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MAIN RESULTS OF THE OECD BEST ESTIMATE METHODS, UNCERTAINTY AND SENSITIVITY EVALUATION (BEMUSE) PROGRAMME

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Abstract

The BEMUSE (**B**est **E**stimate **M**ethods – **U**ncertainty and **S**ensitivity **E**valuation) Programme – promoted by the **W**orking **G**roup on **A**nalysis and **M**anagement of **A**ccidents (WGAMA) and endorsed by the **C**ommittee on the **S**afety of **N**uclear **I**nstallations (CSNI) – represents an important step towards reliable application of high-quality best-estimate and uncertainty and sensitivity evaluation methods. The methods used in this activity are considered to be mature for application, including licensing processes. Skill, experience and knowledge of the users about the applied suitable computer code as well as the used uncertainty method are important for the quality of the results.

Introduction

The CSNI BEMUSE programme is focused on the application of uncertainty methodologies to Large Break Loss of Coolant Accident (LB-LOCA) scenarios in Pressurized Water Reactors (PWR). Uncertainties of code calculation results come from approximations of the balance or conservation equations in system thermal-hydraulic computer codes. Not all interactions between steam and liquid are included. Lacking information has to be supplied by the code users. Averaging over a cross section scale is another approximation whereas velocity profiles occur in reality, for example. These uncertainties are expressed by uncertainties of models in the code. Other uncertainties may be due to imprecise knowledge of initial and boundary conditions, not exactly known flow paths, like bypass flows in the reactor vessel, fuel parameters, and so on.

1. Objectives of BEMUSE

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 from the use of those methods.
- 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 justification for such an activity is that some uncertainty methods applied to BE codes exist and are used in research organisations, by vendors, technical safety organisations and regulatory authorities. Over the last years, the increased use of BE codes and uncertainty and sensitivity evaluation for Design Basis Accident (DBA), by itself, shows the safety significance of the proposed activity. Uncertainty methods are used worldwide in licensing of loss of coolant accidents for power uprates of existing plants, for new reactors and new reactor developments. End users for the results are expected to be industry, safety authorities and technical safety organisations.

2. Main steps of BEMUSE

The programme was divided into two main steps, each one consisting of three phases. The first step is to perform an uncertainty and sensitivity analysis related to the LOFT L2-5 test, and the second step is to perform the same analysis for a Nuclear Power Plant (NPP) LB-LOCA. The programme started in January 2004 and was finished in September 2010.

- Phase 1: Presentation “a priori” of the uncertainty evaluation methodology to be used by the participants; lead organization: IRSN, France.
- Phase 2: Re-analysis of the International Standard Problem ISP-13 exercise, post-test analysis of the LOFT L2-5 large cold leg break test calculation; lead organization: University of Pisa, Italy [1].
- Phase 3: Uncertainty evaluation of the L2-5 test calculations, first conclusions on the methods and suggestions for improvement; lead organization: CEA, France [2].
- Phase 4: Best-estimate analysis of a NPP-LBLOCA; lead organization: UPC Barcelona, Spain [3].
- Phase 5: Sensitivity analysis and uncertainty evaluation for the NPP LBLOCA, with or without methodology improvements resulting from phase 3; lead organization: UPC Barcelona, Spain [4].
- Phase 6: Status report on the area, classification of the methods, conclusions and recommendations; lead organization: GRS, Germany [5].

The participants of the different phases of the programme and the used computer codes are given in Table 1.

3. Used methods

Two classes of uncertainty methods were applied. One propagates “input uncertainties” and the other one extrapolates “output uncertainties”.

The main characteristics of the statistical 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 independent of the number of input uncertainties, but is only dependent on the defined probability content (percentile) and confidence level. The number of calculations is given by Wilks' formula [6]. 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 in the calculations up to the results. Uncertainties are due to imprecise knowledge and the approximations of the computer codes simulating thermal-hydraulic physical behaviour.

Table 1 Participants and used codes

No.	**Organisation**	**Country**	**Code**	**Participation in Phases**
1	AEKI	Hungary	ATHLET 2.0A	1, 2, 4, 5
2	CEA	France	CATHARE2 V2.5_1	1, 2, 3, 4, 5
3	EDO „Gidropress“	Russia	TECH-M-97	2, 4, 5
4	GRS	Germany	ATHLET 1.2C/ 2.1B	1, 2, 3, 4, 5, 6
5	IRSN	France	CATHARE2 V2.5_1	1, 2, 3, 4, 5
6	JNES	Japan	TRACE ver4.05	1, 2, 3, 4, 5
7	KAERI	South Korea	MARS 2.3/ 3.1	2, 3, 4, 5
8	KINS	South Korea	RELAP5 mod3.3	1, 2, 3, 4, 5
9	NRI-1	Czech Republic	RELAP5 mod3.3	2, 3, 4, 5
10	NRI-2	Czech Republic	ATHLET 2.0A/ 2.1A	1, 2, 3, 5
11	PSI	Switzerland	TRACE v4.05 5rc3	1, 2, 3, 4, 5
12	UNIPI-1	Italy	RELAP5 mod3.2	1, 2, 3, 4, 5
13	UNIPI-2	Italy	CATHARE2 V2.5_1	4, 5
14	UPC	Spain	RELAP5 mod3.3	2, 3, 4, 5

Another important feature of the statistical method is that one can evaluate sensitivity measures of the importance of parameter uncertainties for the uncertainties of the results. These measures give a ranking of input parameters. This information provides guidance as to where to improve the state of knowledge in order to reduce the output uncertainties most effectively, or where to improve the modelling of the computer code. Sensitivity measures like Standardized Rank Regression Coefficients, Rank Correlation Coefficients and Correlation Ratios permit a ranking of uncertainties in model formulations and input data with respect to their relative contribution to code output uncertainty. The ranking is a result of the analysis, and not of prior estimates and judgements, like Phenomena Identification and Ranking Table (PIRT) which needs extensive expert staff-hours and is known to be very costly. Uncertainty statements and sensitivity measures are available simultaneously for all single-valued (e.g. peak clad temperature) as well as continuous valued (time dependent) output quantities of interest.

The methods based upon extrapolation of output uncertainties need available relevant experimental data, and extrapolate the differences between code calculations and experimental data at different reactor scales [7]. The main difference of this method compared with statistical methods is that there is no need to select a reasonable number of uncertain input parameters and to provide uncertainty ranges (or distribution functions) for each of these variables. The determination of uncertainty is only on the level of calculation results due to the extrapolation of deviations between measured data and calculation results.

The two principles have advantages and drawbacks. The first method propagating input uncertainties is associated with order statistics. The method needs to select a reasonable number of variables and associated 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 is based on fundamental statistics 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, the majority of participants used the statistical approach, associated with Wilks' formula. Only University of Pisa used its method extrapolating output uncertainties. This method is called the CIAU method, Code with (the capability of) Internal Assessment of Uncertainty. The reason why this method is not used by other participants is the high effort needed to get the data base for deviations between experiment and calculation results in CIAU. That time and resource consuming process has been performed only by University Pisa for the codes CATHARE and RELAP5 for the time being. The data base is available only there.

4. Selected results

4.1 Application to LOFT L2-5 experiment

Based on procedures developed at University of Pisa, a systematic qualitative and quantitative accuracy evaluation of the code results have been applied to the calculations performed by the participants for LOFT test L2-5 in BEMUSE phase 2. The test simulated a 2 x 100% cold leg break. LOFT was an experimental facility with nuclear core. A Fast Fourier Transform Based Method (FFTBM) was performed to quantify the deviations between code predictions and measured experimental data [1]. The proposed criteria for qualitative and quantitative evaluation at different steps in the process of code assessment were carefully pursued by participants during the development of the nodalisation, the evaluation of the steady state results and of the measured and calculated time trends. All participants fulfilled the criteria with regard to agreement of geometry data and calculated steady state values.

The results of uncertainty bands for the four single-valued output parameters first peak cladding temperature (PCT), second peak cladding temperature, time of accumulator injection and time of complete quenching for the calculations of the LOFT L2-5 test are presented in Figure 1 [2]. It was agreed to submit the 5/95 and 95/95 estimations of the one-sided tolerance limits, that is, to determine both tolerance limits with a 95% confidence level each. They are ranked by increasing band width. It was up to the participants to select their uncertain input parameters.

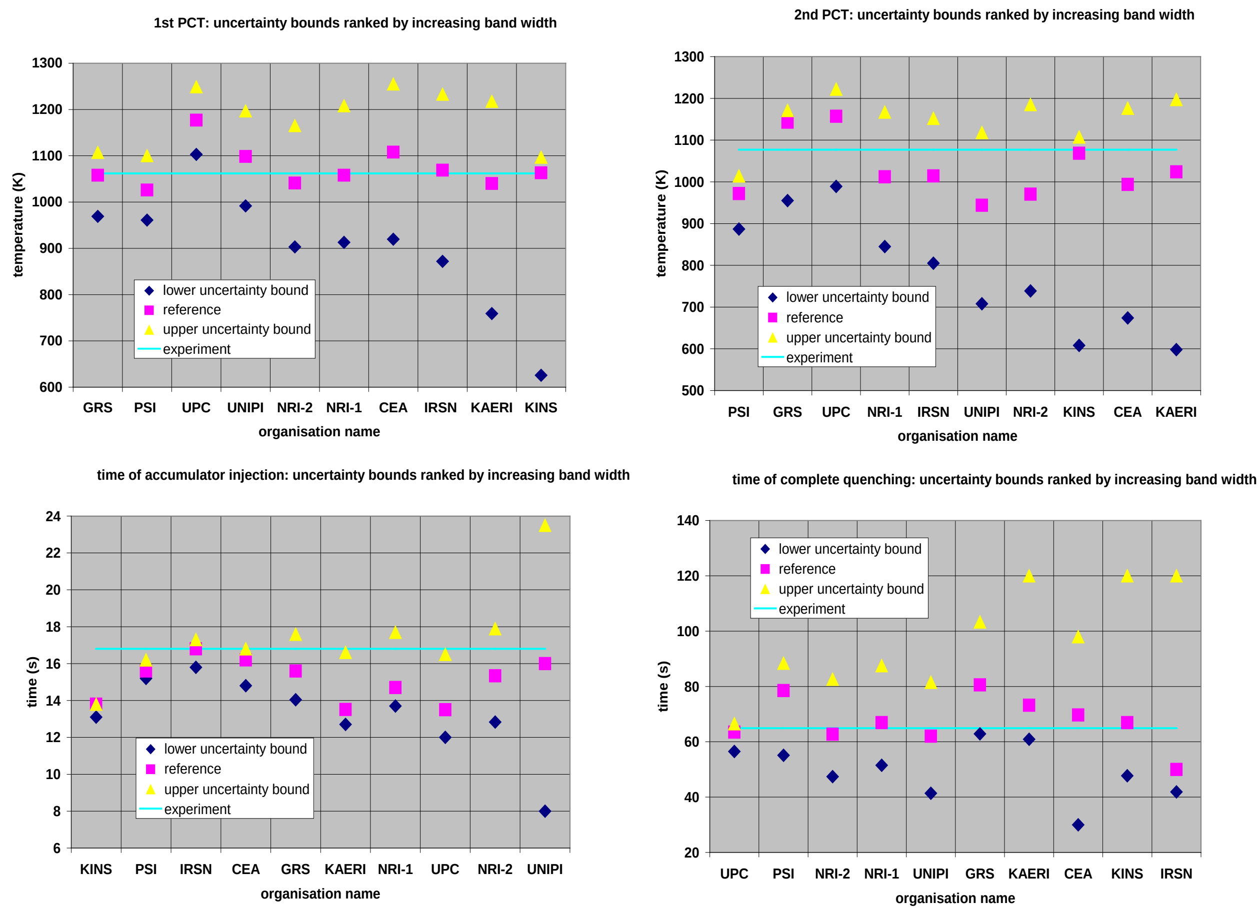

Figure 1 Uncertainty analysis results of LOFT L2-5 test calculations for four single-valued output parameters compared with experimental data

The following observations can be made:

- First PCT: The spread of the uncertainty bands is within 138-471 K. The difference among the upper 95%/ 95% uncertainty bounds, which is important to compare with the regulatory acceptance criterion, is up to 150 K and all but one participant cover the experimental value. 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 narrowest ones. KINS attribute their low lower uncertainty bound to a too high value of maximum gap conductance of the fuel rod.
- Second PCT: In this case, one participant (PSI) does not envelop the experimental PCT, due to a too low upper bound. The reasons are roughly similar to those given for the first PCT: PSI, as several participants, calculates a too low reference value, but has also the

specificity to consider an extremely narrow upper uncertainty band. The spread of the uncertainty bands of all participants is within 127-599 K. The difference among the upper 95%/ 95% uncertainty bounds, which is important to compare with the regulatory acceptance criterion, is up to 200 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 cold leg pressure reaching the accumulator pressure 4.29 MPa. 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. This is mainly due to the consideration of time error for the pressure transient calculated by UNIPI.
- 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 1.

First suggestions for improvement of the methods have not been proposed as result of the exercise; however, recommendations for proper application of the statistical method were given, see under “Conclusions”.

4.2 Application to Zion nuclear power plant

The scope of phase 4 was the simulation of a LBLOCA in a Nuclear Power Plant using experience gained in phase 2. Reference calculation results were the basis for uncertainty evaluation, to be performed in the next phase. The objectives of the activity are 1) to simulate a LBLOCA reproducing the phenomena associated to the scenario, and 2) to have a common, well-known basis for the next comparison of uncertainty evaluation results among different methodologies and codes [3].

The activity for the Zion Nuclear Power Plant was similar to the previous phase 2 for the LOFT experiment. The UPC team together with UNIPI provided the database for the plant, including RELAP5 and TRACE input decks. Geometrical data, material properties, pump information, steady state values, initial and boundary conditions, as well as sequence of events were provided. The nodalisation comprised generally more hydraulic nodes and axial nodes in the core compared with the LOFT applications.

4.2.1 Results of reference calculations

The base case or reference calculations are the basis for the uncertainty evaluation. The calculated maximum cladding temperatures versus time are shown in Figure 2. The highest difference in calculated maximum peak cladding temperatures (PCT) between the participants is 141 K (EDO “Gidropress”: 1326, JNES: 1185 K), what is lower than the difference of BEMUSE phase 2 calculations of the LOFT test.

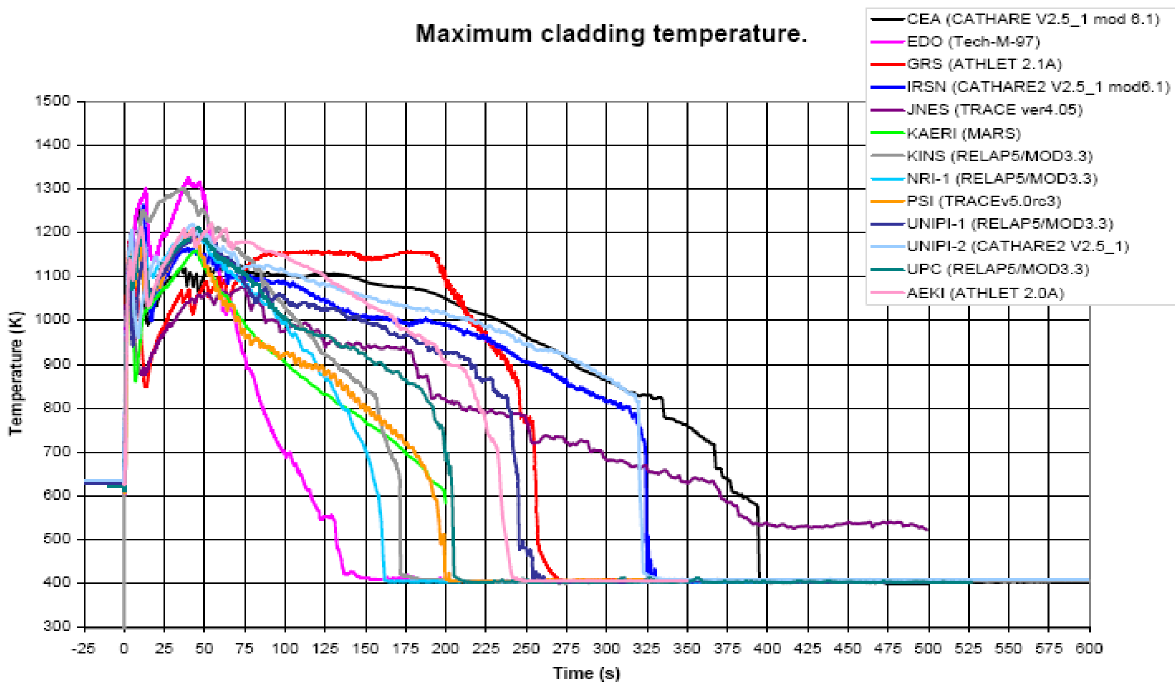

Figure 2 Calculated maximum cladding temperature versus time for the Zion NPP

4.2.2 Results of uncertainty analysis

Phase 5 dealt with a power plant [4], like phase 4. There was no available documentation concerning the uncertainties of the state of the plant, initial and boundary conditions, fuel properties, etc. To solve this situation, it was agreed to provide common information about geometry, core power distribution and modelling. In addition, a list of common input parameters with its uncertainty was prepared. This was done due to the results of phase 3, calculating the LOFT experiment, showing quite a significant dispersion of the uncertainty ranges by the different participants. This list of common uncertain input parameters with their distribution type and range was prepared by the CEA, GRS and UPC teams for the nuclear power plant. These parameters were strongly recommended to be used in the uncertainty analysis when a statistical approach was followed. Not all participants used all proposed parameters. Some considered only those without any model uncertainty. The list is shown in Table 2.

Table 2 Common input parameters associated with a specific uncertainty, range of variation and type of probability density function.

Phenomenon	Parameter	Imposed range of variation	Type of pdf	Comments
Flow rate at the break	**Containment pressure**	**[0.85, 1.15]**	Uniform	Multiplier.
Fuel thermal behaviour	**Initial core power**	**[0.98; 1.02]**	Normal	Multiplier affecting both nominal power and the power after scram.

Phenomenon	**Parameter**	**Imposed range of variation**	**Type of pdf**	**Comments**
	Peaking factor (power of the hot rod)	**[0.95; 1.05]**	Normal	Multiplier.
	Hot gap size (whole core except hot rod)	**[0.8; 1.2]**	Normal	Multiplier. Includes uncertainty on gap and cladding conductivities.
	Hot gap size (hot rod)	**[0.8; 1.2]**	Normal	Multiplier. Includes uncertainty on gap and cladding conductivities.
	Power after scram	**[0.92; 1.08]**	Normal	Multiplier
	UO2 conductivity	**[0.9, 1.1] (T_{fuel} <2000 K) [0.8,1.2] (T_{fuel} >2000 K)**	Normal	Multiplier. Uncertainty depends on temperature.
	UO2 specific heat	**[0.98, 1.02] (T_{fuel} <1800 K) [0.87,1.13] (T_{fuel} >1800 K)**	Normal	Multiplier. Uncertainty depends on temperature.
Pump behaviour	**Rotation speed after break for intact loops**	**[0.98; 1.02]**	Normal	Multiplier.
	Rotation speed after break for broken loop	**[0.9; 1.1]**	Normal	Multiplier.
Data related to injections	**Initial accumulator pressure**	**[-0.2; +0.2] MPa**	Normal	
	Friction form loss in the accumulator line	**[0.5; 2.0]**	Log-normal	Multiplier.
	Accumulators initial liquid temperature	**[-10; +10] °C**	Normal	
	Flow characteristic of LPIS	**[0.95 ; 1.05]**	Normal	Multiplier.
Pressurizer	**Initial level**	**[-10; +10] cm**	Normal	
	Initial pressure	**[-0.1; +0.1] MPa**	Normal	
	Friction form loss in the surge line	**[0.5; 2]**	Log-normal	Multiplier.
Initial conditions: primary system	**Initial intact loop mass flow rate**	**[0.96; 1.04]**	Normal	Multiplier. This parameter can be changed through the pump speed or through pressure losses in the system.
	Initial intact loop cold leg temperature	**[-2; +2] K**	Normal	This parameter can be changed through the secondary pressure, heat transfer coefficient or area in the U-tubes.
	Initial upper-head mean temperature	**[T_{cold} ; T_{cold} + 10 K]**	Uniform	This parameter refers to the “mean temperature” of the volumes of the upper plenum.

The main results of the calculated uncertainty bands can be seen for the single valued code results maximum peak cladding temperature in Figure 3. This temperature is defined as the maximum fuel cladding temperature value, independently of the axial or radial location in the active core during the whole transient. It is the main parameter to be compared with its regulatory acceptance limit in LOCA licensing analyses. For comparison purposes it was agreed to submit the 5/95 and 95/95 estimations of the one-sided tolerance limits, that is, to determine both tolerance limits with a 95% confidence level each.

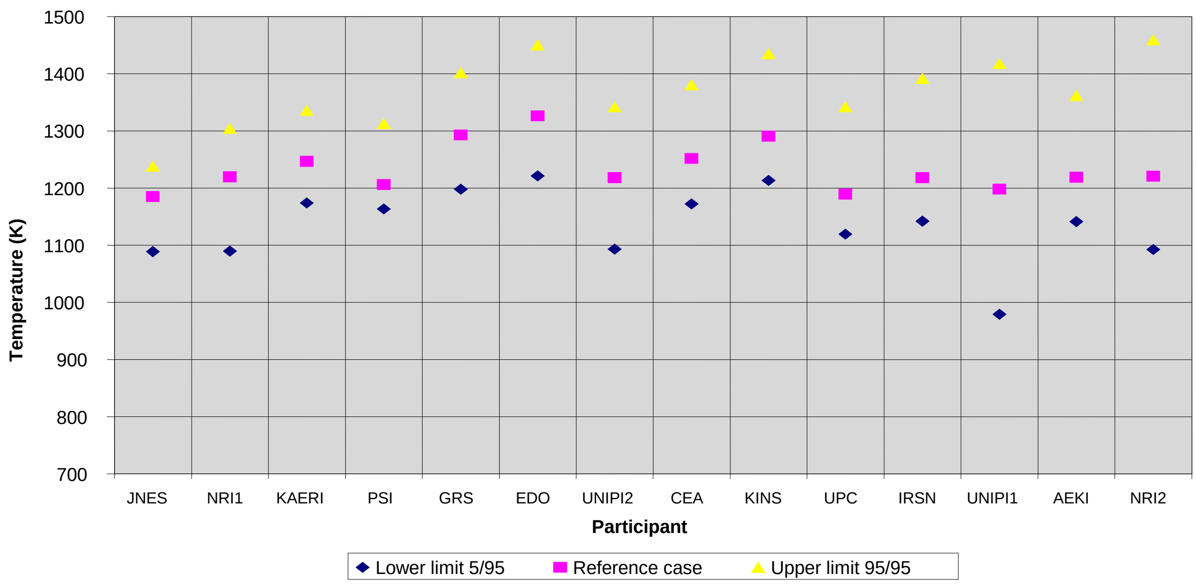

Figure 3 Calculated uncertainty bands of the maximum PCT of Zion NPP LB-LOCA

Comparing results for the maximum PCT, there is an overlap among the participants' results of 17 K (between 1221 K and 1238 K). This overlap region is very small. One of the reasons is the difference in results of the reference calculations, i.e. the difference of maximum peak cladding temperatures between the participants is up to 141 K (EDO "Gidropress": 1326 K, JNES: 1185 K). Another reason is that that EDO, JNES and PSI considered only the proposed common input parameters from Table 2 without model uncertainties.

4.2.3 Results of sensitivity analysis

Sensitivity analysis is here a statistical procedure to determine the influence of uncertain input parameters on the output parameter (result of code calculations). Each participant using the statistical approach provided a table of the most relevant parameters for four single valued output parameters and for two time trends (maximum cladding temperature and upper-plenum pressure), based on their influence measures. To synthesize and to compare the results of these influences, they are grouped in two main "macro" responses. The macro response for core cladding temperature comprise first, second and maximum peak cladding temperature, maximum cladding temperature as function of time before quenching and time of complete core quenching. The summary of the total ranking by participants is shown in Figure 4. Such information is useful for further uncertainty analysis of a LB-LOCA. High ranked parameters are fuel pellet heat conductivity, containment pressure, power after scram, critical heat flux and film boiling heat transfer.

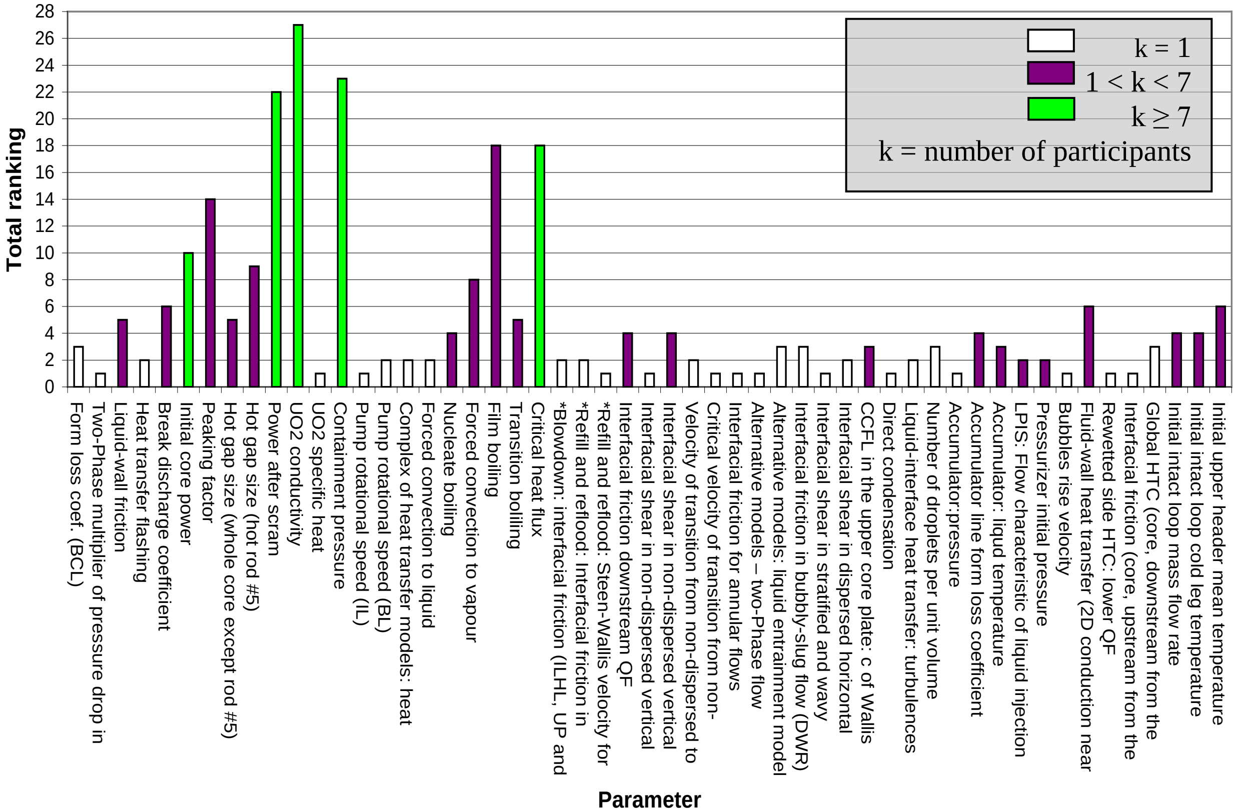

Figure 4 Total ranking of the influence of input uncertainties on cladding temperature per uncertain input parameter for Zion NPP LB-LOCA

All of these parameters determine the heat transfer from fuel rods to the fluid in the core region. Fuel pellet heat conductivity determines the release of stored heat from the fuel pellets. Increasing power after scram increases the cladding temperature and vice versa. Critical heat flux and film boiling heat transfer determine the heat transfer from the fuel rods, and consequently the cladding temperature. Containment pressure has an influence on the primary pressure and saturation temperature in the primary cooling system when the break flow is not critical. Consequently, the temperature difference between saturation temperature of the steam/ water in the core and the fuel rod cladding determines the heat transfer from the fuel rods.

5. Conclusions and recommendations

The methods used in this activity are considered to be mature for application, including licensing processes. Differences are observed in the application of the methods, consequently results of uncertainty analysis of the same task lead to different results. These differences raise concerns about the validity of the results obtained when applying uncertainty methods to system analysis codes. The differences may stem from the application of different codes and uncertainty methods. In addition, differences between applications of statistical methods may mainly be due to different input uncertainties, their ranges and distributions. Differences between CIAU applications may stem from different data bases used for the analysis. However, as it was shown by all BEMUSE phases from 2 through 5, significant differences were observed between the base or reference calculation results. In such an activity the level of knowledge is never the same among the participants, this does not mean that there is a concern with the methods. It can not be expected that 14 calculations will come up with the same PCT and the same uncertainty band for it. It is acceptable that differently experienced persons would calculate the PCT with different uncertainty bands.

When a conservative safety analysis method is used, it is claimed that all uncertainties are bounded by conservative assumptions. Differences in calculation results of conservative codes would also be seen, due to the user effect such as different nodalisation and code options, like for best estimate codes used in the BEMUSE programme. Difference of code calculation results have been observed for a long time, and have been experienced in all International Standard Problems where different participants calculated the same experiment or a reactor event. The main reason is that the user of a computer code has a big influence on how a code is used. The objective of an uncertainty analysis is to quantify the uncertainties of a code result. An uncertainty analysis may not compensate for code deficiencies. Necessary pre-condition is that the code is suitable to calculate the scenario under investigation.

Consequently, before performing uncertainty analysis, one should concentrate first of all on the reference calculation. Its quality is decisive for the quality of the uncertainty analysis. More lessons were learnt from the BEMUSE results. These are:

- The number of code runs, which may be increased to 150 to 200 instead of the 59 code runs needed when using Wilks' formula at the first order for the estimation of a one-sided 95/95 limit tolerance. More precise results are obtained, what is especially advisable if the upper tolerance limit approaches regulatory acceptance criteria, e.g. 1200 °C PCT.
- For a proper use of Wilks' formula, the sampling of the input parameters should be of type Simple Random Sampling (SRS). Other types of parameter selection procedures like "Latin-Hypercube-Sampling" or "Importance-Sampling" may therefore not be appropriate for tolerance limits.
- Another important point is that all the code runs should be successful. At a pinch, if a number of code runs fail, the number of code runs should be increased so that applying Wilks' formula is still possible. That is the case supposing that the failed code runs correspond to the highest values of the output, e.g. PCT.

In addition to the above recommendations, the most outstanding outcome of the BEMUSE programme is that a user effect can also be seen in applications of uncertainty methods, like in application of computer codes. In uncertainty analysis, the emphasis is on the quantification of a lack of precise knowledge by defining appropriate uncertainty ranges of input parameters, which could not be achieved in all cases in BEMUSE. For example, some participants specified too narrow uncertainty ranges for important input uncertainties based on expert judgement, and not on sufficient code validation experience. Therefore, skill, experience and knowledge of the users about the applied suitable computer code as well as the used uncertainty method are important for the quality of the results.

Using a statistical method, it is very important to include influential parameters and provide distributions of uncertain input parameters, mainly their ranges. These assumptions must be well justified. An important basis to determine code model uncertainties is the experience from code validation. This is mainly provided by experts performing the validation. Appropriate experimental data are needed. More effort, specific procedures and judgement should be focused on the determination of input uncertainties.

This last point is an issue for recommendation for further work. Especially, the method used to select and quantify computer code model uncertainties and to compare their effects on the uncertainty of the results could be studied in a future common international investigation using different computer codes. That may be performed based on experiments. Approaches can be tested to derive these uncertainties by comparing calculation results and experimental data. Other areas are selection of nodalisation and code options. This issue on improving the reference calculations among participants is fundamental in order to obtain more common bands of uncertainties of the results. Discussions are underway to initiate an international activity in this area.

6. References

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