

## Coolability of Particulate or Porous Debris in Severe Accidents: Status and Remaining Uncertainties for In- and Ex-Vessel Scenarios

M. Bürger<sup>1</sup>, M. Buck<sup>1</sup>, G. Pohlner<sup>1</sup>, S. Rahman<sup>1</sup>, R. Kulenovic<sup>1</sup>,  
F. Fichot<sup>2</sup>, W.M. Ma<sup>3</sup>, J. Miettinen<sup>4</sup>, I. Lindholm<sup>4</sup>, K. Atkhen<sup>5</sup>

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1) IKE, University of Stuttgart (DE)    3) KTH, Stockholm (SE)    5) EdF, Paris (FR)  
2) IRSN, Cadarache (FR)    4) VTT, Espoo (FI)

This paper is dedicated to the memory of our dear friend Jaakko Miettinen  
who died unexpectedly in August 2008

### Summary

Particulate debris beds may form during different stages of a severe core melt accident. E.g., in the degrading hot core, due to thermal stresses during reflooding, in the lower plenum, by melt flow from the core into water in the lower head, and in the cavity, by melt flow out of a failing RPV into a wet cavity. Deep water pools in the cavity are used in Nordic BWRs as accident management measure aiming at particulate debris formation and coolability.

It has been elaborated in the joint work of SARNET WP11.1 that coolability of particulate debris, reflooding of hot debris as well as boil-off under decay heat (long-term coolability), is strongly favoured by 2D/3D effects in beds with non-homogeneous structure and shape. Especially water inflow from the sides and via bottom regions strongly improves coolability as compared to 1D situations with top flooding, mainly considered in earlier analyses.

Data from experiments performed in the SARNET frame (DEBRIS at IKE and STYX at VTT) and earlier ones (e.g. POMECA at KTH) have been used to validate key constitutive laws in 2D codes as WABE (IKE) and ICARE/CATHARE (IRSN), especially concerning flow friction and heat transfer. Major questions concern the need of explicit use of interfacial friction to adequately treat the various flow situations in a unified approach, as well as the adequate characterization of realistic debris composed of irregularly shaped particles of different sizes. Joint work has been supported by transfer of WABE to KTH and VTT.

Concerning realistic debris, the formation from breakup of melt jets in water is investigated in the DEFOR experiments at KTH. Present results indicate that porosities in the debris might be much higher than previously assumed, which would strongly support coolability. Calculations have been performed with IKEJET/IKEMIX describing jet breakup, mixing and settling of resulting particles. Models about debris bed formation and porosity are developed at KTH.

The application of the codes to reactor conditions aimed at analysing the potential for coolability in the different phases of a severe accident. Calculations have been performed with WABE (MEWA) implemented in ATHLET-CD and with ICARE/ICATHARE for degraded cores and debris beds in the lower plenum, under reflooding and boil-off. Ex-vessel situations have also been analysed. Strong effects of lateral water inflow and cooling by steam in hot areas have been demonstrated. In support, some typical basic configurations have been analysed, e.g. configurations with downcomers considered as possible AM measures. Melt pool formation or coolability of particulate debris is a major issue concerning melt retention in the core and the lower head. Present conclusions from those analyses for adequate modelling in ASTEC are outlined as well as remaining uncertainties. Continued joint actions to reach final solutions are discussed and continued as well as new experiments are considered in this frame.

## A. INTRODUCTION

### A.1 Major Issues and Tasks with Respect to Reactor Safety

A major issue is how to manage even severe accidents with core melting and to reach safely cooled states. Ex-vessel means as deep water pools in BWRs or core-catchers and external flooding of the RPV (Reactor Pressure Vessel) promise retention of melt largely independent of the in-vessel development, as ultimate measures. However, not considering the potential of coolability of corium states before ultimate situations neglects the possibility to get safe states before. This is especially problematic if ultimate measures can not guarantee coolability, i.e. for many existing PWRs.

Indeed, a non-coolable situation with a melt pool in the core occurred in the TMI-2 accident (Ref. [1]) and evolved into a finally cooled situation due to relocation of the melt into the lower head of the vessel, with formation of particulate debris and gaps between low-porosity material (cake) and the RPV wall. Under different conditions of melt relocation from the core in the form of jets into a water-filled lower head, more effective breakup into particles may be expected, as e.g. obtained in the FARO experiments [2], which favour coolability.

Certainly, this does not provide an ultimate measure for coolability and retention. The efficiency depends on the formation of sufficiently broken (surface) and solidified material, on paths of water access, size and shape of debris bed, system pressure, etc. Thus, how can one draw conclusions and gain benefit of such configurations?

From a safety point of view, it is important to evaluate chances of coolability during a severe accident. This is in line with the safety philosophy of defence-in-depth which requires to foresee and to analyse options to stop an accident at every stage. Ultimate measures are also included, but should not be taken as the only ones to be relied on. Mitigating measures and options, in- and ex-vessel, and their chances of success as well as adverse effects (e.g. steam explosions, oxidation of remaining Zirkaloy leading to hydrogen production) are to be analysed at every stage. Such analyses contribute to the overall assessment of the reliability of a plant.

Current PSA Level 2 studies show very large uncertainties about reflooding and coolability. Since a convincing PSA depends on the quality of the analytical tools used, the need of their improvement and validation is thus given. Due to the complex processes involved, it is important to identify strong effects in favour of coolability or against it. Only this can yield clear conclusions. Similarly, a focus on controlling physics for specific issues is envisaged in the ROAAM method [3].

Indeed, such strong effects have been recently the subject of renewed interest and discussion. In earlier investigations on particulate or porous debris coolability, mainly 1D situations with top flooding have been considered (water pool above debris bed with lateral uniform and non permeable conditions). Spatially averaged, a homogeneous inflow of water from above results, against the upward steam flow. Some investigations with water fed from the bottom have also been carried out, which indicated a significant increase of the power which can be removed from the bed before reaching dryout [4]. However, conclusions have practically not been drawn, which point out a significantly improved coolability under realistic multidimensional conditions, due to this effect.

With boil-off under release of decay heat, starting from an initially water-filled bed, friction is decisive for the occurrence of dryout (dryout heat flux – DHF – as maximum cross-sectional heat flux). It was identified that friction laws adapted to top flooding, as the description of Reed [5], yielded significantly too low DHF values for bottom inflow driven by a lateral water column [4]. Missing interfacial water/steam friction effects in the model are a possible cause. Interfacial friction decreases DHF for top flooding (counter-current flow of water and steam) but increases it for bottom flooding (co-current flow). Then, a unified approach requires an explicit interfacial friction term accounting for this difference.

With top flooding, a critical condition of departure from steady states is reached already by slightly increased power, beyond a final steady state with still significant water content

everywhere in the bed. Continuous boil-off results. This may be understood by a strong increase of friction between liquid flow and particles with decreasing liquid content. Then, water inflow from top is strongly hindered in the upmost region with accumulated steam. The water deficit progresses slowly downwards, finally reaching in the limit state the bottom and producing there a first dry spot.

In contrast, bottom flooding tends to yield a first dry spot in the upmost region, since the water flows at bottom into a water-rich region and favoured by co-current flow with steam. Then, the formation of dry zones at top occurs essentially by the accumulation of steam. Such upper dry zones may still be coolable in the steam flow from lower regions. Then, the DHF fails as coolability criterion and continued analyses including extension and heat-up of dry zones are required, with the key question whether such dry zones can be stabilized.

Higher friction than with spherical particles of uniform size is expected with prototypic mixtures of irregularly shaped particles of different sizes. Reduced porosity is in principle obtained by smaller particles in the free volume between larger ones, while the irregular shape counteracts. The local mixture of particles also depends on the process of bed formation, i.e. breakup of material and settling as bed.

Additional problems of coolability arise if initially still hot debris (even if composed of solidified particles) is assumed, as expected in most scenarios. The case of a quenched, water-filled bed has usually been analysed, addressing limits of coolability with respect to decay heat removal, i.e. long-term coolability. However, quenching of hot material is a first problem, e.g. with reflooding of a hot, even partly molten core or quenching of a dry bed of hot particles formed by settling of collapsed fuel rods or particles from breakup of melt jets flowing in the lower head of the RPV or into a water-filled cavity. Again, an adequate analysis must take into account multi-dimensional effects. The critical point here is that quenching competes with heat-up due to decay heat and the possible oxidation of remaining Zr.

## A.2 Structure of Joint Work in SARNET WP11.1

The above status was the starting point for the WP11.1 works in SARNET and defined the specific tasks and joint work organized. As major lines of work may be considered:

1. Identification of realistic debris: debris bed formation.
2. Clarification about key constitutive laws and effects determining coolability.
3. Influence of 2D effects determining coolability in reactor scenarios.
4. Conclusions on adequate modelling in ASTEC.

With respect to 1. and 2., experiments are performed by the participants in WP11.1:

- DEFOR (KTH): Especially, particulate debris formation from breakup of melt jets flowing into a water pool is addressed. Particle sizes, local mixtures of particles (mean particle size) and porosity, bed shape and non-homogeneous structure are major results characterizing the debris.
- DEBRIS (IKE): The emphasis is on constitutive laws (friction, heat transfer) under boil-off and quenching conditions, with top and bottom flooding. A stepwise approach to realistic debris is under way: mixtures of spheres of different sizes, non-spherical particles, debris from breakup experiments, e.g. from PREMIX, FZK. Specific explorations on 2D effects (downcomer structures) are also foreseen.
- STYX (VTT): Experiments with particle mixtures (alumina sand fractions) considered to approach the FARO debris have been performed under boil-off conditions with top flooding. They aim to qualify the SAM measure of debris bed formation and cooling in an ex-vessel deep water pool used in Olkiluoto 1, 2. Emphasis in previous SARNET work was on analysis of earlier experiments. New experiments have been discussed.
- POMEKO (KTH): Analyses of earlier experiments and related scenarios have been performed, with emphasis on downcomers. New experiments have been discussed.
- SILFIDE (EdF): 2D under boil-off. No new experiments. Earlier results published in NED special issue Oct. 2006 [6].

- Quenching experiments are planned at IRSN, with emphasis on multidimensional effects, especially of sideways water inflow into hot particulate debris.

The constitutive laws for friction and heat transfer are being clarified based on the experimental results and joint calculations on the experiments and reactor scenarios. This includes clarification about realistic debris compositions, e.g. about laws for particulate debris composed of particles with different sizes (size distribution), realistic mixing, resulting porosities, and is strongly related to the process of particulate debris formation.

Major analytical tools at present are ICARE/CATHARE developed by IRSN and WABE-2D and MEWA-2D (IKE) modules of ATHLET-CD. WABE has been transferred to KTH and VTT for applications and joint clarification and code improvement work. The final aim in the frame of SARNET is to propose a simpler but adequate modelling for ASTEC. This includes the identification of essential physical processes, the possible simplifications and the level of detail which will be necessary to accurately represent the phenomena.

Partners have performed different work on validation and applications according to their interest. IRSN emphasized quenching of in-vessel states, especially of a degraded, hot core. KTH concentrated on particulate debris formation and multidimensional cooling with bed heterogeneities, in boil-off mode. Validation work was mainly related to POMECO experiments and comparison with WABE calculations. VTT analysed STYX results by use of WABE, with emphasis on particle mixtures and boil-off of a top-fed bed. Checking of effects of the heating method (heating wires) required 2D modelling. Applications to BWR (Olkiluoto) were envisaged. IKE was involved in boil-off as well as quenching analyses, with emphasis on multidimensional behaviour but also the constitutive laws required in the multidimensional codes.

It has continuously been attempted to combine the different works and draw conclusions. As such an attempt and an extended international partnership, the NED special issue Vol. 236 (19-21) has been finalised in 2006.

As follows, specific contributions from these works will be outlined in some detail and the status reached will be summarized. This is finally extended by specifically considering the knowledge reached about coolability in the different phases of a severe accident with core melting. This includes considerations about remaining uncertainties as well as modelling requirements and options for ASTEC.

## **B. DEBRIS BED FORMATION**

As mentioned in the introduction, debris beds may form at different stages of a severe accident: By collapse of hot fuel rods in the core (in case of reflooding), by interaction of a corium molten jet in the water-filled lower plenum or by interaction of corium with water in the reactor pit (in case of vessel failure). In this WP, the debris resulting from melt/water interaction have been mainly studied, because of the interest of Sweden and Finland to demonstrate the coolability of such situations.

BWR plants in Sweden adopt cavity flooding as a cornerstone of their severe accident management strategy. The corium ejected to a highly-subcooled (~80-90K), deep (7-11m) water pool is expected to fragment, solidify, quench, settle, and finally form a debris bed. While a large number of studies were focused on molten fuel-coolant interactions (FCI), very little data and no significant insights are found on debris bed formation itself. This process includes jet breakup, solidification of resulting melt drops and settling of the particles forming a debris bed composed of locally mixed particles of different sizes, re-agglomerated parts, not fragmented liquid corium and more or less porous cakes. The largest experiments performed on breakup of jets of molten corium in water are the FARO experiments [2], [7]. They yielded results on jet breakup, but not on the structure of the debris bed formed.

### **B.1 Conclusions about Jet Breakup from FARO Experiments and Modelling**

Breakup of melt jets penetrating into water pools has been investigated experimentally with corium melt in the FARO experiments, using jets of 5-10 cm diameter with about 5 m/s initial penetration velocity into 1-2 m deep water. Up to 177 kg melt mass were released, mostly into

saturated water under different system pressures from 0.2 – 5 MPa. In cases with low system pressure (0.2 – 0.4 MPa) also subcooling of water of  $\sim 100$  K was chosen. A major outcome of these experiments was that significant breakup occurs with corium melt jets flowing under realistic conditions into water. Further, rather similar particle size distributions were obtained for the fragmented parts, in spite of the significant variation of conditions (see e.g. [2]). On the other hand, there were differences in the part of loose debris (taken for size distribution) and hard debris (cake).

Especially, the remarkably similar distribution of fragment sizes of the fragmented parts in L-28 and L-31 for the same conditions besides system pressure and especially subcooling indicates similar breakup processes. Measured penetration data (gained from thermocouples) show a significant decrease of penetration velocity in the range of 0.7 – 0.8 m below water level for both experiments, which may be taken as an indication of the coherent jet length during the first penetration. Then, complete breakup may be concluded in both cases and the cake part resulting in L-28 would be interpreted as a result of re-agglomeration or even coalescence of still liquid, not sufficiently quenched drops separated from the jet, not as coherent jet arrival at bottom. The result of completely broken material in L-31 could then be understood by more effective quenching due to the higher subcooling. Indeed, closer inspection of the debris in the FARO experiments shows that at least partly the cakes are constituted of agglomerated particles (see [2], although Magallon provides contrary conclusions there, requiring clarification).

Modelling of melt jet breakup and falling behaviour of resulting melt drops under feedback with steam production has been provided in the frame of premixing codes addressing FCI, e.g. with IKEJET/IKEMIX from IKE and MC3D from CEA and IRSN (e.g. [8], [9]). Validation was especially performed with respect to FARO experiments. This part is under continued joint work in the SERENA-2 OECD project and not considered further, here. Inclusion of solidification processes, especially in subcooled water, is also a major subject with respect to prevention of steam explosions by crust formation at the falling melt drops.

It remains to determine the bed structure and especially the bed porosity. While an approximate determination of characteristic particle sizes appears to be feasible with the above modelling and the experimental background and with already less surety also an evaluation of sufficiently crusted parts, this appears presently not possible concerning the bed structure and porosities. Experimental clarification about major trends and influences is required. For this purpose, the DEFOR experiments at KTH are currently performed [10].

## B.2 Results from DEFOR Experiments and Analysis about Breakup and Bed Structure

Six exploring experiments have been performed in the DEFOR-E series with eutectic CaO-B<sub>2</sub>O<sub>3</sub> melt (density 2500 kg/m<sup>3</sup>), one experiment with WO<sub>3</sub>-CaO melt (density 6500 kg/m<sup>3</sup>), released as 2 cm diameter jets into water (falling height in air of 60 cm, water depth varied between 40 and 65 cm). Initial melt temperatures were between 1200 °C and 1350 °C and initial water temperatures varied from 7 °C to 88 °C (0.1 MPa system pressure). First major results from DEFOR-E show very high measured porosities of 50-77%, in the single experiment with higher density WO<sub>3</sub>-CaO melt also 65%. Larger particles resulted with the low-density material CaO-B<sub>2</sub>O<sub>3</sub> than with the higher-density one (WO<sub>3</sub>-CaO), as shown in Fig. 1.

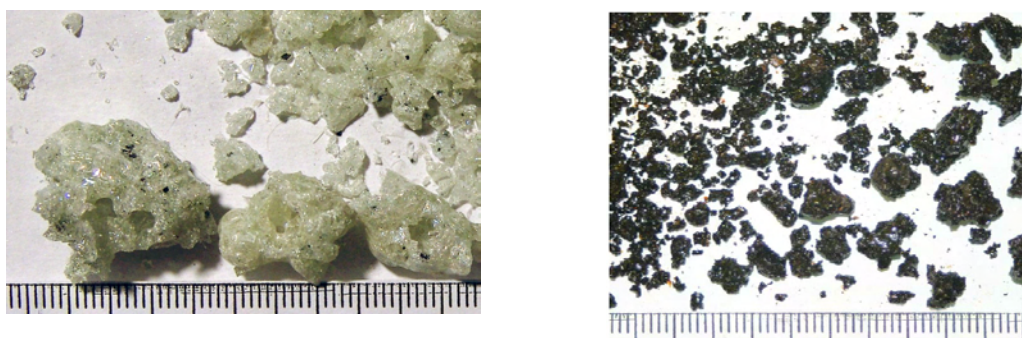


Fig.1: Comparison of debris from DEFOR: low-density (left) and higher density melt (right)

The different breakup features visible in Fig.2 remind of the difference between coarse breakup of the low-density alumina versus relatively fine of high-density corium in the KROTOS experiments [11]. IKEJET/IKEMIX calculations could only reproduce the latter results. It was assumed that strong deceleration combined with coarse breakup occurred close to the water surface in the case with alumina. Similar conclusions may be drawn from the DEFOR-E results in Fig.2, with particles spread over the whole cross-section in contrast to apparent breakup along a coherent jet, as well as from calculations with IKEJET/IKEMIX.

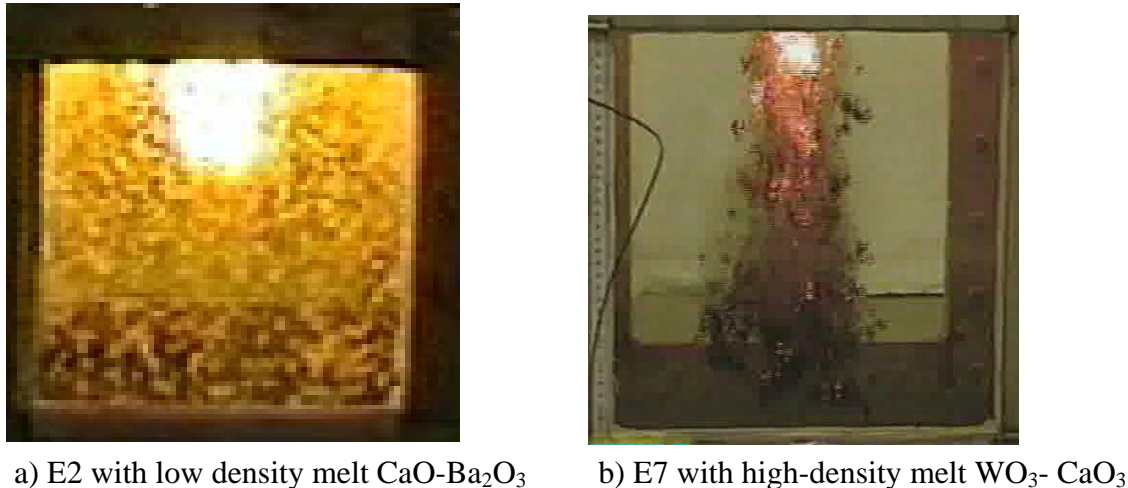


Fig. 2: Breakup behaviour in DEFOR-E

Overall, the DEFOR-E results suggest that beds formed from a fragmented high-temperature melt jet in water have a high porosity and heterogeneity. Both support coolability if no compact regions or cakes are built. Further, higher subcooling of the water yields higher porosities in the resulting debris beds.

For a more systematic examination of effects, a new series DEFOR-S was performed. Critical “snap-shot” experiments were envisaged to yield data under rather well-defined conditions for use in developing phenomenological models of debris packing. Melt materials with higher density have been used as more prototypical materials:  $\text{MnO-TiO}_2$ :  $4300 \text{ kg/m}^3$ ,  $\text{Bi}_2\text{O}_3\text{-TiO}_2$ :  $8400 \text{ kg/m}^3$ ,  $\text{WO}_3\text{-TiO}_2$ :  $6400 \text{ kg/m}^3$ ,  $\text{Bi}_2\text{O}_3\text{-WO}_3$ :  $7800 \text{ kg/m}^3$ . Melt temperatures were between  $980$  and  $1450 \text{ }^\circ\text{C}$ , melt superheats between  $0$  and  $167 \text{ }^\circ\text{C}$ .

As a major result, high bed porosities of  $60\text{--}70\%$  are obtained for high water subcooling of  $\sim 80 \text{ K}$ , independent of the simulant melt composition. Lower porosities of  $46$  and  $59\%$  are obtained with lower subcooling of  $25 \text{ K}$ . Partial agglomeration and cake formation is considered as cause. Nevertheless, these porosities are still higher than usually assumed for coolability analyses (rather  $30\text{--}40\%$ ). Uncertainties remain concerning parts of internal, closed porosity. Questions also remain about the influence of higher melt temperatures.

Solidification and material properties also influence the morphology of particles and by this the structure of debris beds. Non-spherical particles increase the porosity. With high subcooling, a strong trend exists towards irregular, rocky type particles, which partly explains the obtained robust results on high porosity, even independent of the melt material. Non-eutectic melts further favour the trend to irregular particles due to the influence on the solidification process, e.g. by rapid viscosity increase even in still liquid state. This effect can also be concluded from DEFOR-S results.

However, these effects appear not to be sufficient to explain high porosities of  $\sim 70\%$ . In separate experiments at KTH, significant differences in different kinds of bed production have been detected, with “cold” compact packing by shaking in a box yielding  $48\%$ , “cold” loose packing by pouring in air to a box yielding  $58\%$  and “hot” packing in DEFOR-S yielding  $70\%$ . These differences need further investigations. In parallel to the experimental program, addressing e.g. settling against rising steam flow, work has been started at KTH to model major features of settling and packing [12]. For the coolability analysis, it will also be important to consider a local particle diameter as an effective diameter comprising the effect

of the local mixture of particle sizes including irregular shapes. This has not yet been analysed in the DEFOR experiments.

### C. COOLABILITY OF DEBRIS BEDS: BASIC ASPECTS AND VALIDATION

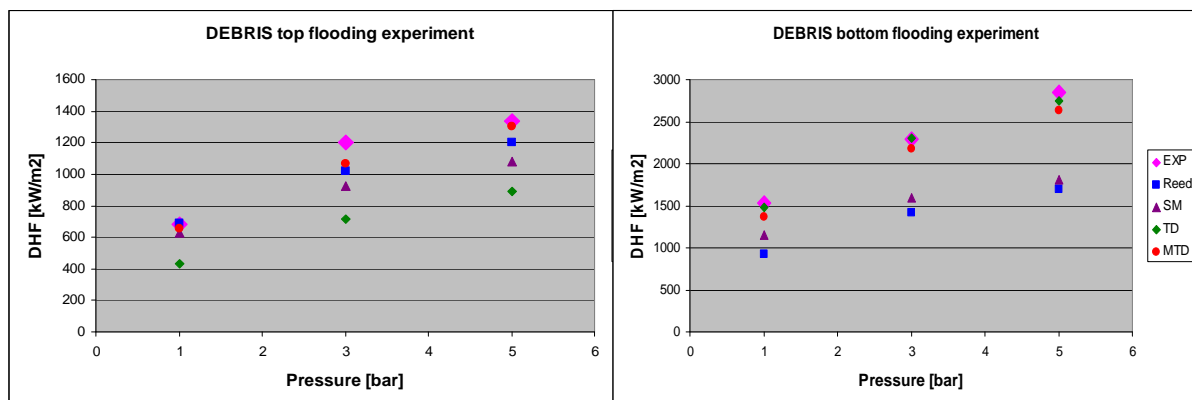
A significant part of basic joint work defining the tasks and steps to be done in SARNET has been published in the NED Special Issue Vol. 236 (19-21), 2006. Therefore, here only major conclusions and new results and insights reflecting the status reached are presented. The main objective concerning the basic laws was to further elaborate a unified description which can be used in the multi-dimensional codes considered as necessary to analyse adequately the coolability under reactor conditions.

#### C.1 Top and Bottom Flooding: DEBRIS Experiments

It has been shown in [13] by the measurement of pressure drops in axial segments of the debris bed that classical friction laws of Lipinski, Reed or Hu/Theofanous not including explicitly interfacial friction terms can in principle not reproduce these pressure drops in a large range of conditions. Even the qualitative behaviour can only be reproduced by including an interfacial friction term as e.g. in the Tung/Dhir (TD) and Schulenberg/Müller (SM) friction laws. However, a clear decision about different approaches for the friction laws could not be further reached on this basis of pressure measurements in extended series varying conditions. Difficulties of sufficiently precise measurements and sensitivity of the quasi-local pressure drops are to be mentioned, especially in the critical range corresponding to DHF.

Therefore, in addition to these attempts (further to be pursued), more global features are investigated. This concerns extended measurements of DHF for top and bottom flooding, the latter provided from a lateral water column of the height of the bed. While beds of spherical particles with the same size (3 and 6 mm) have been investigated in earlier series of the DEBRIS experiments [13], mixtures of spherical particles of 6, 3 and 2 mm have been considered in a subsequent series, then a bed of particles of irregular shapes (Chapter C.2).

In parallel, a further modification of the Tung/Dhir (TD) model has been introduced (MTD). Especially, the transitions between the flow patterns of bubbly, slug and annular flow have been modified to yield a more rapid transition towards slug and annular flows with smaller particle diameters, due to deficits detected for smaller particles and physical plausibility. Fig. 3 shows a comparison of WABE results applying this new MTD description and others with the experimental results of the poly-dispersed bed composed of 6/3/2 mm particles (mass composition: 50% 6 mm, 30% 3 mm, 20% 2 mm) for top and bottom flooding. The measured porosity in these beds was 0.36 and from measurements of single-phase pressure drop an effective particle diameter of 2.9 mm was derived, with this porosity. From the composition, a surface averaged value of 3.53 mm can be derived. From this result, the classical determination needs checking, as already indicated in [14], [15].



a) top flooding

b) bottom flooding

Fig. 3: Dryout heat flux calculations with WABE on DEBRIS experiments with poly-dispersed debris. Application of different friction laws (EXP: Experiment; SM: Schulenberg/Müller; TD: Tung/Dhir; MTD: Modified Tung/Dhir)

First dry spot appearance is in both cases taken as DHF criterion. For top flooding, a sufficiently long time has to be waited experimentally to check this, since dryout starts already with disappearance of steady solutions for still significant water contents in the bed and long times are required for dry spot formation at bottom. For bottom flooding, the first dry spot usually appears at top with high void tending to 100%.

As reference experiment, the classical Hofmann experiment [4] with top and bottom flooding for spherical particles of 3 mm diameter and porosity 0.4, at 1 bar system pressure, is considered in Table 1. A significant improvement with the new friction description (MTD) can be observed considering the aim of a unified description, here for both top and bottom flooding. This can also be concluded from the results for the poly-dispersed beds with variation of system pressure in Fig. 5. Further, the DEBRIS results confirm the strong increase (about twice) of the DHF with bottom versus top flooding also for the poly-dispersed debris.

	DHF [kW/m <sup>2</sup> ]	
	Top flooding	Bottom flooding
Experiment	<b>910</b>	<b>2088</b>
Reed	924	1250
SM	837	1636
TD	619	2070
MTD	919	1917

Table 1: Dryout heat flux calculations with different friction models on Hofmann top and bottom flooding experiments

An additional check was performed for bottom flooding by measuring the water inflow at bottom, which is driven by the lateral water column of same height as the bed against the bottom pressure developing in the bed. The comparison with calculations again confirms the MTD approach against Reed and SM.

## C.2 Mixed and Irregular Particles: STYX and DEBRIS Experiments

### C.2.1 STYX Experiments

In reality, mixtures of particles of different sizes and irregular shapes are to be expected, as e.g. obtained in the FARO and DEFOR experiments (see Chapter B). Specific features of the STYX experiments performed at VTT, Finland, are the broad particle size distribution based on the data from different international fragmentation tests, especially the FARO experiments, and the relatively large size of the bed (max depth 65 cm, diameter 30 cm). Alumina sands have been used as particles. Details about the experiment are given in [14].

The bed was considered to represent closely conditions of beds on the containment floor of Finnish and Swedish BWRs resulting from melt inflow into a deeply flooded cavity as a consequence of a RPV failure. Estimated for Finnish BWRs, a uniformly spread corium rubble could have a maximum depth of 60 cm. With such a uniformly spread bed, water inflow from the above water pool (top-fed bed) would determine the cooling mechanism.

The porosity of the STYX bed has been determined in a separate test bed as 0.37 and measurements of the single-phase pressure drop in this bed yielded an effective particle diameter of 0.8 mm by use of the classical Ergun laws (to be compared with the surface mean of 1.9 mm). Resistance heaters embedded in the gravel are applied to simulate decay heat. Nets of heating bands of dimension 6 mm vs. 1 mm and total length of 1.7 m per level are used in axial distance of 10 cm, i.e. 6 nets for the bed of 60 cm height. Variants have been checked (bed height, heater arrangement). However, the given data correspond to the final test series considered here. The temperature of the bed is measured (with 48 thermocouples) at various radial locations between each pair of heater elements. A local dryout is determined as continuous temperature rise in a thermocouple reading and taken as criterion for the DHF.

Fig. 4 shows DHF results of the final test series and calculations with WABE applying different friction laws. The low experimental values can be understood by the small effective particle diameter and the top flooding configuration. Calculations are shown for two variants

of conditions (porosity  $\epsilon$ , effective diameter  $D_p$ ), which may still lie in the range of uncertainties. With the first choice (Fig. 4 a)), the SM and Reed friction laws yield for the lower pressures very good agreement with the experimental data, while lying somewhat higher for the higher pressures (Reed ~ 25%, SM ~ 15%). In contrast, the MTD approach yields DHF ~ 20% lower than the experiments for the lower pressures and good agreement for the higher pressures. With the different choice of bed conditions (Fig. 4 b)), it still appears that Reed, SM and MTD friction correlations overall yield a similar agreement with the experiments. The different quality of predictions for the lower and higher pressures remains.

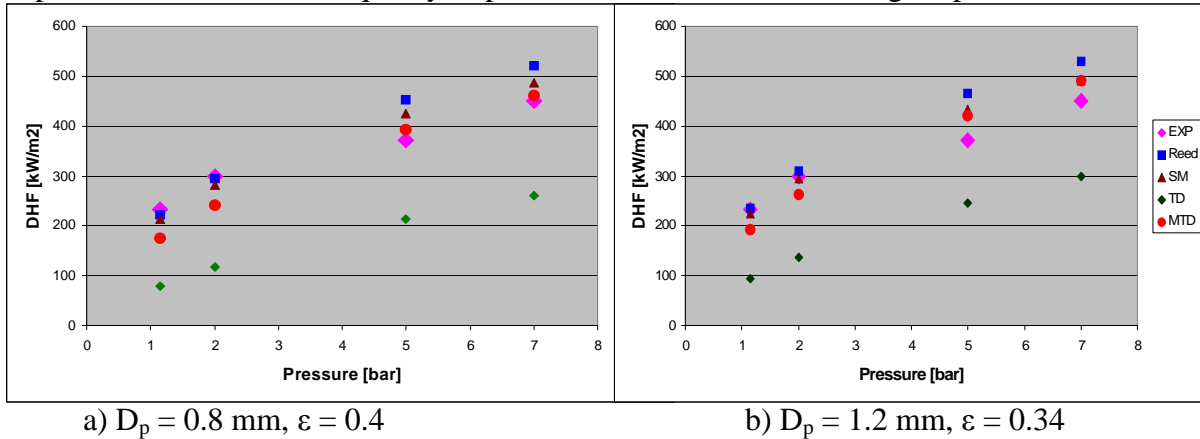


Fig. 4: STYX 2.1-2.4 experimental DHF vs. different model predictions (variants of friction laws and bed conditions)

As an example of the development towards dryout with failure of steady states, Fig. 5 shows the developing nose of saturation (due to loss of sufficient water supply from top) moving downwards until reaching zero saturation at bottom. Water, still in the bed, moves downwards and covers deficits of supply from top in lower regions, thus maintaining the profile there up to the time when the nose reaches the bottom. The nose development results from this loss of supply from top and loss to bottom regions. If the limiting power level is just surpassed, the loss of supply from top must result in a first dry zone at bottom, higher powers will yield first dry spots in higher regions. This result demonstrates the long time required to detect DHF by a dry zone, here after an increase of bed power of about 5%.

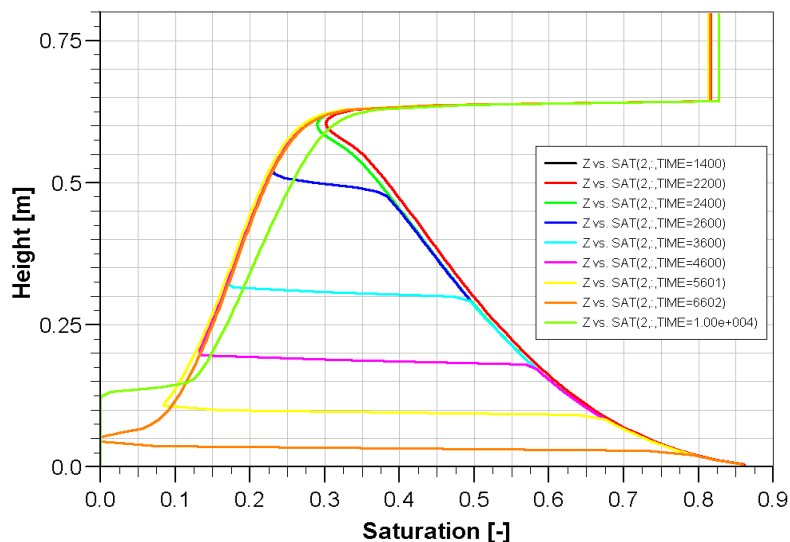


Fig. 5: WABE calculation on STYX-2.1 (here with the Reed model): Axial saturation profiles at different times. Last power level with steady profile is 590 kW/m<sup>3</sup> (1400 s -2200 s: red curve covers black). With power level 618 kW/m<sup>3</sup>, the saturation profile becomes transient (2400s). After 10000 s water up to 12 cm height is evaporated.

A subject of questioning concerning the STYX experiments is the heating method. Strongly localised heating around the heating bands, with enhanced power to yield a certain total power of uniform heating, may produce local voids and thus yield earlier dryout. Calculations

with WABE using approaches to the non-uniform heating were performed with axially and radially distributed heating rings in the cylindrical approach. However, they rather yielded some (small) increase in DHF, due to water downflow occurring between the heating bands. This is the reason why the first dry zone appears at top of the bed which is typical for bottom inflow of water. However, in the STYX experiments, the first dry zone was obtained at bottom, which can be taken as indication for a uniform behaviour, in spite of non-homogeneous heating. Further investigations are being performed jointly by VTT and IKE.

Further questions concern the structure of the debris bed itself and its prototypical features with respect to reactor scenarios. Firstly, instead of laterally uniform beds, heap-like shapes of beds are to be expected, as obtained also from the DEFOR experiments (Chapter B). This yields 2D/3D effects in favor of coolability. Secondly, the composition of the bed, although choosing a prototypical particle size distribution, is not considered as realistic with respect to local mixing and porosities. It makes a difference whether the bed is produced by intense mixing or by settling (Chapter B). Thus, the STYX experiments may be considered more as yielding results for basic investigations and code validation than results directly usable for evaluations on reactor scenarios. Correspondingly, new experiments in the STYX facility are now foreseen dealing with the important effects in this respect, especially multi-dimensional effects and questions of bed construction, also of the heating method.

### C.2.2 DEBRIS Experiments

Experiments with a mixture of irregularly shaped alumina particles from the PREMIX experiments [16], about 48 volume% between 2 and 5 mm in diameter, and spherical steel particles, 19% with 3 mm and 33% with 6 mm diameter, have also been performed in the DEBRIS facility. The measured porosity was 0.38. With this, single-phase pressure drop measurements yielded from the classical Ergun laws an effective particle diameter of 3.2 mm. DHF measurements were performed for the system pressures 1, 3 and 5 bar. Experimental results, compared with WABE calculations, are given in Table 2 for the top flooding case.

Pressure [bar]	DHF [kW/m <sup>2</sup> ]				
	Experiment	Reed	SM	TD	MTD
1	<b>792</b>	841	764	559	829
3	<b>1176</b>	1227	1104	911	1319
5	<b>1622</b>	1432	1283	1119	1602

Table 2: DHF results from WABE calculations compared with experimental results from DEBRIS for a mixture with irregular debris under top flooding

Again, Reed, SM and MTD friction laws show rather good agreement for top flooding. The DHF values of Reed and SM are somewhat too low for the higher pressure of 5 bar, while they were too high for the higher pressures in the STYX experiments. Thus, there remain uncertainties, here especially in the dependence on system pressure.

Experiments with bottom flooding from a lateral water column have also been performed with this bed type. However, since inductive heating yields only a power input into the steel particles, the heating power could not be increased here sufficiently to reach DHF, even not for 1 bar system pressure. For the latter, DHF values from WABE calculations are 1138 kW/m<sup>2</sup> with Reed, 1469 kW/m<sup>2</sup> with SM and 1733 kW/m<sup>2</sup> with MTD (1877 kW/m<sup>2</sup> with TD). The limit in the experiment (which did not yield DHF) corresponds to 1421 kW/m<sup>2</sup>. Thus, the DHF value with Reed friction law is too small, but a decision about SM or MTD approaches is not possible from these results. Further experiments without the present restriction are planned with scrap metal adapted to real debris via single phase pressure drops and allowing complete inductive power input.

### C.3 Quenching of Hot Debris: DEBRIS and Earlier Experiments

Quenching of hot particulate debris has only been investigated in few experiments, although quenching versus heat-up by decay heat mostly determines the coolability question in reactor scenarios. Analyses on experiments of Tutu et al. [17], with bottom injection of water in hot

particulate debris at fixed flow rates, have been performed by IKE with WABE [18] and IRSN with ICARE/CATHARE [19]. Experiments of Ginsberg et al [20] on top flooding of hot debris have also been analysed.

A major result with respect to bottom flooding was that cases of smaller water flows with resulting plateau-like heat and steam fluxes and cases of stronger water flows with resulting peaks of heat and steam fluxes could be distinguished, as shown for a case from [17] with highest initial particle temperature of 775 K in Fig. 6. The difference is roughly spoken related to a more rapid quenching than water progression (plateau) versus the opposite (peak). The latter behaviour is favoured by film boiling stability and means the establishment of an extended heat transfer (boiling) zone with extended heat release after breakdown of film boiling resulting in the peak.

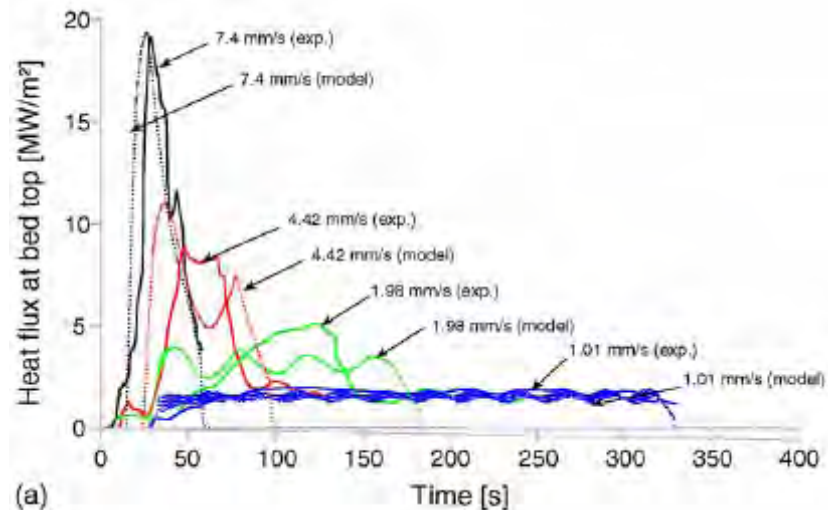


Fig. 6: Comparison of measured and calculated (WABE) heat fluxes at top for quenching experiments of Tutu et al [17] with initial particle temperature of 775 K and different, fixed superficial water injection velocities at bottom (spherical particles of 3.2 mm diameter, porosity 0.39, 1bar system pressure)

Additional calculations with a driving water column indicate that only the lowest inlet velocities ( $< 2$  mm/s) are realistic under such conditions and a column and bed height of about 40 cm. Thus, a thin quenching front due to slow progression of water in the bed yielding the plateau behaviour may be more typical and may also be valid for reactor conditions. This facilitates the heat transfer description. Details in the thin quenching zone are less important.

In DEBRIS experiments, top and bottom flooding have been investigated, the latter driven by a lateral water column. Results for a bed of 6 mm diameter spheres are given in [13]. Temperatures  $> 1000$  K were chosen in the top flooding case while only about 700 K with bottom flooding. Results of the latter case are reproduced in Fig.7 in comparison with WABE

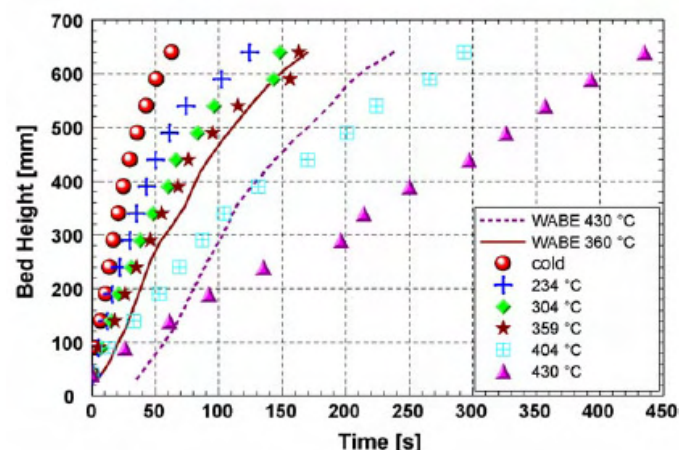


Fig. 7: Quench front propagation for bottom-flooding DEBRIS experiment at different initial bed temperatures

calculations. With the lower particle temperatures, higher quench front velocities, measured by the thermocouples, than the water velocities applied by Tutu et al are obtained, which can be understood by the smaller friction with the larger particles. However, a strong decrease of quench front velocities results above 670 K particle temperature. This could not be reproduced with the (old) WABE calculations and thus needs further analyses.

For further clarification of the quenching process, additional experiments are planned in the frame of the SARNET-2 programme. In addition to new DEBRIS experiments with top and bottom flooding (using also irregular debris) as well as specific 2D effects (lateral inflow via downcomers or lateral regions), larger experimental facilities will be used, as QUENCH (FZK) with formation of debris beds and the new PEARL experiments of IRSN. Fig. 8 gives a sketch of the latter, together with a pre-calculation with ICARE/CATHARE indicating emphasis on non-homogeneous bed structures and multi-dimensional flows. The calculation also indicates the importance of considering quenching and heat-up as competitive processes, the “dry” part of the bed being heated while the “wet” part is quenched.

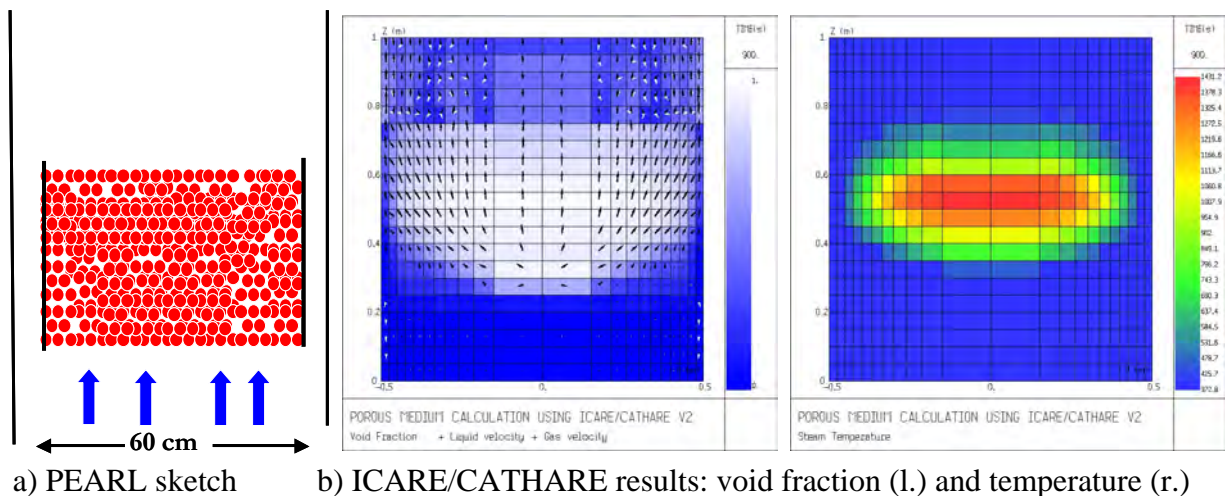


Fig. 8: Sketch of PEARL experiment at IRSN and pre-calculation of a possible transient configuration with heated debris bed by ICARE/CATHARE

#### C.4 Downcomers Yielding 2D Effects: POMEKO Experiments

POMEKO experiments at KTH [21] with downcomers considered as possible AM measures have been performed in relation to reactor safety concepts. Fig. 9 a) shows a sketch with a downcomer tube of 5 cm diameter in the centre of a cylindrical vessel, connected to a lower water-filled gap. The bed is composed of sands with mean particle size of 1 mm and porosity 0.36. Electric heaters are uniformly embedded in the bed to provide internal heating.

Calculations have been performed with WABE at KTH and IKE. A result (Fig. 9 b)) demonstrates the natural-circulation-driven cooling, due to lateral pressure differences between hydrostatic heads of pure water and water/steam mixture. The prediction of DHF is 346 kW/m<sup>2</sup>, only little higher than measured (331 kW/m<sup>2</sup>). Fig. 9 b) gives the calculation for 346 kW/m<sup>2</sup> and shows beginning dryout at the top of the bed. For comparison, the calculation for top flooding without downcomer yields dryout already with about 210 kW/m<sup>2</sup>, then with a first dry spot at bottom. These results have been obtained with the Reed friction law. MTD yields about the same results in this case with the small particles of 1 mm. This indicates a dominance of friction between fluids and particles. For 3 mm particles, with downcomer, MTD yields 1224 kW/m<sup>2</sup> and Reed 979 kW/m<sup>2</sup>, under otherwise the same conditions.

From the calculations, temperatures may rise significantly in dry zones, but not resulting in rapid growth of such zones, due to the energy required for evaporation. STYX experiments and the SILFIDE experiments [6] also indicated such effects. Further analyses are required. Local heating promotes local failures, but slow extension acts against early global failure.

Extended WABE calculations for the case with downcomer show further, that the dry region developing at top of the bed can be stabilized by cooling in the steam flow. Such stabilization

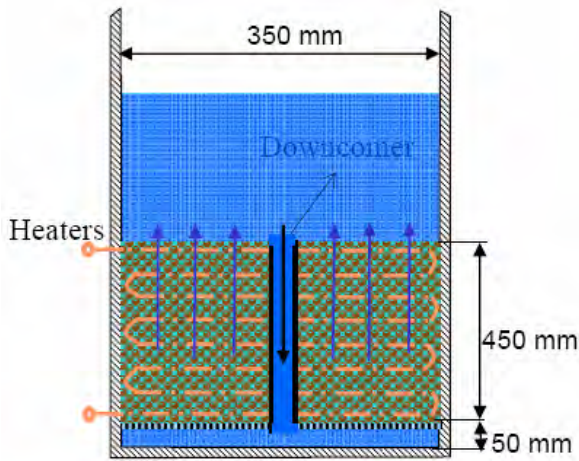
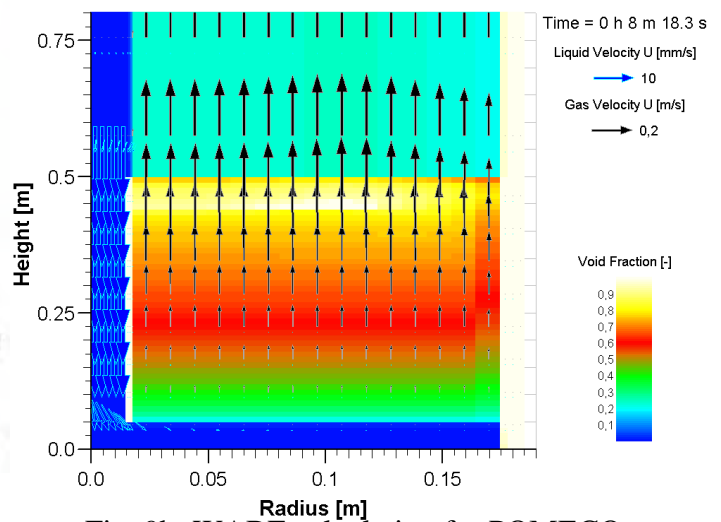


Fig. 9a: POMECO experiment

Fig. 9b: WABE calculation for POMECO  
(half bed section: axisymmetry)

is in the present case still reached with a power of 450 W/kg corresponding to 390 kW/m<sup>2</sup>. The maximum solid temperatures in this dry zone are then maintained at about 250 °C and no further extension of the dry zone is obtained. No coolable situation results with 500 W/kg. The temperatures in the dry zone increase beyond 1000 °C, and the dry zone itself grows downwards reaching about 10 cm height after about 50 minutes. I.e., even in this case of failure, the development towards complete failure takes quite some time. These stabilizing and retarding effects are considered as important for reactor safety, not only the detection of dry zone formation as an (insufficient) indication of failure of cooling.

## D. COOLABILITY OF DEBRIS BEDS IN REACTOR SCENARIOS

Calculations with WABE and ICARE/CATHARE have been performed for reactor scenarios to explore the applicability of the models and the importance of effects, especially the strong effects favouring coolability concluded from experiments and related analyses: lateral water inflow via bottom regions into heap-like beds driven by lateral water heads, further support by taking into account steam/water interfacial friction, non-homogeneities, gaps and downcomers, cooling of dry zones in steam flow from evaporating water penetrating below, extended time to yield failure even in non-coolable situations. In this chapter, results are presented for representative cases, analysing boil-off under decay heat starting with a water-filled bed (long-term coolability) as well as quenching of hot debris. In the latter case, the competition of quenching and heat-up decides about the success of the cooling measures.

### D.1 Boil-off Under Decay Heat with Non-homogeneous Debris

Non-homogeneous debris addresses here firstly beds with non-uniform shape, especially beds with lateral variation of height, as beds filling only a part in the lower head of the RPV or heap-like-beds in the cavity (see Fig. 10). Secondly, internal non-homogeneities are of interest, as paths with increased porosity, e.g. downcomer-like structures and gaps, but also cakes with significantly smaller porosity. As a third category, local compositions of different particles can be considered as local non-homogeneities. These are presently described by effective particle diameters and porosities.

Due to the laterally lower bed heights, it is expected that water can more easily penetrate at the sides, along the RPV wall. This flow is also driven by the lateral pressure differences caused by the radial increase of water content, due to less steam production with less height.

As above, a significant further increase of coolability is expected by taking into account steam/water interfacial friction, at least for cases with large particles (> 1 mm). As expected, significantly higher DHF values result than in 1D top flooding (Table 3). However, here interfacial friction (MTD) gives only a small increase, as compared to that in the 1D bottom

flooding case (Table 3). A reduction of the driving pressure in the lateral water-rich zone along the wall, due to the water flow there, seems to be the cause.

Choosing a gap along the wall in which the water can flow without significant friction losses, yields indeed a stronger effect of interfacial friction (MTD), as can be seen in Table 3. This underlines the importance of non-homogeneities with increased porosities and especially of gaps allowing access of water to bottom regions for coolability.

		Reed	MTD
DHF [MW/m <sup>2</sup> ]	1D top	1.61	1.73
	1D bottom	2.51	3.66
	2D no gap	2.28	2.45
	2D with gap	2.45	3.59

Table 3: Dryout heat fluxes related to a flat 2D debris bed with and without gap along the RPV wall with additional results for 1D top and bottom flooding. Different choice of friction laws: Reed and MTD.

Cases with heap-like bed configurations are considered in Fig. 10, again for the lower head of the RPV, but could also similarly (with plane instead of curved bottom) be taken for a bed produced in a water pool in the cavity (ex-vessel). In this case, the driving water head is mainly given by the height of the heap, not reduced by the resulting water flow. Correspondingly, a similar strong increase of DHF results as in the 1D bottom case between use of Reed and MTD friction laws, namely from 2.27 MW/m<sup>2</sup> to 3.62 MW/m<sup>2</sup>. It is finally to be remarked that different water flow pattern result from use of Reed or MTD (Figs. 10, 11).

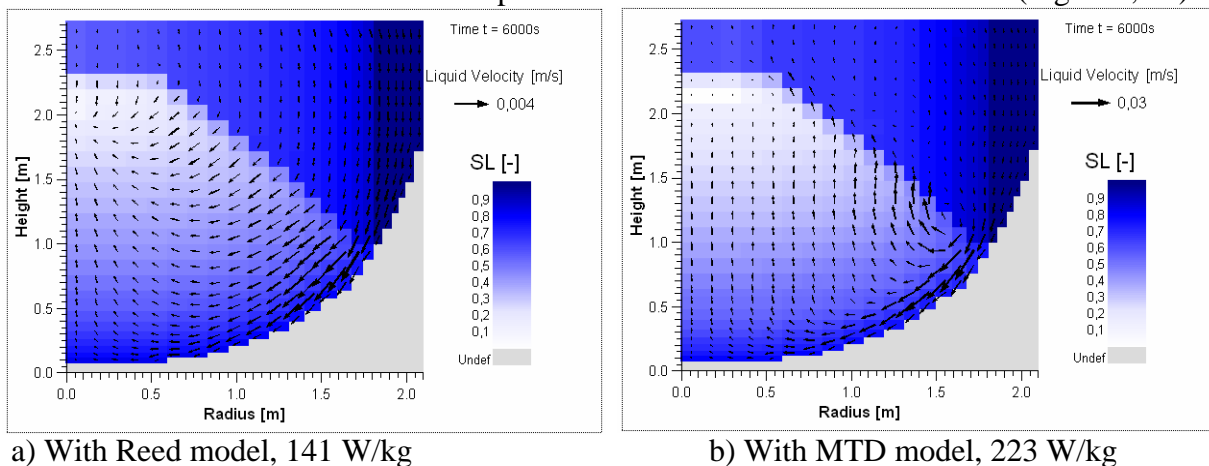


Fig. 10: WABE results on boil-off of initially water-filled bed in lower head of RPV: Distribution of saturation (liquid volume fraction of fluid). Bed data: Heap with maximum height of 2.32 m, water pool above up to 2.72m, mean particle diameter 3 mm, porosity 0.4. System pressure 5 bar.

Even with a dry zone, coolability can still be maintained by cooling in the steam flow, if water has access to lower bed regions. In the case of a particle bed in the lower head, it has been shown by calculations with WABE as well as ICARE/CATHARE (Refs. [18], [19]) that a much higher power than concluded from 1D top flooding and in general from dryout criteria still yields a coolable situation, even after formation of large dry zones. Further, significant time delay until reaching melting temperature has been obtained in cases with failure of cooling. Of course, cooling by steam becomes less effective with lower system pressure.

Fig. 11 shows an example of boil-off calculations with WABE (with the Reed model) for a bed of 2 mm particles, porosity 0.4, at 0.3 MPa system pressure. 200 W/kg is the limit power for which the decay heat can just be removed without dry zone. With 1D top flooding, this limit would be reached for 141 W/kg, showing again improvement by multi-dimensional effects. Coolable situations with dry zones still result up to 300 W/kg, as seen in Fig. 11.

Various cases with non-homogeneities inside the bed, also dense regions with low porosity (cakes), have been investigated to explore limits of coolability. Calculations have also been

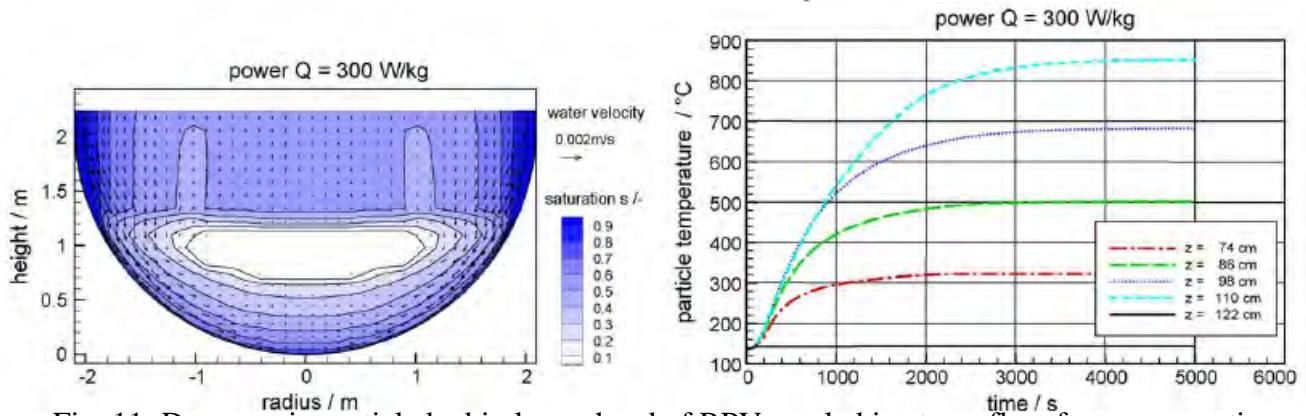


Fig. 11: Dry zone in particle bed in lower head of RPV, cooled in steam flow from evaporating water flowing into lower bed regions along the wall (left: distribution of water volume fraction, right: temperature development in centre of dry zone at different elevations  $z$  from bottom).

performed for large debris beds in a water-filled cavity, related to BWR, exploring effects of additional flow paths (e.g. via sump). Results are given in [18].

## D.2 Quenching of Hot Debris in Core and Lower Head

Fig. 12 shows results of calculations performed by IRSN with ICARE/CATHARE and by IKE with ATHLET-CD modules MEWA and VECO [22] on the quenching of a hot, dry and degraded core. A debris bed in the core is considered from the assumed collapse of damaged rods during quenching, similar to the TMI assumed evolution. The calculations show that quenching is reached by flooding via the downcomer, with water rising in lateral, intact core regions, then penetrating from the sides into the degraded parts, driven by the external water head. Again, the multi-dimensional aspects govern the success of cooling.

Time 400 s from start of reflood

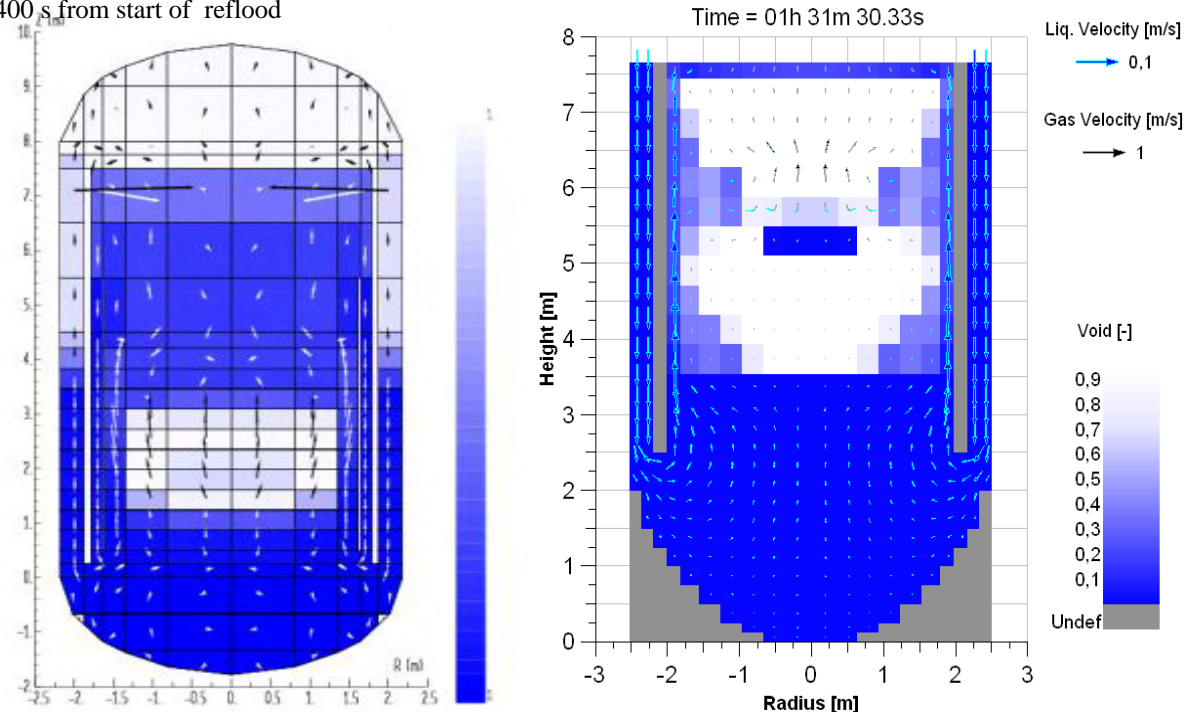


Fig. 12: ICARE/CATHARE (left) and ATHLET-CD-MEWA/VECO (right) calculations on reflooding of a hot core: Water distribution (saturation) in the RPV

In the IRSN case, an initially dry core heated up to maximum temperatures of  $\sim 1700$  K before onset of reflooding, in the IKE case, even a melt pool of  $\sim 20$  t has formed in an assumed particle bed of 1.5 mm diameter particles, still allowing quenching.

Flooding of hot debris in the lower head has also been investigated with WABE and ICARE/CATHARE (Refs. [18], [19]). Again, water inflow from the sides along the wall is decisive. Continued heat-up in the debris acts against quenching. In a case with 0.3 MPa system pressure, 2000 K heat-up in the dry zone was reached before finally cooling succeeds. The influence of model differences, e.g. about interfacial friction and vapour film boiling, has been investigated. However, continued analyses are required for final conclusions. The influence of oxidation as additional heat source has been analysed in calculations IRSN [19].

Related to considerations of Seiler [23], a calculation with WABE has been performed with a dense region of about 50 cm thickness in the centre, low porosity of 0.1 (still high compared to expected porosity in the cake [23]), a thick gap of about 10 cm (i.e. excluding analysis of CHF in the gap), particle diameter 2mm and porosity 0.4 in the upper bed assumed of 1m height above the cake, i.e. another  $\sim 60$  t of corium debris, much more than in TMI. A power of 200 W/kg has been applied, about twice that assumed by Seiler. An initial temperature of 1270 K has been assumed in the initially dry debris and a system pressure of 60 bar. In the gap, the same conditions as in the upper bed have been assumed.

Fig. 13 shows results of the temperatures and water velocity fields after 920 s and 2940 s. While the debris with higher porosity is rather rapidly quenched, with still a temporary increase of temperature up to about 1400 – 1500 K, the quenching of the cake region takes a much longer time and temperatures go beyond 1700 K at 2940 s, although in a reduced region in the cake. Obviously, steam cooling is here effective in the cake, at least avoiding rapid heat-up until melting. This enables slow quenching by water flowing around and partially into the low porosity area. The calculation gives a perspective to evaluate the principal counteraction of heat-up by decay heat and quenching, under conditions with additional handicaps.

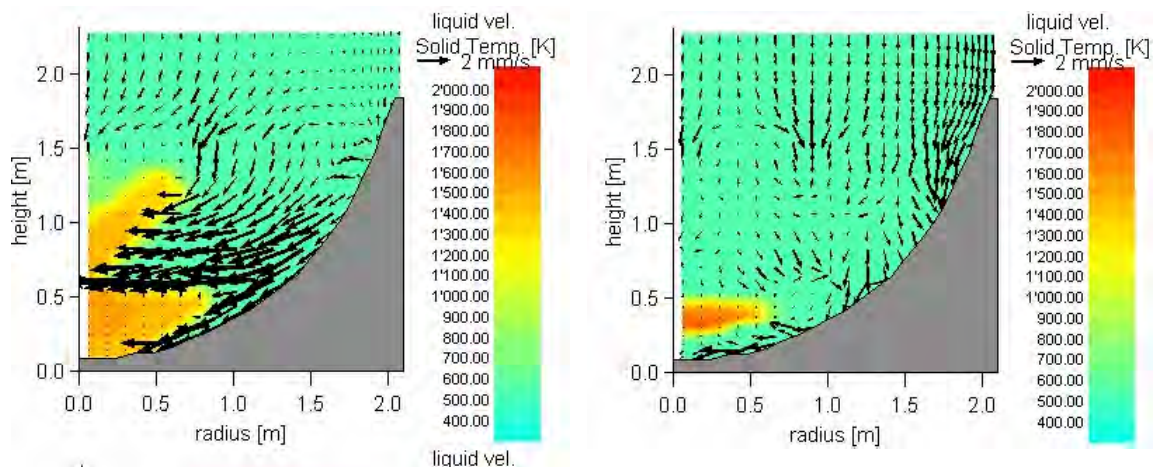


Fig. 13: WABE calculation on quenching of a debris bed in the lower head with a dense (cake) region at bottom and a gap between this and the RPV wall: solid temperatures and water flow field (left: after 920 s, right: after 2940 s).

## E. SUMMARY AND CONCLUSIONS: STATUS AND REMAINING TASKS ON COOLABILITY IN SEVERE ACCIDENTS

A status appears to be reached, which allows applications to an overall analysis of reactor safety issues about coolability. The overall requirements are that the essential features of accident progression are described sufficiently (in a risk oriented way, allowing conclusions about the issues) and that the dependence of accident progression on cooling measures and the coolability options at any stage are included. Concerning these requirements, the status and remaining uncertainties as well as perspectives for ASTEC are finally to be evaluated.

## E.1 Description of the whole course of the accident

The required evaluation has to be done with emphasis on major phases in the accident since all possible effects can not be described in detail. Thus, key physics in key situations is to be elaborated. Key phases and situations for in-vessel cooling concern reflooding of a degraded core and debris beds formed in water in the lower head.

### E.1.1 Cooling of Degraded Core

After boil-off of the core in the frame of an accident, heating and melting may produce a severely damaged, partly molten core with relocated material and broken parts (ruptured cladding and collapsed fuel). With water injection, even increased fragmentation of material, molten and solid, can be expected, the hot solid parts being broken because of high thermal stresses. As in TMI, this may yield formation of extended particulate debris in the core. The question is then whether continued quenching dominates or an increase of temperature occurs in parts of this debris, due to decay heat and limited water access. Steam flow may support cooling but also favours exothermic Zr oxidation. Melt pool formation in the core surrounded by corium crusts, as in TMI, even under water, may not always occur. The major question is how strong the trend to non-coolable situations and melt pool formation is. This can be explored with parametrically assumed configurations, further to be narrowed down by scenario evaluations and calculations on core degradation.

Such calculations can be performed with ATHLET-CD including the MEWA module (combined melting module MESOCO and cooling module WABE, allowing simultaneous and interacting melting and cooling by water, e.g. melt pool formation in a debris bed under water, with inflow of water) as well as with ICARE/CATHARE. Present results indicate that effective cooling even of large debris beds in the core composed of small particles results by the mechanism of Fig. 16, at least for the chosen high system pressure.

Continued core melting was then obtained only with  $< 0.8$  mm particle diameters. From this, melt pool formation in realistic debris with larger diameters may only be understood under dry conditions (dry phase in TMI), not under water. With lower system pressures of 2-3 bar, melting occurs for mean particle sizes of  $\sim 2-3$  mm. Since also extended debris regions with such small particles are not probable, it may be concluded in general that only strongly degraded cores with large melt pools developed in periods with a dry core can not be quenched any more by reflooding. Extensive melting and melt pool formation may occur in a mostly dry core with sufficient cooling from a water level in a low core range or just below the core. The present calculations then yield a strong tendency to pool formation.

The melt pool behaviour is the subsequent key issue. Cooling of a sufficiently large pool in the core appears not possible, according to present results. Then, lateral failure and outflow of melt is expected. This means that limited streams of melt (diameter and velocity) probably occur, rather than a massive flow. There is no driving melt head and outflow from first smaller lateral holes prevents formation of large ones, due to resulting decrease of the melt level. Such limited streams or jets of melt into water in the lower head are considered as favourable for breakup and particulate debris formation.

Further confirmation of the above conclusions from present results is required, concerning

- the stated coolability even of significantly degraded cores,
- the requirements for melt pool formation (dry core, water in low range for some time),
- non-coolability of large (limit?) melt pools in core by reflooding,
- lateral pool failure and outflow of melt in limited streams into water in lower head.

Such confirmation is to be pursued by extended joint analyses with the models. Support is also expected by additional experiments, such as extended QUENCH and LIVE experiments at FZK (concerning debris quenching as well as pool formation, cooling and failure) and the new PEARL experiments of IRSN on quenching of large non-uniform debris beds.

### E.1.2 Debris Coolability in the Lower Head

The TMI accident indicated that, even though coolability of the core is not attained, a coolable configuration may result from breakup of the melt in the water of the lower head

and/or gaps below cakes or partially molten regions. Limited melt streams as usually expected (see above) should further favour the formation of coolable debris. Of course, the options will be limited, depending on the mass of melt relocated and on re-establishment of water injection. Nevertheless, even chances of partial success or of success in a variety of scenarios are worth to be evaluated, especially if much better chances can be envisaged from basic physical analyses than based on earlier considerations.

As outlined in Chapter B, key processes concern in this key situation

- jet breakup,
- crust formation at resulting melt drops and settling of the fragments as debris bed,
- porosities and effective diameters as well as unfragmented parts (cakes) in the bed.

Models for these processes exist in MC3D at IRSN as well as in the frame of ATHLET-CD (VECO module with sub-modules IKEJET and IKEMIX for formation of debris and MEWA for the debris behaviour). Present results, supported by FARO and DEFOR experiments, indicate significant breakup already in water pools of 1-2 m depth, however uncertainties about cake formation (FARO-L28) with small subcooling of water, due to insufficient crust formation at melt drops, and about porosities (high porosities from DEFOR). The modelling on crust formation needs further validation. Determining porosities and effective diameters in prototypic debris needs further experimental support (DEFOR, LIVE, DEBRIS, STYX).

As for the core, quenching analyses have also been performed for the lower head in SARNET WP 11.1. In agreement, the result was a strongly favoured coolability by lateral, downwards inflow of water from the regions with smaller height and along the vessel wall. Further, steam up-flow through bed regions with larger height, produced from the water flowing in laterally, strongly supported the quenching process in the competition with heat-up, limiting the latter. These analyses are to be continued for reaching overall conclusions.

It has been shown with ICARE/CATHARE and WABE calculations for boil-off conditions, i.e. with initially water-filled beds at saturation temperature, that lateral downwards inflow of water in the lower head strongly supports coolability. It is again necessary to analyse the situations by means of validated 2D/3D codes. Only based on a spectrum of such analyses, generalised conclusions may be drawn. Even beyond dry zone development, caused by insufficient water access, coolable states may still be maintained for strongly increased power (or small porosity and particle diameters). With water access to bottom regions, steam flow from evaporating water can cool dry regions and keep temperatures below the melting point.

Again, further joint calculations for reactor scenarios have to be performed for further elaboration. Continued support is required also from more basic investigations, related to respective experiments. Such investigations concern realistic debris with local particle mixtures, effects of non-homogeneous bed structures and of 2D/3D bed configurations, especially providing variants of water access. The STYX (VTT), POMECO (KTH) and new DEBRIS (IKE) experiments deal with these aspects.

### **E.1.3 Debris Coolability in the Cavity**

A failure of the RPV after formation of a large melt pool in the lower head can also be expected to occur in the upper region of the pool. Then outflow of melt is limited as with a pool in the core. Penetrations at bottom may especially with BWRs yield failure there, but then also with a limited opening diameter and limited melt accumulation above. Streams of melt flowing through the bundle of control rod drives with BWRs are further splitted into partial streams. Nevertheless, thicker streams of higher velocity into water may occur, here.

In PWRs only water pools of small depth (~1-2 m) are possible, due to the narrow space. Melt breakup and cooling is then limited. In a deep water pool below the RPV in a BWR, complete breakup even of thicker melt jets as well as quenching of fragments until settling can be expected. In principle, the models and codes can be applied as for the lower head. Remaining uncertainties and tasks for confirming work concern breakup of thick melt jets (>10 cm diameter) in deep water pools (~10 m) at eventually higher entrance velocities (>5 m/s) and with possible high water subcooling. The latter favours the formation of particulate debris

beds by crust growth at the drops of melt. On the other hand, questions of steam explosions may be raised, also about formation of smaller particles which may hinder coolability.

## E.2 Proposals for ASTEC

As outlined, adequate modelling for the key processes and situations during a severe accident with core melting exists, including the major coolability issues. It has been shown that the models are applicable to key reactor scenarios. Further, integration of these models in an overall accident code exists, as indicated above. The major present task is further consolidation and validation, with respect to experiments but also joint detailed comparisons between the codes, emphasising the key situations and effects. From such analyses performed already partly in comparison with ICARE/CATHARE and ATHLET-CD in SARNET WP 11.1, the adequate modelling for ASTEC shall be proposed.

From the above analyses, it can presently be concluded:

- 2D/3D modelling of separated flow of water and steam in porous structures is required for adequate analysis of coolability, i.e. not to underestimate coolability strongly. At least the debris bed must be described with several zones, including the particle bed and denser cake regions. Additional zones corresponding to possible downcomer regions should be taken into account.
- Friction laws with explicit steam/water interfacial terms are required for a unified modelling of top and bottom flooding and in general various situations with different conditions of water inflow into the bed.
- Heat transfer can be described in a simplified way:
  - For boil-off, a thermal equilibrium approach is sufficient.
  - For quenching of hot debris with friction dominated, slow water progression (thin quenching zones), a rather simple heat transfer model may be sufficient, but with dependence on the temperature differences between particles and fluids.
- Heat-up and melting in dry zones simultaneously with quenching or cooling processes by water inflow and cooling flow of steam are to be enabled in order to describe the key competing processes deciding about coolability.
- Modelling of breakup of melt jets and settling of resulting fragments under solidification (crust formation) is required to gain a perspective on particulate debris formation depending on water depth, melt inflow conditions, system pressure, etc.
- Simplified models are, from IKEJET/IKEMIX experience, sufficient for breakup, as
  - 1D/cross-section jet model with wave-stripping model adapted to experiment,
  - simplified approach for the steam flow along the jet causing wave formation and stripping, with feedback to the surrounding mixture driving this flow.
- 2D model for mixing of melt with water under settling is required to describe void production and its influence on solidification as condition for particulate bed formation. A simplified model for crust growth on drops is implemented in IKEMIX.

As outlined, existing models are already simplified emphasising the key effects and exist already in the frame of severe accident codes as ATHLET-CD and ICARE/CATHARE. Applications have been performed dealing with sequences from core heat-up to core melting and continued melt pool formation or cooling under reflooding, melt release to water in the lower head, breakup, particulate debris formation, cooling and quenching or dry zone formation with heat-up and melting, even under reflooding. Further simplifications of these approaches for implementation and use in ASTEC may be checked more in detail depending on specific ASTEC requirements.

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