

5.3. Phenomena that could lead to delayed containment failure: Molten Core-Concrete Interaction (MCCI)

5.3.1. Introduction

In the event of reactor-vessel failure during a core melt accident, the corium resulting from this core melt and the melting of internal structures will pour onto the reactor pit basemat. Contact between corium and concrete leads to what is called Molten Core-Concrete Interaction. This interaction involves gradual erosion of the concrete basemat (see Figure 5.36) and the walls of the reactor pit, which could lead to basemat penetration, and consequent release of radioactive substances outside the containment building into the ground. Furthermore, contact between the corium and any water present in the reactor pit and adjacent rooms could contribute an increase in the pressure inside the containment building *via* vapourisation of this water, or could even lead to a steam explosion (see Section 5.2.3). Gases resulting from reactions between corium and concrete also contribute to increasing the pressure inside the containment building. Taking uncertainties into account, the penetration time for the concrete basemat will be from one to several days, depending on the quantity of corium, its possible cooling and the type of concrete (siliceous or calcareous). It should be noted finally that the aerosol production that accompanies MCCI also affects how the behaviour of radioactive aerosols inside the containment changes and therefore affects any resulting releases.

5.3.2. Physical phenomena involved

The residual heat released by fission products within the corium spread on the basemat of the reactor building (20 to 30 MW at the start of the accident for a 900 MWe PWR) cannot be removed by conduction *via* the basemat due to its thickness and the very low thermal conductivity of concrete; it is only partially dissipated by radiative heat transfer from the surface of the corium. The corium, whose liquidity depends on its composition (which depends on the development of core damage during the accident), therefore heats up to the melting point of the oxide materials (UO_2 , ZrO_2) and the metals from the vessel (i.e. to a temperature of approximately 2200 °C), leading to the formation of a corium pool with a temperature exceeding the decomposition temperature of concrete. The heat released by the fission products is transferred by convection to the edges of the corium pool and provokes the destruction of the concrete walls of the reactor pit and their loss of integrity by decomposition of concrete (this process is generally called erosion or ablation). Siliceous or silico-calcareous concrete erodes from 1330 °C and calcareous concrete from a temperature several hundred degrees higher than that. After an initial corium heating phase, MCCI therefore leads to a phase of continuous erosion of the concrete walls. During this phase, the residual heat is largely dissipated at the corium-concrete interfaces *via* erosion of the concrete, and to a lesser extent by radiative heat transfer from the surface of the corium pool (see Figure 5.36).

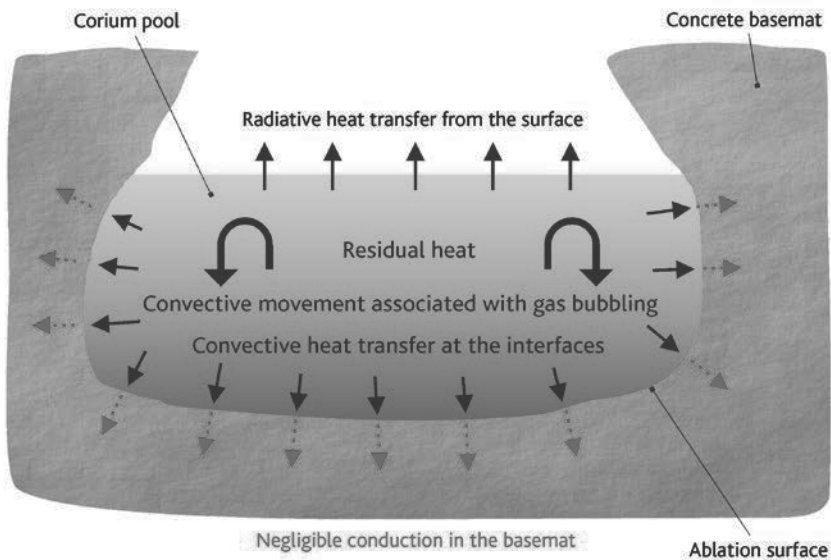


Figure 5.36. Formation of a cavity by erosion of the reactor-pit basemat.

As the concrete is made up mainly of SiO_2 , CaCO_3 and H_2O , its decomposition leads to the release of condensed (SiO_2 and CaO) and gaseous (H_2O and CO_2) phases into the pool. The corium pool therefore contains heavy oxides from the reactor core (UO_2 and ZrO_2), light oxides from the concrete (mainly SiO_2 and CaO) and metals (Fe, Cr, Ni and Zr), all subject to the mixing induced by the concrete decomposition gases. The mixing of metals with oxides in condensed or gaseous form can lead to exothermic oxidation reactions that produce gases such as H_2 , CO and $\text{SiO}(\text{g})$. Finally, contact between hot corium and colder concrete can lead to local formation of a crust by solidification, and fragments of this crust can become suspended in the liquid corium. The corium pool therefore has several constituents and several phases (liquid, solid and gas) whose composition and physical properties constantly change during MCCI, due to decomposition of the concrete and to chemical reactions.

As the rate of erosion of the horizontal and vertical walls is directly correlated to the relationship between the heat flux received by the walls and the energy density required for their erosion, determination of the rate of erosion of these walls requires calculation of the heat flux distribution at the edges of the corium pool. Even if there are multiple immiscible phases, the liquid pool produced by MCCI is uniform due to the mixing induced by the gases; however, steep temperature and concentration gradients may exist at the interfaces (see Figure 5.37). The heat flux at the pool interfaces may therefore be calculated using a convective heat transfer coefficient (h_{conv}), the pool temperature (T_b) and the temperature of the interface (T_i) between the corium pool and an interface layer separating the concrete from the corium (the composition and temperature of this interface layer are intermediate between those of the corium pool and those of the concrete; the layer may be liquid or solid depending on the conditions); the interface temperature

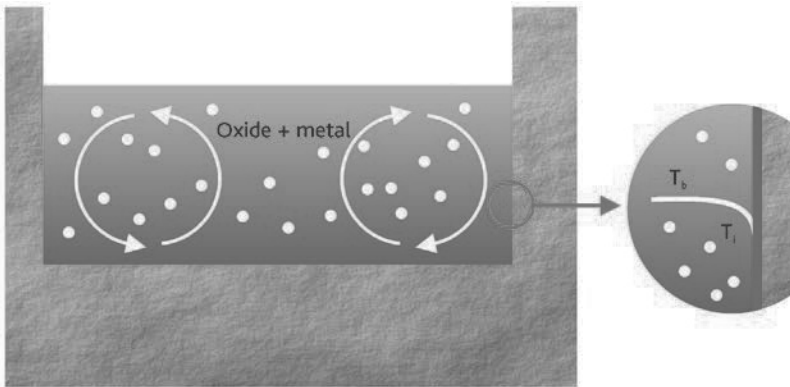


Figure 5.37. Perfectly mixed oxide-metal pool produced by an MCCI. Right: Detail of the pool-concrete interface.

depends on the type of interface between the corium and the concrete (i.e. whether a stable crust forms or not). The configuration of the pool produced by MCCI may be single layer (oxide and metal mixed) or two layer (oxide and metal stratified based on their respective densities), depending on the gas flowrate released by the concrete and the densities of the oxide and metal phases (which are only partially miscible). In the latter case (see Figure 5.38), determination of temperature at the interface, and of heat transfer coefficient is therefore necessary not only for the interfaces between the layers and the concrete, but also for the interface between the “oxide” liquid and the “metal” liquid.

To facilitate reading of the rest of this section, three phases of MCCI are distinguished: short term, medium term and long term. As will be seen below, the behaviour of the pool produced during MCCI depends on:

- its physical transport properties (density, thermal conductivity, specific heat capacity, viscosity and, to a lesser extent, liquid-gas surface tension) and its

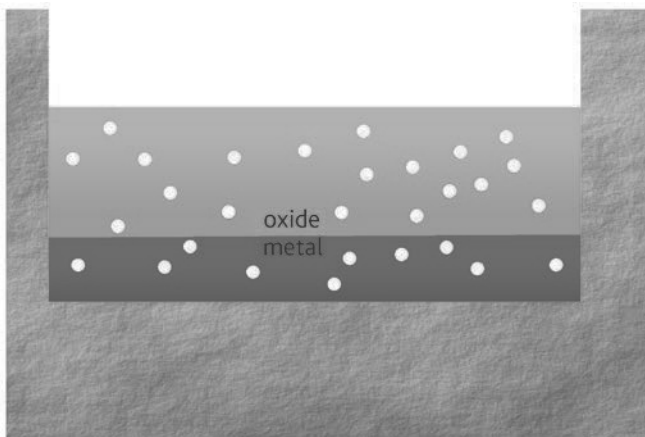


Figure 5.38. MCCI pool in a stratified configuration.

thermochemical properties, which are themselves a function of the composition of the pool, in particular the concentration of compounds from concrete erosion;

- the heat flux at the pool interfaces, which is a function of pool volume, and therefore of the quantity of matter from concrete erosion;
- the superficial gas velocity (volume flowrate of gases per unit surface area) along the interface between pool and concrete, proportional to the heat flux.

It therefore seems appropriate to distinguish various phases of MCCI, depending on the concentration of “concrete oxides” in the pool:

- the short-term phase corresponds to a mass fraction of “concrete oxides” in the pool below 25% (in practice, for a power reactor this corresponds to the initial hours of MCCI), with physical and thermochemical properties little different from those of the materials coming from the core, and vigorous gas bubbling;
- the medium-term phase corresponds to a higher mass fraction of “concrete oxides” in the pool (up to around 50%), i.e. in practice, for a power reactor, to the period between 5 and 15 hours from the start of MCCI, where the physical and thermochemical properties have significantly changed from those of the materials coming from the core but where heat flux at the pool interfaces and gas bubbling remain strong;
- finally, the long-term phase corresponds to a mass fraction of “concrete oxides” in the pool over more than 50%, i.e. in practice, for a power reactor, to the period beyond 15 hours from the start of MCCI, where heat flux at the interfaces and gas bubbling are significantly lower.

5.3.3. *Experimental programmes*

Study of MCCI includes experiments and computer models. The purpose of the experiments is to identify and understand the corresponding phenomena (heat transfers, solidification, mixing etc.); they are supplemented by studies using simulation software that include models that have been qualified on the basis of experimental data.

Tests devoted to the study of molten core-concrete interactions can be classified into two categories:

- analytical tests, which study one or more specific phenomena using simulant materials at a reduced scale; these tests can determine certain physical values concerning the phenomena studied (interface temperatures, heat transfer coefficients etc.);
- integral tests during which concrete erosion rates are measured, and in certain cases, pool temperatures during MCCI for coriums made up of simulant materials (containing alumina or thermite) and for coriums more representative of the composition expected during a core melt accident on a power reactor (generally containing a $\text{UO}_2 + \text{ZrO}_2$ mixture).

5.3.3.1. Analytical tests

► Heat transfer coefficients

Numerous analytical tests were performed between 1980 and 2010, see [1], [2] and [3], aiming to determine the heat transfer coefficients between a liquid pool and a bubbling porous wall. Examination of the results of these various tests, see [5], shows that the physical properties of the liquids used have often been close to those of water and that the data available mainly involves horizontal walls. For water, measurements performed during the various experimental programmes give similar results for the same superficial gas velocity. Data regarding viscous liquids (as for corium “enriched” with concrete erosion compounds) and vertical walls are quite rare, see [4]. However, test results in water show that the heat transfer coefficients between a fluid and a vertical wall are similar to those obtained for a horizontal wall. The CLARA experiments [6], which are described below, were launched in 2007, with a view to filling in gaps in knowledge regarding distribution of heat transfer coefficients along pool interfaces, which influence the distribution of heat fluxes and radial and vertical erosion of concrete during an MCCI.

Results pertaining to heat transfer coefficients between two immiscible liquids with gas bubbling (stratified pool configuration, see Figure 5.38) are less common, see [7] and [8]. In particular, examination of these results shows a significant dispersion of results (by around a factor of 5). Furthermore, the tests are not representative of situations where there is solidification at the interface between the pool and the concrete. However, the ABI tests, see [9], performed until 2008, show that the order of magnitude of the heat transfer coefficient between two stratified oxide and metal layers is comparable to that determined using the correlation deduced from the Werle tests, see [8], and that this heat transfer coefficient is probably large compared with the heat transfer coefficient between a liquid pool and a porous wall mentioned above. These results mean that, in a stratified configuration, heat transfer from the oxide layer into the metal layer could accelerate erosion of the concrete wall in contact with the metal layer (in the lower part, see Figure 5.38). This also highlights the interest of a reliable prediction of pool stratification (mixing and separation phenomena).

► Interface temperatures at the edges of a corium pool

The ARTEMIS programme (see [10]), performed by CEA from 2003 to 2008, is the only one that aimed to determine temperatures at the edges of a corium pool. It studied the coupling between physico-chemistry and thermal-hydraulics through tests conducted with simulant materials (LiCl and BaCl₂ salt mixtures), whose phase diagram has a similar form to that of the compounds present during an MCCI for a power reactor, as shown in Figure 5.39.

Tests performed in one-dimensional configurations (horizontal corium-concrete interface) confirmed that, under test conditions representative of the long-term phase of MCCI for a power reactor in terms of concrete erosion rate and gas bubbling,

the interface temperatures at pool edges were close to the liquidus temperature of the pool and that the pool temperature decreased with liquidus temperature due to enrichment of the pool with compounds from concrete erosion. However, the interface structure seems to be more complex than expected, with the formation near the interface of a solid porous zone out of thermal equilibrium (i.e. with liquid-solid interface temperature and composition that deviate from those imposed by thermal equilibrium between the liquid and solid phases). Examination of the results of ARTEMIS 1D experiments, see [11] and [12], also shows that, under conditions comparable to those of the short-term and medium-term phases of an MCCI for a power reactor, the results are not compatible with an assumption of thermodynamic equilibrium: the temperature of the pool-crust interface deviates from the liquidus temperature, the pool becomes mushy in the event of significant gas bubbling, and crusts form at the corium-concrete interface with a composition less refractory than that deduced from the phase diagrams.

Following an initial stage of the ARTEMIS programme dedicated to tests with purely axial erosion, the second stage (ARTEMIS 2D) was dedicated to the study of configurations with two-dimensional concrete erosion (i.e. in both axial and radial directions) during MCCI tests with differing compositions between pool and concrete and “concrete-concrete” tests with no difference in composition between pool and concrete. The results show significant concrete erosion on the upper part of the concrete side walls for all tests, very little erosion on the lower interface between pool and concrete during concrete-concrete tests and the formation, during MCCI tests, of a very thick

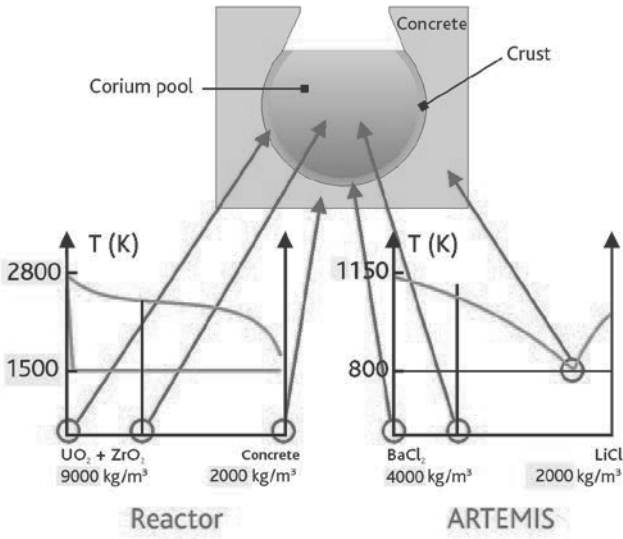


Figure 5.39. Comparison between the phase diagrams of simulant materials from ARTEMIS tests and those of corium materials which would form during a core melt accident on a power reactor (the $BaCl_2$ salt simulates the refractory behavior of corium and the $LiCl$ - $BaCl_2$ eutectic simulates the behavior of concrete), see [10].

mushy crust of corium at the lower interface between the pool and the concrete (covering around a third of the pool); during the tests, this crust remained hot and embedded itself into the concrete. These unexpected results in terms of concrete erosion (in all cases, more concrete erosion was expected in the lower part of the pool) are probably explained by pool bypass by the gases injected into the lower part, due to the formation of stable, leaktight crusts at the lower pool-concrete interface; these crusts meant that gases could not pass during most of the tests. At the scale of a power reactor, it is unlikely that a large non-cracked crust would form at the lower pool-concrete interface. The results of the ARTEMIS 2D tests are therefore not directly applicable to a power reactor; however, they have brought to light the strong dependence of the 2D erosion profile on gas flow conditions in the pool.

► **Mixing and separation of immiscible liquids with gas bubbling**

The mixing and separation of immiscible liquids with gas bubbling has been studied with the aim of predicting the corium pool configuration during MCCI (i.e. whether the pool is mixed or stratified). The main experimental work on this subject was performed using simulant materials at the Argonne National Laboratory (ANL, [13]) and the University of Wisconsin (see [14]) in the United States, and more recently at CEA Grenoble (BALISE tests), see [15]; all experiments were purely hydrodynamic (with no study of phase change effects). They aimed to determine limit values in terms of superficial gas velocity (or void fraction) leading to a mixed or stratified pool depending on the density difference between the liquids. The results summary given in [15] shows a – sometimes wide – dispersion of results, partially due to differences in the physical properties of the liquids used. Nevertheless, these experiments clearly demonstrate that stratification of a corium pool can only take place for low superficial gas velocities, which are only possible during the long-term phase of MCCI for a power reactor.

► **Physical properties of the materials**

Analytical tests with prototypic corium compositions, like those which would form during core melt accident on a power reactor, have also been performed to validate and supplement knowledge regarding the thermophysical properties (in particular viscosity, see [21]) and thermochemical properties of corium, which are needed for the computer models of heat transfer and solidification phenomena for the corium pool outside the reactor vessel. These tests meant that improved estimates could be made of the viscosity of a corium formed from a mix of oxides (as a function of silica concentration), and of the solidus and liquidus temperatures of the corium-concrete mixes.

5.3.3.2. Integral tests

Integral tests provide an overview of MCCI, with all phenomena involved operating in a coupled manner. These tests are difficult to perform given the associated technological difficulties (very high temperatures and materials used etc.). All integral MCCI tests performed up to 2012 are summarised in Table 5.5 below.

Table 5.5. Summary of integral MCCI tests.

Programme	Characteristics	Mass of corium	Geometry	Parameters
SURC (1D)	Prototypic corium compositions + fission products	200 kg	0.4-m-diameter cylinder	Concrete composition, power
ACE (1D)	Prototypic corium compositions + fission products	250 to 450 kg	Rectangular box 0.5 m x 0.5 m x 0.4 m	Concrete composition, power
MACE (1D)	Prototypic corium compositions water injection	100 to 1800 kg	Rectangular box (0.5 to 1.2 m) x (0.5 to 1.2 m) x 0.4 m	Concrete composition, power, water flowrate
BETA (2D)	Thermite-alumina + iron oxide-metal stratified pool	450 kg	0.4-m-diameter conical frustum	Concrete composition, power
COMET-L (2D)	Thermite-alumina + iron oxide-metal stratified pool	920 kg	0.6-m-diameter cylinder	Concrete composition, power
OECD-MCCI (2D)	Prototypic corium compositions	350 to 550 kg	Rectangular box 0.5 m x (0.5 m or 0.7 m) x 0.6 m	Concrete composition, power, pool geometry
ARTEMIS 2D	Simulants (salts)	110 kg	0.3-m-diameter, 0.6-m-high cylinder	Power, gas flowrate
VULCANO-ICB (2D)	Prototypic corium compositions	40 kg	0.3-m-diameter, 0.3-m-high half-cylinder	Concrete composition, power

Interpretation of these integral tests is complex due to the limited number of measurements and the lack of precision associated with some of them, the difficulty of estimating heat losses and sometimes the difficulty in quantifying the influence of certain phenomena associated with the test set-up which may affect heat transfers above the pool: effects of the heating method and scale effects which could affect pool formation, ejection of matter (which changes the inventory of corium participating in MCCI), and crust adhesion on the walls. Despite these difficulties, the tests performed have brought to light phenomena which had not been previously identified and which could be significant: the strong influence of the type of concrete on the progress of axial and radial erosion and on the ejection of corium during an MCCI under water during the MACE tests; MCCI under water is presented in more detail in Section 5.4.2.

From a chronological standpoint, 1D tests with oxides (ACE, MACE and SURC) date from twenty years ago or more. Their analysis has provided an improved understanding of MCCI, supported certain assumptions regarding the corium behaviour models (decrease in pool temperature close to the liquidus temperature) and partially validated simulation software.

2D tests performed between 2003 and 2012 with oxides representative of a corium which would form during a core melt accident on a power reactor, have provided information on the 2D heat flux distribution during MCCI (see [16] and [17]). The results of these tests tend to show that, at least at the beginning of MCCI (the first four hours), concrete erosion is preferentially in the radial direction for siliceous concrete and similar in both radial and axial directions for silico-calcareous concrete (see [18]), as shown in Figure 5.40.

Tests using siliceous concrete show a possible scale effect on the anisotropy of erosion during the initial phase of MCCI. Analysis and interpretation of these results helped better understand the effect of the type of concrete on 2D erosion and to produce a model to better appreciate the erosion kinetics for the case of a power reactor.

Very few results exist for tests performed with materials representative of a corium which would form during a core melt accident on a power reactor and with pool heating representative of the residual heat of a corium for oxide-metal stratified configurations. The BETA and COMET tests were performed with simulant materials and their (induction-based) heating method meant that the heat was injected into the metal phase, whereas it would come from the oxide phase for a power reactor. The BETA tests showed preferential concrete erosion in the axial direction; however, this behaviour cannot be extrapolated to a power reactor for the reasons mentioned above and because the mass of metal is overestimated with respect to that of a power reactor, see [19]. Only the VULCANO tests, performed with a more representative heating method and composition of pool oxides and metals (see [20]), could provide answers to the question of possible existence of pool stratified during MCCI, which would lead to a high axial erosion rate, as illustrated by the applications to a power reactor presented in Section 5.3.5.

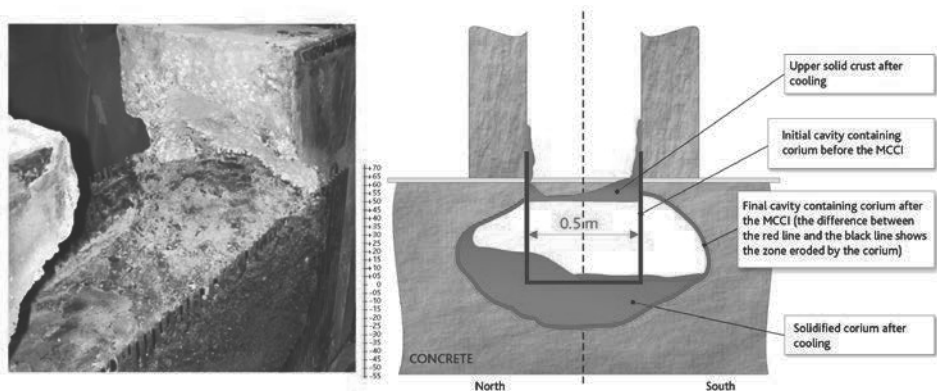


Figure 5.40. Final cavity obtained during the OECD-MCCI CCI-2 experiment, performed with a silico-calcareous concrete; the photo on the left shows the cavity formed in the concrete; this is represented in red on the diagram on the right (cross-section on the vertical axis).

5.3.4. Computer modelling and simulation software

5.3.4.1. Models

► Pool behaviour and pool-concrete interface temperatures

The oldest approach to determining the behaviour of the corium pool and pool-concrete interface temperatures during an MCCI assumed that, if the mean temperature of the corium pool is between the liquidus temperature and the solidus temperature, the pool is in a “mushy” state, intermediate between a solid phase and a liquid phase. The crust that forms at the interfaces has the same composition as the corium pool and the same solid fraction as the corium at the pool-crust interface. The interface between the pool (with or without crust) and the concrete is made up of a thin layer of decomposed concrete, called the “slag layer”. The solid-liquid equilibrium temperature is therefore the solidus temperature and the entire mushy zone is assumed to participate in convective flow near the solid interface. However, use of this assumption does not reproduce the temperature variations measured during certain ACE and OECD-MCCI tests.

In 2000, CEA produced a model called the “phase-segregation model” to describe the behaviour of the corium pool during an MCCI. This model is deduced from the model that couples thermal-hydraulics and physico-chemistry, used to describe the behaviour of the corium in the reactor vessel, see [21]. It is assumed that the pool is liquid and that crusts made up of refractory compounds (UO_2 and ZrO_2) form at the interface between the corium pool and the concrete. These crusts may be unstable. Mechanisms of crust formation at the interfaces and mechanisms that could affect their stability are little understood, in particular those that could explain the instabilities of the crusts formed at the interfaces with the vertical concrete walls, the presence of crusts during initial corium-concrete contact, and then the longer-term disappearance of crusts even at the bottom of the pool, as shown by certain inspections performed after VULCANO tests with an oxide pool. For applications to power reactors, the permanent existence of crusts at the interfaces is considered plausible given the duration of MCCI and the large pool volume. At the pool-crust interfaces, thermodynamic equilibrium is assumed to exist between the two physical phases present (the pool liquid and the crust solid), with the interface temperature being the liquidus temperature of the pool. If a departure from equilibrium occurs, liquid-solid segregation is partial or absent in the pool, which becomes mushy and the pool-crust transition may therefore correspond to a solid fraction threshold above which conduction dominates convection. The pool-crust interface temperature would then be lower than the liquidus temperature of the pool. This type of approach is adopted in the model used in the MEDICIS code developed at IRSN [27], described in detail in Section 5.3.4.2.

The phase segregation model has been partially validated using the results of ARTEMIS 1D tests, with regard to interactions with a horizontal wall and for low erosion and bubbling rates, which correspond to the long-term phase of MCCI for a power reactor. However, this “ideal” model, which assumes thermodynamic equilibrium at the pool-concrete interface, does not satisfactorily explain the results of the ARTEMIS 1D tests, with rapid erosion and significant bubbling, which corresponds to the initial

highly-transitory phase of the interaction; furthermore, this model is not relevant for the long-term phase for a power reactor, despite the good agreement with the ARTEMIS 1D test results corresponding to these conditions, due to the high concentration of silica in the pool in the long-term phase, which reduces the diffusion of chemical species in the pool and delays attainment of equilibrium at the interface, see [22].

► Distribution of heat fluxes at the corium-concrete interface

Numerous correlations of heat transfer between a pool and a bubbling horizontal wall are cited in the literature, see [1] to [4] and [7]. They have been produced on the basis of the experimental data mentioned above, or from more theoretical approaches. They are expressed as correlations which give the Nusselt number Nu as a function of the Reynolds number Re and the Prandtl number Pr under the assumption that heat transfer is associated with a forced convection produced by the concrete decomposition gases, or Nu as a function of the Rayleigh number Ra and Pr under the assumption that heat transfer is associated with natural convection; the Prandtl number Pr only depends on the fluid properties; the Reynolds number Re depends on the transport properties of the pool and the superficial gas velocity; the Rayleigh number Ra depends on the transport properties of the pool and the void fraction, and therefore indirectly on the superficial gas velocity. The ranges of variation of the physical properties of fluids used for the tests with simulant materials (see Section 5.3.3.1) are narrow and do not always cover those of a corium pool representative of an MCCI, see [23]. Although the correlations give identical results for the experimental conditions of tests performed with simulant materials, a wide dispersion of results is observed when these correlations are used with parameters representative of a power reactor. This dispersion probably shows that the dimensionless numbers used in the correlations do not correctly reflect all physical phenomena involved or the respective weightings of the various physical parameters, due to the narrow range of experimental data used to establish these correlations. For this reason, a model based on a more phenomenological approach was proposed in 2005, see [24]; it provides satisfactory results for the conditions of available experimental data (horizontal wall and vertical wall, see [5]) but would need additional validation for viscous liquids. Finally, it is important to note that, rather than the local value of the heat transfer coefficient between pool and the crusts, it is the distribution of the value of the heat transfer coefficient at the surface of the pool that is crucial to determining the distribution of local heat fluxes and erosion rates during the pseudo-steady state which exists during the longest part of MCCI.

For this reason, the CLARA analytical test programme was launched by CEA and IRSN to improve understanding of the distribution of heat transfer coefficients along the pool interfaces and their variations as a function of superficial gas velocity and pool viscosity.

With regard to heat transfers between the oxide and metal layers which form during pool stratification, several models are found in the bibliography, deduced from analytical tests, see [7], [8] and [25]. Due to the lack of experimental results and the dispersion of the available results, these models were reviewed in 2010, see [1] taking into account the most recent results obtained for measurement of the convective heat

transfer coefficient in the context of the ABI experimental programme performed at CEA Grenoble, see [9]. The main conclusion of this work, see [1], is that convective heat transfer between the layers is greater than radial heat transfer, which leads to a rate of axial concrete erosion that is higher than that of radial erosion; however, possible formation a permeable crust at the interface between the two liquids, which would reduce this heat transfer, is difficult to model, precisely because of the probable instability of this crust.

► Mixture and separation of immiscible liquids with gas bubbling

Test results produced with simulant materials are the basis of the development of experimental correlations, see [15], used to estimate the superficial gas velocity thresholds that lead to mixture or stratification of the pool; the values obtained present a non-negligible dispersion (several tens of%). These correlations have not been validated on test results with real materials, and their use for a power reactor would lead to highly varied configurations: a largely mixed configuration or a stratified configuration or a partially stratified configuration over a longer or shorter period of MCCI. In particular, uncertainties concern the dependence of the correlations on the physical properties of the liquids, the respective volumes of the metal and oxide layers and the size of bubbles.

5.3.4.2. Simulation software

Various software packages developed for MCCI studies, see [26], [27] and [30], are based on identical basic assumptions:

- the corium pool is made up of various layers (of oxides or metals) each of uniform temperature and chemical composition;
- the corium pool can be in a mixed (uniform) or stratified configuration;
- the structure of the interface is described by a thermal resistance model that takes into account the possible formation of a solid crust or a zone of concrete decomposition products (a thin layer of decomposed concrete called the “slag layer”). The concrete erosion rate is estimated using Stefan’s law, which determines the quantity of heat coming from the corium pool that is not removed by conduction in the concrete and which serves to erode the concrete.

These software packages are mainly distinguished by their corium behaviour models and by the sub-models (or correlations) that they use (such as correlations to calculate void fraction, heat transfers etc.).

The TOLBIAC-ICB code (see [26]), developed by CEA, is based on the phase segregation model described above, which assumes the pool of liquid corium and the formation of crust of refractory material at the interface: the interface temperature is the liquidus temperature of the pool (over 2200 K for a large part of MCCI). It is calculated from the pool composition using a coupling with the GEMINI2 thermodynamic code.

In contrast, the CORCON code (see [30]), developed by Sandia National Laboratories in the United States, considers that the pool is a mix of liquid and solid debris in suspension and assumes the existence of a mushy zone, if the pool temperature is between the liquidus and solidus temperatures. The thin layer of decomposed concrete ("slag layer") model is used describe the corium-concrete interfaces. In this approach, the pool-crust interface temperature is close to the concrete decomposition temperature.

The MEDICIS code (see [27]), developed by IRSN, uses a more flexible model to describe the behaviour of the pool interfaces: it is assumed that a mushy zone exists at the interface between the liquid pool and the concrete, including a convection zone and a conduction zone. In this approach, the interface temperature used for convective heat transfers from pool to interface is the threshold temperature at the border between the convective part of the pool and the conductive part of the mushy zone ($T_{\text{solidification}}$ on Figure 5.41). As no model can satisfactorily determine this interface temperature in all circumstances, it is arbitrarily set by the user between the liquidus temperature and the solidus temperature, or deduced from a threshold value for the molten fraction of pool corium. The extreme options correspond to the interface model in TOLBIAC (liquidus temperature) and that adopted in CORCON (solidus temperature). MEDICIS validation leads to recommending an interface temperature value a little lower than the liquidus temperature, or a molten fraction threshold of approximately 50%. Phase segregation in the crusts is not taken into account, as the crusts are usually thin at the corium-concrete interface; however, liquidus and solidus temperatures and the relationship between the molten corium fraction, its composition and its temperature are assessed using the GEMINI2 code prior to an MCCI calculation. It is also assumed that a thin layer of decomposed concrete (the "slag layer") exists between the concrete and the pool (with or without crusts).

The main steps of an MCCI calculation are as follows:

- calculate the physical properties of the pool;
- calculate the (possible) solid fraction in the pool;
- determine the interface temperature;
- calculate the heat transfer coefficients;
- estimate the concrete erosion rates;

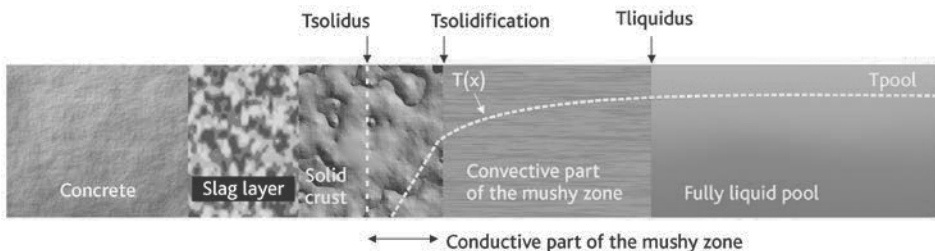


Figure 5.41. Model of the corium-concrete interface used in the MEDICIS code.

- perform a mass balance (taking chemical reactions into account) and an energy balance (including radiative heat transfer from the surface) to obtain the composition and temperature of each pool zone;
- calculate the thicknesses of crusts and erosions;
- update the form of the cavity and the heat transfer surfaces.

Simulation software is validated using the test results presented in the previous section. For integral tests, this validation process is made more complex by the numerous phenomena observed during these tests that are not covered by the computer models (such as corium ejection and deposits of matter on the walls of the test sections) and the specifics of the experimental set-ups, as mentioned previously.

Generally, the validity of simulation software for application to a power reactor is limited by uncertainties on scale effects, as the models implemented in this code have only been validated using test results at a scale 10 to 20 times smaller than that of a power reactor. The obvious solutions for overcoming this difficulty are the performance of larger-scale tests with prototypic materials, or the development of mesh-based simulations able to represent the thermal-hydraulics and heat transfer physics at various scales, in order to confirm extrapolation from the scale of the tests to that of a power reactor. The first solution runs into issues of technical feasibility and cost. The second solution assumes development and validation of turbulence models applicable to a pool with gas bubbling; these models would only be applicable to idealised situations with regard to the structure of the pool interfaces and would require the implementation of simulations that may not be available for many years.

5.3.5. Application to a power reactor

As an example, this section presents application to a 900 MWe PWR performed using the MEDICIS code, see [27] and [28], for the case of a reinforced siliceous-concrete basemat with an axial thickness of 4 m. Conservative bounding assumptions have been used for the initial conditions to obtain bounding results in terms of concrete erosion; in particular, all the reactor core that becomes corium is assumed to be present in the reactor pit at the beginning of MCCI and the effects of any water present and of radial erosion of the basemat are ignored.

The main calculation assumptions adopted are similar to those used for interpreting the MCCI tests of the MCCI programme at the ANL, see [16], leading to 2D isotropic erosion, see [29]. For a uniform pool, a heat transfer model is adopted that is independent of the orientation of the interfaces, and an interface temperature slightly below the liquidus temperature is used. The convective heat transfer coefficient between the oxide and metal layers, which applies to the stratified configuration, has been deduced using Greene's correlation, see [7], which tends to overestimate heat transfer.

Large uncertainties exist regarding pool configuration and how it changes over time. For this reason, three very different scenarios have been considered for the concrete erosion calculation.

(1) A scenario with a uniform pool maintained throughout MCCI (see Figure 5.42), which leads to slow erosion and a basemat penetration time of approximately 5 to 9 days, depending on the thickness of concrete to be eroded (3 m to 4 m).

Axial and radial erosion rates remain low due to the uniform distribution of heat flux at the pool-concrete interfaces, leading to uniform erosion and a very large zone of eroded concrete as shown in Figure 5.42.

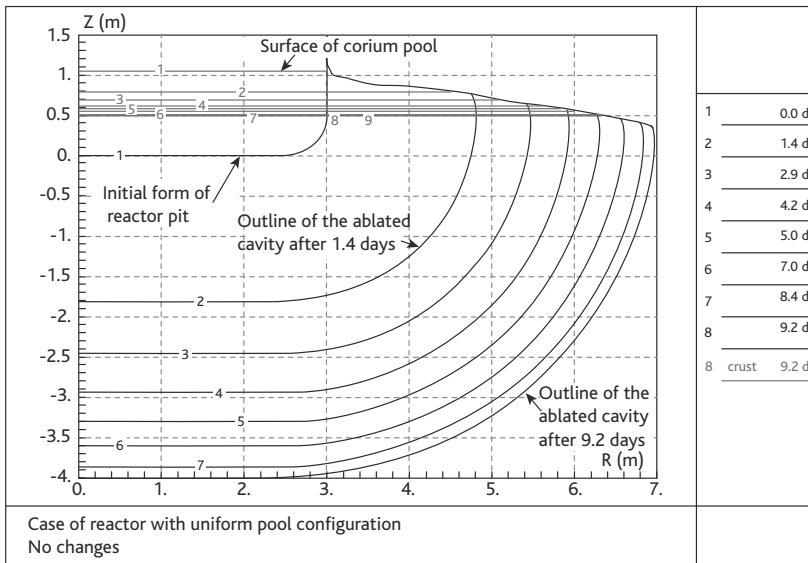


Figure 5.42. Case of a power reactor with a uniform pool configuration changes calculated for the cavity resulting from concrete erosion (axial erosion along the Z-axis and radial erosion along the R-axis) until basemat penetration after 9.2 days. The last curve corresponds to the time that axial basemat penetration occurs.

(2) For illustrative purposes, an unrealistic scenario with a stratified pool where the metal layer is assumed to be below the oxide layer from the start of the interaction, which leads to a very high rate of axial erosion, with a basemat penetration time of between 14 and 24 hours depending on its thickness. The reason for rapid erosion in this case is the high heat transfer coefficient at the metal-oxide interface, which leads to residual heat removal being concentrated at the bottom of the pool, thereby promoting axial erosion (see Figure 5.43).

(3) A more realistic scenario, which involves four phases with changing pool configurations (see Figure 5.44). In this scenario, the pool is assumed to be initially stratified with the oxide layer below the metal layer due to the higher density of the oxides (initial short-term phase), then it mixes and becomes uniform due to significant gas bubbling (second medium-term phase); then, in a third phase (start of the long-term phase), the pool become stratified again but with the metal layer below the oxide layer due to the reduction in oxide density caused by the addition of compounds from concrete erosion;

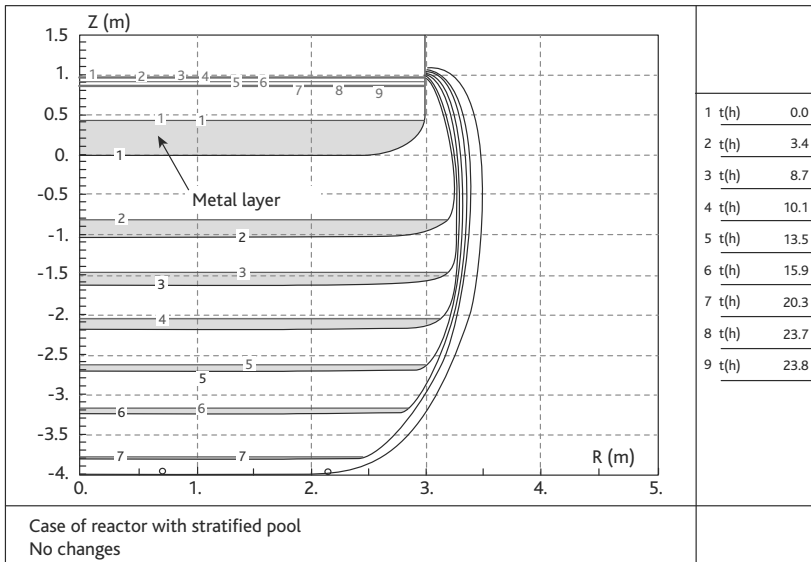


Figure 5.43. Case of a power reactor with a stratified configuration – changes calculated for the cavity resulting from concrete erosion (axial erosion along the Z-axis and radial erosion along the R-axis) in approximately 3-hours steps, with axial penetration after approximately 24 hours. The last curve corresponds to the time that axial basemat penetration occurs.

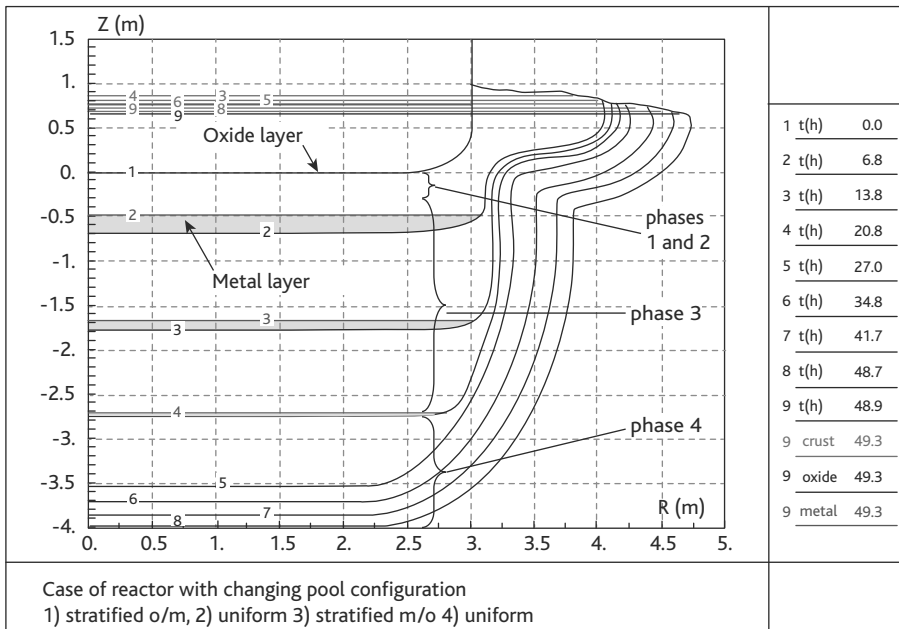


Figure 5.44. Case of a power reactor with changing pool configuration – changes calculated for the cavity resulting from concrete erosion in approximately 6-hours steps, with axial penetration after approximately 49 hours (o/m: the oxide layer is above the metal layer; m/o: the metal layer is above the oxide layer).

finally in a fourth longer-term phase, the pool becomes uniform again as the metal layer disappears due to oxidation. Changes in pool configuration are determined using criteria deduced from the BALISE tests mentioned above in Section 5.3.3.1, see [15]. When configuration changes are taken into account, basemat penetration time is extended by at least 24 hours with respect to a fixed stratified configuration with the metal layer below the oxide layer (compare Figures 5.43 and 5.44).

The results of basemat penetration time calculations are given in Figure 5.45 below. This figure shows that the effect of pool stratification on basemat penetration time would only disappear if the heat transfer coefficient between the oxide and metal layers was very small (by a factor of more than 20) compared with the available experimental data. However, high values of the oxide-metal heat transfer coefficient due to the mixing caused by gas bubbling have been confirmed (at least in terms of order of magnitude) by the experiments in the ABI programme cited in Section 5.3.3.1, see [9].

It should be noted that the calculations given above are based on certain conservative assumptions:

- the assessment criteria for pool configuration assumes that its stratification occurs from the beginning of separation of the oxide and metal phases and that this stratification is maintained even for a thin metal layer; a more realistic criterion for configuration changes, taking into account limitation of stratification in the event of a thin metal layer which is still to be confirmed, would probably lead to axial penetration times of several days;
- the heat transfer coefficient at the pool-concrete interface is assumed to be independent of the orientation of this interface for an oxide pool (and for a metal pool). However, for a siliceous concrete and in an oxide pool configuration, heat transfers could be less at the lower interface than at the lateral interface, as shown by certain results from the MCCI-OECD programme, see [16]; a model taking these results into account leads to a reduction in axial erosion rates;
- corium reflooding in the event of water injection is ignored.

Figure 5.45 shows that penetration of the reactor-pit walls (leading to partial spillage of corium outside the reactor pit into the containment building) takes place before axial penetration in the event of slow to moderate axial erosion, and slows later axial erosion by reducing the corium inventory in the reactor pit.

Finally, it should be noted that axial erosion is slower for a silico-calcareous concrete than for a siliceous concrete:

- gas velocity is greater for a silico-calcareous concrete due to the concrete's greater gas content, which has the effect of reducing the period during which stratification is possible;
- the decomposition enthalpy is higher, which reduces axial and radial erosion rates in a uniform configuration.

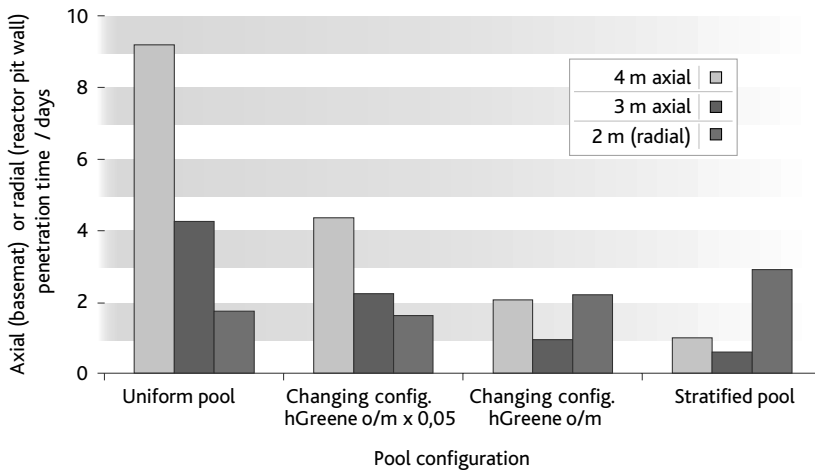


Figure 5.45. Reactor-pit basemat and wall penetration times as a function of pool configuration: uniform pool (see Figure 5.42); stratified pool (see Figure 5.43); changing pool configuration for a calculation performed using a convective heat transfer coefficient between the oxide and metal layers deduced from Greene's correlation ($h_{\text{Greene}} \text{ o/m}$, see Figure 5.44); changing pool configuration for a calculation performed using a heat transfer coefficient reduced by a factor of 20 compared with that given by Greene's correlation ($h_{\text{Greene}} \text{ o/m} \times 0.05$) and convective heat transfers between the oxide and metal layers.

5.3.6. Summary and outlook

The results of experiments and calculations performed for a power reactor using the MEDICIS and TOLBIAC-ICB code bring to light the following main areas of uncertainty, see [31]:

- the nature and properties of the corium pool interfaces: pool solidification temperature, and heat and mass transfers at the corium-concrete interfaces;
- the 2D (radial and axial) distribution of convective heat fluxes in a uniform pool;
- heat and mass transfers between metal and oxide layers in a stratified configuration;
- changes in pool configuration (stratification).

Knowledge of the interface structure has progressed over the last decade but remains inadequate. Indeed, analysis of the ARTEMIS 1D experiments, performed with a uniform pool and a horizontal interface, shows that the phase segregation model at thermal equilibrium (with a pool-crust interface temperature close to the liquidus temperature) applies well to a case of slow concrete erosion and low gas velocities, a situation that could correspond to the long-term phase for a power reactor; however, the high pool viscosity in this phase slows diffusion of chemical species and could lead to a different composition at the interface than that for thermodynamic equilibrium. For faster erosion, a situation that corresponds to the short- and medium-term phases for a power reactor, the phase segregation model is no longer suitable due to being far from thermodynamic equilibrium. Furthermore, analysis of 2D MCCI tests performed with real

materials also shows that the pool is often mushy and the pool-crust interface temperature lower than the liquidus temperature, in particular for siliceous concrete, see [29]; in addition, associated inspections did not bring to light a crust on any corium-concrete interface, including the horizontal interface, contrary to what was observed during tests with simulant materials (ARTEMIS 1D tests).

Major uncertainties also exist regarding the last three points mentioned above, i.e. the distribution of heat fluxes at pool interfaces, heat transfers between the metal and oxide layers in the stratified configuration, and changes in pool configuration. In particular, improved understanding of heat transfers between the metal and oxide layers and of the types of pool configuration and their changes, would strongly reduce uncertainties regarding axial and radial erosion rates for a stratified pool configuration, which remain major, see [33].

In 2015, end of the VULCANO MCCI experiments (with materials representative of a power-reactor corium) and associated work – such as interpretation of the tests and comparison of the results obtained with various code packages – provided further understanding of the physical phenomena that govern the structure of the interfaces, and supplemented knowledge of the 2D distribution of heat fluxes for a uniform pool configuration. Additional MCCI tests for stratified pool configurations are envisaged to contribute to reducing remaining uncertainties by providing results regarding heat transfers between oxide and metal layers and regarding changes to the pool configuration.

The CLARA programme, which ended in 2012 and used simulant materials, aimed for better understanding of 2D erosion for a uniform pool, by detailed study of convective heat transfers between a heated pool and a bubbling porous wall, in a 2D situation with simplified boundary conditions (without erosion) over a large range of pool viscosities.

Qualification using a large-scale test would be necessary, due to probable scale effects on convective heat transfer and on the structure of the corium-concrete interfaces. Such a test, with an initial pool size of around one metre, was planned in Russia in 2011 in the context of the programmes of the International Science and Technology Center (ISTC), but the project was not completed due to administrative difficulties.

Pool stratification criteria should also be better defined and better validated, in particular the superficial gas velocity threshold and maximum thickness of metal below which stable pool stratification appears.

Furthermore, a programme of additional studies aiming to reduce uncertainties on the thermochemical properties of corium was performed in the context of the ISTC programme (the PRECOS project) and mainly involved determination of the phase diagrams for certain mixtures of oxides and metals of compositions selected in a range where thermochemical data is inadequate or uncertain. Analysis of the associated experimental results should provide additional data for the thermochemical databases used by software (such as GEMINI2, see [32]) to calculate thermodynamic values for corium.

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