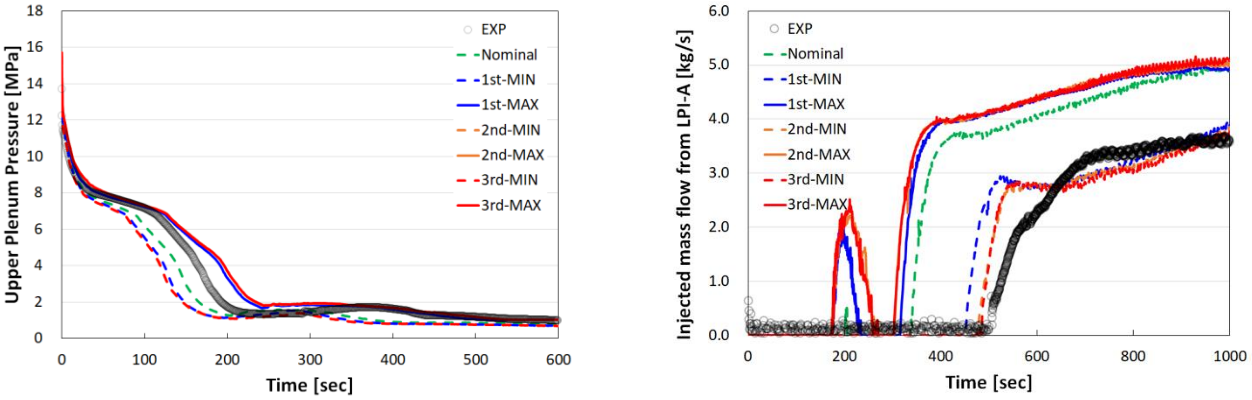
The transient is characterized by an initial rapid depressurization of the primary system, followed by a reactor scram and a subsequent loss of off-site power. As the primary pressure declines, various safety systems—excluding the high-pressure injection—are activated. The cladding temperature continues to rise until the coolant enters the core via the accumulator injection. Key physical phenomena for IBLOCA observed during the test include critical flow, depressurization, phase separation, Loop Seal Clearing (LSC), the formation of a natural circulation loop, the occurrence of Counter-Current Flow Limitation (CCFL) at upper plenum, the steam generator U-tubes and the hot leg, and the eventual recovery of the core inventory via low-pressure safety injection (LPSI).

Figure 6 shows the major transient results of the LSTF test, comparing the forward uncertainty propagation across the three successive stages from Step 1 to Step 3. The major transient variables generally align well with experimental observations, with the calculated uncertainty bands successfully enveloping the measured data. Notably, the input uncertainties introduced in Step 3 exerted a more significant influence on the Peak Cladding Temperature (PCT) than the progression from Step 1 to Step 2, underscoring the dominant effects of CCFL and power distribution on PCT behaviour. The primary system pressure in the long term is underpredicted and remains outside the uncertainty coverage, as shown in Figure 6(c). Consequently, this led to the earlier injection of the LPSI than the experiments (Figure 6-d). Table 3 summarizes the coverage of the Figures of Merit (FoMs) across the three uncertainty quantification stages. In Step 1, the break mass flow rate and PCT elevation were overpredicted, while the break density and low-pressure safety injection (LPSI) initiation time were underpredicted. Step 2 showed improved system pressure prediction, and Step 3 further enhanced the accuracy of the PCT results. However, the break mass flow rate, density, and LPSI initiation time remained outside the uncertainty coverage. The premature LPSI initiation is attributed to the underprediction of primary system pressure, whereas the underpredicted break density is linked to an overestimation of the vapor fraction. These findings suggest that further model refinements are necessary to achieve adequate coverage for these FoMs.



(a) Peak cladding temperature

(b) Break flow rate



(c) Upper plenum pressure (d) Integrated flow rate from LPI A

Figure 6: Major results of uncertainty quantification of LSTF test no.1

Table 3: Result of percentile for the FoMs with different Steps

No.	**FoMs**	**Percentile [%]**		
		Step 1	**Step 2**	**Step3**
1	Int_mass_break_20s	Lower outlier	Lower outlier	Lower outlier
2	Int_mass_break_90s	42.43	31.52	31.95
3	Int_mass_break_180s	97.92	97.17	97.31
4	Max_break	5.80	5.57	5.52
5	Break_density	Upper outlier	Upper outlier	Upper outlier
6	HL_B_level	41.48	71.12	73.62
7	PCT	99.95	99.58	93.82
8	Min_core_level	28.17	26.66	28.36
9	Time_min_core_level	53.04	55.36	54.03
10	PCT_elevation	Lower outlier	Lower outlier	0.33
11	Time_CHF_appear	58.47	69.80	70.03
12	Duration_core_uncover	17.37	24.02	21.76
13	Time_complete_quench	73.24	80.65	78.86
14	Time_PCT	75.18	81.60	79.94
15	Time_Acc_starts	38.04	53.61	53.23
16	Time_Acc_A_ends	11.80	10.10	10.29
17	Time_Acc_B_ends	0.42	0.14	0.09
18	Time_Pr_below_SG_pres	Upper outlier	99.76	99.72
19	Time_LPSI_starts	Upper outlier	Upper outlier	Upper outlier
20	Time_LS_clear_A	44.22	62.81	63.57
21	Time_LS_clear_B	42.33	59.41	60.45

4 CONCLUSION

This study performed uncertainty quantification (UQ) for an Intermediate Break Loss of Coolant Accident (IBLOCA) scenario as part of the OECD/NEA ATRIUM international joint research project, adhering to the SAPIUM methodology. Two key phenomena—critical flow (Exercise 1) and Post-CHF (Exercise 2)—were selected, and an adequate experimental database was established by the adequacy analysis of candidates. Inverse Uncertainty Quantification (IUQ) was subsequently conducted for the primary input parameters based on the selected ED, enabling the re-evaluation of parameter uncertainties and the identification of dominant contributing factors.

The uncertainty distributions derived from these core phenomena were applied to LSTF Test No. 1, an Integral Effect Test (IET) simulating an IBLOCA scenario. The assessment was executed in three sequential steps, incorporating uncertainties from fundamental input parameters, boundary conditions, and material properties, alongside critical phenomena such as Counter-Current Flow Limitation (CCFL) and radial power distribution. The results validated the effectiveness of the SAPIUM methodology and reaffirmed the significance of CCFL as a pivotal factor in IBLOCA transients. Given that the Korean safety analysis framework is currently shifting toward designating IBLOCA as a Design Basis Accident (DBA), the experience gained through the ATRIUM project and the SAPIUM methodology is expected to provide a vital technical foundation for national Best-Estimate (BE) safety analysis initiatives.

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