DEVELOPMENT AND ASSESSMENT OF A METHOD FOR EVALUATING UNCERTAINTY OF INPUT PARAMETERS

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ABSTRACT

Best-Estimate plus Uncertainty Evaluation methods are gaining increased interest in the licensing process. Besides, lessons learnt from the OECD/NEA BEMUSE benchmark and other projects show that improvements of the present methods are necessary. In particular, methods to properly estimate input parameter uncertainties need to be developed and assessed.

An Input Parameter Range Evaluation Methodology (IPREM) has been proposed and developed at University of Pisa for the quantification of the variation ranges of the input parameters through comparison of sensitivity calculations results of a selected system thermal-hydraulic code with experimental data, utilizing the mathematical apparatus of the FFTBM (Fast Fourier Transform based method). Within the framework of OECD/NEA PREMIUM benchmark, IPREM has been applied to the quantification of the uncertainty of the RELAP5 code models related to the simulation of reflood phenomena.

Calculations of an experimental test of FEBA facility (KIT, Germany) have been performed with RELAP5 Mod3.3 code and the uncertainties of reflood-influential models (e.g. wall-to-fluid heat transfer) were quantified. The obtained model uncertainties were verified by performing blind calculations of various tests from FEBA and PERICLES test facilities, performing the uncertainty analysis of obtained results and verifying that the uncertainty band envelopes the experimental data. Within EC-funded NURESAFE project same methodology has been applied to quantify uncertainty of reflood-related models of CATHARE2 code and obtained ranges have been verified against experimental data of FEBA and ACHILLES facilities.

Comparison of the RELAP5 and CATHARE2 calculated results with the FEBA, PERICLES and ACHILLES test data shows that the uncertainty bands envelope the experimental data in the majority of the measurement points. This supports the validity of obtained ranges of reflood-related models of RELAP5 and CATHARE2 codes. Based on the selected validation matrix, the IPREM has proved to be test, facility and code independent.

KEYWORDS
UNCERTAINTY, REFLOOD, RELAP, CATHARE, PREMIUM

1. INTRODUCTION

The IAEA Safety Guide on safety assessment offers two acceptable options for demonstrating safety of nuclear reactor system, namely the use of best-estimate (BE) computer codes combined with conservative input data or combined with realistic input data [1]. Both of these options include evaluation of the uncertainties of results. The second option is particularly attractive because it allows for a more precise specification of safety margins and thus leads to greater operational flexibility.

Best-Estimate plus Uncertainty Evaluation (BEPU) methods are gaining increased interest in the licensing process. In recent years, various methods for the treatment of uncertainty have been proposed and developed for realistic calculations of different scenarios (e.g. LOCA). Among most applied approaches for evaluation of uncertainty of thermal-hydraulic calculations the following should be mentioned [2]:

- Input error propagation method [3];
- Output error propagation method [4];
- Methods based on Adjoint Sensitivity Analysis Procedure [5].

These approaches use different techniques and procedures to obtain the uncertainties on key calculated quantities. In this paper we will focus on Input Error Propagation methods and we will address one of the highly important questions: how to quantify the uncertainty connected with the input parameters. The propagation of code input errors may be considered as one of the most adopted procedures nowadays, endorsed by industry and regulators. It is based on the statistical combination of values from selected input uncertainty parameters to calculate the propagation of the errors throughout the evaluation model.

The lessons learnt from various international benchmarks on BEPU application to safety analysis (e.g. BEMUSE) showed that one among the most important steps in applying a statistical method is the determination of ranges and distributions of the uncertain input parameters [6]. The important parameters have significant influence on the uncertainty ranges of the results. Therefore, improvements of the present methods are necessary, especially developing methods to properly estimate input parameter uncertainties.

The partial objective of OECD/NEA Post-BEMUSE Reflood Model Input Uncertainty Methods (PREMIUM) benchmark and NURESAFE project is to progress on the issue of the quantification of the uncertainty of the physical models in system thermal-hydraulic codes by considering a specific case: core reflooding. Within the framework of these international activities, the Input Parameter Range Evaluation Methodology (“IPREM”) has been established, developed [7] and applied to quantify the ranges of variation of reflood-related models of RELAP5 Mod3.3 and CATHARE2 V2.5_3 Mod3.1 system thermal-hydraulic codes. This paper provides the description and the results of reflood-related models of these codes and their further validation by an uncertainty analysis of calculated separate effect experimental tests.

2. INPUT PARAMETER RANGE EVALUATION METHODOLOGY

2.1. The FFTBM tool

The Fast Fourier Transform Based Method (FFTBM) has been originally developed to quantify the accuracy of a given code calculation [8]. With FFTBM, the quantification of the accuracy of code calculations is performed using amplitude of the Fourier Transform of the experimental signal and of the difference between this one and the calculated trend. Therefore, the comparison between experimental data and calculation results is performed in frequency domain, eliminating the dependence of the method on time duration of experiment and shape of analyzed time trends. The FFTBM tool itself has been validated and applied in the numerous international benchmarks [9].

The Fourier transform can translate a given time function *g(t)*, in a corresponding complex function defined, in the frequency domain, by the Equation (1):

$$\tilde{g}(f) = \int_{-\infty}^{+\infty} g(t) * e^{-j*2\pi*f*t} dt \tag{1}$$

Since Fourier integral is not suitable for machine computation, a discrete Fourier transform is evaluated. When using functions sampled in digital form, the Fast Fourier Transform (FFT) can be used. The accuracy quantification of a code calculation considers the amplitude, in the frequency domain, of the experimental signal $F_{exp}(t)$ and the error function (Equation (2)):

$$\Delta F(t) = F_{calc}(t) - F_{exp}(t) \tag{2}$$

Applying FFT to both $\Delta F(t)$ and $F_{exp}(t)$, a dimensionless figure-of-merit can be calculated – Average Amplitude (**AA**), see Equation (3):

$$AA = \sum_{n=0}^{2^m} |\tilde{\Delta}F(f_n)| \Big/ \sum_{n=0}^{2^m} |\tilde{\Delta}F_{exp}(f_n)| \tag{3}$$

The Average Amplitude (**AA**) represents the relative magnitude of the discrepancy deriving from the comparison between the addressed calculation and the corresponding experimental trend: the lower is the AA – the better is agreement between the experiment and calculation. Therefore, the accuracy of a calculation with respect to experiment can be quantified by applying the FFTBM to relevant thermal-hydraulic responses (output parameters).

2.2. Description of IPREM

The feature of FFTBM to provide a quantitative evaluation of the accuracy of a time-dependent code output parameter with respect to experimental data has been used to establish a methodology for quantifying the ranges of variation of input parameters. The methodology has been defined as Input Parameter Range Evaluation Methodology (IPREM) and it is characterized by the following steps outlined on the flowchart of Fig. 1.

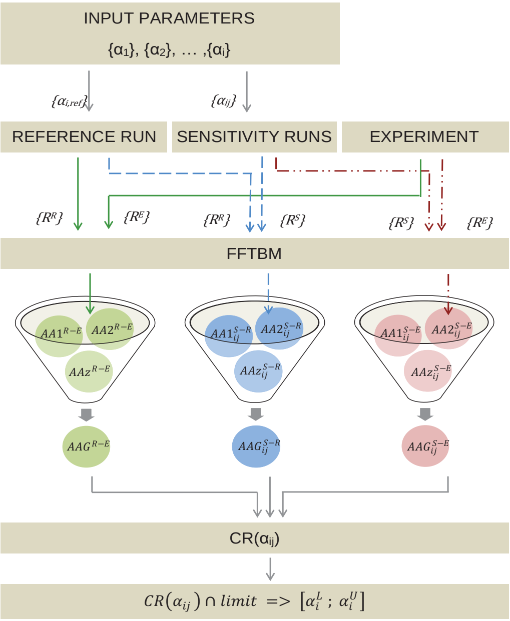


Figure 1. Flowchart of IPREM.

The quantification of variation ranges of input parameters for physical models is achieved through running the calculations of reference case of a physical model and “sensitivity” cases, constituted by a single-parameter variation, application of the FFTBM for quantification of the accuracy of calculated responses respect to experimental data and further comparison of differences between **AA** values obtained from sensitivity cases and an **AA** of the reference case.

The relevant thermal-hydraulic parameters that describe the phenomena of interest should be selected as responses $\{R^R\}$, e.g. cladding temperature and quench front propagation are the representative code output parameters for the selected reflood phenomenon. The reliable and rather precise experimental measurements $\{R^E\}$ must be available for the responses of interest. The list of studied input parameters $\{\alpha_i\}$ should be established. A preliminary sensitivity analysis may be applied to identify those parameters that are influential to the selected responses.

For each i-th input parameter of interest a number of **j** calculations must be performed, by varying only the i-th parameter. As a results, each response Rz^S has $i \times j$ time trend results $\{R_{ij}^S\}$, e.g. in case of selection of 3 responses (z = 1,2,3): $[R1_{ij}^S;\ R2_{ij}^S;\ R3_{ij}^S]$.

Two FFTBM analyses must be performed for each j-th sensitivity run of each i-th input parameter:

- “Sensitivity calculation – Experiment data” pair (i.e. $\{R_{ij}^S\}$ vs $\{R^E\}$);
- “Sensitivity calculation – Reference calculation” pair (i.e. $\{R_{ij}^S\}$ vs $\{R^R\}$).

As a result, the analyst obtains 2 sets of **AA** for each j-th sensitivity run of each i-th input parameter:

- AAz_{ij}^{S-R} that quantifies the “deviation” of sensitivity run from reference case;
- AAz_{ij}^{S-E} that quantifies the “accuracy” of sensitivity run with respect to experimental data;

where **z** is the consecutive number of a response. For example, in case of 3 responses it would be:

- $[AA1_{ij};\ AA2_{ij};\ AA3_{ij}]^{S-R}$;
- $[AA1_{ij};\ AA2_{ij};\ AA3_{ij}]^{S-E}$.

Hence, the set of AAz_{ij} values is available for each selected response for each j-th sensitivity run of each i-th input parameter. Next step is performed in order to produce a single Figure-of-Merit that allows to:

- Quantify the sensitivity of entire nodalization to the input parameter variation;
- Quantify the accuracy of entire nodalization performance in each sensitivity run with respect to experimental data.

This is achieved by calculation of a Global AA (**AAG**) for each of 2 sets of AAz_{ij} derived from j-th sensitivity run of i-th input parameter (Equation (4)):

$$\mathrm{AAG} = \sum_{\mathrm{z}} \mathrm{w_z AA_z} \tag{4}$$

where $\mathbf{w_z}$ is the weighting factor assigned for each type of response. The weighting factors are determined by the type of thermal-hydraulic parameter selected as a response. A proposed set of weighting factors (Table 1) has been developed for “intermediate” experimental tests on the basis of weighting factors used in original FFTBM procedure for evaluation of code calculation accuracy [8]. After the weights are selected and assigned to the AAz_{ij} of corresponding responses, they are normalized (Equation (5)):

$$w_z = \frac{W_z}{\sum_{i=1}^{Nz} W_i} \tag{5}$$

Once the AAG values are calculated for each j-th value of input parameter $\boldsymbol{\alpha_i}$, the empirically established criterion quantity $\mathbf{CR}(\boldsymbol{\alpha_{ij}})$ is defined by Equation (6) [10]. The obtained dependence $\mathbf{CR}(\boldsymbol{\alpha_{ij}})$ is convenient to analyze in graphical mode. A typical trend obtained for 1 input parameter is shown on the Fig. 2.

$$\mathrm{CR}(\alpha_{ij}) = \frac{\mathrm{AAG}^{\mathrm{S-E}}(\alpha_{ij}) + \mathrm{AAG}^{\mathrm{S-R}}(\alpha_{ij}) - \mathrm{AAG}^{\mathrm{R-E}}}{\left(1 - \mathrm{AAG}^{\mathrm{S-E}}(\alpha_{ij})\right)} \tag{6}$$

In Equation (6) the following constituents are included:

- $\mathrm{AAG}^{\mathrm{S-E}} + \mathrm{AAG}^{\mathrm{S-R}}$ is a measure of the total “deviation” of a sensitivity calculation from both the reference calculation and the experimental data;
- $\mathrm{AAG}^{\mathrm{R-E}}$ is calculated from the comparison of reference calculation an experimental data;
- $(1 - \mathrm{AAG}^{\mathrm{S-E}})$ “slows” the increase of CR if the change of an input parameter leads to improvement of results with respect to experiment.

As a last step, the variation ranges of each parameter $\boldsymbol{\alpha}$ are quantified by applying the limiting value (threshold) to $\mathbf{CR}(\boldsymbol{\alpha})$. The lower and upper bounds of $\boldsymbol{\alpha}$ are defined by Equation (7):

$$[\alpha^{\mathrm{L}};\ \alpha^{\mathrm{U}}] = \mathrm{CR}(\alpha) \cap \mathrm{limit} \tag{7}$$

The limit value must be set once and consistently applied for all the analyses performed. The variation of this value is not allowed unless proper justification. In the present research a value of ***limit=0.22*** has been adopted [10]. The value of 0.22 is based on the consideration of the maximum allowed “deviation” of responses (at extremes of the range of input parameters) of 10% (AAG ≤ 1in the metrics of Average Amplitude) in the hypothetical case when reference calculation exactly matches the experimental data, as obtained in Equation (8) by assuming $AAG^{S-E} = AAG^{S-R}$ in Equation (6):

$$\mathrm{CR} = \frac{2\cdot\mathrm{AAG}}{(1-\mathrm{AAG})} \leq 0.22 \quad \Longleftrightarrow \quad \mathrm{AAG} \leq 0.1 \tag{8}$$

Table 1. Weighting factors for IPREM procedure

Parameter type	W_z
Primary pressure	1.000
Secondary pressure	0.660
Pressure drop	0.245
Mass Inventory	0.648
Flow rate	0.200
Fluid temperature	0.256
Cladding temperature	1.080
Level	0.432
Power	0.320
Quench front elevation	0.864

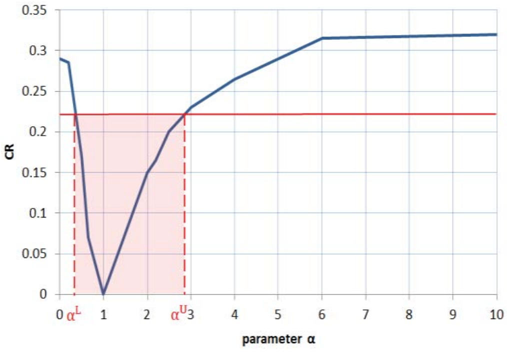


Figure 2. Sample trend of CR quantity.

2.3. Advantages and disadvantages of IPREM

The IPREM methodology proved to allow evaluation of input parameter uncertainty from a single “intermediate” experimental test. Though, the use of a number of other experimental test is required to validate the obtained ranges [α^L ; α^U]. This methodology does not depend on the applied thermal-hydraulic system code, as well as on the type of investigated input parameter and analyzed responses, since the procedure involves only post-processing of calculation results. In principle, it also does not require code modification for assessment of an input parameter uncertainty given access to a parameter of interest (e.g. CATHARE code and other system thermal-hydraulic and severe accident codes like MELCOR etc.). However, the proposed methodology is based on rather engineering considerations and previous experience from the application of FFTBM rather than on statistical methods. It does not take into account or provides as a result the Probability Density Function for each input parameter (adoption of uniform or likewise distributions is therefore suggested). The IPREM reduces the use of engineering judgment in terms that the proper procedure, mathematical apparatus and corresponding criteria are clearly defined. However, the choice of analyzed code responses may affect the resulting ranges of input parameters, and in some particular cases the CR(α) may not reach the limit value.

It should be also noted that the evaluated ranges of input parameters with IPREM correspond to default/reference values of these parameters. On the contrary, methods that are based on model calibration and Bayesian inference gives the input parameter uncertainties corresponding not to the default but calibrated values of parameters. However, industrial application of updated/calibrated values of code input parameters may not be accepted by national regulatory bodies which typically endorse the application of “frozen” versions of a code with non-altered models/correlations.

3. APPLICATION OF THE IPREM TO REFLOOD-RELATED MODELS

The proposed IPREM methodology has been applied in the framework of the OECD/NEA PREMIUM and EU NURESAFE projects. The primary objective was to demonstrate IPREM capabilities and to extend the methodology validation database to as many reflood tests as possible. Therefore, the evaluation of uncertainty of reflood-related input parameters has been performed using the experimental test 216 that was conducted in FEBA facility. Once the variation ranges are quantified, these results have been extensively validated against experimental tests of FEBA, PERICLES and ACHILLES facilities through uncertainty analysis of thermal-hydraulic calculations.

In the present study is considered only a ‘bottom-top’ reflood and the eventual ‘top-bottom’ effects at the top of rod bundle (due to injection into hot legs or a liquid fall-back from the separation devices installed above test section) are not considered. These components were not modeled and, consequently, the top-bottom reflood phenomenon was not represented to full extent. However, this does not affect the bottom-top quench front propagation for the major part of the assembly and, therefore, the discrepancies between predicted quench front elevation and experimental data at the top of fuel assembly may be neglected in the scope of the present analysis.

3.1. The reflood phenomena and the FEBA/SEFLEX Experiments

The FEBA (Flooding Experiments with Blocked Array) program has been performed at KfK Karlsruhe, Germany [11]. This Separate Effect Test Facility (SETF) was designed for the reflooding tests with possibility of maintaining constant flooding rates and constant back pressure. The test section consists of a full-length 5 x 5 rod bundle of PWR fuel rod dimensions (Fig. 3) utilizing electrically heated rods (Nichrome wire and cladding with magnesium oxide insulator inside) with a cosine power profile. The rod bundle is placed in housing made of stainless steel and insulated to reduce heat losses to environment.

3.2. Calculation of FEBA test 216 with RELAP5 and CATHARE2 codes

A 1-D nodalization for RELAP5 Mod3.3 code has been developed to model the FEBA test section. The model consists of the heated part of test section, lower and upper plena (Fig. 4). The heated part of the section has been modeled with 20 hydraulic nodes (with average length of 0.2 m). The heater rods are modeled with a single heat structure component with imposed power profile. Reflood and rod bundle without cross-flow options were activated for this heat structure. The housing is modeled with a heat structure isolated on the external side.

On the other hand, FEBA test assembly has been modelled by CATHARE2 V2.5_3 mod 3.1 code [12] by one single 1-D component representing the core bundle (heated part, 3900 mm) with only 1 heat rod element, inlet and outlet boundary conditions (Fig. 5). The 1-D component is composed of 39 vertical meshes in the core (length of 1 mesh is 0.1 m). The thick-wall housing is modelled (thickness is 6.5 mm), whereas unheated part of rods, lower and upper plenum are not modelled. The CATHARE reflood correlations (REFLCHAR) are used for both the heater rods to fluid and housing to fluid heat transfers. The thermal-hydraulic conditions of FEBA test 216 are presented in Table 5 [13].

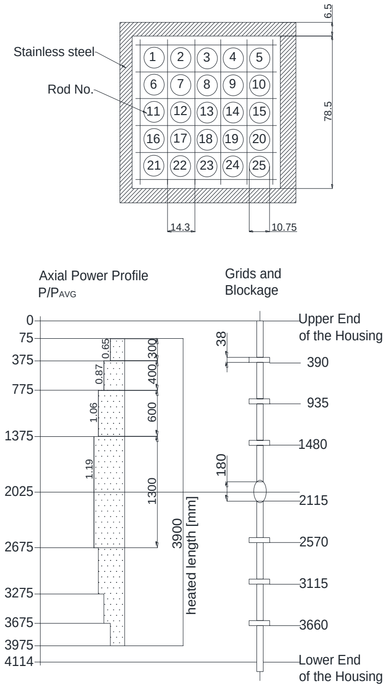


Figure 3. FEBA rod bundle – cross-section view and axial power profile distribution.

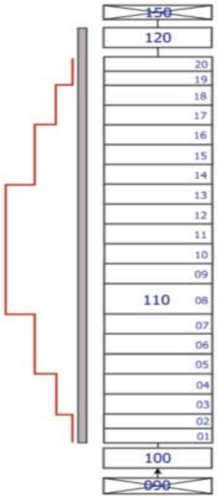


Figure 4. RELAP5 model of the FEBA rod bundle.

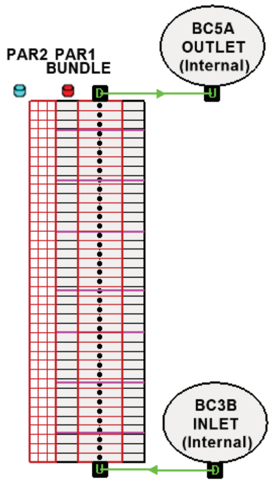
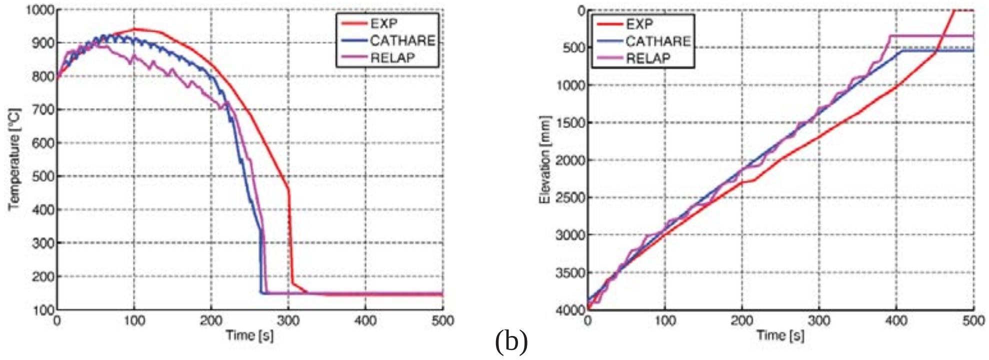


Figure 5. CATHARE model of the FEBA rod bundle.

The results of reference calculations are shown on Fig. 6a (cladding temperature at elevation where the peak cladding temperature (PCT) has been observed) and Fig. 6b (quench front elevation). Both codes underestimate the PCT value (~ 50K in case of CATHARE and ~ 100K in case of RELAP) and predict faster quench front propagation comparing to experimental data (~ 40s in PCT).



(a) (b)

Figure 6. FEBA test 216: calculated and measured clad temperature 1680 mm from top of the assembly (a) and quench front elevation (b).

It should be noted that presented calculations have been performed as "post-test", i.e. experimental results were available to the analysts. No special tuning has been applied to the models in order to achieve best agreement possible with experimental data. The observed discrepancies of calculation results using the standard nodalization practices with respect to the experimental data were deemed as acceptable.

3.3. Identification of influential models/parameters

An initial list of input parameters which potentially have an influence on relevant thermal-hydraulic responses of reflood phenomena has been established [14]. It includes various boundary conditions (e.g. pressure, bundle power, flooding velocity etc.) and representative parameters of system thermal-hydraulic codes' physical models (e.g. film boiling heat transfer coefficient, interphase friction coefficient etc.). A series of sensitivity calculations have been performed with single parameter variation (i.e. all other parameters fixed at their best-estimate values) in order to determine those IP which actually have an influence on calculation results.

The following criteria have been applied in order to determine the influential parameters. An influential IP has to be such that its extreme value in the large but reasonable range of variation causes the following change in at least one of the two main reflood responses (at least one out of two criteria should be fulfilled):

- The absolute value of variation of rod surface temperature T_{clad} is $\Delta T_{ref} = 50K$;
- The variation of rewet time t_{rew} is $\Delta t_{rew} = 10\%$.

The identified influential parameters for both RELAP5 and CATHARE2 codes are presented in the Table 2. It should be noted that the present study does not aims to compare the prediction of reflood phenomena by the codes, but rather considers application of IPREM methodology separately to each of these codes.

3.4. Quantification of model uncertainties

The IPREM has been applied for identified influential input parameters (Table 2). It should be mentioned that the RELAP5 parameter "minimum droplet diameter" has been discarded from the further analysis since it contributes to other analyzed parameters like interphase friction or heat transfer. A series of single-parameter variation sensitivity runs have been performed for each input parameter in Table 2 covering a large range of variation of the multipliers α applied to the parameters. The following output parameters have been selected as relevant thermal-hydraulic responses:

- Cladding temperature at the level where exp. PCT was observed;
- Cladding temperature at top of fuel;
- Quench front elevation.

Table 2. Identified influential parameters

	Parameter	Affected response
	RELAP5	
1	Interphase HTC	$\Delta T_{clad}, t_{rew}$
2	Interphase friction coefficient	t_{rew}
3	Film boiling HTC	$\Delta T_{clad}, t_{rew}$
4	Convection to vapor HTC	ΔT_{clad}
5	Minimum droplet diameter	t_{rew}
	CATHARE2	
1	Wall-fluid global Heat Transfer	$\Delta T_{clad}, t_{rew}$
2	Conduction near quench front	t_{rew}
3	Interfacial friction	$\Delta T_{clad}, t_{rew}$

The FFTBM tool has been applied to the selected responses of each sensitivity run, and the corresponding **AA** and **AAG** values have been computed. Then, the $CR(\alpha)$ (Equation (6)) has been calculated for identified influential parameters and the limiting value of $CR=0.22$ has been applied in order to quantify the range of variation of each influential input parameter. The resulting ranges are presented in Table 3 (for RELAP5 Mod3.3 code) and in Table 4 (for CATHARE2 V2.5_3 mod 3.1 code).

Table 3. Ranges of RELAP5 input parameter variations

	Parameter	Ref	From	To
1	Wall-to-liquid HTC multiplier	1.0	0.5	1.2
2	Wall-to-vapor HTC multiplier	1.0	0.35	2.3
3	Interphase friction multiplier	1.0	0.86	1.62
4	Interphase HTC multiplier	1.0	0.1	1.58

Table 4. Ranges of CATHARE2 input parameter variations

	Parameter	Ref	From	To
1	Wall-fluid global Heat Transfer	1.0	0.56	1.08
2	Conduction near quench front	1.0	0.50	1.2
3	Interfacial friction	1.0	0.77	4.0

4. VALIDATION OF THE IPREM AND OF THE EVALUATED INPUT PARAMETER UNCERTAINTIES

The validation of the proposed methodology is a fundamental pre-requisite for the application of the method itself. Thus, the ranges of reflood-related parameters of RELAP5 and CATHARE codes, quantified on the basis of FEBA test 216 has been applied to perform uncertainty analysis of thermal hydraulic calculations of various experimental reflood tests. The sufficient coverage of experimental data by resulting uncertainty bands is the success criteria for validation.

In the framework of PREMIUM benchmark and NURESAFE project the previously quantified ranges of input model parameters (Table 3 and Table 4) were validated through calculations of the following experimental tests (Table 5):

- For RELAP5 code
    - 6 tests performed at FEBA facility;
    - 6 tests performed at PERICLES facility;
    - 2 tests performed at ACHILLES facility.
- For CATHARE2 code
    - 1 test performed at FEBA facility (test 214);
    - 2 tests performed at ACHILLES facility.

It shall be pointed out that the validation has been performed by simulating tests with identical geometry but different conditions (the FEBA tests) and tests with different geometry and conditions (the PERICLES and the ACHILLES tests) with respect to one used for the quantification of ranges of input model parameters (i.e. FEBA Test 216). The calculation of all FEBA tests have been performed using the same RELAP5 model developed previously for test 216. The calculations of PERICLES and ACHILLES tests have been performed in a “blind” mode: i.e. the experimental data was not revealed to the analyst until the uncertainty study has been performed.

Table 5. Boundary conditions of FEBA, PERICLES and ACHILLES tests

FEBA				
Test	Inlet velocity, cm/s	Pressure, bar	Water temperature, °C	Bundle power, kW
223	3.8	2.2	44-36	120% ANS curve
216	3.8	4.1	48-37	120% ANS curve
220	3.8	6.2	49-37	120% ANS curve
218	5.8	2.1	42-37	120% ANS curve
214	5.8	4.1	45-37	120% ANS curve
222	5.8	6.2	43-36	120% ANS curve
PERICLES				
Test	Inlet velocity, cm/s	Pressure, bar	Water temperature, °C	Nominal heat flux (HA), W/cm^2
RE0062	3.7	3.0	73	2.93
RE0064	3.7	3.0	73	4.2
RE0069	3.7	3.0	73	2.93
RE0079	3.7	3.0	43	4.2
RE0080	5.1	3.0	73	4.2
RE0086	3.7	4.0	85	4.2
ACHILLES				
Test	Inlet velocity, cm/s	Pressure, bar	Water temperature, °C	Max linear heat rate, W/cm
A1R030	2.0	2.1	100	11.5
A1R048	4.0	2.1	100	11.5

4.1. Description of PERICLES and ACHILLES facilities

The PERICLES tests [15] have been carried out to investigate 2-D effects (e.g. like cross flows) which can occur in a PWR core where the rod power is not identical from one assembly to the other ones. The test section consists of three different rectangular assemblies contained in a heated vertical housing with a rectangular section. Each assembly contains 119 full length heater rods of 9.45 mm diameter. Thus, the total number of heater rods is 357 [16]. Each fuel rod simulator consists of three helical Nichrome wires embedded in boron nitride. The cladding is made of stainless steel. The chopped cosine axial power profile with the peaking factor of 1.6 over a 3656 mm heated length is implemented.

The ACHILLES test facility [17] was designed to investigate the heat transfer in the core of a Pressurized Water Reactor (PWR) during the reflood phase of a postulated large break loss of coolant accident. The ACHILLES test section consisted of 69 fuel rod simulators, assembled into a cluster using spacer grids, and mounted vertically within a cylindrical shroud vessel. The cosine-like axial power profile is applied with the maximum peaking factor of 1.4.

4.2. Modelling of PERICLES and ACHILLES test section

Model of PERICLES test section for RELAP5 Mod3.3 code have been developed for “blind” calculations: only the geometrical specifications and test conditions were available. The same modelling approach has been used for the simulation of PERICLES facility as adopted previously for the calculation of FEBA test: one 1-D hydraulic channel representing the one fuel assembly with 1 element representing the fuel bundle. Resulting three parallel vertical channels were connected by cross-flow junctions.

The same “blind” approach has been adopted while setting up models of ACHILLES test section for RELAP5 and CATHARE2 codes: one 1-D hydraulic channel representing the test section with 1 element representing the entire fuel bundle. The number of adopted hydraulic meshes is similar to corresponding RELAP5 or CATHARE2 models of FEBA facility.

It should be pointed out that limited amount of information regarding the geometry of PERICLES facility has been available for model development. Especially this concerns the upper plenum above the heated part of the rod bundles, where steam-water separators are typically installed in such type of experimental facilities. Considering this issue and the fact that the calculations have been performed in 'blind' mode, it can be expected that reference calculation results do not provide the best prediction of experimental data.

4.3. Uncertainty evaluation of selected tests

Once the models of FEBA, PERICLES and ACHILLES test sections were set up and reference calculations have been performed, the uncertainty analysis has been carried out with input uncertainty propagation method in order to obtain the uncertainty bands of selected output parameters with specified probability and confidence level.

The probability distribution of uncertain input parameters has been described with histogram law (50% probability to intervals below and above reference value) with ranges as presented in Table 3 and Table 4. GRS method [3] has been adopted and Software System for Uncertainty and Sensitivity Analyses (SUSA) has been used in order to perform uncertainty propagation. The samples were generated using the Simple Random Sampling technique. Moreover, in order to avoid a too strong "sample effect", the sample size was set to 200 (i.e. 200 code runs have been performed for each test).

For the selected output parameters, the uncertainty band is defined by 2.5th and 97.5th percentiles. Therefore, the 5th order statistics analysis has been applied to results of 200 runs. The [2.5%; 97.5%] uncertainty bands were evaluated for the following output parameters:

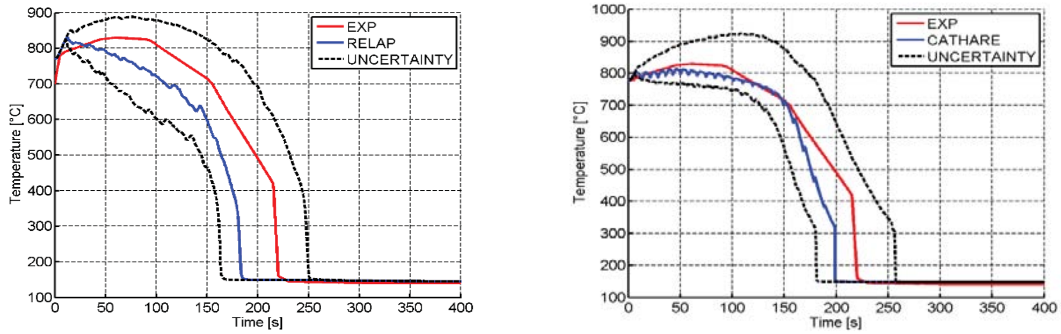
- Cladding temperature at various elevations;
- Quench front elevation.

The resulting uncertainty bands for selected output parameters are compared with the experimental data of FEBA test 214 and ACHILLES test A1R030 in Fig. 7 and Fig. 8. In accordance to the arguments given in Section 3, the 'top-bottom' reflood phenomenon was not represented by the codes to full extent and thus it is not shown on the figures.

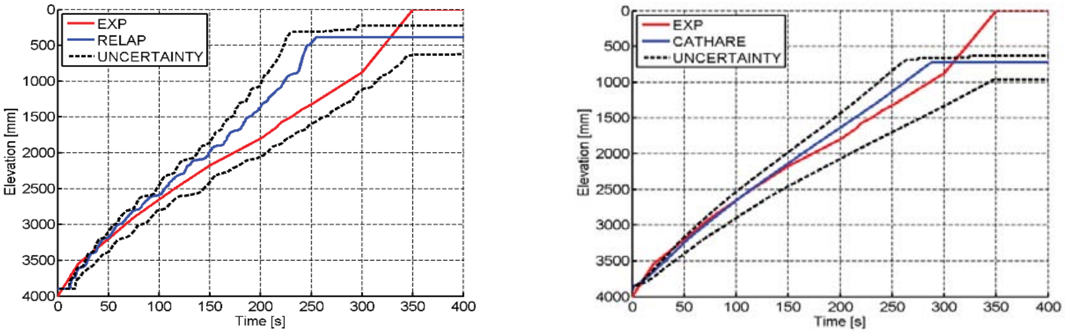
The following main outcomes shall be outlined:

- The reference calculations of ACHILLES test A1R030 by both RELAP5 and CATHARE2 predict the cladding temperature evolution more similar to the experimental time trend of the colder external heater rod than the hotter rods in the central part of the assembly;
- Both codes predict slightly earlier rewetting of the test assembly;
- Calculated uncertainty bands sufficiently encompass the experimental data;
- Experimental peak cladding temperature is reasonably well covered by the upper uncertainty band.

Similar bands have been evaluated for all FEBA and PERICLES tests simulated by RELAP5 Mod3.3 code. As the main nuclear safety issue related to reflood phenomena is a peak cladding temperature, the corresponding values of PCT from results of validation activity are summarized in Table 6 and Table 7 where the experimental values of PCT are compared with predicted reference ones and corresponding maximum values of upper uncertainty bands.

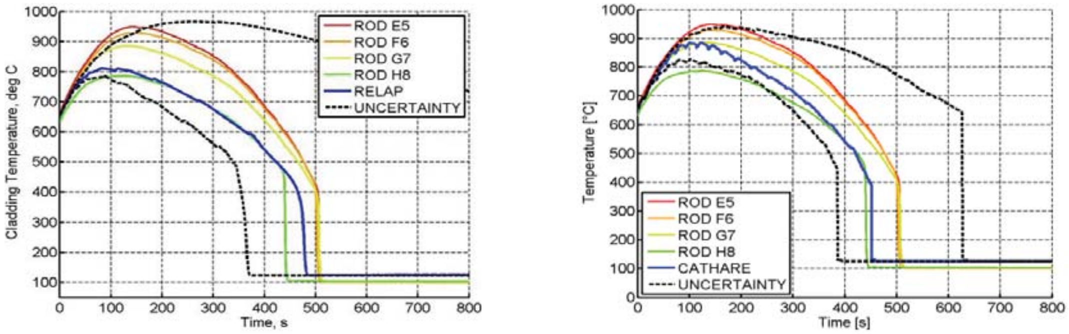


a) Clad temperature at 1680 mm, RELAP5. c) Clad temperature at 1680 mm, C2.

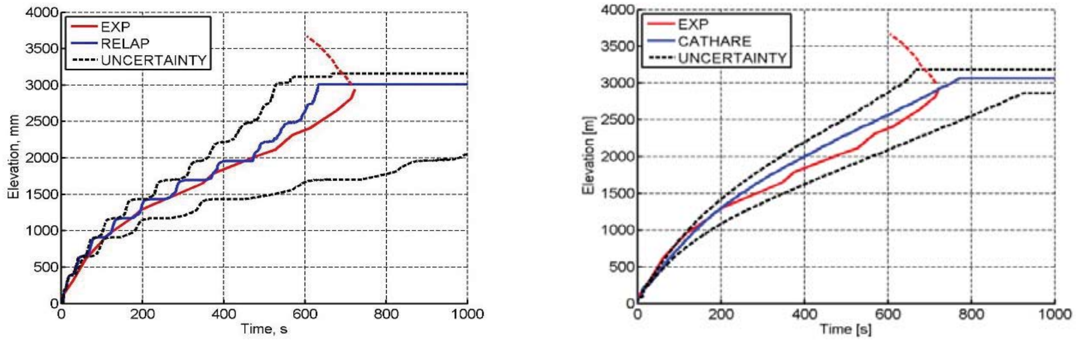


b) Quench front elevation, RELAP5. d) Quench front elevation, CATHARE2.

Figure 7. Predicted uncertainty bands for test FEBA 214.



a) Clad temperature at 2.130 m, RELAP5. c) Clad temperature at 2.130 m, C2.



b) Quench front elevation, RELAP5. d) Quench front elevation, CATHARE2.

Figure 8. Predicted uncertainty bands for test ACHILLES A1R030.

Table 6. Summary of uncertainty analysis of FEBA and PERICLES tests with RELAP5 code

FEBA				PERICLES			
Test	Exp. PCT, °C	Ref. PCT, °C	Max Upper Band, °C	Test	Exp. PCT, °C	Ref. PCT, °C	Max Upper Band, °C
223	935	905	1050	RE0062	725	665	733
216	920	883	948	RE0064	789	735	821
220	850	828	956	RE0069	605	578	640
218	830	833	892	RE0079	792	734	830
214	805	803	847	RE0080	729	671	755
222	935	905	1050	RE0086	810	739	796

Table 7. Summary of uncertainty analysis of ACHILLES tests with RELAP5 and CATHARE2 codes

	RELAP5			CATHARE2		
Test	Exp PCT, °C	Ref PCT, °C	Max Upper Band, °C	Exp PCT, °C	Ref PCT, °C	Max Upper Band, °C
A1R030	946	817	972	946	881	945
A1R048	778	705	842	778	712	796

It can be seen that the experimental peak cladding temperature is below the PCT of the upper uncertainty band for all the FEBA and PERICLES tests, except test RE0086 where the PCT is underpredicted by 14 °C. However, it should be considered that the reference calculation of test RE0086 (high pressure), showed the biggest underprediction of experimental data. This fact and the mentioned above considerations on expected discrepancies due to limited knowledge of hardware geometry, give the basis to judge the validation against PERICLES tests as successful in general.

5. CONCLUSIONS

The present paper shows the efforts carried out to address one of the important issues in the framework of the application of BEPU methodologies – the development and validation of the methods for proper estimation of input parameter uncertainties. An Input Parameter Range Evaluation Methodology (IPREM) has been developed at University of Pisa on the basis of previous experience of successful application of FFTBM for the evaluation of code calculation accuracy. The procedure, factors and criteria have been developed and set up in order to quantify the variation ranges of considered code input parameters.

The IPREM has been applied to quantify the ranges of variation of reflood-related influential input parameters of system thermal-hydraulic codes RELAP5 Mod3.3 and CATHARE2 V2.5. The obtained ranges were validated on experimental reflood tests featuring different geometry and thermal-hydraulic conditions. The obtained uncertainty bands of relevant code output parameters envelop the experimental results. The results contribute to the OECD/NEA PREMIUM benchmark and NURESAFE project.

Although the IPREM is based on rather engineering considerations than on substantial statistical basis (and therefore does not provide the probability distribution of considered parameters), it proved to be code-, geometry- and condition-independent. The methodology is cost efficient and requires few experimental tests with time-dependent measurements in order to quantify and validate the ranges of variation of input parameters of interest.

The developed IPREM methodology reduces the use of engineering judgment in terms that the proper procedure, mathematical apparatus and corresponding criteria are clearly defined. However, the choice of analyzed code responses may affect the resulting ranges of input parameters, and in some particular cases the proposed figures-of-merit did not allow to quantify the one side of the range of an input parameter. Therefore the engineering judgment is still unavoidable, however reduced.

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