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Status of steam explosion understanding and modelling

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ABSTRACT

The main results of the major international activities related to fuel–coolant interactions (FCI) of the last 4-year period are presented and a summary of the knowledge gained regarding understanding and the improvements of modelling is provided. At first, the major outcomes of the OECD SERENA-2 program are presented and discussed. Important clarifications were obtained on the so-called material effect and on FCI code capabilities. We then summarise complementary analytical analyses and experimental programs performed in the frame of the SARNET community. The focus was put on the role of melt fragmentation and solidification, the impact of void on the intensity of an explosion and the triggering mechanisms. As a conclusion, tables summarising the improvements are proposed as well as research priorities.

1. Introduction

A steam explosion can occur in the course of the (pre)mixing of a hot liquid (molten fuel in a nuclear power plant (NPP) accident) within a cold volatile fluid (the coolant: water or sodium). The initial conditions of a steam explosion are then totally determined by the premixing process. The later depends itself largely on the configuration of the problem, i.e. geometry of the surrounding structures, length scale and melt-water contact conditions. However, the risk for the NPP safety is of course also largely determined by the strength of the structures containing the mixture. The steam explosion problem is then a three-step problem, where each step needs to be described with sufficient accuracy: premixing, explosion and mechanical effects.

The analytical preliminary phase of the OECD SERENA project (SERENA-1, 2002–2005 (Magallon et al., 2005; Meignen et al., 2005) concluded that an explosive interaction in the reactor pressure vessel should not bring a failure of the vessel. This conclusion was drawn based on the assessment of mechanical strength of the vessel against high internal pressure and shock waves (not accounting for potential effects of thermal loads and ageing). Indeed, the evaluated pressure loads from the calculations were rather high in general. This complemented the previous analyses that concluded on the low probability of risk related to so-called α-mode (e.g. Theofanous and Yuen, 1995). It is also recognised (based on experimental results) that the conditions of mixing in the vessel, involving low amounts of saturated water, are not favourable for the triggering of a steam explosion.

Nevertheless, the analyses of the in-vessel mixing should be continued in order to gain knowledge of the process of melt relocation regarding in particular melt oxidation and debris bed formation on the vessel bottom.

Such favourable conclusions regarding the risk related to in-vessel steam explosion could not be drawn for the ex-vessel situation, due to the weaker mechanical strength of concrete structures of the containment, and it was then recommended to pursue the risk assessment for this configuration. Nevertheless, the physics are exactly the same for both in- and ex-vessel situations.

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To describe steam explosion, the premixing is a crucial point that needs to be determined with sufficient accuracy. Unfortunately, the description of premixing is at least as challenging as the steam explosion description itself. If numerous improvements have been done these last years, particularly regarding the fragmentation and heat transfer processes, it was also found that, for the sake of realistic or even sufficient evaluations on a risk perspective, several additional effects had to be analysed and modelled. These are the solidification and the oxidation of the melt during the quenching process. The OECD SERENA-2 project was launched with the premise that the observed low "explosivity", i.e. ability to trigger an explosion, and low explosion efficiencies of previous corium-water steam explosions might be confirmed experimentally, i.e. generalised to different geometries and corium materials, and explained. This issue was firstly raised from the clear difference in behaviour between the KROTOS tests performed with alumina and those with a corium of composition 80%w UO_2/20%w ZrO_2 (Huhtiniemi et al., 2001). The question was then to clarify the intrinsic characteristics of corium having mild explosions compared to alumina. Different intrinsic characteristics, in particular density and solidification mechanisms, were supposed to be at the origin of the differences. The higher corium density should lead to a higher velocity difference between melt and water, then to smaller drops and thus to a faster solidification. Meanwhile, there were issues raised about the possible impact of eutectic/non eutectic nature of the material, non-eutectic compositions being thought to be less subject to spontaneous explosion with lower loads due to specific effects during solidification (Song et al., 2003). Thus, the mitigation through solidification was one of the major investigated issues. Also, due to the formation of small drops, corium-water premixings were suspected to be subject to a significant boiling and void build-up in contrast to alumina cases. Consequently, the second point of interest was related to void production, itself being identified as a major mitigating effect.

Regarding the theoretical modelling, 9 computer codes (or couples of codes for the premixing and explosion) were used in SERENA-1 (see Meignen et al., 2005 for a review), most of them being actively developed. The evaluations performed in the programme revealed that the codes were capable in principle to simulate fuel–coolant interaction in actual reactors, but it also showed the strong discrepancies in predictions, together with strong discrepancies in general understanding of important phenomena such as:

- jet fragmentation: coherent jet versus drops, tangential stripping versus Rayleigh–Taylor breakup;
- heat transfers: film boiling versus radiation;
- fine fragmentation: thermal versus hydrodynamic;
- pressurisation mechanism: micro-interaction concept versus direct vaporisation.

The codes numerical robustness was rather limited with difficulties to handle strong subcooling situations during premixing and rather coarse meshes were used in general, with 3D evaluations being very limited. These difficulties were probably at the origin of the decrease of the effort of developments. At the beginning of the period of the SARNET-2/SERENA-2 projects, only two codes, MC3D (developed by IRSN and CEA with the support of EDF) and JEMI/IDEMO (IKE with the support of GRS) among those used in SARNET and SERENA were still under important developments. Meanwhile, the needs appeared to be quite increasing, with several requests for the codes (MC3D in particular) from organisations that are not developing models (or participating to their financial support).

The main objectives of the SERENA-2 project (2008–2012), pictured in Fig. 1, gave a clear path for improvements of models. It should be highlighted that integral experiments as those performed in the SERENA-2 project cannot help to investigate the precise mechanisms involved in the steam explosion. These topics could find some attention only within the work performed in the frame of SARNET through the analysis of the calculated loads in analytical situations.

2. Major outcomes of SERENA-2

It is briefly recalled that the SERENA-2 experimental program was conducted under the auspices of the OECD with the major objective to investigate the role of corium properties on FCI. There were two series of six experiments conducted in the TROI (KAERI, Korea) and KROTOS (CEA, France) facilities. Four different melt compositions were investigated:

- UO_2/ZrO_2 with ~70/30% weight ratio;
- UO_2/ZrO_2 with ~80/20% weight ratio;
- $UO_2/ZrO_2/Zr$ with ~80/10/10% weight ratio;
- a mixture with (target composition) 73 wt% UO_2, 20.4 wt% ZrO_2, 4.1 wt% Fe_2O_3, 1.3 wt% Cr_2O_3, 0.3 wt% BaO, 0.8 wt% LaO, and 0.2 wt% SrO, supposed to be more prototypic of a real corium (but still fully oxidised), with the main characteristic to have a large interval between solidus and liquidus temperatures.

The KROTOS tests (Fig. 2) involved about 4 kg of melt (heated by direct radiation) delivered as a jet of 3 cm diameter into a pool of water with 1.1 m depth and 20 cm as diameter. The tests were then essentially one-dimensional. The pressure loads were measured using dynamical pressure transducers and the bottom impulses were evaluated with a force sensor. An important specificity was the X-ray system allowing a visualisation of the melt destabilisation and of the void during FCI. The TROI tests involved 15–20 kg of melt (cold crucible) delivered as a jet with a diameter of 5 cm in a pool with a diameter of 60 cm. The loads were also obtained from dynamical pressure transducers and a measurement of the impulse at the bottom.

The outcomes of SERENA-2 are not all favourable from a FCI risk assessment perspective but significant improvements in knowledge and modelling were obtained. A negative outcome is the fact that the explosion strengths (peak pressures, impulses) were higher than in previous experiments (with the same melt composition). This could be unclear in the TROI experiments at first sight due to the important "venting effect" due to the 2D geometry: the pressure wave strongly decreases while travelling radially in the water surrounding the melt-water mixture. Calculations with IDEMO (Fig. 3) and MC3D confirmed this effect, indicating that the pressure in the mixture could be much higher than that measured at the wall. It is likely that the recorded higher loads and efficiencies are due to improvements of the injection systems, allowing larger melt mass in interaction with water.

However, this venting effect is also a positive outcome of the program (although it could have been stated before) in the sense that it is now expected that, due to this effect, in the hypothetical case of a central vessel break, the loads on the containment structures might be admissible or at least might not lead to immediate failure of the containment integrity (at least for the studied PWR geometry).

Another positive outcome, from the point of view of the research efforts, was also the observation that the difference in explosion strengths owing to the eutectic nature of the corium was only of second order: UO_2/ZrO_2 compositions might be considered as a coherent family of compositions with no important discontinuous behaviour.

Nevertheless, the mitigating effect of solidification appeared quite clearly, although the actual mechanisms need further clarifi-