Workshop on Evaluation of Uncertainties in Relation to Severe Accidents and Level 2 Probabilistic Safety Analysis
Hotel Aquabella, Aix-en-Provence, France, November 7-9, 2005.

FCI Phenomena Uncertainties Impacting Predictability of Dynamic Loading of Reactor Structures
(SERENA programme)

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Abstract

The paper presents the results of Phase 1 of OECD SERENA programme on fuel-coolant interaction under the aspect of the implications uncertainties on FCI phenomena may have on the predictability of steam explosion induced loads. SERENA, in its Phase 1, made a status of the predictive capabilities of the FCI codes through comparative calculations of most relevant existing experiments and reactor cases. All the codes were able to calculate reactors situations. The way they have been used in the exercise, the calculated in-vessel loads were found far below the capacity of a typical intact vessel and above the capacity of a typical cavity. Confidence in these conclusions are challenged by the large scatter of the results, and by the uncertainties related to the description of the flow patterns in the premixing phase, in particular void fraction evolution, and to the missing physical justification of the reduced energetics observed with corium melts. Addressing these issues as well as considering other reactor situations is required to confirm these conclusions for in-vessel steam explosion and quantify the safety margins for ex-vessel steam explosion.

1. Introduction

SERENA is an OECD programme on fuel-coolant interaction (FCI), which has the scope of making a status of the code capabilities to predict FCI induced dynamic loading of the reactor structures (Phase 1), and performing the complementary research possibly needed to increase the level of confidence of the predictions (Phase 2). Phase 1 has been completed. It consisted of comparative calculations by available tools of selected existing experiments and reactor cases, in order to identify those areas where lack of understanding induced large uncertainties in the predictions of the loads in reactors [1]. Phase 2 is intended to carrying out the confirmatory analytical and experimental research needed to reduce these uncertainties to acceptable level for risk assessment. Phase 1 was the first comparative exercise undertaken since ISP-39, which however concerned premixing only [2].

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Organisations participating in Phase 1 were Commissariat à l'Énergie Atomique (CEA) jointly with Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France, Korea Atomic Energy Research Institute (KAERI) jointly with Korea Maritime University (KMU), Nuclear Regulatory Commission (NRC), USA, University of Wisconsin (UW) and University of California Santa Barbara (UCSB) sponsored by NRC, Institute für Kernenergetik und Energiesysteme (IKE) sponsored by Gesellschaft fuer Anlagen und Reaktorsicherheit (GRS), Germany, Forschungszentrum Karlsruhe (FZK), Germany, Electrogorsk Research and Engineering Centre (EREC), Russian Federation, Japan Atomic Energy Research Institute (JAERI), Japan and Nuclear Power Engineering Corporation (NUPEC), Japan.

The FCI codes used were ESPROSE-m (UCSB), IDEMO (IKE), IFCI (KINS), IKEMIX (IKE), JASMINE (JAERI), MATTINA (FZK), MC3D (CEA-IRSN, IKE), PM-ALPHA (UCSB), TEXAS-V (UW, KAERI), TRACER (KMU) and VESUVIUS (NUPEC), respectively.

As being a status of the code capabilities to calculate FCI in reactor situations, it was not within the scope of SERENA to establish whether or not a specific code was qualified to be in. It was let to the responsibility of each partner to judge whether his code or the code he is using had the required degree of qualification and verification to participate. Most data used for code validation and verification last decade came from the FARO and KROTOS programmes performed under international sponsorship at the Joint Research Centre of the European Commission, Ispra site (Italy). However, about half of the partners in SERENA were not involved in these programmes and had not full access to the detailed data prior to SERENA.

Consequently, calculating typical experiments prior to reactor application had the twofold objective of establishing a "setting to zero" of the codes and each participant starting with verification of their tools on a similar basis. It allowed partners to verify in which conditions of parameters and model options the codes were able to capture the essential features of experiments performed in so-called "realistic conditions", and set up model options and parameters for calculating the reactor situations. Integrating information coming from this variety of backgrounds allowed identifying the common areas where uncertainties are consequential to the estimate of the loads.

The scope of the paper is to give a general picture of the present FCI code capabilities to reproduce existing data, to summarise the conclusions that have been reached to tentatively explain the observed differences, and to deduce the consequences for reactor application. It is not intended to draw conclusions on which code performs better than another, or the best, if any. For these reasons, calculation results are presented without any reference to the codes. A comparative review of the codes and models has been performed in the frame of SERENA [3]. The detailed analysis of the results is found in the final report of the project in preparation.

2. Methodology

First, generic situations corresponding to plausible melt relocation scenarios and capable to produce potentially damaging steam explosion were identified [1]. For ex-vessel, large pour equivalent to some tens of centimetres in diameter of UO_2-ZrO_2-Zr-Steel melt into a cavity flooded with subcooled water was selected as a situation matching the above criteria. For in-vessel, multi-jets arriving off-centre in the lower head was considered the most challenging for the vessel. Then, existing experiments as far as possible in relation with these reactor situations were selected. Noting that no relevant multi-pour experiment exists, the best we could extract today from experimental database in relation to the SERENA Phase 1 objectives was found in the FARO, KROTOS and TROI programmes.

Participants were given same sets of initial conditions and reference data. They translated these initial conditions into adequate inputs for their codes. Participants were let free to set model options and parameters as they used to. However, they were asked to provide at least one calculation with using standard parameters, to document their choices and possibly make sensitivity calculations. Explosion phases of the experiments were calculated both for imposed and calculated pre-mixing whenever required. Comparison was made on a set of pre-established quantities, either for codes-to-data comparison or code-to-code comparison. These quantities included nodalisation, pressure and impulse, vaporization/condensation rates, energy release, component fraction, debris characteristics.

The calculation work was divided into 3 tasks, namely, calculation of pre-mixing experiments, calculation of explosion experiments, reactor applications. In SERENA, phenomena were considered important as far as they induce large uncertainties on the loads calculated for reactor configurations. For this reason, conclusions drawn from code application to experiments about the importance of a given phenomena were considered as provisional until reactor application were performed.

3. Calculated cases

3.1. Experiments

Pre-mixing gives the initial conditions of steam explosion. The strength of an explosion is highly depending on how the components (liquid water, steam, melt) were mixed together at the time the explosion triggers. It was therefore found important, as a first step, to verify whether the codes are able to calculate this phase for large-scale pre-mixing experiments. Two FARO experiments, namely, FARO L-28 [4], which investigated the premixing phenomena only, and FARO L-33 [5], which was an integral experiment covering both premixing and explosion, were used as the major support for assessing code performance for the pre-mixing phase. In these experiments quantities up to 175 kg of 80 wt% UO_2 -20 wt% ZrO_2 molten corium were poured into water at different pressures and subcooling levels. Table 1 summarises the specific conditions of L-28 and L-33 tests. Note that FARO L-28 was performed with saturated water typical of in-vessel conditions, and FARO L-33 with sub-cooled water typical of ex-vessel conditions

Table 1: Conditions of FARO experiments used for premixing calculations

Experiment	FARO L-28 (Premixing test)	FARO L-33 (Integral test)
Melt and composition	80 wt% UO_2 20 wt% ZrO_2	80 wt% UO_2 20 wt% ZrO_2
Melt mass released	175 kg	100 kg (40 kg at trigger)
Melt temperature	3053 K	3070 K
Melt superheat	203 K	220 K
System pressure	0.51 MPa	0.41 MPa
Water temperature	424 K	294 K
Water subcooling	0 K	124 K
Release diameter	0.05 m	0.05 m
Δp melt delivery	Gravity	Gravity
Free fall in gas space	0.89 m	0.77 m
Water depth	1.44 m	1.62 m
Water pool diameter	0.71m	0.71 m
Free-board	Closed volume (3.5 m^3)	Closed volume (3.5 m^3)
Trigger	No	Yes (applied at bottom at melt-bottom contact)

In addition to FARO L-33, two other experiments were selected for testing the code performance for the explosion phase, namely, KROTOS-44 with alumina melt [6] and TROI-13 with 70 wt% UO_2-30 wt% ZrO_2 melt [7]. Table 2 summarises the main conditions of these tests. An experiment with alumina melt was chosen because it is a well-characterised 1-D steam explosion with well-defined external trigger, producing a very energetic interaction and thus well appropriate to test the explosion models. Then, TROI-13 dealing with a similar quantity of corium and 2-D geometry represented an extension to more realistic conditions. Finally FARO L-33 with 25 kg of corium melt in water at the time of the trigger and 2-D geometry represented a step further in scale. Calculations were performed either for a given pre-mixture (K-44), or for both a given and a calculated pre-mixture (TROI-13, L-33). Note that a blind exercise was done also on a TROI test, subsequently performed as TROI-34. Results did not significantly differ from TROI-13.

Table 2: Conditions of KROTOS and TROI experiments used for explosion calculations

Experiment	TROI-13	KROTOS-44
Melt and composition	70 wt% UO_2-30 wt% ZrO_2	100 % Al_2O_3
Melt mass released	7.7 kg	1.5 kg
Interacting melt mass	1.14 kg	1.44 kg
Melt temperature	~3300 K	2673 K
Melt superheat	~500 K	359 K
System pressure	0.1 MPa	0.1 MPa
Water temperature	292 K	363 K
Water subcooling	81 K	10 K
Release diameter	0.02 m	0.03
Δp melt delivery	Gravity	Gravity after crucible impact
Free fall in gas space	3.9 m	0.43 m
Water depth	0.69 m	1.115 m
Water pool diameter	0.60 m	0.20 m
Free-board	Closed volume (8.03 m^3)	Closed volume (0.23 m^3)
Trigger	No	Yes (at bottom)

3.2. Reactor cases

Figures 1 summarises the initial and boundary conditions used for in- and ex-vessel cases, respectively. When looking at these conditions, one has to keep in mind that the scope was not to calculate a specific scenario in a reactor specific geometry and draw conclusions about the FCI risk for that geometry. The scope was to verify whether the codes used by the partners as their tools for FCI analysis are able to calculate plausible generic reactor situations, and to compare the results in order to identify the differences and the actions required to understand and reduce them.

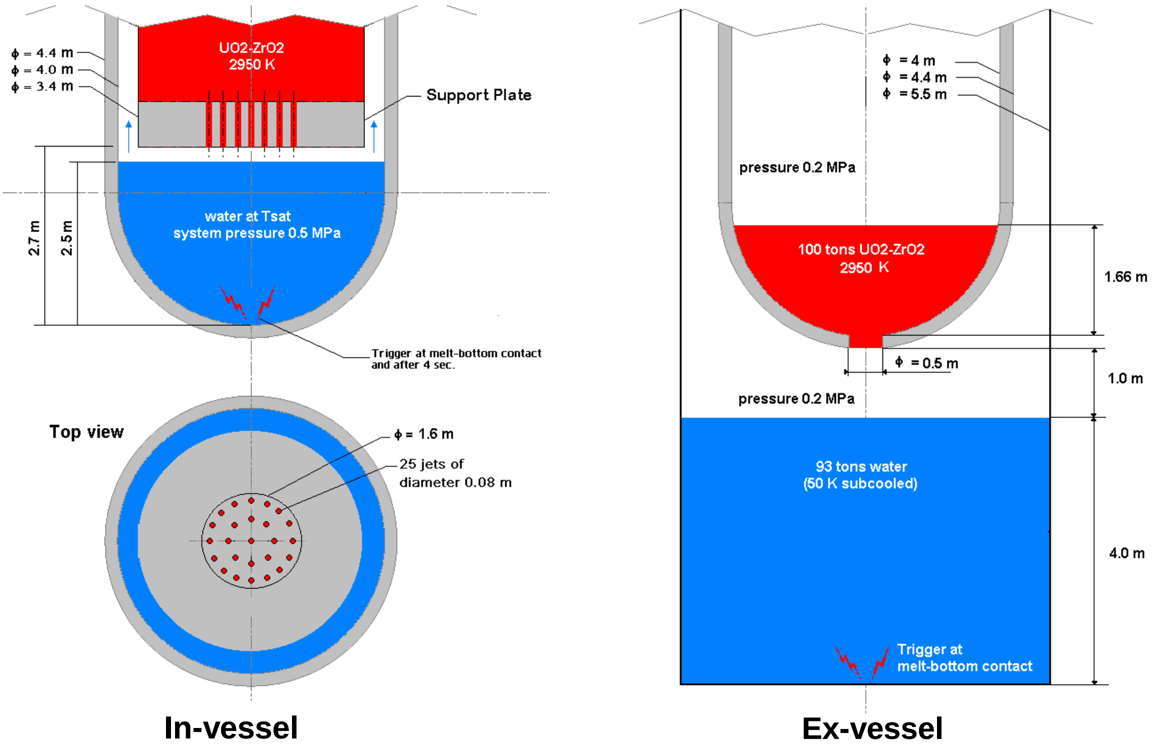

Figure 1: Calculated reactor situations

In both cases, a gravity pour was considered. For in-vessel, the multi-jet configuration is obviously fully 3-D, while most codes have to be run 2-D axi-symmetric even when applied to reactor situations. This was made deliberately in order to include in the simulation all the aspects related to code application to reactor cases, and, in particular, the simplifications that have to be made to reduce to 2-D the actual 3-D situations.

The calculations were made for both the pre-mixing and the explosion phases. A trigger was applied when the melt front reached the bottom of the vessel or cavity. For the in-vessel case, this occurs approximately after 1 s. It was planned to perform a calculation with a trigger applied after 4 s. However, it was found that this case had little interest as practically no liquid water was present in the mixing zone at that time according to the codes, and in any case negligible loads were calculated. Note that for the ex-vessel case, oxidic melt was also chosen not to introduce metal oxidation process that most codes are not modelling at present stage.

4. Major uncertainties as deduced from experiment calculations

4.1. Major uncertainties related to the pre-mixing phase

Figures 2 and 3 compare the various predictions for pressure and energy release with the experimental records for FARO L-28 and FARO L-33, respectively. Actually, experimental energy data were calculated by using the pressure and temperature records. Time zero corresponds to start of melt delivery to the water. In FARO L-28 melt delivery duration is approximately 6 s, and the melt front reaches the bottom of the test section after about 1 s. In FARO L-33, pre-mixing ceases at about 1.1 s when the explosion is triggered, corresponding approximately to melt-bottom contact. Figure 4 shows the global void fractions at 1s and 4s, respectively. Experimental values in Figure 4 have been calculated by using the level swell records.

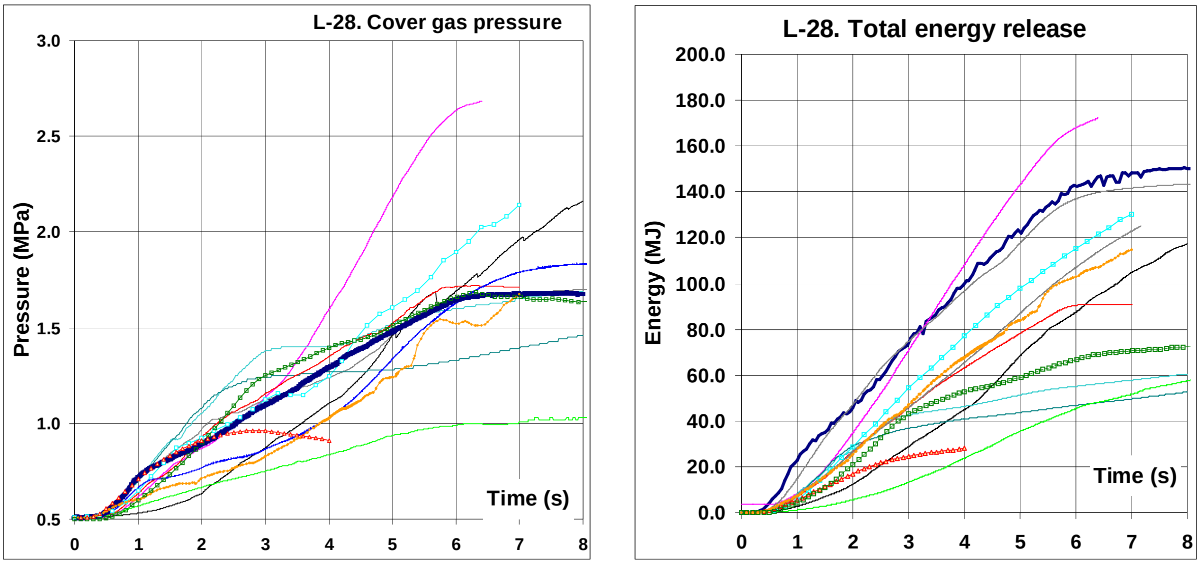

Figure 2: Comparison of calculated vessel pressure and energy release with data (bold curves) for FARO L-28 (pre-mixing of 175 kg of corium melt in 1.5-m-deep saturated water pool; melt-bottom contact at ~1 s)

Figure 2 shows that the codes have difficulties to reproduce the pressure data both for the initial phase of the pressurisation up to melt-bottom contact and for the linear increase of the pressure, which roughly corresponds to a steady state phase. They tend to underestimate heat transfer (Figure 3) and overestimate void (Figure 4) when compared to data. Void distribution in pre-premixing is a key issue as void is considered having a key limiting effect on explosion strength. Highly water depleted pre-mixtures (void fraction > 50%) are considered to be an obstacle to strong steam explosions. Therefore, the discussions in SERENA focused on finding the major processes impacting the level of void.

Sensitivity calculations showed that reducing significantly interfacial steam/water friction, or changing the transition range between water and steam continuous regimes allowed reducing void to values comparable to the data. Reducing the initial particle diameter or forcing heat exchange in continuous steam flow regime improved the pressurisation curve. However, no physical basis exists, which could justify one or another modification. In addition, large uncertainties affect experimental data in the absence of detailed information of the pre-mixing zone internals: experimental void fraction is global value retrieved form water level swell measurements, which does not allow to identify where the void is located actually. The reasons for the initial strong pressure increase in L-28 and the contribution of the debris cooling to the overall void level are not well understood.

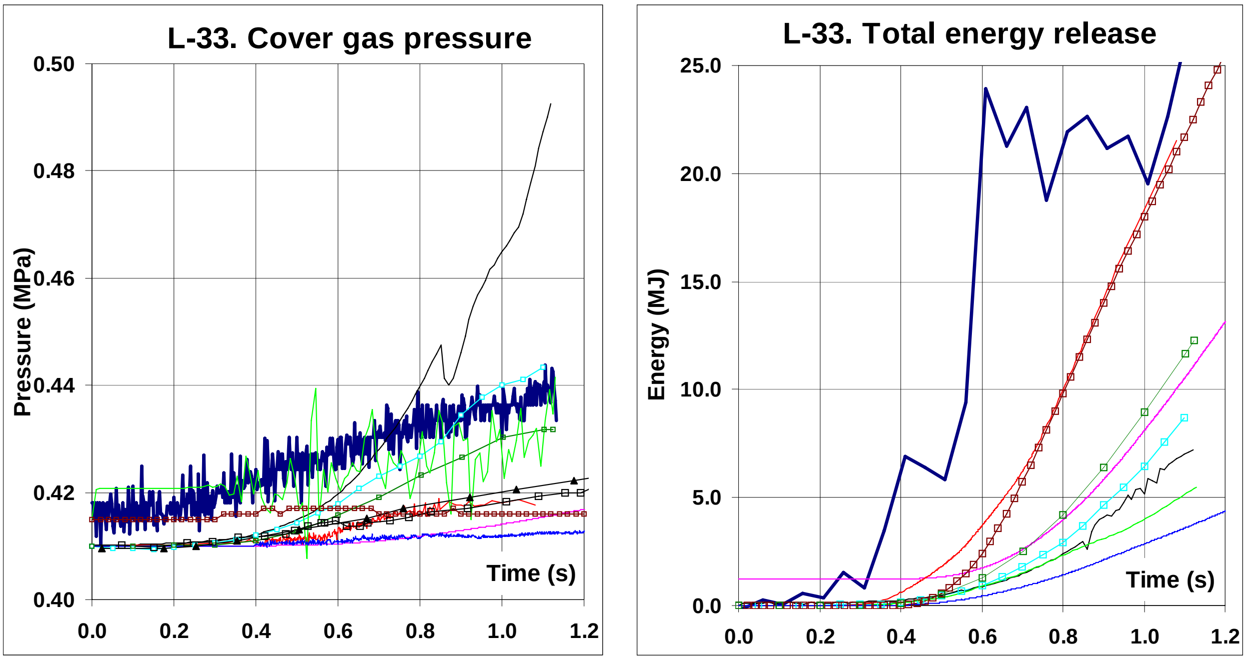

Figure 3: Comparison of calculated vessel pressure and energy release with data (bold curves) for FARO L-33 (1.5-m-deep subcooled water pool; triggering at 1.1 s, i.e., approximately at melt bottom contact with 25 kg of corium melt in pre-mixing)

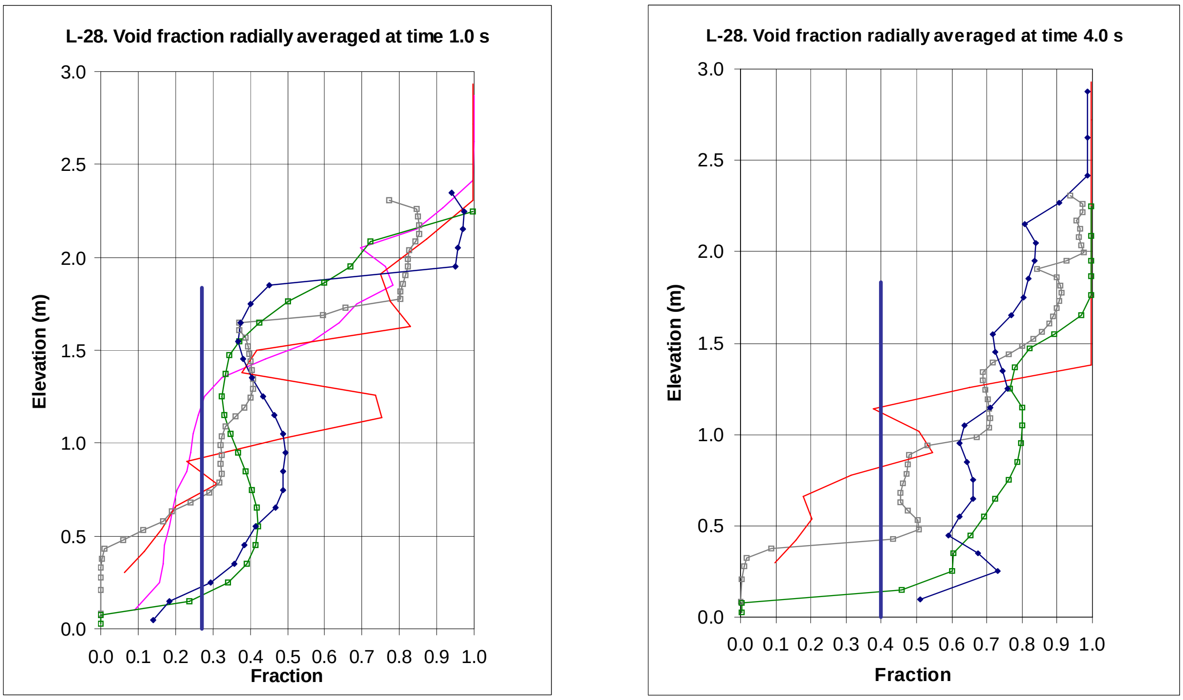

Figure 4: Comparison of radially-averaged void fraction calculated by the codes with global value calculated from experimental level swell (bold lines) for FARO L-28 at time 1.0 s and time 4.0 s, respectively.

Large differences exist also on modeling [3], in particular concerning jet and jet/particle break-up description, and the importance of far-field radiation effects. The scatter of the predictions, their distance to the data and the uncertainties of the data in the pre-mixing region makes not possible to establish whether a model is more appropriate than another to describe a given phenomena.

Concluding, one can say that the major uncertainty on pre-mixing as can be deduced form application to the selected experiments stands in void (prediction and data). The major question in relation to the scope of SERENA is whether the differences in modelling and the scatter of the predictions are relevant for reactor applications. This question will be answered after analysis of reactor calculations (next section). One can simply say for now that most codes overestimate void fraction with respect to that calculated from the integral experimental data, especially in saturated conditions.

4.2. Major uncertainties related to the explosion phase

Figure 5 shows the explosion pressure and corresponding impulse for KROTOS K-44. It can be seen that most of the models applied to the same initial and boundary conditions were able to globally reproduce the strong event observed in the experiment even with differences in modelling of the key effects of fragmentation, and non-homogenous heat transfer to the coolant. Comparison with the other pressure records at different levels in the water shows a common interpretation of the experimental results as a propagating-escalating event. This is somehow not surprising since KROTOS data has been used as a basis to validate the models. In general, standard values of the parameters have been used in the calculations. Note however that some predictions noticeably underestimate the loads.

For TROI-13 (Figure 6) and FAROL-33 (Figure 7) tests, the agreement seems of the same order than for KROTOS, despite the events in these experiments were significantly less energetic than in KROTOS K-44, with however a larger overestimate of the loads for TROI-13 than for L-33. Actually, these loads have been obtained with reducing more or less arbitrarily key effects such as heat transfer and fragmentation. Possible physical explanations for the observed reduced explosion energetics are melt freezing and hydrogen production during pre-mixing. But differences in test and/or pre-mixing geometry (radially 2-D in FARO and TROI instead of 1-D in KROTOS alumina) may also have a reducing effect because they allow venting during the explosion. Visualisation performed in KROTOS has shown that such differences in pre-mixing lateral extension exist between alumina and corium [6]. It should be noted also that the data concern two similar types of oxidic corium only, namely, 70 wt% UO_2-30 wt% ZrO_2 and 80 wt% UO_2-20 wt% ZrO_2. Therefore, it would be hazardous to extend the conclusion of “low explosivity” to other corium melt compositions before understanding the very reasons that led to mild explosions in the FARO, KROTOS and TROI corium experiments.

Two basic descriptions of the explosion are used in the codes, namely the micro interaction and the non-equilibrium heat transfer models. For both, a number of parameters have to be given for the fragmentation, heat release and partition between steam and water. Playing with these parameters allows in general finding back the order of magnitude of the data, but basic physical explanation is missing.

Concluding, one can say that the major uncertainties on explosion as can be deduced form application to the selected experiments stands in pre-mixing geometry and material behaviour during propagation of the explosion as a function if its state in pre-mixing at the time the explosion triggers (material effect). Again this is important relatively to the objective of SERENA as far as it is relevant for reactor estimates. This question is addressed in the next section.

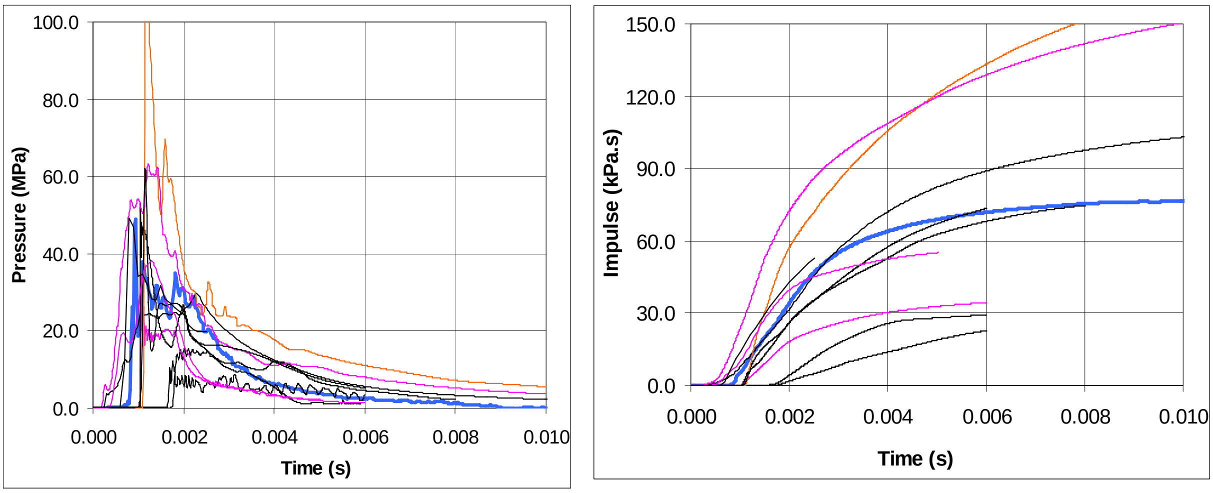

Figure 5: Comparison of dynamic pressure and corresponding impulse calculated by the codes with experimental value (bold lines) at mid-height in the water pool for KROTOS-44.

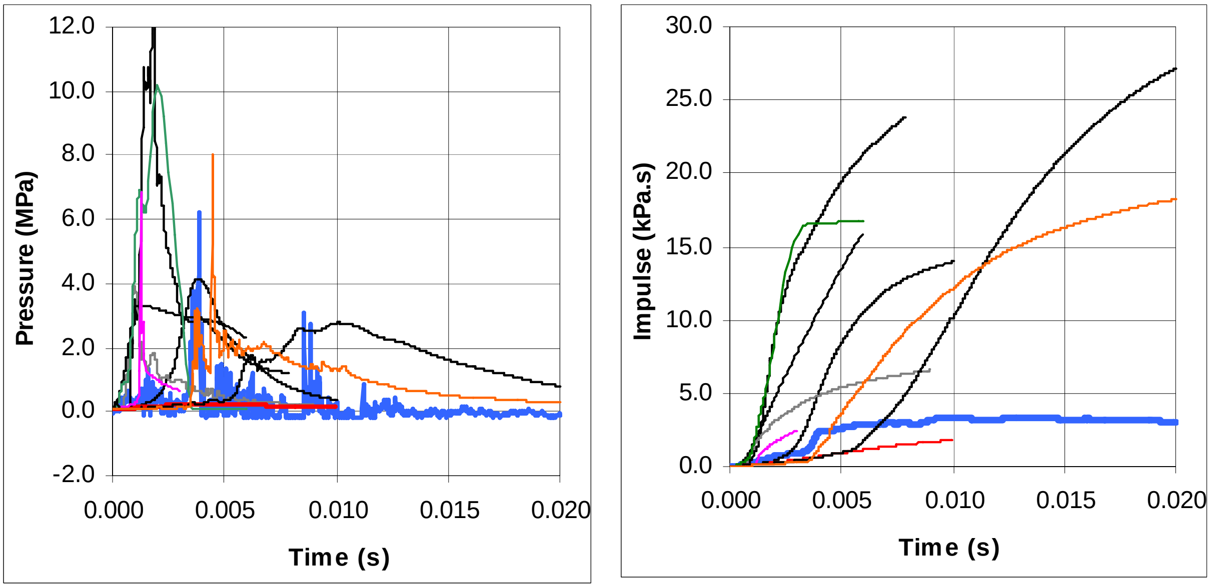

Figure 6: Comparison of dynamic pressure and corresponding impulse calculated by the codes with experimental value (bold lines) for TROI-13.

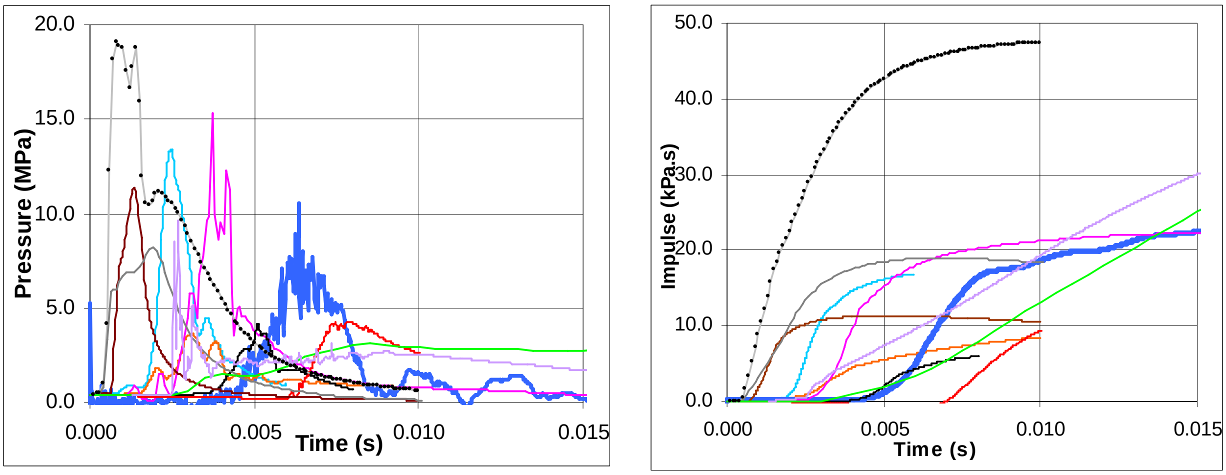

Figure 7: Comparison of dynamic pressure and corresponding impulse calculated by the codes with experimental value (bold lines) at level 1390 mm in the water pool for FARO L-33 (highest value measured). Full calculations pre-mixing +explosion

5. Major uncertainties relevant for reactor load assessment

Figures 8 shows the dynamic pressure histories calculated at the wall for the in-vessel and ex-vessel configurations illustrated in Figure 1. For each code, it corresponds to the pressure history at the location where the maximum value was obtained at a time during the explosion. Figure 9 shows the corresponding impulses. In general those impulses were also the maximum obtained. In a few cases, the impulse was slightly higher at another location, but not such as to bias the conclusions that can be drawn from the exercise.

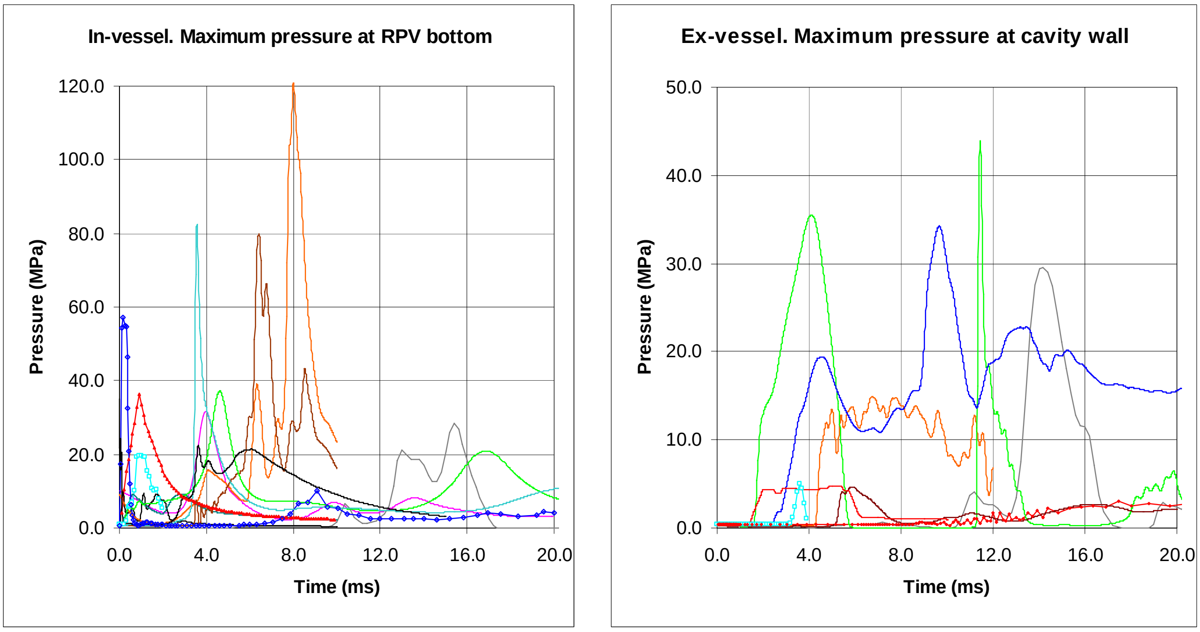

Figure 8: Calculated pressures for reactor

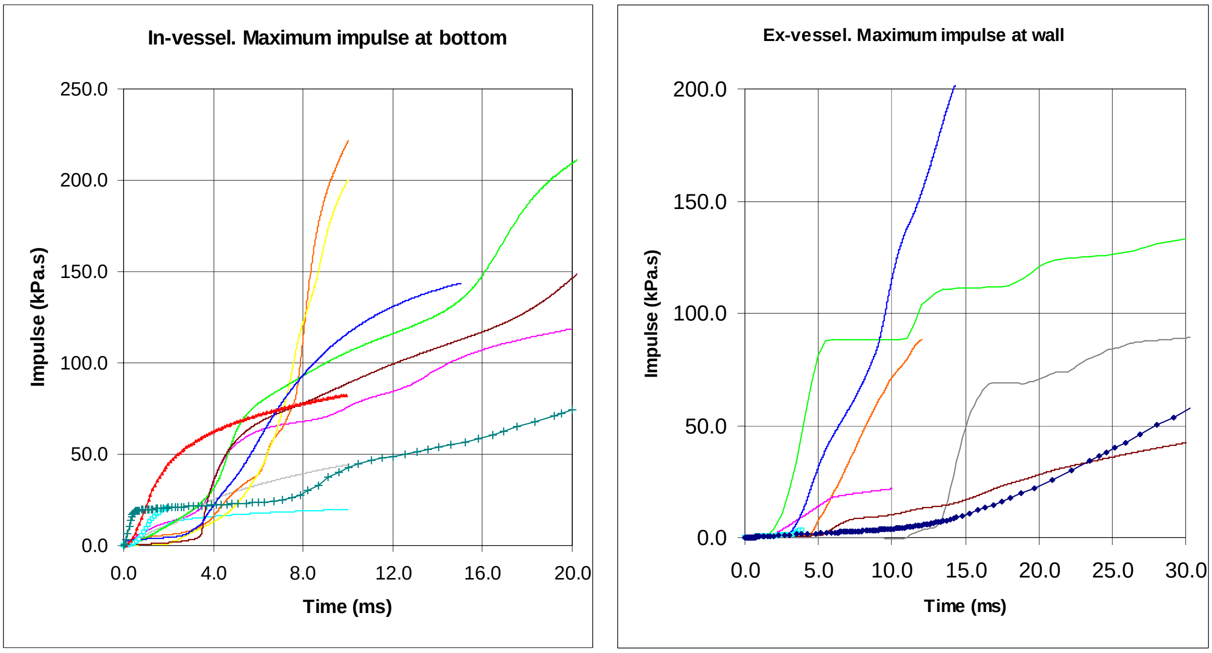

Figure 9: Calculated impulses for reactor

The in-vessel results show noticeable differences in predicting the peak pressure at the RPV bottom (ranging from ~10 MPa to ~120 MPa) and a rather reduced prediction range for the impulse (from some tens of kPa.s to ~200 kPa.s). These loads are far below the capacity of the defined-model intact vessel and, therefore, the safety margin for in-vessel steam explosion may be considered as sufficient. This conclusion is challenged by the large scatter of the results and the uncertainties on the void predictions revealed by experiment calculations. Figure 10 shows that the level of the averaged void is high for both in- and ex-vessel cases. In addition, only one in-vessel case has been calculated that might not be the worst possible (This is somehow in contradiction with the choice of a multi-jet configuration which was supposed *a priori* to give the largest mass in pre-mixing, but which is compensated in part by the large voiding of the pre-mixing region as calculated).

The ex-vessel results show noticeable differences in the predictions for both the explosion pressure and the impulse. The calculated maximum pressure loads at the cavity lateral wall vary from a few MPa to ~40 MPa and the impulses from a few kPa.s to ~100 kPa.s (except one case where the impulse is significantly higher due to the fact that the pressure level remains high for a long time). These loads, even low, are above the capacity of cavity walls. The question of the safety margin for ex-vessel steam explosion already raises here prior to any further consideration related to the scatter of the results, the level of void (very high here too, see Figure 10), or the melt relocation scenario. Therefore, besides reducing the uncertainties on void, it is important to increase the knowledge level of steam explosion behaviour of corium melts to be able to quantify the safety margin for ex-vessel steam explosion. This would certainly minimize the scatter of computer code predictions as well.

In the reactor calculations the choice of the parameters for explosion was not made consistently with respect to Task 3. Some partners used the reduced parameters. Some used the standard ones, as they were considered to be conservative. Despite the variety of the approaches and parameter setting philosophy, all codes calculate loads that are rather low, which might be due to relatively limited melt mass in pre-mixture, high voids and venting possibilities existing in large geometry. It is not clear which effect is dominant in the codes. Answering this question would have required more sensitivity calculations, which could not be performed within the time frame of SERENA Phase 1. But the reactor calculations confirm that these effects have to be accounted for together with the material effects (not modelled in the codes) to analyse the reasons for the reduced energetics observed in corium experiments.

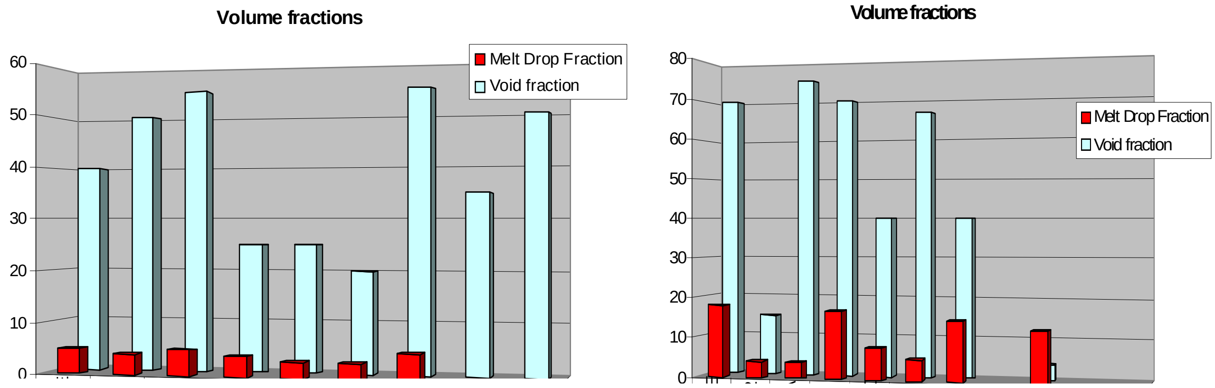

Figure 10: Global component fractions at melt-bottom contact averaged over a cylinder of height the water depth, and diameter 1 m. Ordinate: component fraction in %; Abscissa: codes.
Left: In- vessel case; Right: Ex-vessel case.

6. Concluding remarks

Phase 1 of SERENA is the most accomplished international comparison exercise ever undertaken on steam explosion. The scope was to verify the predictive capability of the FCI codes when applied to reactor situations, to identify the major overall uncertainties which limit the confidences in those predictions and to propose confirmatory research to reduce these uncertainties to acceptable levels for risk assessment. SERENA Phase 1 was also a state-of-the-art on the way people are using the codes for FCI induced load assessment.

One positive outcome of Phase 1 is that whatever the modelling and numerical approaches all the codes were able to calculate the reactor situations of concern, which was far from being evident at the start of the programme. Another positive outcome is that, despite the different choices for setting the code parameters for the reactor applications, all the calculated loads were relatively low. Concerning in-vessel steam explosion all the calculated loads are far below the capacity of a typical vessel, which allows thinking that the safety margin for in-vessel FCI might be sufficient. For ex-vessel steam explosion all the calculated loads, even low, are above the capacity of a typical cavity walls. The scatter of the results raises the problem of the quantification of the safety margin for ex-vessel FCI.

These rather attractive conclusions have to be balanced by the following considerations:

- Only one case has been calculated for in-vessel and ex-vessel, respectively.
- These cases might not be the worst possible.
- Only a few parameter variations were performed.
- There is a tendency to predict large void in premixing, which was judged to be an overestimation of voiding according to pre-mixing experiment analysis,
- Some partners have used “reduced” parameters to model the explosion without firm physical reasoning.

The first three items require analytical work to be performed in continuation of what performed in Phase 1. Uncertainties on the pre-mixing flow patterns, especially on void distribution, and on material influence on steam explosion energetics have to be addressed experimentally. This will be proposed as a Phase 2 of SERENA with the support of KROTOS and TROI experimental facilities.

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