Material Properties Influence on Steam Explosion Efficiency:
Prototypic versus Simulant Melts,
Eutectic versus Non-Eutectic Melts

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ABSTRACT

A steam explosion may occur during a severe nuclear reactor accident if the molten core comes into contact with the coolant water. A strong enough steam explosion in a nuclear power plant could jeopardize the containment integrity and so lead to a direct release of radioactive material to the environment. Details of processes taking place prior and during the steam explosion have been experimentally studied for a number of years with adjunct efforts in modelling these processes to address the scaling of these experiments.

Steam explosion experiments have shown that there are important differences of behaviour between simulant and prototypical melts, and that also at prototypical melts the fuel coolant interactions depend on the composition of the corium. In experiments with prototypic materials no spontaneous steam explosions occurred (except with an eutectic composition), whereas with simulant materials the steam explosions were triggered spontaneously. The energy conversion ratio of steam explosions with prototypic melts is at least one order of magnitude lower than the energy conversion ratio of steam explosions with simulant melts. Although the different behaviour of prototypic and simulant melts has been known for a number of years, there is no reliable explanation for these differences. Consequently it is not possible to reliably estimate whether corium would behave so non-explosive also in reactor conditions, where the mass of poured melt is nearly three orders of magnitude larger than in experimental conditions. An even more fascinating material effect was observed recently at corium experiments with eutectic and non-eutectic compositions. It turned out that eutectic corium always exploded spontaneously, whereas non-eutectic corium never exploded spontaneously.

In the paper, a possible explanation of both material effects (prototypic/simulant melts, eutectic/non-eutectic corium) on the steam explosion is provided. A model for the calculation of the temperature and material conditions in the melt droplets during premixing was developed, and a number of calculations for the most representative melt materials, varying the premixing conditions, were performed. The calculation results show significant differences in droplets behaviour between prototypic and simulant melts and also between eutectic and non-eutectic corium, based on which the material effect can be explained.

1 INTRODUCTION

A steam explosion is a fuel-coolant interaction process where the heat transfer from the melt to water is so intense and rapid that the timescale for heat transfer is shorter than the timescale for pressure relief. This can lead to the formation of shock waves and production of missiles that may threaten surrounding structures. Details of processes taking place prior and
during the steam explosion have been experimentally studied for a number of years with adjunct efforts in modelling these processes to address the scaling of these experiments. Most attention is given to the study of steam explosions in nuclear power plants, since a steam explosion may occur during a severe accident if the molten core comes into contact with the coolant water [1, 2].

Steam explosion experiments showed that there is a large influence of melt properties on the steam explosion potential and the steam explosion efficiency. In experiments with prototypic materials (UO$_2$ + ZrO$_2$ +...) no spontaneous steam explosions occurred (except with an eutectic composition), whereas with simulant materials (Al$_2$O$_3$, …) the steam explosions were triggered spontaneously. The energy conversion ratio of triggered steam explosions with prototypic melts (typically 0.1%; often only ~0.01%) is at least one order of magnitude lower than the energy conversion ratio in steam explosions with simulant melts (typically 1%; up to 19.5% in experiment STX019 performed with 20 kg Fe-Al termite in the ALPHA facility at JAERI, Japan) [3, 4, 5]. Although the different behaviour of prototypic and simulant melts has been known for a number of years, there is no reliable explanation for these differences. Consequently it is not possible to reliably estimate whether corium would behave so non-explosive also in reactor conditions, where the mass of poured melt is nearly three orders of magnitude larger than in experimental conditions.

An even more fascinating material effect was observed recently in the TROI facility at KAERI, Korea, where corium experiments with eutectic (70% UO$_2$ + 30% ZrO$_2$) and non-eutectic composition (80% UO$_2$ + 20% ZrO$_2$) were performed [6, 7]. It turned out that eutectic corium always exploded spontaneously, whereas non-eutectic corium never exploded spontaneously. The energy conversion ratio of the steam explosions with eutectic corium (up to 0.4%) was larger than at the triggered steam explosions with non-eutectic corium (~0.02%). These eutectic versus non-eutectic differences are still less understood than the differences between prototypic and simulant melts, since the thermo-physical properties of eutectic and non-eutectic corium are nearly the same (density, thermal conductivity, melting temperature, …). Due to the importance for nuclear safety, the material effect is being addressed in different national and international programs, like the 5.FP EU KROTOS/PLINIUS experiment at CEA, Cadarache, France, that we proposed, and the planned OECD SERENA 2 programme.

In the paper we provide a possible explanation of both material effects (prototypic/simulant melts, eutectic/non-eutectic corium) on the steam explosion, based on the calculated temperature and material conditions in the melt droplets during premixing. The temperature and material conditions in the melt droplets during premixing were calculated by our developed model, which is described in the next section.

2 MODEL DESCRIPTION

During premixing, the molten jet breaks up in melt droplets. Due to the high temperature of the melt droplets, a vapour film forms around the droplets and so heat is transferred from the melt to water by film boiling and radiation. The film boiling heat flux can be calculated by

\[ q_{\text{film}} = h_{\text{film}} (T_{\text{mel}} - T_{\text{water}}^\text{sat}), \]  

where \( h_{\text{film}} \) is the film boiling heat transfer coefficient, \( T_{\text{mel}} \) is the melt droplet surface temperature and \( T_{\text{water}}^\text{sat} \) is the water interface temperature, which equals to the water saturation temperature. The radiation heat flux can be calculated from
\[ q_{\text{rad}} = \sigma \frac{\varepsilon_{\text{melt}} \varepsilon_{\text{water}}}{\varepsilon_{\text{melt}} + \varepsilon_{\text{water}} - \varepsilon_{\text{melt}} \varepsilon_{\text{water}}} (T_{\text{melt}}^4 - T_{\text{water}}^4) \]  

(2)

where \( \sigma \) is the Stefan-Boltzmann constant, \( \varepsilon_{\text{melt}} \) and \( \varepsilon_{\text{water}} \) are the melt and water emissivities, and \( T_{\text{melt}} \) and \( T_{\text{water}} \) are the melt droplet surface temperature and the water bulk temperature. Typical values of the coefficients appearing in equations (1) and (2), obtained from MC3D premixing simulations [8], are presented in Table 1.

Table 1: Typical values of model coefficients and variables during premixing.

<table>
<thead>
<tr>
<th>Coefficient, Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film boiling heat transfer coefficient - ( h_{\text{film}} )</td>
<td>1000 W/m(^2).K</td>
</tr>
<tr>
<td>Melt emissivity - ( \varepsilon_{\text{melt}} )</td>
<td>0.79</td>
</tr>
<tr>
<td>Water emissivity - ( \varepsilon_{\text{water}} )</td>
<td>0.96</td>
</tr>
<tr>
<td>Water bulk temperature - ( T_{\text{water}} )</td>
<td>290 K</td>
</tr>
<tr>
<td>Water interface temperature - ( T_{\text{sat}} )</td>
<td>400 K</td>
</tr>
<tr>
<td>Melt droplet radius</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Stefan-Boltzmann constant - ( \sigma )</td>
<td>( 5.67 \times 10^{-8} ) W/m(^2).K(^4)</td>
</tr>
</tbody>
</table>

The heat transfer conditions during premixing are quite complex and it is difficult to calculate the heat transfer rates from the melt droplets to other phases in the pre-mixture, since they depend also on the phases distribution, which is not known a priori. To get an qualitative and quantitative impression about the heat transfer rates, on Figure 1 the typical film boiling and radiation heat transfer rates of a melt drop in premixing conditions, as listed in Table 1, are presented as a function of the melt drop surface temperature. We see that at higher temperatures the radiation heat transfer is much larger than the film boiling heat transfer.

![Figure 1: Film boiling and radiation heat transfer rate for a melt droplet in water as a function of the melt droplet surface temperature at conditions presented in Table 1.](image-url)
In this calculation we did not take into account the radiation between different melt droplets and the influence of void, both reducing the heat losses of melt droplets. For our comparative material effects study on the temperature and material conditions in the melt droplets it is not so important that the heat losses are calculated accurately, but mainly that the applied heat losses are of the right order of magnitude and that they are an appropriate function of the melt droplet surface temperature. Due to the large uncertainties we simplified our heat transfer model even more by taking the radiation heat transfer contribution into account with a reasonably increased film boiling heat transfer coefficient, which was set to $h_{\text{film}} = 2000 \, W / m^2 \, K$ and presents a united heat loss coefficient.

The temperature conditions in a melt droplet do not depend only on the heat transfer conditions on the droplet surface, but also on the melt flow conditions inside the melt droplet. Since the melt flow conditions inside the melt droplet are not known a priori, we decided to make two bounding assumptions, by which the real melt flow conditions are captured:

- Assumption 1: There is no melt flow in the droplet; consequently heat inside the droplet is transferred only by conduction.
- Assumption 2: The melt flow in the droplet is so intense that the convective mixing inside the droplet is perfect; consequently the temperature profile inside the droplet is constant.

2.1 Assumption 1: Heat Transferred only by Conduction

If heat inside the melt droplet is transferred only by conduction, the transient temperature profile inside the droplet can be calculated by

$$ \frac{\partial T_{\text{melt}}(r,t)}{\partial t} = \frac{\lambda_{\text{melt}}}{\rho_{\text{melt}} c_{\text{melt}}(T_{\text{melt}})} \nabla^2 T_{\text{melt}}(r,t), $$

(3)

where $T_{\text{melt}}$ is the melt temperature, which is a function of the radial position $r$ inside the droplet and the time $t$, $\rho_{\text{melt}}$ is the melt density (assumed constant), $\lambda_{\text{melt}}$ the melt thermal conductivity (assumed constant), and $c_{\text{melt}}$ is the melt specific heat, which is a function of temperature. To be able to treat also phase changes, an effective specific heat was introduced, defined as

$$ c_{\text{eff}}^{\text{melt}} = \frac{L_{\text{melt}}}{T_{\text{melt}}} + 0.5 \left( c_{\text{melt}}^{\text{solidus}} + c_{\text{melt}}^{\text{liquidus}} \right) \left( T_{\text{liquidus}} - T_{\text{solidus}} \right), $$

(4)

where $L_{\text{melt}}$ is the melt latent heat, $c_{\text{melt}}^{\text{solidus}}$ and $c_{\text{melt}}^{\text{liquidus}}$ are the melt solidus and liquidus specific heats, and $T_{\text{melt}}^{\text{solidus}}$ and $T_{\text{melt}}^{\text{liquidus}}$ are the melt solidus and liquidus temperatures. In case of an eutectic or a pure material, there is no solidification interval and so the solidus and liquidus temperatures are equal $T_{\text{solidus}} = T_{\text{liquidus}}$. To be able to treat numerically also such cases we defined also for eutectics and pure materials a small solidification interval.

The temperature profile in the melt droplet was calculated numerically with the finite differences method by discretizing equation (3). At the melt droplet surface the film boiling heat transfer boundary condition (1) was applied. The melt droplet was discretized in 50 radial slices, and the time integration was carried out over 10000 time steps. The calculation was performed using Microsoft Excel® software.
2.2 Assumption 2: Constant Temperature Profile

If the melt inside the droplet is well mixed, the temperature profile is constant and so the droplet melt temperature can be calculated by a simple energy balance equation

\[
\frac{dT_{\text{melt}}(t)}{dt} = \frac{q_{\text{film}} S_{\text{melt}}}{\rho_{\text{melt}} V_{\text{melt}} c_{\text{eff}}^{\text{melt}}(T_{\text{melt}})},
\]

where \( T_{\text{melt}} \) is the melt temperature, \( q_{\text{film}} \) is the film boiling heat flux calculated by (1), \( \rho_{\text{melt}} \) is the melt density, \( S_{\text{melt}} \) and \( V_{\text{melt}} \) are the melt droplet surface and volume, and \( c_{\text{eff}}^{\text{melt}} \) is the effective melt specific heat as defined in (4).

The temperature transient was calculated numerically with the finite differences method by discretizing equation (5). The time integration was carried out over 10000 time steps. The calculation was performed using Microsoft Excel© software.

3 CALCULATION RESULTS

The temperature and material conditions in the melt droplets during premixing were calculated for the most representative melt materials, varying the droplet diameter and in one case also the melt temperature. The calculated cases are presented in Table 2. Beside the classical melt compositions (corium UO\(_2\)/ZrO\(_2\) of non-eutectic 80/20 and eutectic 70/30 composition, alumina Al\(_2\)O\(_3\)) also the more complex and more realistic corium composition established for the KROTOS/PLINIUS experiment K-101 [8] (steel oxides and fission product oxides added) was considered. To find out whether it would make sense to increase in experiment K-101 the melt temperature from the planned 3100 K to the highest achievable temperature in the KROTOS furnace (~3350 K), where the risk of equipment failure is already significant, the calculations were performed also for the melt temperature 3350 K (case K-101-max in Table 2). For each considered case a parametric study, varying the melt droplet size in a reasonable range, was performed. The considered droplet radii were: 0.5 mm, 1.5 mm and 5 mm. The calculations were performed for both bounding assumptions of the melt flow conditions inside the melt droplet, which are described in Section 2, and result in a purely conductive heat transfer inside the melt droplet or a constant temperature profile inside the melt droplet.

It was assumed that in the steam explosion the solid part of the drop and the mushy zone with a solid content of more than 20% (arbitrary chosen based on viscosity data [9]) cannot participate. Based on this assumption the temperature of the melt below which the melt cannot participate in the steam explosion - either due to solidification or due to too high viscosity - was calculated (in Table 2 denoted with \( T_{\text{participating}} \)).
Table 2: Typical values of model coefficients and variables during premixing for the considered cases.

<table>
<thead>
<tr>
<th>Case and melt composition</th>
<th>UO$_2$/ZrO$_2$ 80/20</th>
<th>UO$_2$/ZrO$_2$ 70/30 Eutectic</th>
<th>Al$_2$O$_3$</th>
<th>K-101 UO$_2$/ZrO$_2$/SS+FP oxid</th>
<th>K-101-max UO$_2$/ZrO$_2$/SS+FP oxid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>8000</td>
<td>8000</td>
<td>2600</td>
<td>8000</td>
<td>8000</td>
</tr>
<tr>
<td>T$_{\text{liquidus}}$ (K)</td>
<td>2840</td>
<td>2820</td>
<td>2330</td>
<td>2640</td>
<td>2640</td>
</tr>
<tr>
<td>T$_{\text{solidus}}$ (K)</td>
<td>2820</td>
<td>2815</td>
<td>2325</td>
<td>1640</td>
<td>1640</td>
</tr>
<tr>
<td>T$_{\text{participating}}$ (K)</td>
<td>2836</td>
<td>2815</td>
<td>2325</td>
<td>2600</td>
<td>2600</td>
</tr>
<tr>
<td>c$_{\text{liquid}}$ (J/kg.K)</td>
<td>565</td>
<td>565</td>
<td>1420</td>
<td>651</td>
<td>651</td>
</tr>
<tr>
<td>c$_{\text{solid}}$ (J/kg.K)</td>
<td>445</td>
<td>445</td>
<td>1370</td>
<td>530</td>
<td>530</td>
</tr>
<tr>
<td>Latent heat (J/kg)</td>
<td>3.62E5</td>
<td>3.62E5</td>
<td>1.17E6</td>
<td>2.8E5</td>
<td>2.8E5</td>
</tr>
<tr>
<td>c$_{\text{effective}}$ (J/kg.K)</td>
<td>1.86E4</td>
<td>7.29E4</td>
<td>2.35E5</td>
<td>8.71E2</td>
<td>8.71E2</td>
</tr>
<tr>
<td>Therm. cond. (W/m.K)</td>
<td>2.88</td>
<td>2.88</td>
<td>8</td>
<td>2.88</td>
<td>2.88</td>
</tr>
<tr>
<td>T$_{\text{saturation}}$ (K)</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>T$_{\text{melt}}$ (K)</td>
<td>3100</td>
<td>3100</td>
<td>3100</td>
<td>3100</td>
<td>3350</td>
</tr>
</tbody>
</table>

3.1 Assumption 1: Heat Transferred only by Conduction

On Figures 2 to 6 the temperature profile inside the melt droplet and the volume fraction of the melt, which is participating in the steam explosion, are presented for cases listed in Table 2. At each case three droplet radii were considered (0.5 mm, 1.5 mm, 5 mm). The calculated transient duration was 0.5 s and on Figures 2 to 6 the corresponding snapshots at 20% (0.1 s), 40% (0.2 s), 60% (0.3 s), 80% (0.4 s) and 100% (0.5 s) of the calculated transient are shown. The temperature profile curves reflect how heat is extracted from the droplet. First the outer droplet layer is cooled, which during the cooling process grows and spreads towards the centre of the droplet. With larger droplets the droplet core remains hot also after 0.5 seconds of cooling (Figures 2-6 bottom), whereas with smaller droplets the droplet core starts to cool quite fast (Figures 2-6 top). With materials with a small solidification range the temperature profile breaks at the solidification point due to the large latent heat, which has to be extracted to cool the melt further, and consequently the temperature profile in the solid region is nearly linear (Figures 2 and 3) since there is enough time that in the outer layer nearly steady state conditions are reached. With materials with a large solidification range the temperature decreases also during the solidification process and so the temperature profile remains curved (Figures 5 and 6). With smaller drops the drop is completely frozen already after 0.5 seconds (Figures 2, 3, 5 and 6 top), whereas with larger drops the core remains liquid and only a crust is formed (Figures 2, 3, 5 and 6 bottom).

Based on the comparison of calculation results for different materials a number of interesting conclusions can be made. They are presented in Subsection 3.3 together for both considered assumptions of the melt flow inside the droplet.
Figure 2: Temperature profile and volume fraction of melt, participating in the steam explosion, at 0.1 (20%), 0.2 (40%), 0.3 (60%), 0.4 (80%) and 0.5 seconds (100%) for drop with radius 0.5 mm (top), 1.5 mm (middle) and 5 mm (bottom).
Figure 3: Temperature profile and volume fraction of melt, participating in the steam explosion, at 0.1 (20%), 0.2 (40%), 0.3 (60%), 0.4 (80%) and 0.5 seconds (100%) for drop with radius 0.5 mm (top), 1.5 mm (middle) and 5 mm (bottom).
Figure 4: Temperature profile and volume fraction of melt, participating in the explosion, at 0.1 (20%), 0.2 (40%), 0.3 (60%), 0.4 (80%) and 0.5 seconds (100%) for drop with radius 0.5 mm (top – no results since calculation diverged), 1.5 mm (middle) and 5 mm (bottom).
Figure 5: Temperature profile and volume fraction of melt, participating in the steam explosion, at 0.1 (20%), 0.2 (40%), 0.3 (60%), 0.4 (80%) and 0.5 seconds (100%) for drop with radius 0.5 mm (top), 1.5 mm (middle) and 5 mm (bottom).
Figure 6: Temperature profile and volume fraction of melt, participating in the steam explosion, at 0.1 (20%), 0.2 (40%), 0.3 (60%), 0.4 (80%) and 0.5 seconds (100%) for drop with radius 0.5 mm (top), 1.5 mm (middle) and 5 mm (bottom).
3.2 Assumption 2: Constant Temperature Profile

On Figure 7 the time evolution of the melt drop temperature and the volume fraction of the melt, which is participating in the steam explosion, are presented for cases listed in Table 2. In each case three droplet radii were considered (0.5 mm, 1.5 mm, 5 mm). The melt droplet temperature curves reflect the initial melt superheat and the solidification range. At a higher melt superheat a longer time is needed till solidification starts to occur. Therefore in cases Al$_2$O$_3$ and K-101-max, where the melt superheat is 770 K and 710 K (see Table 2), a much longer time is needed to reach the liquidus temperature than in cases 80/20 UO$_2$-ZrO$_2$ and K-101, where the melt super heat is only 260 K and 460 K (see Table 2). The volume fraction of the melt, which is participating in the steam explosion, is much larger with a eutectic or pure material than with an non-eutectic composition. With an eutectic or pure material we have some amount of pure liquid melt also during the phase transition, whereas with a non-eutectic during the phase transition a mushy phase is formed, which can not participate in the explosion if the solid content is too high.

Based on the comparison of calculation results for different materials, a number of interesting conclusions can be made. They are presented in Subsection 3.3 together for both considered assumptions of the melt flow inside the droplet.

3.3 Conclusions Based on Calculation Results

The comparison of calculation results for different materials reveals the following:

_Eutectic 70/30 UO$_2$-ZrO$_2$ versus non-eutectic 80/20 UO$_2$-ZrO$_2$:_

- “Only conduction” Assumption 1: The differences are negligible since the thickness of the phase transition layer is very thin due to the large temperature gradients (Figures 2 and 3). Consequently the same steam explosion efficiency can be expected.
- “Perfectly mixed” Assumption 2: The differences are significant (Figure 7) since with a eutectic we have some amount of pure liquid melt also during the phase transition, whereas with a non-eutectic during the phase transition a mushy phase is formed, which can not participate in the explosion if the solid content is too high. Consequently an increased steam explosion efficiency can be expected. This could be a possible explanation of the observed differences in TROI, KAERI, Korea, eutectic 70/30 UO$_2$-ZrO$_2$ vs. non-eutectic 80/20 UO$_2$-ZrO$_2$ experiments [6, 7].
- Since the reality is probably somewhere in-between both assumptions, a slightly increased steam explosion efficiency can be expected.

_Al$_2$O$_3$ versus 80/20 UO$_2$-ZrO$_2$:_

- There are significant differences in both assumptions.
- “Only conduction” Assumption 1: With 80/20 UO$_2$-ZrO$_2$ a crust is formed already before 0.1 s for all considered drop sizes (Figure 2), whereas with Al$_2$O$_3$ no crust is formed for the drop with radius 5 mm, and for the drop with radius 1.5 mm the crust starts to form only after 0.4 s (Figure 4). Consequently an increased steam explosion efficiency can be expected.
- “Perfectly mixed” Assumption 2: With Al$_2$O$_3$ the availability of melt, which can participate in the steam explosion, is 4 times longer than with 80/20 UO$_2$-ZrO$_2$ (Figure 7). Consequently an increased steam explosion efficiency can be expected.
Figure 7: Temperature time evolution and volume fraction of melt, participating in the steam explosion, for drop with radius 0.5 mm (top), 1.5 mm (middle) and 5 mm (bottom).
**K-101 versus 80/20 UO$_2$-ZrO$_2$:**

- “Only conduction” Assumption 1: There are no significant differences. For the drop with radius 1.5 mm the non-participating crust in K-101 is slightly thicker due to the large solidification range, which compensates the lower liquidus temperature (Figures 2 and 5). Consequently a slightly decreased steam explosion efficiency can be expected.

- “Perfectly mixed” Assumption 2: In K-101 the availability of melt, which can participate in the steam explosion, is due to the lower liquidus temperature about 50% longer than with 80/20 UO$_2$-ZrO$_2$ (Figure 7). Consequently an increased steam explosion efficiency can be expected.

- Since the reality is probably somewhere in-between, consequently a slightly increased steam explosion efficiency can be expected.

**K-101-max versus K-101:**

- There are significant differences in both assumptions.

- “Only-conduction” Assumption 1: In K-101-max the crust is formed at least 0.1 s later than in K-101. For the drop with radius 1.5 mm the thickness of the crust at K-101-max is after 0.5 s about one half of the crust thickness in K-101; before 0.5 s it is still less than one half (Figures 5 and 6). Consequently an increased steam explosion efficiency can be expected.

- “Perfectly mixed” Assumption 2: In K-101-max the availability of melt, which can participate in the steam explosion, is due to the larger melt superheat significantly longer than in K-101. The difference between K-101-max and K-101 is the same as between K-101 and 80/20 UO$_2$-ZrO$_2$ (Figure 7). Consequently an increased steam explosion efficiency can be expected.

### 4 CONCLUSIONS

Steam explosion experiments have shown that there are important differences of behaviour between simulant and prototypic melts (efficiency of steam explosions with prototypic melts is one order of magnitude lower than that of simulant melts), and that also with prototypic melts the fuel-coolant interactions depend on the composition of the corium (eutectic corium always exploded spontaneously, whereas non-eutectic corium never did). In this paper we provide a possible explanation of both material effects (prototypic versus simulant melts, eutectic versus non-eutectic corium) based on calculated temperature and material conditions in the melt droplets during premixing.

The calculated temperature and material conditions in the melt droplets differ significantly between prototypic and simulant melts, and also between eutectic a non-eutectic melts. The comparison between simulant Al$_2$O$_3$ and prototypic 80/20 UO$_2$-ZrO$_2$ calculations revealed that with the prototypic material a crust is formed on the droplet very soon (before 0.1 s for all considered drop sizes – radius 0.5 mm, 1.5 mm, 5 mm), whereas with the simulant material the crust forms much later (after 0.4 s for drop with radius 1.5 mm, no crust for drop with radius 5 mm till end of calculation 0.5 s). Since in addition prototypic melts form smaller drops (typical diameter 1.5 mm) during premixing than simulant Al$_2$O$_3$ (typical diameter 15 mm), which cool faster, the crust formation and solidification with prototypic melts is still more extensive in comparison to simulant melts. This extensive crust formation and solidification with prototypic melts during premixing could be the reason for the observed so low steam explosion efficiency of prototypic melts in comparison to simulant melts. Namely, in a steam explosion only the liquid melt content can participate and with prototypic
melts the solidification is extensive. Beside that also the remaining liquid droplet core can not participate in the steam explosion since it is trapped inside the thick solidified droplet crust.

The comparison between eutectic 70/30 UO$_2$-ZrO$_2$ and non-eutectic 80/20 UO$_2$-ZrO$_2$ calculations revealed that with a eutectic we have some amount of pure liquid melt also during the phase transition, whereas with a non-eutectic during the phase transition a mushy phase is formed, which can not participate in the explosion if the solid content is too high. This could be a possible explanation of the observed differences in the TROI, KAERI, Korea experiments performed with eutectic and non-eutectic corium.

In addition the influence of the melt temperature at the KROTOS/PLINIUS experiment K-101 on the temperature and material conditions in the droplets during premixing was analysed. The calculation results revealed that despite the more complex and more realistic corium composition in K-101 with a lower liquidus temperature, a significantly increased steam explosion efficiency in comparison to 80/20 UO$_2$-ZrO$_2$ can be expected only if the melt temperature will be sufficiently high. The K-101 corium has a lower liquidus temperature than 80/20 UO$_2$-ZrO$_2$, but since it has also a larger solidification range these differences compensate each other as long as the melt temperature is not sufficiently high. To be able to confirm or disprove the hypothesis, that the main reason for the observed low efficiency at steam explosion experiments with corium is corium droplet freezing during premixing, it is highly recommended that in the experiment K-101 the corium will be heated to the highest achievable temperature in the KROTOS furnace (~3350 K).

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