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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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BEMUSE Phase III Report

Uncertainty and Sensitivity Analysis of the LOFT L2-5 Test

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BEMUSE PHASE III REPORT

Uncertainty and Sensitivity Analysis of the LOFT L2-5 Test

February 2007

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EXECUTIVE SUMMARY

Background

Evaluating nuclear power plant performance during transient conditions has been the main issue in thermal-hydraulic safety research worldwide since nuclear energy was first used to produce electricity in the 1950s (see State of the Art Report by CSNI and Compendium of ECCS Researches by US NRC, both issued in 1989).

A huge amount of experimental data have been made available from very simple loops (basic test facilities and separate effect test facilities) and from very complex Integral Test Facilities simulating all the relevant parts of a light water reactor (LWR). Sophisticated computer codes such as ATHLET, CATHARE, RELAP, TRAC and TRACE have also been developed, mainly in Europe and United States, and are now widely used. Such codes can calculate time trends of any variable of interest during any transient in LWRs. The reliability of the predictions cannot be assessed directly due to the lack of suitable measurements in plants. The capabilities of the codes can consequently only be assessed by comparison of calculation results with experimental data recorded in small scale facilities. To evaluate the applicability of a code in predicting a plant situation, it is necessary to check, at least, that experimental data used for qualifying the codes are representative of phenomena expected in the plant and, subsequently that codes can qualitatively and quantitatively reproduce such data. Furthermore the best-estimate character of the software quoted above involves adding an evaluation of the uncertainties of the results to calculation of the plant transient. Another issue of interest is sensitivity analysis, which provides additional information on the results of uncertainty analysis.

In this context, the BEMUSE (Best Estimate Methods – Uncertainty and Sensitivity Evaluation) Programme – promoted by the working group on accident management and analysis (GAMA) and endorsed by the committee on the safety of nuclear installations (CSNI) – represents an important step towards reliable application of high-quality best-estimate and uncertainty and sensitivity evaluation methods. The activity consists in two main steps, devoted to the application of these methods to a transient of type Large-Break Loss of Coolant Accident (LB-LOCA).

- Step 1: best-estimate and uncertainty and sensitivity evaluations of the LOFT L2-5 test (phases 2 and 3). LOFT is the only integral test facility with a nuclear core where safety experiments have been performed.
- Step 2: best-estimate and uncertainty and sensitivity evaluations of a nuclear power plant (phases 4 & 5).

Phase 1 is the presentation a priori of the uncertainty methodologies to be used by the participants and the (final) phase 6 is the synthesis of the results of the previous phases with conclusions and recommendations.

This report presents the results of phase 3, i.e. the phase devoted to uncertainty and sensitivity analysis applied to the LOFT L2-5 test. Ten participants from nine organisations and seven countries took part in the exercise (not including an additional participation which arrived too late). Five thermal-hydraulic codes have been used, sometimes with different versions. The end users for the results are expected to be industry, safety authorities and research laboratories.

Specifications

Participants received step-by-step requirements, with four main parts clearly defined:

1. List and uncertainties of the input parameters
2. Uncertainty analysis results
3. Sensitivity analysis results
4. Improved methods, assessment of the methods (optional).

5% and 95% percentiles have to be estimated for 6 output parameters, which are of two kinds:

- Scalar output parameters.
  - First peak cladding temperature.
  - Second peak cladding temperature.
  - Time of accumulator injection.
  - Time of complete quenching.

- Time trends output parameters.
  - Maximum cladding temperature, whatever the location of the fuel rod in the core.
  - Upper plenum pressure.

Used methods

Two classes of uncertainty methods can be distinguished. One propagates "input uncertainties" and the other one extrapolates "output uncertainties".

The main characteristics of the methods based upon the propagation of input uncertainties is to assign probability distributions for these input uncertainties, and sample out of these distributions values for each code calculation to be performed. The number of code calculations is not dependent on the number of input uncertainties, and is only dependent on the defined probability content (percentile) and confidence level. The number of calculations is given by Wilks' formula. By performing code calculations using variations of the values of the uncertain input parameters, and consequently calculating results dependent on these variations, the uncertainties are propagated. Uncertainties are due to imprecise knowledge and the approximations of the computer codes simulating thermal-hydraulic physical behaviour.

The methods based upon extrapolation of output uncertainties need available relevant experimental data, and extrapolate the differences between code calculations and experimental data at reactor scale. This procedure is not supported by theoretical formulations.

The two principles have advantages and drawbacks. The probabilistic methods need to select a reasonable number of variables and to associate range of variations and possibly distribution functions for each one. Selection of parameters and their distribution must be justified. Uncertainty propagation occurs through calculations of the code under investigation. The "extrapolation on the outputs" method has no formal analytical procedure to derive uncertainties, and needs to have "relevant experimental data" available. In addition, the sources of error cannot be derived as result of application of the method. The method seeks to avoid engineering judgement as much as possible.

In BEMUSE phase 3, nine out of ten participants use the probabilistic approach, associated with Wilks' formula. Only University of Pisa uses its method extrapolating output uncertainties. This method is called the CIAU method, Code with (the capability of) Internal Assessment of Uncertainty.

Main results

Uncertainty analysis results are quite satisfactory. For cladding temperature-type outputs (i.e. both PCT, time of complete quenching and the maximum cladding temperature time trend), 8 out of 10 participants find uncertainty bands which envelop the experimental data. For the pressure-type outputs (time of accumulator injection and the time trend upper plenum pressure), 6 out of 10 envelop roughly the experimental data. Nevertheless for both kinds of outputs, the spread of the uncertainty band is large depending on the participants: between 100 K and 700 K for the temperatures, between 0.2 and 2 MPa for the pressure, without taking into account the UNIPI method because of its specificity in its way of considering time uncertainty.

Synthesis tables and figures have been set up. The first one (Table 4) lists all the input parameters considered before uncertainty analysis by at least one participant: it allows to each participant to check whether a potentially influential parameter has not been omitted. The other ones (especially Figure 19 and Figure 20, respectively for clad temperature and pressure-type outputs) are based on the results of sensitivity analysis and list the parameters considered relevant by at least one participant. Some recommendations are given to use these lists properly, which constitute a database of the parameters to be considered in further uncertainty analyses for LB-LOCA.

In the improved methods, all the participants have increased the number of code runs compared with the 59 code runs required by Wilks' formula to have a majoring value of the α = 95% percentile with a confidence level β equal to 95%. They lead to the same conclusion: it is worth performing more code runs. For uncertainty analysis, with 150-200 code runs it is possible to use Wilks' formula at the order 4 or 5 for α and β unchanged, which substantially decreases the "sample-effect", i.e. the dispersion of the estimated tolerance limit according to the considered sample. This approach is especially recommended for the upper tolerance limit if it is close to a threshold which must not be exceeded (e.g. 1 204°C for a PCT), because it avoids "over-conservatism" in estimating the 95% percentile. For sensitivity analysis, it provides more reliable influence measures, due to less spurious correlations between input parameters.

In conclusion, recommendations are provided. They concern only the methods based on the propagation of input uncertainties, because they are used by all the participants, excepted UNIPI.[1] These recommendations are:

- Increasing the number of code runs, as explained above. For uncertainty analysis, performing 150 to 200 code runs and consequently applying Wilks' formula at the order 4 or 5 for the estimation of the 95% percentile, reduces the dispersion of the estimated tolerance limit. Besides, the results of sensitivity analysis become more reliable, due among others to less spurious correlations between independent input parameters.
- A compromise seems to be found for the number of input parameters. In uncertainty analysis, there is no limitation of this number due to the use of Wilks' formula. However, some difficulties can be encountered to determine the range of variation of numerous input parameters. In sensitivity analysis, the results are more reliable if the number of code runs is significantly higher than the number of input parameters.
- The appropriate type of sampling when using Wilks' formula is the simple random sampling (SRS).
- For a proper use of Wilks' formula, all the code runs must be successful or corrected in case of failure. Nevertheless, in case of one or two code failures, a conservative approach may be used by performing more code runs.

1. In particular, the CIAU does not consider Wilks' formula, does not need to use expert judgement for the quantification of the uncertainty of the input parameters and the calculations performed for the CIAU do not allow to have sensitivities.

- Focusing further studies on quantifying input parameter uncertainty. If experimental data exist, methods for statistical analysis of these data compared with the code results must be developed. Otherwise, expert judgement seems impossible to avoid, although such an approach would be definitely questioned by the authorities. In any case, expert judgement must be more formalised.
- For sensitivity analysis, it seems difficult to perform additional code runs with respect to those already performed for uncertainty analysis, due to the CPU cost of each calculation of a reactor case. But in this case, only the very influential input parameters can be found with the classical influence measures such as the Pearson’s Correlation Coefficients, the Standardized Regression Coefficients, etc. In the case where more information from sensitivity analysis is desired, a comparative study of the advantages and drawbacks of each influence measure would be useful. Dealing with the issue of the best design of experiment, which is not necessarily the simple random sampling (SRS), might also be of interest.

1. INTRODUCTION

1.1 Framework and rapid survey of literature

The BEMUSE [1] (Best Estimate Methods – Uncertainty and Sensitivity Evaluation) Programme has been promoted by the Working Group on Accident Management and Analysis (GAMA) and endorsed by the Committee on the Safety of Nuclear Installations (CSNI).

The high-level objectives of the work are:

- To evaluate the practicability, quality and reliability of Best-Estimate (BE) methods including uncertainty and sensitivity evaluation in applications relevant to nuclear reactor safety.
- To develop common understanding.
- To promote and facilitate their use by the regulatory bodies and the industry.

Operational objectives include an assessment of the applicability of best-estimate and uncertainty and sensitivity methods to integral tests and their use in reactor applications.

The scope of the Programme is to perform Large Break Loss-Of-Coolant Accident (LB-LOCA) analyses making reference to experimental data and to a Nuclear Power Plant (NPP) to address the issue of "the capabilities of computational tools" including scaling and uncertainty analysis.

The justification for such an activity is that, since the first uncertainty analysis performed with the CSAU methodology [2], [3] and [4], a wide spectrum of uncertainty methods applied to BE codes exist and are used in research laboratories. A rapid description of the methods since the CSAU is made below, in order to place BEMUSE in context:

The first complete uncertainty analysis is performed in 1989 with the TRAC-PF1 code for a LB-LOCA with the CSAU methodology. The main issues of uncertainty analysis are already tackled: selection of the input parameters, determination of their range of variation and propagation step. The number of input parameters is limited, less than 10, via a PIRT process. Levels are assigned to the input parameters inside their range of variation and roughly 100 TRAC calculations are performed by shifting the input parameters one by one, two by two, etc. according to these levels. The obtained values of the outputs are used to build a polynomial response surface. A large number of Monte-Carlo histories, typically 50 000, are then performed with the response surface to estimate the desired percentiles of the outputs. This method can be seen as a mixing between a deterministic approach during the building of the response surface and a probabilistic one with the Monte-Carlo histories.

In 1985, GRS proposed a probabilistic method and demonstrated its application using Wilks' formula [5] to determine the number of code runs needed to obtain a given tolerance limit with a given confidence level [6]. The first thermal-hydraulic application by GRS was published in 1994 [7]. Unlike the CSAU, this number of code runs is independent of the number of input parameters and all the input parameters are sampled simultaneously. This method is presently largely used, especially for this Phase 3 of BEMUSE and is described in more detail in §1.6.1.

At the beginning of the eighties too, UNIPI started the research about another method, the UMAE, based on the extrapolation of the code experiment differences on the outputs, determined via a large experimental database [8], [9], [10]. The proof of the capability of UMAE was provided in 1994 [11]. In 1998, the idea of UMAE was extended and the method made “automatic” and connected with the code within the framework of the concept ‘Internal Assessment of Uncertainty’: this automatic method was called CIAU [12] and is the one used by UNIPI for BEMUSE. More details are given in §1.6.2.

An international exercise is organised in 1997: the UMS [13]. It is applied to a Small Break LOCA: LSTF SB-CL-18. Five organisations participate to this exercise, including GRS and UNIPI with their method, but also IRSN, ENUSA and AEAT. IRSN and ENUSA use a method close to that of GRS, but AEAT proposes another approach, which can be considered as a deterministic one: “reasonable uncertainty ranges” for the input parameters and selection of conservative combinations of the values of the input parameters. For all the methods, UMS constitutes a pilot study which shows that the methods are operational. Nevertheless the five methods produce significant differences for the predicted uncertainties. The difficulty to model adequately the uncertainty of the input parameters is also pointed out.

Nowadays Best Estimate Plus Uncertainty Methods are broadly used worldwide, in licensing (USA, Netherlands, Brazil, etc.) or significant activities are developed for a future use in licensing (Canada, Czech Republic, France, etc.). CSAU is often used, but more as a general framework including the use of a PIRT to limit the number of considered input parameters associated with the use of other statistical methods than that explained in the demonstration case [4]. Among these statistical methods, Wilks’ formula, coming from GRS method, is often considered. The UNIPI method has been also broadly applied. For example, it has been used in Brazil in Angra-2 NPP licensing for verification of the retained method performed by Siemens. But even for the methods based on propagation of input uncertainties (CSAU and GRS), there is not yet a complete consensus for some questions. One can quote for example for these methods: number of code runs, of input parameters, choice of these input parameters, determination of their range of variation, etc. The interest of the BEMUSE programme, and especially of the phases devoted to uncertainty and sensitivity analyses such as Phase 3, lays in providing an opportunity to gain insights on these different approaches, but also on different codes and different analysts given a common problem.

End users for the results are expected to be industry, the safety authorities and research laboratories.

1.2 Description of the BEMUSE Programme

The programme consists of six phases carried out in two steps.

The first step is aimed at performing LB-LOCA analysis making reference to the experimental data of LOFT L2-5 [14], [15], [16], [17]. The interest of using the results of this experiment can be described as follows:

- LOFT is the only Integral Test Facility with a nuclear core where safety experiments have been performed.
- The ISP-13, already devoted to the study of LOFT L2-5, was completed more than 20 years ago and open issues remained from the analysis of the comparison between measured and calculated trends.
- For the general goal of BEMUSE, it seemed easier to start by considering an experiment rather than directly a nuclear power plant, because it provides an experimental reference.

The second step concerns the study of LB-LOCA for a Nuclear Power Plant (NPP).

Six phases are defined, which cover the following work:

- Phase 1: Presentation a priori of the uncertainty methodology to be used by participants [18].
- Phase 2: Best-estimate calculation of the LOFT L2-5 test, re-analysis of the ISP-13 exercise [19].
- Phase 3: Uncertainty and sensitivity analyses of LOFT L2-5, first conclusions on the methods and suggestions for improvement.
- Phase 4: Best-estimate calculation of the LB-LOCA transient applied to the NPP.

- Phase 5: Uncertainty and sensitivity analyses for this transient, taking into account the improvements resulting from Phase 3.
- Phase 6: Status report on the area, classification of the methods, conclusions and recommendations.

Phases 2 and 3 are related to step 1, phases 4 and 5 to step 2, whereas the phases 1 and 6 are more general.

This report is devoted to the presentation of the results of Phase 3 and includes numerous comparison and synthesis tables and figures. It ends with some recommendations, especially valid for the following Phase 5 of BEMUSE.

1.3 Participating organisations

Eleven participants coming from ten organisations and eight countries have participated in the exercise. Ten of them have followed very precisely the requirements of Phase 3. The last contribution, that of JNES, was sent too late to have the same level of reviewing as the other ones. Besides, JNES does not consider all the specified output parameters both for uncertainty and sensitivity analysis. As a consequence, this contribution is presented in this report in the same way as the other ones, in the appendix, but is not taken into account in the first part of this report, devoted to the analysis and synthesis of results.

Five different thermal-hydraulic system codes have been used, sometimes with different versions:

- ATHLET: 2 participants.
- CATHARE: 2 participants.
- MARS: 1 participant.
- RELAP5: 4 participants.
- TRACE: 2 participants.

The list of the organisations participating in Phase 3 of BEMUSE is given in Table 1.

Table 1. **List of participants to BEMUSE Phase 3**

Number	Name of Organisation	Country	Name	E-mail	Code name
1	CEA	France	P. Bazin A.de Crécy	pascal.bazin@cea.fr agnes.decrecy@cea.fr	CATHARE V2.5
2	GRS	Germany	H. Glaeser T. Skorek	gls@grs.de SKT@grs.de	ATHLET
3	IRSN	France	J. Joucla P. Probst	jerome.joucla@irsn.fr pierre.probst@irsn.fr	CATHARE V2.5
4	KAERI	South Korea	B. Chung	bdchung@kaeri.re.kr	MARS 2.3
5	KINS	South Korea	D.-Y. Oh	k392ody@kins.re.kr	RELAP5/MOD3.3
6	NRI-1	Czech Republic	M. Kyncl R. Pernica	milos.kyncl@ujv.cz per@ujv.cz	RELAP5/MOD3.3
7	NRI-2	Czech Republic	J. Macek R. Meca	mac@ujv.cz mec@ujv.cz	ATHLET Mod 2.0
8	PSI	Switzerland	R. Macian	Rafael.macian@psi.ch	TRACE V4.05
9	UNIPI	Italy	F. D'Auria A. Petruzzi	f.dauria@ing.unipi.it a.petruzzi@ing.unipi.it	RELAP5/MOD3.2
10	UPC	Spain	M. Perez F. Reventos	marina.perez@upc.edu frances.reventos@upc.es	RELAP5/MOD3.3
11	JNES	Japan	K. Fujioka	fujioka-kazuharu@jnes.go.jp	TRACE V4.05

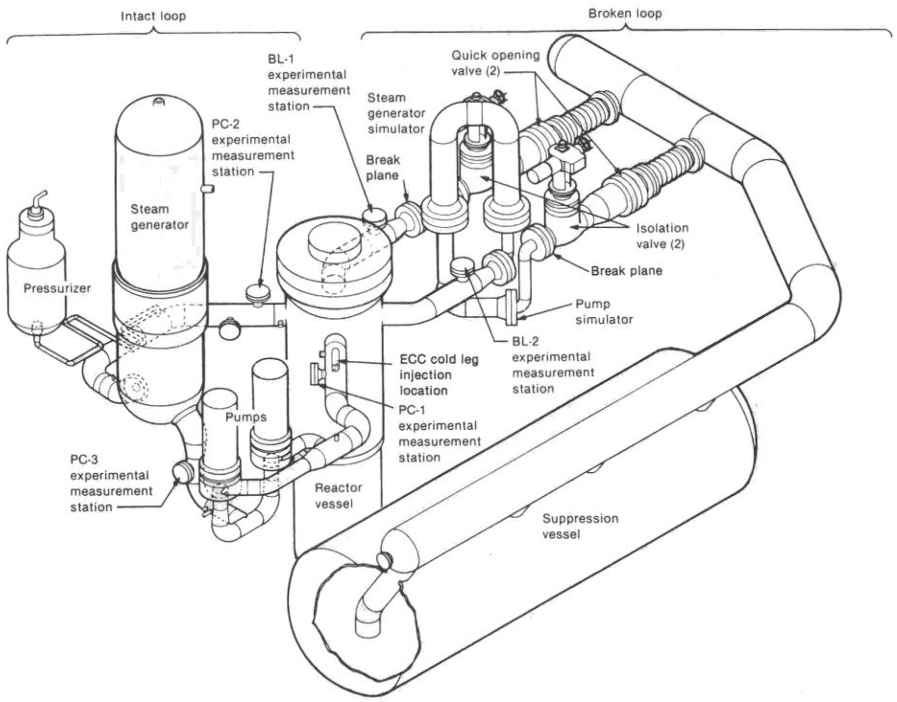
1.4 LOFT facility configuration and test L2-5 rapid description

The LOFT facility [15], [16], [17] is a 50-MWt designed to simulate a pressurised water reactor (PWR) with instrumentation to measure and provide data on the thermal-hydraulic and nuclear conditions throughout the system. Operation of the LOFT system is typical of large (~1000 MWe) commercial PWR operations. The LOFT facility (Figure 1) consists of:

- A reactor vessel including a core with 1 300 unpressurised nuclear fuel rods with an active length of 1.676 m.
- An intact loop with an active steam generator (SG), pressuriser (PRZ) and two primary coolant pumps connected in parallel.
- A broken loop with a simulated pump, simulated steam generator, two break plane orifices, two quick opening blowdown valves (QOBV) and two isolation valves.
- A blowdown suppression system consisting of a header, suppression tank and a spray system.
- An emergency core coolant (ECC) injection system consisting of two low-pressure injection system (LPIS) pumps, two high-pressure injection system (HPIS) pumps, and two accumulators.

The LOFT facility is designed to simulate the major components and system responses of a commercial PWR during a LOCA.

Figure 1. **LOFT system configuration for Experiment L2-5**



For the performance of Experiment L2-5 [14] the LOFT facility was configured to simulate a double-ended 200% cold leg break. The experiment was initiated from nominal operating conditions by opening the quick-opening blowdown valves in the broken loop hot and cold legs. The reactor scrammed on low pressure at 0.24 ± 0.01 s. Following the reactor scram, the operators tripped the primary coolant pumps at 0.94 ± 0.01 s. The pumps were not connected to their flywheels during the coastdown. This atypical primary coolant pump operation (approximating a loss-of-coolant accident (LOCA) simultaneous with a loss of site power and atypically fast pump coastdown) was specified in an attempt to cause early flow stagnation in the core and preclude the early bottom-up core-wide rewet.

The system depressurised to upper plenum fluid saturation conditions, and the core cladding temperature started to deviate from saturation. A rewet of the upper portion of the central fuel assembly began at approximately 12 s and ended at approximately 23 s. The fuel rod peak cladding temperature of 1078 ± 13 K was attained at 28.47 ± 0.02 s. The cladding was quenched at 65 ± 2 s, following the core reflood.

Accumulator injection of ECCS to the intact loop cold leg began at 16.8 ± 0.1 s. ECCS injection from the HPIS and LPIS began at 23.90 ± 0.02 s and 37.32 ± 0.02 s, respectively. This delay was intended to simulate the delay expected for a PWR emergency diesel to begin delivering power (in response to the loss of site power). The LPIS injection was stopped at 107.1 ± 0.4 s, after the experiment was considered complete.

It should be noted that the L2-5 transient is very short. The core is completely quenched by about 65 s, which is significantly shorter than the 200-450 s required for total core quench in a LB-LOCA of a typical PWR. The short core height (1.676 m) in LOFT probably contributes to this. One can also guess that experimenters have taken precautions for the core reflood due to the fact that the fuel rods of LOFT were with UO_2. Other specificities of LOFT can be quoted. The experiment consists of only two loops. The fuel rods are pressurised with a low pressure (2.4 MPa) and only the central assembly. There is a simulator of steam generator in the broken loop, etc. The duration of the transient and the specificities of the experiment do that all the conclusions of the Phase 3 are not necessarily valid for a LB-LOCA of a NPP. That is the reason why the Phases 4 or 5 of the BEMUSE programme are planned.

1.5 Requirements for Phase 3

Six output parameters are considered, described in Table 2. Two of them are time trends whereas the four others are scalar.

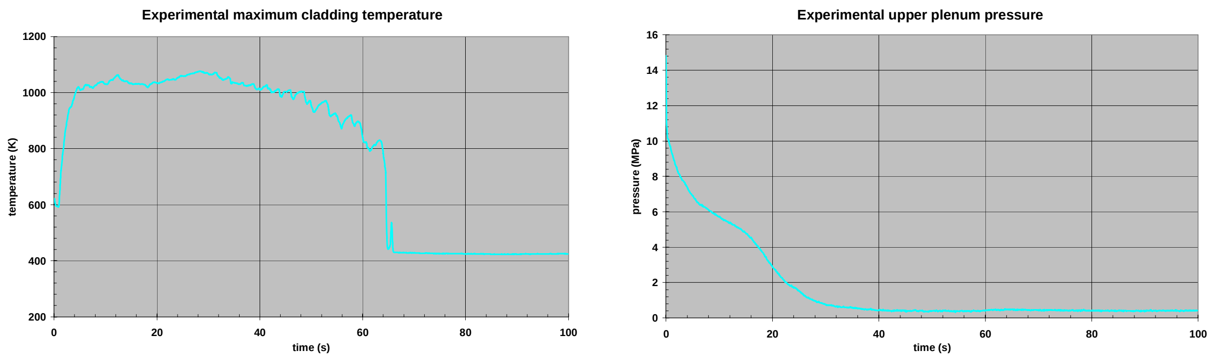
Table 2. **The output parameters for uncertainty and sensitivity analysis**

Type	Definition	Criterion	Experimental value
Time trend	Maximum Cladding Temperature: Max_TC	See comment below	See Figure
	Pressure in the upper plenum: P_{up}	No criterion	See Figure
Single valued parameter	1st PCT (blowdown phase)	Max_TC and $t < t_{inj}$	1062 K (at t = 12.5 s)
	2nd PCT (~ reflood phase)	Max_TC and $t > t_{inj}$	1077 K (at t = 28.5 s)
	Time of accumulator injection: t_{inj}	Time of beginning of injection	16.8 s
	Time of complete quenching: t_{que}	$T_{clad} \leq T_{sat} + 30$ K	65.85 s

Comment about Max_TC

The maximum cladding temperature (Max_TC) is defined as the maximum value (envelope value) of all the rod surface temperatures irrespective of the location (assembly or elevation) and the power level. This definition can be applied either to the 1-D or 3-D modelling of the core. Its experimental value versus time has been determined on the basis of 165 thermocouple measurements and is given in Figure 2. In order to homogenise the contributions of the participants, the same maximum linear power: 40.1 kW/m had to be considered by the participants.

Figure 2. **Case of output parameters of type time trends: experimental values**



For each of the output parameters, both percentiles must be estimated: 5% and 95%.

Precise requirements were provided in 10 steps [20], corresponding to 4 main parts. These requirements were organised on the basis of the probabilistic approach used by all the participants apart from one (UNIPI). As a consequence, they involve the notion of input parameters, of propagation, etc. The different steps and parts are defined below:

Part 1. The input parameters and their uncertainties.
- Step 1. List the general sources of uncertainties considered for BEMUSE Phase 3.
- Step 2. How is the list of uncertain input parameters established?
- Step 3. How are the uncertainties of the uncertain input parameters quantified?
- Step 4. List the uncertain input parameters and quantify their uncertainties: the synthesis.

Part 2. Uncertainty analysis.
- Step 5. Sampling for the probabilistic approach.
- Step 6. Running the code.
- Step 7. First uncertainty analysis results.

Part 3. Sensitivity analysis.
- Step 8. Sensitivity analysis.

Part 4. Complementary methods, assessment methodology.
- Step 9. Complementary methods.
- Step 10. Assessment methodology.

The contents of this report follow the organisation of the requirements.

1.6 Rapid description of the methods

The methods were extensively described for Phase 1 of BEMUSE [18].

Except for UNIPI with its CIAU method (code with the capability of internal assessment of uncertainty), all the participants use a fully probabilistic approach, based on the use of Wilks' formula. Both methods (probabilistic and CIAU) are rapidly recalled below. Some words are added about the use of response surfaces.

1.6.1 Probabilistic methods

A list of uncertain input parameters has to be defined. These uncertain parameters can be of different kinds:

- Physical models (e.g. Models used to describe heat transfer).
- Initial and boundary conditions (e.g. Initial total power or containment pressure).
- Material properties (e.g. Fuel conductivity).
- Numerical parameters (e.g. Convergence criterion).
- Alternative models (choice among two or three correlations to describe the same physical phenomenon).
- Etc.

No limitation of the number of considered parameters is necessary.

In a second step, the input parameters are assumed to be random variables, characterised by a pdf (Probability Density Function): it is during this step that input parameter uncertainties are quantified. For example, the uncertainty on the fuel conductivity can be described by a multiplicative parameter, which obeys a normal law, the mean value of which is 1 and the standard deviation of which is 0.1.

The following step is the propagation step: N code runs are performed by varying simultaneously the values of all the input parameters, according to their pdf. Wilks' formula gives the number N of code runs to be performed in order to obtain an estimation of the value of a α-percentile with a β confidence level [5]. For that, the N values of the considered output parameter are ordered: Y(1) < Y(2) …< Y(N-1) < Y(N), which justifies the name of order statistics used for Wilks' formula. On the basis of this ranking, a majoring value of the 95% percentile with a confidence level of 95% ($\alpha = \beta = 0.95$) is obtained by considering:

- Y(N), with N = 59: Wilks at the first order (r = 1).
- Y(N-1), with N = 93: Wilks at the second order (r = 2).
- Y(N-2), with N = 124: Wilks at the third order (r = 3).
- Y(N-3), with N = 153: Wilks at the fourth order (r = 4), etc.

The same number of code runs is required to obtain a minoring value of the 5% percentile, always with a confidence level of 95%, but by considering Y(1), Y(2), etc.

1.6.2 The CIAU method [12]

Unlike the probabilistic approaches, the CIAU (code with the capability of internal assessment of uncertainty) does not need to consider uncertain input parameters. The key feature of CIAU is the continuous full reference to the experimental database. Accuracies detected from the comparison between experimental and calculated data are propagated to obtain uncertainty in the system code predictions. A solution to the issues constituted by the "scaling" and "the qualification" of the computational tools is embedded into the method. Furthermore, the UMAE (Uncertainty Methodology Based on Accuracy Extrapolation) [11], constitutes the engine for the development of CIAU and for the creation of the error database. Assigned a point in the time domain, the accuracy in predicting the time of occurrence of any point is distinguished from the accuracy that characterises the quantity value at that point. Time and quantity accuracies (and uncertainties) are defined in the time-domain and in the phase-space hypercubes (e.g. 13 hypercubes for LOFT L2-5), respectively. Quantity and time accuracies can be assumed to derive by errors-in-code-models and uncertainties-in-boundary-and-initial-conditions including the time sequence of events and the geometric modelling (or nodalisation) of the problem. In practical terms:

a) The 'transient-time-dependent' calculation by a code resembles a succession of steady-state values at each time step and is supported by the consideration that the code uses and is based on a number and a variety of empirical correlations valid (and qualified) at steady-state with assigned geometric discretisation (or nodalisation) for the concerned system. Therefore, quantity accuracy can be associated primarily with errors-in-code-models

b) Error associated with the opening of a valve (e.g. the time when the equivalent full flow area for the flow passage is attained) or inadequate nodalisation induce time errors that cannot be associated with code model deficiencies. Therefore, time accuracy can be associated primarily with uncertainties-in-boundary-and-initial-conditions.

Statements a) and b) do not constitute an assumption for either the development or the application of the CIAU method.

1.6.3 Response surfaces

One participant, JNES, uses response surfaces in addition to Wilks' formula, for the scalar output parameters. By using the results of the code runs required for the application of Wilks' formula, they choose the most influential parameters by considering Spearman's Correlation Coefficients. They thus obtain typically five input parameters, with which they build a response surface. This response surface is a polynomial of the second degree, fitted using the least-squares method. After that, JNES carries out 50000 Monte-Carlo calculations with the response surface. With the 50000 results, they directly estimate the empirical percentiles at 5% and 95%.

2. PART 1:
LIST AND UNCERTAINTIES OF THE INPUT UNCERTAIN PARAMETERS

2.1 Introduction

The following option: “each participant is free to define the list of his input parameters” was agreed at the beginning of this Phase 3. This option can be justified by several reasons. Firstly, information was available for the participants with the sensitivity studies performed within Phase 2. But and that is the most important point, imposing a list of common parameters would have presented the risk to forget one or several relevant parameters for all the contributions. The information gained with the way of doing chosen for BEMUSE is certainly richer, owing to the high number of participants. Besides it has the advantage to show objectively the state of the knowledge in the world about this question. Anyway, imposing the same parameters to all the participants would have been impossible for the parameters related to the physical models, due to the variety of the used codes.

The consequence of this choice is that a systematic study of the input parameters considered by the participants is compulsory. That is the purpose of this part, especially the steps 1 and 4.

2.2 Step 1. List the general sources of uncertainties

To list the sources of uncertainties, two kinds of uncertainty methods need to be distinguished: the CIAU method, based on the propagation of output errors and used by UNIPI and the fully probabilistic methods with propagation of uncertainties of input parameters, used by the other participants.

- According to UNIPI, the CIAU method takes into account implicitly all the sources of uncertainties, as they are listed below for the probabilistic methods.
- For the probabilistic methods, two kinds of uncertainties can be distinguished:

The uncertainties of the first kind are directly modelled by uncertain input parameters (e.g. physical models). Table 3 summarises the different types of input parameters and those considered by each participant, including UNIPI despite it is not considering input uncertainties.

Table 3. **Different kinds of uncertain input parameters considered by the participants**

	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UNIPI	UPC
	CATHARE V2.5	ATHLET 1.2C	CATHARE V2.5	MARS 2.3	RELAP5 / MOD3.3	RELAP5 / MOD3.3	ATHLET Mod 2.0 - Cycle A	TRACE v 4.05	RELAP5 / MOD3.2	RELAP5/ MOD3.3
Number of input parameters	52	49	42	14	13	31	64	24	N.A.[1]	14
Physical models	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes[2]	Yes
Material properties	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes[2]	Yes
Initial and boudary conditions	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes[2]	Yes
Alternative models	No	Yes	No	No	No	Yes	Yes	No	Yes[2]	No
Numerical parameters	No	Yes	No	No	No	No	Yes	No	Yes[2]	No
Geometrical data, except for fuel[3]	Form loss coefficients, heat slab structures	Form loss coefficients, bypass cross section, etc.	No	Break area, form loss coefficient	No	Loss coefficients, accumulator liquid volume	Break valve area, form loss coefficient, bypass flow paths, etc.	Accumulator volume	Yes[2]	Form loss coefficient

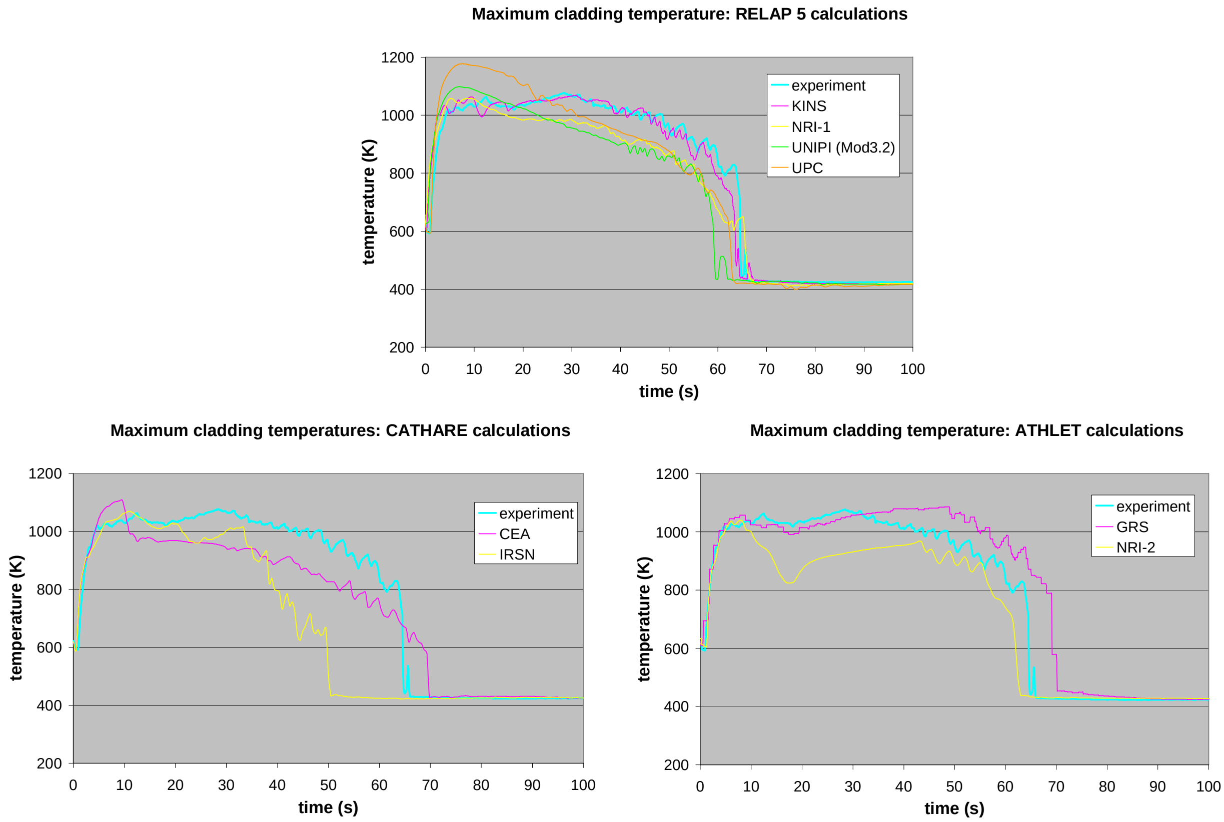
Notes:
1. Not Applicable
2. The method does not consider these input parameters but takes into account implicitly the sources of uncertainties that they represent.
3. The cold gap size, considered by a lot of participants, has been classified among the parameters of type "initial and boundary conditions".

The uncertainties of the second type are not modelled via input parameters. They are uncertainties due to the nodalisation, treatment of (relative) deficiencies of the code, scaling effect and user's effect. The participants take them partly into account in different ways, for example:

- By respecting the code user's guidelines: uncertainties related to nodalisation and user's effect.
- By adapting the range of variation of the input parameters: uncertainties related to nodalisation and scale-up effect (CEA, GRS, etc.) more precisely:
  - Nodalisation. It has been performed by respecting rules of the user's guidelines and it has been assessed in Phase 2 of BEMUSE. But for example, some participants using a 3-D meshing of the vessel, consider a number of axial meshes of the core which can be quite low. It leads to broaden the range of variation of the parameters related to the core behaviour if this range of variation has been determined with a finer meshing corresponding to a 1-D description of the core (CEA).
  - Scale-up effect. The results of experiments to a scale too different from the scale of LOFT are not considered. That is the case for example of UPTF for the downcomer bypass (CEA, PSI). If there is insufficient information for a particular geometry, the range of variation is broadened (GRS).
- By adding a bias on the output parameter in case of very complex phenomena, not necessarily well described by the code, such as ECC bypass or steam binding (KINS). But the used codes do not generally have deficiencies, except for a few cases (dissolved nitrogen (KAERI) or CCFL (PSI)).

The user's effect has been extensively quantified in phase 2 of BEMUSE. Nevertheless, Figure 3 shows the differences of the best-estimate calculation of the maximum cladding temperature for the users of CATHARE, of ATHLET and of RELAP5/Mod3.3 or Mod3.2.

Figure 3. **Best-estimate calculation of the maximum cladding temperature for different users of the same code**



The most important user's effect seems to be related to both users of CATHARE, but there is an explanation to this result: CEA has corrected a mistake in the friction form loss in the accumulator line, found after completion of phase 2 whereas IRSN has kept the results of phase 2 unchanged, with the aim of performing a blind study for phases 2 and 3. Before this correction, both time trends were very close. Figure 3 is given to compare the dispersion of the best-estimate calculations with the widths of the uncertainty bands found presented in part 2. It can be checked that this dispersion is significantly lower than the widths of the uncertainty bands. It must be noticed that the comparisons performed in Figure 3 show only the user's effect on the base case calculations, but, as written above, is not included in the treatment of the sources of uncertainties in uncertainty analysis.

2.3 Step 2: How is the list of input uncertain parameters established?

Roughly speaking, there are two kinds of approaches to list the uncertain input parameters. UNIPI is not quoted, because its method, the CIAU lies on propagation of output errors and consequently does not consider input parameters.

In the first approach (KAERI, KINS, PSI and UPC), participants use a PIRT process. It leads to a rather low number of input parameters, ranging from 13 to 24. It is reminded that the limitation of the considered input parameters is not necessary for the use of Wilks' formula. But considering a limited number of input parameters allows participants to use results of previous studies. It is the case for the quantification of the uncertainties of the inputs: it seemed difficult for some participants to consider more input parameters due to the lack of resources to quantify their uncertainties. The PIRT is generally established on the basis of CSAU study [2] and previous studies performed by the organisation, but also sometimes on the results of UMS [13] or by considering the sensitivity calculations carried out for Phase 2 of BEMUSE [19]. LOFT

L2-5 documentation [14] is also used, especially to take into account the specificities of the LOFT L2-5 test: it makes it possible to decrease the number of input parameters: phenomena such as oxidation and deformation of the fuel rods, non-condensable gas effects, steam binding for some participants, etc. are not taken into account.

In the second approach (CEA, GRS, IRSN, NRI-1, NRI-2), the participants consider all the potentially influential parameters. It leads to a quite high number of input parameters, ranging from 31 to 64. An elicitation process is nevertheless used: the important phenomena occurring during the transient are identified, generally on the basis of the expert judgement helped by some sensitivity calculations, and in a second step the corresponding code models of parameters are also identified. As for the first approach, previous studies performed by the organisation, including the UMS [13] are used. The sensitivity calculations carried out for Phase 2 of BEMUSE [19] and the LOFT L2-5 documentation [14] lead to consider additional parameters with respect to previous studies, especially related to the material properties.

2.4 Step 3: How are the uncertainties of the input uncertain parameters quantified?

2.4.1 The method of quantification

There are three main methods to quantify the uncertainty of the input parameters: literature review, fitting of experimental data and expert judgement. For the same reasons as in step 2, UNIPI is not concerned by this step.

Literature review is used by all the participants, except for IRSN.

- It concerns at least uncertainties about initial and boundary conditions, including the fuel thermal behaviour and is found in the LOFT L2-5 documentation [14] or in the specifications provided by UNIPI for Phase 2 of BEMUSE [21].
- RELAP5 Code Manual [22] is also broadly quoted by the users of this code (KINS and NRI-1, but not UPC) and even of MARS 2.3 (KAERI).
- Depending on the participants, assessment studies are also considered (mainly by GRS and PSI).
- Previous studies are also used, either already performed by the participant (GRS, KINS, NRI-1, NRI-2, UPC) or studies such as CSAU [3](KAERI, PSI) or UMS [13](GRS, NRI-1, UPC).
- Other sources are MATPRO [23] for the material properties (KAERI), the norm ANSI/ANS-5.1-1979 [24] for decay heat power (a majority of participants), the sensitivity studies performed during Phase 2 of BEMUSE (KAERI), etc.

The set of the references can be found in the synthesis tables of the input parameters provided by each participant in his contribution (see the appendix).

Fitting of experimental data is used by several participants (CEA, GRS, IRSN, PSI and to a less extent KINS). Detailed explanations on the employed method are not given, except for IRSN, but references can be found in the contributions. The experiments considered for each parameter appear in the synthesis tables quoted above. In the majority of the cases, they are separate effect tests experiments, as recommended by GRS.

Expert judgement is broadly used in case of lack of experimental data, of specific literature or even of time. The only participants who do not make explicitly reference to it are KINS and PSI.

Sometimes the three approaches are partly combined. For example, expert judgement depends on literature or results of Integral Test facilities (GRS, NRI-1 and NRI-2). Specific methods have been developed using also literature findings (NRI-1). Or expert judgement is used on the basis of recommendations found in the UMS literature: ± 15%, increased to ± 20% if no experimental data are available (NRI-1).

2.4.2 Uncertainties and conservatism

In order to obtain a "conservative" upper bound for the temperatures, one participant (KINS) has assigned limiting values for two input parameters: the containment pressure and the peaking factor. For example, the considered containment pressure is equal to the measured pressure minus measurement uncertainty, on the basis of the specifications provided for Phase 2 of BEMUSE. Besides, KINS also adds two biases to the upper bound found for both PCT, to take into account the ECC bypass and the steam binding, because they are complex and combined phenomena, for which it is difficult to find the relevant parameters.

2.5 Step 4: List the input uncertain parameters and quantify their uncertainties: the synthesis

2.5.1 The synthesis table

All the input parameters considered by participants, apart from UNIPI which does not need to consider input parameters with the CIAU method, are listed in Table 4 (4 pages) with the indication "y" (yes) if they are considered by the participant. As far as possible, they are classified according to the phenomena they are associated with (for example: "flow rate at the break" or "fuel thermal behaviour"). Otherwise, they are also classified by main types of physical laws (for example: interfacial friction). This classification is only an attempt to make things clearer and other classifications would have been certainly possible.

Some rules were observed when this table was established. They are:

- Depending on the participants, some parameters are globally defined or are defined according to some conditions. That is the case for example for the break discharge coefficient: KINS and UPC consider only one global parameter, whereas NRI-1 considers two parameters: one if the flow is subcooled, another one if it is saturated. Finally, three parameters are quoted in Table 4 for the break discharge coefficient: one global, one in case of subcooled flow, one in case of saturated flow. This case occurs also for:
  - Flow rate at the break: interface to liquid heat flux (flashing).
  - Pump behaviour: 2-phase head and torque degradation.
  - Forced convection with liquid: laminar and turbulent for IRSN, global for the other participants.
  - Film boiling: conduction and convection term for UPC, global for the other participants.
- Phenomenon "reflood (if not quoted in heat transfer in the dry zone)": In this phenomenon, only the heat transfers very close to the quench front are quoted. The other ones, such as film boiling are in the "heat transfer" phenomena even if the correlation applied during reflood is different from the case where there is no reflood.
- Some parameters appear twice in Table 4. That is the case for "complex of heat transfer", considered by NRI-1 for all the modes of heat transfer. The choice has been made to indicate "complex of heat transfer" twice: once for heat transfer in the rewetted zone, another time for heat transfer in the dry zone. That is also the case for the four parameters related to the liquid-interface heat transfer (Shah, stratified flows, droplet flows, droplet flows in reflood) considered by IRSN: they appear in both "condensation" and "evaporation" phenomena, the same correlations being used in the CATHARE code for both condensation and slow vaporisation.

Besides, some indications are written in red for KINS: "limit" for the parameters a limiting value of which is considered, "bias" for the parameters which are treated via a bias on the output parameters (see §2.3.2). Alternative models are indicated in blue characters.

Table 4. **Input parameters considered by the participants (using a probabilistic approach). Associated phenomena or physical laws**

		CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
number of input parameters		52	49	42	14	13	31	64	24	14
list of phenomena or main physical laws	**list of parameters**									
flow rates repartition in the circuit/pressure drops	form loss coefficient (active core)	y					y			
	form loss coefficient (core bypass)	y								
	core: pipe junction form loss coefficient									y
	form loss coefficient (broken cold leg)	y								
	form loss coefficient (broken hot leg)	y	y					y		
	form loss at branch (all branches)		y					y		
	form loss coefficient (RABS line)	y								
	form loss at upper bundle tie plate and spacers		y					y		
	momentum term approximation **(yes or no)**		y					y		
wall friction	**selection** of wall friction model		**y**					**y**		
	pipe wall friction: option 1		y					y		
	rod bundle wall friction: option 1		y					y		
	pipe wall roughness: option 2		y					y		
	rod bundle wall roughness: option 2		y					y		
	two-phase multiplier of pressure drop in vertical pipe (Martinelli-Nelson correlation)		y					y		
	two-phase multiplier of pressure drop in horizontal pipe (Martinelli-Nelson correlation)		y					y		
	void fraction dependent correction coefficient for fraction of water and steam in total wall friction		y					y		
	liquid-wall friction (pipe)			y						
	liquid-wall friction (volume)			y						
	vapour-wall friction (pipe)			y						
	vapour-wall friction (volume)			y						
flow rate at the break	initial fluid temperatures at the broken hot leg	y						y		
	initial fluid temperatures at the broken cold leg	y					y	y		
	containment pressure	y				limit	y	y		
	subcooled and saturated region: interface to liquid heat flux: flashing			y						
	subcooled region: interface to liquid heat flux: flashing	y								
	subcooled region: interface to liquid heat flux: flashing delay	y								
	subcooled region: wall-liquid friction	y								
	saturated region: interface to liquid heat flux: flashing	y								
	saturated region: interfacial friction	y								
	saturated region: wall-liquid friction	y								
	turbulence factor for evaporation in critical break flow model		y					y		
	Weisbach-Darcy wall friction coefficient		y					y		
	critical flow subcooled								y	
	critical flow two-phase								y	
	critical flow vapor								y	
	break area				y			y		
	subcooled and saturated region: break discharge coefficient					y				y
	subcooled region: break discharge coefficient						y			
	saturated region: break discharge coefficient						y			

Table 4 . **Input parameters considered by the participants (using a probabilistic approach). Associated phenomena or physical laws** (Cont'd)

		CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
number of input parameters		52	49	42	14	13	31	64	24	14
list of phenomena or main physical laws	**list of parameters**									
fuel thermal behaviour	initial core power	y	y	y		y	y	y	y	y
	peaking factors	y			y	limit	y	y	y	y
	pellet radius under cold conditions	y								
	gap size	y	y	y	y		y	y	y	
	gap conductivity	y		y				y	y	y
	gap conductance				y	y				
	decay power	y	y	y	y	y	y	y	y	y
	UO2 conductivity	y		y	y	y	y	y	y	y
	UO2 specific heat	y		y				y	y	y
	cladding thermal conductivity									y
	cladding volumetric heat capacity									y
	time of scram						y		y	
pump behaviour	2-phase head/torque degradation				y					
	2-phase head degradation	y	y			y		y		
	2-phase torque degradation	y				y				
	vapour flow: head	y								
	vapour flow: torque	y								
	2-phase degradation input of the pump						y			
	pump rotational speed						y			y
	time to trips PUMPS								y	
heat transfers in the rewetted zone	heat exchanges surfaces of structures	y								
	forced convection with liquid	y	y		y	y		y	y	
	liquid-wall heat transfer (laminar forced convection)			y						
	liquid-wall heat transfer (turbulent forced convection)			y						
	nucleated boiling	y	y	y	y	y		y	y	
	liquid-wall heat transfer (nucleate boiling) during reflood			y						
	single phase natural convection to water		y					y		
	complex of heat transfer models						y			
heat transfers in the dry zone	forced convection with vapour	y	y	y	y	y		y	y	
	alternative models:single phase forced convection to vapour: Dittus-Boelter or Mc Eligot		**y**					**y**		
	film boiling	y	y	y	y	y		y	y	
	film boiling during reflood			y						
	alternative models: film boiling: Dougall-Rohsenow or Condie-Bengston		**y**					**y**		
	conduction term of the wall to fluid HT in the film boiling regime									y
	convection term of the wall to fluid HT in the film boiling regime									y
	transition Film Boiling				y	y				y
	pool film boiling at natural convection		y					y		
	vapour-wall heat transfer (natural convection)			y						
	reflood: global heat transfer	y								
	complex of heat transfer models						y			
	Tmfs	y	y	y				y	y	
critical heat flux	critical heat flux	y	y	y	y	y	y	y	y	
	alternative models for CHF: minimum value or Biasi		**y**					**y**		

Table 4 . **Input parameters considered by the participants (using a probabilistic approach). Associated phenomena or physical laws** (Cont'd)

		CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
number of input parameters		52	49	42	14	13	31	64	24	14
list of phenomena or main physical laws	**list of parameters**									
ECC bypass	**alternative models**: liquid entrainment model in the DC						**y**			
	interfacial shear in the downcomer in bubble-slug flow	y								
	rate of entrainment E for annular flows in the downcomer	y								
	form losses of bypass between upper DC and UP		y		y		y	y		
	bypass area between lower plenum and upper plenum							y		
	flow cross section of RABV		y					y		
	ECC bypass (global)					bias				
interfacial friction	* blowdown:interfacial friction: co-courant flow in the DC and lower plenum draining	y								
	* reflood: interfacial friction upstream from the QF	y								
	* reflood:in the core downstream from the QF: drag coefficient in the expression of interfacial friction for annular flows	y								
	* interfacial friction in the core, the UP and the intact hot leg	y		y						
	interfacial shear in non-dispersed vertical pipe flow		y	y				y		
	interfacial shear in non-dispersed vertical bundle flow		y	y				y		
	interfacial shear in non-dispersed vertical DC flow		y	y				y		
	velocity of transition from non-dispersed to dispersed droplet flow in vertical bundle		y					y		
	critical velocity of transition from non-dispersed to dispersed droplet flow in vertical pipe and DC		y					y		
	interfacial shear in dispersed vertical droplet pipe flow		y					y		
	interfacial friction (annular flows)			y						
	alternative model for interfacial drag model of 2-phase flow (EPRI or Bestion)						**y**			
	interfacial drag (global)								y	
CCFL	CCFL in the upper core plate: c of Wallis correlation						y			
	CCFL in the UP: m of Kutateladze correlation						y			
	CCFL at the inlet of the SG tubes: c of Wallis correlation						y			
	CCFL in the DC: c of Wallis correlation						y			
	CCFl in the filler gap: c of Wallis correlation						y			
steam binding	interfacial shear in stratified and wavy horizontal pipe flow	y	y	y				y		
	interfacial shear in bubbly, slug and churn horizontal pipe flow		y					y		
	critical velocity of transition from stratified to slug flow in horizontal pipes		y					y		
	velocity of transition from non-dispersed to dispersed droplet flow in horizontal pipes	y	y					y		
	interfacial shear in dispersed horizontal droplet pipe flow		y					y		
	steam binding (global)					bias				

Table 4 . **Input parameters considered by the participants (using a probabilistic approach) Associated phenomena or physical laws** (Cont'd)

		CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
number of input parameters		52	49	42	14	13	31	64	24	14
list of phenomena or main physical laws	**list of parameters**									
condensation	direct condensation	y	y					y		
	liquid-interface heat transfer ("Shah" correlation)			y						
	liquid-interface heat transfer (stratified flows)			y						
	liquide-interface heat transfer (turbulences induced by injection)			y						
	liquid-interface heat transfer (droplet flows)			y						
	liquid-interface heat transfer (droplet flows) during reflood			y						
	jet temperature for injection of subcooled liquid			y						
	vapor-interface heat transfer in condensation (axial and 3D)			y						
	vapor-interface heat transfer in condensation (volume)			y						
evaporation	vapor-interface heat transfer	y								
	vapor-interface heat transfer (axial and 3D)			y						
	vapor-interface heat transfer (volume)			y						
	droplet diameter	y								
	number of bubbles per unit volume		y					y		
	number of droplets per unit volume		y					y		
	liquid-interface heat transfer in vaporization ("Shah" correlation)			y						
	liquid-interface heat transfer in vaporization (stratified flows)			y						
	liquid-interface heat transfer in vaporization(droplet flows)			y						
	liquid-interface heat transfer in vaporization(droplet flows) during reflood			y						
data related to injections	accumulator: available liquid volume	y					y		y	
	accumulator: gas volume above the level	y								
	accumulator: mass fraction of N2 dissolved in the water	y								
	accumulator pressure						y	y	y	
	accumulator set point								y	
	accumulator line form loss coefficient	y					y	y		
	initial accumulator liquid temperature							y		
	flow characteristic of liquid injection from the HPSI						y			
	flow characteristic of liquid injection from the LPSI						y			
data related to the pressurizer	pressure drop coefficient in the surge line	y						y		
	wall thickness of the pressurizer	y								
	pressurizer initial pressure						y		y	
	pressurizer level						y		y	
data specific to 0-D module	droplets fall velocity			y						
	bubbles rise velocity			y						
	phases distribution coefficient in volumes			y						
reflood (if not quoted in heat transfers in the dry zone)	k2: heat transfer accounted locally near the quench front (2-D meshing)	y		y						
	enhanced interface-wall heat transfer downstream quench front			y						
	HTC of rewetted side, upper QF		y					y		
	HTC of rewetted side, lower QF		y					y		
	alternative models: reflood activation model						y			
initial conditions: primary system	initial intact loop mass flow rate							y		
	initial intact loop cold leg temperature							y		
numerical parameters	convergence criterion		y					y		
	upper local absolute error of void fraction		y					y		

2.5.2 *Comparison of the considered phenomena*

Despite its relative arbitrariness, information can be obtained from Table 4. Table 5 lists the number of input parameters considered by each participant2 for each phenomenon/physical law.

Table5. **Number of input parameters considered for each phenomenon / physical law by each participant**[2]

(using a probabilistic approach, i.e. with propagation of the uncertainty of input parameters)

phenomena or main physical laws	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
	CATHARE V2.5	ATHLET 1.2C	CATHARE V2.5	MARS 2.3	RELAP5 /MOD3.3	RELAP5/MOD3.3	ATHLET Mod 2.0 - Cycle A	TRACE v 4.05	RELAP5/MOD3.3
	52	**49**	**42**	**14**	**13**	**31**	**64**	**24**	**14**
flow rates repartition /pressure drops	5	4				1	4		1
wall friction		8	4				8		
flow rate at the break	9	2	1	1	1	4	6	3	1
fuel thermal behaviour	8	3	6	5	4	6	7	8	8
pump behaviour	4	1		1	2	2	1	1	1
heat transfers in the wet zone	3	3	4	2	2	1	3	2	
heat transfers in the dry zone	4	6	5	3	3	1	6	3	3
critical heat flux	1	2	1	1	1	1	2	1	
ECC bypass	2	2		1		2	3		
interfacial friction	4	6	5			1	6	1	
CCFL						5			
steam binding	2	5	1				5		
condensation	1	1	8				1		
evaporation	2	2	6				2		
data related to injections	4					5	3	3	
data related to the pressurizer	2					2	1	2	
data specific to 0-D module			3						
reflood (if not quoted in heat transfers in the dry zone)	1	2	2			1	2		
initial conditions: primary system							2		
numerical parameters		2					2		

It may be noted that:

- 20 phenomena are considered in total.
- 3 phenomena, indicated in yellow, are considered by all the participants (i.e. 9 participants). They are:
  - Flow rate at the break.
  - Fuel thermal behaviour.
  - Heat transfer in the dry zone.
- 3 other phenomena, indicated in blue, are considered by all the participants apart from one (i.e. 8 participants). They are:
  - Pump behaviour.
  - Heat transfer in the wet zone.
  - Critical heat flux (which could be included into the item "heat transfer in the dry zone").
- The other phenomena are considered by a maximum of 6 participants.

2.5.3 *List of the most commonly considered input parameters*

More than 150 input parameters are considered. In addition to the part of arbitrariness used by each participant to establish the list of the uncertain input parameters coming from expert judgement, this high number can be explained because the used codes are different: the way of modelling the same phenomenon depends of course on the code being used.

2. Due to the fact that "complex of heat transfer" and four correlations related to liquid-interface heat transfer are quoted twice respectively for NRI-1 and IRSN (see §2.4.1), the sum of the numbers of parameters related to each phenomenon is higher than the real number of input parameters considered by these two participants.

However, one can list the input parameters which are most often considered. These parameters are of course related to the 6 phenomena quoted above, considered by 9 or 8 participants. No parameter associated with the break flow rate is considered by 9 or 8 participants: in fact, some participants consider directly the break area or the discharge coefficient at the break, others consider physical laws a priori influential for the break flow rate such as liquid-interface heat transfer, and others still consider boundary conditions such as the containment pressure. The parameters associated with pump behaviour are also rather dispersed: 2-phase head or torque degradation in the majority of the cases, but also pump velocity or time to trip pumps. The results are presented on the tables below, the critical heat flux being in the table for parameters related to the heat transfer in the dry zone. The indications of colours are the same as for Table 5, i.e. yellow for the parameters considered by all the participants, and blue for those considered by all the participants apart from one.

Table 6. **Fuel related parameters considered by the participants** (using a probabilistic approach)

fuel related parameters	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
	CATHARE V2.5	ATHLET 1.2C	CATHARE V2.5	MARS 2.3	RELAP5 /MOD3.3	RELAP5/MOD3.3	ATHLET Mod 2.0 - Cycle A	TRACE v 4.05	RELAP5/MOD3.3
	8	**3**	**6**	**5**	**4**	**6**	**7**	**8**	**8**
initial power	yes	yes	yes		yes	yes	yes	yes	yes
peaking factor	yes			yes	limit	yes	yes	yes	yes
pellet radius under cold conditions	yes								
gap size	yes	yes	yes	yes		yes	yes	yes	
gap conductivity	yes		yes				yes	yes	yes
gap conductance				yes	yes				
decay power	yes	yes	yes	yes	yes	yes	yes	yes	yes
fuel conductivity	yes		yes	yes	yes	yes	yes	yes	yes
fuel specific heat	yes		yes				yes	yes	yes
clad conductivity									yes
clad specific heat									yes
time of scram						yes		yes	

Concerning the gap, two options are equivalent. The first one consists in considering both cold gap thickness and gap conductivity, the second one in considering only gap conductance, associated with the heat transfer from the fuel pellets to the clad. The first option makes probably easier the determination of the ranges of variation associated to the input parameters. For Table 6, as 3 participants consider either only the cold gap thickness, or only the gap conductivity, it cannot be said that input parameters associated to the gap are considered by all the participants, or even by all the participants apart from one. As a consequence, they are indicated in orange.

Table 7. **Parameters related to the heat transfer in the dry zone considered by the participants** (using a probabilistic approach)

parameters related to the heat transfer in the dry zone	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
	CATHARE V2.5	ATHLET 1.2C	CATHARE V2.5	MARS 2.3	RELAP5 /MOD3.3	RELAP5/MOD3.3	ATHLET Mod 2.0 - Cycle A	TRACE v 4.05	RELAP5/MOD3.3
	5	**8**	**6**	**4**	**4**	**2**	**8**	**4**	**3**
forced convection with vapour	yes	yes	yes	yes	yes	*included in complex of HT*	yes	yes	
alternative models for forced convection		yes					yes		
film boiling	yes	yes	yes	yes	yes	*included in complex of HT*	yes	yes	
film boiling during reflood			yes						
alternative models for film boiling		yes					yes		
conduction term in the film boiling regime									yes
convection term in the film boiling regime									yes
transition film boiling				yes	yes	*included in complex of HT*			yes
pool film boiling at natural convection		yes					yes		
vapour-wall heat transfer (natural convection)			yes			*included in complex of HT*			
reflood: global HTC	yes								
complex of heat transfer						yes			
Tmfs	yes	yes	yes				yes	yes	
critical heat flux	yes	yes	yes	yes	yes	yes	yes	yes	
alternative models for CHF		yes					yes		

Film boiling is not strictly considered by all participants. But NRI-1 considers the same parameter, with the same pdf for all the modes of heat transfer, including of course film boiling. UPC separates two processes in film boiling: conduction and convection. Consequently, saying that film boiling is considered by all the participants seems correct.

Table 8. **Parameters related to the heat transfer in the wet zone considered by the participants** (using a probabilistic approach)

parameters related to the heat transfer in the wet zone	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
	CATHARE V2.5	ATHLET 1.2C	CATHARE V2.5	MARS 2.3	RELAP5 /MOD3.3	RELAP5/MOD3.3	ATHLET Mod 2.0 - Cycle A	TRACE v 4.05	RELAP5/MOD3.3
	3	**3**	**4**	**2**	**2**	**1**	**3**	**2**	**0**
heat exchange surfaces of structures	yes								
forced convection with liquid	yes	yes		yes	yes	*included in complex of HT*	yes	yes	
forced convection with liquid: laminar			yes						
forced convection with liquid: turbulent			yes						
nucleated boiling	yes	yes	yes	yes	yes	*included in complex of HT*	yes	yes	
nucleated boiling during reflood			yes						
single phase natural convection to water		yes				*included in complex of HT*	yes		
complex of heat transfers						yes			

These 3 tables can be summed up as follows:

- Roughly 150 parameters are considered in total.
- 2 parameters, indicated in yellow, are considered by all the participants (i.e. 9 participants). They are:
  - Decay heat.
  - Film boiling.
- 6 other parameters, indicated in blue, are considered by all the participants apart from one (i.e. 8 participants). They are:
  - Initial power.
  - Fuel conductivity.
  - Forced convection with vapour.
  - Critical heat flux.
  - Forced convection with liquid.
  - Nucleate boiling.

Parameters related to the gap are considered by all the participants, but not in the same way. 4 participants consider the gap thickness plus the gap conductivity, 2 participants the gap conductance.

2.5.4 Comparison of the ranges of variation of the input parameters

Introduction

This comparison is made only for the most commonly considered input parameters, i.e. fuel related parameters and parameters related to heat transfers. Only the spread of the distributions is easily comparable, and not the shape of this distribution. Nevertheless, it must be noticed that this shape is also important: a broader distribution that tapers off towards the ends can be largely equivalent to a uniform but much narrower distribution. A study about the choice of the PDF: uniform instead of normal and log-uniform instead of log-normal, has been made by a participant in the Step 10 (CEA, cf. §5.1.4).

Fuel related parameters

The width of the uncertainty bands is plotted in Figure 4, for each parameter if it is considered by a rather large number of participants. An exception is made for gap conductance, considered only by two participants but equivalent to the gap size if associated with gap conductivity, this case being considered by a larger number of participants.

The plotted widths correspond to the (max-min) value in the case of a naturally truncated law, such as uniform law. For the not naturally truncated laws, the widths correspond to [m-2σ; m+2σ] for a normal law, to [$e^{m-2\sigma}$; $e^{m+2\sigma}$] for a log-normal law. All the widths have been converted in % of the reference value, to allow comparison. The uncertainties of gap conductivity, fuel conductivity and fuel specific heat are given in the unit of the parameter by PSI and to a less extent by UPC. In this case too, they have been converted in %, but by considering a mean value instead of a reference value, which is not defined. These mean values are given by UPC in its contribution for the fuel properties. For the gap conductivity, the value at 1 000 K, i.e. 0.35 W/(mK), has be retained. In Figure 4, these special cases are indicated by a dark yellow colour for PSI and a pale blue colour for UPC.

For each parameter, the largest uncertainty band is plotted in red, whereas the narrowest one is plotted in yellow.

The way with which the uncertainties have been quantified can explain the differences among the participants. There are three main cases:

1. For the initial power and the peaking factor, the LOFT documentation is used but is not understood in the same way by all the participants. The majority of them consider that the uncertainty found in the LOFT documentation corresponds with two times the standard deviation, whereas NRI-1 considers that it corresponds with one standard deviation.
2. For the decay heat, an international norm exists but is not considered by all the participants (CEA, GRS and IRSN).
3. For the other parameters, expert judgement is used.

Figure 4. **Comparison of the ranges of variation of most of the fuel related input parameters**

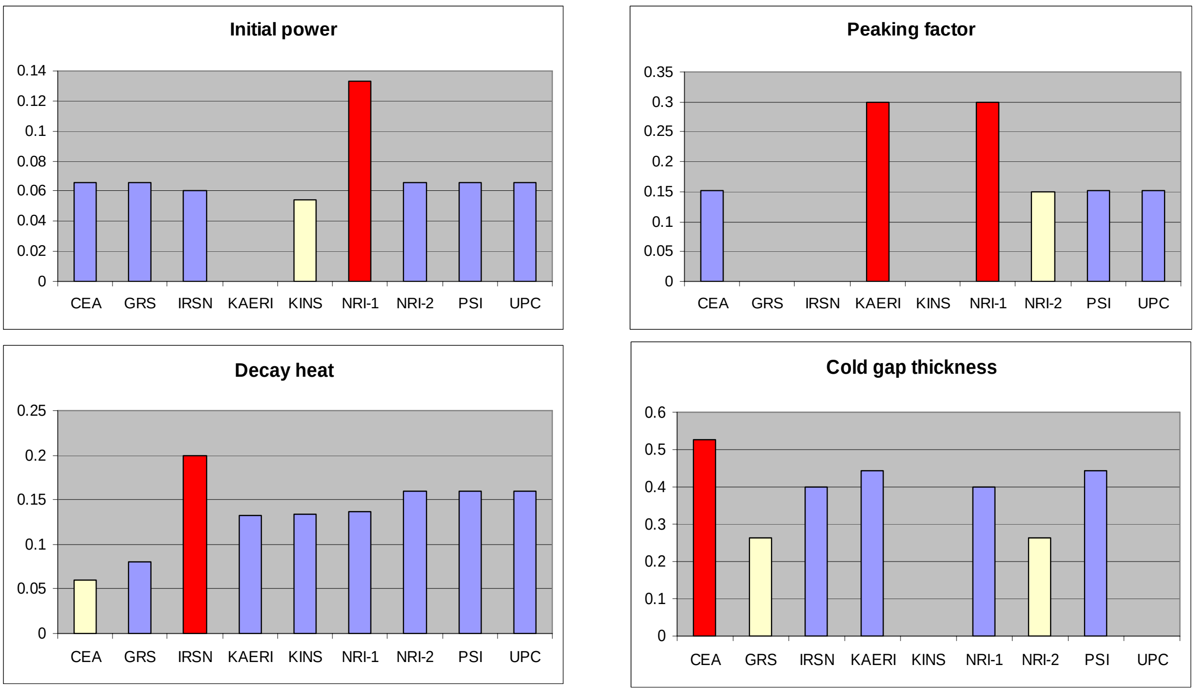
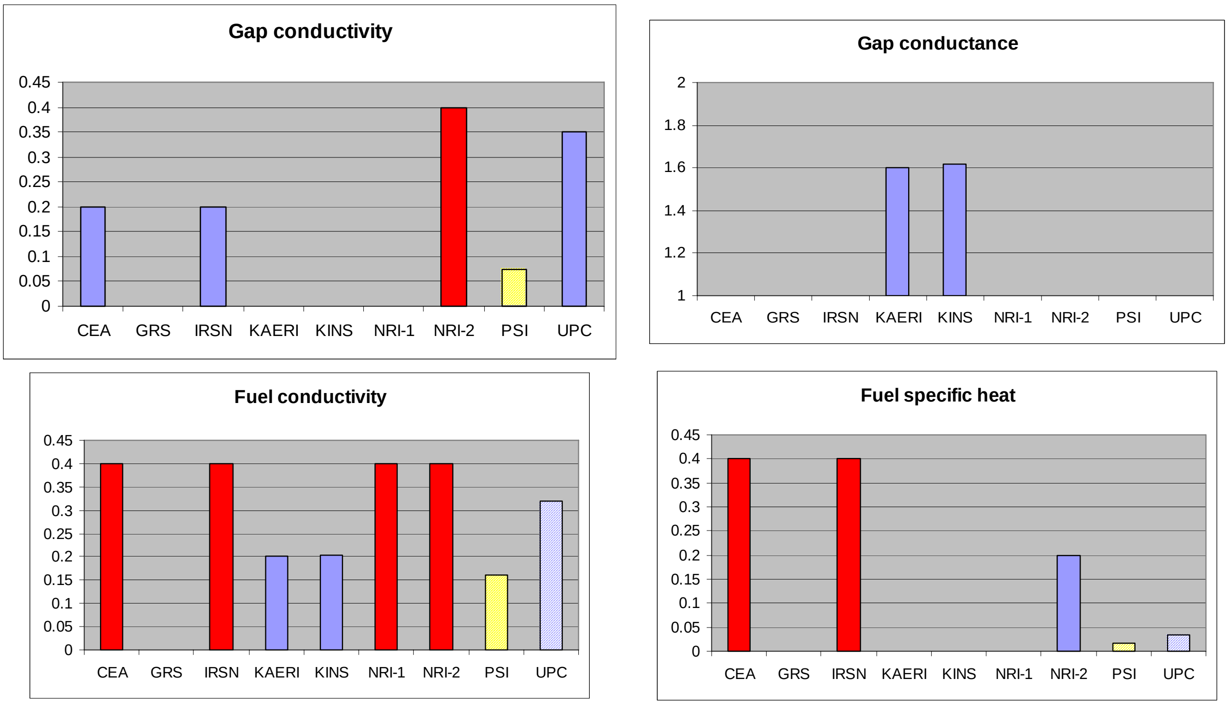


Figure 4. **Comparison of the ranges of variation of most of the fuel related input parameters** (Cont'd)



Parameters related to the heat transfer (dry and wet zones)

The width of the uncertainty bands is plotted in Figure 5, with the same conventions as for the fuel related parameters: red for the largest uncertainty band, yellow for the narrowest one. It is apparent that two values are given by CEA for forced convection with vapour and film boiling, depending on the phase of the transient: before or during reflood. In this latter case, only a global heat transfer coefficient is given.

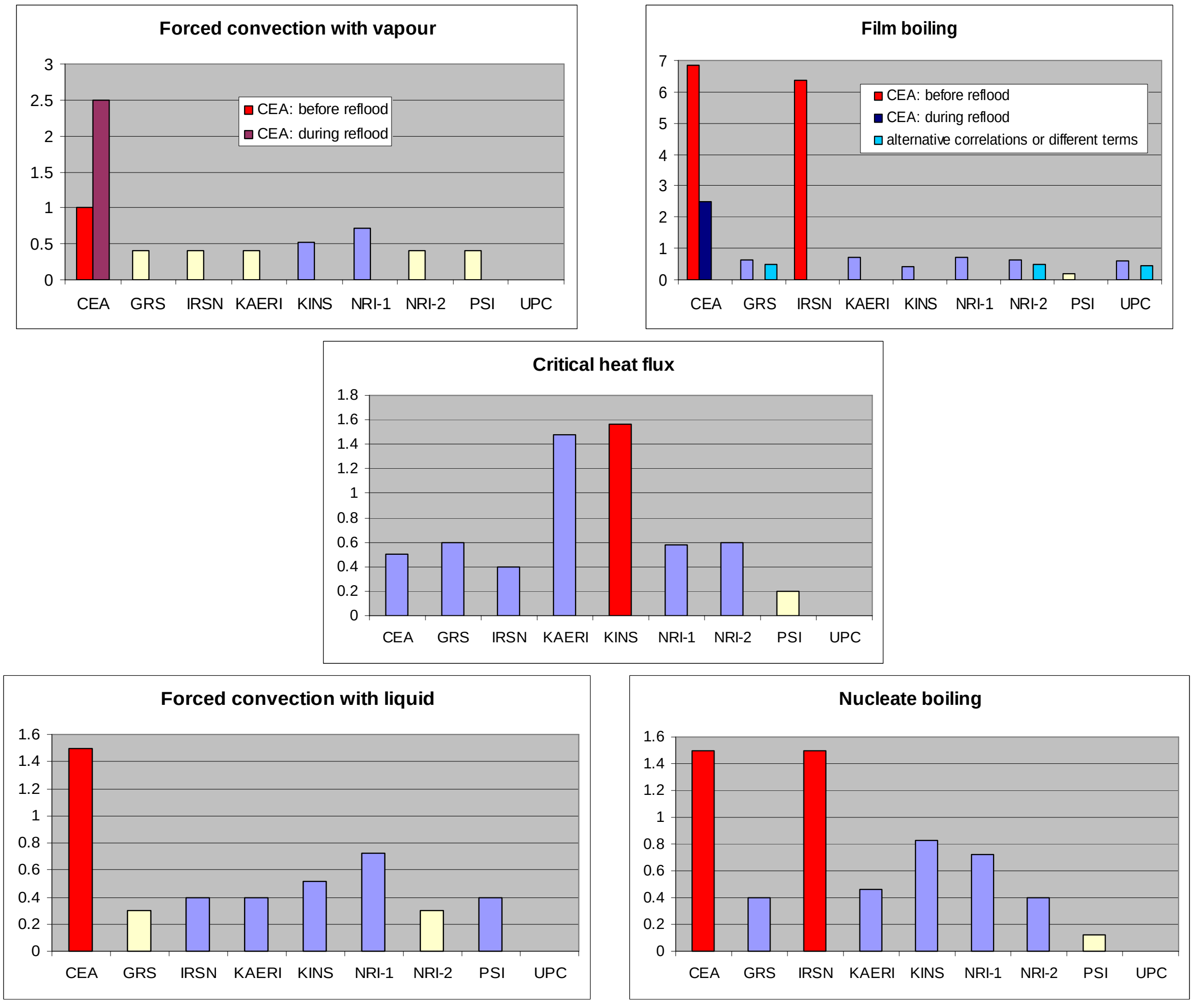
In the same way, two correlations are considered by GRS and NRI-2 for forced convection with vapour and film boiling. But for forced convection with vapour, the width of the uncertainty bands is the same for both correlations, and consequently only this common value is plotted. For film boiling, the width of both uncertainty bands is plotted.

Finally, UPC considers two input parameters for film boiling: the first one is the conduction term in the film boiling regime, whereas the second one is the convection term. The width of both uncertainty bands is plotted.

It should be noted that, unlike the fuel related parameters, the parameters associated with heat transfer are dependent on the code and do not necessarily correspond with the same modelling. As a consequence, their comparison is more doubtful. It is moreover apparent that their ranges of variation display much greater variety than those of the fuel related parameters.

For example, that is probably the case of the film boiling considered by the CATHARE users (CEA, IRSN) for which the uncertainty is larger that the one found by the other participants. Two other reasons can be given to explain this difference about the film boiling. The fist one is that the method used by the CATHARE users is different from the method used by the majority of the other participants. For example, CEA has determined the uncertainty of the film boiling before reflood by comparing extensively code and experimental results of WINFRITH and INEL experiments, whereas the users of RELAP5 take their information from the RELAP5 Code Manual. However that is not the only reason because ATHLET users (GRS and NRI-2) consider also experimental results. But in this case, the way of doing is probably different: CEA makes the hypothesis that the uncertainty of the film boiling is the only cause of the differences of code and experimental results, whereas different correlations (forced and natural convection, etc.) are considered by GRS.

Figure 5. **Comparison of the ranges of variation of the parameters related to the heat transfer**



2.6 First conclusions about the input parameters

This part was mainly aimed at comparing the input parameters considered by the participants using a probabilistic method. The number of the inputs ranges from 13 to 64. The list of all the inputs is given in Table 4 and shows a large variety since, among a total of more than 150 input parameters, only two parameters are considered by all the participants, and six by all the participants apart from one. The use of different codes with different models for a same physical phenomenon can only partly explain this observation.

On the basis of this observation, the comparison of the sensitivity analysis results is going to be particularly of interest. It is performed in Chapter 4: “Part 3: Sensitivity Analysis Results”, with synthesis tables and figures of the potentially influential parameters (Tables 12 and 13, Figures 19 and 20).

3. PART 2:
UNCERTAINTY ANALYSIS RESULTS

3.1 Steps 5 and 6: Main features of the methods

Except for UNIPI, all the participants use a fully probabilistic approach with propagation of the uncertainties of input parameters and associated with Wilks' formula. The main features of these fully probabilistic methods are reported in Table 9. UNIPI does not appear on this table, because its column would be empty. Its method can be seen as a method of propagation of output errors.

The main common features and the main differences of the participants using a probabilistic approach are:

3.1.1 Common features (not reported in Table 9)

- Sampling: Simple Random Sampling (SRS) as it is advisable for the use of Wilks' formula.
- Dependencies between the input parameters: no dependency. The main reason for that is the difficulty to find dependencies from a physical point of view. In addition to that, even if dependencies do exist, estimating the marginal laws is too difficult. Besides, in the case of two strongly dependent parameters, it is preferred to consider only one of them. The only exception for independence is the case of alternative correlations: in this case, the correction factor for an alternative model is used under the condition that this model is selected by another parameter.

3.1.2 Differences (reported in Table 9)

The two main differences are:

- The order at which Wilks' formula is applied: order 1 for four participants, 2 for four participants and 3 for one participant. It is reminded below how Wilks' formula can be applied to different orders. The n realisations of the considered output parameter Y are sorted in increasing order: Y(1)<Y(2)….Y(n-2)<Y(n-1)<Y(n).

  To obtain an upper tolerance limit of a α-percentile with a β confidence level, one can consider:

  − Y(n): Wilks at the order 1. For α = β = 95%, 59 code runs are needed.
  − Y(n-1): Wilks at the order 2. For α = β = 95%, 93 code runs are needed.
  − Y(n-2): Wilks at the order 3. For α = β = 95%, 124 code runs are needed.

  It may be noted that some participants consider a little more code runs than needed for Wilks' formula. For example, CEA and GRS perform 100 successful code runs for Wilks at the order 2. In this case, the α-percentile is always 95%, but it is obtained with a slightly higher level of confidence (β = 96.3%).

- The treatment of failed calculations.

  In fact, there are four cases:

  1. No failure (GRS, NRI-1)
  2. Some code failures, but they are all corrected (CEA, NRI-2)

3. Some code failures, but there are sufficient successful code runs to apply Wilks' formula with $\beta \geq 95\%$ (KAERI, PSI, UPC).
4. Some code failures, discarded as in the former case, but there are not sufficient samples of the output parameters to apply Wilks' formula, at least with $\beta \geq 95\%$ (IRSN, KINS).

In the two last cases, attention is generally paid to check that the discarded code runs correspond, just before the time of failure, to values of the output parameter falling within the tolerance bands. It must be added that the failures occur generally rather late in the transient.

Another less important difference is the truncation of the pdf. It concerns only the participants using normal or log-normal laws for some of their input parameters. The most severe truncation ($\mu \pm 2\sigma$) is performed by KAERI and NRI-1, but they use also uniform distributions, not concerned by truncation. CEA uses a less severe truncation ($\mu \pm 3.09\sigma$) but this time, it concerns all its considered input parameters. In Part 4, CEA has studied the effect of a change of truncation: ($\mu \pm 2\sigma$) instead of ($\mu \pm 3.09\sigma$): it leads to a slight decrease of the upper bound of the first PCT: around 15K.

Table 9. **Main features of the probabilistic methods* used for uncertainty analysis**

	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
Mean CPU time (s)	7200	7858	12070	560	1000	2753	3127	5664	1320
Number of parameters	53	49	42	14	13	31	64	24	14
Types of laws	Normal Log-normal	Uniform Log-uniform Triangular Log-triangular Log-normal Histogram Polygonal discrete	Uniform histograms	Uniform normal	Uniform Normal	Uniform Normal Discrete	Uniform Log-uniform Triangular Log-triangular normal Log-normal Histogram Polygonal discrete	Uniform normal	Uniform Normal trapezoidal
truncation	$\mu \pm 3.09\sigma$	Log-normal: not truncated except for one parameter	Naturally bounded	Normal: $\mu \pm 2\sigma$	Normal: $\mu \pm 3.09\sigma$	Normal: $\mu \pm 2\sigma$	Normal and log-normal: not truncated except for one parameter	Normal: $\mu \pm 3\sigma$	Normal: not truncated
Number of computations, including failed code runs	100	100	59	100	59	59	60	150	100
Wilks' order	2	2	1	2	1	1	1	3	2
Calculation failure	All the code failures are corrected	No failure	11 code failures after the reflood beginning, discarded	7 code failures, discarded	2 code failures, discarded	No failure	All the code failure are corrected	22 code failures, discarded	1 code failure, discarded

*: Propagation of the uncertainties of input parameters

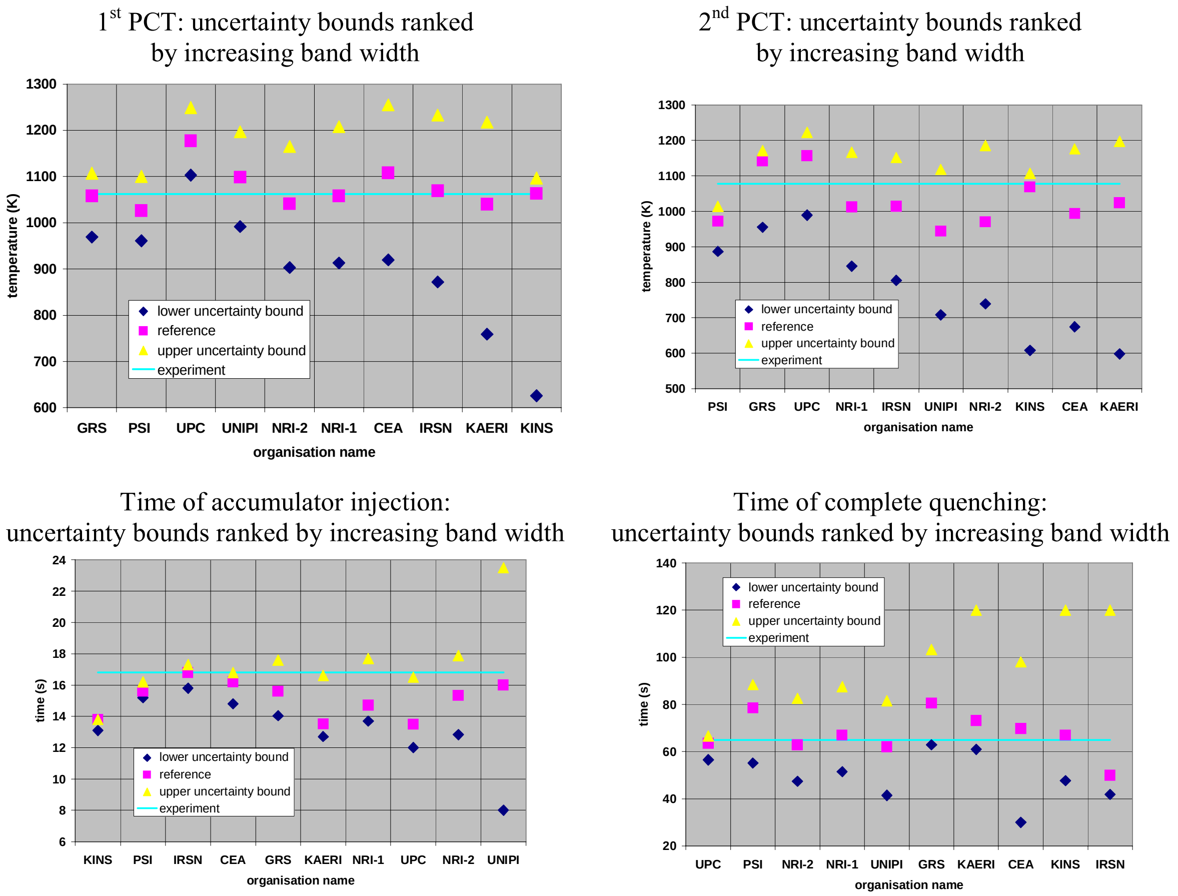
3.2 Step 7: Uncertainty results

3.2.1 For the four single-valued output parameters

Uncertainty bands

The results are presented in Figure 6. They are ranked by increasing order of the band width.

Figure 6. **Uncertainty analysis results for the four single-valued output parameters**



The following observations can be made:

- First PCT: Only one participant (UPC) does not envelop the experimental PCT, due to a too high lower bound. Two reasons can explain this result: among all the participants, on the one hand, UPC has the highest reference value, on the other hand, its band width is among the most narrow ones. The spread of the uncertainty bands is within 138-471 K.
- Second PCT: In this case too, only one participant (PSI) does no envelop the experimental PCT, due this time to a too low upper bound. The reasons are roughly similar to those given for the first PCT: PSI finds a too low reference value, as several participants, but has also the specificity to consider a narrow uncertainty band. The spread of the uncertainty bands is within 127-599 K.
- Time of accumulator injection: Four participants among ten calculate too low upper bounds (KINS, PSI, KAERI and UPC), whereas CEA finds an upper bound just equal to the experimental value. These results are in relationship with the prediction of the pressure of the upper plenum. The band widths vary within 0.7-5.1 s for all the participants except for UNIPI which finds a much larger band, equal to 15.5 s.
- Time of complete quenching: All the uncertainty bands envelop the experimental value, even if the upper bound is close to the experimental value for one participant. The width of the

uncertainty range varies from 10 s to more than 78 s (If the core is not yet quenched at the end of the calculation as it is the case for two participants (KAERI, KINS), or if there are several code failures before the complete quenching (IRSN), the upper bound is plotted at 120 s in Figure 6).

Empirical distributions

Empirical distributions of the four scalar output parameters have been plotted for each contribution. For each participant, the number of classes is taken according to a quite classical rule, i.e. roughly equal to $\sqrt{n}$, n being the number of code runs. As a consequence, it must be noted that the width of each class is different according to the participant. Besides, all these results must be considered with caution due to the rather low number of realisations (roughly between 50 and 150, depending on the order at which Wilks' formula is applied and the number of failed code runs).

No general trend can be observed for the form of the distributions. Indeed all the following cases occur:

1. A smooth distribution, with a clear maximum. This case is the most frequent for both PCT. Depending on the participant, the distribution can be considered as symmetrical or not. A good example of a symmetrical distribution is the case of the 1^{st} PCT found by CEA, whereas an example of an asymmetrical distribution is the case of the 2^{nd} PCT found by NRI-1. In such cases, it seems possible to fit a theoretical distribution to the empirical one.
2. A continuous distribution, but the maximum is difficult to identify. It is the case especially for the time of accumulator injection, the result found by UPC being perhaps the best illustration of this kind of results. Fitting a theoretical distribution to the empirical one seems more difficult than in the first case, nevertheless the hypothesis of a uniform distribution is plausible.
3. A distribution with one or two realisations far from the other realisations. This case is encountered several times: KINS for the 1^{st} PCT, KAERI for the 2^{nd} PCT, KINS and to a less extent NRI-1 for the time of full quenching, etc. It explains why KAERI and KINS find large band widths for the temperature-type responses (including the time of full quenching): the lower bound corresponds to only one or two code runs, the results of which are very different from the other ones.
4. A distribution with a high number of realisations at a bound of the distribution. This case occurs for the 2nd PCT (KINS) and for the time of complete quenching (KAERI).
5. A distribution with few isolated peaks. It occurs only for the time of accumulator injection (IRSN, PSI).

As a conclusion, except for the first case, testing the fit of classical distributions to the empirical distributions does not seem always possible. Even when it seems possible, that is to say for the first case (1^{st} and 2^{nd} PCT), making inference on the basis of 59 realisations or even 150 is dangerous: no confidence can be attributed to such distributions. Consequently it is preferable to determine an estimation of the 5% and 95% percentiles by the direct use of Wilks' formula, even if it is a minoring (respectively a majoring) value in β cases (β = confidence level) and not by using the properties of a fitted classical distribution.

3.2.2 For the time trend: maximum cladding temperature

As for both PCT, the two main features of the results are: the majority of the participants envelop the experimental data during the whole transient (if the very first times are not considered) and the width of the uncertainty bands is much dispersed. Table 10 summarises the features of all the contributions.

Table 10. **Maximum cladding temperature: main features of uncertainty results and reference calculation**

		CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UNIPI	UPC
Envelops the experimental data?		yes, but upper bound close to experiment between 30 and 50 s	yes	yes, except around 50 s: upper bound slightly lower than exp.	yes	yes	yes, but upper bound close to experiment around 50-60 s	yes	no	yes	no
Features of the uncertainty band before the quench front completion	Width	large	narrow	medium	large	large	medium	large	narrow	medium	narrow
	Lower bound	very low			very low	very low		very low			
	Upper bound	close to experimental data		close to experimental data			close to experimental data		too low		too low
Reference calculation	Maximum code-experiment differences before the quench front completion	between 150 and 250 K	less than 150 K	more than 250 K	less than 150 K	less than 150 K	between 150 and 250 K	between 150 and 250 K	less than 150 K	less than 150 K	between 150 and 250 K
	Under or over-estimated?	under-estimated after 10 s	slightly under-estimated before 30 s, over-estimated after 30 s	under-estimated	under-estimated	very close	under-estimated after 10 s	under-estimated	under-estimated	under-estimated after 20 s	over-estimated before 25 s, under-estimated after 25 s

Both Figure 7 and Figure 8 illustrate the width of the uncertainty band. In these figures, both contributions which do not envelop the experimental data are indicated in bold. Figure 8 is a zoom of Figure 7, between 10 and 50 s. Table 10 makes reference to the latter observation. The uncertainty bands ranging from 100 to 700 K, three classes of widths can be distinguished even if it is a little bit arbitrary: 100-300, 300-500; 500-700. As a consequence, if its width is less than 300 K, the band is considered as narrow, if it is wider than 500 K, it is considered as large.

Figure 7. **Maximum cladding temperature: uncertainty band widths**

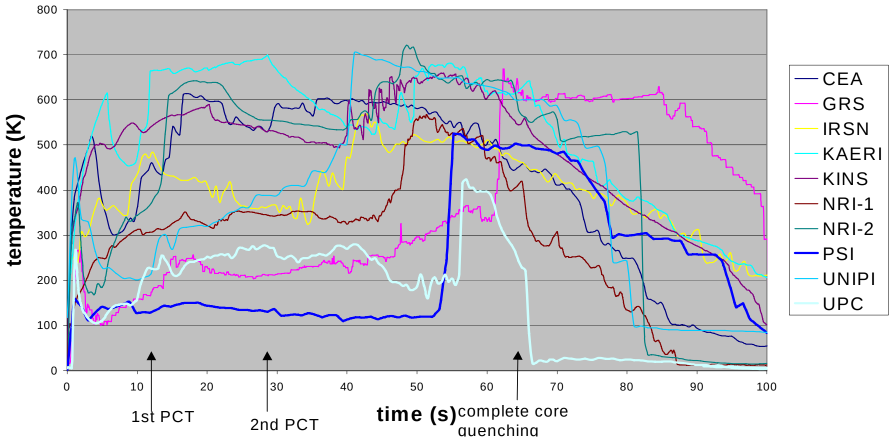
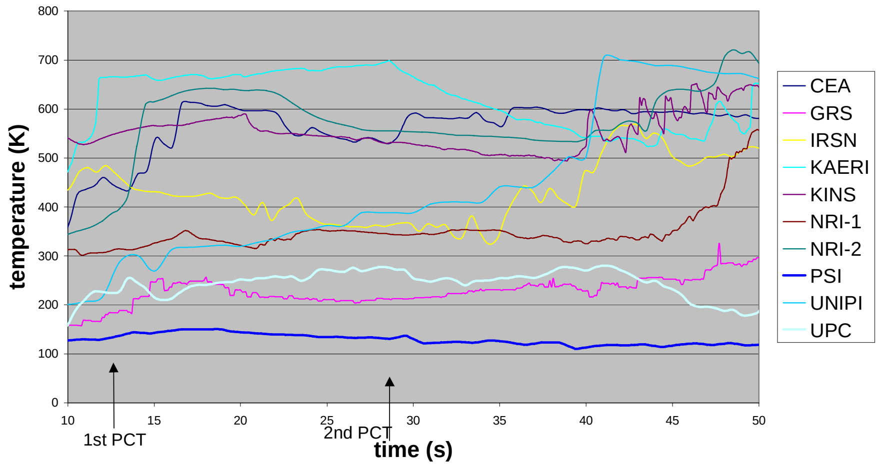
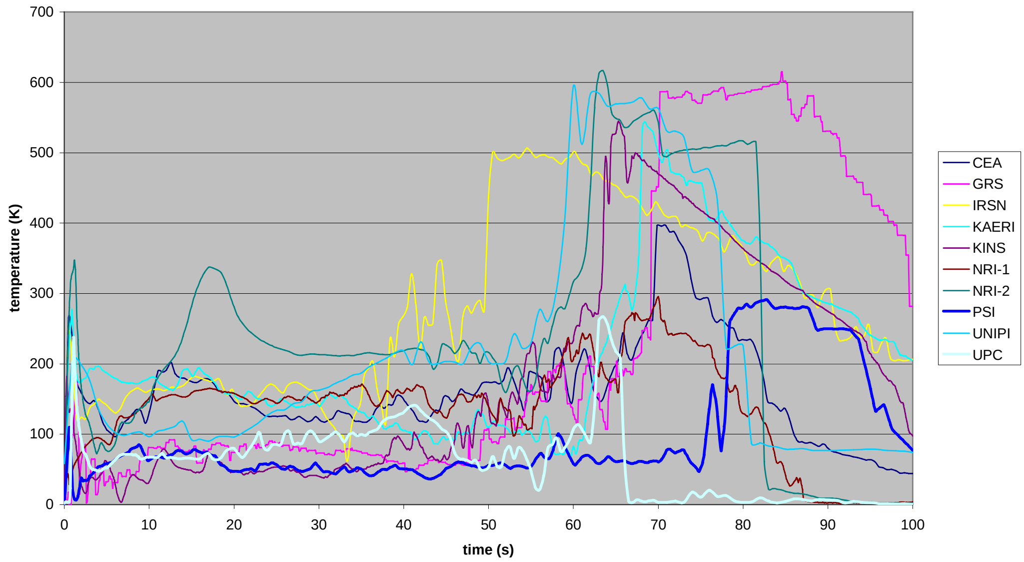


Figure 8. **Maximum cladding temperature: uncertainty band widths: zoom**



Another way to present the results is to plot the difference between the upper bound and the reference calculation for all the participants, since in a safety analysis, the upper bound is the quantity of interest. It is performed in Figure 9, with, as for Figure 7 and Figure 8, the contributions which do not envelop the experimental data indicated in bold. The dispersion of this difference is less than the dispersion of the uncertainty band itself, at least before 50 s: it is less than 200 K, except for NRI-2 around 20 s and IRSN from 40 s, where it exceeds slightly 300 K. One can note also that the lowest differences are observed for the same participants as those who obtain the most narrow uncertainty bands: PSI, UPC and GRS. There is however an exception: the KINS uncertainty band is large (more than 500 K, see Figure 7) whereas its difference "upper bound minus reference calculation" is around 50 K.

Figure 9. **Maximum cladding temperature: upper bound minus reference calculation**



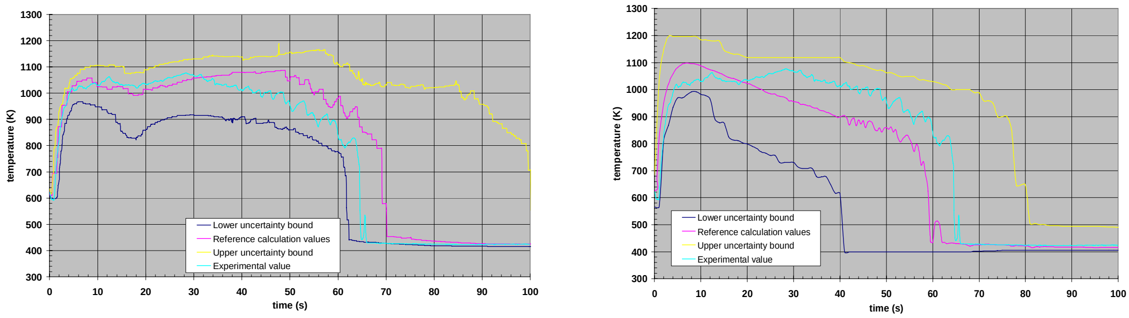
Finally four cases can be roughly distinguished, even if there is a certain continuity from a case to another one.

- Case 1: GRS and to a less extent UNIPI (Figure 8). The uncertainty band envelops the experimental data without being very large. This good result can be partly explained because the reference calculation is rather close to the experiment. Concerning GRS, another explanation might be that this participant does not consider material properties among its uncertain parameters, which can lead to a narrower uncertainty band with respect to the other participants. The UNIPI method (the CIAU) is different from the method used by the other participants, not considering input parameter uncertainties but extrapolating deviations between calculation results and measured data.

Figure 10. **Uncertainty analysis of the maximum cladding temperature – case 1**

GRS: maximum cladding temperature

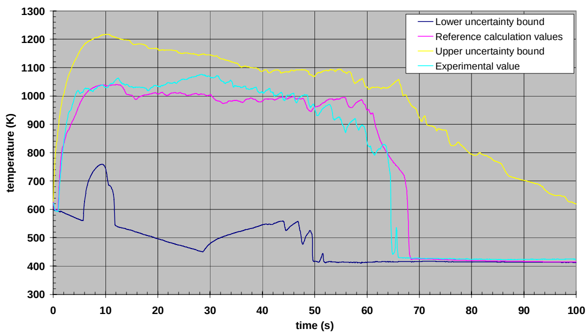
UNIPI: maximum cladding temperature



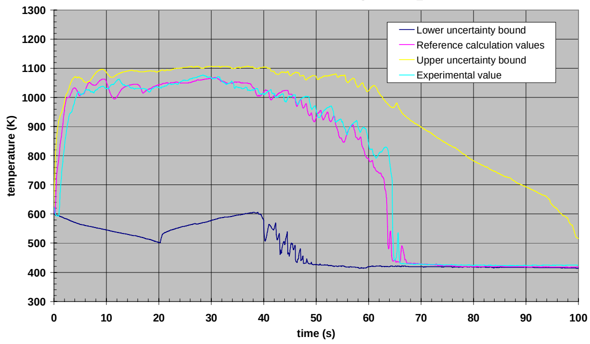
- Case 2: KAERI, KINS and to a less extent NRI-2 (Figure 11). The uncertainty band envelops the experimental data but is large. In particular, the lower bound is very low, close to the saturation temperature. In this case, the quality of the reference calculation is less important than in the case 1. Nevertheless, KAERI and KINS calculations are very close to the experimental results whereas it is less true for NRI-2. KAERI notices that uncertainty ranges assigned to the input parameters requires a subjective decision, often with conservative assumptions. It explains the width of the uncertainty band, but not the fact that the lower bound is almost at saturation. KAERI does not introduce biases for its input parameters (except for the break area). But it can be observed that this bound is obtained with only one or two isolated code runs among the 100 performed code runs, which correspond may-be to a change of scenario, a kind of “bifurcation”. KINS explains the value of the lower bound by the high upper value of the uncertainty of the gap conductance: it is multiplied by 3.1 for (μ + 3.09σ. Another explanation is perhaps the fact that KINS considers limiting conservative values for the containment pressure and the peaking factor. NRI-2 does not give explanations. Nevertheless, it may be noted that NRI-2 uses the same code as GRS: ATHLET, but not with the same version and especially with an increased number of uncertain parameters: 64 instead of 49, the 48 first parameters of GRS being also considered by NRI-2 with the same pdf. Then some of these additional parameters are found as being relevant in sensitivity analysis for the PCT and the time trend of the maximum cladding temperature. That is the case of the fuel conductivity, the form loss in broken loop hot leg, the intact loop cold leg initial temperature, the break valve area, the form loss in accumulator injection line and the fuel specific heat capacity.

Figure 11. **Uncertainty Analysis of the maximum cladding temperature – case 2**

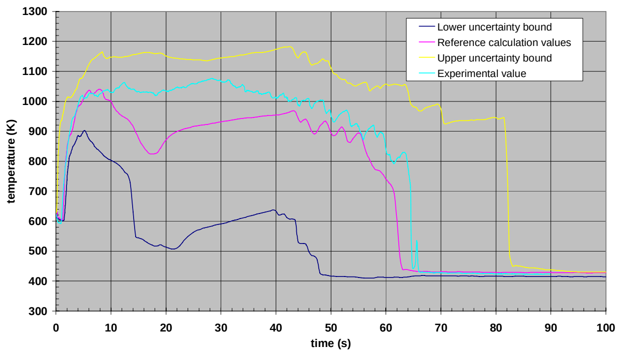
KAERI: maximum cladding temperature



KINS: maximum cladding temperature

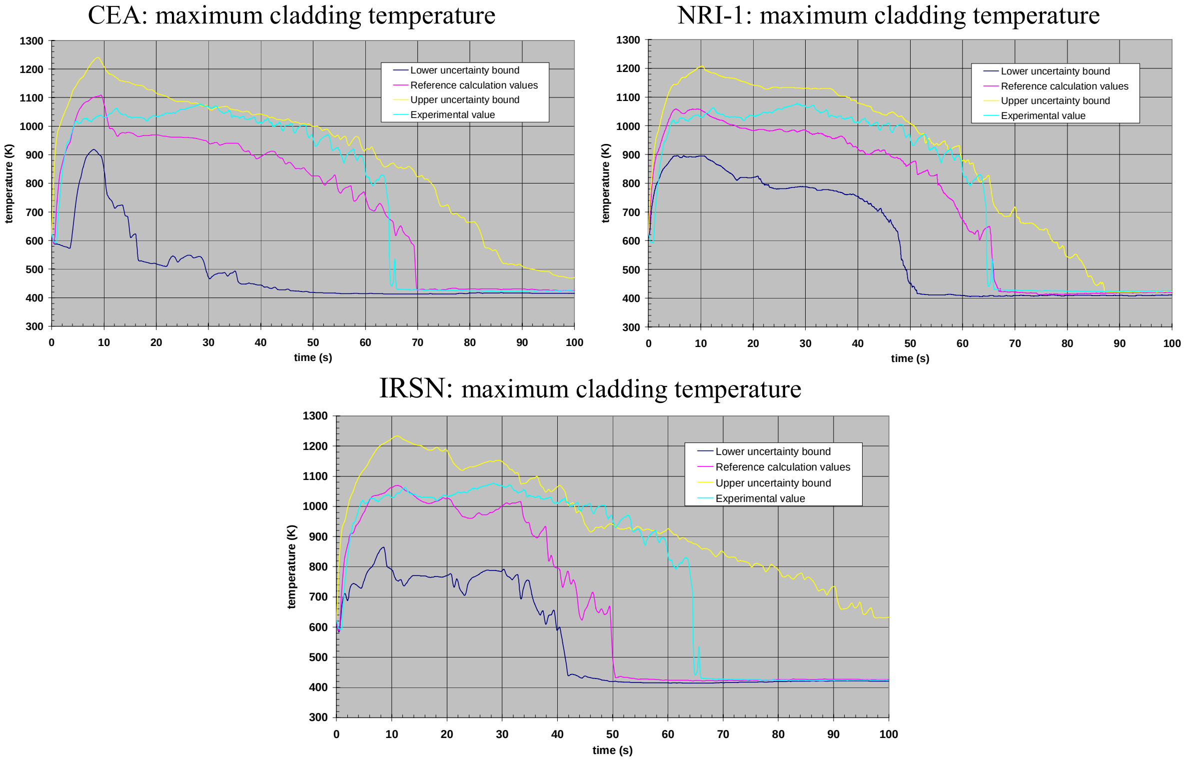


NRI-2: maximum cladding temperature



- Case 3: CEA, NRI-1 and to a lesser extent IRSN (Figure 12). The uncertainty band envelops the experimental data, but the upper bound is very close (CEA, NRI-1) to the experimental reference or even is, during a few seconds, slightly lower than the experimental values (IRSN), whereas the uncertainty band is rather wide. In the case of CEA, the lower bound is even quite low. These results can be firstly explained by the not very satisfactory reference calculation, at least for CEA and IRSN. A mistake on the friction form loss in the accumulator line, which has to be strongly increased to have a good prediction of the pressure in the accumulator has been corrected by CEA and NRI-1 for phase 3 of BEMUSE, but not by IRSN who kept the results of phase 2 unchanged. Although its calculation is rather good, NRI-1 points out also the non-modelling of the passive structure, which leads to an underestimation of the temperatures, but only after 87s, due a too low pressure. But the main explanation comes from the uncertain parameters: expert judgement is very often used to quantify the uncertainty of the input parameters, due to the lack of appropriate experimental data (CEA). NRI-1 uses the results of sensitivity analysis to know the most influential parameters. They consider that it would have been better to consider different parameters to describe the uncertainty about the heat transfer coefficients and that interfacial drag should be addressed not only by alternative correlations, but also by an uncertainty range for each correlation. For IRSN, another reason can perhaps be given: among the 59 code runs needed for $\alpha = \beta = 0.95$, 9 code failures have occurred before 50 s: consequently after 50 s, the highest value of the maximum cladding temperature does not strictly correspond with the upper tolerance limit at 95% with a confidence level of 95%.

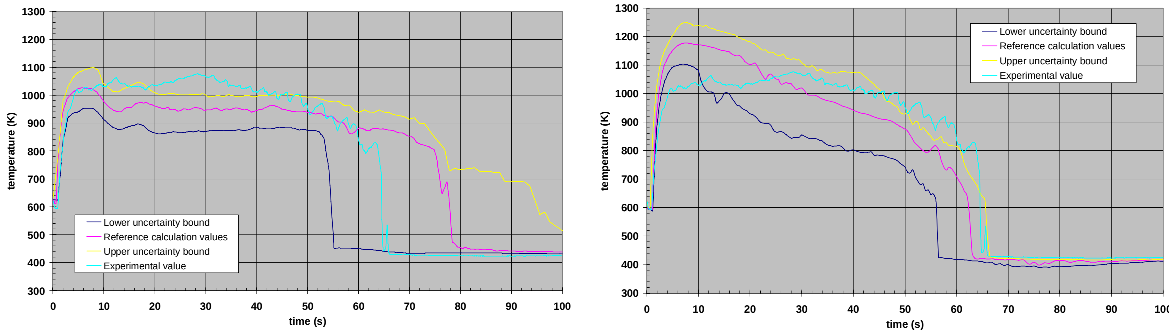
Figure 12. **Uncertainty analysis of the maximum cladding temperature – case 3**



- Case 4: PSI, UPC (Figure 13). The uncertainty band does not envelop the experimental data. These results are consistent with those found for the first PCT: too high lower bound for UPC and for the second PCT: too low upper bound for PSI. For UPC, two kinds of explanations are given: firstly the base case should be improved by means of a better downcomer nodalisation, modelled with one pipe only. Some potentially important uncertain parameters are also missing: it is among others, the case of the critical heat flux. The base case of PSI is better, even if the clad temperature is globally underestimated, due to the inability of the code to correctly capture the core dry-out after the first PCT. Possible explanations for this behaviour given by PSI can be inaccuracies in the interfacial drag or in the break flow at the beginning of the transient. In addition to that, the range of variation of both parameters, especially that of interfacial drag, is not large enough.

Figure 13. **Uncertainty analysis of the maximum cladding temperature – case 4**

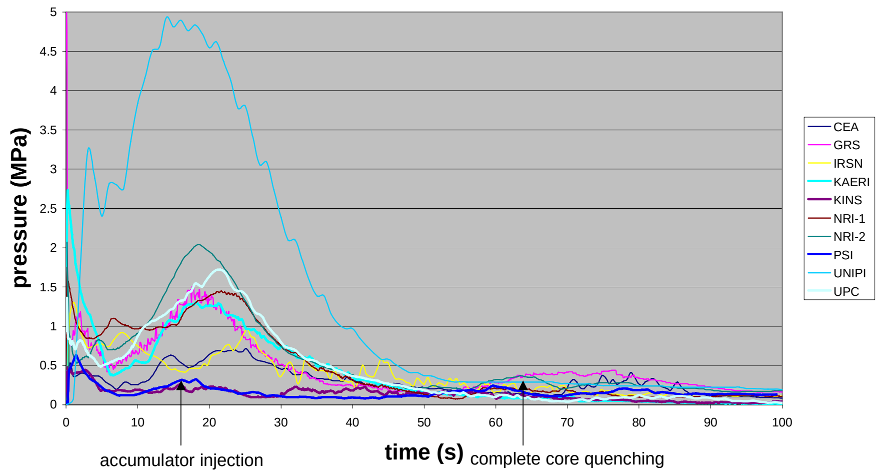
PSI: maximum cladding temperature UPC: maximum cladding temperature



3.2.3 For the time trend: upper plenum pressure

The two main features of the results are: a small majority of participants (6 out of 10) envelop, completely or almost, the experimental data. The width of the uncertainty bands are not so dispersed, except for UNIPI which finds a very large band width. Figure 14 shows the different band widths. The four curves indicated in bold correspond to the contributions which are far from enveloping the experimental pressure.

Figure 14. **Upper plenum pressure: uncertainty band widths**



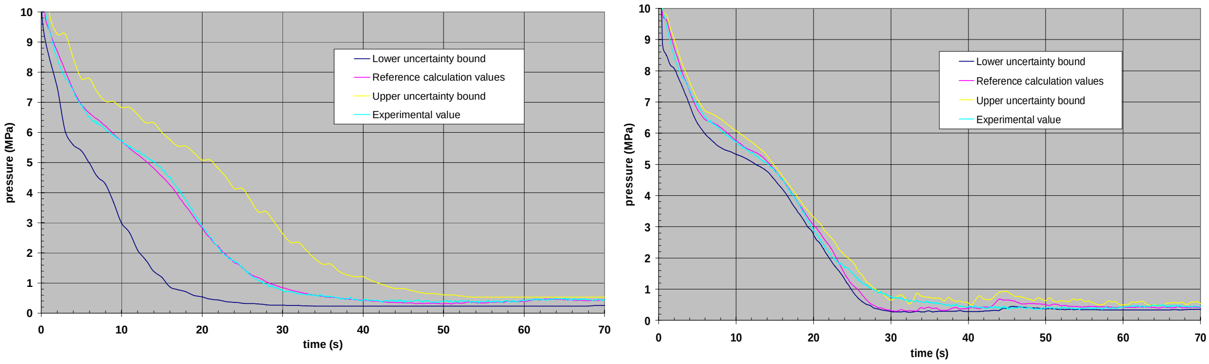
Before 50 s, the width of the uncertainty bands varies from less than 0.3 MPa (KINS, PSI) to a little more than 2 MPa (NRI-2). UNIPI is a special case with a band width reaching 5 MPa. After 50 s, the uncertainty band is very narrow, and must be compared with the experimental uncertainty (± 0.12 MPa). In the following analysis, this last part of the transient is not considered.

Three cases can be distinguished, with of course a certain continuity from one case to another.

- Case 1: UNIPI, IRSN and NRI-2 (Figure 15 for UNIPI and IRSN). Globally, the uncertainty band envelops the experimental data. More strictly speaking, IRSN finds a lower bound very slightly higher than the experimental pressure between 45 and 50 s, and NRI-2 finds a too low upper bound before 3 s. UNIPI gives two reasons for its wide uncertainty band. The first one is that the CIAU can lead to large band widths for time trends with steep gradients because it takes into account explicitly time shifts to the Total Quantity Uncertainty (which is the uncertainty finally provided) by considering the Quantity Uncertainty and the Time Uncertainty. The second reason is that the percentile corresponding to the Total Quantity Uncertainty is higher than 95%, both Quantity and Time Uncertainties corresponding to 95%.

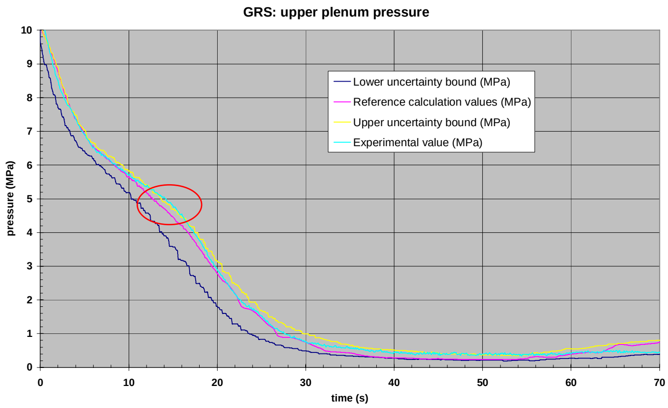
Figure 15. **Uncertainty analysis of the upper plenum pressure – case 1**

UNIPI: upper plenum pressure IRNS: upper plenum pressure



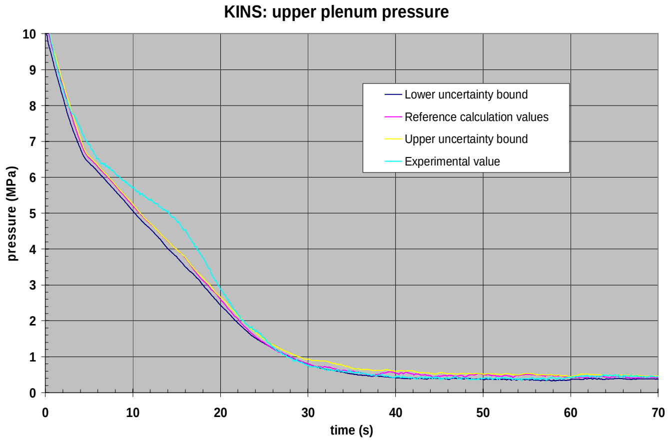
- Case 2: CEA, GRS, NRI-1 (an example in Figure 16 for GRS): The uncertainty band does not envelop the experimental data during a certain time interval, but the lower or upper bounds stay nevertheless very close to them. For two cases out of three (GRS, NRI-1), the upper bound is slightly lower than the experimental pressure, consequence of a too fast depressurisation, due to, for example, deficiencies of the discharge modelling (GRS, NRI-1) or to too low values of heat transfer fouling factor (NRI-1). CEA used results of experiments with too low nozzle diameter compared to LOFT (Super-Moby-Dick, REBECA) to determine the uncertainties of the input parameters of discharge flow.

Figure 16. **Uncertainty analysis of the upper plenum pressure – case 2**



- Case 3: KINS, PSI, KAERI and UPC (an example in Figure 17 for KINS): During at least 10 s, the upper bound is really lower than the experimental pressure. For PSI, the case is even more complex: the upper bound is lower than the experiment data during 12 to 25 s, but before and after this time interval, the contrary is observed: the lower bound is too high compared to the experimental pressure. The explanations given by these participants for these results are of two kinds. Firstly, the reference calculation does not predict correctly the pressure, either by calculating a too sharp depressurisation (KINS, UPC), which can be due to the choked flow model resulting to a too high break flow (KINS) or by predicting not correctly the dry-out observed in the core (PSI). The second explanation makes reference to the too narrow ranges of uncertainty (quoted only by PSI, but the width of the KINS uncertainty band is also very narrow) or to not including potentially influential parameters (UPC, KAERI). In particular, the KAERI contribution was more devoted to the uncertainty of the PCT; the list of uncertain parameters is set up for the uncertainties of temperatures. Besides that, it may be noted that these four contributions (KAERI, KINS, PSI, UPC) are those which predict a too low upper bound for the time of accumulator injection.

Figure 17. **Uncertainty analysis of the upper plenum pressure – case 3**



3.2.4 First conclusions and observations about uncertainty analysis

The majority of the participants find an uncertainty band which envelops the experimental data: for example in 8 cases out of 10 for the time trend "maximum cladding temperature" (Max_TC), in roughly 6 cases for the time trend "upper plenum pressure". Enveloping the experimental data is easier for participants who have a good reference calculation (for example GRS, KAERI, KINS, UNIPI for Max_TC: less careful determination of PDF of the input parameters or omitting a few parameters does not necessarily lead to discrepancy between uncertainty range and experimental curve. However that is not always the case: always for Max_TC, PSI has a rather good reference calculation, at least before 50 s, but does not envelop experimental data due to a very narrow uncertainty band.

There are the other cases where the reference calculation is less satisfactory. If this inaccuracy comes from the physical modelling, it has to be expressed via adequate uncertainties of the input parameters. But other causes of inaccuracy are possible, for example a not suitable spatial modelling of the test facility (UPC). Such causes are more difficult to take into account by uncertainty analysis. In addition to these considerations, it must be recalled that knowing the quality of the best-estimate calculation is not possible if no experimental data are available, and that is the case for a nuclear power plant.

As a consequence, studying the width of the uncertainty band of the outputs is may-be more interesting. This width depends strongly on the participants: between 100 and 700 K for the time trend "maximum cladding temperature", between 0.2 and 2 MPa for the upper plenum pressure (and even up to 5 MPa for UNIPI). Finding the reason of such a variety is difficult for the two following reasons:

- Of course, if a user increases the number of his inputs, he will increase too the width of the uncertainty band of his outputs. But if one considers the different contributions, there is not a clear relationship between the width of the uncertainty band and the number of the input parameters. For example and always for Max_TC, GRS considers a high number of inputs (49) and finds a narrow uncertainty band, whereas KAERI or KINS use a kind of PIRT and as a consequence consider a limited number of inputs (respectively 14 and 13), and despite that obtain a large uncertainty band. The only roughly sure affirmation is that omitting an influential parameter can lead to a too narrow uncertainty band (e.g. critical heat flux for Max_TC or list devoted to the study of the clad temperature and used for the primary pressure). The results of sensitivity analysis provided in §4.2 can be helpful for each participant to check their list of uncertain parameters. Besides the advisable number of input parameters to be considered is the result of a compromise: Wilks' formula allows the consideration of a large number of them, but in this case a large amount of work is needed to determine appropriate ranges of variation of these inputs.

- There is certainly a relationship between the range of variation of the outputs and that of the inputs. But this relationship is not obvious when considering the different contributions (except maybe for PSI which obtains narrow output uncertainty ranges with having narrow input ranges) because to show it, it would be necessary to compare the ranges of variation of the input parameters among the participants. An attempt has been made in §2.5.4, but only for few input parameters. In the other cases, a systematic comparison is not possible for all the parameters because their list depends on each participant.
- Not only the width of the uncertainty band of the output, but also its distribution with respect to the reference calculation has been studied for Max_TC. Depending on the participants, the difference between the upper bound and the reference calculation varies from roughly 50 K to 300 K, at least during the 50 first seconds of the transient (cf. Figure 9). This difference comes from the distribution about reference value of the input parameters, which must also be considered in addition to the range of variation itself. For example the two following ranges of variation for the film boiling Heat Transfer Coefficient: [0.5; 2] and [0.1; 1.6] have the same width but do not result in the same upper bound of Max_TC.

4. PART 3:
SENSITIVITY ANALYSIS RESULTS (STEP 8)

Sensitivity was not considered initially as mandatory in the initial requirement for phase 3 of the BEMUSE programme. The choice has been done at the October 2005 meeting to ask to each participant to provide their sensitivity analysis, from their previous work.

Some definitions will be used in this paragraph.

4.1 General Definitions: Sensitivity and Influence, Global and Local Sensitivities

We will call **sensitivity** (of the output parameter Y versus the input parameter X_i) a measure having the dimension of $\frac{\partial Y}{\partial X_i}$ that is independent of the range of variation of the parameter X_i.

We will call **influence** (or importance) a measure of the effect of the variation of the parameter X_i on its full range (ΔX_i) having the dimension of $\frac{\partial Y}{\partial X_i}\Delta X_i$ (same as Y) or more often the dimensionless form: $\frac{\partial Y}{\partial X_i}\frac{\Delta X_i}{\Delta Y}$.

Sensitivities can be considered as local or global. Sensitivities are considered as local when they are computed locally around fixed values of the set of parameters (Xi0, the nominal values for instance). They have the form: $\left(\frac{\partial Y}{\partial X_i}\right)_{X_j \neq X_i}\left(X_1^0,\ldots,X_i^0,\ldots,X_p^0\right)$. They measure the effect of the variation of one single parameter X_i for fixed values of all the other parameters ($X_j = X_j^0$).

They are considered as global when they use the variation of the output Y for the parameters varying at the same time in their full range, as it is the case when using the numerous computations of the propagation step of the probabilistic method.

With these definitions, a parameter cannot be influential but may be sensitive (meaningful sensitivity but small range of variation of the parameter).

4.1.1 Definitions of influence measures [25]

The participants were asked to provide influences for different outputs (the same outputs for which uncertainty bands have been provided), with the associated ranking, to determine the relevance of the different parameters. As no method was prerequisite, they used different kinds of influence measures. Those based on a linear dependency between the output and the inputs:

- Pearson's Correlation Coefficients: $\rho(X_i,Y) = \frac{cov(X_i,Y)}{\sigma_{X_i}\sigma_Y}$.

- Standardised Regression Coefficients (SRC): they are the coefficients α_i^* of the (multi-) linear least square regression of the standardised values: $\frac{Y-\overline{Y}}{\sigma_Y}=\sum_{i=1}^{p}\alpha_i^*\frac{X_i-\overline{X}_i}{\sigma_{X_i}}+\varepsilon$
- Partial Correlation Coefficients (PCC): cf. PSI contribution step 8.

Remarks: SRC and PCC needs that the number of code runs n is significantly higher than the number of parameters **p**. If the parameters are independent (for i ≠ j, $\rho(X_i, X_j)$ = 0) the Pearson's Correlation Coefficients and the SRC coefficients are equal. This hypothesis of independence of the input parameters is made by the participants, but is not rigorously respected for the random sampling process due to the low number of code runs.

Those based on a monotonic dependency between the output and the input. The same coefficients are defined, replacing the output and the inputs by their ranks:

- Spearman's Rank Correlation Coefficients.
- Standardised Rank Regression Coefficients (SRRC).
- Partial Rank Correlation Coefficients (PRCC, not used by participants).

4.1.2 Definitions of sensitivity measures

For global sensitivity measures, two are used:

- Slope coefficient of the single linear regression Y versus X_i: $b_i=\rho(X_i,Y)\frac{\sigma_Y}{\sigma_{X_i}}=\frac{cov(X_i,Y)}{\sigma_{X_i}^{\,2}}$
- Coefficients α_i of the multi-linear regression: $Y=\alpha_0+\sum_{i=1}^{p}\alpha_i X_i+\varepsilon$ with $\alpha_i=\alpha_i^*\frac{\sigma_Y}{\sigma_{X_i}}$

Remark: As above, if the parameters are independent (for i ≠ j, $\rho(X_i, X_j)$ = 0) the b_i coefficients and the α_i coefficients are equal.

For **local** sensitivity, different computations at different values of one parameter (X_i^1, X_i^2…) could be carried out. They make it possible to compute the finite difference $\frac{Y(X_i^2)-Y(X_i^1)}{X_i^2-X_i^1}$ or to use the slope of the linear regression of $Y \sim X_i^k$ (more than one computation per parameter are needed) (UPC method).

4.1.3 Summary of influence and sensitivity measures used by the participants

The only participant using a not-fully probabilistic method (UNIPI) provides some sensitivity studies. They are mainly performed for phase 2 programme (as the majority of participants) but some extra sensitivity studies concerning the gap size value have been added for phase 3. The comparison of these sensitivities has been done in phase 2 report and is not recalled here.

All other participants provide "influence" results from their computations obtained with the randomly generated parameters used during the propagation process (59 to 150 code runs according the participants). The kind of influence measures and eventually sensitivity measures are summed-up in Table 11.

Table 11.**Summary of the influence and sensitivity measures used**
(using a probabilistic approach)

Participants	**CEA**	**GRS**	**IRSN**	**KAERI**	**KINS**	**NRI-1**	**NRI-2**	**PSI**	**UPC**
Number of code runs	100	100	59	100	59	59	60	150	100
Influence	SRRC	Spearman	Spearman & SRC	α_i / range(X_i)	α_i. / range(X_i)	Spearman	Spearman	PCC & Pearson	Spearman
Sensitivity	α_i.	α_i	α_i	α_i	α_i	α_i	Pearson $\times \frac{\sigma(Y)}{\sigma(X_i)}$ *	α_i	UPC method

*: Which has the same dimension as α_i. This way of doing has been chosen because the α_i regression coefficients cannot be obtained, due to the too high number of input parameters (64) with respect to the number of code runs (60).

4.1.4 Preliminary remarks on the influences

The influences are obtained from the propagation step of the probabilistic method using the **n** code runs (n = 59 to 150) for the **p** parameters (p = 13 to 64). For low values of the code run number **n**, the random sampling generates artificial correlations between parameters (although none is assumed) and these artefacts affect the quality of the correlation coefficients (Pearson and Spearman). Multi-linear regression (on the parameters or on the ranks) gives better results by increasing the ratio of the number of code runs to the number of parameters (**n/p**). Some confirmations of that have been provided when increasing the number of code runs during the step 9 of some participations. As a conclusion, it can be considered that the number **n** is not sufficiently large with respect to the number of parameters **p** to get a good accuracy and the method could not detect accurately low levels of influence for parameters.

4.2 Ranking of the phenomena and parameters according to their influence

4.2.1 Method of ranking

Each participant provides a table of the most relevant parameters for the four single valued output parameters and for the two time trends (maximum cladding temperature and upper-plenum pressure), based on their influence measures. To synthesise and to compare the results of these influences, there are grouped in two main "macro" responses.

Phenomena and parameters influential for the core cladding temperatures:

- 1^{st} PCT.
- 2^{nd} PCT.
- Time of the quench completion.
- Maximum cladding temperature as a function of time (before quenching)

Phenomena and parameters influential for the primary pressure behaviour:

- Time of the accumulator injection
- Upper-plenum pressure versus time, mainly before roughly 30 s.

For each participant, each parameter is ranked according to its influence on these two kinds of macro-responses.

For parameters quoted in their table of relevant parameters, a kind of new ranking (from 0 to 3) of relevance is given for both macro-responses:

- 0: the parameter is considered by the participant but never appear as relevant.
- 1: for the less relevant quoted parameter.
- 2: for medium relevance parameter.
- 3: for the highest level of relevance.

It must be noted that the total ranking of a parameter cannot exceed 3 for one participant, even if it is found as being relevant for several outputs making up a macro-response. For example, a form loss very influential both for the time of accumulator injection and for the upper plenum pressure, will have a final rank equal to 3 (and not 3 + 3 = 6).

This ranking is quite arbitrary, for example because the difference between a medium and a high level of relevance is not always obvious. Nevertheless, this part of arbitrariness does not modify the conclusions given in §5.4 and consequently can be seen as acceptable.

After that, for each parameter, the sum is done among all the participations and this sum is considered as the **total ranking** of this parameter. The total ranking of a phenomenon is simply the sum of the total ranking of the parameters related to this phenomenon.

4.2.2 Ranking of the phenomena

Figure 18 presents the total ranking concerning both macro-responses, for the 20 phenomena (or physical laws) listed in Table 4. This ranking is provided only to give a rapid idea of the most influential phenomena for each macro-response. The value of the influence of a given phenomenon (for example: more than 70 for the influence of the fuel thermal behaviour on the cladding temperature) is not really meaningful, because the distribution phenomena-parameters is somehow arbitrary: the same weight is not assigned to each phenomenon.

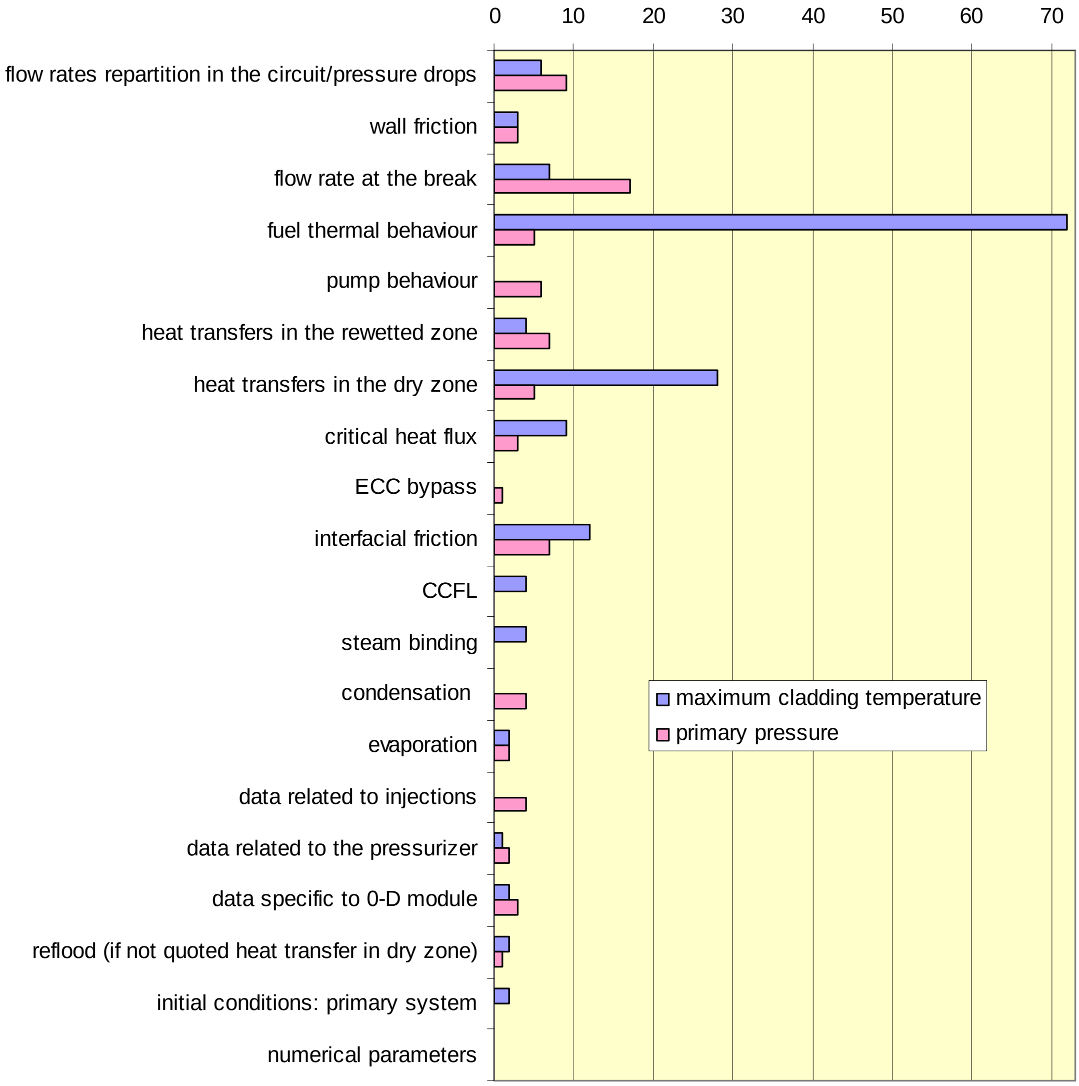
Despite the above remarks about the limited interest of the ranking of phenomena, some trends can be noted:

- Concerning the influence on the cladding temperature, the thermal behaviour of the fuel is from far the most influential phenomenon (it concerns essentially parameters on UO_2 thermal properties and gap conductance). It illustrates the fact that this transient is mainly controlled (specially the initial core heat-up) by the initial energy stored in the fuel rods.

- The second most relevant phenomenon is the heat transfer in the dry zone, as it could be expected from the complexity of the post DNB heat transfer during large break LOCA.

- The influence on the primary pressure is mainly due to parameters controlling the break flow-rate and in a less important manner different kinds of friction (wall friction, interfacial friction or pump behaviour).

Figure 18. **Total influence ranking per phenomenon**



4.2.3 Ranking of the parameters

Concerning the influence on the cladding temperature (as defined in §4.2.1, i.e. the "macro-response" formed by the 1st and the 2nd PCT, the time of complete quenching and the time trend "maximum cladding temperature"), among the initial amount of more than 150 parameters, 41 have been quoted at least once by one participant among their relevant parameters.

Concerning the influence on the primary pressure (as defined in §4.2.1, i.e. the "macro-response" formed by the time of accumulator injection and the time trend "upper plenum pressure"), among the initial amount of more than 150 parameters, 35 have been quoted at least once by one participant among their relevant parameters.

The summary of the ranking per participant and of the total ranking for all the parameters used by participants (whose total ranking is not zero) is done in Table 12 and Figure 19 (cladding temperature), in Table 12 and Figure 20 (primary pressure). These tables and figures make up a data base, useful for further uncertainty analysis of LB-LOCA, with some precautions as explained in the §4.5 of this part 3: "Finally what does the relevance ranking provide?"

Remark: Both macro-responses are partly dependent: for example, if pressure is lower, the safety injections will start earlier and the quenching of the fuel rods will be better. A consequence of this dependence might be that a parameter very dominant for a type of macro-response should be found as rather influential for the other macro-response (e.g. case of the break area, see Figure 19 and Figure 20), too. This effect is of course taken into account by the considered types of influence measures. For example, since the maximum cladding temperature is influenced mainly after accumulator injection by break discharge or break area due to the influence of pressure, this influence is lower for maximum clad temperature than for pressure, what is reasonable (Figure 19 and Figure 20). On the other hand, other input parameters will influence the maximum cladding temperature more than pressure and vice versa, what will have an effect on the importance measures of the different results. Nevertheless, due to the low number of code runs used in sensitivity analysis and to the non-linear or not monotonic behaviour of the output with respect to the inputs (measured by the coefficient of determination R^2) the sensitivity results are not always reliable, especially for the low influence measures, e.g. less than 0.3 (see also Part 4) and an influential parameter can be omitted. Due to this consideration, it can be advisable to consider both figures even for only a type of macro-response.

Table 12. **Ranking per participant of the influence on the cladding temperature of the input parameters** (for participants using a probabilistic approach)

Phenomena or main physical laws	**Parameter description**	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC	**Total**
Flow rates repartition in the circuit/pressure drops	Core pressure drop	0	3				0	0		0	**3**
	Form loss in broken loop HL, in DC/CL at branch							3			**3**
Wall friction	Fraction of water and steam in total wall friction		3					0			**3**
Flow rate at the break	Critical flow subcooled	0		1			0		1		**2**
	Critical flow two-phase	0		1			0		0		**1**
	Break area				0			2			**2**
	Break discharge coefficient					0				2	**2**
Fuel thermal behaviour	Initial core power	0	0	0		1	2	0	3	2	**8**
	Peaking factor	2			3		2	0	0	3	**10**
	Gap size	2	3	1	3		3	0	3		**15**
	Decay power	0	0	0	3	0	0	2	1	0	**6**
	UO_2 conductivity	3		3	0	2	3	3	1	3	**18**
	Gap conductivity	0		0	3	3		0	0	3	**9**
	UO_2 specific heat	3		3				0	0	0	**6**
Heat transfers in the rewetted zone	Liquid forced convection HTC	0	0	0	0	0		0	1		**1**
	Nucleate boiling HTC	0	0	0	0	1		0	0		**1**
	Complex of heat transfer models*						2				**2**
Heat transfers in the dry zone	Vapour forced convection HTC	1	0	0	2	1		0	1		**5**
	Film boiling HTC	3	0	3	0	3		0	2		**11**
	Conduction term of the wall to fluid HT in the film boiling regime									2	**2**
	Heat transfer in the dry zone HTC (global in reflood)	2									**2**
	Transition film boiling				0	1				0	**1**
	Pool film boiling at natural convection		0					2			**2**
	Complex of heat transfer models*						2				**2**
	Minimum film boiling temperature	0	0	0				0	3		**3**
Critical heat flux	Critical Heat Flux	3	0	0	0	3	0	0	1		**7**
	CHF selection of correlations		2					0			**2**
Interfacial friction	Dispersed flow interfacial shear	2		0							**2**
	Interfacial shear in non-dispersed vertical pipe flow		2	0				0			**2**
	Interfacial shear in non-dispersed vertical bundle flow		2	0				2			**4**
	Interfacial shear in non-dispersed vertical DC flow		2	0				0			**2**
	Interfacial shear in bundle: alternative model						2				**2**
CCFL	CCFL in the upper core plate: c of Wallis correlation						2				**2**
	CCFL in the UP: m of Kutateladze correlation						2				**2**
Steam binding	Interfacial shear in stratified flow	0	0	2				0			**2**
	Transition velocity from stratified to slug flow in horizontal pipes		2					0			**2**
Evaporation	Number of vapour bubbles per unit volume		0					2			**2**
Data related to the pressuriser	Pressuriser initial level						0		1		**1**
Data specific to 0-D module	O-D module: bubble rise velocity			2							**2**
Reflood (if not quoted heat transfer in dry zone)	HTC of rewetted side, upper QF		2					0			**2**
Initial conditions	Initial intact loop cold leg temperature							2			**2**

*: Complex of heat transfer is counted twice: in the dry zone and in the wet zone.

Figure 19. **Total ranking of the influence on the cladding temperature per parameter**

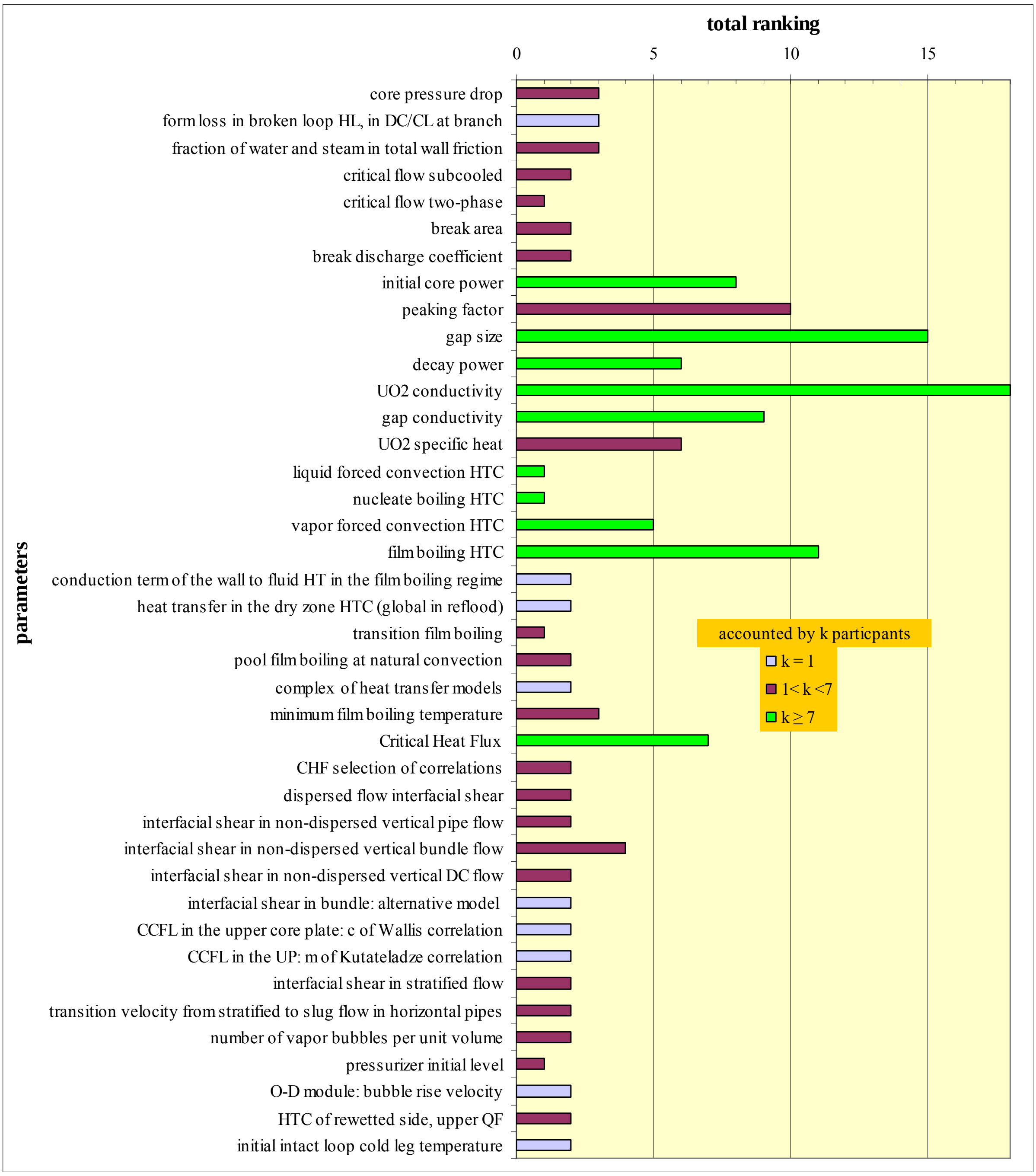


Table 13. **Ranking per participant of the influence on the primary pressure of the input parameters** (for participants using a probabilistic approach)

Phenomena or main physical laws	**Parameter description**	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC	**Total**
Flow rates repartition in the circuit/pressure drops	Form loss in broken hot leg	3	3								**6**
	Form loss in broken loop HL, in DC/CL at branch							3			**3**
Wall friction	Liquid-wall friction (pipe)			1							**1**
	Vapour-wall friction (volume)			2							**2**
Flow rate at the break	Initial broken loop cold leg temperature	0					1	0			**1**
	Critical flow subcooled	0		0			0		3		**3**
	Critical flow two-phase	0		0			3		0		**3**
	Break area				3			3			**6**
	Break discharge coefficient					1				3	**4**
Fuel thermal behaviour	Initial core power	0	0	2		0	0	0	0	1	**3**
	UO_2 conductivity	0		1	0	0	0	0	0	0	**1**
	Gap conductivity	0		0	0	1		0	0	0	**1**
Pump behaviour	Two-phase pump head	0	0		3	0	0	0			**3**
	Two-phase torque	0			3	0					**3**
Heat transfers in the rewetted zone	Structure heat transfer surfaces	2									**2**
	Liquid forced convection HTC	0	0	0	0	0		0	2		**2**
	Nucleate boiling HTC	0	0	0	2	0		0	0		**2**
	Complex of heat transfer models*						1				**1**
Heat transfers in the dry zone	Film boiling HTC	0	0	1	2	0		0	0		**3**
	Complex of heat transfer models*						1				**1**
	Minimum film boiling temperature	0	0	1				0	0		**1**
Critical heat flux	Critical Heat Flux	0	0	0	0	3	0	0	0		**3**
ECC bypass	Liquid entrainment in the downcomer	0					1				**1**
Interfacial friction	Dispersed flow interfacial shear	2		0							**2**
	Interfacial shear in non-dispersed vertical pipe flow		3	0				0			**3**
	Interfacial shear in non-dispersed vertical DC flow		2	0				0			**2**
Condensation	Direct condensation	0	2					0			**2**
	Jet temperature for injection of subcooled liquid			2							**2**
Evaporation	Liquid interface energy transfer (Shah)			1							**1**
	Gas-interface energy transfer			1							**1**
Data related to injections	Initial accumulator pressure						1	0	0		**1**
	Accumulator pressure set-point								3		**3**
Data related to the pressuriser	Pressuriser initial pressure						0		2		**2**
Data specific to 0-D module	0-D module: bubble rise velocity			2							**2**
	0-D module: phase distribution coefficients at junctions			1							**1**
Reflood (if not quoted heat transfer in dry zone)	Alternative models: reflood activation model						1				**1**

*: Complex of heat transfer is counted twice: in the dry zone and in the wet zone

Figure 20. **Total ranking of the influence on the primary pressure per parameter**

4.3 Use of the sensitivities

According a request made during the October 2005 meeting, all the participants using a probabilistic method with propagation of the uncertainties of inputs, provide also sensitivity measures (independent of the range of variation of the parameter). It was required to separate, in the influence measures as they are presented in the former Paragraph 4.2, the effect of the sensitivity (dimension of $\frac{\partial Y}{\partial X_i}$) from the effect of the range of variation δX_i.. To minimise the amount of work, it was proposed to the participants to use the results of their code runs for the four scalar output parameters and to carry out with them the multi-linear regression with respect to the input parameters. The sensitivities are then the α_i coefficients of the regression. All the participants have used this method except for NRI-2 for the reason given below and UPC, which has shifted one by one each input parameter (cf. §4.1.2).

Several difficulties have been encountered. They are:

- If the number of inputs is higher than the number of code runs, performing the multi-linear regression becomes impossible. It is the case for NRI-2 (64 input parameters, 60 code runs) which has been forced to consider as sensitivity measure the quantity $\rho(X_i ,Y)\times\frac{\sigma_Y}{\sigma_{X_i}}$, $\rho(X_i ,Y)$ being the Pearson's Correlation Coefficient.
- As shown in Part 4, influence measures, including the α_i^* Standardised Regression Coefficients (SRC), are reliable only for the very relevant input parameters. Due to the relationship: $\alpha_i = \alpha_i^* \frac{\sigma_Y}{\sigma_{X_i}}$, the i coefficients are also reliable only for these very relevant input parameters. Especially one can find an artificial high sensitivity for parameters with a low or medium influence, measured for example by α_i^* and a low uncertainty standard deviation σ_{X_i}. As a consequence, CEA, GRS and NRI-2 have chosen to provide the sensitivities only for the most influential parameters.
- Input parameters have to be normalised so that all the sensitivities (dimension of $\frac{\partial Y}{\partial X_i}$) are expressed in the unit of the output Y, since the inputs Xi become dimensionless.
  - The majority of the parameters are normalised by definition: that is the case of multiplicative factors such as the input parameter associated with fuel conductivity.
  - The normalisation is possible for other input parameters such as gap size expressed in µm. A new normalised input parameter must be considered, defined by: $X_{new} = \frac{X_{old}}{X_{ref}}$, X_{ref} being the reference value of the input, equal for example to 95 µm for cold gap size.
  - This normalisation becomes doubtful for temperatures (the normalisation depends on the unit with which is expressed the temperature: K or °C) and for parameters the reference value of which is time dependent, as the pump velocity.
  - The normalisation is impossible for dimensional parameters the reference value of which is equal to 0 (case of some GRS input parameters) and for alternative correlations (GRS and NRI-2).

As a consequence, calculating the sensitivities in the same unit is difficult or even impossible for the input parameters which are not multiplicative factors.

Due to all these difficulties, providing a sensitivity ranking for each scalar output parameter would not be correct. Only some very crude trends can be observed. For example, the most sensitive parameters for the blowdown PCT seem to be initial reactor power, peaking factor, fuel conductivity and cold gap size or conductance/conductivity. The sensitivity results for these input parameters are presented in Table 14.

Table 14. **Sensitivities[a], expressed in K, of the 1st PCT to four input parameters**
(for participants using a probabilistic approach)

	CEA	GRS	IRSN	KAERI	KINS	NRI-1	NRI-2	PSI	UPC
Initial reactor power	Not provided[b]	329	510	Not considered[c]	560	161	Not provided[b]	652	1054
Peaking factor	369	Not considered[c]	Not considered[c]	659	Considered via a bias	307	Not provided[b]	–27	556
Fuel conductivity	–345	Not considered[c]	–357	–22	–338	–332	–244	–136	–225
Cold gap size	173	237	195	45	Not considered[c]	378	Not provided[b]	188	Not considered[c]
Gap conductance or conductivity	Not provided[b]	Not considered[c]	Not provided[b]	–106	–143	Not considered[c]	Not provided[b]	–134	–195

Notes: a: Obtained after normalization of the input parameters X_i.
b: This parameter is considered among the input parameters, but its sensitivity is not provided, because it is not a very relevant parameter.
c: This parameter is not considered by the participant.

For each input parameter, the sensitivities found by the participants are almost always consistent, if we consider, as stated before, that only rough trends can be really observed: the sensitivities are higher than 100K and have the same sign for all the participants. There are few exceptions: the sensitivity to the fuel conductivity found by KAERI (-22 K, too low) and to the peaking factor found by PSI (-27 K, to low, bad sign), and to a less extent the cold gap size found by KAERI (45 K, a little too low). In the two first cases, the influence measure was quite low, for example 0.07125 for PSI with the Pearson's Correlation Coefficient and consequently can be considered as very doubtful. For the cold gap size, the low sensitivity measure found by KAERI comes may-be from the fact that KAERI considers at the same time as uncertain parameters the cold gap size and the gap conductance and that the uncertainty of the conductance includes the uncertainty of the gap size.

As a conclusion, the initial purpose of this study, separate in the influence the effect of the sensitivity from that of the range of variation, has not been successful. As explained above, at least two reasons lead to this sobering result: a too low number of code runs with respect to the number of input parameters and the difficulty to normalise all the input parameters (whereas this normalisation is necessary to have all the sensitivities expressed in a same unit, the unit of the output). Another attempt to answer this question is presented in next paragraph 4.4. In fact these sensitivity measures could be used to answer a question like: *what is the variation of the response Y if the parameter Xi is shifted by x%?* (Without knowing the range of variation of the parameter). This kind of information is of interest before performing uncertainty analysis. It allows focusing its efforts to determine the range of variation of the most sensitive input parameters. For instance, for the 1st PCT, the range of variation of the fuel conductivity has to be estimated very carefully (The three other input parameters raise fewer difficulties because their uncertainty can be found in the LOFT documentation [14]).

Another lesson learnt from this study is that using the coefficients of the multi-linear regression is not reliable, especially if the number of input parameters is high when compared to the number of code runs. Using simple methods such as "One a Time" screening or as the UPC method is certainly more recommended.

4.4 Comparison of the influence rankings

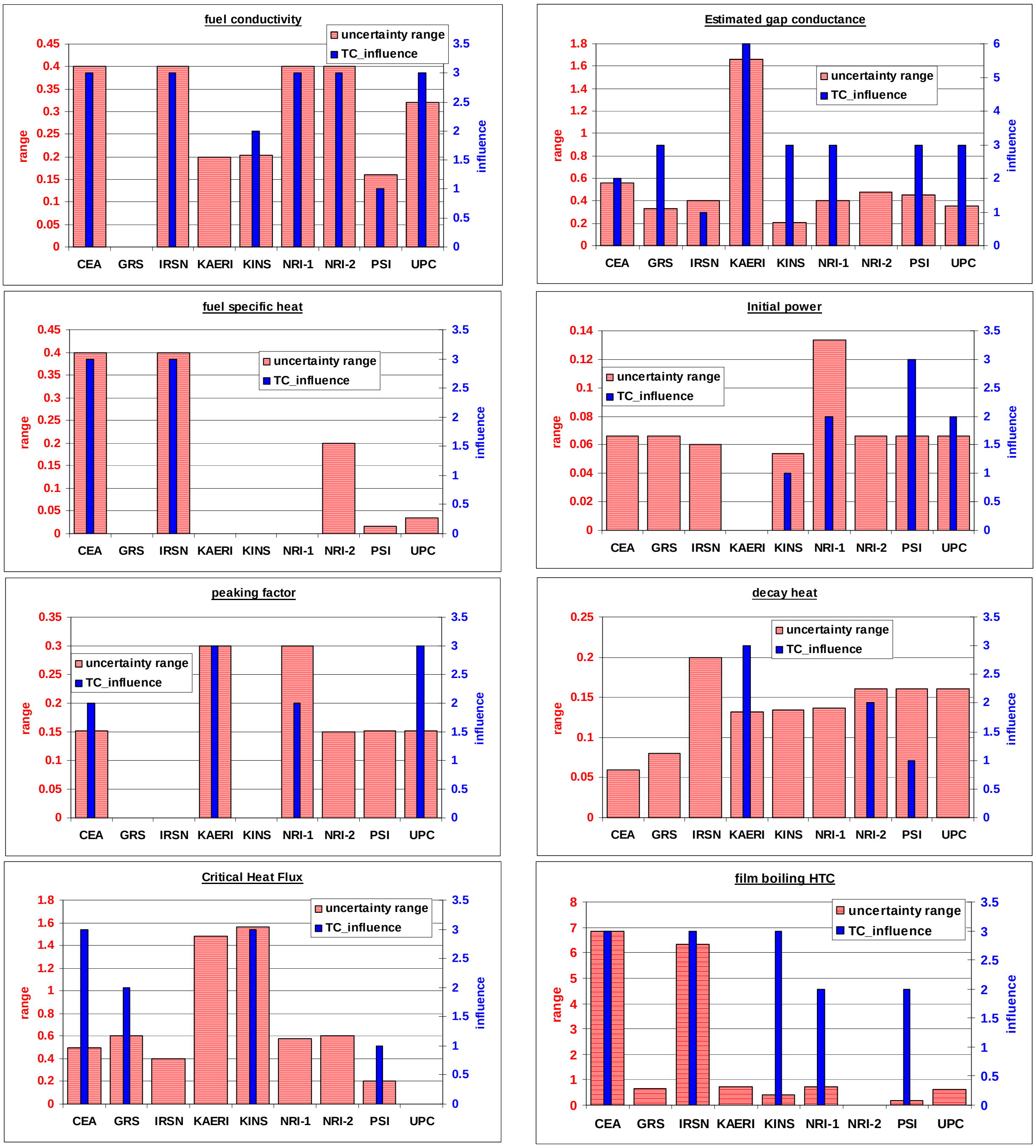
For some parameters considered by a lot of participants and found as relevant by some of them, it seems natural to compare among the participants:

- Their range of variation as it is shown in Figure 4 and Figure 5.

- Their influence ranking as it appears in Table 12 for the “cladding temperature”-type macro-response: it ranges from 0 (no influence) to 3 (high influence).

This work is presented in Figure 21 to make easier the comparison, the 3 different parameters: gap width, gap conductivity and gap conductance have been combined in one parameter called gap conductance (for both the uncertainty range and the relevance ranking, which can reach 6 for that reason).

Figure 21. **Ranges of variation and influences for some input parameters***



*: Film boiling in the NRI-1 contribution: NRI-1 considers together all the modes of heat transfer via a single parameter: complex of heat transfer models (cf. Table 9) the influence of which is 2. But as in the NRI-1 reference calculation, film boiling is the dominant heat transfer mode in the dry zone, an influence equal to 2 is indicated on Figure above concerning film boiling HTC.

A correlation between the range of variation of the input parameter and its influence is partly apparent only for the first three parameters: fuel conductivity, estimated gap conductance and to a less extent fuel specific heat. As a matter of fact, this comparison is skewed for the following reasons:

- The range of variation of each input parameter is expressed in % of the reference value and can be actually compared among the participants, as already explained in step 4.
- The measure of influence has 4 levels (0, 1, 2 or 3, except for the gap conductance with a level reaching 6), whatever the participant. It is an absolute value which does not take into account the range of variation of the macro-response, impossible to define, but different for each participant. As a consequence, this influence can be used to rank the different input parameters for a same participant, but not to compare the influence of one parameter according to the different participants.

Consequently a participant such as PSI finds naturally influential parameters - as the other participants - whereas the ranges of variation of its input parameters are almost always the narrowest ones. Always for PSI, the result is that, for example, film boiling has a quite high level of influence, equal to 2 whereas its range of variation is very low if compared to that of the other participants. With such considerations, it becomes clear that no correlation can be expected between the range of variation of the parameter and its influence.

Other reasons can explain the lack of correlation between the range of variation of an input parameter and its influence. As shown in Part 4, the results of sensitivity analysis are sometimes doubtful. Besides, parameters associated with the dry-out and post-dry-out heat transfer, i.e. Critical Heat Flux and the film boiling HTC, are part of global heat transfer model which is specific to each code (logic, distribution between phases, etc.)

However, information can be gained from Figure 21, in a more synthetic way than with Figure 4, Figure 5 and Table 12. Particularly it makes it possible for a participant to wonder at the results of its sensitivity analysis if on the one hand its parameter has an influence equal to 0 whereas that is not the case of the other participants and if on the other hand its range of variation is comparable with that of the other participants (ex: fuel conductivity or critical heat flux for KAERI). On the contrary, a participant can also wonder if it finds a parameter relevant whereas on the one hand its range of variation is low, on the other hand the uncertainty band of the macro-response is large (ex: film boiling for KINS).

4.5 Finally, what does the relevance ranking provide?

The above lists of influential parameters (Table 12 for the cladding temperature response and Table 13 for the primary pressure response) and the associated Figure 19 and Figure 20 constitute the conclusion of the sensitivity study performed by the nine participants using a fully probabilistic approach. It constitutes a list of all the parameters that should be regarded starting an uncertainty study for a similar transient. Nevertheless, the total rankings of influence of these parameters have to be used with caution, by taking into account the following observations:

- High total ranking parameters are taken into account by most participants and found influential by them.
- Medium total ranking can be obtained by combination of numerous participants having taken it into account and found them slightly influential or found highly influential by a few participants.
- Low total ranking can be obtained for an influential parameter considered by a few participants (numerous parameters of the tables have been considered by only one (/9) participant).

In any case, the ranking of a parameter has to be interpreted as the participation of this parameter in the variation of the response.

All these parameters should be considered whatever their relevance to total ranking is. A parameter may be eliminated because:

- This parameter is redundant with another one.
- This associated physical effect is clearly accounted by another parameter.
- This parameter is not applied in the used code and input-deck.
- The parameter is not applicable for the case of analysis under consideration.

but never because its total ranking is low.

Finally, Table 12 and Table 13 constitute a basis of work useful for starting a future uncertainty study. The main piece of information learnt from these tables and the associated figures (Figure 19 and Figure 20) is the list (and not the total ranking) of input parameters found as relevant by the participants. In Table 12 and Table 13, the ranking found by each participant is given so that each participant can compare his results with the other ones. It must be noted that both rankings, per participant and total, are not entirely reliable because:

- The method of ranking, described in §4.2.1, is somehow arbitrary.
- The number of code runs is too low, as it is clearly shown in the Part 4 by three participants (cf. §5.1.3).
- The used influence measures make a hypothesis of linearity or monotony of the output parameters with respect to the inputs, which is not always valid.

4.6 First conclusions about sensitivity analysis

Table 12 and Table 13 (in §4.2) propose a list of input parameters to be considered for each type of response: cladding temperature and primary pressure, with all the precautions listed in the §4.5. But in addition to this information, some lessons can be learnt from this Step 8:

- As explained in §4.1, influence measures (dimension of $\frac{\partial Y}{\partial X_i}\Delta X_i$ or dimensionless form $\frac{\partial Y}{\partial X_i}\frac{\Delta X_i}{\Delta Y}$) must be distinguished from sensitivity measures (dimension of $\frac{\partial Y}{\partial X_i}$). Classical influence measures are for example Pearson’s Correlation Coefficients and Standardised Regression Coefficients.
- After having performed uncertainty analysis, influence measures are more meaningful than sensitivity measures, because they really give the contribution of each input parameter to the total uncertainty of the output parameter. Sensitivity measures are more difficult to be used, in particular because all the input parameters X_i do not have naturally the same unit. However they allow to know what is the variation of the output if the input is modified by x%; that is the reason why they can be used before performing uncertainty analysis (cf. §4.3).
- For both measures, using directly the results of the code runs needed by Wilks’ formula at the order 1 or 2 for uncertainty analysis, allows knowing only the very influential parameters, in particular because the number of code runs is not sufficient. It will be shown more in detail in the Step 9 (cf. §5.1.3).
- An attempt has been made to find a relationship between the range of variation ΔX_i of the input parameter X_i and its influence (cf. §4.4): the conclusion is that there is not a clear relationship.

5. PART 4:
COMPLEMENTARY METHODS, ASSESSMENT METHODOLOGY

5.1 Step 9: Complementary methods

5.1.1 Increasing the number of code runs

Five participants have increased the number of code runs with respect to their base case, as shown in Table 15.

Table 15. **Number of code runs and output parameters considered for the improved methods**

	CEA	IRSN	KAERI	NRI-1	NRI-2
Base case: number of code runs	100	59	100	59	60
Improved method: number of code runs	1003	590	3500	93	100 / 1000
Considered output parameters	1^{st} PCT	1^{st} PCT	1^{st} and 2^{nd} PCT	Temperature-type outputs + time of accumulator injection	Temperature-type outputs + time of accumulator injection
Upper tolerance limits obtained in the base case	1^{st} PCT: 1246 K	1^{st} PCT: 1233 K	1^{st} PCT: 1218 K 2^{nd} PCT: 1197 K	1^{st} PCT: 1208 K 2^{nd} PCT: 1167 K	1^{st} PCT: 1165 K 2^{nd} PCT: 1185 K

NRI-1 has performed 34 additional code runs to compare the results of uncertainty analysis obtained by using Wilks' formula at the second order with respect to those obtained at the first order: the results are only very slightly modified. Other participants have significantly increased their number of code runs, by considering for some of them only the first PCT to avoid problems of code failures. The information gained from these studies is related both to uncertainty analysis and sensitivity analysis.

5.1.2 Uncertainty analysis

The most important conclusions are:

- The dispersion of the upper tolerance limit obtained by using Wilks' formula at the first and the second order is studied (CEA, KAERI). Both organisations have divided their N code results into several separate samples of size n = 59 and for each sample, have considered the highest value of the output (Wilks at the first order). For CEA, the spread of this tolerance limit is about 150 K for the 1st PCT, whereas KAERI finds roughly 200 K for the 1^{st} PCT and 250 K for the 2^{nd} PCT. KAERI has also performed the same work with samples of 93 code results and by applying Wilks' formula at the second order. The found dispersion is twice as low.
- Estimating directly the empirical 95% percentile becomes possible. CEA and KAERI show that this estimation is converged from 600-700 code runs for the blowdown PCT, 1000 code runs for the reflood PCT. The obtained values are lower than the upper tolerance limits obtained by using Wilks' formula at the first or the second order, which is obvious since upper tolerance limits are higher than

the 95% percentile in 95% of the cases (β = 95%): for example, the difference is of 30 K for CEA. IRSN associates with the estimation of this percentile an uncertainty band. Its width is estimated either from the properties of the incomplete Beta law [26] or by bootstrap (re-sampling by using the original parameter selections, [27]). Both methods give very comparable results: the width of the 95% uncertainty band decreases with the number of code runs, converging from roughly 500 code runs to reach 25 K with 590 code runs. In addition to these techniques, IRSN proposes to study response surfaces methodologies such as Krigging.

Other studied issues are:

- The determination of the upper tolerance limit of the same percentile (α = 95%) with the same confidence level β = 95%) as in the base case, but by applying Wilks' formula at a higher order since the number of code runs is higher. In this way, CEA finds 1225 K for the 1st PCT (Wilks at the order 39) to be compared to 1 246 K in its base case (Wilks at the second order), whereas IRSN finds 1 186 K to be compared to 1 233 K in its base case (Wilks at the first order).
- A last possibility is to consider an upper limit of the same α-percentile, but with a higher β confidence level. CEA and IRSN find 1239 K and 1198 K with β = 99.99% instead of respectively 1 225 K and 1 186 K with β = 95%. NRI-2 considers, as for it, Wilks at the first order and consequently increases β when increasing the number of code runs. For example, it finds for the 1st PCT 1 165 K with 60 code runs and β = 95%, 1201 K with 100 code runs and β = 99.4%, 1211 K with 1000 code runs and β almost equal to 1.

5.1.3 Sensitivity analysis

CEA, IRSN and NRI-2 have compared the influence measures obtained with the increased number of code runs with respect to the base case. The results are rather different. Concerning the 1st PCT, CEA and IRSN find that parameters not relevant in the base case become relevant with a larger number of code runs. NRI-2 finds similar results for all the outputs, but also the opposite case: for the 1st PCT, one parameter quoted as relevant performing 60 code runs with a Spearman's Correlation Coefficient almost equal to 0.3 becomes negligible with 1000 code runs ($\rho < 0.03$). However it may be noted that NRI-2 considers a high number of uncertain input parameters, equal to 64, compared to 60 base case code runs.

All these participants use influence measures based on ranks (Spearman's Correlation Coefficient or SRRC). Two explanations are given for the change of ranking when the number of code runs is increased. The first one is the existence of spurious correlations between the input parameters if the number of code runs is low compared with the number of input parameters (CEA, IRSN). It must be noted that this problem is relevant for sensitivity analysis but not for the uncertainty analysis applying Wilks' formula. Besides that, IRSN points out that using simple random sampling, as recommended for Wilks' formula, may not be optimal for sensitivity analysis.

5.1.4 Modifying the type of probability law and the truncation

CEA, which uses only normal and log-normal laws truncated at $\mu \pm 3.09\sigma$ in its base case, has carried out two tests. They performed 100 calculations each, using the same selection of parameter values for both ranges.

In the first test, all the normal density functions of the inputs are replaced by uniform density functions (the same with log-normal laws replaced by log-uniform laws), with a minimum value equal to (μ - 2σ) in case of a normal law, to $e^{(\mu - 2\sigma)}$ in case of a log-normal law (the same with (μ + 2 σ) and $e^{(\mu + 2\sigma)}$ for the maximum value). The influence of this change of density is studied on the upper bound of the maximum cladding temperature: it is significantly increased, by 30 K for the 1st PCT and up to 55 K if considering the whole transient.

In the second test, the normal and log-normal laws are kept but truncated at $\mu \pm 2\sigma$ instead of $\mu \pm 3.09\sigma$. This time, it leads to a slight decrease of the upper bound of the maximum cladding temperature: by 15 K for the 1st PCT.

5.1.5 First conclusions about complementary methods

The studies performed in the part 4 lead all of them to the same following conclusions. For uncertainty analysis, and if one is interested to match the 95% percentile close, it is advisable to apply Wilks' formula at orders higher than 1 or even 2, to decrease the dispersion of the tolerance limit (sample effect). It leads to perform more than 100 code runs. For sensitivity analysis, increasing the number of code runs compared with the number of uncertain input parameters is also recommended to obtain reliable results, not skewed by spurious correlations among these input parameters. But the number of code runs needed for sensitivity analysis has not relationship with the number of code runs required for a proper use of Wilks' formula, and depends, for example, on the number of inputs parameters especially for the coefficients of regression type.

Modifying the type of laws or of truncation in case of normal or log-normal laws, also has an effect on the results of uncertainty analysis, but this effect is less important compared with the dispersion of the tolerance limits resulting from the application of Wilks' formula at first or second order.

These conclusions are explained more in detail in the general conclusions and recommendations.

5.2 Step 10: Assessment methodology

5.2.1 UNIPI method: propagation of output errors

Only UNIPI presents a qualification process, in two steps: the Internal Qualification Process and the Independent (External) Qualification Process.

The internal qualification process

This process is continuously ongoing during the development of the method. For instance, it might happen that data from the analysis of several SB-LOCAs produce uncertainty values much higher than data from the analysis of a similar number of LB-LOCAs, when the same hypercubes are concerned. In this case, the number of hypercubes, i.e. the ranges of variation of the driving quantities, must be changed or the transient type must be identified inside each hypercube. More in detail, it must be shown that accuracy and uncertainty values in each hypercube or in each time interval do not depend upon:

1. Time (into the transient) when the hypercube is reached.
2. Volume scaling factors.
3. Transient type (e.g. SB-LOCA, LB-LOCA, LOFW, etc.).
4. Dimension of hypercubes.
5. ITF or SETF or NPP characteristics.

The independent (external) qualification process

The second qualification step is carried out when a reasonable number of hypercubes and time intervals have been filled. In this case, CIAU is run to simulate qualified transients measured in ITFs that have not been utilised for getting uncertainty values (SB-LOCA experiment LSTF SB-CL-18 for BEMUSE). The success is the demonstration that CIAU-calculated uncertainty bands envelop the experimental data. This must be intended as the reference Independent (External) Qualification process for the CIAU, together with the condition that uncertainty bands are reasonably large. The completion of this step will also allow one to establish, on an objective basis, the confidence level of the uncertainty statements. The increase in the number of positively completed qualification analyses will increase the confidence level of the procedure.

Examples of how the internal and external qualification processes are lead are given in the section devoted to the participant's contributions.

5.2.2 Probabilistic methods: propagation of input uncertainties

No assessment of the results has been performed in the framework of BEMUSE. Nevertheless, the probabilistic methods can be assessed by a check against an independent experimental database. When the uncertainty ranges of relevant results bound the data, one can be confident that all important uncertain input parameters are considered, and the ranges of their distributions are not too narrow. After such a step, a reactor analysis for the same scenario like investigated by the experiment may be performed. Such an assessment increases the confidence in performing such an uncertainty analysis. Additional relevant uncertain input parameters for the reactor case may be introduced, for example scaling effect.

6. CONCLUSION AND RECOMMENDATIONS

This report summarises the various contributions (ten participants, not including the JNES contribution which arrived too late to be carefully reviewed, but is nevertheless presented in the appendix) for phase 3 of BEMUSE: Uncertainty and Sensitivity Analyses of the LOFT L2-5 experiment, a Large-Break Loss-of-Coolant-Accident (LB-LOCA).

For this phase, precise requirements step by step were provided to the participants. Finally, four main parts are clearly defined, which are:

1. List and uncertainties of the input uncertain parameters.
2. Uncertainty analysis results.
3. Sensitivity analysis results.
4. Improved methods, assessment of the methods (optional).

5% and 95% percentiles have to be estimated for 6 output parameters, which are of two kinds:

- Scalar output parameters.
  - First Peak Cladding Temperature (PCT).
  - Second Peak Cladding Temperature.
  - Time of accumulator injection.
  - Time of complete quenching.
- Time trends output parameters.
  - Maximum cladding temperature
  - Upper plenum pressure

The main lessons learnt from phase 3 of the BEMUSE programme are:

- For uncertainty analysis, all the participants use a probabilistic method associated with the use of Wilks' formula, except for UNIPI with its CIAU method (Code with the Capability of Internal Assessment of Uncertainty). Use of both methods has been successfully mastered.
- Compared with the experiment, the results of uncertainty analysis are good on the whole. For example, for the cladding temperature-type output parameters (1st PCT, 2nd PCT, time of complete quenching, maximum cladding temperature), 8 participants out of 10 find upper and lower bounds which envelop the experimental data.
- Sensitivity analysis has been successfully performed by all the participants using the probabilistic method. All the used influence measures include the range of variation of the input parameters. Synthesis tables of the most influential phenomena and parameters, especially Figure 19 and Figure 20, have been plotted and participants will be able to use them for the continuation of the BEMUSE programme.

Looking more closely at each of the four parts of the requirements, the following may be noted.

Part 1: Uncertain input parameters

- Depending on the participants, the number of uncertain input parameters ranges from 13 to 64. When a rather low number of input parameters are considered, it is mainly due to the difficulty of associating an appropriate range of variation to them. Nevertheless, it must be pointed out that the lists of uncertain input parameters are very different depending on the participants. To minimise this effect in the future, a table (Table 4) comparing the input parameters considered by the participants and indicating the phenomena to which they are associated is provided. With this table, each participant can check if he has not omitted a potentially influential parameter.

- This remark is not applicable to the CIAU method, based on compilation of a very large number of results of Integral Effects Tests (IET) experiments, because the CIAU does not consider explicitly uncertain input parameters. Based on the extrapolation of errors on the outputs, the CIAU takes into account implicitly all the sources of uncertainties. Despite this advantage, the CIAU has also a drawback if the number of IET experiments for a part of the transient is too low: quantity and time uncertainties are determined with a poor precision. Increasing the number of experiments in the error database has the potential to avoid the above drawback.
- Quantification of the uncertainty of the input parameters is performed in general by expert judgement or by literature review, especially on the basis of LOFT L2-5 documentation and Code Manuals (e.g. for RELAP5 Mod3.3). There are some attempts to use the results of Separate Effect Tests (SET) experiments, via a statistical process. A comparison of the ranges of variation of parameters related to fuel behaviour and parameters related to different modes of heat transfer has been performed (13 parameters). Depending on the parameters, the observed differences come from different interpretations of the LOFT L2-5 documentation, from the use of expert judgement or the fact that physical models are code-dependent.

Part 2: Uncertainty analysis results

- Depending on the participants, Wilks' formula is used at the first order (59 code runs with a confidence level β of 95%), at the second order (93 code runs for β = 95%) and even at the third order (124 code runs for β = 95%). In all the cases, for the propagation phase, parameters are generated by Simple Random Sampling (SRS) and the input parameters are assumed to be independent. Roughly ten types of laws are considered for the input parameters: normal, uniform, histogram, triangular, discrete, etc. Another difference among the participants is how they deal with failed code runs, which are sometimes simply discarded.
- As stated before, the results are quite good for the cladding temperature-type output parameters. Despite its specificity, the CIAU method gives results quite comparable to those of the other participants. The width of the uncertainty bands is rather spread: from 100 to 700 K.
- For the pressure-type output parameters (time of accumulator injection, upper plenum pressure), 6 participants out of 10 find upper and lower bounds enveloping roughly the experimental data. That is the case of the CIAU method, but with an uncertainty band width much larger than the width found by the other participants: up to 5 MPa to be compared with a maximum of 2 MPa for the other participants. For this type of output parameters too, the width of the uncertainty bands is very different, from 0.2 to 2 MPa, without considering the CIAU method.
- A first observation which can be made for the cases where the uncertainty band does not envelop the experimental data, is the following. Enveloping the experimental curve is more difficult if the quality of the reference calculation is poor: too sharp depressurisation, bad value of the friction form loss in the accumulator line, 1-D modelling of the downcomer, etc. But the main reason is related to the uncertainties of the input parameters: omission of some influential parameters such as critical heat flux or list devoted to the study of temperature-type output parameters, or too narrow uncertainty bands of the input parameters. In such cases, sensitivity analysis is helpful to get information on the uncertain parameters which have to be determined with greater accuracy.

- It should be noted that the LOFT experiment and the L2-5 test are different from a typical LB-LOCA in a PWR. In this latter case, additional input parameters, for example related to the thermo-mechanical behaviour of the fuel rod or steam binding, should be considered and the duration of the LB-LOCA is longer. These considerations show that finding different uncertainty bands must be expected in the case of a NPP. Phase 5 of BEMUSE is devoted to this study.

Part 3: Sensitivity analysis results

- Sensitivity measures are distinguished from influence (or importance) measures. The influences include the range of variation of the input parameters ΔX_i and have the dimension of $\frac{\partial Y}{\partial X_i}\Delta X_i$ or more frequently the dimensionless form $\frac{\partial Y}{\partial X_i}\frac{\Delta X_i}{\Delta Y}$, whereas it is not the case for sensitivities which have the dimension of $\frac{\partial Y}{\partial X_i}$.
- All the participants, except for UNIPI, calculate influences by using the results of the code runs performed for uncertainty analysis. UNIPI has also performed sensitivity calculations, but mainly in the frame of phase 2 (Comparison and Evaluation of Sensitivity Results [19]).
- The measures of influences are classical: Pearson's or Spearman's Correlation Coefficients, Standardised Regression Coefficients, etc.
- Synthesis tables have been drawn up for the influences of two "macro-responses": cladding temperature-type responses and responses related to the primary pressure. The first table (Figure 18) ranks the phenomena listed in Table 4 of part 1, the other ones (Table 12 and especially its illustration in Figure 19 for the cladding temperature-type responses, Table 13 and especially its illustration in Figure 20 for the primary pressure-type responses) are the ranking of the parameters taken also from Table 4 of part 1. For each influential phenomenon and yet more for each influential input parameter, users are asked to check whether they consider it, mainly with Figure 19 and Figure 20. Nevertheless this ranking must be used with care. Some phenomena (or parameters), such as fuel thermal behaviour or heat transfers in the dry zone for the temperature-type macro-response are clearly dominant, because they are considered a priori by many participants and found relevant *a posteriori* by a majority of them. But some others have a medium influence, because they are considered by few participants, sometimes only one, but found relevant by almost all these participants. In this case, it might be advisable to consider such parameters despite their apparently medium influence.
- It should be also noted that these synthesis tables and figures are not entirely valid for a LB-LOCA in a typical PWR due to the specificity of the LOFT L2-5 transient.
- In addition to the influences, sensitivities have been calculated for the four scalar output parameters, via the coefficients of the multi-linear regression of each output with respect to the inputs. This calculation raises difficulties: poor quality of the regression, necessary but not always possible normalisation, etc. Shifting one by one the input parameters seems more advisable and could indicate the input parameters the range of variation of which must be determined carefully before performing the uncertainty analysis.
- Finally, a comparison of the range of variation and the influence according to participants has been carried out for several fuel related parameters, the critical heat flux and the film boiling. Contrary to what might be expected, there is not an obvious relationship between the range of variation and the influence.

Part 4: Complementary methods, assessment methodology

- Five participants have performed a critical study of Wilks' formula when it is applied at the first or the second order, i.e. respectively with 59 and 93 code runs to obtain an upper tolerance limit of the 95% percentile with a confidence level equal to 95%. For that, they carried out a large number of code runs, typically 1000. They can, in this way, obtain several estimations of the upper tolerance limit: they observe that the dispersion of this limit (the same with the lower tolerance limit) is large, reaching for the PCTs more than 200 K to 250 K when Wilks is used at the first order. This dispersion decreases rapidly when Wilks' formula is considered at higher orders but more code runs need to be performed.
- Three participants have also considered directly the empirical percentile instead of the tolerance limit. For the first PCT, it converges from around 500 code runs. One participant associates with this estimation of the percentile, an uncertainty band obtained by using the properties of the incomplete Beta law or the bootstrap technique.
- Three of these participants took advantage of their numerous code results to perform a new sensitivity analysis and compare its results with those of their base case. The results are quite significantly different and those of the base case seem not very reliable, at least for the not very influential parameters. The main reason of that is the too low number of code runs with respect to the number of input parameters, leading to spurious correlations among the input parameters.
- One participant quantified the effect of changing the density functions of the input parameters: normal and log-normal laws changed into uniform and log-uniform laws or more severe truncation of the normal and log-normal laws. The effect of such a change is less important than the effect observed when the order of Wilks' formula is increased: it modifies by 15-30 K the upper tolerance limit of the first PCT if the pdf of all the input parameters are modified. 100 calculations were performed for both investigations, using the same selected uncertain input values.
- Except for UNIPI, the only participant not using a probabilistic method, no participants propose an assessment methodology. The UNIPI methodology involves two steps: internal and external assessment.

Final observations and recommendations

Final observations and recommendations can be made at the end of this phase 3 of BEMUSE. The most frequently used approach being the probabilistic one with propagation of the uncertainties of input parameters (9 out of 10 participants), the recommendations are related to this approach.

- If feasible, particularly when the upper tolerance limit approaches regulatory acceptance criteria, e.g. 1204°C PCT, the number of code runs may be increased to 150 to 200 calculations instead of the 59 code runs needed, using Wilks' formula at the first order for the estimation of a α = 95% tolerance limit with a confidence level β of 95%. This would be advisable for two reasons: 1) with increasing sample size the uncertainty results will be less dispersed, and consequently less conservative, and 2) the sensitivity results will be more reliable. Firstly, for uncertainty analysis, it is possible to use Wilks' formula at the order 4 or 5 for α and β unchanged, which may strongly reduce the effect of conservativity of tolerance limits from small number of code runs, i.e. the dispersion of the estimated tolerance limit in conservative direction tending to substantially overestimate the 95%-quantile one is originally interested in. Regulators, however, may be more interested in approaching 100% percentiles. Secondly the results of sensitivity analysis will become more reliable, particularly for less important parameters, because the variances of the estimators of the sensitivity measures will decrease and spurious correlations between independent input parameters will appear less frequently when sample sizes increase. The issue of the number of code runs required for a proper sensitivity analysis is independent of that required for Wilks' formula. For example and unlike Wilks' formula, mainly for Regression Coefficients, the number of code runs should be significantly higher than the number of input parameters, which can be typically around 50.

- Concerning the number of input parameters, a compromise seems to be found among the following considerations:
  - In uncertainty analysis, Wilks' formula makes it possible to consider a high number of input parameters.
  - Nevertheless, a too high number of input parameters may raise difficulties to define meaningful uncertainty distributions. It can also contribute to code failures, whereas, as explained below, a proper use of Wilks' formula requires no code failure.
  - In sensitivity analysis, the results are more reliable if the number of code runs is significantly higher than the number of input parameters. But the question can be raised if one is really interested to have precise influence measures or only to know the very influential input parameters.

- It is also important to note that the model outcome sample values $y_1,\ldots,y_N$ from which the tolerance intervals/limits are determined must constitute a random sample of the model outcome Y in the statistical sense, i.e. they must be realisations of stochastically independent and identically distributed random variables $Y_1,\ldots,Y_N$. This is ensured if the underlying input parameter sample is generated according to the simple random sampling (SRS) principle. Other types of parameter selection procedures like "Latin-Hypercube-Sampling" or "Importance-Sampling" etc. may therefore not be appropriate for tolerance intervals.

- For a proper use of Wilks' formula, all the code runs must be successful, or corrected in case of failure. This requirement becomes more and more difficult when the number of code runs increases. Nevertheless, a failed run from which the result of interest (e.g. PCT) cannot be reproduced nor estimated or bounded may be treated conservatively by assuming that the result from this run will exceed all the results from the completed runs. Thus, according to "Wilks' 95%/95%-formula", the sample size must correspondingly be increased: for one failed run at least 93-1=92 correct runs are needed, for two failed at least 124-2=122 correct, for three failed at least 153-3=150 correct, etc. However, it is not clear how to proceed for sensitivity analysis in this case.

- Focussing further studies on the issue of input parameters would be desirable. Comparison tables provided in this synthesis report: a priori (part 1) and a posteriori (part 3) tables can be helpful to list the uncertain parameters in the case of a LB-LOCA. It remains the issue of the definition of the pdf (Probability Density Functions) of the input parameters. If uncertainties cannot be found in literature as it is the case for many physical models, there are roughly two cases. Either appropriate experimental data exist and methods of statistical analysis of these data compared to code results should be applied, for instance by the code developers.[3] In this case, formal methods, like Bayesian and Maximum Entropy methods, can be used to help to specify probability distributions for the parameters. Or, in the absence of experimental data, expert judgement is used but generally without much explanation. Such an approach would be definitely questioned by the authorities, if done in conjunction with a safety case. Nevertheless, if it is really impossible to avoid the use of expert judgement, it might be worth formalising it, by describing how the experts give their judgements, the confidence they have in their judgements, how the experts are selected, how they are "managed", etc. [28].

- With respect to sensitivity analysis the following issues should also be taken into account: Since in reactor safety analyses very often extremely complex and computationally expensive models are used, it is clear that in most cases additional model runs only for the purpose of sensitivity analysis will not be affordable. Thus, the selection of influence indices must be restricted the most often to those which can be computed from the available sample values already generated for uncertainty analysis, i.e. from the simple random sample (SRS) generated to determine non-parametric tolerance limits. Suitable/feasible indices in such cases are e.g. the Pearson's Correlation Coefficients, the Standardised

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3 It can be noticed that this comparison with experimental data is recommended also for another reason: it allows to take into account not only the mathematical formulation of the physical models but also their implementation in the code, what is not the case with uncertainties found in literature.

Regression Coefficients (SRC) and the Partial Correlation Coefficients (PCC) and their rank-based counterparts computed from the available SRS-sample values. These indices are not intended to provide a full complete and precise sensitivity information with respect to all parameters and all possible outcomes. But they rather seem sufficient and satisfactory to identify only the dominating uncertain parameters, i.e. those few with the highest influence on the output uncertainty, at least if a sufficient number of code runs has been performed (see the first item of this conclusion). Nevertheless, the previously quoted influence measures are not exactly equivalent and a systematic study of their advantages and drawbacks would be useful. In the case where more accurate and more exhaustive sensitivity information is wanted, one can raise the question of the most appropriate Design of Experiment, which is perhaps not the Simple Random Sampling (SRS). Using variance-based Sobol or FAST indices does not seem very appropriate because it requires an extremely large number of model runs that makes them impracticable for computationally demanding models. The only means would be to replace the code by a response surface, which is another issue not tackled in the framework of BEMUSE.

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ABBREVIATIONS

0-D	Zero Dimension or point
1-D	One Dimension
2-D	Two Dimension
3-D	Three Dimension
AEAT	AEA Technology plc
ANS	American Standard Society
ANSI	American National Standard Institute
BE	Best Estimate
BEMUSE	Best Estimate Methods Uncertainty and Sensitivity Evaluation
CCFL	Counter Current Flow Limitation
CEA	Commissariat à l'Energie Atomique (France)
CHF	Critical Heat Flux
CIAU	Code with the Capability of Internal Assessment of Uncertainty
CL	Cold Leg
CSAU	Code Scaling, Applicability and Uncertainty methodology
CSNI	Committee on the Safety of Nuclear Installations
DBA	Design Basis Accident
DC	Downcomer
DNB	Departure from Nucleate Boiling
ECC	Emergency Core Coolant
ECCS	Emergency Core Coolant System
ENUSA	Empresa Nacional del Uranio, SA
EPRI	Electric Power Research Institute
GAMA	Group on Accident Management and Analysis
GRS	Gesselschaft für Anlagen und Reaktorsicherheit mbH (Germany)
HL	Hot Leg
HPIS	High Pressure Injection System
HT	Heat Transfer
HTC	Heat Transfer Coefficient
IET	Integral Effect Test
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
ISP	International Standard Problem
ITF	Integral Test Facility
JNES	Japan Nuclear Energy Safety (Japan)
KAERI	Korea Atomic Energy Research Institute (South Korea)
KINS	Korean Institute of Nuclear Safety (South Korea)
LB-LOCA	Large Break Loss of Coolant Accident
LOCA	Loss of Coolant Accident
LOFT	Loss of Fluid Test
LOFW	Loss of Feed Water
LPIS	Low Pressure Injection System
LSTF	Large-Scale Laboratory Facility
LWR	Light Water Reactor
MATPRO	Materials Properties correlations and computer subcodes
Max_TC	Maximum Cladding Temperature
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
NRI	Nuclear Research Institute (Czech Republic)
PCC	Partial Correlation Coefficient
PCT	Peak Cladding Temperature
pdf	Probability Density Function
PIRT	Phenomena Identification and Ranking Table
PRCC	Partial Rank Correlation Coefficient
PSI	Paul Scherrer Institute (Switzerland)
Pup	Upper Plenum Pressure
PWR	Pressurised Water Reactor
QF	Quench Front
RABV	Reflood Assist Bypass Valve
SB-LOCA	Small Break Loss of Coolant Accident
SET	Separate Effect Test
SETF	Separate Effect Test Facility
SG	Steam Generator
SRC	Standardised Regression Coefficient
SRRC	Standardised Rank Regression Coefficient
SRS	Simple Random Sampling
T_{clad}	Cladding Temperature
T_{mfs}	Minimum Stable Film Temperature
T_{sat}	Saturation Temperature
t_{inj}	Time of Accumulator Injection
t_{que}	Time of complete quenching
UMAE	Uncertainty Methodology based on Accuracy Extrapolation
UMS	Uncertainty Methods Study
UNIPI	University of Pisa (Italy)
UP	Upper Plenum
UPC	Universitat Politècnica de Catalunya (Spain)
UPTF	Upper Plenum Test Facility