SESSION 2: Corium issues, Paper 2.9

Quenching of Melt Layers by Bottom Injection of Water in the COMET Core-Catcher Concept

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Summary

The COMET concept has been developed to cool an ex-vessel corium melt, in case of a hypothetical severe accident leading to vessel melt-through. After erosion of a sacrificial concrete layer the melt is passively flooded by bottom injection of coolant water. The open porosities and large surface that are generated during melt solidification form a porous permeable structure that is permanently filled with the evaporating water and thus allows efficient short-term as well as a long-term removal of the decay heat. The advantages of this concept are the fast cool-down and complete solidification of the melt within less than one hour typically. This stops further release of fission products from the corium. A drawback may be the fast release of steam during the quenching process which results in a steam pressurization of the containment, although condensation would subsequently reduce the steam pressure.

Several experimental series have been performed by FZK (Germany) to test and optimise the functionality of the different variants of the COMET concept. Thermite generated melts of iron and aluminium oxide were used. The large scale COMET-H test series with sustained inductive heating includes nine experiments performed with an array of water injection channels embedded in a sacrificial concrete layer. Variation of the water inlet pressure and melt height showed that melts up to 50 cm height can be safely cooled with an overpressure of the coolant water of 0.2 bar. The second variant of the COMET design uses a layer of porous, water filled concrete (CometPCA= COMET Porous Concrete Advanced) from which flow channels protrude into the layer of sacrificial concrete. This modified concept combines the advantages of the original COMET concept with flow channels and the high resistance of a water-filled porous concrete layer against downward melt attack. Four large scale CometPCA (FZK, Germany) experiments have demonstrated an efficient cooling of melts up to 50 cm height using the recommended water overpressure of 0.2 bar.

An important step in validating the concept was the use of the reactor typical oxide melt (UO_2 + ZrO_2 + molten concrete). Experiments were performed at ANL (USA) and CEA (France) in which cooling of UO_2 rich oxide melt was successfully demonstrated. Here, results of the experiments in the VULCANO facility (CEA, Cadarache, France) with about 40 kg corium melt are considered. A unit cell of the CometPCA device was used. The melt was internally heated by sustained induction power until complete cooling was achieved. The melt was safely arrested, solidified and quenched within a period of less than 20 minutes without any energetic event, as expected from previous experiments with simulant melts.

The conceptual and experimental work was accompanied by theoretical investigations at IKE, University of Stuttgart. These investigations address porosity formation as well as quenching and long-term coolability of layers with resulting porosities. A model for porosity formation is presented, which assumes that this process is essentially determined by strong local pressure buildup from strong evaporation due to water injection from below and the restriction of steam removal by friction in the melt. The effect of key parameters is investigated and compared to experimental findings.

A. INTRODUCTION

Ex-vessel melt cooling is one of the demanding challenges which is essential to stabilize and terminate a core melt accident if the melt should penetrate the reactor pressure vessel. Resolving the coolability issue does not only require the removal of the sensible and the latent heat of the corium, but also of the fission product decay heat, which is a long lasting source of internal heat generation. Different options of direct contact of melt and coolant water are considered in various research institutions to resolve the coolability issue.

A core catcher concept based on the fragmentation of corium and porosity formation has been developed at Forschungszentrum Karlsruhe [1] and was investigated further on within the COMET project [2], [3], [4]. After erosion of a sacrificial concrete layer, the melt is passively flooded from the bottom by injection of coolant water. The water is forced up through the melt, the resulting evaporation process of the coolant water breaks up the melt and creates a porously solidified structure from which the heat is easily removed. The melt is expected to solidify within less than one hour from onset of flooding, and continuous boiling removes the decay heat from the permanently flooded corium bed.

The conceptual and experimental work at FZK was accompanied by theoretical investigations at IKE, University of Stuttgart. The latter addresses porosity formation as well as quenching and long-term coolability of layers with established porosities. The aim of this theoretical work was to get a better understanding of the underlying processes in order to generally support the applicability of the concept for real conditions and to allow checks and optimisation for various conditions.

B. THE COMET CORE-CATCHER CONCEPT

The advantages of this concept are the fast cool-down and complete solidification of the melt. This stops further release of fission products from the corium. The solidification of a porous melt is the basis for safe, permanent long term cooling. The structures in the lower containment and the basement remain cold and intact. A drawback may be the fast release of steam during the quenching process which results in a steam pressurisation of the containment, although condensation would subsequently reduce the steam pressure. Two variants of the COMET design are presented for the basic processes of passive flooding and cooling, and have been evaluated by experiments:

(i) The first variant uses an array of plastic tubes, embedded in a horizontal concrete layer (Fig. 1). Connected to a water reservoir and pressurized by static overhead, water is fed into the melt through the plastic tubes after the melt has eroded the sacrificial concrete layer on top.

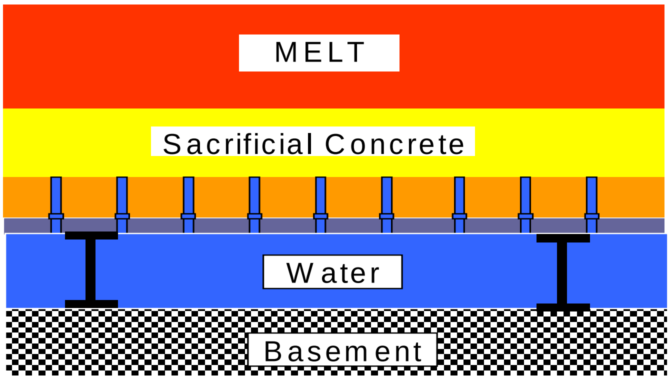

Fig.1: COMET bottom plate for water injection through an array of plastic tubes

(ii) The second variant uses a layer of porous, water filled concrete (CometPCA) from which flow channels protrude into the layer of sacrificial concrete (Fig. 2). The porosity of the concrete and the flow resistance of the flow channels can be adjusted to yield an appropriate coolant water flow into the melt. This modified concept combines the advantages of the original COMET concept with plugs of porous concrete instead of plastic tubes and the high resistance against downward melt attack by the use of the water-filled porous concrete layer.

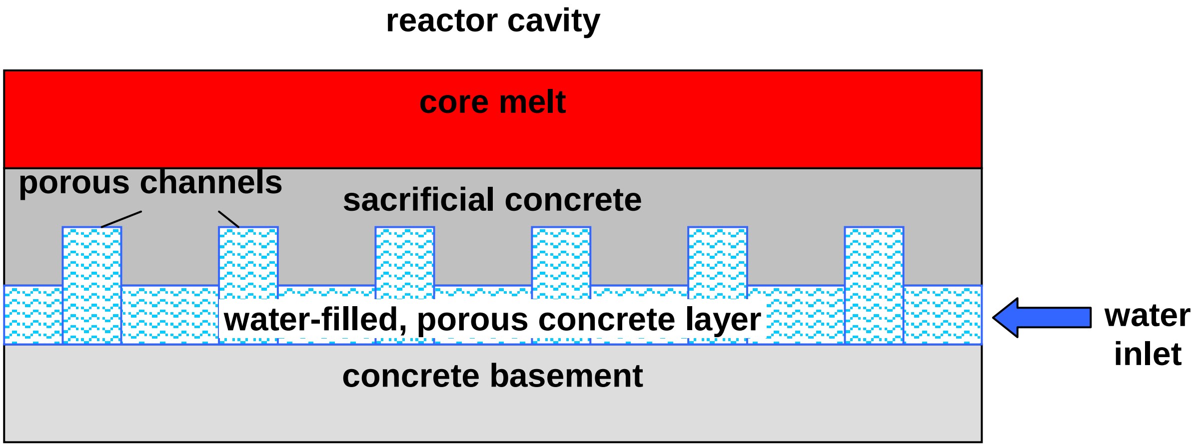

Fig.2: The CometPCA concept as a combination of concrete plugs and porous concrete layer.

The performed investigations have been used to optimise the COMET concepts and to define the range of applicability under reactor conditions. The COMET concept with the injection tubes is considered to be mature for reactor application. Also for the CometPCA concept, investigations have demonstrated its technical applicability for corium layers up to 0.5 m high. The COMET bottom cooling concept is thus able to guarantee safe arrest and cooling of the melt under ex-vessel conditions.

C. COMET EXPERIMENTS

A variety of experiments have been performed in the COMET facility (Fig. 3) at FZK (Karlsruhe, Germany) to test and optimise the functionality of the different variants of the COMET concept. Within the framework of large-scale COMET-H experiments the basic concept with melting plugs and in the CometPCA-H test series the cooling process of the melt using a layer of porous, water filled concrete with flow channels was studied. Thermite generated, high temperature melts of iron and aluminium oxide were used, with addition of approximately 35 wt% CaO to the oxide. This admixture reduces the solidification temperature of the oxide from that of pure Al_2O_3 (2323 K) to about 1670 K. Also the viscosity of the melt is decreased and is comparable with that of a corium melt upon the admixture of the sacrificial concrete. In all experiments, which use metal and oxide melts simultaneously, the heavier metal melt is layered below the oxide melt, a situation which is also expected after admixture of major concrete constituents to the UO_2/ZrO_2 part of corium melt. Unfortunately, no oxide/metal pair for simulant experiments is available that matches the conditions of a lighter metal on a heavier oxide as would exist during the initial phase after corium release. These conditions are therefore represented by some experiments with a pure oxide melt.

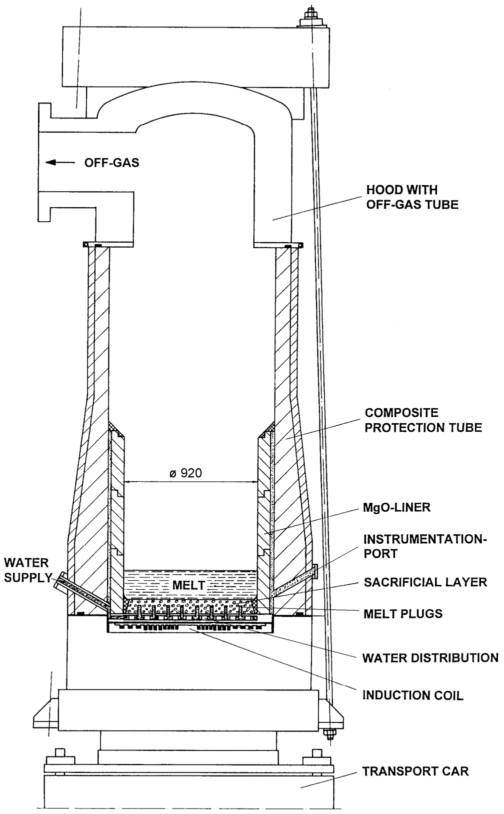

Fig. 3: COMET test facility.

C.1 COMET-H experiments

The experiments represent a 92 cm diameter circular section of the large cooling facility in a reactor. The geometrical heights of the melt correspond to the real accident situation. Also the temperatures of the melt and further properties that govern the heat transfer process correspond to those of a real core melt after partial erosion of the sacrificial layer. The characteristic heat fluxes and solidification processes during cooling are therefore representative. Long-term heat fluxes that have to be removed from the inductively heated melt, are in the range of 450 kW/m^2, referred to the bottom contact surface of the melt, and represent the decay power level shortly after melt release. In all experiments, the melt is poured onto the cooling facility. The erosion rate of the sacrificial concrete layer is highest immediately after the pouring of the melt. Due to the decreasing temperature of the melt, the erosion rate is rapidly reduced to a nearly constant value which is determined by the decay power simulated in the melt.

The COMET-H test series includes nine experiments performed with the array of water injection channels embedded in sacrificial concrete as shown in Fig. 1. Melt cooling was so efficient that the support plate was not attacked by the melt with an initial temperature of 2200 K and could be reused for all tests. The test series was performed under variation of the water supply pressure, the height of the melt, the presence of unoxidised zircalloy, and the possible occurrence of inhomogeneous downward concrete erosion.

As an example, Fig. 4 shows a section through the porously solidified melt in experiment COMET-H2.2 after removal from the support plate. The melt mass poured on the cooling device was 650 kg. This experiment studied inhomogeneous downward erosion, provoked by earlier onset of cooling on one side of the cooling device. This did not prevent safe arrest and final cooling of the melt on the large surface, and complete coolability of the melt was safely achieved through porous solidification.

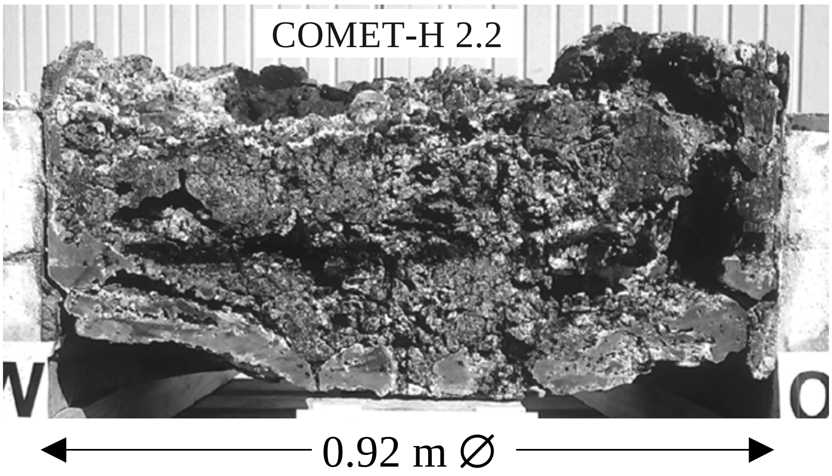

Fig. 4: Porously solidified melt from COMET-H 2.2 experiment.

Fig. 5 shows the energy balance for this experiment, which is typical for the cooling process, and compares the simulated decay power (some 300 kW throughout the test) with the enthalpy of the steam flow in the off-gas. Passive injection of the coolant water starts 1200 s after melt release, when the 80 mm thick layer of sacrificial concrete is eroded. Bottom injection leads to fast steam formation with melt fragmentation and to rapid solidification of the heated melt. The steam spike ends after some 2500 s, indicating complete quenching and solidification of the melt. The peak power during quenching is about one magnitude above the steady decay power and thus accounts for the highly efficient cooling. The ongoing lower steam release removes the decay heat of 300 kW that is deposited in the solidified melt throughout the further course of the test. Safe cooling has thus been achieved, and the temperature of the solidified melt is so low that no attack of structures does occur. Fast reduction of the melt temperature and onset of solidification limits the release of hydrogen to a short time period, characterised mainly by the erosion of the sacrificial concrete layer. Shortly after onset of bottom flooding, H_2 and aerosol release come to an end as the melt starts to solidify.

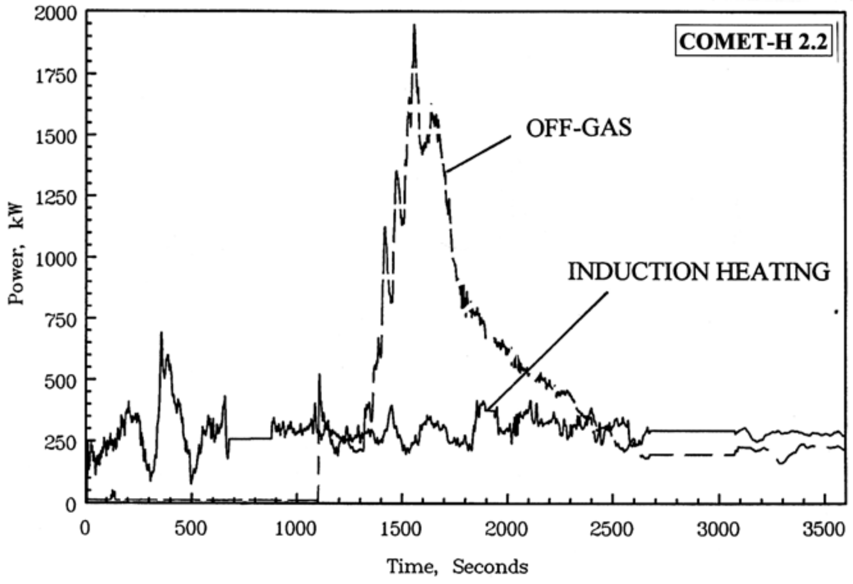

Fig. 5: Heat removal by coolant evaporation in COMET-H 2.2 experiment.

C.2 CometPCA experiments

Four large scale experiments were performed which demonstrated the efficient cooling. Variation of the water inlet pressure and melt height showed that melts up to 50 cm height can be safely cooled with the recommended overpressure of the coolant water of 0.2 bar. Fig. 6 shows the final test result with 1300 kg of initial melt, an initial compact melt height of 50 cm and sustained heating of 300 kW (230 W/kg). After complete solidification of the melt within 15 minutes, safe long term cooling was demonstrated by further inductive heating with 300 kW over 30 minutes, during which continuous boiling in a completely stable geometry was observed, as indicated by the comparison of the decay power and the removed power in Fig. 7.

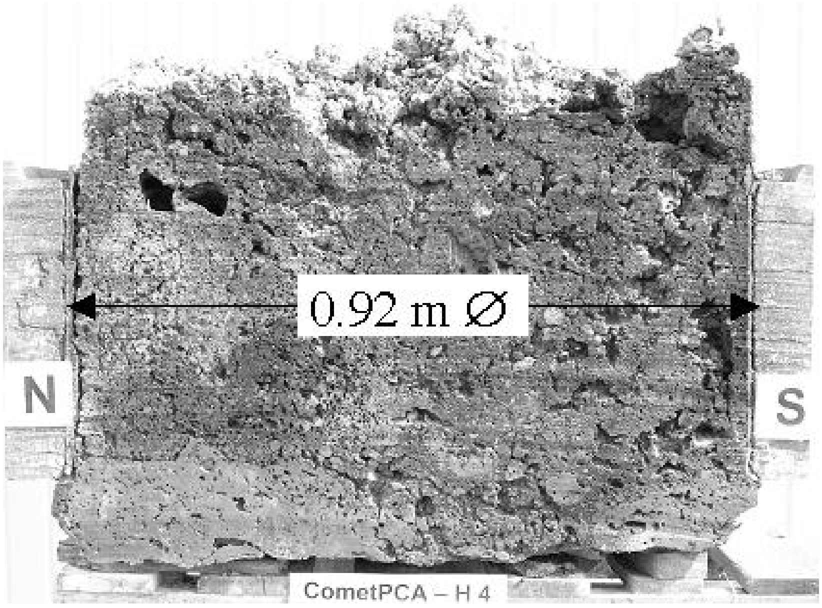

Fig. 6: CometPCA-H4 solidified melt.

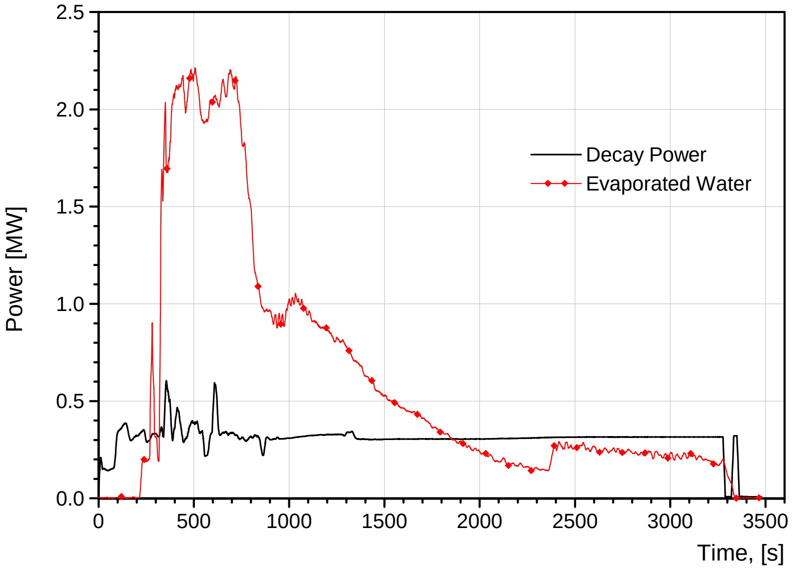

Fig. 7: Heat removal by coolant evaporation in CometPCA-H4 experiment.

C.3 VULCANO VW-U1 experiment

The VULCANO VW-U1 PCA type experiment has been performed at CEA Cadarache (France) to validate this concept with prototypic corium and simulated decay heat. Approximately 40 kg melt (45 wt.%UO_2, 19.3 wt.% ZrO_2, 19.6 wt.% SiO_2, wt.15.3% FeO_x, 0.7 wt.% CaO and 0.1 wt.% Al_2O_3) has been generated and poured from the VULCANO plasma arc furnace [5] into a COMET cooling device (Fig. 8) at an initial temperature above 2000 K. The inductive heating power generated in the corium melt varied from 10 to 30 kW (250-750 W/kg).

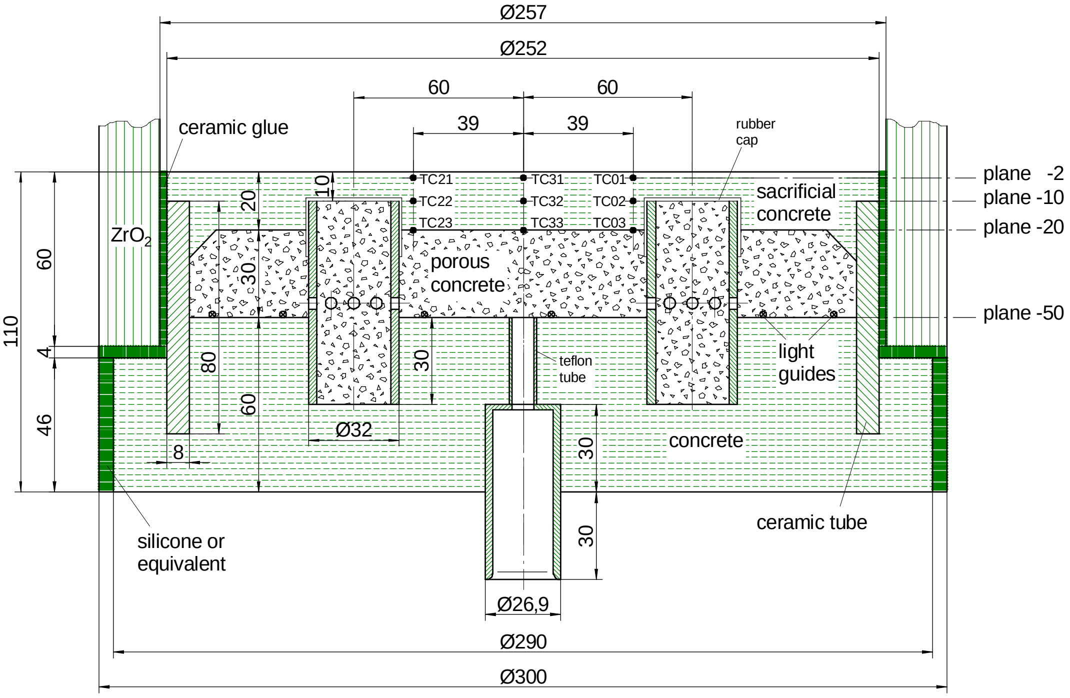

Fig.8: The COMET PCA insert used in the VULCANO test section.

After the erosion of 1 cm of the sacrificial concrete layer in 57 s, the bottom flooding was established. The melt was quenched within approximately 20 minutes (Fig. 9).

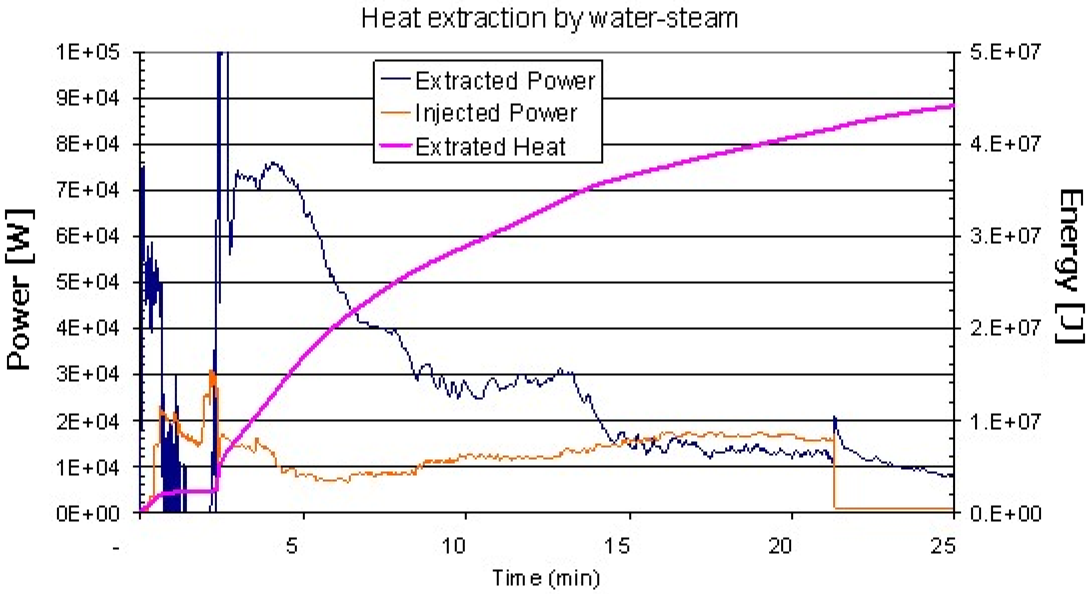

Fig.9: VULCANO VW-U1, heat removal by coolant evaporation.

The performed series of experiments have shown the high efficiency and reliability of the bottom flooding COMET and CometPCA concepts:

(i) Up to 50 cm high oxide plus metal melts are safely arrested and cooled through bottom flooding with 0.2 bar overpressure of the coolant water.

(ii) The flooding rate of the coolant water is about 2 kg/(m^2s), and results in a transient high cooling rate of some 3 MW/m^2 which is about one order of magnitude above the decay power level.

(iii) The dominant process for the highly efficient heat removal is the fragmentation of the melt by evaporation of the injected water which creates open porosities and large surfaces for heat transfer from the melt.

Based on these results, a reliable design and operation of either COMET or CometPCA cooling facility in nuclear power plants seem to be possible.

D. INTEGRAL MODEL IN WABE CODE: WABE-COMET

The large number of various successful cooling experiments for the bottom flooding concept shows the high potential to achieve rapid quenching and safe long-term cooling of the melt for various cooling scenarios. The crucial process for a successful cooling is sufficient breakup of the compact corium layer and the formation of a porous structure. It is therefore especially important to understand the processes that determine the porosity formation. However, the underlying mechanisms for porosity formation are very complex as demonstrated by the experimental experience. Therefore, one cannot expect a very detailed mechanistic modelling and calculation of the process of porosity formation. A general pattern of processes is assumed, as sketched in Fig. 10, describing breakup of melt and porosity formation from the beginning of water injection. This picture corresponds to the observations in the experiments that initially all water evaporates (only possible by strong lateral spreading of water which also produces the finally obtained lateral distribution of porosities) and that strong steam outflow at top of the melt occurs from the beginning.

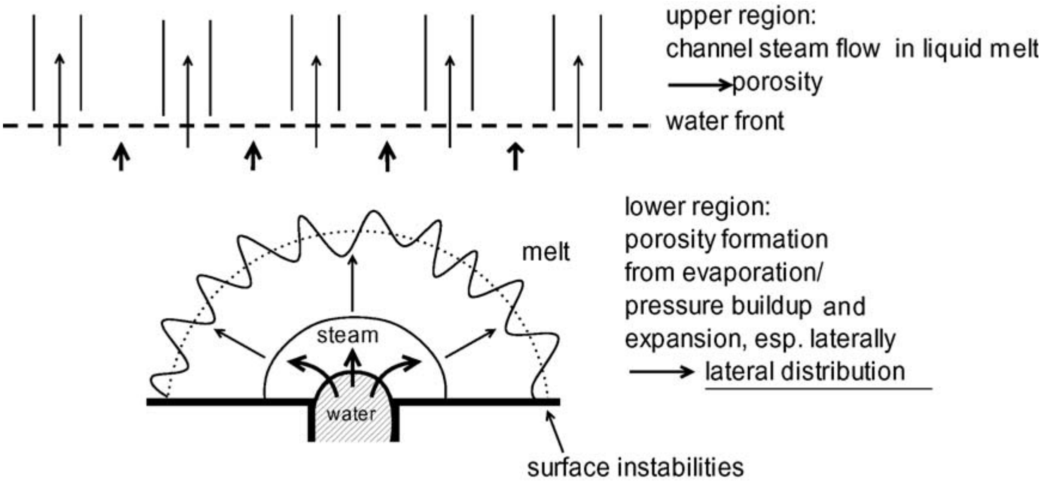

Fig. 10: Sketch of the two regions in the melt envisaged to determine porosity formation.

In the lower region, the injected water evaporates, thereby forming porosity and quenching the melt. Lateral distribution of porosity within this region is provided due to the strength of interaction, self-escalating by fragmentation, and the resulting pressure buildup driving lateral expansion and spreading of water. In case of too little pressure buildup from evaporation (or gas injection), the gas would mainly flow upwards, thus only forming a limited region of porosity as upwards channel around the water or gas injection location. From a laterally extended steam production region, the produced steam may flow upwards through channels. Only by such a pattern, the experimentally detected strong steam outflow from the beginning appears to be explainable. Then, interconnected porosity is produced in the upper region. In later stages, the water progresses further upwards and may there also come into contact with still liquid melt producing additional lateral porosity. But, the major effect will be quenching and thus freezing the porosities (channels) formed in the liquid state. Generally, porosity formation by evaporation with resulting local pressure buildup should become weaker when the steam can better escape through porosities. On the other hand, pressure buildup is favoured by high friction hindering steam to escape.

Especially, the rapid lateral expansion of the interaction between melt and injected water must be explained, in contrast to a formation of thick channels supporting axial upflow of steam and water. As only mechanism yielding the observed phenomena in principle, a strong local pressure buildup with subsequent strong expansion is envisaged here. This produces lateral motions as compared to only axial ones from buoyancy. Further, these lateral expansions produce oscillations (expansion/ collapse effects) giving rise to enhanced fragmentation. Thus, local pressure buildup is considered as a key feature of the process of porosity formation with lateral extension.

For getting an overall picture about the processes in the melt layer, including counter-effects to porosity formation as building only few paths of steam escape or too rapid solidification in the entrance region or around such paths, the WABE code [6], [7] has been adapted for local porosity formation depending on local pressurization which exceeds the hydrostatic head of melt [7]. The inverse process of porosity disappearance is also included. Freezing stops both processes. This and temperature dependent viscosity of the melt are included as effects in the correlation of local porosity formation rate. For starting, very small initial porosity and hydraulic diameters are initialized.

Within the validation process, applications have been done especially to the COMET experiments of FZK [7].

D.1 WABE-COMET application to VULCANO VW-U1 experiment

Results of pre-calculations with WABE-COMET in Fig.11a and Fig. 11b show the porosities and temperatures at 200 s, respectively, as well as the water and steam flow patterns. A cylindrical as well as a planar approach have been performed, here results of the latter are given. A comparison of measured and calculated steam mass flow rate and total mass is given in Fig. 12. The short quenching times from the experiment as well as the calculation support the present understanding of mechanisms. In view of uncertainties of the initial conditions for the calculation (e.g. initial melt temperature at inlet opening after concrete ablation) and the complexity of processes, the comparison is quite promising. However, discrepancies must also be remarked. Although only a slightly higher final amount of steam of about 18 kg results, as compared to about 15 kg from the experiment (Fig. 12), this occurs according to the model already within about 10 min while from the experiment in more than 25 min (best estimate mass given from experiment, lower mass from Pitot measurement). An explanation of the stronger steam production from the model may also be that in the experiment no simultaneous opening of the two inlets occurred, which was assumed in the calculation. Thus, post-test calculations are being performed to account for this and also to consider other variants of parameters, as e.g. with respect to friction in the porous concrete, especially in the inlet region..

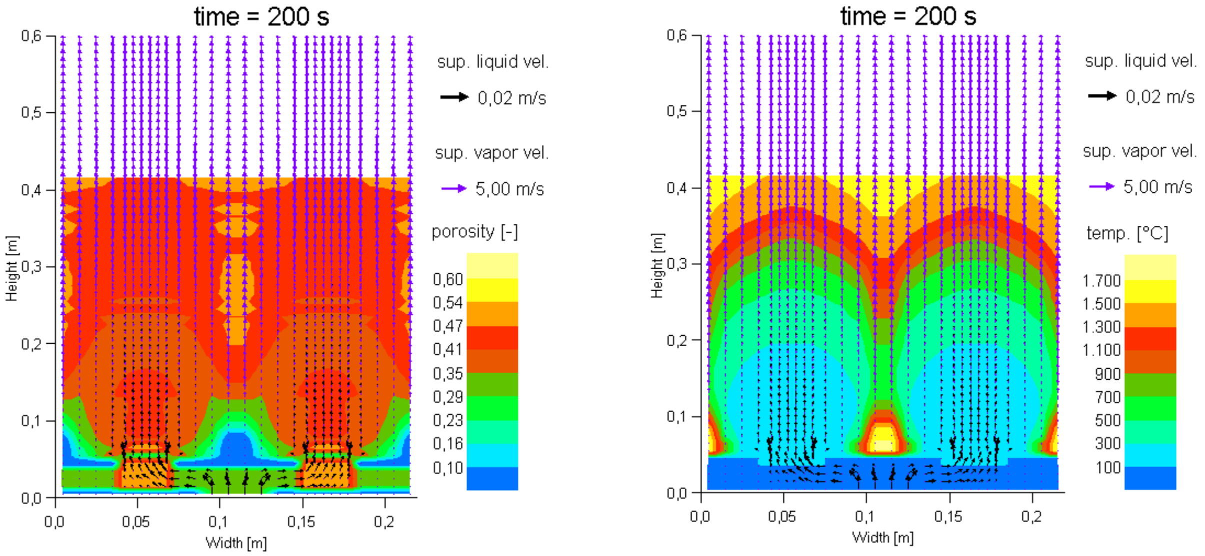

Fig.11: a) Porosity and b) temperature (1800 K: solidus temperature) after 200s

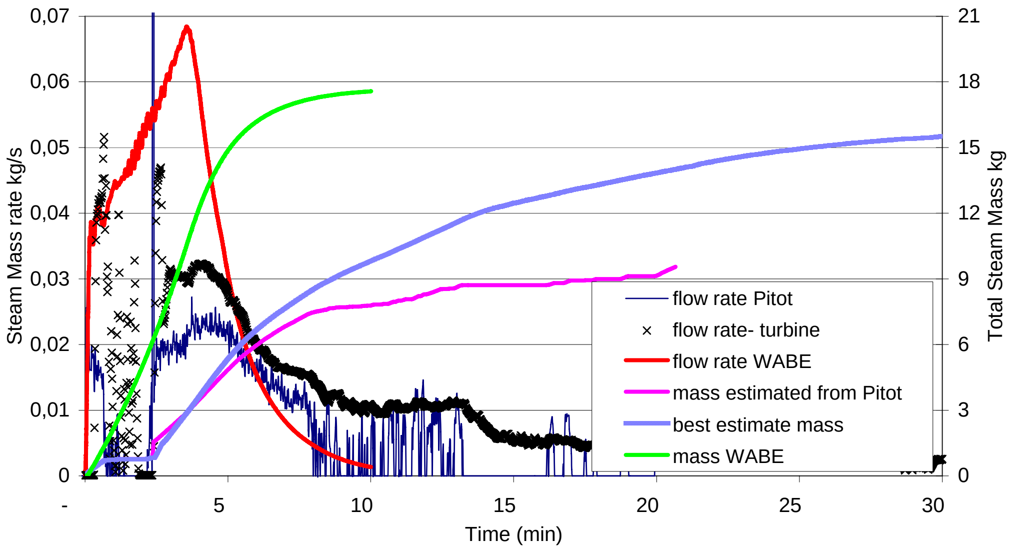

Fig.12: Comparison of measured and calculated steam mass flow rate and total mass.

E. CONCLUSIONS

The COMET concept on ex-vessel melt cooling is based on water injection at the bottom of the ex-vessel corium melt which leads to melt fragmentation, fast quenching and solidification, and permanent cooling of the porously solidified melt. Different test series are described and reviewed which identify and underline the dominant physical processes for melt cooling and are the basis for technical realisation of the cooling concept. According to large scale tests with sustained heating of metal and oxide melts, two variants of the concept are mature for plant application. These are the original COMET concept with water injection through an array of plastic tubes, and a modified version, which combines a water filled porous concrete layer and dedicated flow channels for water injection. The latter version may even enhance the passive operational safety for melt cooling and melt retention by the high stability of the flooded porous concrete layer. The height of the high temperature melt for which safe cooling with simulation of decay power was demonstrated is 0.5 m and requires an overpressure of the coolant water of 0.2 bar.

The experimental findings are the basis for the model development of melt fragmentation and cooling. Rapid evaporation of injected water in the low regions of the melt layer leads to the conclusion that rapid radial extension of porosity formation must have occurred, instead of a dominating axial motion of steam and water. The latter would tend to establish thick channels of upwards fluid flow, rather than laterally extended porosities. Only pressure buildup by strong evaporation, limited upward flow of steam and resulting strong expansion processes are considered to explain the lateral melt and fluid motion, melt breakup and porosity formation. The presented model concentrates on key features in a heuristic correlation approach on local porosity formation, which is considered to be directly proportional to the local overpressure. Temperature dependent melt viscosity is included. It hinders porosity formation. Freezing is taken into account via a temperature criterion. It finally stops porosity formation.

Overall, the essential processes of porosity formation and quenching appear to be understood and modelled with WABE-COMET. Present results support the technical application of the COMET concept. Future applications, especially to reactor-related cases, will more in detail address discussion points about freezing at the inlet and crust formation at the top of the melt layer and their consequences. In the present calculation no problematic influences from such effects have been obtained. Freezing in the lower region occurs as a result of porosity formation and quenching and thus fixes the successful porosity formation instead of hindering it. In the upper region, the steam flow and escape governs the behaviour. Further confirmation is expected by the extended studies envisaged. Mostly, the future analyses will concentrate on the CometPCA concept using a porous concrete as injection medium instead of nozzles and promising even improved features and adaptation possibilities to overall retention concepts.

References

[1] Alsmeyer, H. and Tromm, W., 1994. Experiments for a core catcher concept based on fragmentation. ARS '94 - International Topical Meeting on Advanced Reactor Safety, April 21 - 24, Pittsburgh (PA), USA.

[2] Alsmeyer, H. and Tromm, W., 1999. The COMET concept for cooling core melts: Evaluation of the experimental studies and use in the EPR. Report FZKA 6186, EXV-CSC(99)-D036.

[3] Alsmeyer, H. et al., 2000. Corium cooling by bottom flooding: results of the COMET investigations. Proc. of the OECD Workshop on Ex-Vessel Debris Coolability, Karlsruhe, November 15-18, 1999, Wissenschaftliche Berichte, FZKA-6475, 345-355.

[4] Tromm, W. et al., 2001. Ex-vessel corium cooling by passive water addition through porous concrete. ICONE 9, Nice, France, April 8-12.

[5] G. Cognet, G. Laffont, C. Jégou, J. Pierre, C. Journeau, F. Sudreau, A. Roubaud, Utilisation d’un four tournant à arc plasma transféré pour fondre et couler des mélanges d’oxydes autour de 2000°C., Ann. Pharm. Fr., 57 , 131 – 136 (1999).

[6] Bürger, M., Buck, M., Schmidt, W., Widmann, W., 2006. Validation and application of the WABE code: Investigations of constitutive laws and 2D effects on debris coolability. Nucl. Eng. Des. 236, 2164-2188.

[7] W. Widmann, M. Bürger, G. Lohnert, H. Alsmeyer, W. Tromm, 2006. Experimental and theoretical investigations on the COMET concept for ex-vessel core melt retention. Nucl. Eng. Des. 236, 2304-2327.