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# UNCERTAINTY AND SENSITIVITY ANALYSIS FOR A NUCLEAR POWER PLANT LARGE BREAK LOSS OF COOLANT ACCIDENT (LB-LOCA) IN THE CONTEXT OF OECD BEMUSE PROGRAMME

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## Abstract

The second comparative exercise performed as part of BEMUSE (**B**est **E**stimate **M**ethods – **U**ncertainty and **S**ensitivity **E**valuation) Programme, was devoted to Nuclear Power Plant (NPP) application. The BEMUSE progamme has been 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). The programme was divided into two main steps. The first step was to perform an uncertainty and sensitivity analysis related to the LOFT L2-5 test, and the second step was to perform the same analysis for a Nuclear Power Plant Large Break Loss of Coolant Accident (LB-LOCA). The second step, also known as Phases IV and V, started in May 2006 and was finished in September 2009.

Phase IV of BEMUSE Program is connected with previous Phase II, being a necessary step for an uncertainty analysis: the simulation of the reference scenario and sensitivity analysis. The selected plant was Zion 1 NPP, a 4 loop PWR unit. Thirteen participants coming from ten different countries have taken part in the Phase IV of the program.

Phase V main objective was to obtain uncertainty bands for the maximum cladding temperature (time trend), upper plenum pressure (time trend), maximum peak cladding temperature (scalar), 1st peak cladding temperature (scalar), 2nd peak cladding temperature (scalar), time of accumulator injection (scalar), time of complete core quenching (scalar).

Fourteen groups from twelve organizations and ten countries have participated in BEMUSE Phase V.

Both Phases IV and V compared procedures with experience gained in the previous step of the programme.

## Introduction

This paper is strongly connected with paper number 71 presented in the conference. While paper number 71 is a general overview of the CSNI BEMUSE programme, in this one some additional information is given for the second step of the programme with the purpose of facing more particular details. The second step of BEMUSE programme is focused on the application of uncertainty methodologies to Large Break Loss of Coolant Accident (LB-LOCA) scenarios for a commercial Pressurized Water Reactors (PWR).

The analysis of the commercial plant scenario is organized as Phases IV [3] and V [4]. Phase IV of BEMUSE Program is connected with previous Phase II [1], being a necessary step for an uncertainty analysis: the simulation of the reference scenario and sensitivity analysis. Phase V main objective was to obtain uncertainty bands for selected output parameters.

Since the effort of summarizing the whole programme has been already done, the present paper is intended not to duplicate explanations and go straightforward to additional interesting information on Phases IV and V of BEMUSE.

## 1. Areas selected for development or comment

The following areas have been selected to be developed or commented with the general aim of completing the information already available on the project.

- Regarding Phase IV:
  - Specification information
  - Reference case results

- Regarding Phase V:
  - Lessons learned from Phase III [2]
  - Treatment of code failures

## 2. Phase IV specification information

Phase IV had the goal of simulating a LBLOCA in a Nuclear Power Plant using experience gained in Phase II. As said in reference [3], the objectives of the activity were 1) to simulate a LBLOCA reproducing the phenomena associated to the scenario, and 2) to have a common, well-known basis for the future comparison of uncertainty evaluation results among different methodologies and codes.

The selected plant was Zion Station a dual-reactor nuclear power plant operated and owned by the Commonwealth Edison network. No other options were available. This power generating station is located in the extreme eastern portion of the city of Zion, Lake County, Illinois. It is approximately 40 direct-line miles north of Chicago, Illinois and 42 miles south of Milwaukee, Wisconsin.

The main features of the plant are:

- 4 loops

- Pressurized water reactor
- Westinghouse design
- Net Output: 1040 MWe
- Thermal power 3250 MWth
- Permanently shut down
- Date started: June 1973
- Date closed: January 1998

The Steady-State conditions are summarized in Table 1

Table 1: Steady-State main parameters

| Parameter | Steady-State value |
|---|---|
| Power (MW) | 3250.0 |
| Pressure in cold leg (MPa) | 15.8 |
| Pressure in hot leg (MPa) | 15.5 |
| Pressurizer level (m) | 8.8 |
| Core outlet temperature (K) | 603.0 |
| Primary coolant flow (kg/s) | 17357.0 |
| Secondary pressure (MPa) | 6.7 |
| Steam generator's downcomer level (m) | 12.2 |
| Feed water flow per loop (kg/s) | 439.2 |
| Accumulator pressure (MPa) | 4.14 |
| Accumulator gas volume – only tank (m3) | 15.1 |
| Accumulator liquid volume – only tank (m3) | 23.8 |
| Reactor coolant pump's velocity (rad/s) | 120.06 |

The scenario is a cold leg Large Break LOCA in double guillotine without HPIS. Table 2 and the following statements specify the scenario description:

- LPIS injection with a pressure set point of 1.42 MPa (driven by a flow-pressure table)
- Accumulators injection with a pressure set point of 4.14 MPa
- Containment pressure imposed as a function of time after the break
- Reactor coolant pumps velocity imposed as a function of time after the break

Table 2: Time sequence of imposed events

| Event | Time(s) |
|---|---|
| Break | 0.0 |

| | |
|---|---|
| SCRAM | 0.0 |
| Reactor coolant pumps trip | 0.0 |
| Steam line isolation | 10.0 |
| Feed water isolation | 20.0 |
| HPIS | NO |

All the information needed to carry out Phase IV calculations was organized by the coordinator as the “BEMUSE Phase IV Input Specification” and distributed among participants.

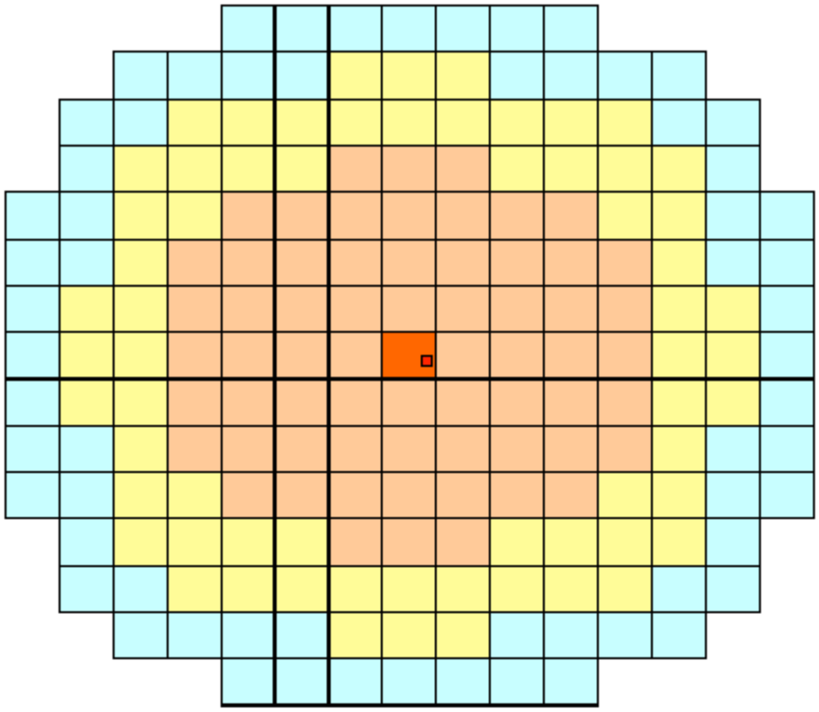
All the available details related to the plant lay-out were included in the specification.

It is important to point out that, as the plant was in permanent shutdown condition from 1998, no detailed information could be made available if needed during the development of the project. In order to work on this problem along with plant parameters, the main features of the LBLOCA scenario were specified in order to ensure common initial and boundary conditions.

Five active heat structures were nodalized simulating the fuel elements. Figure 1 shows a sketch of core heat structures zones, listed below:

- Zone 1: average fuel rods in peripheral channels
- Zone 2: average fuel rods in average channels
- Zone 3: average fuel rods in hot channels
- Zone 4: average fuel rods in hot fuel assembly
- Zone 5: hot rod in hot fuel assembly

Figure 1: Core heat structures



| # FA | # rods per FA = 204 | # fuel rods |
|---|---|---|
| 64 | peripheral channel | 13056 |
| 64 | average channel | 13056 |
| 64 | hot channel | 13056 |
| 1 | hot FA in hot channel | 203 |
| 1 rod | hot rod in hot FA | 1 |
| 193 | TOTAL | 39372 |

The specification also included information on:

- Decay power multiplier
- LPIS pressure-flow curve
- Containment pressure
- Pump velocity for primary coolant pumps in intact loops
- Pump velocity for primary coolant pumps in broken loop

An input deck for Relap5 and TRACE codes was also supplied. Figure 2 show the sketch of the nodalization schemes used by UPC team.

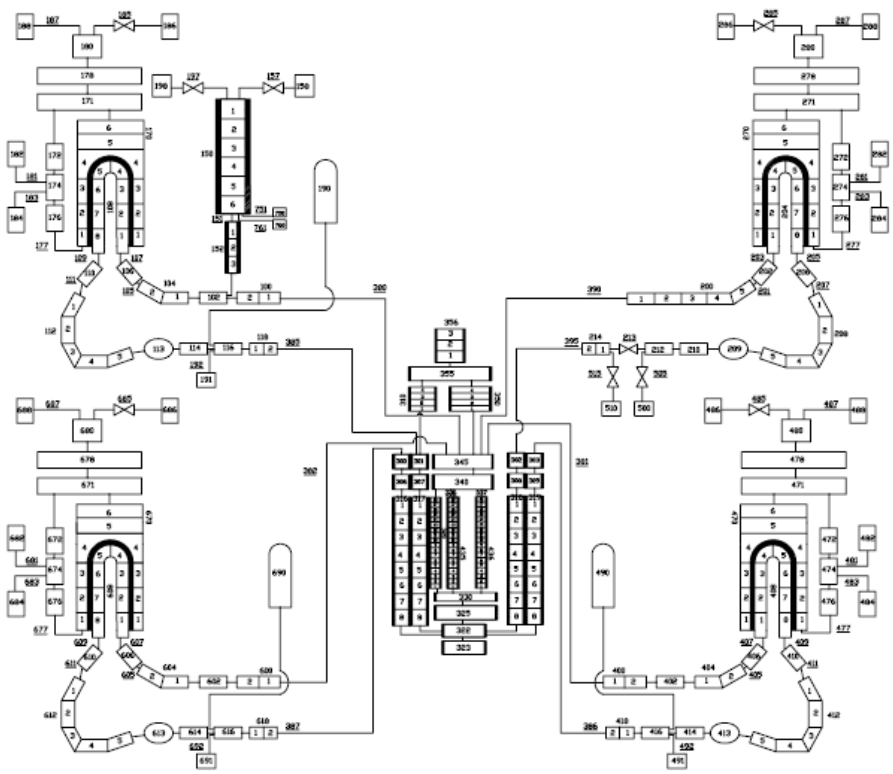
The most relevant differences among the nodalizations used are the core vessel detail and the fuel rods. Core vessels have been modelled using one dimensional and three dimensional codes. In each particular case the resulting flow distribution, ECCS bypass and the behaviour of liquid in the upper head, among others, significantly explain the diversion of results. Among one-dimensional codes an influent feature in nodalization is the use or the availability of cross flow junctions between the core channels and between the downcomer pipes.

The specifications document for BEMUSE Phase IV devoted a whole section to list a number of requirements and recommendations for nodalization performance with the aim to have a common basis for comparison. Among them:

- Some initial conditions
- Some nodalization characteristics (core, downcomer, lower plenum and the break itself)
- The use of code options (reflood and CCFL)

The level at which each participant followed the recommended procedures strongly affects the dispersion of the results.

Figure 2: Example of 1-D Relap5 nodalization scheme used by UPC

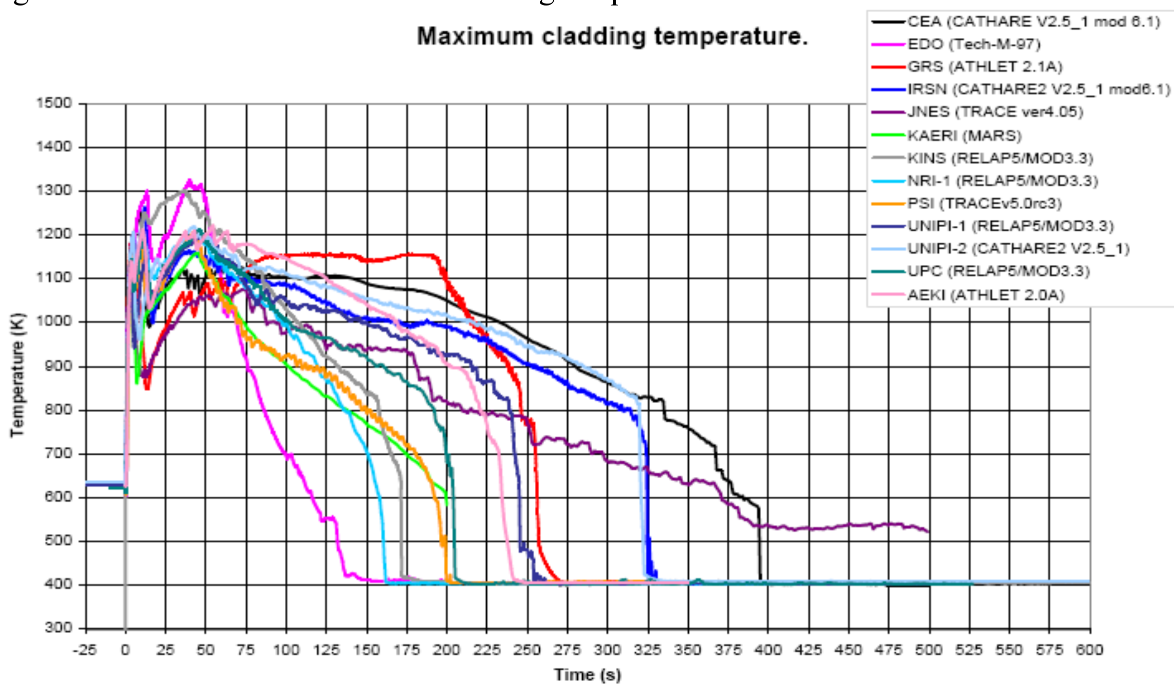


## 3. Phase IV reference case results

Figure 3 shows maybe the most significant result of Phase IV.

The most relevant comments presented there, are related to core thermal behavior, and mainly the full quench. Dispersion and major differences between results are commented and future activities depend basically on such results.

Figure 3: Time trends of maximum cladding temperature




The following figures show comparisons on other time trends of the reference case. They are helpful to catch the general picture of the simulation exercise performed. The most significant ones have been selected and are shown below in Figures 4 to 8.

Figure 4: Time trends of intact loop 1 pressure in hot leg.

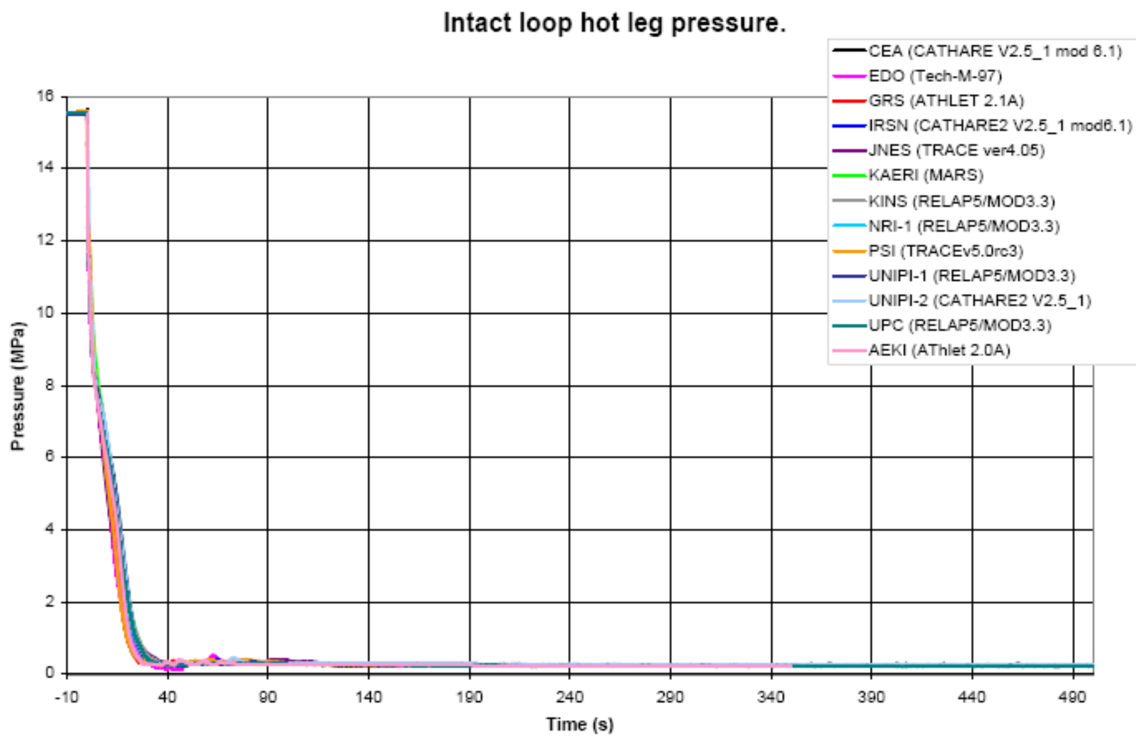



Figure 5: Time trends of accumulator 1 pressure.

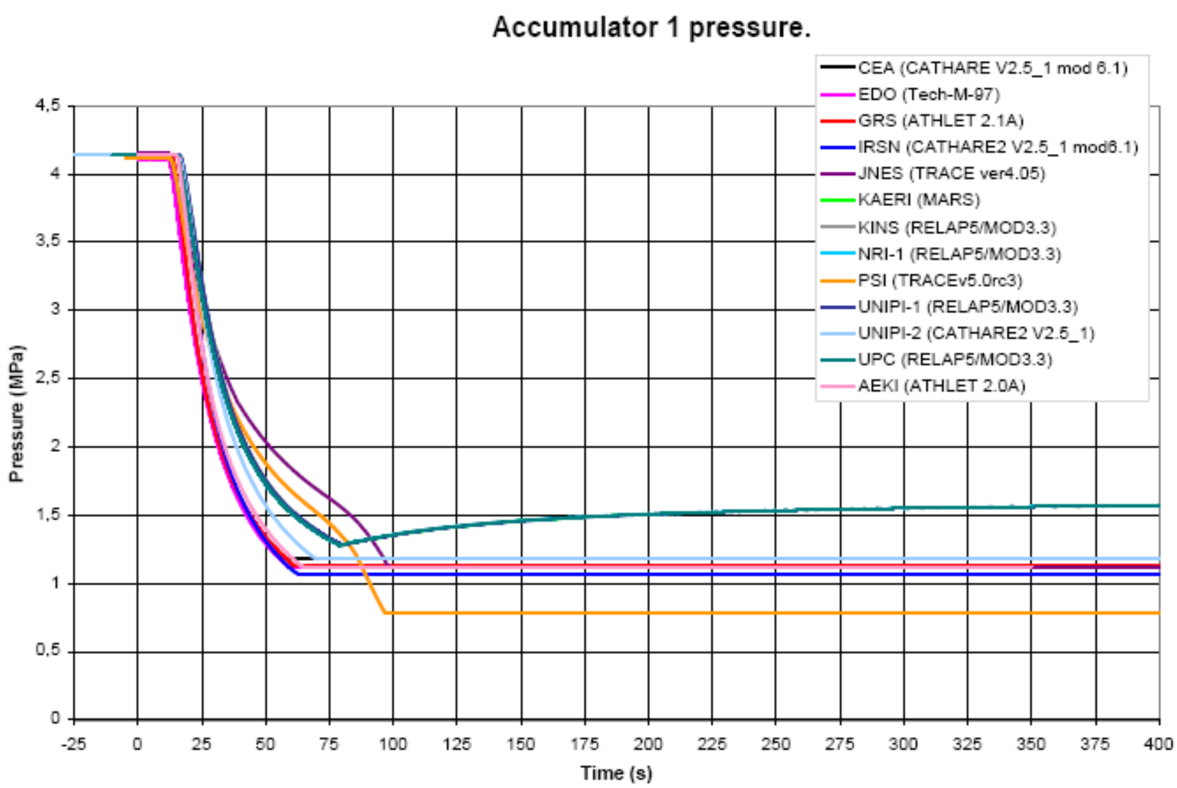



Figure 6: Time trends of integral break mass flow

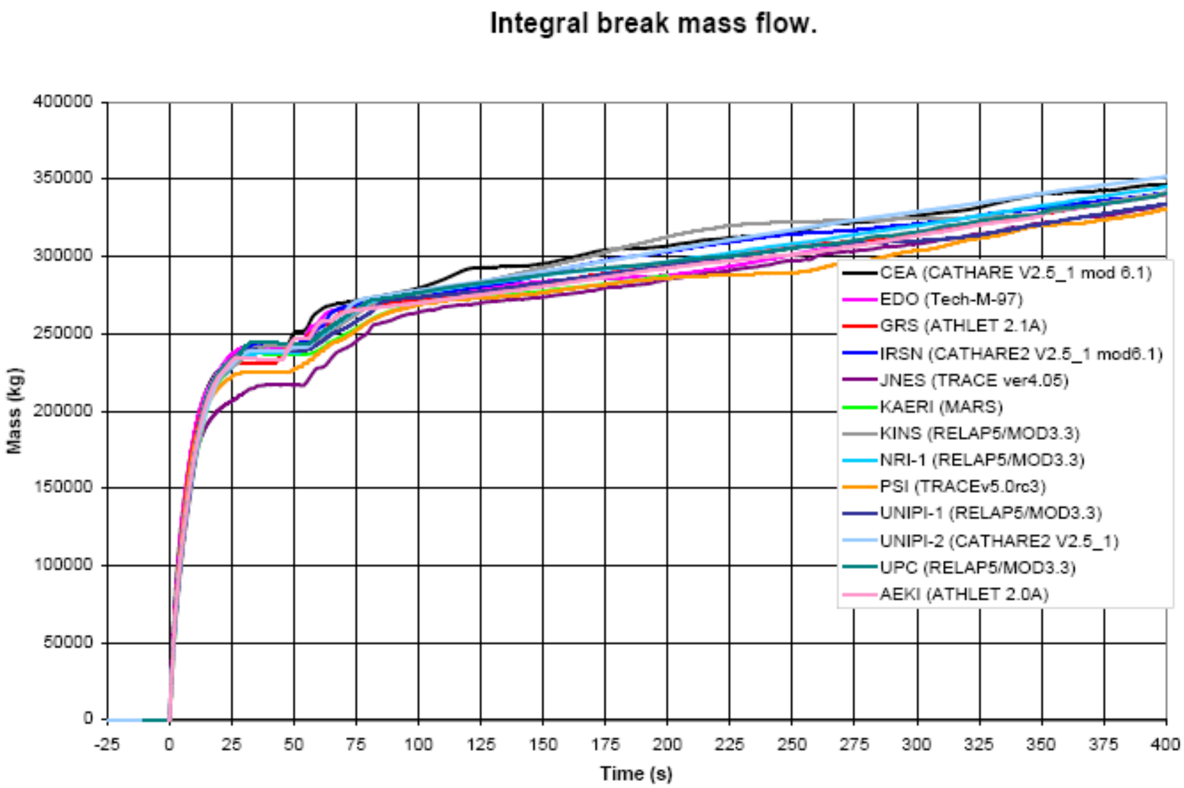



Figure 7: Time trends of ECCS integral mass flow.

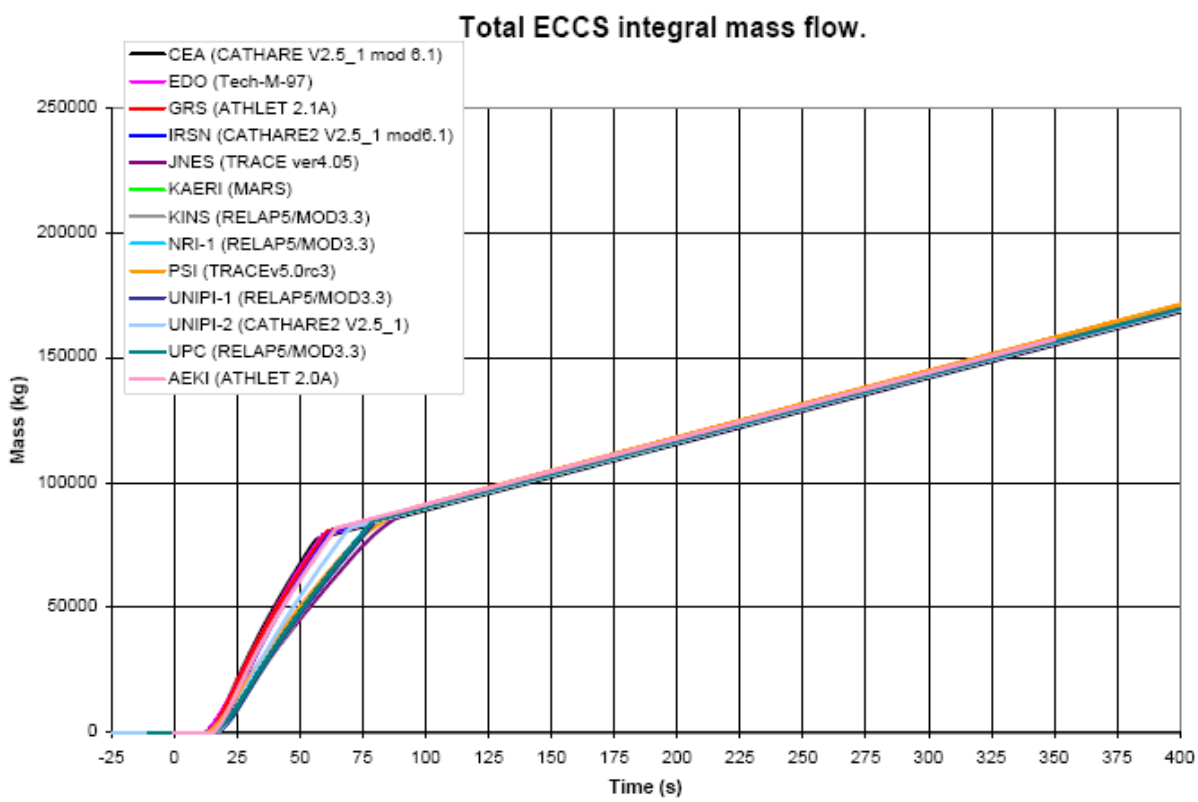
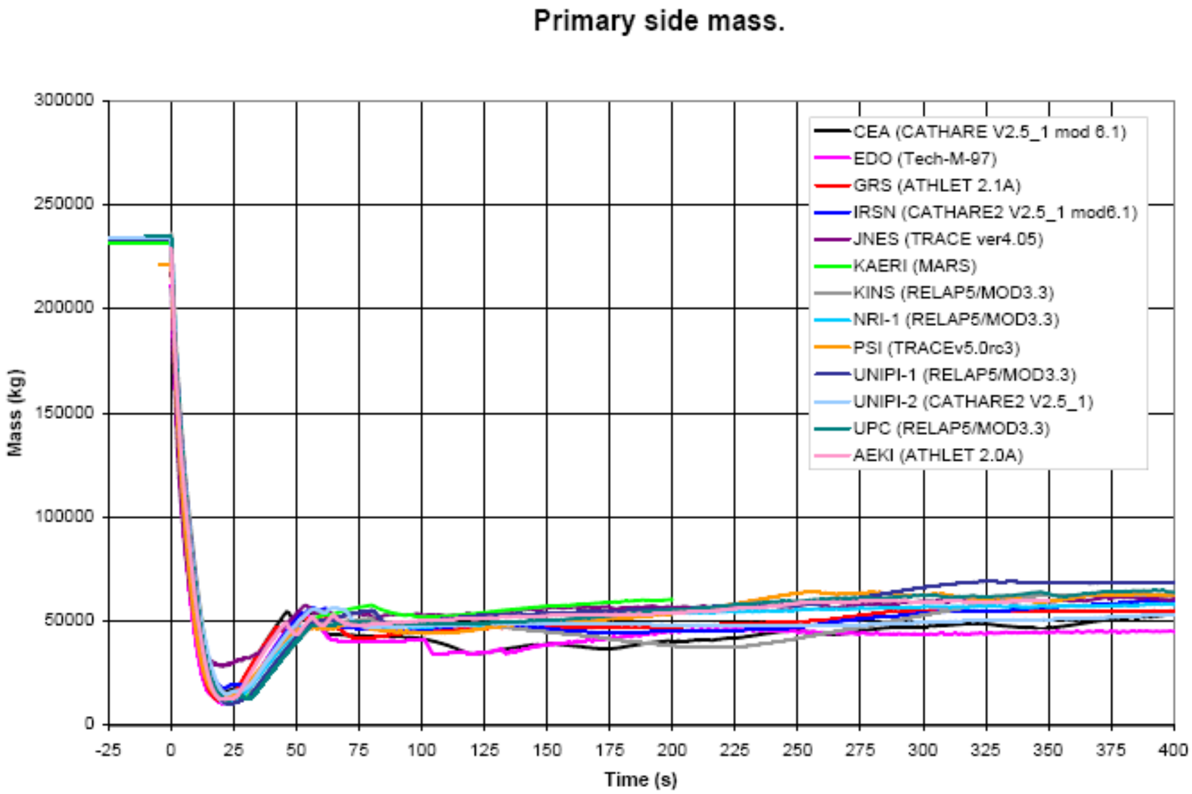



Figure 8: Time trends of primary system mass (including pressurizer).




Most of the events related to the scenario are strongly dependent on primary pressure time trend. Despite of the dispersion shown in some of the figures, some events are predicted in a consistent way by participants among these:

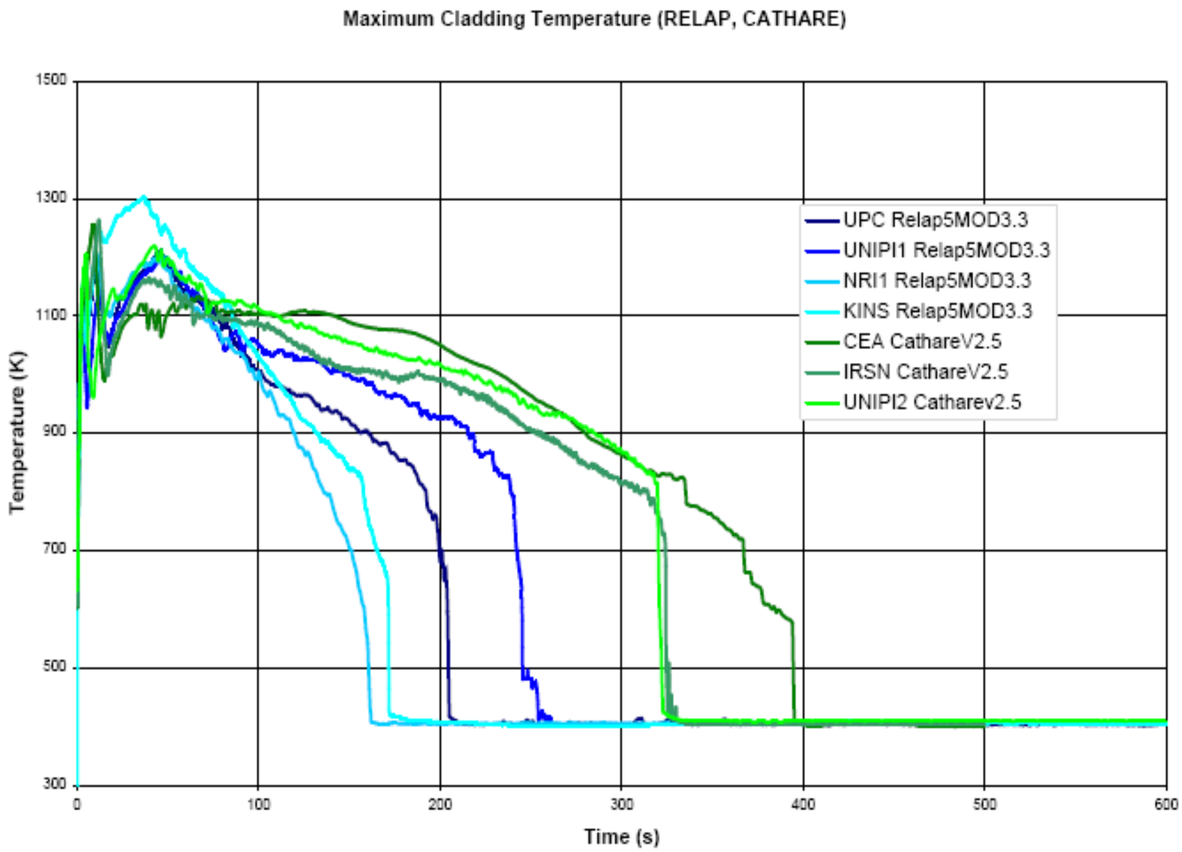
- Subcooled blowdown ended
- Cladding temperature initially deviated from saturation (DNB in core)
- Pressurizer emptied
- Accumulator injection initiated
- LPIS injection initiated

Events related to the partial top-down rewet need some explanation. After analyzing the corresponding figures, despite of a non-negligible dispersion, the shape of the curves shows some consistency. All participants predict a first PCT, a temperature decrease (at the initiation of the partial rewet) and a further temperature increase (at the end of the partial rewet). These events are not so clearly shown when participants are asked to define a time quantity related to each event but there is a general agreement on the shape of the curves. Clearly the time trend analysis (instead of the simple comparison of the time of occurrence of the events) is the best way to show the discrepancies and similarities among results.

A similar comment can be made regarding accumulator behavior. Despite injection initiation is consistently predicted by participants and properly shown in Figure 5 the prediction of accumulators emptying shows some dispersion. As it is a phenomenon depending on intact leg pressure, pressure error and cumulative time error have a strong effect on the occurrence of the event and dispersion increases.

It is clear that dispersion bands exist but it is also clear that the effort of explaining the reasons of such dispersion is a valuable outcome from this phase. The outcome of BEMUSE Phase IV is also helpful to understand the nuances existing inside the user effect. The discussion on the point related to the full quench has been useful to clarify the "border" between user effect and code effect. Figure 9 enlights these considerations putting together CATHARE and RELAP5 calculations results for this particular aspect. Despite the consistency of both groups of calculations some code effect appears. This point is a minor result of Phase IV detected within the programme although it cannot be solved in its framework.

Figure 9: Calculated hot rod temperature / Code effect considerations




## 4. Lessons learned from Phase III and implemented in Phase V

First of all, and independently of the lessons learnt of Phase III, a new scalar quantity is defined: Maximum Peak Cladding Temperature (MPCT). It is the maximum temperature value reached on the cladding surface during the whole transient, independently of its location (axial or radial).

The whole group of participants agreed this implementation. The reason of including it is because it is the main parameter which is compared with its design safety limit in LOCA licensing analyses. Dispersion on this value is smaller than that of first and second Peak Cladding Temperature.

The first lesson learned from Phase III is related to the input parameters considered in Wilks' methods. More precisely, two changes clearly appear with respect to Phase III:

The first change is the definition of "recommended parameters" in Phase V: Indeed, in Phase III, uncertainties of initial and boundary conditions could be found in the LOFT L2-5 documentation. As this information did not exist for the Zion NPP, the coordinator decided to recommend to the participants a list of input parameters, with their uncertainties, related to these initial and boundary conditions, but also to the material properties and friction form loss factors. This common list consisted of 20 input parameters.

The second change is related to the total number of input parameters. Summing up contributions from all participants, the total number of parameters taken into account has decreased: it was higher than 150 in Phase III, whereas it is about 110 in Phase V.

Table 3 compares the number of parameters used by participants in Phases III and V . Generally speaking, the mean number of uncertain input parameters considered by each participant is roughly the same but the dispersion has decreased. As it can be seen in Table 3, when the group of participants limiting the list of parameters to the commonly specified ones is not considered, the mean number increases (since there's no limitation) to almost 39 and the dispersion between participants diminishes to 11. When comparing these values with previous Phase III the mean number increases by almost six parameters while the dispersion decreases by seven parameters.

Table 3. Number of input parameters. Comparison with Phase III.

| | AEKI | CEA | EDO | GRS | IRSN | JNES | KAERI | KINS | NRI1 | NRI2 | PSI | UPC | Mean | Standard deviation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase III | - | 53 | - | 49 | 42 | 27 | 14 | 13 | 31 | 64 | 24 | 14 | 33.1 | 18.1 |
| Phase V | 36 | 44 | 17 | 55 | 54 | 20 | 25 | 24 | 33 | 44 | 20 | 32 | 33.7 | 13.2 |
| Phase V (*) | 36 | 44 | - | 55 | 54 | - | 25 | 24 | 33 | 44 | - | 32 | 38.6 | 11.4 |

(*) Only participants considering more parameters than the ones proposed in the specifications document.

The differences between the two phases can be explained by several reasons: the need of modifications due to the few differences between the LBLOCA in an NPP and L2-5 experiment, the use of different versions of BE codes (thus the changes of models), the use of new acquired experimental data, and the added input uncertain parameters on the basis of the sensitivity results performed during the Phase III or the overcome of difficulties had in previous phase.

To evaluate the use of the synthesis tables for sensitivities produced in Phase III as a selection tool for Phase V, parameters which *appeared influential* in Phase III are compared with parameters *considered* in Phase V. It is important to remind, as stated in Phase III report, that the synthesis tables produced in the previous phase are not entirely valid for a LBLOCA scenario in a typical PWR due to the specificity of both the L2-5 transient and LOFT facility. Table 4 summarizes this comparison.

An explanation of the meaning of some of the entries in Table 4 follows:

- The line "Uncertain parameters (Phase V)" refers to the number of uncertain parameters used in Phase V.
- The line "Ph.III and not in Ph.V-Specs" refers to parameters identified as influent in Phase III (no matter which participant found them influential) and considered by the participant in Phase V, that are NOT included in the common list for Phase V.
- The line "Ph.III and in Ph.V-Specs." refers to parameters identified as influent in Phase III (no matter which participant found them influential), that are specified in the specifications of Phase V.
- In "Total" line there is the total number of parameters considered by the participant in Phase V and that appear in the influence ranking tables of Phase III.
- A number is added to illustrate the use of more than one multiplier for the same parameter. This situation happens when ranges are defined and different multipliers are used for each range, or when alternative models are considered together with a multiplier to the correlation coefficient.

Table 4. Comparison with sensitivity synthesis tables of Phase III

| Participant | AEKI (*) | CEA | EDO | GRS | IRSN | JNES | KAERI | KINS | NRI1 | NRI2 | PSI | UPC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Uncertain parameters (Phase V) | 36 | 44 | 17 | 55 | 54 | 20 | 25 | 24 | 33 | 44 | 20 | 32 |
| Ph.III and not in Ph.V-Specs. | 3 | 10 | - | 17 | 15+5 | - | 6 | 8 | 9+1 | 11 | - | 7+3 |
| Ph.III and in Ph.V-Specs. | 11 | 11 | 10 | 11 | 9+2 | 11 | 11 | 9 | 11 | 10 | 11 | 11+2 |
| Total | 14 | 21 | 10 | 28 | 24+7 | 11 | 17 | 17 | 20+1 | 21 | 11 | 18+5 |

(*) AEKI group was included in the comparison even though they did not participate in Phase III

Eleven parameters from the common list of Phase V were found influential in the sensitivity studies performed in Phase III. The majority of the participants considered these eleven parameters in Phase V (third line in Table 4). Three participants have empty entries for the parameters not quoted in the common list (second line in Table 4) as they only took into account the proposed set, for the other participants the number of these parameters ranges from three to a maximum of seventeen. The total number of parameters that appear in both Phase III synthesis tables and the selected ones in Phase V ranges from ten to twenty eight.

Finally the second lesson learned is also with Wilks' methods and related in this case to the number of calculations. A clear recommendation of Phase III was to increase this number, which makes it possible to apply Wilks' formula at higher order than 1. This recommendation applies especially if the tolerance limit approaches regulatory acceptance criteria, e.g. 1204°C.

Consequently, among such participants there is a wide variety of applications coming from the order used for Wilks' formula and therefore the number of calculations.

Table 5 resumes the comparison on the use of Wilks' formula: the order and the number of code calculations (in parentheses) including code failures are indicated per each participant and phase. The importance of comparing them comes from the fact that there were no recommendations on this issue in neither of the specifications documents of Phase V.

Table 5. Order of Wilks' application. Comparison with Phase III.

| | AEKI | CEA | EDO | GRS | IRSN | JNES | KAERI | KINS | NRI1 | NRI2 | PSI | UPC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase III | - | 2 (100) | - | 2 (100) | 1 (59) | 1 (100) | 2 (100) | 1 (59) | 1 (59) | 1 (60) | 3 (150) | 2 (100) |
| Phase V | 2 (105) | 5 (200) | 2 (93) | 4 (153) | 9 (300) | 2 (110) | 3 (200) | 3 (124) | 5 (200) | 2 (93) | 2 (120) | 3 (124) |

Some remarks to this table are:

- The minimum order used has increased in Phase V from 1st order to 2nd order, and the minimum number of calculations in Phase V is 93, while in Phase III it was 59.
- The maximum order used has increased in Phase V from 3rd to 9th order, and the maximum number of calculations in Phase V is 300, while in Phase III it was 150.
- All participants except for PSI increased at least by one the order of application, and therefore also increased the number of code runs. The mean order for Phase V is 3.33 while in Phase III is 1.6.

## 5. Treatment of code failures

This issue was already mentioned in Phase III report [2], but is more extensively explained in Phase V report [4], as well as in the final synthesis report [5]. Regarding the treatment of failed calculations in the application statistical methods, three cases were distinguished:

- No failure
- Code failures but they are all corrected or successfully repeated on another computer
- Code failures discarded. There are *sufficient* successful code runs to apply Wilks' formula with confidence level $\geq 0.95$

Some comments should be added regarding the treatment of code failures when they are discarded. For a proper use of Wilks' formula there should be no code failures so the general recommendation is to correct them. Nevertheless, when that is not possible and in case of a relatively low number of code failures, two approaches were used although only the second one is correct. Let us consider the case of 100 code runs with 4 code run failures, applying Wilks' at second order. The first approach is to consider that the 96 successful code runs are sufficient to apply Wilks at the order 2, since at this order and for $\alpha = \beta = 95\%$, only 93 code runs are needed. So with this approach, the 95th highest value of the output is considered for the upper tolerance limit. But this approach is not correct because the discarded code runs can correspond to the highest values of the output. The second approach relies on the hypothesis that the 4 failed code runs would have corresponded to the highest values of the output, if they had been successful.

So, considering the highest value among the 96 successful code runs is equivalent to apply Wilks' formula at the order 5. The problem is that to apply Wilks' formula at the order 5 with $\alpha = \beta = 95\%$, 181 code runs are needed, and not 100.

## 6. Conclusions and recommendations

The main conclusion of Phases IV and V of BEMUSE programme is that emphasis of an international follow-up activity has to be on a high quality of the basis calculation and the specification of the input uncertainties.

As discussed, Phase V results corroborate for NPP analysis the recommendations performed in Phase III for test facility case. Besides such general recommendations some other minor aspects need to be treated in order to assure the success of future applications. Among them: specification contents, reference case results analysis, "lessons learned" implementation or even the treatment of code failures, have revealed to be essential.

## 7. References

[1] "BEMUSE Phase II Report", Re-analysis of the ISP-13 exercise, post-test analysis of the LOFT L2-5 test calculation; NEA/CSNI/R(2006)2, May 2006.

[2] "BEMUSE Phase III Report", Uncertainty and sensitivity analysis of the LOFT L2-5 test; NEA/CSNI/R(2007)4, October 2007.

[3] "BEMUSE Phase IV Report", Simulation of a LB-LOCA in Zion nuclear power plant; NEA/CSNI/R(2008)6, November 2008.

[4] "BEMUSE Phase V Report", Uncertainty and sensitivity analysis of a LB-LOCA in Zion nuclear power plant; NEA/CSNI/R(2009)13, December 2009.

[5] "BEMUSE Phase VI Report", Status report on the area, classification of the methods, conclusions and recommendations; NEA/CSNI/R(2011)X, to be published.