Review of 10 years of molten corium concrete interaction R&D – potential applications for containment integrity

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Abstract:
In the frame of severe accident studies for Light Water Reactors, Corium Concrete Interaction (CCI) is one of the phenomena that might lead to a containment failure through a direct leak to the ground water or as a consequence of a progressive overpressurization. At the end of the 90s, the remaining uncertainties on the melt-through delay and the impossibility to conclude on the corium melt stabilization by water addition on top of a corium melt conducted the scientific community to maintain their R&D efforts. During the last 10 years, experimental programs in United States or in different European countries have provided additional results on corium concrete interaction mechanisms for standard top cooling conditions but also with an advanced cooling concept designed for a new reactor generation. Associated interpretation activities performed in the frame of international workgroups and the status of models improvement are briefly described. Regarding the containment integrity, if we can perform now more realistic simulations, there is still the need to increase the knowledge on the different cooling mechanisms in order to identify in a proactive way the more promising mitigation options and evaluate the designers’ or utilities’ proposals for both new generation and existing plants. In that perspective the remaining issues for the different mitigation options are summarized and the perspectives for new programs underlined.

1 INTRODUCTION

In the frame of Light Water Reactor severe accident studies, Corium Concrete Interaction (CCI) is one of the phenomena that might lead to a containment failure through a direct leak to the ground water or as a consequence of a progressive over pressurization created by the release of hot gas coming from the concrete degradation.

Before reviewing the last 10 years of R&D activity, revisiting the beginning of the 2000s will give us the opportunity to recall the historical status of knowledge on CCI at that time, including the remaining uncertainties related with melt-through delay and the impossibility to conclude on the corium melt stabilization by water addition on top. It introduces why and how the scientific community maintained its R&D efforts during the following decade.
1.1 Knowledge at the end of the 90s

1.1.1 Learning from experimental programs

Even if other programs have been perform to study CCI mechanisms, we decided to remember two programs only, MACE at Argonne National Laboratory (USA) and COMET at Karlsruhe Institute of Technology (Germany), due to their consequences for CCI R&D orientations and new coolability options.

The primary objective of the international MACE Project (Melt Attack and Coolability Experiments, 1989-2000) was to study the coolability of the melt pool interacting with a concrete basemat by water overlayer [1]. The MACE experiments were large scale (mostly 1D) CCI tests with prototypical materials and with simulated decay heat, in rectangular test sections ranging from 30 x 30 cm to 120 x 120 cm, melt masses have ranged from 100 to 2000 kg. Early in the experiments, just after the onset of CCI, the melt was flooded with water from the top. For corium concrete ablation, although different hypotheses on corium concrete interface were debated without consensus (mushy layer versus pool liquidus temperature with refractory corium crust), the ablation velocity and the pool temperature decrease are quite well reproduced by the different models and simulations tools.

The principal finding from these tests was that -after water addition- a stable insulating crust, anchored to the sidewalls of the experimental cell, always formed on the top of the melt after a short period of efficient bulk cooling. Melt stabilization could not be achieved because only small additional heat transfer out of the melt was measured. The additional heat transfer was linked to the water ingestion into cracks in the crust and also to the ejections of molten corium (melt eruptions) into water above the crust. Melt eruptions, and subsequent debris accumulation over the crust, may transfer a considerable amount of energy to the overlying water. This phenomenon was observed but its intensity was rapidly limited by the decoupling of the crust from the melt as the CCI progresses downwards and the crust remains anchored to the lateral walls.

From the very beginning it was believed that the crust anchoring cannot be prototypical at the plant scale, with typical cavities of about 6 m diameter span. In that condition, it is still possible to think that the stabilization of the melt could be achieved by the combination of the above mentioned cooling mechanisms. These observations resulted in establishing new experimental programs (aimed at coolability issues) launched in the last decade.

As a promising alternative to the process of flooding the melt with water at the top, the efficiency of cooling the melt by bottom water injection was investigated in the COMET concept proposed by KIT [2, 3]. A considerable potential of the COMET concept was assumed since it avoids the counter-current flow situation of water flooded at the top and intruding downwards and steam flowing simultaneously upwards like in the MACE experiments. Large-scale experiments related to this concept were performed at KIT employing up to 1300 kg of a high temperature simulant melt at sustained induction heating. The melt was based on iron and alumina and was generated by a thermit reaction. After erosion of a sacrificial concrete layer, the melt is passively flooded from the bottom by injection of coolant water from an elevated water reservoir through a special device (porous concrete layer with injection nozzles). Rapid quenching of the melt was obtained in these experiments typically within 1 hour for a 50 cm deep melt pool heated at approximately 300 kW. Local pressure build-up and steam expansion were identified as key processes, resulting in high degree of melt fragmentation and porosity formation with a corresponding fast increase of the melt surface, supported by the co-current flow mode of water and steam. A drawback may be the fast release of steam during the quenching process, which may be a
significant contributor to the containment pressurization during that phase. An optimization of the design has been performed to balance coolability efficiency and containment pressurisation by adjusting the superficial nozzles density.

1.1.2 Reactor application and remaining uncertainties

At the beginning of 2000s, reactor simulations were performed with different simulation codes on the basis of existing models. Despite the lack of knowledge on physical heat transfer mechanisms between melt and concrete on the micro-scale, macroscopic heat flux models were derived from separate effect tests and used in conjunction with consistent assumptions on boundary conditions and on the evaluation of the melt viscosity. These models were validated against experiments performed in 1D geometry: the different codes were able to predict concrete ablation in the dry situation. Even if slag layer, gas film or crust instability models are implemented in some tools there were no obvious reasons to consider a different behaviour for bottom and lateral interfaces and, as a consequence, a homogeneous concrete ablation is usually predicted for pure oxidic melt in 2D geometry. The use of simplified cooling models for water ingression or melt ejection conduced to delay the meltthrough time or to the melt stabilization [4] but such results have not been confirmed from experimental side.

To consider also realistic vessel melt through scenarios, reactor simulations have been performed with both metal and oxide phases offering the possibility to observe a mid-term melt stratification with a metal layer below the oxide layer due to the lightening of the oxide layer with ablated concrete. For such a melt, the heat transfer between oxide layer and metal layer and the duration of the stratified situation affects significantly the concrete ablation profile. Dominant axial ablation has been reported in BETA (KIT) experiments using a heated metal layer below an oxidic layer. These results supply important information for the concrete erosion by a steel melt for the long term reactor situation, but, however, the specific configuration in BETA with the heat release concentrated in the metal layer and the large density difference between oxide and metal have not been founded prototypic enough. Nevertheless, stratified pool capabilities have been implemented in simulations tools to perform sensitivity study and reactor applications.

IRSN performed such simulations with the MEDICIS module of the ASTEC code [5] for a 900 MW PWR ex-vessel inventory (40 tons of metal and 100 tons of oxide) and for a 4 m thick basemat. In a conservative approach the calculations have been set-up for a siliceous concrete with a low gas content and higher heat transfer coefficients at the metal-oxide interface (Greene correlation between two liquids percolated by gas [6]) than those usually considered at the liquid/solid interface with gas sparging, and with a fixed configuration, where metal is stratified below the oxide layer. This approach concluded to a pessimistic melt trough time of about 11 h; as a comparison, the same calculation for pure oxide melt give a time about 9 days. According to the safety requirement that imposed to respect at least a 24 h delay, these results are clearly not acceptable. As a consequence for a substantial part of the next decade R&D was defined to reduce uncertainties on heat transfer between metal and oxide and on the duration of stable melt stratification.

1.2 Consequences in terms of program orientations

At the beginning of the 2000s the US NRC and OECD-NEA launched the MCCI program taking benefit of the excellent know-how and the long experience of ANL’s experimenters team. This program was dedicated to the study of the different cooling mechanisms involved
during top flooding. Both the separate effect approach to evaluate the efficiency of each mechanism and also a more integral approach were used. The latter employed 2D test sections with dry and wet phases to address long term behaviour and then observe the combined effects of water addition. Due to the difficulties to demonstrate the melt stabilization by water addition on top and because new mitigation concepts are being developed, the program has been extended to advanced cooling designs, such as the COMET concept with bottom water injection through porous concrete, or to a bottom cooling plate like in the EPR spreading room design.

At the same time French partners (CEA, EDF and IRSN) engaged a complementary program on the VULCANO (CEA) facility in order to address in prototypic material the specificity of corium melt composed by metal and oxide phases. This kind of tests involving a large metal ratio in the melt is not possible at ANL due to the direct current heating technology used at ANL, so the CEA team required the development of an alternative solution based on high frequency heating with magnetic shielding to inject power after stratification in the oxide phase only. Additional analytical programs with simulant fluids where defined by CEA to address the stratification stability issue (BALISE [7]) and validate high heat transfer values reported by Green at the interface of two immiscible layers percolated by gas sparging (ABI [8]).

The COMET concept was quite mature and the KIT’s facility was used for the LACOMERA-COMET-L tests to provide additional data for 2D ablation under dry and wet conditions using alumina and iron melt [9-11] whereas a test in prototypic material with sustained heating has been scheduled in the frame of PLINIUS European transnational access program to complete the validation of the cooling concept [12].

2 OUTPUTS OF 10 YEARS OF MCCI R&D

During the last 10 years, experimental programs in United States or in different European countries have provided additional results on corium concrete interaction mechanisms for standard top cooling conditions but also for advanced cooling concept designed for new reactor generation. The main results are summarised and the associated interpretation activities, such as the status of models improvement, are briefly described.

2.1 Learning from experimental programs

2.1.1 Outputs from MCCI-OCDE program

The OECD-MCCI (2002-2005) and MCCI-2 (2006-2010) Projects were primarily aimed at

- assessing the potential of various cooling mechanisms and their synergistic effects for stabilizing the ex-vessel core debris
- address the uncertainties related to long-term 2D CCI under both dry and flooded cavity conditions

Looking at the cooling of the crusted melt in cavity by water overlayer, three modes of heat removal (above that by mere heat conduction) were identified: bulk cooling with a direct melt-water contact, water ingression through cracks in the crust, and ejection of melt into water above the crust (eruptions). To study the water ingression mechanism in the MCCI project,
the series of the SSWICS (Small Scale Water Ingression and Crust Strength) experiments [13] was performed. The main objective of these tests was to measure the dry-out heat flux, above the limit imposed by pure conduction through crust (and also to obtain data on crust permeability). If the cooling process - by water coming from the top - of the molten materials in the cavity is limited just by conduction through the (solid) upper crust then it would be impossible to extract any significant portion of the decay heat to the overlying water. The SSWICS results indicate that the water ingestion is able to augment the heat transfer out of the melt but only for melts with low concrete content, i. e. early in the accident when only a small amount of concrete has been ablated and dissolved in the melt.

The other part of the SSWICS experiments was the post-test measurements of the crust strength [14]. The measured crusts were shown to be relatively weak (which had been anticipated). In consequence, it is expected that the mere weight of the actual crust at a plant scale would fracture the crust (if it is anchored) and that the contact with the melt will always be retained (unlike the MACE results).

Another coolability mechanism, melt eruptions, are driven by gases generated from the decomposition of the ablated concrete. Even though the planned separate-effect melt eruption tests were not successful in the MCCI Project, the data from the (integral) 2D CCI tests show that the melt eruptions represent a viable mechanism for cooling of the debris, more efficient than pure water ingestion. In the last CCI test of the program, water was injected at the very beginning and for the first time the stabilisation of the melt was obtained. In this case, the melt cooling can be a result of the combination of an efficient water ingestion mechanism (low concrete content) and an ejection mechanism. The ejection mechanism could be enhanced by an additional source of gas coming from water ingress into a degraded lateral concrete wall. Nevertheless such a very early flooding could not be considered as a generic management procedure.

As an important part of the MCCI projects, 6 large scale 2D CCI experiments were conducted in specially-designed two-dimensional concrete test sections [15]. The first three CCI tests in the OECD-MCCI project employed ~ 400 kg of prototypical, fully oxidized (homogeneous) PWR core melts containing 8 wt % of the concrete decomposition products in the melt. The decay heat was simulated by direct electrical heating. One of the main outcomes of the 2D CCI experiments was the determination of the power split ratio, radial-to-axial, i. e. how much heat from the melt pool is going sideward as compared to heat going downwards. This power split could decide at an accident whether, primarily, the containment structures are threatened by the radial erosion of concrete or whether the axial erosion of the basemat is more pronounced, leading possibly to ground contamination.

In the CCI experiments of the OECD-MCCI projects, the long-term 2D ablation behaviour was found to be closely linked to the concrete type, i. e. limestone (or LCS) type versus siliceous. For the tests with siliceous concrete, the radial-to-axial heat flux ratio was estimated to be always much higher than 1:1, whereas for the limestone concrete this ratio was always near unity. Between the two types of concrete, a possible explanation for differences in 2D erosion behaviour is the concrete gas content [15]. Variations in the characteristics of the corium-concrete interface for the two types may also have influenced the ablation behaviour. However, a certain controversy still exists about the interpretation of the 2D CCI test results, about those with siliceous concrete in particular [16]. These questions are again being addressed in the ongoing MCCI-2 project.

There were a lot of other interesting results in the OECD-MCCI program, one of them was the demonstration that the bottom water injection (an engineering feature) is an efficient concept for cooling the melt. Very important were also the supporting analytical activities:
phenomenology models development (dry-out heat flux modelling, melt eruptions), recalculations of experiments, plant analyses.

2.1.2 Outputs from French corium concrete interaction program

The French program on corium concrete interaction has been designed in a complementary way with the OECD-MCCI program. Funded initially in the frame of a CEA-EDF-IRN agreement, GDF-Suez joined recently the program that is also open since 2009 to the European partners in the frame of SARNET with the support of the European Commission. Its main objective was to focus on prototypic corium melt composed with oxide and metal non miscible phases that could stratified in two separate layers during interaction with concrete according to oxide density evolution, gas release intensity and metal oxidation progression. Separate effect experiments using simulant fluids were also designed to validate correlation or models developed for safety codes. Tests are performed with 40 kg of oxide and up to 24 kg of stainless steel poured in a half cylindrical concrete crucible that allows observing ablation up to 15 cm in radial and axial direction. In order to avoid un-prototypic short circuit through metal layer with a direct current heating method the CEA developed for the VULCANO facility a high frequency heating technology with specific magnetic shielding to guaranty at least a 90% power deposit in the oxide layer.

Because reference cases are needed, the first test campaign was dedicated to pure oxidic melt in interaction with concrete of different composition [17]. As for OECD-MCCI the main output was the impact of the concrete composition on the axial versus radial ablation rates. The same trends with high radial ablation for siliceous concrete were reported but here for a different geometry and with a different heating technology, two points that reduce the possible impact of system effects on the conclusions.

In the second test campaign, tests were performed with one third of metal and two third of oxide [18]. As a main conclusion, no fast axial ablation was observed for siliceous concrete as for siliceous-limestone ones. We can only mention that for siliceous concrete a more important axial ablation has been observed when compared to pure oxide test. Post Test Examinations show a very small quantity of remaining metal, around 10% to 25 % of the initial amount. It could be explained only by a fast and large oxidation process with concrete decomposition gases but also with liquid oxide. The detection of stratification time and its duration from modification of electric signal was not obvious and thus direct learning for reactor application are not possible. Due to the difficulty to understand the influence of all phenomena, the next tests will be performed at parameters that can increase the chance to observe the effect of pool stratification for a longer duration even if they are less prototypic (larger amount of metal, higher initial concrete content in the oxide phase…)

In parallel with the second test campaign devoted a third campaign has been defined to support interpretation of anisotropic ablation in homogeneous pool using a separate effect approach with analytical concrete to discriminate explanations coming from thermal-hydraulic origins from those linked to boundary conditions or material effects [19].

The separate effect tests are designed to emphasize one of the specific behaviour of a real concrete in order to discriminate the different contributions to ablation anisotropy. In the first test the limestone aggregates have been replaced by clinker in order to avoid the decarbonation process of limestone aggregates but with the same chemical composition for melted concrete. This composition reduces the amount of released gas and tends to an aggregate behaviour similar to siliceous, i.e. a melting or partial melting without decomposition in powder at quite low temperature. In this test, the radial ablation was more pronounced which means that more than the chemical composition of melted concrete the
behaviour of aggregates plays a role in the ablation mechanism. New tests are ongoing to obtain additional evidence of the influence of the macrostructure of the concrete. The use of a siliceous mortar for example will reproduce the composition of a siliceous concrete but with sand size aggregates that normally will reduce the release of un-melted gravel in the corium pool or offer less porosity for gas bypass in a partly degraded concrete sub layer (the part for concrete where cement paste becomes liquids whereas aggregates are not fully melted).

Additional separate effect experiments in simulant fluids have been performed or are still ongoing at CEA to observe:

- entrainment thresholds between two immiscible layers percolated by gas flow (BALISE [7]),
- heat transfer coefficients between two immiscible layers percolated by gas flow with high density difference in order to avoid entrainment (ABI [8]),
- boundary conditions in binary non eutectic mixture that simulate the behaviour of a corium-concrete mixture (ARTEMIS [20, 21]),
- heat transfer coefficient distribution in a pool with gas injection at bottom and lateral boundaries (on going CLARA program).

They provide new data and give us additional elements for model or correlation validation in terms of:

- thresholds correlations for beginning of entrainment and full mix,
- new heat transfer correlation validated also on the Green’s data that confirm high heat transfer coefficient values at interface between metal and oxide,
- interface temperature that is close to liquidus, pool temperature that follows the pool liquidus evolution and bottom crust thickness that is larger than the pure conduction one which means that a convective flow occurs in a kind of solid debris accumulation.

If these experiments offer measurement possibilities that are impossible in prototypic high temperature material their limitation concerns the choice of simulant that is not always justified in the absence of a consolidated mechanistic model or due to the fact that couple of fluids that satisfied all the criteria are not available. In that condition the reactor extrapolation is difficult without a validation phase based on real material experiments even if only indirect parameters are measured such as ablation profile evolution and final phase distribution from PTE.

To overcome these difficulties, IRSN develops in parallel a numerical “experimentation” approach based on multi-scale approach with decomposition domain support by DNS calculation to observe the consequences of bubbles crossing the interface between the two layers in terms of liquid entrainment or local induced convection motion to evaluate global heat transfer, fig. 1.

Figure 1: multi-scale approach to evaluate the heat transfer coefficient between two stratified layers percolated by 3mm diameter gas bubbles. Temperature field calculated by DNS at metal oxide interface [22]
Such calculations are performed also for miscible layers at corium concrete interface to observe the mixing process, fig.2, including the influence of gas sparging, fig. 3. If first encouraging results have been obtained in terms of heat transfer coefficient evaluation, an important validation effort is still needed to give quantitative reliable information.

![Figures 2 and 3](image)

**Figure 2:** mixing process between siliceous concrete and oxide corium, DNS calculation shows solid fraction evolution resulting from local composition and temperature (C. Introini [23])

**Figure 3:** disappearance of concrete plumes due to recirculating flows induced by gas release, DNS calculation shows solid fraction evolution resulting from local composition and temperature [23]

### 2.1.3 Outputs from German corium concrete interaction program

The German program on CCI featured two experimental teams and facilities: the COMET facility at KIT in the frame of the large-scale 2D LACOMERA-COMET-L tests [9-11] and the small-scale MCCI experiments performed for 1D CCI configurations at AREVA’s SICOPS facility at Erlangen [24].

The COMET-L test series was designed to investigate a long-term CCI of a steel melt in a cylindrical cavity made of siliceous concrete with a decay heat simulation of intermediate power level. In contrast to the former BETA tests the induction coil used for sustained heating of the melt was located beneath the concrete crucible, not beside. In two experiments (L2, L3) the metal melt was overlaid by an oxide melt. After substantial cavity erosion flooding of the melt with water at the top was initiated in test L3. Two subsequent phases of interactions were observed: in the early phase there was a strong gas production and an intense agitation of the melt surface. The steel melt looses fast its initial overheat and similar erosion in axial and lateral direction was observed during this transient phase.
Afterwards a steady-state phase is initiated: periods of slow concrete erosion and slow gas release are interrupted by more intense gas eruptions and melt agitation. Consequently, surface crusts on top of the oxide layer may grow and are re-melted periodically. There are also indications of periods with a steel crust present along the metal interface with the concrete. During this steady-state phase the erosion is pronounced (factor 2-3) to the downward axial direction compared to the lateral one.

The objectives of the 1D CCI tests in AREVA’s SICOPS facility were first to compare the ablation behaviour of generic concretes including iron-oxide as foreseen for the EPR with standard siliceous concretes, then to check the mechanical integrity of such concretes in terms of cracks etc. and finally to test if the course of melt temperatures during MCCI correlates with thermodynamic equilibrium assumptions. The findings are respectively that the ablation of the investigated concretes can be described by traditional melting models; the investigated concretes showed a good mechanical stability and for the 1D tests the melt temperatures are close but 50-100 K below the liquidus.

2.1.4 Outputs from Finish corium concrete interaction program

The EPR reactor, which is in construction in Finland and in France, uses a special hematite-containing concrete type in its reactor pit. The duty of the hematite (Fe₂O₃) in the concrete is to decrease the solidus temperature of the corium–concrete mixture in order to facilitate melt spreading in the core catcher. Another feature of the special concrete is that hematite reacts chemically with molten zirconium, thus oxidizing the metal without generating hydrogen. If zirconium is oxidized by water, the reaction generates hydrogen, which is a flammable gas.

There was very scarce public experimental data about the special hematite-containing concrete type. Therefore VTT started an experimental program to investigate the behaviour of the special concrete at high temperatures. In the HECLA experiments [25], 50 kg of molten stainless steel at almost 1800 °C was poured into cylindrical concrete crucibles. The tests were transient, i.e. no decay heat simulation was used. Five experiments were conducted between 2006 and 2009.

On the basis of the HECLA tests, it is concluded that no clear differences between the ablation of the hematite-containing concrete and ordinary siliceous concrete were observed. No dramatic effects, such as cracking of large pieces of concrete due to the thermal shock, took place. An important side result of the test series was gaining knowledge of the properties of the special concrete type. Chemical analyses were conducted and mechanical properties were measured. For example, the hematite-containing concrete is about 13 % heavier than ordinary concrete.

In the frame of European transnational access program to CEA severe accident facilities, a complementary test has been performed on VTT proposal with pure oxidic melt, sustained heating and EPR vessel pit concrete. The fast radial ablation observed in this test is very similar to the behaviour in test performed for siliceous concrete. It could be correlated to the fact that as for siliceous aggregates hematite aggregates will melt without preliminary degradation process and that they could be release partly melted as a function of their size.
2.2 Consequences for modelling

2.2.1 Corium concrete interaction mechanisms

During corium concrete interaction, if the pool can be considered well mixed and quite uniform in temperature, the corium concrete interface is difficult to describe. It is because of heterogeneity of the material in presence and because of the fact that the solidification of one component is expected simultaneously with the melting of the other one. To reproduce the ablation mechanism, usually several layers are considered. This reflects the necessity to have an evolution between solid concrete to liquid corium concrete mixture compatible with a gas and liquid concrete releases in a thermal gradient that will promote corium freezing at a mobile interface. The schematic view, fig. 4, presents from concrete to liquid pool: solid concrete, a slag layer, a solid or partly solid crust where heat transfer is performed mainly by conduction and a mushy layer where heat transfer is governed by convection up to the point where the temperature reaches the liquidus and where we can consider a full liquid pool.

![Figure 4: corium concrete interface description](image)

This vision gives us the possibility to consider different interface temperatures, from pool solidus to liquidus, with a consistent evaluation of viscosity to calculate the heat transfer coefficients. It also enables us to take into account the additional thermal resistance in a slag layer to model concrete accumulation (liquid or partly solid…) or the presence of a gas film. The use of a high thermal resistance value for the slag in this approach gives us the possibility to simulate an absence of crust at the interface; in that case, the model considers the convective heat transfer coefficient, the thermal resistance of the slag layer and the concrete melting temperature. As concrete is not a pure material, the definition of a melting temperature is a language abuse, in fact, this melting temperature can range between concrete solidus (beginning of melting) and concrete liquidus (full melting) and, as a consequence, impacts the composition of the slag layer (liquid concrete accumulation or partially melted accumulation…). More over, to be consistent with the description of ablation mechanism and energy balance defined in simulation tools, this temperature has to be understood usually as the temperature for which concrete is released and mixed within the corium melt.

To explain the anisotropy of the ablation we can assume that it could be connected to different effective values of heat transfer coefficients or to different boundary conditions as a function of the orientation of the corium concrete interface. Obviously, it could be also a contribution of the two factors. Different assumptions including more mechanistic descriptions to increase models predictability but also global approaches, that are compatible with the level of modelling of safety codes, are presented hereafter.
The experiments performed with separate effect concretes at the VULCANO facility underlined the role of the aggregate composition leading to different specific behaviour for limestone and siliceous concretes during decomposition: the decarbonatation of limestone aggregates that form calcia powder before the liquefaction of the cement paste around 840°C and the behaviour of other aggregates like silica, clinker or hematite that will be melted at a high temperature and that could be released after the liquefaction of the cement paste in only partly melted form. As a consequence we can imagine that the behaviour of partly melted aggregates will not be the same according to the orientations of the concrete interface.

For siliceous concrete or hematite rich concrete, on the lateral wall where a stable crust or solid debris accumulation is unlikely there is a reasonable interpretation that the lighter concrete aggregates are released within the melt with melted cement paste and concrete gas flow directly in a high viscous (large solid fraction) slag layer. At contrary at the bottom surface, dense solid debris accumulation could create a layer that blocks the lighter partly unmelted aggregates and remains porous enough to allow gas and melted concrete or small size sands to be released as concrete plumes within the melt. So, the fast radial ablation could be interpreted as a mechanical collapse after a threshold of cement paste liquefaction with - as a consequence - less energy consumed for the ablation and different temperature and decomposition enthalpies for lateral and bottom interface. From energy balance point of view to consider the additional aggregate melting, energy sink has to be added in the pool bulk or at the upper pool boundary if we assume at this place an accumulation of light concrete aggregates. At the bottom the melting of aggregates proceeds in place at the ablation front and this justifies to consider in average a melting concrete temperature at concrete liquidus temperature. For evaluation of corium melt heat transfers, the interface temperatures could be linked to the debris accumulation at the bottom with convective hot liquid concrete flow in a porous medium, whereas at lateral interface we may assume a mushy convective layer including partially melted gravels and corium debris. For transient state, after initial bottom crust formation it is possible to assume also a liquid concrete accumulation that leads to a crust re-melting. Such phenomenon, if it is reproduced after crust renewing could result in axial ablation instability.

Figure 5: pseudo binary diagrams for VULCANO LCS and siliceous concretes extracted from [17]

For LCS concrete the understanding is more and more consolidated that the limestone aggregate decarbonation at low temperature leads to a homogenous release of gas, melted concrete and calcia powder within the melt with or without debris accumulation, i.e. for lateral or bottom wall. More over if we look at a pseudo-binary diagram for LCS concrete, in
fig. 5, we observe contrary to the siliceous case a eutectic valley and a symmetric evolution of solid fractions that could be understood in a simple way as a justification to consider similar or close interface temperature with debris accumulation at bottom or without at sidewalls.

A more in depth analysis of these pseudo binary diagrams in connection with DNS calculations of the mixing process, fig. 3, can help us to define mushy layers and interface conditions.

In order to draw conclusion at reactor scale it is important to understand and discriminate what could be the system effect related to the size of the experiment or to the influence of transient phase concerns by the re-melting of crust formed initially or by power injection heterogeneity in case of a pool only partially melted initially. For this reason it is important not to focus on the initial stage but to consider also the mid and long term behaviour in the interpretation of the results.

Dealing with the size effect, another explanation for the ablation heterogeneity could be advanced; it is based on the possibility that the gas could by-pass the pool, especially in a siliceous concrete where gas can flow around un-melted aggregates. Without gas released in the pool, the natural convection in the melt creates a pool temperature distribution and explains higher values of heat flux upward and along the lateral wall. At the contrary in LCS concrete the gas is also released from aggregates and a gas by-pass in calcia powder and melted cement paste is not possible. If this kind of behaviour could be a possible explanation for experimental observations, it is nevertheless more difficult to imagine that the same mechanism could be extrapolated to reactor scale. It we could assume such a by-pass mechanism in the vicinity of the lateral wall it is difficult to consider a natural convection regime that is not affected by the gas released in the centre of the pool.

The phenomenon of natural convection in an internally heated liquid layer is from experimental and theoretical point of view well understood. If this phenomenon would be exclusively responsible for the effective heat fluxes in the CCI pool a preference of the lateral erosion compared to the axial one would be expected. However, since most of the related separate effect experiments on heat transfer are performed with liquids like water, which does not form such a complex viscous boundary layer near the cooled walls as in the oxidic corium case, the extrapolation to a prototypical CCI pool is complicated. From experiments performed with heated water layers a Nusselt correlation of the form \( \text{Nu} = f_1 \cdot \text{Ra}^{f_2} \), with the modified Rayleigh number \( \text{Ra} \) for internally heated pools, is concluded. Different coefficients \( f_1, f_2 \) for the bottom, lateral and top interfaces of the liquid with the cooled boundaries account for the typical heat flux distribution (top > side >> bottom) in such pools. Since the viscosity of corium is highly dependent of the temperature, the ratio of Nusselt numbers due to natural convection, and correspondingly, heat transfer coefficients between the different interface orientations is also dependent on temperature, see fig. 6 for the heat transfer coefficients of a corium typical of the OECD-CCI-5 experiment. For comparison the experimental heat transfer coefficients in the experiments CCI-5, derived from ablation rates, are included in this figure at bulk temperature. Taking into account, that the temperature in the cold boundary layer is smaller than the bulk temperature, the lateral-to-axial heat transfer ratio of the experiment CCI-5 is nearly confirmed by the correlation for natural convection. The large uncertainty of estimating corium viscosity as function of temperature has to be underlined with regard to this finding.
The various streams of discussion outlined above is very complex and a clear reason for the anisotropy of radial versus axial ablation in the case of siliceous concrete compared to the more isotropic behaviour in case of LCS concretes has not been identified yet without ambiguity. As long as the various mechanisms are not understood in sufficient detail, it is necessary to provide also an estimate for the heat transfer between corium and concrete on a much more empirical basis. In a second step mechanistic models will justify in a predictive way the adopted simplifications for other type of concretes. Such a more empirical approach is introduced into MEDIcIS [26] by GRS. This simplified approach does not consider the detailed existence of crusts or other complex mechanisms at the interface, but rather requires an approximation of the overall effective heat transfer coefficient at the interfaces of different orientation. From a simplified evaluation of effective heat transfer coefficients observed in several 2D MCCI experiments approximate heat transfer coefficients for the interface between corium and concrete (axial, radial) as listed in the following table are estimated:

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Interface orientation</th>
<th>Axial</th>
<th>Radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siliceous</td>
<td>~ 80 W/(m²K)</td>
<td>~ 300 W/(m²K)</td>
<td></td>
</tr>
<tr>
<td>LCS</td>
<td>~ 200 W/(m²K)</td>
<td>~ 200 W/(m²K)</td>
<td></td>
</tr>
</tbody>
</table>

However, for a correct geometrical partition of heat fluxes also, the heat transfer coefficient to the top surface must be known. Unfortunately, from the “dry” experiments (“dry”: without top flooding) no adequate data for the top surface heat transfer coefficient can be obtained, since the surface temperature is not measured in most cases (screening effect due initially to fumes and aerosols and then to crust anchoring phenomena). A reasonable hypothesis is that in case of siliceous concretes with small gas content and possibility of gas pool by-pass

Figure 6: Course of effective heat transfer coefficients due to natural convection in an internally heated corium layer as function of temperature. Material properties are selected close to OECD-CCI-5, however, viscosity as function of temperature is very uncertain. The correlation is only valid for viscosity corresponding to indicated temperature band.
there is a significant preference of the radial ablation direction because of the impact of natural convection with internal heating. Due to this phenomenology and the known convection patterns, the heat transfer to the top can be expected at least as equal efficient as the lateral heat transfer; probably it is even more efficient. With higher gas superficial velocities in the case of LCS concrete it is expected that the heat transfer distribution is more uniform: switching from siliceous to LCS concrete the downward heat transfer is increased because of the bubbling of the gases and the sideward heat transfer is reduced. The reason for the latter is not clear: maybe because of a formation of gas films at vertical walls or of the counteracting effects of gas rising upwards and cooled melt flowing downwards.

Regarding the additional options for expressing effective heat transfer coefficients in ASTEC, introduced by GRS, it is either possible to express a constant effective heat transfer coefficient (like the values given in the table above) or to express a characteristic surface renewal time $\tau$ in combination with the option "surface renewal model". The idea is, that there is an ideal contact of a conducting solid ( mushy or solidified melt near the interface to the concrete) with an isothermal solid interface (concrete ablation contour), and the heat flux is obtained by time-averaged transient heat conduction in the immobilised melt towards the isotherm. After the renewal time $\tau$ the crust is re-melted and the accumulated degraded concrete is periodically mixed with the melt which is brought again with uniform temperature into ideal contact with the isotherm of the ablation contour. The shorter the renewal time $\tau$ is, the larger is the contribution of initial high heat fluxes after first contact of the conducting melt at uniform temperature with the cold boundary and the higher is the time-averaged heat flux. The variation of pool properties with time (due to dilution with concrete slags etc.) may lead to a transient behaviour of the renewal time $\tau$. However, for many experiments, the application of a constant renewal time $\tau$ for the different interfaces seems already satisfactory. The assessment of this empirical approach is still ongoing at GRS.

2.2.2 Metal-oxide stratified layers stability

To describe the heat transfer between two stratified layers, a new global (bulk to bulk) correlation has been developed on the basis of ABI (CEA) experimental results and confirms higher heat transfer values than sideward or upward ones in the oxide layer. For simulant fluids, DNS calculations show thermal gradients in both layers but also in a liquid sub layer at the interface. It justifies the fact that the heat transfer can’t be described with two thermal resistances in series on the basis of a correlation established with the properties of only one fluid as proposed by Green. Keeping a simple and global approach, a new correlation taking now into account the fluid properties in both layers has been satisfactorily validated against all Green’s results [22].

Associated with the oxide-metal heat transfer coefficient, the interface temperature is also an important issue and has to be consistent with the definition of the heat transfer correlation. The nature of the interface between oxide and metal will depend indirectly on the boundaries conditions with concrete. If the metal is in direct contact with concrete its temperature will be cold enough to create an oxide crust between oxide and metal; we can wonder about the stability of such a crust due to the gas bubbling but from thermal point view it will create a thermal resistance and fix the downward interface temperature for the oxidic phase. Some tests performed in ABI facility with glass balls at the interface to simulate this porous crust show that the heat transfer is reduced only by 15% and that correlation remains valid if applied between oxide bulk and pool liquidus temperatures. If we consider a fully mixed situation before stratification we can consider that oxide debris are accumulated at the bottom and when the metal stratified it remains at high temperature above these debris that have no reason to be dissolved. In that case the interface between oxide and metal remains liquid and bulk to bulk heat transfer correlation can be applied.
The correlations for entrainment thresholds deduced from BALISE results give us the possibility to consider now in ASTEC a free evolution of the melt pool configuration. They are quite simple and correlate the superficial gas velocities to the relative density differences between the two layers. If at the beginning metal layer is lighter, the increase of concrete content in the oxide phase decreases the oxide density, the pool becomes fully mixed before reaching the point where remaining metal starts to stratify at the bottom (we are then just below the full mixing threshold), the stratified metal layer thickness continues to grow if the gas release decreases. When the beginning entrainment threshold is reached, the pool is fully stratified. Nevertheless, as soon as the metal is stratified at the bottom, heat transfer in the oxide to the metal increases and as a consequence axial concrete ablation would be more intense with a higher gas and concrete release that promote mixing. As the two effects are antagonistic, it is difficult to conclude in those conditions on the stability of two stratified layers and perhaps it will be more appropriate to consider a succession of transient state with partial stratification. In that perspective, it is necessary to define a renewal time from a mechanistic approach or in a simplest way by fitting with experimental results. Two other phenomena play an indirect role on the stability, the oxidation rate of the metal phase and a fast radial ablation that leads especially at test scale to a significant reduction of the liquid metal layer thickness. As a matter of fact, we can also assume that the situation is no more stable for small liquid metal thickness as soon as it reaches the diameter of a few gas bubbles. This additional criterion should be defined by additional entrainment experiments where the thickness of the denser liquid will vary up to very small values. For the time being, the minimum thickness for stratification stability will be imposed as a parameter of the calculations. The on going analysis of VULCANO post test examinations and their interpretation with thermodynamic calculations will give us information on phase composition distribution to identify metal oxidation mechanisms and the possibility to assess existing models (chemical equilibrium with gas release) or to extend them with additional reactions.

2.2.3 Coolability mechanisms and melt stabilization

Coolability models -for cooling the melt pool by water from the top- include bulk cooling at the direct melt-water contact, dry-out heat flux modelling (water ingestion), melt eruptions and debris coolability, and crust stability modelling.

Standard models are employed in codes (for already a long time) for the description of the boiling heat transfer at the melt-water interface. These models are based on standard pool boiling correlations, with corrections for the effect of water subcooling and, also, for the effect of non-condensable gases ejection at the melt-water interface (which increases the heat transfer by increasing agitation of the melt surface and of the coolant as well) -see for example [27]. Calculations of the water ingestion through crust, as currently used in some of the CCI codes, found its origin in geological research, in theory of water penetration into hot rock [28]. The derived equations enable to calculate the permeability of the cooling (cracking) material from which the dryout heat flux is directly obtained. The permeability -and thus the dryout heat flux- is described as a function of thermophysical properties of the material: crust density, thermal conductivity, linear expansion coefficient, fracture stress, elastic modulus, and others. In 2006, Epstein [29] came with a new formulation of this model where the description of the dry-out heat flux in a porous medium was combined with modelling of a steady-state, 1D phase change (solidification of the crust). This model was further refined in the frame of the MCCI project [30]. The resulting correlation for the corium dry-out heat flux has one empirical constant which was adjusted to fit the SSWICS dry-out heat flux data [31]. In such a form, the correlation is employed in the CORQUENCH code and a simpler formulation is also used in the integral ASTEC code. Models of the effect of gas sparging on dry-out heat flux are still missing (it affects the morphology of the crust: adds some new porosity in the crust when sparging gases enter it from bellow).
The melt entrainment (eruptions) is primarily driven by sparging gases released from the decomposition of concrete at CCI; thus, in general, more important for limestone concrete with higher gas content than for siliceous concrete. The melt has to pass through the cracks and crevices (channels, holes) in the upper crust to get atop of it. An early model of the melt entrainment mechanism, proposed in [4], simply correlated the melt entrainment rate with the gas volumetric flow rate. The ratio of the two, the entrainment coefficient Ke, was an input parameter to the model. Ke, deduced from the MACE results, was about 0.01%-0.1%. A simple model, based on this, is coded in ASTEC and also, as an option, in CORQUENCH.

The PERCOLA experimental program at CEA studied eruptions using simulant fluids. Based on the experimental data, models of the single-phase extrusion (“fountain” model) and two-phase jetting eruption mechanism were developed by Tourniaire et al [32]. In this modelling, the channel (single hole) diameter and the number of channels (eruption sites) have to be known quantities. A detailed model, derived from the PERCOLA analyses, is incorporated in the CEA code TOLBIAC. Most recent work [33] on eruption modelling takes the key features of the Tourniaire et al [32] approach, adding some new ideas. Firstly, the idea from the single-phase extrusion model by Farmer [34], of setting the channel diameter to the minimum to prevent melt freezing in a channel. This is used to determine the size of the hole. And then the analysis on water flooding of the channels gives closure relations which enable to determine, among other things, the eruption site density of uniform sized and uniformly spaced flow channels. The new model is now being tested as a part of the MCCI-2 analytical activities.

Recent parametric studies [35] with the CORQUENCH code indicate that, among the MCCI phenomena, the melt entrainment cooling mechanism has the greatest impact on the total concrete ablation. It increases the upward heat flux by the melt ejection and the subsequent quenching of melt, with the formation of particle bed atop the crust. The particle bed weight is also taken into account, together with other parameters, when calculating the crust stability. With this, it is easier to obtain bulk cooling of the melt, at least for some time, when the crust is breaking.

As for the engineering features to enhance coolability, such as the bottom water injection - COMET concept, currently there are no simple models of the respective cooling mechanisms (which are otherwise believed to be very effective in stabilizing the corium in cavity).

3 POTENTIAL APPLICATION FOR CONTAINMENT INTEGRITY

3.1 Reactor applications with updated knowledge

3.1.1 Parametric ASTEC reactor study for 900 MWe PWR

The bounding approach followed at the beginning of 2000s conducted for a 4m thick siliceous basemat to a melt-trough delay about 9 days for homogeneous oxidic melt and around 1 day only if we consider a constant stratification for a metal-oxide pool. Ten years after these reactor simulations, new studies have been performed with ASTEC after the integration of the current state of the art in order to provide more realistic evaluations.
For metal-oxide melt, experimental results show that a stable stratification over a long duration seems more and more unlikely. So, it is more logic to include the evolution of the pool configuration with stratification criteria that limit the duration of a stable metal layer at the bottom and thus impact significantly the melt-through delay.

In these new simulations [36], the melt-through time for a 4m thick siliceous concrete and a PWR 900 MW ex-vessel inventory (40 tons of metal and 100 tons of oxide) is extended from 1 day to almost 5 days fig. 7. This delay is the direct consequence of a stratification period reduced to 7h after 20h of interaction in full mixed regime fig. 8.

Free pool configuration evolution are based on the use of two superficial gas velocity criteria obtained from BALISE results, one for the full mixing (0.18 $\Delta \rho/\rho_L$) and one for the onset of entrainment (0.06 $\Delta \rho/\rho_L$). These two thresholds give us the possibility to consider a stratification and then to go back to a mixed situation with a delay in order to avoid oscillation. The intermediate situations with partial metal entrainment in the oxide pool are nevertheless not described.

![Figure 7](image_url)
Because the extrapolation of stratification criteria to reactor conditions is not obvious (the choice of simulant fluid is only partially justified), a parametric study has been performed and the melt trough time plotted in fig. 9 as a function of the constant that appears in the full mixing criterion.

We can observe that this criterion governing the change between homogeneous to stratified pool configuration affects strongly the melt-trough time because it accelerates or delays the stratification onset and consequently the overall duration of the stratified period during when the axial ablation is increased.
A sensitivity study on heat transfer coefficients between oxide and metal layer shows that it has a weak influence on the melt-through time (left part of fig. 9). This trend can be explained by the fact that even if the heat transfer at the interface is reduced by a factor 5, it remains high enough compared to the lateral heat transfer between oxide melt and concrete.

A sensitivity study on the minimum metal thickness to consider that layer stratification is still possible shows (right part of fig. 9) a larger dependency because its increase reduces directly the time duration of a stable stratified configuration.

For pure oxidic melt and because predictive mechanistic concrete ablation models are not yet available, the experimental results that show a dependency to concrete composition have to be considered in simulation as an adjustment of axial and radial heat transfers. It could be done adjusting convective heat transfer coefficients, boundary temperatures or thermal resistance of the slag layer. It is this last choice that has been considered in the MEDICIS calculations described hereafter using values giving effective heat transfers close to the GRS recommendations. For siliceous concrete, a larger thermal resistance value at the bottom is assumed due to the hypothesis of an accumulation of silica aggregates, which are blocked below a refractory debris crust, whereas a lower sidewall value accounts for the assumed continuous release of aggregates within the melt in the absence of a stable crust.

Finally, if we combine the ablation anisotropy observed for siliceous concrete with a free configuration evolution the axial melt-through time is delayed up to 11 days because a larger fraction of the internal power is released to the side wall, fig. 10. We can add that if a radial melt-through of the RPV occurs, the amount of corium melt located above the breach could be poured and spread in the reactor building reducing the corium inventory in the vessel pit extending again the melt trough time.

**Figure 10**: ASTEC simulation with free pool configuration evolution and heterogeneous ablation [36]
3.1.2 Application to EPR vessel pit

The EPR severe accident management strategy [37] is based on temporary melt retention in the reactor pit and then spreading the molten corium–concrete mixture as a thin layer over a large area (170 m²) in the core catcher (fig. 11). When the reactor pressure vessel fails, the molten corium is discharged to the reactor pit. There is no water in the pit, which prevents steam explosions. The pit floor and walls are coated with 50 cm thick layer of sacrificial material, which is made of the hematite-containing concrete. Due to the high temperature and decay heat of the corium, the sacrificial concrete melts. Eventually the melt plug at the bottom of the pit fails, and the melt flows through the discharge channel to the core catcher, which is dry at that moment in order to prevent steam explosions. Arrival of the melt triggers passive flooding of the core catcher. The large heat transfer area makes it possible to cool the melt by water from top and bottom. Because the core catcher is separated from the reactor pit, mechanical loads due to the pressure vessel failure do not damage the core catcher.

Ablation of the sacrificial concrete in the floor of the reactor pit should last sufficiently long time so that practically all corium is discharged from the reactor before the failure of the melt plug. Too early failure of the melt plug could cause some late-coming melt to flow to the core catcher when it is already flooded with water. This, in turn, could cause a steam explosion or hamper the spreading of the corium to a coolable configuration. Predicting the failure time of the melt plug requires knowledge of the interaction between molten corium and hematite-containing sacrificial concrete.

The interaction between molten materials and the hematite-containing concrete has been investigated in the HECLA experiments at VTT [25] and in the VULCANO VB-U7 experiment at CEA. It has been observed that the special concrete behaves in a similar way as ordinary siliceous concrete: the sidewall ablation is significantly faster than the basemat ablation when the melt is mostly oxidic corium. This was an interesting result since limestone-common-sand concrete, another common concrete type, behaves in a different way and ablates at about the same rate in the basemat as in the sidewall.

The faster sidewall ablation is expected to cause a relatively slow ablation of the melt plug in the EPR reactor pit floor, which is good for ensuring that the molten corium is released to the core catcher in one batch. It is likely that the melt will contact the protective layer in the pit sidewalls before the failure of the melt plug. The protective layer is made of ZrO₂, which has
been observed to be resistant to corium melt as long as the melt temperature remains below
the liquidus temperature. Naturally there are still uncertainties in predicting corium melt
behaviour in the EPR containment, but experimental research has significantly improved our
understanding of the progression of a hypothetical severe accident.

3.2 Review of different mitigation concepts

The containment integrity and the fission products retention are clearly important stakes for
safety. In an international competitive market, the choices in terms of mitigation devices are
strategic for the competitiveness of new reactors. Designers adopt different approaches like
a dedicated spreading core catcher concept with bottom cooling plate designed for EPR or
ATMEA reactors or a vessel pit flooding solution proposed in AP600 or AP1000 reactors to
maintain the corium within the flooded vessel.

This last solution is also declined to a certain extent in VVER 1000 Russian reactors with an
intermediate concept based on a vessel core catcher located below the reactor vessel,
including sacrificial material and external cooling to collect and stabilize the corium melt.

Coming back to the coolability issue during corium concrete interaction, the Korean
APR1400 reactor will include a COMET concept basemat but with a simultaneous water and
gas injection in order to reduce steam explosion risks and limit the over pressurisation due to
a too fast water vaporization. Other designs consider alternative bottom cooling devices
(channels or several inclined pipes like in BIMAC concept [38]) embedded in a sacrificial
concrete layer at the surface of more or less larger pits to reduce the corium melt thickness
and as a consequence the heat flux values that have to be extracted to stabilize the melt. For
such designs – after bottom cooling – water generally arrives also by the side and then from
the top to avoid sidewall melt-through and enhances the overall corium melt coolability.

In most of these concepts an interaction phase with sacrificial concrete will precede a
coolability phase. In some cases it is possible to dissociate the cooling aspect from the
corium concrete interaction mechanism. It is the case for the EPR cooling plate for which
thermalhydraulic aspects can be considered separately looking for heat removing
mechanism and critical heat flux limitations but it is clear that for water injection from a
porous concrete we need to take into account simultaneously corium concrete interaction,
corium porosity formation and corium cooling. The BIMAC concept is close to the EPR
design but with pipes embedded in a sacrificial concrete layer to replace bottom plate and
here also the critical heat flux limitations can be address separately from pure thermal-
hydraulic tests. Nevertheless like in EPR, the transient heat fluxes received by the cooling
device are connected with the concrete degradation phenomena including the gas release
and the ablation mechanisms that could present different kinetics as a function of concrete
composition and melt composition.

Beyond new reactors, another stake concerns existing plants for which we are concerned
with the life extension issues and the possibility to be faced with the cohabitation of existing
and new generation plants. In that case for the public acceptance, it is difficult to imagine that
for a given site we can justify a higher level of safety to build new reactors and explain at the
same time that we will extend the operation duration of an existing reactor that will appear to
be less safe. For that reason additional mitigation measures will have to be defined to extend
the operation duration for existing plants tending toward the level of safety reached by GEN-
III reactors.

For existing plants, the water addition on top of a corium melt in interaction with basemat
concrete is certainly the most simple and generic mitigation measure. Nevertheless in terms
of efficiency the demonstration has not been yet fully performed and we have to wonder if it is possible to consider other solutions or to implement after adaptation some of the concepts that have been designed for new reactors.

For Boiling Water Reactors, Sweden rely on reactor specificities to flood the pit over a high water elevation before the vessel rupture to promote a full corium fragmentation compatible with a debris bed cooling, if we assume that no energetic event such as steam explosion occurs during the jet fragmentation process. Beyond the dynamic loading that could damage the containment, such an event will reduce drastically the particle size and the possibility to cool the debris bed.

As it is a real challenge to perform modification in the basemat of an operating plant due to high radiological constraint, the possibility to adapt existing concepts or imagine new ones need to be address in parallel from an engineering point of view by utilities. From R&D point of view we can only give orientations toward what could be the more promising mechanism on the basis of the past and future generic investigation.

According to the actual knowledge status, the COMET concept that will provide water by the bottom from a porous concrete is a good candidate to imagine an evolutionary design that could be implemented with remote control operations in a way close to the operations that could be deployed to simply increase the thickness of a reactor basemat in order to obtain an extra delay on melt-through time for the thinner one.

3.3 Possibility to address remaining issues in future programs

Up to now the OECD-MCCI program provides a large database that will be completed from a more analytical point of view with the ongoing programs in the frame of SARNET European network of excellence. By the end of 2012, we will obtain additional data from separate effect tests to conclude on concrete composition impact on the local ablation mechanism and as a consequence on the overall ablation shape. For dry situation the main remaining effort is to improve models in a more mechanistic way or with the support of mechanistic approaches only if we want to keep models simple enough to be appropriate for severe accident codes, to give them the missing predictive feature. The support of the direct numerical simulation that offers the possibility to visualize the phenomena in prototypic fluid should be useful to support the development of mechanistic models.

For metal-oxide pools, the sensitivity studies shows that axial erosion will be strongly linked with the period of time when a metal layer is stratified at the bottom. This duration is connected with the stratification criteria but also with the oxidation kinetics or, at a less extent for reactor geometry, with the radial ablation. Because of the counterbalance between downward heat flux focusing induced by stratification and re-mixing of the two layers induced by gas release increase, the existence of a likely intermediate situation between full mixing and total stratification has to be evaluated and appropriate models proposed in connection with a minimum metal layer thickness for which stratification and downward heat flux focusing is still observed. If first global results have been obtained in prototypic material with VULCANO experiments, their interpretation is complex and a more analytical approach should be followed in prototypic material or in simulant fluids according to our experimental capabilities to support this activity. In a near future, a better understanding of the oxidation mechanisms is expected from the interpretation of the VULCANO post test examinations. It could be completed by the revisit of the past KIT’s experiments to discriminate the oxidation of a stratified metal layer percolated by concrete gas and oxide, from the oxidation that could occur also when the metal is initially dispersed in the corium oxide phase. In parallel, the ongoing progress in the field of direct numerical simulation will give us the possibility, after a
remaining intensive validation step, to quantify liquid entrainment criteria and heat transfer coefficient at metal-oxide interface in order to validate the extrapolation of existing correlations.

For melt coolability the water addition by top and the related cooling mechanisms have been studied in the OECD-MCCI program. If significant knowledge has been increased for water ingresson mechanism and crust mechanical strength, the melt ejection is still a key issue and a challenge for experimental investigation in a separate effect way. Global experiments in 2D geometry show – but from one test only – a promising way to evaluate the efficiency of melt ejection mechanism in the overall cooling process. It is clear that one test with very early reflooding is not enough to conclude on the efficiency of the top cooling to stabilize the melt and that this result can not extend to more generic severe accident management strategies for which water could be added later.

For alternative mitigation concepts, additional tests including both corium concrete interaction and coolability aspects could be needed depending on their design. These tests could be supported by vendors for new reactors or by utilities in a back-fitting strategy but we can also imagine to perform them in a more cooperative international program if we can extract the general key mechanisms on which we still need to improve our knowledge.

To perform such complex tests it is obvious that our interest is to continue to rely on existing experimental capabilities taking into account also the know-how and the experience of the teams. Argonne National Laboratory proposes recently a new program – Advanced Plant Accident Management Analysis and Testing (APAMAT) – to address these issues through three categories of tests:

- Additional combined effect tests to investigate the interplay of different cooling mechanisms, and to provide data for model development and code assessment purposes.
- Integral tests to investigate design features to enhance coolability, focused on new reactor concepts.
- Integral tests to examine debris coolability under early top flooding conditions that is applicable to both existing as well as advanced plant designs.

Aside from these various testing categories, it is also foreseen to carry out a parallel analysis activity in the frame of an international collaboration to fully realize the benefits from the experiment. This new program with other proposals coming may be from Korea will be discussed during the final seminar of the MCCI-OECD project that will take place at Cadarache (France) from the 15th to the 17th of November 2010.

4 CONCLUSION

During the last 10 years, the experimental data base has been extended and several improvements have been performed in terms of interpretation and model development. If we can now perform more realistic reactor simulations that consider the impact of metal-oxide configuration evolution, numeric tools are not yet fully predictable. We still need to postulate heat transfer distribution as a function of concrete composition and use criteria for melt stratified layers that are extrapolated from simulant material and are not yet confirmed in prototypic material. By the end of 2012, the data base for homogeneous configurations would be normally sufficient to support remaining interpretation and modelling efforts, and for metal-
oxide configurations, we can hope that more analytical approaches will be followed to evaluate definitively the impact of a metal stratification at reactor scale.

In terms of containment failure mitigation, the top flooding strategy is the simplest especially for existing plants. Several cooling models have been developed and checked on separate effect experiments. For the melt ejection models, it is clear that the community need additional validation in prototypic conditions to establish that the corium melt progression could be stopped (for different water addition times and for different concrete types) in order to draw more generic conclusions regarding safety management procedures.

For more advanced cooling concepts, we need to develop the appropriate level of knowledge to evaluate the solutions that are, or will be, proposed by vendors for new reactors. According to their innovative content we can rely on existing generic data or we will need new validation programs. In parallel, if utilities are ready to investigate from engineering point of view the possibility to perform some modifications on existing concepts to implement them in existing plants, we can imagine here also that specific experimental validation programs will be requested.

To improve our knowledge and to keep the possibility to validate advanced designs with significant mass of prototypic material we need to maintain the existing facilities in operation or to develop new ones. As the development of the appropriate technology is a long process we can hope that the community will be able to converge – after the final seminar of the OECD-MCCI project – on the definition and on the funding with the support of utilities and vendors of a new international program: this has been proposed by ANL to investigate coolability issues for both existing plants and new reactors.

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