

STATUS AND PROSPECTS OF RESOLUTION OF THE VAPOUR EXPLOSION ISSUE IN LIGHT WATER REACTORS

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The past two decades were mainly devoted to model validation and computer code verification against global corium experiments, code application to reactor situations, and investigation of the role of melt properties in steam explosion energetics. Corium data were essentially provided by JRC-Ispra in the FARO and KROTOS facilities and by KAERI in the TROI facility. Verification of code applicability to reactor situations was performed essentially in the frame of the international OECD/SERENA programme. The paper makes a synthesis of the findings made during the above-mentioned period and expresses a personal view of the author with respect to the progress made and expected for the resolution of the steam explosion issue for light water reactors.

KEYWORDS : Fuel-coolant Interaction, Steam Explosion, Light Water Reactors, Reactor Applications, Corium FCI Behaviour

1. INTRODUCTION

In a nuclear reactor severe accident molten core material (corium) containing a large fraction of molten fuel may enter into contact with the coolant, generating a so-called fuel-coolant interaction (FCI). In a LWR severe accident, melt-water interactions capable of resulting in a steam explosion with potential damage to the structures are those in which a large mass of corium melt can pre-mix with water before the explosion triggers somewhere in the pre-mixture and propagates through it, in a way similar to a chemical detonation [1]. Practically, this is only possible when the corium melt relocates into the water-filled lower head of the reactor pressure vessel (in-vessel steam explosion) or in a flooded cavity (ex-vessel steam explosion). Thus, these situations have been given most attention so far and are the subject of this paper.

A steam explosion can occur at any stage during melt penetration into water. It can be defined as a class of FCI in which a significant part of the energy stored in the corium melt of the pre-mixing zone is transferred to the water so rapidly (in milliseconds) that explosive vaporisation of the water occurs, i.e., vapour is produced more rapidly than the system can expand, generating high pressure, dynamic loading of the structures and possibly missiles during expansion, thus converting thermal energy of the melt into mechanical energy of the

coolant. This can result in damage to the reactor structures and, if it affects the containment, in release of radioactive fission products to the environment. Steam explosion risk evaluation requires being able to quantify the level of the generated loads in order to verify whether reactor structures can withstand them and possibly design appropriate counter-measures.

Over the past two decades, research work has been definitely reactor-oriented. It was mainly devoted to model validation and computer code verification against global corium experiments, code application to reactor situations, and investigations of the role of corium melt properties in steam explosion energetics. Corium data were first provided by large-scale FARO and small-scale KROTOS experiments performed under international sponsorship by JRC-Ispra [2,3]. After the European Commission stopped the FARO/KROTOS programme in 1999, all the corium data were provided by the TROI facility operated by KAERI-Taejon [4]. Code application to reactor situations was the subject of Phase 1 of the international undertaking SERENA (SERENA-1), realised under the auspices of the OECD with the aim of identifying areas in which uncertainties were prejudicial to the predictability of steam explosion induced loads, and defining confirmatory experimental and analytical work to be done to reduce these uncertainties to acceptable levels for steam explosion risk assessment and management

[5]. This confirmatory work has been proposed as a Phase 2 of SERENA [6,7].

The present paper makes a synthesis of the findings made during the above mentioned period and expresses a personal view of the author with respect to the progress made and expected from on-going programmes for the resolution of the steam explosion issue for light water reactors.

2. STEAM EXPLOSION SAFETY ISSUES

2.1 In-vessel Issues

At some stage in the melting of the core, molten corium flows down and relocates into the lower head. In PWRs, a TMI-2-like scenario is generally taken as a reference, i.e., formation of a large molten pool in the core with subsequent failure of the surrounding crust and side discharge of the melt as a jet. A similar scenario may occur in BWRs. A steam explosion occurring during melt interaction with the water present in the lower head may induce failure of the lower head and/or a liquid slug playing against the uppermost structures of the RPV, accelerating them up to hitting the upper head with a significant amount of kinetic energy. This energy is at a maximum if the lower head does not fail and may induce rupture of the bolts that hold the upper head into place. The upper head is then in turn accelerated upwards to the containment roof like a missile and may cause failure of the roof. This mode of failure of the containment, known as "alpha-mode failure", received most attention in the past because it was believed to be potentially the main cause of containment failure due to a steam explosion and because of its early occurrence in the accident sequence. The second international steam explosion review [8], complemented by experimental programme BERDA performed at FZK [9], allowed the conclusion that this risk was negligible and the alpha-mode failure issue was closed.

On-going studies on in-vessel steam explosion focus on the risk of lower head failure. In existing reactors, lower head failure is expected due to thermal loading of the corium debris and accident management procedures are designed accordingly¹. But a steam explosion inducing

an early vessel failure during core melt slump into water would challenge those procedures. For new generations of PWRs based on in-vessel retention of the corium debris, it has to be demonstrated that the risk of lower head failure from a steam explosion is negligible.

2.2 Ex-vessel Issues

If the vessel melts through, the corium melt relocates into the cavity. In PWRs, water is expected to be present in the cavity at different heights either because of accumulation after discharge from the primary system or because it is part of the accident management strategy to flood the cavity to delay vessel failure or even to prevent it. In Swedish and Finnish BWRs, the drywell beneath the reactor pressure vessel is deliberately flooded before vessel failure, which means a water depth of the order of 7-8 m with the scope of completely fragmenting and quenching the melt before it reaches the pedestal floor. In PWRs, failure is most likely to occur at the side of the vessel due to the focusing effect of the thin metal layer overlaying the ceramic pool. In this case the melt would be essentially metallic. But, due to the uncertainties in the scenarios and in the melt composition and distribution of the different phases, ceramic and bottom failure pours are also considered in safety assessment [10]. In BWRs one mode of failure is at instrument tube penetration at the bottom [11]. The main issue associated with ex-vessel steam explosion is failure induced to the containment by a steam explosion occurring in the cavity or drywell with potential release of fission products to the environment. Another issue concerns the impact of the explosion on the RPV and primary circuit. An excessive impulse load on the lower head may induce an uplift of the vessel and leaks at the containment penetrations.

There are no phenomenological differences between in- and ex-vessel steam explosions except that the different initial and boundary conditions can have a significant impact on the strength of the explosion. These differences are essentially the pressure of the system (less than 0.5 MPa ex-vessel vs. a few MPa in-vessel at the time of melt relocation), the temperature of the water (sub-cooled ex-vessel vs. saturated in-vessel), the melt composition (e.g., higher steel content ex-vessel), the melt delivery conditions (e.g., single large pour ex-vessel vs. multi-jet pour in-vessel for PWRs), the depth of the water (up to 8 m ex-vessel in Swedish and Finnish BWRs vs. 2 m in-vessel in PWRs).

It should be noted that for both in- and ex-vessel situations, one or more mild explosions occurring in one or the other situations would produce very fine particles that may challenge debris bed coolability and induce a dispersion of part of the debris in different locations in the primary circuit or in the containment that may compromise the debris retention strategies. This issue has not been carefully looked at so far.

¹A particular case is the TMI-2 accident where no vessel failure occurred. The reasons for that have been the subject of numerous investigations and are not fully understood yet. But it is generally admitted that the high pressure maintained in the primary circuit during all the accident sequence combined with the thermal load from the debris allowed a gap to form between the debris and the lower head, which played a major role in preventing the lower head from failing by permitting water to enter the gap and ensure sufficient cooling of the wall.

3. STATUS OF KNOWLEDGE OF THE PREMIXING PHASE

3.1 Description

As the corium melt penetrates into the water of the lower head or cavity, it breaks up into mm-size to cm-size particles and releases part of its energy to the water, part of which is transformed into vapour. This process, which produces a corium-water-steam mixture, is called pre-mixing (or coarse mixing) in steam explosion terminology because it precedes a possible steam explosion. The pre-mixture is the feeding medium of the explosion and may be compared to a fuel-air mixture, which may detonate if exposed to an adequate temperature increase. If exposed to an event that induces locally fine fragmentation of the melt (the trigger), this fine fragmentation may propagate to all or part of the pre-mixture, giving rise to rapid energy transfer to water and subsequent increase of temperature and pressure. The fine fragmentation process plays here the role of the chemical reaction in a classical detonation.

Energy transfer during pre-mixing is limited by the low conductivity of the corium and the film boiling regime of the water, so that the corium fragments may remain liquid inside a surrounding crust that grows with time. If we consider a corium melt penetrating into the water as a jet, jet break-up occurs by lateral erosion of the jet column and fragmentation at the jet front, so that a coherent core may still exist at a distance from the water surface. Non-condensable gases may also be present in the pre-mixture, due either to entrainment by the melt when penetrating into the water or to chemical reactions occurring during the pre-mixing (in this case essentially hydrogen). Gas (steam plus non-condensable gases) fraction in the pre-mixture is often referred to as void fraction. If a steam explosion has not occurred when the mixture reaches the bottom of the lower head or cavity and spreads, vapour production from settled debris cooling may increase the vapour fraction of the pre-mixture still falling.

Therefore, a realistic pre-mixture is a very complicated combination of different substances and phases, which all play a role in the energetics of the steam explosion that may follow. Based on past research and experimental data, it is believed that all what deviates from the ideal pre-mixture of melt-water-steam makes it more resistant to steam explosion triggering and has a mitigating effect on the energetics of the explosion if triggered (except in case of chemical reactions occurring during the explosion phase, which may augment the energetics [12]). These effects must be taken into account for realistic estimates.

During pre-mixing and for a given melt-water system, the heat transfer rate and pressurisation of the system if closed are governed by the mass pouring rate of the melt. If no explosion occurs until the end of melt relocation, one speaks of melt quenching rather than pre-mixing. The (partly) quenched debris eventually settles on the bottom, where it forms a debris bed and possibly re-melts

due to decay heat forming a molten pool. This is what occurred in the TMI-2 accident, in which about 20 tons of corium melt relocated in the lower head in approximately 2 min while the vessel was full of water. This resulted in a vessel pressure increase of 2 MPa due to steam production, but no steam explosion occurred.

Examples of two pre-mixing configurations obtained with two different melts in the KROTOS facility at JRC-Ispra are shown in Fig. 1. The video pictures show that the mixing region occupies all the cross section of the test tube with alumina while it is more concentrated around the centre-line with corium. The mean size of alumina debris was 10 mm against 2 mm for 80w%UO₂-20w%ZrO₂ corium. Video resolution is not sufficient to see details such as the distribution of the fragments and void in the pre-mixture, or whether a coherent jet still exists in one case and not in the other. High energy radiography is required to have more details and is used in the new KROTOS experiments performed at CEA-Cadarache [13]. Fig. 2 shows typical sizes of 80w%UO₂-20w%ZrO₂ corium particles collected after FCI without steam explosion in KROTOS (5-kg-scale melt, melt release nozzle of 30 mm, water depth 1 m, 1/3 melt injected at high velocity initially then gravity release, system pressure 0.1MPa, saturated and subcooled water) and FARO (100-kg-scale melt, melt release nozzle of 100 mm, gravity release, water depth 1 m and 2 m, system pressure 2.0 and 5.0 MPa, saturated water) experiments. Differences are noticeable between the KROTOS and FARO tests, but not between the KROTOS tests themselves and the FARO tests themselves even though the test conditions were significantly different. So, the differences between KROTOS and FARO tests can be attributed essentially to the differences in melt release conditions.

3.2 Status of Understanding and Modelling of Pre-mixing

It is clear that the quality of the pre-mixture plays a fundamental role in the energetics of the steam explosion that may follow. This is the reason why effort to understand this phase has not been discontinued, especially since corium melt steam explosion behaviour has been found to significantly differ from alumina, for years used as a corium simulant. Alumina produced explosions ten times more energetic than corium in KROTOS and differences in pre-mixing characteristics are believed to be one of the major reasons of the low energetics with corium (other reasons are linked to the explosion phase and are addressed in the next section). These differences may be an artefact of the experiment geometry and conditions, or due to differences in melt properties such as density (inducing smaller fragments for corium and a more concentrated mixing zone with more venting potential for the explosion) and solidification temperature (inducing more radiation heat transfer from corium, and thus higher void, and formation of a strong crust that reduces the amount molten

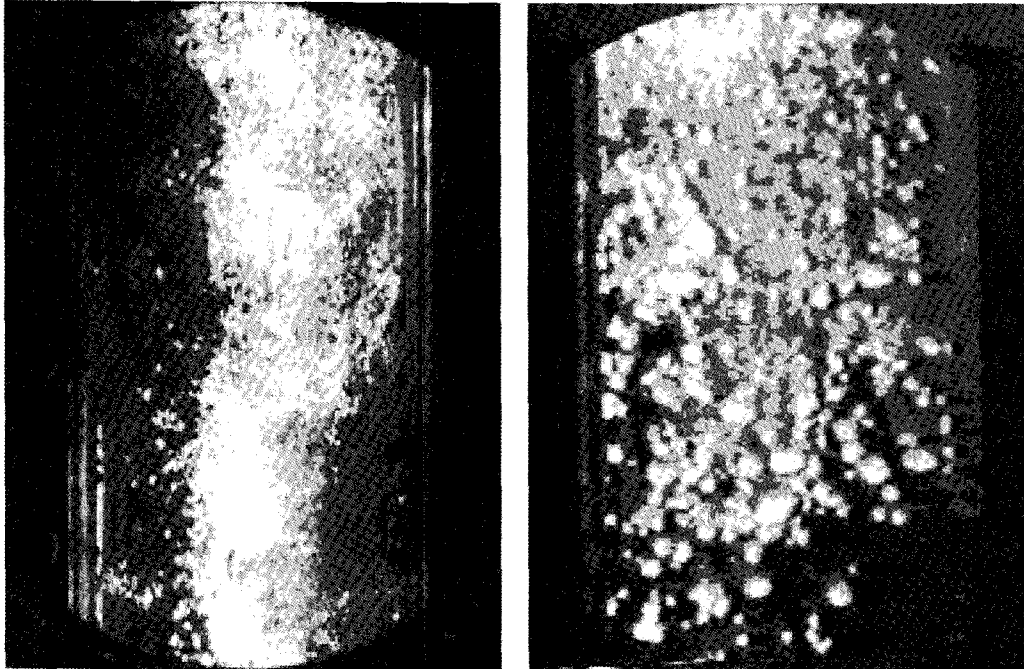


Fig. 1. Pre-mixing Configurations in KROTOS Tests (Test Section Diameter 200 mm, Melt Discharge Orifice 30 mm). Left: 80w%UO₂-20w%ZrO₂ Melt. Right: 100% Alumina Melt. Viewing Area is 100 mm High, 200 mm Width, Centred about 300 mm Under Water Level. (From [3])

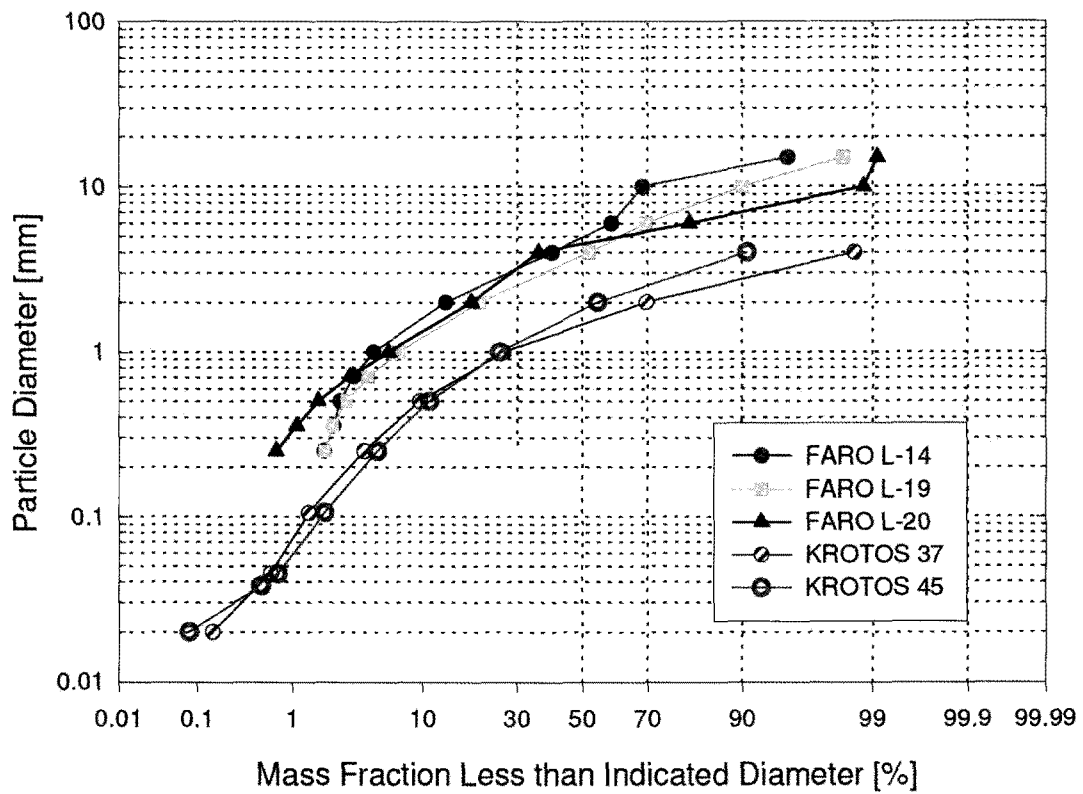


Fig. 2. Pre-mixing Particle Size Distributions in Selected FARO and KROTOS Corium Tests

material available for the explosion). In the former case the question is whether or not those pre-mixing configurations that produced strong explosions with alumina are possible for corium in other geometries, and in particular in reactor geometries. In the latter case, the question is whether or not the corium melts tested have basic components or properties that can be extended to all corium compositions (e.g. presence of UO_2 as a major constituent, production of hydrogen during pre-mixing). This opens the very attractive prospect of increased safety margins for the reactor structures.

Calculating pre-mixing consists of establishing the time dependent flow maps associated with melt penetration into water, and thus, at any time, the properties of the mixture a steam explosion may propagate through, i.e., determining the distribution of water, gas(es) and corium in the pre-mixture as well as the state of the corium (jet, fragments, molten part, frozen part) considering that essentially liquid fragments are involved in an explosion. Deterministic FCI codes are used for this purpose. These codes resolve systems of mass, momentum, and energy equations for coolant and melt with different degrees of approximation. They vary essentially by the description of the melt jet (continuous or collection of drops), drop break-up processes, film boiling models, coolant flow description, partitioning of energy release between steam and water, and importance given to thermal radiation. A few take into account the production and/or presence non-condensable gases. A detailed comparative description of the models may be found in [14]. With the exception of the non-condensable gases (that sooner or later will have to be introduced in all codes) the major phenomena that govern pre-mixing are modelled in the codes. All the melt and component properties (thermo-physical) that play a role in the pre-mixing process are taken into account. The possible uncertainties may come from the level of approximation of the phenomena and from the uncertainties in the properties more than from not taking into consideration an important phenomenon or property. But, the differences in modelling highlight a lack of understanding of these phenomena and of their importance for calculating real situations. This is due in large part to the difficulty in getting the required data in the extreme conditions under which testing must be performed.

If we consider a corium melt jet penetrating into water, we may distinguish between jet break-up into particles (primary break-up) and fragmentation of those particles into smaller particles (secondary break-up). In a reactor accident, it is very unlikely that a nice corium jet will form, so that the usefulness of addressing jet break-up for reactor application is still a matter of debate. In some codes (IFCI, MATTINA, PM-ALPHA, TEXAS, VAPEX) the melt is considered to enter into water as a collection of drops. The initial given size(s) of the particles is (are) deduced from experimental data (the FARO tests debris data have been extensively used for this purpose) or other

considerations more related to the code structure. Note that when jet break-up is calculated (IKEMIX, JASMINE, MC3D, VESUVIUS) the size of the particles generated from the break-up process is also given by the user and is varied as a function of the melt-water system on the basis of debris experimental data. But unlike the former case, the fragments are produced as the jet descends through the water according to jet break-up laws, which in turn may be different from one code to another. The particles generated from the jet or given *a priori*, experience, in principle, further fragmentation as they progress down into water until cohesive forces (surface tension) balance the disruptive forces (inertia). Here again different models are used, none of them having being fully validated so far. In some applications, secondary break-up is even suppressed by the user.

As in a reactor accident melt pour into water may last minutes, part of the corium may solidify before an explosion occurs. This limits, for a given scenario, the quantity of melt that may be involved in the explosion. Had a steam explosion occurred towards the end of melt relocation in TMI-2, it is clear that not all the 20 tons would have been involved because part of the fragments that formed and pre-mixed with water during melt descent towards the lower head would have solidified or re-agglomerated at that time. If we consider that only melt in flight in water can be involved in a steam explosion, it would have been a few hundred kilograms at the most in TMI-2. Some scenarios predict a multi-jet situation, as for instance a flow through the outer holes of the lower core plate, so that a circular set of simultaneous jets may form [11]. In this case, it is expected that a large amount of melt can pre-mix with water, leading to a stronger explosion than that resulting from a single jet. Such a multi-jet situation has been addressed in SERENA-1 for the in-vessel case (Fig. 3) as, *a priori*, more challenging than a single jet. Calculations showed that this configuration induced large voiding of the pre-mixing region and relatively small fragmented melt masses in the less voided regions, which resulted in relatively mild explosions [15]. This highlights the fact that in situations of practical interest counter-effects makes it difficult, if not meaningless, to anticipate the role of a single parameter (e.g., melt mass in water) and make global estimates on this basis.

The models generally contain a number of parameters that are adjusted according to the experimental data. One may think that it is relatively easy to find, for a given melt-water system (e.g., corium-water), a set of parameters that reproduces experimental data with a good level of approximation, and then use this set of parameters faithfully for reactor calculations. The reality is not so straightforward. ISP-39 on FARO L-14 quenching test demonstrated that it is not so easy to reproduce all the data consistently [16]. For example, if one succeeded in reproducing the pressure increase during quenching, which was considered to be the signature of the FCI, it

was to the detriment of a reasonable agreement with the debris and/or void fraction data. Little progress on this issue has been made so far.

3.3 Prospects for the Resolution of the Uncertainties and Discrepancies in Pre-mixing

Given the limited resources that have been allocated to steam explosion research since the beginning of the 90s, it is unlikely that the discrepancies existing in understanding and modelling the pre-mixing phase will be resolved within a few years. This is the reason that a reactor-oriented approach has been adopted in SERENA, i.e., looking at determining where improvements were to be made to bring predictability of reactor situations to an acceptable level of confidence for risk assessment, setting aside further fundamental research if not strictly needed for that purpose. All the codes used today for steam explosion calculation contain models that, even though not fully validated and having different levels of approximation, are based on plausible interpretations of the experimental data, which for corium and other high temperature melts are essentially global in nature. Therefore, one cannot say that one model is better than another. As a matter of fact, all the above-mentioned codes are used for safety assessment by one or another safety organisation or utility. What is missing is a sufficient level of confidence in the calculations in order that not overly conservative estimates of the loads can be made.

The notion of realistic or not overly conservative or reasonably conservative estimates may look rather subjective and arbitrary, but the only alternative is the thermodynamic estimate as proposed by Hicks and Menzies in 1965 for fast sodium reactors [17], which gives the maximum conversion ratio (ratio between the mechanical energy output and the thermal energy of the melt) that can be expected for a given melt-coolant pair. For corium-water systems this ratio is between 0.5 and 0.6, depending on the corium composition. Obviously, this method is not applicable to reactor situations because the melt to consider cannot be defined and it does not allow direct calculation of the loads on the walls. First, even if we considered the melt in the pre-mixture, which is already a restriction with respect to the Hicks-Menzies approach and supposes that we are able to properly calculate pre-mixing, such a yield would induce prohibitive damage to a reactor². Second, in any of the experiments performed since the beginning of the steam explosion research, even in experiments in which all the melt mass could be considered pre-mixed, such a high conversion ratio has been obtained.

The maximum efficiency found is around 3% considering the total melt mass interacting (efficiency is the conversion ratio expressed in % of the thermal energy the melt. See Appendix for discussion)³. This value is already a high value. In KROTOS tests, 1.3% efficiency explosions with 1.5 kg of alumina could generate supercritical pressures in excess of 100 MPa and induce severe damage to the interaction vessel: the 40 mm thick steel bottom plate of the test tube bent 10 mm, and the 16-mm diameter bolts connecting the plate to the tube elongated 10 mm and shrunk 8 mm [19,20].

It is precisely to make less conservative (more realistic) estimates that deterministic FCI codes able to calculate all the phases of the explosion from pre-mixing to loads on structures have been developed. Reducing conservatism with respect to Hick-Menzies estimates makes sense only if the codes are applied to realistic scenarios. If a code is able to reasonably reproduce the data of a set of experiments performed in conditions as close as possible to reactor conditions (realistic conditions), the next step would be to verify that the code is still able to reproduce experiments performed at a larger scale (say, one order of magnitude larger). But at the end of the day, the only way to grant trust to the extrapolation capabilities of a code to reactor situations is to compare the results of reference scenarios with the results of other codes having different approaches and validation criteria, and to reduce the discrepancies of the predictions to acceptable levels by targeted research, if required.

Turning to pre-mixing, SERENA-1 showed that all the codes calculated high void fractions in the reactor simulations, with values larger than 50% in some regions. Highly voided regions are considered to be an obstacle to the propagation of the explosion. Also, the codes calculated moderated loads for both the in-vessel and ex-vessel reference cases (Fig. 3). But in the experiment simulations, calculated void values were overestimated when compared to the data, so that the relatively mild loads calculated for the reactor cases could have been the result of a spurious mitigating effect induced by large voiding in the pre-mixing zone. On the other hand, existing data are not detailed enough to establish that the code void predictions were wrong. In general, only global void fractions are deduced from experimental data, which means that if high voided regions exist together with less voided regions they are completely hidden in the global value. Reducing uncertainties on experimental void data by confirmatory testing with improved instrumentation to give access to local information of the pre-mixing region

² The Hicks-Menzies method is sometimes used as design criteria for small-scale experiments, which involves considering all the melt available and generally leads to very strong structures even for small quantities of melt.

³ There is an exception with up to 10% claimed by Sandia National Laboratory for tests of the FITSB series, but their way of calculating the energy output has been seriously criticised and it is likely that the actual efficiency was around 2% [18].

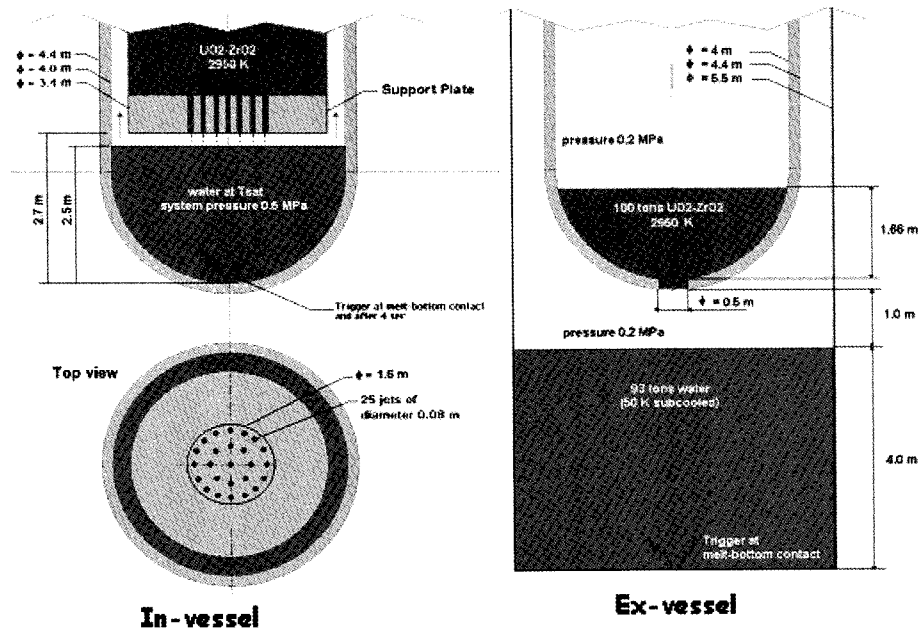


Fig. 3. Calculated Reactor Cases in SERENA-1 (From [6])

is the first priority here. This is part of the phase 2 of the SERENA programme with KROTOS and TROI facilities.

For the in-vessel case considered in SERENA-1 (Fig. 3), in spite of the large differences of the hypotheses, approaches, models, parameter-setting philosophies, geometrical representations and results, all the codes calculated loads well below the capacity of the vessel [15]. If the calculated void could be confirmed, the uncertainties in the explosion phase and in the melt composition would not change this conclusion. As mentioned earlier, a multi-jet scenario was selected because it was considered more pessimistic than a single-jet pour. In line with this, further research on in-vessel steam explosion would not be necessary and the issue could be closed from the perspective of risk failure of the lower head by dynamic loading. In reality, the conclusions from the multi-jet situation are not so clear and it would be suitable to verify anyway that no other in-vessel FCI scenario can produce melt-rich void-poor mixtures susceptible to induce strong explosions.

For ex-vessel, the conclusion is not so straightforward, as damage to the cavity is expected anyway (see next section).

4. STATUS OF KNOWLEDGE OF IGNITION AND PROPAGATION OF AN EXPLOSION IN A PRE-MIXTURE

4.1 Triggering

The stability of the pre-mixing regime depends on the stability of the vapour film that surrounds the molten

fragments, preventing them from direct contact with liquid water (film boiling regime). If an event occurs that collapses the film somewhere, the direct contact between the melt and the water (“liquid-liquid” contact) may initiate locally fine fragmentation of the melt and rapid heat transfer to the water, which, escalating and propagating to all the pre-mixture in a few milliseconds, will give rise to high pressurisation of the system. The initiating event is called the trigger of the explosion and may be either an internal event (e.g., melt arrival at the bottom) or an external event (e.g., shock on the structure).

Systems are more or less resistant to triggering but it is difficult, if not impossible, to predict whether or not a steam explosion will occur in a given situation, although we know conditions that are more or less favourable to spontaneous steam explosions. For instance, it has been observed in experiments that, when a steam explosion occurs spontaneously, it often triggers when the melt contacts the bottom. The reasons for this are not clear but it is believed that the change of the boiling regime due to melt impact on the structure (transition from film boiling to transition or nucleate boiling) may generate localised pressure pulses that are capable of triggering an explosion. Installing a thermoplastic liner on steel structures have revealed sufficient to suppress spontaneous steam explosions in some experiments, indicating that change of boiling regime was the most likely cause of the ignition of the explosion in experiments without a liner. Another possibility is water entrapment by melt, followed by rapid vaporisation of the entrapped water. If the pressure is increased or the steam fraction augmented (e.g., use of

saturated water), the same melt-water system might not produce a spontaneous explosion. Slightly changing the melt composition from eutectic to non-eutectic or having inert gas in the pre-mixture (e.g., hydrogen from melt oxidation) may also prevent a spontaneous explosion from occurring. No spontaneous steam explosion has been observed in any of the FARO and KROTOS tests performed with up to 175 kg of 80w% UO₂-20w% ZrO₂ melts (~20K solidification range) at pressures between at 0.1 and 5.0 MPa in either saturated or subcooled water. But, spontaneous steam explosions are easily obtained in the TROI facility with 70w% UO₂-30w% ZrO₂ melts (eutectic composition, no solidification range). As a matter of fact, no steam explosion was observed in the TMI-2 accident, which brought together most of the conditions that are unfavourable to a spontaneous steam explosion: high pressure (>100 bars), saturated water (large void fraction), hydrogen production during quenching (Zr oxidation) and non-eutectic corium.

However, if some trigger is applied intentionally to those situations that exhibit a certain resistance to spontaneous explosion, an explosion may be obtained, and rather easily [3,21]. Actually, any melt-coolant mixture involving high temperature melt such that film boiling is the dominant boiling regime of the coolant may generate a vapour explosion if a sufficiently energetic trigger is provided⁴. The problem is establishing how much energetic is energetic enough for a given system, and in particular if such an external trigger can be available in reactor situations. Past studies have been inconclusive in that respect and, according to the present situation of the FCI research, little progress is expected in this area in the near future. Consequently, it is hazardous to rely on the "triggerability" of a system to evaluate the steam explosion risk associated to a fuel-coolant interaction: "low triggerability" cannot be used as a criterion to eliminate the risk of steam explosion. Rather, one has to evaluate for a given melt-coolant interaction the risk associated to a steam explosion occurring in that system, i.e., determine the level of dynamic loading of the structure should a steam explosion occur. This is the reason that a trigger is

always postulated in present analyses of reactor situations (i.e., probability 1 affected to triggering).

4.2 Propagation

It is generally admitted that vapour film collapse upon triggering induces rapid fine fragmentation of the melt and heat transfer to the water. This process, called thermal fragmentation, which initially affects a small number of molten drops, may induce neighbouring drops to explode the same way and propagate step by step to all the pre-mixture. If the mixture conditions are favourable (e.g., large concentration of melt drops, low void and sufficient liquid water), the propagation velocity may rapidly increase and reach supersonic values (with respect to the pre-mixture). This phenomenon presents the characteristics of a detonation: a shock wave sustained by energy released (and pressure increase) in the zone immediately following the shock front propagates quasi-steadily throughout the mixture. It is generally considered that thermal fragmentation alone cannot produce such a detonation wave, and that it is progressively substituted or complemented during escalation by hydrodynamic fragmentation induced by differential velocity between melt and coolant created by the passage of the shock front. At reactor scale, this process may be completed in a few milliseconds, which is short enough to induce dynamic loading of the reactor structures.

Fig. 4 shows the differences in particle size distribution between exploded and non-exploded alumina debris. For the most energetic explosion, the mean size of debris is 100 µm, i.e., two orders of magnitude lower than that of the debris from pre-mixing.

4.3 Status of Understanding and Modelling of Propagation

The apparent stochastic character of the triggering of a steam explosion does not allow prediction of where and when it will occur. So, in the codes, the trigger time and position are always imposed by the user. Because in experiments spontaneous explosions often trigger when the melt contacts the bottom, this condition is generally assumed in numerical simulations of reactor accidents. However, this might not give the strongest explosion for a given pre-mixture and the effect on the explosion strength of changing the trigger time and position is required for risk assessment. The trigger is generally simulated by assigning a computational cell a pressure of the order 10-15 MPa or an instantaneous energy release corresponding to a few kJ. Sensitivity calculations indicate that the explosion strength is not very sensitive to the trigger strength.

The differences in the modelling of the explosion phase lie in the description of the generation of fine fragments and rapid heat release to the coolant. Nowadays, there are two models used in the codes to describe the explosion phase from a given or calculated pre-mixture: the micro-interaction model [22] and the non-equilibrium model [14].

⁴Note that there is no experimental evidence that it would be possible to trigger an explosion in the pouring mode for very high system pressures such as in TMI-2 accident. The maximum system pressure used to experimentally trigger an explosion with UO₂-based melt in the pouring mode was 1.0 MPa (SUW series performed at Winfrith with a 81%UO₂-19%Mo mixture at 3600K [32]). Triggering the explosion was not easy, but when it occurred an enhanced melt quantity participated in the explosion (with respect to tests performed at lower pressures), inducing severe damage to the facility. Since TMI-2 accident, accident management strategies plan depressurisation of the vessel to 1-2 MPa before melt relocation, which may increase the risk of steam explosion.

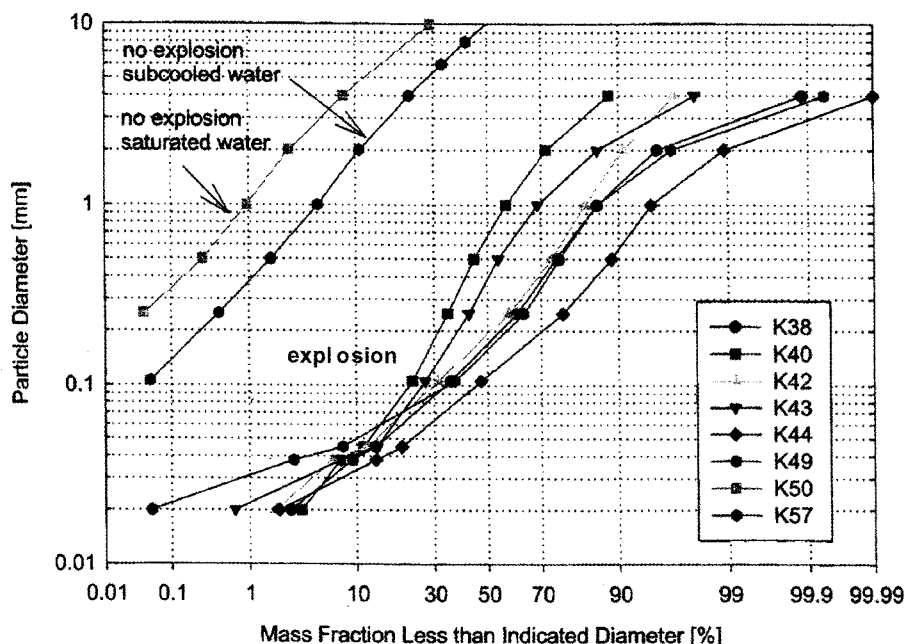


Fig. 4. Debris Size in Selected KROTOS Alumina Tests with Steam Explosion Compared to Debris Size without Steam Explosion

In the micro-interaction model (used, e.g., in ESPROSE and IDEMO codes) a certain amount of water, steam and melt fragments are mixed together in thermal equilibrium, forming an m-fluid the expansion of which is the cause of the pressure build-up. In the non-equilibrium concept (used, e.g., in MC3D and TEXAS codes) part of the heat from the fragments is used to produce vapour, which is the cause of the pressure build-up.

Like for pre-mixing, the diversity of the approaches reveals a lack of understanding of some fundamental aspects of FCI and steam explosion phenomena. Low temperature experiments or/and experiments performed at high temperature with “simulant” melts, e.g., alumina, have been used to set up and validate the models. But when applied to experiments performed with corium melts the codes have difficulties reproducing the results. In particular, they cannot reproduce the low explosivity of corium melts as found in KROTOS and TROI tests as compared to alumina⁵. It is not clear yet if the main causes of the differences in the explosion energetics are due to the melt properties’ influence on the pre-mixing characteristics (addressed in previous section) or on the propagation characteristics. Both are difficult to treat separately.

⁵“Explosivity” is a somewhat vague notion expressing the ability of a melt to produce mild or strong explosions, with implicit reference to alumina melt, which is considered to have high explosivity. It is different from “triggerability”, which rather refers to the stability of a melt-water pre-mixture.

Corium melt properties may affect the propagation of the explosion in different ways. The presence of a solid crust around the corium fragments makes them more resistant to fine fragmentation by the shock wave, which may result in significant reduction of melt available for the explosion (crust plus encapsulated melt). Recent work has also showed that the different radiative properties between alumina and corium (alumina is semi-transparent to thermal radiation while corium is opaque) may enhance the role of solidification in the case of corium [24]. Work on alumina exploded and non-exploded debris [25] has revealed that the chemical properties of alumina may exhibit features favourable to an enhanced rapid release of energy during the explosion phase with respect to heat transfer based on thermal characteristics alone (presence of gamma alumina in exploded debris meaning specific area of several m^2/g , undercooling down to 1910 K, absorption and adsorption of water...). Corium behaviour with respect to these chemical phenomena is still largely unknown.

Differences in energetics have been observed also between eutectic and non-eutectic corium compositions in the TROI facility [23]. Eutectic composition 70w% UO_2 -30w% ZrO_2 produced higher efficiency explosions than non-eutectic 78w% UO_2 -22w% ZrO_2 (solidification interval ~ 20 K, very similar to that used in FARO and KROTOS), while remaining of the order of a few tenths of percent. The difference may be attributed to the presence of a mushy zone of high viscosity, which makes an obstacle to the fine fragmentation of the melt. This possibility, already suggested some ten years ago [26], has been given

more attention since the TROI results have become available [27]. Note that the differences in the thermo-physical properties are negligible between the two compositions, meaning that the pre-mixing characteristics should be very close and that different propagation behaviours should be here the cause of the different steam explosion responses of the two compositions. The presence of fission products and iron oxide in real corium may increase by several hundred K the solidification range [28]. If the mushy zone plays a key role, explosion with real corium should exhibit very low energetics. On the other hand, recent tests indicate that the presence of metallic phases may act the opposite way [29], so that the relative importance of all these phenomena and properties should be carefully assessed.

4.4 Prospects for the Resolution of the Uncertainties and Discrepancies of the Explosion Phase

Presently, the codes do not model directly the above mentioned physico-chemical effects, except for hydrogen production/presence in some of them. For the two basic descriptions of the explosion used in the codes, namely the micro-interaction and the non-equilibrium heat transfer concepts, a number of parameters have to be given for the fragmentation (e.g., fragmentation rate/time, final size of fragments) and heat release (e.g., heat transfer coefficient, heat transfer cut-off values as a function of void fraction, heat transfer partitioning between steam and water). These parameters govern escalation and propagation of the explosion for a given pre-mixture, which

determines the strength of the explosion. As shown in SERENA-1, used for corium experiments, the default values for these parameters, in general established from alumina experiments, lead to significant overprediction of the loads with respect to the experimental data. Playing with these parameters allows in general finding back the order of magnitude of the data. But missing a physical explanation of the corium behaviour, some code users/developers are reluctant to modify the models/parameters on the sole basis of more or less speculative arguments. As a matter of fact, some partners in SERENA-1 did not use the reduced parameters in their calculations of the reactor situations, which contributed to enhance the scatter of the predictions. As we have seen, this had no consequences for the in-vessel case. But the predictions of the loads for the ex-vessel case of Fig. 3 spanned over one order of magnitude (Fig. 5), which would induce from moderate to significant damage to the cavity and, depending on the design, to the containment [30]. Clearly, the scatter has to be reduced to make ex-vessel predictions credible and to put a figure on the level of the loads.

What was already said for the pre-mixing phase is also true here, i.e., it is unlikely that the discrepancies existing in modelling the explosion phase will be resolved in a reasonable time frame. Existing explosion models already contain sufficient fragmentation and heat transfer parameters to accommodate the specific behaviour of a large spectrum of melt-water systems. As a first approximation one has 'just' to be confident that the set of parameters used for that system is legitimate for the

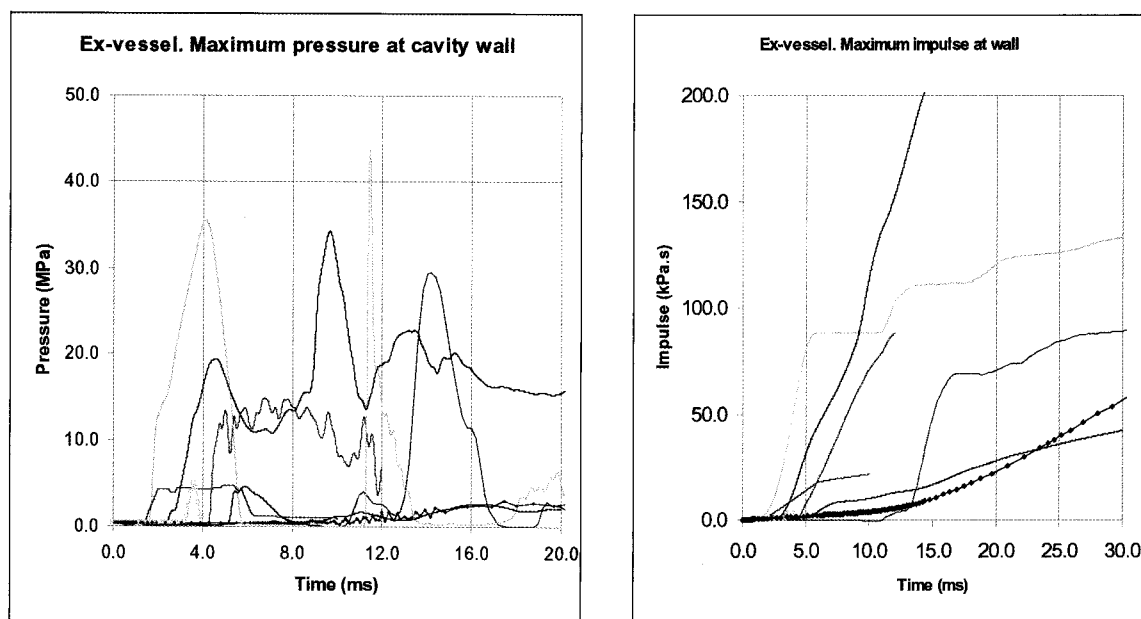


Fig. 5. Ex-vessel Calculated Pressures and Loads According to the Various Codes Used in SERENA-1 Exercise (From [6])

purpose of providing reasonably conservative estimates of energetics in representative melt progression sequences. As far as the explosion phase is concerned this reduces the process to verifying whether or not it is an inherent property of realistic corium melts to exhibit low energetics. It will remain to verify whether using those parameters consistently is sufficient to reduce the scattering of the predictions.

The discussion made so far is strictly applicable to UO₂-based oxidic corium only. It is legitimate to think that it will be established that real oxidic corium with UO₂ as the dominant species, will constantly produce mild explosions in realistic accident conditions. It should therefore be possible to determine a unique set of explosion parameters applicable for oxidic compositions. It is also legitimate to think that the 70%UO₂-30%ZrO₂ composition is a bounding composition for oxidic corium, meaning that it will allow establishing upper limits of the loads to the structures (one scope of SERENA-2).

However, pure oxidic corium is far from being the rule in core melt down accidents and non-oxidised zirconium may be present in the melt in variable quantities. In FARO large-scale experiments, 4w% Zr in a UO₂-ZrO₂ corium induced such a huge steaming when quenched in nearly saturated water that a steam explosion seemed very difficult to trigger [31]. But in the small-scale ZREX experiments [12], ZrO₂-Zr melts containing a large fraction of zirconium ($\geq 60\text{w}\%$) produced externally triggered explosions having efficiency of the same order as alumina in KROTOS (taking into account the chemical energy due to Zr oxidation in addition to the thermal energy of the melt in calculating the efficiency), even in saturated water. Clearly, the possibility of having FCI accidental sequences with melts containing large fractions of zirconium on the one hand, and the steam explosion behaviour of UO₂-based melts containing small fractions of zirconium on the other, should be investigated.

For the ex-vessel situation, a large proportion of non-oxidized metallic phases is expected, if not 100% (mainly steel), as a first pour in case of lateral vessel failure by focusing effect. The steam explosion behaviour of 100% steel-water systems has not received great attention in the discussions that have taken place in the last few years and would need to be considered in the on-going programmes. Experiments exist that show moderate efficiencies (<1%, [12]), but comparative analyses with oxidic melts in terms of influence of melt properties on the steam explosion energetics and reactor applications are missing. Hole ablation would lead sooner or later to the release of a complex mixture of metal-oxide melts. In the case of an inversion layer (metal below oxide) due to the separation of uranium metal from the oxide pool, a bottom failure would also yield first to a pure metal release followed by an oxide-metal. A UO₂-based melt containing a large fraction of metal (19% Mo) has produced very energetic explosions (SUW series [32]). It is advisable to revisit

these experiments to look at whether the conditions under which the tests were performed are pertinent to some accident scenarios.

Multi-component mixtures containing non-miscible species are not easy to address experimentally because the phase distribution in the melt at the time of release to the water is difficult not only to control (it depends on the heating process) but also to deduce from post-test observation of the debris. Lateral vessel failure is not easy to calculate either, because it is a full 3-D situation with possible interaction with the cavity wall. Most codes do not yet have 3-D capability and artefacts are required to address those situations with 2-D codes [33].

Steam explosion risk is scenario-dependant and design-dependant. In reactor-oriented approaches aiming at realistic estimates, melt composition, melt release conditions and design should never be dissociated from each other. In light of the suspected importance of the corium melt properties on the energetics, using "prototypical" or "realistic" corium as a generic term without specifying which composition it refers to is puzzling and should be avoided. Assigning corium melts low explosivity as an inherent property of "corium" is ambiguous and misleading as well. According to the present state of knowledge it is probably true for realistic oxidic compositions having UO₂ as the dominant species (in-vessel case), but experimental confirmation is still required for realistic oxide-metal compositions having large fractions of metallic phases (ex-vessel case).

5. CONCLUDING REMARKS

Steam explosion research has been successful in producing FCI codes able to calculate all the phases of a steam explosion in an LWR, both in- and ex-vessel. These codes differ in physical and numerical modelling, and have been validated against experimental data to various degrees. Present knowledge does not allow a conclusion on the validity of a specific model against others, and in light of the historical development of FCI research it is not expected that this situation will change in a reasonable time frame. The codes are used for safety assessment by different organisations, but suffer from a lack of strong predictive power. A comparative assessment was made in the frame of the international OECD/SERENA programme on the basis of two reference scenarios, one in-vessel and one ex-vessel. Significant discrepancies have been found in the predictions indeed, but it has been established that they could be significantly reduced if uncertainties concerning void fraction prediction in pre-mixing and steam explosion behaviour of corium melts could be resolved. These issues are addressed in the on-going phase 2 of the SERENA programme.

The exercise also brought about the important conclusion that confirming that melt-rich void-poor mixtures cannot

be obtained for in-vessel FCI scenarios would definitively eliminate the risk of lower head failure by in-vessel steam explosion, no matter whether the uncertainties of the explosion phase are resolved or not. Thus, as alpha-mode failure has been eliminated from the risk perspective years ago, the in-vessel steam explosion issue as a whole could be considered as resolved. This is not the case for ex-vessel steam explosion, in which damage to the cavity is expected. Predictions differ by one order of magnitude, which means that it is not possible to specify the level of loads on the cavity walls and thus establish safety margins for the containment.

With the scope of increasing the safety margin as far as physically reasonable, great importance is attached to experiments performed in the last two decades that have shown that UO₂-based corium melts produced relatively mild explosions compared to alumina-based melts. A number of reasons have been invoked to explain the low energetics, such as formation of crusts, presence of mushy zones, and role of chemical properties, but no definite conclusions have been drawn so far. Detailed modelling of these effects is not expected in the short term. Such modelling might not be necessary in a reactor-oriented approach if the use of reduced fragmentation and heat transfer parameters in the existing explosion models could be legitimated by confirmatory testing and analysis. Confirmation of the reduced energetics is expected for oxidic corium compositions having UO₂ as the dominant species, but might be more difficult for oxide-metal mixtures, especially in the case of phase separation. Experimental and analytical efforts undertaken in SERENA-2 on these issues should bring answers to these questions and allow a sufficient reduction of the scatter of the predictions to achieve predictability of the loads for ex-vessel situations.

As the response of the structure while an explosion is developing may have a mitigating effect on the loads, fully coupling FCI and structure analysis codes is also desirable if further increase of safety margins is required.

It is a little frustrating for people who have been involved in steam explosion research for many years that no solution can be proposed to prevent steam explosions from occurring. Adding substances to the water to change its properties (e.g., increase surface tension and/or viscosity) has been studied in the past but did not provide reliable results. Expecting that damage to the cavity may affect containment integrity, a solution to mitigate the consequences of an ex-vessel steam explosion would be, for future reactors, to design cavities as much as possible mechanically independent of the containment walls and as large as possible to allow sufficient venting of the explosion and prevent any uplift of the pressure vessel.

Lastly, beyond the issue of dynamic loading, an explosion produces very fine debris that will form a layer above non-exploded debris in the lower head or cavity floor. This may challenge the coolability of the particulate

debris bed. On the other hand, an explosion may disperse both exploded and non-exploded debris in various parts of the primary circuit or containment, which may challenge debris retention strategies as well. This issue has not received a great attention so far.

APPENDIX: ABOUT EFFICIENCY

In steam explosion research, efficiency is one of the most ambiguous notions, and should be used with great care. Conversion ratio is defined as the ratio of the mechanical energy output to the thermal energy of the melt. Efficiency is the conversion ratio expressed in percentage of the thermal energy of the melt⁶. It is nonsense to use it in as an absolute value for a given melt-water pair or to transpose inconsiderately the efficiency inferred from given experimental conditions to other conditions and, in particular, to reactor situations. The mechanical energy refers to a given melt-water-structures' system. In experiments, the mechanical energy is recovered from transducers located at the wall of the test section. So, the efficiency refers to this particular system and does not necessarily represent an intrinsic characteristic of the melt-water pair. In addition, the methods of calculating the mechanical energy are often the subject of interpretations and of lively debate [18].

The melt quantity to be considered for calculating the thermal energy to be placed as denominator of the ratio is a somewhat subjective data. In small scale jet experiments, in which the total melt amount is in the water and has not yet reached the bottom of the test section before the explosion triggers (or is triggered), it makes sense to consider all the melt in water. The efficiency obtained is a global efficiency, which does not take into account which part of the melt mixed with water (a coherent jet is not supposed to be mixed) nor which part actually participated in the explosion (part of the melt in a pre-mixture may not participate, e.g., the frozen part). Thus, for a given melt composition and flow rate, global efficiency of an explosion occurring at the same time during pre-mixing may change if the melt pouring conditions are changed (e.g., single jet vs. multiple-jet). Another perhaps more consistent way to express the efficiency of a melt-water system is to refer to the melt mass that actually participated in the explosion, i.e., the part that was finely fragmented. Based on theoretical considerations, one may find a maximum fragment size consistent with a release of energy within the characteristic time of the explosion (e.g., 280 µm in [33]). Debris of size below this value is then used to calculate the participating mass and the efficiency, which results of course in higher values than if the total

⁶Efficiency is also sometimes expressed as a percentage of the Hicks-Menzies efficiency considered as the maximum achievable.

mass were considered. However, this practice also has uncertainties because the size criterion is questionable, particles can experience post-interaction shrinkage cracking, and pre-mixing can also produce fine particles. At the end of the day, if we were able to eliminate one after the other all the spurious effects that affect the participating mass, we would probably reach conversion ratios nearer and nearer to the Hicks-Menzies values. Therefore, such a method is of no use to evaluate the efficiency in reactor situations nor would it allow prediction of the loads on the structure.

When an explosion is triggered while the melt jet is still penetrating into the water, it is of course the part in water that should be used as the maximum melt mass to take into account for the thermal energy. Determining this is difficult in experiments performed with high temperature melts. Taking all the melt collected at the bottom post-test may lead to significant underestimation of the efficiency. If the melt has already started to collect at the bottom when the explosion triggers, this part should be removed from the mass estimate because a fraction of it has certainly already quenched and, essentially, melt in flight in the water may have the required pre-mixing characteristics for explosion propagation.

Even if the melt mass is fixed, it is the author's experience that in integral tests absolute errors in calculated global efficiencies can hardly be reduced below 0.05% due to the uncertainties in the mechanical energy evaluation [21]. Taking into account all these aspects, drawing conclusions on the relative explosivity of different systems having low global efficiencies requires careful attention. Major differences in explosion behaviour may be expected only if, in a given geometry and release conditions, the efficiencies differ by one order of magnitude at least.

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