

Material Influence on Steam Explosion Efficiency: State of Understanding and Modelling Capabilities

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Summary

Steam explosions as explosive melt-water interactions may happen in the course of a severe reactor accident with core melting. It is to be analyzed whether such explosions could lead to severe consequences, e.g. jeopardizing the lower head in in-vessel events or especially the containment integrity in ex-vessel events. Major mechanisms limiting the strength of explosions have been identified and elaborated in the past, recently in the OECD-SERENA Phase 1 project. Continued analyses are being performed in SARNET. Void buildup in premixtures has been considered as a major limitation, reducing by compressibility the potential of mixtures of being triggered and of yielding strong pressure escalations. Material influences are under discussion. Exclusion of strong explosions with corium has been concluded from experiences with KROTOS experiments, in comparison with explosions obtained with alumina melts. Spontaneous and triggered explosions with corium have been obtained in TROI experiments, but not spontaneously and with less strength under triggering for non-eutectic corium.

In the present paper, the status of knowledge about the material influences is analyzed, as well as possible consequences to be drawn. In general, the effects limiting the strength of explosions are discussed and demonstrated by applications to an in-vessel scenario. Conclusions are drawn on the status of modelling and guidelines for further resolution of remaining problems and uncertainties are proposed.

1 Introduction

Understanding and modelling of steam explosions [1] is important since such explosive melt-coolant interactions caused by rapid fine fragmentation of melt and heat transfer to coolant may endanger structures and thus reactor cooling measures by water injection counter-productive. Cooling options under given conditions would gain from exclusion of strong steam explosions.

Steam explosion experiments have indicated important differences of behaviour between simulants and prototypical melts, and that also with prototypical melts the fuel-coolant interactions depend on the composition of the corium. It appears and is under discussion that metal melt and alumina melt are vulnerable to explosions, i.e. they tend to be easily triggered and yield strong explosions, whereas binary and multi-component melts, like corium melt, exhibit low disposition to triggering and escalation. Energy conversion may be considered as an indication for the strength of explosions, although problematic because depending on geometrical confinements, etc.. In the KROTOS test series the steam explosion energy conversion ratio in experiments performed with corium melt (80%UO₂/20%ZrO₂) is about

one order of magnitude lower than in experiments with alumina melt (Al_2O_3) [2]. The alumina melt explosions partly appeared spontaneous, while corium melt exploded only if an external trigger was applied. Recently, experiments with eutectic and non-eutectic corium compositions in the TROI facility indicated that also corium can explode spontaneously, if its composition is eutectic ($70\%\text{UO}_2/30\%\text{ZrO}_2$) [3].

The influence of the material properties on the steam explosion is very complex, since in the fuel-coolant interaction phenomenon multiple processes are involved during the coarse mixing, the triggering, the escalation and the propagation, and all these processes are influenced by the material properties of the melt. Several mechanisms may be identified in general how the material properties in conjunction with experimental conditions influence the fuel-coolant interaction (see Fig. 1) [4], e.g.:

- Density: At a higher density the melt penetrates at a higher velocity through water, causing deeper sequential fragmentation of the melt drops. This results in smaller drop sizes and larger heat transfer surface area. Consequently the cooling rate of the melt droplets is larger and the local void content in the premixture is increased.
- Liquidus temperature: A high liquidus temperature implies a high melt temperature. At a higher temperature the cooling rate of the melt droplets and the local void content in the premixture are larger. In addition, at high temperatures the radiative heat flux penetrates

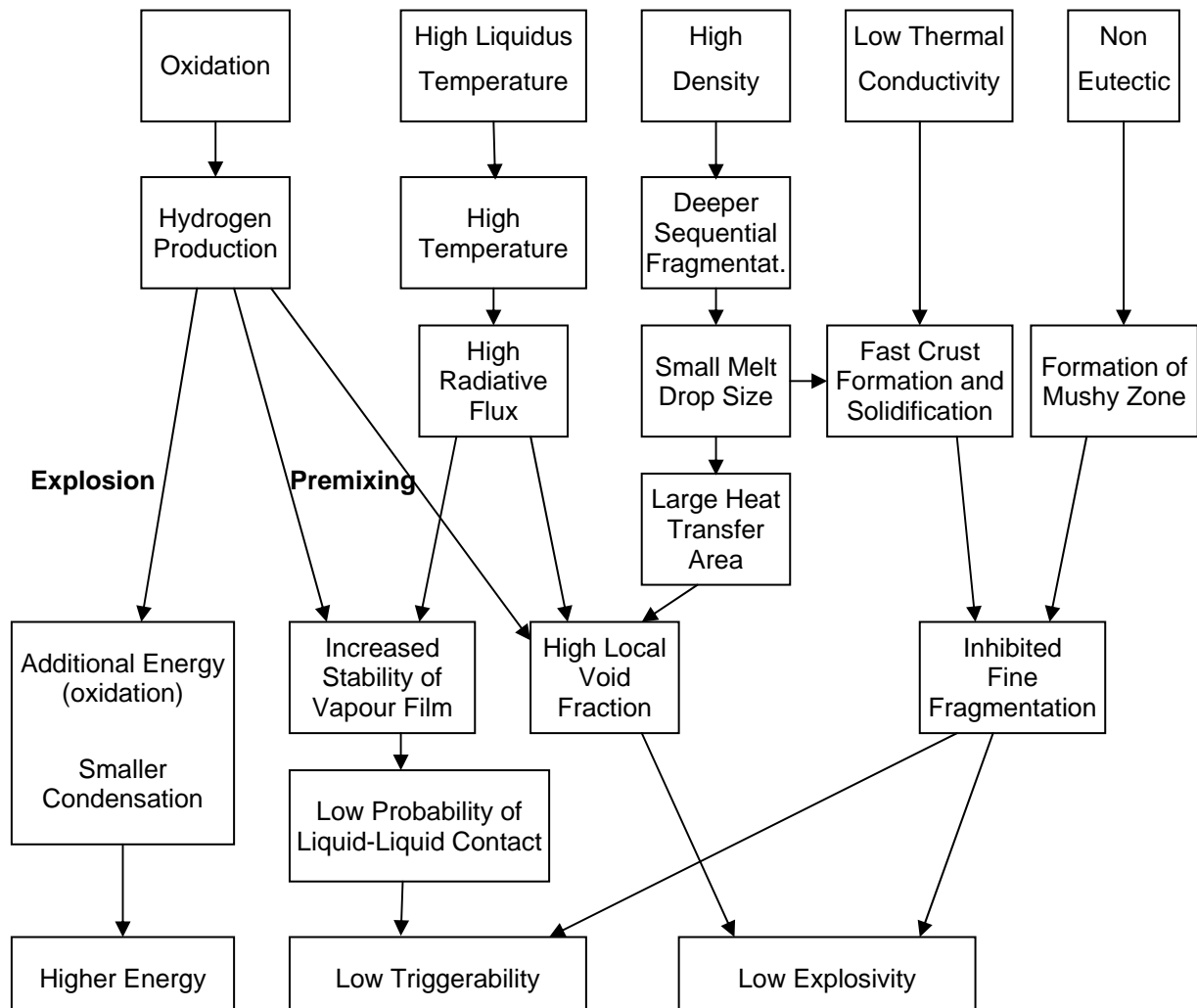


Fig. 1: Influence of material properties on the steam explosion.

deeply into the coolant pool, heating it up and thereby reducing the effect of water subcooling and increasing the stability of the vapour film around molten particles.

- Thermal conductivity: At a larger thermal conductivity heat from the inside of the droplet is transferred more effectively to the droplets surface and so the formation of the solid crust is delayed.
- Non-eutectic composition: With a non-eutectic melt composition, during the solidification process a mushy zone is formed, which may inhibit the fine fragmentation of the droplet.
- Oxidation: Depending on the melt composition, at high temperatures the melt oxidation in water vapour may be significant. During this chemical reaction hydrogen is produced, which is a non-condensable gas and so inhibits the liquid-liquid contact between melt and water. But if the explosion is triggered the explosion may be amplified due to the released oxidation energy.

As follows, such hypotheses and conclusions from experiments will be discussed, especially with respect to the relevance for reactor scenarios and safety evaluations. Other effects inhibiting strong steam explosions, related to melt breakup and void production in premixtures, are also considered. Finally, a roadmap to solve open questions and to reach a modelling and computer code status enabling conclusions for reactor safety issues is provided.

2 Material effects from small scale experiments

A different behaviour of melts was early observed in experiments with single melt drops in water, depending on material and initial conditions (see e.g. [1]). However, the observed effects are partly contradicting or depend on relations between different influences. E.g., high temperatures of the melt stabilize film boiling and may avoid triggering and explosive reaction if the film boiling remains stable until relevant crust formation or transition to mushy behaviour occurs. This should be favoured by ceramics with high melting temperatures and low conductivity, but also with oxidizing metals yielding sheltering non-condensable gases. However, triggers producing film collapse may yield a different picture, i.e. explosive interactions with both materials. These interactions may be stronger with higher water temperature if the trigger is strong enough (due to increased heat transfer and evaporation under melt-water contact) or weaker with less trigger strength (due to stabilization of film boiling by higher water temperature). Higher ambient pressures may yield stronger interactions with sufficient triggers (due to extended melt/water contacts with less void production), but suppress interactions with smaller triggers due to stabilizing vapour films.

Thus, no overall conclusions on material as well as temperature effects on explosive strength could be drawn from these small scale experiments, especially if external triggers are considered. Occurrence of such triggers is to be expected in the mixing and settling processes of large melt masses, due to collisions of melt drops or lumps and enclosure of water in or under settling melt (“entrapment explosions”). Large-scale experiments showed such triggering with resulting significant explosions at conditions previously considered as not favouring explosions. E.g., $\text{Al}_2\text{O}_3\text{-Fe}$ thermite mostly showed spontaneous explosions in the FITS experiments at SNL, although H_2 production inhibited explosions in drop experiments without triggering. Further, explosions occurred regardless of the water subcooling.

Major discussions on material effects possibly excluding strong vapour explosions under reactor conditions have then been initiated by the experiences from FARO and especially KROTOS experiments [2], recently by results from the TROI experiments [3]. While the

KROTOS experiments with alumina showed strong pressure escalations, up to a range of 100 MPa within some tens of cm, with or without external triggering, only much weaker increases up to 10-22 MPa were obtained with applied triggers of 10 MPa for corium melts. This significant reduction of explosion strength with corium melt was mainly attributed to:

- Rapid solidification (crust formation) with corium due to lower thermal conductivity and lower superheat.
- H₂ production with corium yielding high void, sheltering the melt against contact with water and increasing compressibility of the system.
- Smaller fragments due to higher density of corium.
- Less effective fine fragmentation from thermal interaction (possible causes may be: solidification, high viscosity in liquidus-solidus range – mushy zone).

Also, in a final FARO experiment (FARO L-33) only a weak explosion could be triggered with corium, in spite of a high subcooling applied to avoid extensive steam formation. However, a premature triggering occurred in this experiment, before complete melt release. Thus, the melt mass in mixture was limited by this.

Final clarification and agreement about major material effects in the KROTOS experiments explaining the difference in behaviour between corium and alumina is not yet reached (Chapter 3). However, it was concluded from visual observation as well as fragment size distributions of experiments without explosions [2] that the average fragment size in the premixing phase was much smaller with corium than with alumina. This means that an increased void from steaming and H₂ production can be understood just from the smaller fragment sizes, as well as rapid solidification. Thus, breakup into smaller fragments appears to be the key to understand weaker interactions, at least in case of the KROTOS experiments. Of course, the effects of solidification, inert gas, low superheat may separately play a role and limit the strength of explosions also in cases with breakup of melt into larger drops. General conclusions in this respect, especially concerning a general argument about explosion strengths of corium versus alumina cannot be drawn from the KROTOS experiments. The major difference there appears already to be related to breakup under premixing and this requires further explanation.

It is also to be remarked concerning corium breakup in premixing that larger particles have been obtained in FARO experiments than in KROTOS experiments (both non-explosive). This is valid over a wide range of conditions in these experiments. Fig. 2 shows fragment distributions from non-explosive experiments and a clear division between FARO and KROTOS results. The FARO experiments even cover a range of ambient pressures from 0.22 to 5.04 MPa, ambient temperatures from 100 K subcooling up to saturation temperature and melt jet diameters of 5 or 10 cm as well as released melt masses from 92 up to 174 kg. Thus, especially in view of the detected importance of fragment sizes for understanding the corium-alumina difference in KROTOS experiments, it is also important to understand the FARO-KROTOS difference of corium breakup in premixing.

Further indications on material effects have been given recently from the TROI experiments. Even, strong effects of UO₂/ZrO₂ melt composition are remarked, with non-eutectic compositions of 80 wt% UO₂, 20 wt% ZrO₂, yielding only weak steam explosions under triggering, whereas eutectic compositions of 70 wt% UO₂ and 30 wt% ZrO₂ yielded stronger and spontaneous explosions. Explanations have been attempted based on solidification, depending on the composition, i.e. on differences in liquidus and solidus temperatures, or on viscosity effects in a mushy zone between liquidus and solidus temperatures. Final

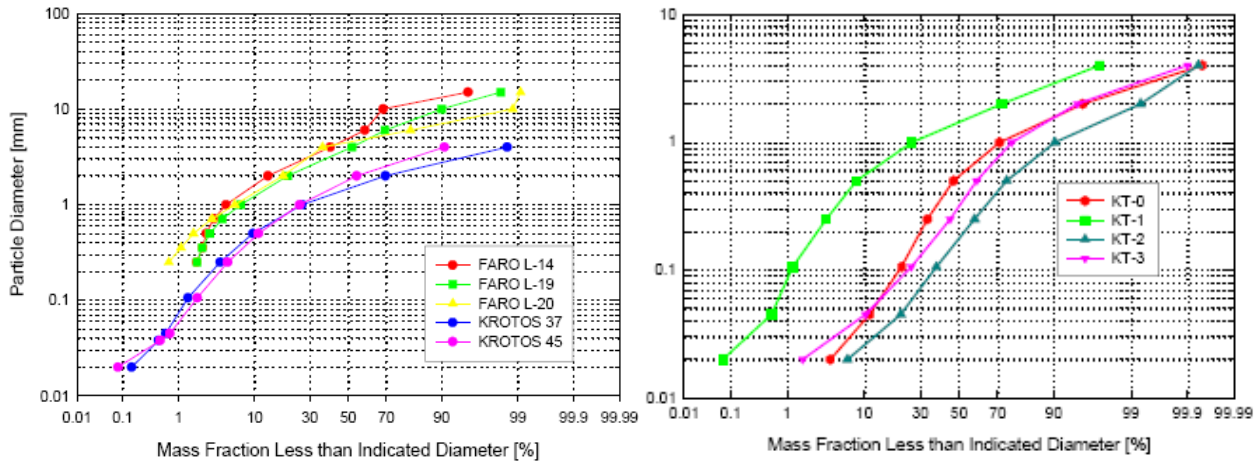


Fig. 2: Particle size distribution of FARO and non-explosive KROTOS tests with corium (KT series: KT-1 without trigger, others triggered).

explanations are not yet attained. Other influences may overlap. E.g., increasing the water depth from about 0.7 m to 1.3 m resulted in suppression of spontaneous explosions also for the 70/30 wt% composition. This may be explained by the larger time for settling under film boiling, allowing solidification processes. Expected effects of melt superheat, melt jet diameter and mass were not obtained, at least not to a significant extent.

It appears further not to be clear whether the differences mainly concern the occurrence of spontaneous explosions or also the strength of triggered explosions. Overall, since spontaneous triggering depends on scale, it should be more important to consider the possible strength of pressure escalations under imposed triggers than to judge with respect to occurrence of spontaneous explosions. The question is then, to which extent the explosion strength depends on the material.

Below, major effects observed as well as possible consequences for limitations of explosion strength under reactor conditions are considered in more detail, in order to promote explanations. It is to be explored whether expected limitations from material behaviour can be presently clearly concluded in a sufficient way or whether other limitations may be sufficient to conclude on reactor safety issues of steam explosions.

3 Corium and alumina in KROTOS experiments

The main conditions of KROTOS tests are: jet diameter: 3 cm, free fall: 0.2-0.45 m, test section diameter: 0.2 m, water depth: 0.9-1.1 m, water subcooling: 5-125 K, system pressure: 0.1-0.4 MPa, melt temperature: up to 3150 K, melt mass: alumina up to 1.8 kg and corium up to 5.4 kg. A series of 28 fuel-coolant interaction tests have been performed in the KROTOS facility with alumina (Al_2O_3 ; 15 tests) and corium (80% UO_2 /20% ZrO_2 ; 13 tests). The main finding is that no spontaneous steam explosions have been obtained with corium melts poured into highly subcooled or near-saturated water pools under a range of different initial conditions. On the other hand, independent of water subcooling, alumina melt pour can produce a coarse mixture with water that readily produces a strong steam explosion either spontaneously or by means of an external trigger.

As already mentioned, visual observations of premixing processes in KROTOS experiments revealed strong differences between corium and alumina melts. Fig. 3 shows photos from the upper part of the KROTOS test vessel with water mixing with alumina melt (test K-57, right) and corium melt (test KT-2, left), taken from [10]. In both tests, the water was strongly

subcooled (83 K with K-57 at ambient pressure of 0.1 MPa, 125 K with KT-2 at ambient pressure of 0.37 MPa) and no explosion occurred. In the alumina case no coherent melt jet is visible any more but the melt is broken up in relatively large drops seemingly distributed over the whole cross-section. In contrast, the corium appears to be concentrated in a limited range and still forming a coherent jet with small parts stripped off. This impression and interpretation is supported by photos from KT-1 in a lower region (Fig. 3 middle, taken from [10]). KT-1 was performed at similar conditions as KT-2, but without applying a trigger. Thus, the drops are larger than from the other experiments of the KT series with application of triggers (Fig. 2), but still with 30% mass fraction smaller than 1 mm and 70 % smaller than 2 mm diameter. In contrast, test K-57 with alumina, also without spontaneous explosion and without trigger, yielded much larger fragments, with 50% above 10 mm in the saturated and 70% above 10 mm in the subcooled case [11]. These results from the debris analysis are consistent with the visual observations.

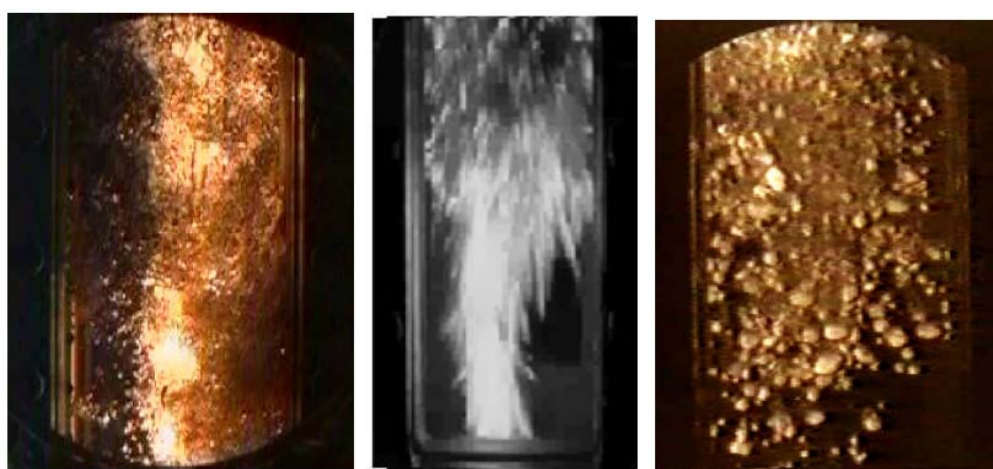


Fig. 3: left: Corium melt mixing in KT-2 (viewing area 10 by 20 cm),
middle: Corium melt mixing in lower part of test vessel in KT-1,
right: Alumina melt mixing in KT-57 (viewing area 10 by 20 cm).

Can different initial conditions for corium and alumina experiments explain the different behaviour? There was a different behaviour of alumina in experiment K-57, the first with a changed test section geometry. Differing from the previous experimental experience in KROTOS that alumina always produces spontaneous explosions with subcooled water, there was no such event in K-57. However, this only indicates again (as discussed above) that decisions about “explosivity” based on the occurrence of spontaneous explosions are questionable. Anyway, the different premixing behaviour is not affected by this result. Further, it is evident that the coarse breakup with alumina, with spatial distribution of melt drops, favours stronger steam explosions while the relatively fine breakup (stripping mode) around the corium melt jet favours high void in the mixture region, solidification, etc., all effects acting against explosion strength. Thus, it is important to understand whether this difference between corium and alumina behaviour in the premixing phase contains systematic features which support general conclusions about low strength of explosions with corium. On the other hand, the behaviour may also be linked to specific differences in the KROTOS experiments or specific conditions emphasizing material differences.

No differences were considered to exist in the process of melt release to the water. The crucible with melt falls down through a 5 m long release tube, then being broken at bottom by a puncher which provides release of the melt to the water. The velocity development of released melt is given in [10]. It starts from velocities higher than that of the crucible at

impact, thus indicating further acceleration of parts of melt due to the impact, until establishment of a quasi-steady outflow at a velocity of about 3 m/s, 30–40 cm above the water level.

From these evaluations on a similar melt release to water as well as a relatively low final (steady state) velocity of ~ 3 m/s of outflow from the release funnel and thus impact velocity (~ 3.8 m/s into water), it becomes difficult to derive such a completely different breakup and mixing pattern from the available models as shown in Fig. 3. Calculations with IKEMIX/IKEJET on this basis for corium (4.0 kg) and alumina (1.3 kg) yield with the same set of model parameters drop diameters of 3 mm for corium (too large compared to experimentally ~ 1 mm, rather in the size range of typical FARO particles, see Fig. 2) and 4.2 mm for alumina (much too small compared to experimentally ~ 15 mm). Thus, from the above statement that the difference in explosion behaviour between corium and alumina is already determined by a strongly differing breakup under premixing, it must be considered as important to understand the failure of the model. Otherwise the respective material effect cannot be described in an assured way for reactor conditions.

Another line could be to consider the breakup behaviour with alumina in KROTOS as untypical, not prototypic for corium and reactor conditions. Then, the model may be considered as applicable for relevant cases. This remains problematic if not supported at least by better understanding of the phenomena. Also, the difference between FARO and KROTOS for corium, with still smaller fragments in KROTOS emphasizing the less explosive character, remains to be explained.

A strong breakup of alumina in KROTOS already before or at impact on the water surface (see also [12]) may be assumed on the observation in Fig. 3 (right), on the high impact velocities of the crucible on the puncher with even increased outflow velocities indicating strong disturbances and partial mass accelerations and breakup and on observed strong leading edge disturbances of jets even with corium above the water surface. Compared to corium in KROTOS, such effects should be much stronger with the low density alumina. Then, no compact jet would have entered the water in the alumina case but already broken parts, whereas with the higher density of corium still a jet enters in spite of the detected strong leading edge disturbances. Such disturbances have also been observed in FARO experiments, there for the final debris less important due to the large mass yielding finally a long duration of smoother coherent jet flow (however also indicated to some extent by the detected steady state outflow of ~ 3 m/s in KROTOS, see above).

In contrast to these speculations on the alumina entrance into water in KROTOS, a jet entering water with subsequent breakup (phenomenologically interpreted by stripping of melt) is clearly observed in PREMIX experiments [13]. Again, the model does not reproduce the large fragment sizes of ~ 9 mm obtained also here, e.g. in PM16, with the initial conditions given on melt outflow. However, a significant reduction of the jet velocity after entrance in the water can be derived from the experimental data which is not given by the model. Considering this reduction in the calculation yields significantly larger drops, close to the experimental results [12]. This can be understood from the resulting shorter melt jet, due to the smaller penetration velocity, yielding smaller steam velocities along the jet as cause of breakup (see also [12]).

Thus, it may be concluded in general that deficits of the model can mainly be attributed to special effects of impact and deceleration with the low-density alumina during penetration into water and that the breakup model is applicable for corium, for which also such strong velocity reductions do not occur. Then, KROTOS-FARO difference remains to be clarified. A

general explanation may be that in an initial phase different or additional mechanisms of breakup are effective, finally ending in the dominance of stripping under strong steam flow along the melt jet. A special mechanism may be the so-called “thin-film Kelvin-Helmholtz breakup” analyzed for FARO L-28 in [14]. Finally, remaining uncertainties in the description considered as applicable to corium and reactor conditions (if the above view is supported) may be handled by parametrizing the breakup in some range varying influencing parameters.

Although the different breakup in premixing already strongly determines the subsequent different behaviour of corium and alumina in KROTOS, i.e. freezing, void formation and finally the escalation potential after triggering, it is of interest to consider the dependence of freezing on the material and the drop size as well as the initial and ambient conditions. Fig. 4 shows a comparison for non-eutectic 80/20 $\text{UO}_2\text{-ZrO}_2$ (left) as used in KROTOS and alumina drops (right). 3 mm (top) and 10 mm (bottom) drop sizes are considered. With the latter, no crust develops in the alumina drop whereas a crust of about 0.25 mm thickness develops until 0.5 s in the corium case even with this large drop. The model of JSI is based on a conduction solution assuming a mushy region (i.e. no composition change). With 80/20 $\text{UO}_2\text{-ZrO}_2$, $T_{\text{liquidus}} = 2840 \text{ K}$ and $T_{\text{solidus}} = 2820 \text{ K}$ are taken. Thus, the thickness of this region is rather small and the difference with calculations for the eutectic composition 70/30 $\text{UO}_2\text{-ZrO}_2$ is negligible. With the 3 mm drop, a crust also develops for alumina, but significantly slower than with corium (about 0.17 mm for alumina and 0.45 mm for corium after 0.5 s). To which extent crust formation limits explosive escalation in reactor scenarios needs further exploration for realistic conditions and depends on the drop sizes. The rapid growth with corium may yield significant limitations also for larger drops, so that more general conclusions about limitations by solidification may be possible. However, this needs

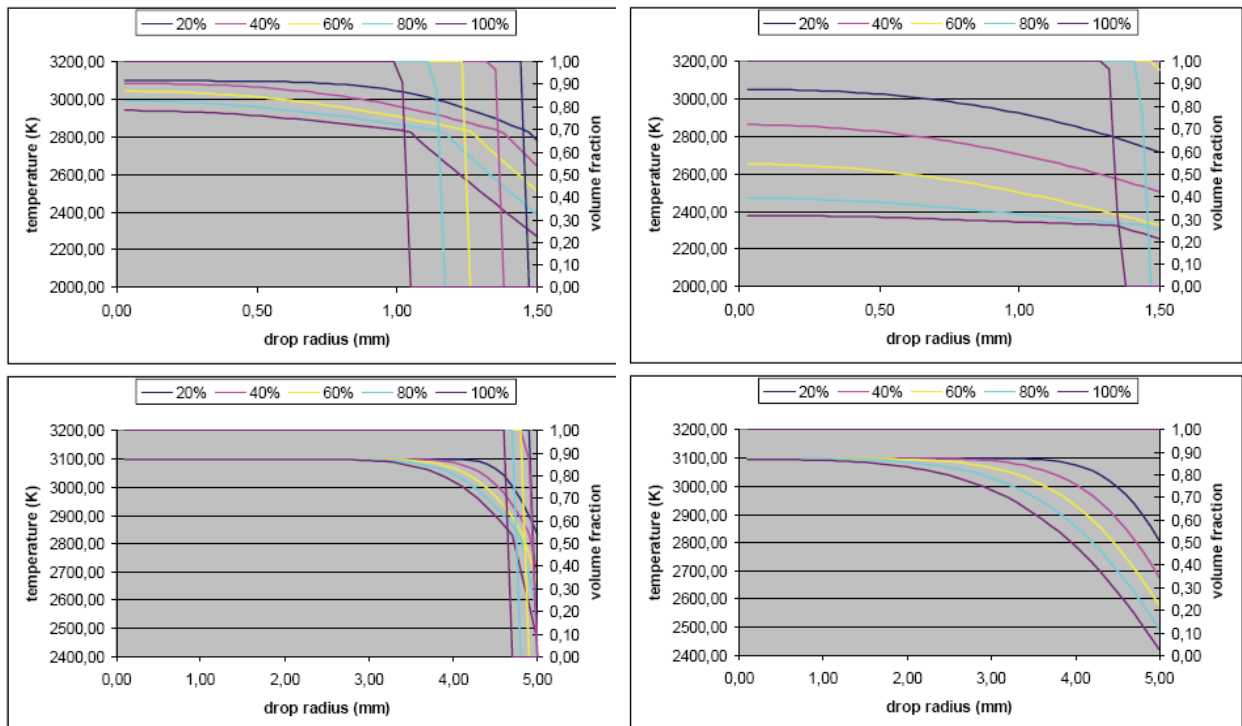


Fig. 4: Freezing behaviour of 3 mm (top) and 10 mm (bottom) sized drops:
 Left: 80/20 $\text{UO}_2\text{-ZrO}_2$. (Volume fraction means liquid part of drop, 20% ... 100%: parts of time, final: 0.5 s),
 Right: Alumina.

exploration of a sufficient variety of scenarios and also evaluations on crust thickness required to limit triggering and escalation, i.e. fine fragmentation within these processes.

4 TROI experiments: different corium compositions

TROI is a facility dedicated to steam explosion experiments in a wide range of conditions, located in KAERI, South Korea [3]. It is somewhat bigger than the KROTOS facility and enables the performance of experiments with larger melt masses in 3-D water pool geometry. The main conditions of TROI tests are: jet diameter 6-10 cm, free fall: 3.0-3.9 m, test section diameter: 0.6 m, water depth: 0.7-1.6 m, water temperature: up to saturation, system pressure: 0.1-0.5 MPa, melt temperature: above 3000 K, melt composition: variable composition UO_2/ZrO_2 , melt mass: 5-30 kg.

A number of fuel-coolant interaction tests have been performed in the TROI facility varying the corium UO_2/ZrO_2 composition and the experimental conditions. The FCI experiments performed at sub-cooled water at atmospheric pressure and a pool depth 0.67 m showed a significant effect on the corium composition concerning the occurrence of spontaneous steam explosions.

The most interesting findings of these TROI experiments are that corium with a eutectic composition 70 wt% UO_2 / 30 wt% ZrO_2 may explode spontaneously in contrast to 80/20 UO_2 - ZrO_2 , and that the strength of triggered explosions with eutectic corium (efficiency up to 0.4%) is higher than with non-eutectic corium (efficiency ~0.02%). The differences in the corium physical properties between the eutectic 70/30 and non-eutectic 80/20 compositions are so small that they probably do not result in different breakup and premixing behaviours.

Then, only different states of the melt itself can cause the different explosion behaviour. Different crust formation is a first candidate but only negligible differences have been obtained from calculations with the JSI model for the 80/20 versus 70/30 corium compositions. This model is based on conduction only, convection in the liquid melt is not considered, and the solidification is considered to occur with constant composition. As an alternative, an extended mushy zone may be considered, due to increased heat transport in liquid parts by convection (more uniform temperature profile). More detailed analyses are then required to compare eutectic crust growth and non-eutectic crust + mushy zone growth. An extended thickness of mushy zone could further hinder fine fragmentation by strongly increased viscosity, even with only small solidified parts.

However, emphasizing different triggering and escalation potentials with different compositions as conclusions from the TROI results, especially with rather close compositions of 80/20 and 70/30 UO_2 - ZrO_2 , is in general problematic. If there would really be a strong difference relevant for reactor safety considerations, the problem arises how to distinguish possibilities or probabilities of occurrence of (strongly) explosive or much less explosive compositions within reactor accident scenarios, how to decide about safety issues.

Of course, better understanding of different behaviour should be attempted in general in order to reach assured conclusions. However, rather delicate processes may e.g. decide on a trend to spontaneous explosions, as indicated. These may indeed depend even on the strength of an initial crust, depending on the material composition. Then, it remains questionable whether there is a gain from specific analyses on such effects for conclusions on reactor safety issues.

Other effects may also influence the decision about spontaneous explosions and even on the strength of triggered explosions. E.g. the TROI experiments revealed that there is a strong

influence of the water pool depth and the water pool cross section on the steam explosion triggerability and explosivity [3], [7].

With a water depth of 0.67 m, eutectic corium mostly exploded spontaneously, whereas with deeper water of 1.3 m no spontaneous steam explosions occurred. Also, the steam explosion energy conversion ratio of triggered explosions was higher with the lower pool depth. This can be explained by a longer time for freezing with the deeper water, if triggering is assumed at bottom contact.

Also, all triggered tests using the wide test section (diameter 60 cm) resulted in more energetic steam explosions, whereas in the triggered tests using the narrow test section (diameter 30 cm) even with the eutectic corium composition no steam explosion occurred. Noting that the area of the narrow test section is four times smaller than the area of the wide test section, leading to a four times bigger fuel to water ratio, it is suggested that an increase in the average void fraction might have prevented the development of a steam explosion.

Thus, it is important to find the major conclusions from the experimental results which support major limitations to explosion strength addressed in the models and of course to check the modelling in this respect. The major outcome from the TROI experiments up to now appears to be that even with spontaneous and triggered explosions the explosion strength with the corium melt remains limited. This has to be understood and adequately described in the models.

5 Major processes to be modelled for analyses of reactor scenarios

As discussed mainly from the KROTOS experiments, but also considering FARO and PREMIX experiments, significant differences in penetration of melt into water related to material density may yield extremely coarse melt breakup with alumina (≥ 10 mm in the KROTOS and PREMIX experiments) as compared to breakup of corium melt in KROTOS (~ 1 mm) or FARO (~ 3 mm). From this difference, much less potential to strong explosions, either spontaneous or triggered, results with corium, especially due to enhanced quenching with freezing and enhanced steam production with high void formation. It must still be explored to which extent this behaviour determines the explosion features in relevant reactor accident scenarios. This is a task of checking model results for various realistic conditions, also of parametric studies on breakup in some spectrum of uncertainties and of further experimental checking. Extended scenario checks (3D mixtures, larger and denser mixtures, etc.) were also envisaged in the TROI experiments for SERENA Phase 2.

The breakup process also limits the mass in mixture produced in realistic scenarios. A large melt pour (large diameter, large velocity) into water may be considered as most critical since it yields the potential of extended and melt-rich mixtures. However, at least with one pour of large diameter, only partial melt breakup by stripping of fragments or breakup at the leading edge will occur and higher release velocity will also limit this mass by more rapid penetration to the bottom. It will further emphasize formation of smaller droplets from the higher steam velocity reached along the longer jet of melt. A lateral outflow of melt from a melt pool in the core or in the lower head is to be expected at the top side boundary and should thus be limited in the diameter of outflow holes as well as in the outflow velocity. Then, the mass available in mixture during a time window until settling at bottom will also be limited.

A strong limitation to the development of strong explosions is given by the void buildup in premixing as especially explored in the SERENA Phase 1 [9]. High void in mixture limits the triggering and escalation potential at least beyond certain voids [14], due to compressibility

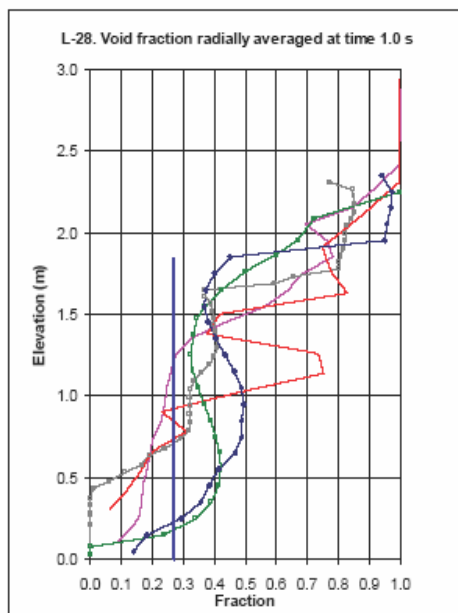


Fig. 5: Axial void distribution (radially averaged) in FARO L-28 after 1 s. Calculations from different codes, compared with exp. level swell (bold blue line).

effects, although increased relative velocities result for a given pressure rise (jump) thus enhancing fine fragmentation.

Further, although there is clearly a strong effect of void buildup in premixing due to the high heat transfer from the hot melt (already from radiation heat transfer, in spite of parts going in long range into water) and a limited steam removal from the mixture, still significant uncertainties exist in the modelling and a significant overestimation of void has in general been concluded from the SERENA Phase 1 comparison calculations (see Fig. 5). An improved, more detailed friction description for steam flows, as proposed by IKE [14] appears to be crucial to achieve realistic, assured predictions on the void effect of reducing explosion strength.

No specific material influences could be identified up to now in the fine fragmentation process in the explosion, others than taken into account in fragmentation models (as in [15]) which form the basis of simplified descriptions in IDEMO or MC3D [8]. A comparison calculation with IDEMO for the same premixtures of corium and alumina melts even predicted stronger escalations with corium, understandable from the higher

heat content. The MICRONIS/DROPS experiments at CEA may yield further insight by experiments with various materials, especially corium melts. The DROPS facility of IKE for producing rapidly strong relative water flows has been transferred to CEA for supporting such studies. In SERENA Phase 1, some partners have used different parameters for fine fragmentation of corium than of alumina in order to account for the weaker explosion results with corium. However, this is not supported here, since breakup into small versus large drops in premixing and resulting different void formation and freezing are considered to determine already most of the differences in the explosion phase. The difference then would be attributed to the wrong process which would yield problems for understanding and extrapolating to other conditions.

Additional limitations to the fine fragmentation from the material state are indeed to be considered as result of the cooling and freezing processes. Thus, crusts and mushy states may be considered. However, resulting states and limitations must be linked to the development under premixing. E.g., crust thicknesses are to be determined and possible breakup or exclusion of drop fragmentation has to be considered within the fine fragmentation models (see e.g. [15]). More rough evaluations may also be applied based on criteria excluding fine fragmentation. Especially, it may be checked to which degree an exclusion of parts of the melt from participation in fine fragmentation and thus the explosion process, based on calculated solidification in premixing, can explain the experimentally obtained reduced explosion strengths.

Such analyses have e.g. been done for KROTOS K-53. In simulations with MC3D for KROTOS K-53 (Fig 6), a predefined premixture was assumed within a radius of 4 cm, with homogeneous distribution of phases. The phases fractions were determined based on experimental measurements of the average void fraction and the mass of the released melt. A

parametric analysis was performed assuming a size distribution of non-exploded K-37 and that droplets with a diameter smaller than a cut-off diameter (label: CUT05 to CUT2 - cut-off diameter 0.5 to 2 mm) can not participate in the explosion due to solidification. For the cut-off diameter 2 mm (curve: R4CUT2) the simulation results are in quite good agreement with the experimental measurements. This is an indication that at least in principle the explosion phase

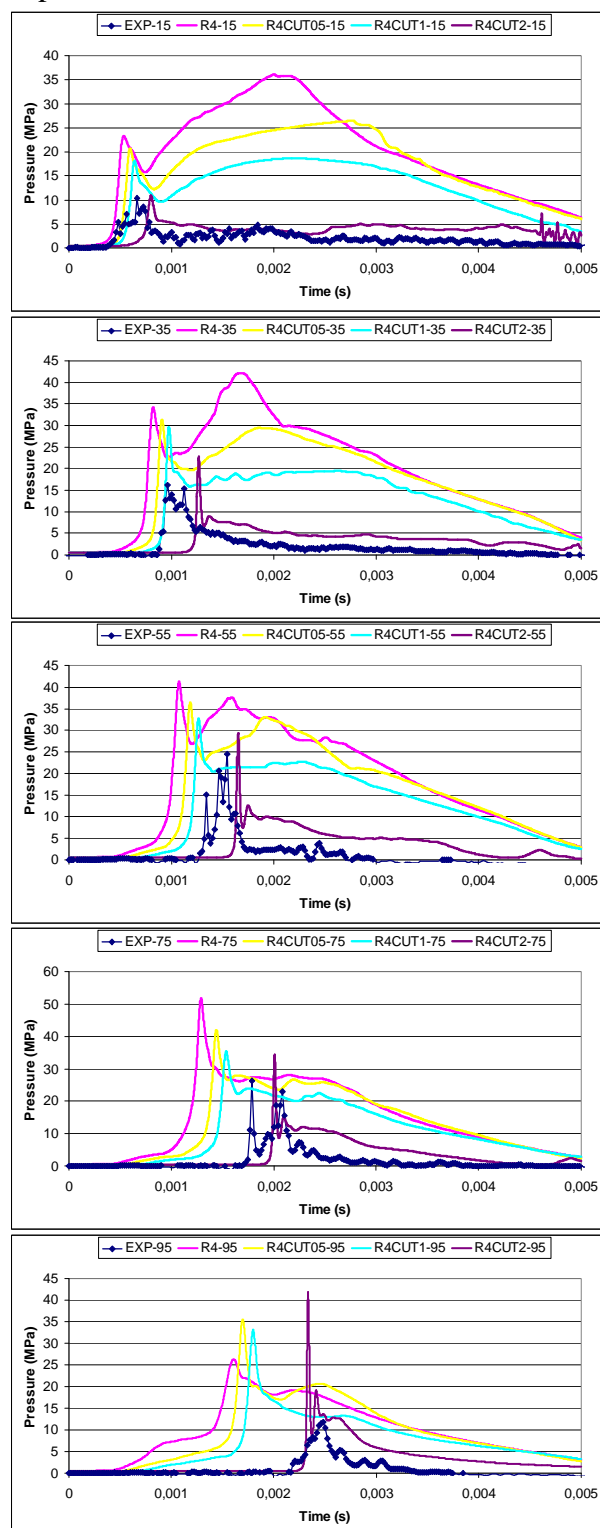


Fig. 6: MC3D calculation for KROTOS K-53.

can be reasonably well simulated if the premixture conditions at triggering time are adequately determined and if we could judge based on the droplet solidification conditions (like crust and mushy zone thickness) whether the droplet can effectively participate in the steam explosion or not.

For FARO L-33 much too strong explosions have been obtained from calculations, with an adequately chosen premixture (based on experimental indication) and parameters of the fine fragmentation and heat transfer processes in pressure waves adapted to KROTOS 44 [9]. However, excluding large parts of 80-90 % of melt from the fine fragmentation due to solidification, agreement with the experimental data could be obtained in IDEMO calculations. The chosen solidified part was considered realistic based on breakup and premixing calculations including solidification with IKEMIX.

The present difficulties with taking into account solidification effects in more detail is obvious, but the more rough approaches at least provide explanation options and may be sufficient for evaluation of major effects. However, at present, it appears to be more adequate to pronounce the limitations already given by scenarios of melt release to water, the breakup limitations yielding mass limitations for mixture in realistic scenarios as well as probably relatively small fragments in most scenarios and the limitations by void buildup.

This is finally demonstrated with calculations on reactor scenarios performed with IKEMIX and IDEMO for an in-vessel scenario [14], choosing a lateral outflow of a melt jet from a pool in the core into water in the lower plenum (3050 K corium temperature, 0.2 MPa system pressure, water at saturation, melt outflow 2.3 m above

bottom of vessel with chosen 3 m/s). The non-symmetrical configuration is approximated by consideration of cylindrical areas around the melt jet. The radius of these surroundings was varied in order to allow different lateral extensions of premixtures and consider different confinements for which the distance to the vessel wall gives an indication. An increased lateral distribution of melt means a leaner mixture but also less void with a spatially extended mixture. Finally, a radius of 1 m, found to maximize the explosion effects, has been chosen. The diameter of the melt jet has been varied between 10 and 40 cm, water levels of 1 m and 2 m have been chosen.

Table I gives results of the premixing calculations. The mass in mixture in regions below certain voids is evaluated. Taking e.g. only a mass in mixture below 60% void as explosive, the maximum mass participating is reached with a water level of 2 m and melt jet diameter of 40 cm. But only 31 kg from 380 kg in mixture would then participate, i.e. 8%, while 20% with the 10 cm diameter jet, but only 22 kg. Thus, although increasing the mass of melt in

	Water level = 1 m			Water level = 2 m		
	10	20	40	10	20	40
Djet [cm]	10	20	40	10	20	40
Melt bottom contact [s]	0.42	0.42	0.42	0.72	0.44	0.43
Mass flow rate [kg/s]	188	754	3016	188	754	3016
Dp mean [mm]	2.4	2.7	2.8	2.6	2.3	2.5
Total mass in mixture [kg]	13	33	70	105	170	380
Mass in mixture with void less than 30% [kg]	0.4	0.7	1.3	3.5	0.3	1.5
Mass in mixture with void less than 40% [kg]	0.8	1.5	3.2	6.5	0.6	4
Mass in mixture with void less than 50% [kg]	1.3	3.3	9	12.5	5.3	11
Mass in mixture with void less than 60% [kg]	2.8	6.8	19.5	22	11	31

Table I: Overview of IKEMIX calculations for premixing.

mixture, the fragmented part in void regions considered as explosive remains rather small. The larger mass participating with deeper water level is in contrast to the above conclusion from TROI experiments. However, in the present calculations solidification was not taken into account. Thus, further limitations to the participating mass can be considered. A counter-effect is that the deeper pool provides a longer time for jet breakup and mixing which becomes relevant for the thicker jets, probably not in TROI.

With the most challenging case of 40 cm diameter jet in 2 m deep water from Table I, explosion calculations have been performed with IDEMO assuming triggers at different times. Only pressure peaks up to 13 MPa were obtained at the bottom of the reactor pressure vessel for a very short time of less than 0.5 ms if triggered at bottom, but with longer times of about 3 ms if triggered later, after some settling. More details of these calculations and results are given in [14]. The major result is the strong limitation of explosive mass by limited breakup and high void in mixture regions in spite of attempts to increase the participating melt mass by the performed variations of conditions.

6 Conclusions: Guidelines for further Resolution on Open Issues

Major physical mechanisms have been elaborated which show a high potential to inhibit the development of an energetic steam explosion under reactor conditions. However, material effects could not be found as generally excluding such explosions with prototypic material. Especially, breakup of corium melt into relatively small drops and solidification appear as decisive material effects.

Understanding of breakup into much larger drops with alumina is not yet clearly provided. Stronger deceleration effects with the melt of much smaller density appear to play a major role. Only by assuming such effects in the model (adapting the dynamics of the melt jet in water) produced comparable, for KROTOS still not sufficient results of breakup. Assuming

the present modelling at least as approximately adequate for high density melts as corium may be sufficient for reactor applications. Nevertheless, further clarification should be attempted on the differences and the applicability for corium needs further checking.

The new KROTOS experiments will especially address the clarification part, due to the relation to the earlier experiments (influence of inflow conditions) and more detailed inspection methods on premixing (X-ray). The continued TROI experiments with larger and pronounced 3D mixtures emphasize checking of various scenarios on the breakup and mixing. Rather, support and understanding of a general weakness of explosions with corium should be envisaged than focusing on composition effects on spontaneous occurrence or strength of explosions. It has been outlined that there exists no clear understanding of the different explosivity detected, but that this may not be necessary to be clarified in detail. If there would be such strong differences between 80/20 and 70/30-UO₂-ZrO₂ compositions that they could become critical issues for the safety considerations, this could be hardly managed. The present results are still in a range of explosion strengths considered as relatively weak.

From both experiments, KROTOS and TROI, more information about the structure of premixtures is expected in order to support the model checks and improvements. This concerns especially the drop sizes and the void established in the mixture region. The SERENA phase 1 results have clearly indicated the role of void as a crucial area with remaining deficits in modelling (overestimation of void), but also with the nevertheless strong trend to a high void acting strongly against development of energetic explosions. Even with adaptations to reduce the void and better simulate FARO L-28, as e.g. performed with IKEMIX [14], strong trends to high void remained in the reactor calculations. This was even the case with relatively lean mixtures. Solidification should be an important effect for inhibiting energetic explosions with corium, even if breakup into relatively small drops of melt determines already essentially such inhibiting effects. Further clarification about the role of solidification is expected from the planned KROTOS/PLINIUS experiment with melt superheat maximized by lowering the corium liquidus temperature (by adding fission products and steel oxides) and heating the corium melt to the highest achievable temperature in the KROTOS furnace [6].

To resolve the identified uncertainties on the premixing flow patterns, especially on the void and melt distribution, and on the material influence on the steam explosion energetics a limited number of well-designed tests with advanced instrumentation reflecting a large spectrum of ex-vessel conditions and complementary analytical work to bring the code capabilities to a sufficient level for use in reactor case analyses is needed. This does not mean clarification of every detail but elaboration and assurance about the major limiting effects.

Therefore, SERENA phase 2 was proposed, with the following objectives:

- Provide experimental data to clarify the nature of prototypic material having mild steam explosion characteristics.
- Provide innovative experimental data for computer code validation, including spatial distribution of fuel and void during premixing and at the time of explosion, and explosion dynamics for the validation of explosion models. This would certainly minimize the scatter of computer code predictions.
- Provide experimental data for the steam explosion in more reactor-like situations to verify the geometrical extrapolation capabilities of the codes.

These goals can be achieved by using the complementary features of KROTOS [2] and TROI [3] corium facilities including fitness for purpose oriented analytical activities. The planned

SARNET FCI activities will be closely connected to the proposed activities in SERENA phase 2.

Based on these experimental and validation works, the improved codes will also have to be checked by applications to reactor scenarios. The explanation of effects under these conditions must be continued, especially for checking whether the inhibiting effects emphasized are strong enough to allow clear conclusions about safety. The present status from applications to reactor scenarios is, as given by the above examples, that significantly less critical results were obtained than from earlier evaluations, even without taking into account solidification effects. Major reasons for this are limitations to explosion strength from limited melt breakup under realistic scenario choice, thus limited mass in mixture (spatial size of mixture as well as melt volume parts), resulting size range of melt drops and produced void in mixture.

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