A Study on the Coolability of Ex-vessel Corium by Late Top Water Flooding

by

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Abstract

The molten core-concrete interaction (MCCI) is treated as one of the important phenomena that may lead to the late containment failure by basemat penetration in a hypothetical severe accident of light water reactors (LWRs). The earlier research has showed that heat transfer limitation exists for the coolability of ex-vessel corium by atop water flooding due to crust formation on the melt/water interface that will isolate melt from water. However, several cooling mechanisms were identified in a series of intense investigations. A code (CORQUENCH) was developed and updated to incorporate the newly identified cooling mechanisms for the better predictions of cavity erosion and corium cooling behaviors. A description about such cooling mechanisms (i.e., bulking cooling, water ingression, eruption and crust breach) and the concrete ablation models implemented in the code is presented in this thesis.

The technical work in the thesis includes two parts: first, the verification and validation of the code were performed against the CCI tests from the OECD/MCCI projects; and then a reactor-scale simulation was carried out for MCCI and ex-vessel corium coolability of a reference PWR with LCS concrete. The calculations of CCI tests have a plausible agreement with the experimental data. The calculation predicts an optimistic result for the reactor case, and a fast quenching achieved at about 145 minutes. In addition, a sensitivity study was also conducted on several important parameters, i.e., concrete type, corium composition, water flooding time, atmosphere pressure, concrete ablation temperature, initial temperature, decay power, cavity geometry, concrete decomposition model and melt upper heat transfer model. An attempt to explain the physics of the different predicted phenomena is presented as well.

Finally, comparative calculations were performed by the other codes (ASTEC and FinCCI) for the same reactor-scale configuration. Discrepancies are found in the results. Some suggestions are proposed to improve the CORQUENCH code.

Keywords: Severe accident, Molten Core-Concrete Interaction (MCCI), Concrete ablation, Coolability, CORQUENCH code, Sensitivity analysis.
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1. Introduction

1.1. Background

The Fukushima Daiichi nuclear disaster in 2011 raises the safety problem of nuclear power plants to a new level in the world. The rigorous inspections are enforced in any nuclear power plant in service or under construction after the accident. The probability of severe accident, especially, is considered in a more serious and extensive way. Actually, after the Three Mile Island accident in U.S., fruitful researches have devoted a great deal of effort to acquire a comprehensive knowledge of the principles and progressions of various severe accidents scenarios. The main objective is to keep the containment building intact and prevent a large release of radioactive materials to the environment.

During a hypothetical severe accident, for instance, the reactor core will melt due to decay heat. The molten corium will relocate downwards and finally fall into the water pool in the lower plenum. The melt fragments in the coolant and a debris bed is expected to form on the pool bottom. If the debris is coolable during a long term, the integrity of the reactor pressure vessel (RPV) will be secured. The fission products are thereby contained and the corium is arrested. However, if the emergency water injection is unavailable or fails to cool the debris bed, the debris will re-melt. In that case, the vessel will fail under the aggressive attack of the molten corium in the lower plenum, and the melt jet ejects into the cavity beneath the RPV. In case the cavity is flooded (as a strategy of severe accident management or a result of containment spray), the melt jet will breakup and the debris will settle down on the floor. This causes a Molten Core–Concrete Interaction (MCCI). The concrete in the floor and sidewalls of the cavity starts to melt. The process is driven by the high initial temperature of the molten corium and the decay heat that is generated inside the melt by the radioactive decay of the fission products. If the interaction cannot be stopped, the containment basemat may be penetrated eventually, thereby producing a leak path for radioactive materials to the environment. Obviously, the progression of MCCI takes paramount importance and plays a key role to threaten the integrity of the containment, the last barrier of fission products. In accessing the safety of nuclear reactors, there is a clear need to know the process and consequence of such an interaction.
Figure 1.1 illustrates the schematic diagram of MCCI. When MCCI occurs, the solid concrete and the molten corium pool may be separated by a thin layer of partly molten concrete. The concrete melt rises upwards as “streamer” because it is less dense than the overlying core melt. Also the gas bubbles, which mainly include hydrogen, CO, CO$_2$ and steam, cause mixing of the liquids. A layer of solid corium crust may also exist at the core-concrete interface. The crust is probably porous and permeable to gases from the concrete.

![Figure 1.1 The Schematic Diagram of MCCI (Sevón, 2005).](image)

The core melt pool is stirred by the rising gas bubbles, which enhances the heat transfer. On the other hand, the possible corium crust at the interface inhibits heat transfer. Because the heat conductivity of concrete is poor, most of the heat goes to the heat-up and melting of the surface of the concrete wall. Therefore the concrete ablation is controlled by the heat transfer from melt to concrete.

Accordingly, in order to prevent the progress of MCCI, the most straightforward way is to cool down the corium in order to arrest the concrete erosion. Then both of basemat melt-through and containment failure caused by gas production from concrete can be avoided. There are two different progressions of melt cooling, as shown in Figure 1.2, where lists the main severe accident phenomena after a RPV failure for most current light water reactors.
It can be seen that there are two different scenarios about ex-vessel cooling, as in Figure 1.2. When corium relocates to the cavity after PRV failure, the melt jet discharged from RPV will break up and form a particulate debris bed if there is water in the cavity. The fragmentation process increases the contact surface area of melt and water, which results in the larger amount of heat removal from melt. But steam explosion may occur and the coalescence of particles which form a heap-like particle debris bed will decrease the surface again. So a porous debris bed with water entry is a key factor for cooling. This measure is only adopted by Nordic BWRs.

Otherwise, if there is no water when corium discharged into the dry cavity, the water should be flooded from top or bottom after the arrival of corium. Since an “insulating” crust greatly restrains the heat transfer between core melt and water, the porosity of the crust on the top also is an important property for the melt coolability. This ex-vessel melt cooling measure is employed in most Generation II PWRs and BWRs, except the Nordic BWRs. This thesis project is contributed to the corium cooling by late water injection from top. At the same time, a simulation based on one prototypic PWR configuration designed by Westinghouse is performed by computer code, which provides a view about MCCI behavior in a nuclear power plant scenario under the current ex-vessel cooling design.

1.2. Code status

Based on the studies conducted by different project groups, the improved understanding and description of processes in MCCI have been achieved. However, a complete model with an overall description, which can be applied for a real nuclear power plant, is not visible yet due to the remaining uncertainties. As a result, several different computer codes have been developed based on different models, correlations and experimental data, for example, CORCON (Bradley et al., 1993), WECHSL (Foit et al., 1995) and CORQUENCH (Farmer, 2011). Accordingly, very different results and predictions may be produced by such different codes under certain conditions. A brief introduction about several major analytical codes is made hereunder. A very detailed review of the MCCI models and codes was done by Allelein et al. (2006) and the comparisons of the codes on some specific models were performed by Spindler et al. (2008).
Generally, the two earlier codes are CORCON and WECHSL. The CORCON code was developed at Sandia National Laboratories around the end of 1980’s. The final version is CORCON-Mod3, which has been integrated into the MELCOR Cavity (CAV) package.

Figure 1.2 Main Severe Accident Phenomena in Cavity (Allelein, 2006).
with the VANESA code which is a separate code about fission-product release. The WECHSL-code was developed at KIT (formerly, Forschungszentrum Karlsruhe) in Germany. Based on WECHSL, the WEX modified some models including new heat transfer coefficients. Currently, WECHSL/WEX has been integrated into the codes ASTEC and COCOSYS. One key characteristic of these codes is that their results can be very consistent with some experimental results but discrepant with others. Besides, several new computer codes have been developed as some new approaches were done to modify the underlying modeling of the processes in the codes. Such codes include TOLBIAC-ICB developed by Commissariat A L’Energie (CEA) and Électricité de France (EDF), COSACO developed by AREVA, ASTEC/MEDICIS released by IRSN and GRS, MAAP developed by FAI/EPRI (the newest version is MAAP5), FinCCI developed by VTT in Finland (a simple Excel macro used to simulate some certain experiments). In respect to ASTEC (Accident Source Term Evaluation Code), it is an integral code for evaluation of source term in water-cooled reactors (initially PWR, currently including BWR, VVER and CANDU). Its MEDICIS module is the MCCI model which can be coupled with the other modules to simulate the whole behavior in the containment until radioactive productions release out of the containment. The very recent update of version 2.0 has been done in 2010. In addition, transient heat conduction in debris and concrete was calculated by COCO code in COTEL MCCI tests at NUPEC (Maruyama et al., 2002). The validation work have been performed for some of the codes, nevertheless none of the codes can achieve a common agreement among the experts under different conditions. The further investigations are ongoing to quantify and improve the relevance and contribution of the different cooling mechanisms under the real plant scale situations.

1.3. Introduction about CORQUENCH code

CORQUENCH code is developed by Argonne National Laboratory as part of the OECD/MCCI project. The philosophy behind the code is to build a simple, modular model of MCCI behavior. The most significant feature of this code is that it is readily adapted to incorporate different heat transfer models as they became available on the basis of experiment observations. The latest version 3.03 has been upgraded to include all four cooling mechanisms mentioned above and experimental data have been used to get the key data about the physicochemical properties and modify the models or correlations.
implemented in the code. Furthermore, a series of validation calculations have been carried out with the code in order to provide an indication of its predictive capability.

One drawback of CORQUENCH is that the code currently does not possess the capability to import or evaluate the complete set of thermophysical property data that would be needed to adequately calculate stimulant material experiments. Besides, it cannot calculate density-driven phase segregation because further experiments with segregation phenomenon are required to set such models. However, it is important to consider the segregation phenomenon since it leads to the melt pool stratification which strongly affects the MCCI behavior.

1.4. Research scope

For the ex-vessel cooling scenario, the main question that needs to be addressed is whether and when the corium will melt through the containment which would lead to ground contamination. As mentioned above, all MCCI models implemented in CORQUENCH code are at the State of the Art. Pre-test calculations on the experimental configurations (e.g. ACE/MCCI tests, MACE and OECD/MCCI tests) were done with the code for validation and prediction. However, simulations on a plant scale have not been studied yet. It is meaningful to extend the models into a real nuclear power plant configuration. In the thesis, although some validation calculations were conducted as part of the CORQUENCH developmental activities, the verification and validation were carried out prior to the reactor scale calculation. The work helps to understand the code structure and check the errors on parameters setting. Actually, the validation in respect to OECD/MCCI CCI-6 was done again owing to the discrepancy of input parameters found during the code verification. Afterward, the calculation on a PWR cavity configuration was performed for analysis the reliability of the application of CORQUENCH in plant scale. For better understanding the cooling mechanisms by flooding atop, parametric studies were also performed to identify the sensitivity of different conditions. Finally, the calculations with same assumptions were carried out by the codes of ASTEC V2.0 and FinCCI. A brief comparison was presented to analysis the discrepancy and predictability of different codes on a plant scale.
2. Physical models

2.1. Cooling mechanisms under atop flooding

Several experiments (COTELS, MACE, and OECD/MCCI programs) were conducted to construct the coolability database under the top flooding condition. Based on such experiments, there are four main heat transfer mechanisms have been found; namely i) bulk cooling, ii) water ingestion, iii) melt eruption, and iv) crust breach. Here, a brief description about such mechanisms is presented below and a general sequence of them is illustrated as Figure 2.1.

When melt contacts water, the melt temperature is very high and the bulk cooling mechanism predominates during the period. In the bulk cooling regime, melt sparing rate is high enough to preclude a stable crust formation at the melt/water interface. Then due
to conduction and radiation, a large amount of heat can be removed across the agitated melt/water interface. The effective heat transfer coefficient is a function of melt sparging rate, gas bubble diameter, melt/crust thermophysical properties, coolant properties, containment pressure and the crust fracture strength. Most models and data about such correlation have been obtained by experiments. Thus, among the four cooling mechanisms, bulk cooling is considered as the best understood model which can be applicable to the real plant scale.

As the melt temperature declines due to bulk cooling, melt sparging caused by concrete decomposition decreases as well. Then the two conditions, i.e., i) the melt/water interfacial temperature is lower than the melt freezing temperature; ii) the incipient crust is mechanically stable in the presence of the sparging gas and local loads, can eventually be satisfied to form a stable crust between the melt zone and water overlayer (Farmer et al., 1992). Since the concrete decomposition gas should be vented out from melt, the crust generally will be characterized by some degree of porosity or cracks, which actually also provide pathways for water to penetrate the crust. Then the other three potential mechanisms can be activated to augment the heat removal ability from melt zone. One of the three mechanisms is water ingression through the porosity or cracks inside the crust, which can be considered as thinning the thermal boundary layer within the crust at the crust-melt interface, augmenting the otherwise conduction-limited heat transfer process. Water ingression mechanism highly depends on the cracks propagation process within the crust. As such, it is a strong function of crust permeability. A steady state model of water ingression has been developed by Epstein to predict the field measurements obtained by water injection of molten lava flow (Bjornsson, 1982).

Another important mechanism is melt eruption. After a stable crust formation, melt eruption cooling phenomenon has been observed predominately in various reactor and simulant material coolability experiments which are mainly conducted with limestone/common sand concrete. During melt eruption, melt is carried through the crack/porosity to the overlying water by concrete decomposition gases. As a result, the dispersed melt is quenched and forms a particle bed in the upper surface of the crust (see Figure 2.2). The evidences from experiments show that this kind of particle bed usually has a high porosity and large particle diameter. It is known that melt entrainment rate relies on the gas volumetric flowrate and the crust configuration, as well as the system pressure. Thus, it is understood that melt eruption was rarely observed in the siliceous concrete which has lower gas content. The last mechanism is crust breach after crust
anchoring. A sustained suspended crust formation is not expected in a plant scale since the large lateral span of the cavity, up to 6 meters. However, the MACE test results show that the scenario is plausible because the strength of the crust formed by water ingression may be sufficient to separate the crust from the melt temporarily. But the crust configuration is still not expected to be stable owing to its mechanical weakness. Once the anchoring crust fails, water will penetrate through the crust and fill the intervening voided region. The other three cooling mechanisms will occur periodically on the surface of the melt zone. Since water ingression and melt eruption cooling mechanisms require melt feedstock to proceed, it is important to model the crust anchoring phenomenon which leads to insulating gap between melt zone and the upper crust.

Figure 2.2 Sketch of Cavity Configuration with Water Ingression and Melt Eruption (Farmer, 2009).
2.2. Models in CORQUENCH

2.2.1. Mass and energy conservation

The basic energy and mass conservation equations are solved to calculate the MCCI process. Such heat source/sink terms are considered in the code: i) decay heat, ii) heat from melt addition discharged from the failure RPV, iii) chemical reactions between metallic melt constituents Zr, Cr, Fe and concrete decomposition gases H₂O, CO₂, iv) condensed phase chemical reactions between Zr and SiO₂ (see Table 2.1), v) heat transfer to concrete, including slag heat sink, and vi) heat transfer to overlying atmosphere. Decay heat within the debris is treated by user-specified decay heat function or user-specified interpolation table, rather than tracking fission product decay chains. In real reactor conditions, the melt composition can range from fully metallic to fully oxidic, but the two phases are assumed to be well mixed in all cases. The mass conservation considers most core, concrete metals and their corresponding oxides. And the mass conservation equations are established according to every melt constituent. Else, the conservation of mass equations for the crusts and the particle bed are solved in separate ways, and then the material properties can be evaluated on the basis of the actual compositions in different layers.

<table>
<thead>
<tr>
<th>Oxidation reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr + 2H₂O → ZrO₂ + 2H₂; Zr + 2CO₂ → ZrO₂ + 2CO</td>
</tr>
<tr>
<td>2Cr + 3H₂O → Cr₂O₃ + 3H₂; 2Cr + 3CO₂ → Cr₂O₃ + 3CO</td>
</tr>
<tr>
<td>Fe + H₂O → FeO + H₂; Fe + CO₂ → FeO + CO</td>
</tr>
<tr>
<td>Zr + SiO₂ → ZrO₂ + Si(l) for T≤2784 K; Zr + 2SiO₂ → ZrO₂ + 2SiO(g) for T&gt;2784 K;</td>
</tr>
</tbody>
</table>

2.2.2. Melt/concrete heat transfer models

With respect to heat transfer at the melt/concrete interface, three options are offered for calculating the concrete heat conduction and decomposition by CORQUENCH, corresponding to three physical models to solve the heat transfer between melt and concrete.
1) **Quasi-steady ablation model.** In this model, the conduction heat transfer into the concrete behind the ablation front is neglected. In another word, the model does not consider the concrete heat-up process. An effective decomposition enthalpy, which lumped with the concrete latent heat of fusion and the sensible heat required to raise the concrete to the ablation temperature, is used to relate the heat flux to the ablation rate. This model is also the traditional modeling approach employed in many system-level codes.

2) **Fully developed concrete dryout model.** The conduction heat transfer into the concrete has been considered in the model, but the early transient surface heat-up phase is neglected.

3) **Transient concrete dryout model.** The full transient model accounts for both conduction into the concrete and initial concrete surface heat-up phase, along with a model for the growth and eventual failure of an interfacial corium crust. This is a complete model developed for calculating the transient crusting behavior in order to aid in the interpretation of the CCI test results. The criteria of local crust growth and failure are treated in the model to simulate the dynamic process during melt/concrete interaction.

The logic flow diagram about the concrete ablation evolution in the code is shown in Figure 2.3. It should be pointed out that a parabolic temperature profile is assumed in the concrete to solve thermal boundary layer depth by the boundary layer theory.

Currently, CORQUENCH is able to perform a 1-D or simplified 2-D (either idealized cylindrical or simple notch geometry) ablation calculation only. In the calculation, the surface area on the top of the melt pool is simplified as same as the area of the basemat for all the time. Unlike some other codes, the spatial discretization and finite volume methods are not be employed in the CORQUENCH. So the melt zone, crust layer and water layer are respectively treated as one whole mesh with all the same properties. The phase stratification in melt pool is neglected. It should be stated that there are two cases, porous or impervious crust, for the contact models of melt and concrete. But the heat transfer processes are very similar except the extra conduction in slag film which has to be built into the energy balance between the crust and concrete.
2.2.3. Melt/water (or air) heat transfer models

In terms of heat transfer at the melt upper surface, a framework of different models and their boundary conditions is shown in Figure 2.4. Two branches are determined by the initial conditions, i.e., dry cavity conditions and wet cavity conditions.

When the cavity is dry, there are two heat transfer mechanisms between the melt and atmosphere, i.e., natural convective heat transfer and radiant heat transfer. Since the convective heat transfer from melt to overlying structure is limited, only the radiant heat transfer from melt to atmosphere is treated in the code. Then the energy balance between melt-atmosphere without crust formation has a simple expression:

$$h_t(T_m - T_{t,I}) = h_r(T_{t,I} - T_{bound})$$

(2-1)

where:

$h_r$ is radiation heat transfer coefficient between the interface and atmosphere,
is convective heat transfer coefficient between melt and interface, which is evaluated by the correlation developed by Kutateladze and Malenkov (1978),

\[ T_m, T_{t,i}, T_{\text{bound}} \] denote the temperature of the melt, melt/atmosphere interface and atmosphere, respectively.

Further, the stable floating crust boundary can be formed at certain conditions, i.e., the thermal condition is possible to form a crust and the incipient crust is mechanically stable with respect to local mechanical loads. Here the mechanical stable condition for crust most depends on the superficial concrete decomposition gas velocity. The correlation of Blottner (1979) is used to solve the critical gas velocity. As well, such assumptions are made in the code to get the heat transfer equations set; i.e., 1) heat transfer in the crust is quasi-steady, 2) decay heat is uniformly distributed, and 3) crust thermal properties are constant. The differential equation and boundary conditions for the heat transfer through the crust are:

\[ k_{t,c} \frac{d^2T}{dx^2} = -\dot{Q}_{t,c} \quad (2-2) \]

\[ T(x = 0) = T_{t,froz} \quad (2-3) \]

\[ -k_{t,c} \frac{dy}{dx} \bigg|_{x=\delta_t} = h_f(T(x = \delta_t) - T_{\text{bound}}) \quad (2-4) \]

where: \( k_{t,c} \) is thermal conductivity in the top crust,

\( \dot{Q}_{t,c} \) is volumetric decay heat in the top crust,

\( T_{t,froz} \) is the freezing temperature of the top crust,

\( \delta_t \) is the crust thickness. Here the coordinate system is set as the x=0 at the melt-crust interface.

The other status is wet cavity which is more complex than the dry one outlined above. Except the crust formation and evolution at the melt upper surface, the wet cavity also considers additional three cooling mechanisms mentioned above, i.e., bulk cooling, melt eruption, water ingression and crust breach. During the initial phase (above three mechanisms have not occurred yet), the overall methodology is very similar to the dry cavity case. However, the heat transfer coefficient between melt and atmosphere is modified to account for the presence of the water. The two significant differences are
considered in the evaluation of the overall heat transfer rate, which are conduction across
the gas film and sparging gas causes bulk pool mixing and area enhancement at the melt-
water interface. The details about the model and correlations to calculate the overall heat
transfer rate from melt to water in the bulk cooling regime are presented by Farmer et al.
(1990). And the effective heat transfer coefficient is found as a function of the gas
spraying rate, bubble diameter, coolant properties, melt/crust thermophysical properties,
containment pressure and the crust fracture strength. Similar with the dry cavity case, the
dynamic incipient crust growing progression is calculated before a stable crust formation.
Once a stable crust is achieved, the bulking cooling will be terminated and the other three
heat transfer mechanisms will be initiated in the following phase.

*Melt eruption*

The melt eruption cooling mechanism was observed predominately in reactor material
melt cooling with limestone/common sand concrete. Melt entrainment through the top
crust by sparing concrete decomposition gases can greatly augment the debris cooling
rate. The melt entrained into the overlayer water is assumed to be quenched to form a
particle bed on the crust. Generally, melt entrainment rate is assumed to be proportional
to the gas volumetric flowrate. In the code, it is calculated in the equation below.

\[ j_m = K_{ent} j \]  \hspace{1cm} (2-5)

where \( j_m \) is melt entrainment rate, \( j \) is gas volumetric flowrate and \( K_{ent} \) is melt
entrainment coefficient.

*Crust water ingression modeling*

If the crust is impervious, for instance, water ingression phenomenon does not exist, the
average heat transfer coefficient declines as the crust grows. It is explicit that the heat
transfer resistance from melt to water is proportional to the thickness of the crust which
has to be passed through. So the heat removed from the upper coolant (water) is limited
by the conduction in the crust. Fortunately, the water ingression cooling mechanism can
augment the heat transfer process which should be conduction-limited otherwise. The
criterion for onset of water ingression into the crust is that the total heat flux at the
crust/water surface must fall below the crust dryout limit; i.e.

\[ q_{c, dry}^w \geq k_{t,c} \frac{(T_{t,frz} - T_{sat})}{\delta_t} + \frac{\delta_t \delta_t}{2} + \rho_v h_{lv} j |T_{sat}\]  \hspace{1cm} (2-6)
where:

\( j \) is the gas velocity from the concrete decomposition;

\( h_{lv} \) is the latent heat of vaporization;

the subscripts \( l \) and \( v \) denote coolant liquid and vapor phases;

The dryout heat flux in the above expression took into account the counter-current flow of noncondensable gases from core-concrete interaction and the decay heat within the crust. And the gas volumetric flowrate is evaluated at the coolant saturation temperature, since the debris bed is assumed at the saturation temperature during all times.

After water infiltrates the crust, the thermal boundary layer within the crust can be treated as a relatively thin or even dry. Here the temperature of the upper surface of the crust should be near the water saturation point and the value of the lower surface (crust/melt surface) should be maintained near the crust freezing temperature. At the same time, the heat flux to the upper water should approach the crust dryout limit, \( q_{c,\text{dry}} \).

Two models can be used to determine the heat flux of the crust dryout limit. The first one is to evaluate the dryout heat flux by Jones’ model (Jones et al., 1984). The second one is to use the correlation developed by the OECD/MCCI SSWICS tests (Lomperski, 2006). In late phase, with the augmented heat transfer caused by water ingestion, the crust will continue growing until the dryout heat flux cannot support additional crust growth.

**Crust anchoring**

Although crust anchoring is expected impossible for the real plant scale, it actually happened in the prototypic experiments under the top flooding (Farmer, 2009). So crust anchoring has to be considered in this case rather than a simple floating crust is treated in the dry cavity. Firstly, the criterion for crust anchoring criterion can be treated simply by the mechanical stability. According to the formula given by Roark and Young (1975), the equation to determine the minimum crust thickness required for mechanical stability can be expressed as:

\[
g \left( m_{\text{particle bed}} + \rho_{t,c} A_p \delta_{t,\text{min}} + m_{\text{water}} \right) \leq C_{\text{geom}} g \delta_{t,\text{min}} \delta_{t,\text{min}}^2 \]  

(2-7)

where:

\( \rho_{t,c} \) is density of the upper crust;

\( A_p \) is the top surface area of the crust;
$C_{geom}$ is a constant determined by the cavity geometry, crust edge boundary condition, and crust failure model;
$
\delta_{t,f}$ is the effective macroscopic crust strength including the effects of crack structure;
$m_{\text{particle\ bed}}, m_{\text{water}}$ are mass of the particle bed and water, respectively.

From the above equation, the minimum crust thickness can be solved. Once the crust thickness meet the requirement ($\delta_t \geq \delta_{t,\text{min}}$), the crust upper surface is considered being fixed and the elevations of the bottom surface of the crust and the top surface of the melt will be saved. With the progressing of MCCI, the melt-crust separation occurs when the two elevations are different. If the crust anchoring is initiated, it remains that way unless the crust thickness falls below the minimum value by remelting process. Then the crust is declared to return to floating case, correspondingly heat transfer equations and floating crust boundary conditions are applied again.

The heat transfer modeling for the crust anchoring is very similar with the case without anchoring, except that the intervening gap between the melt layer and the crust layer have to be built into the heat transfer process. Detailed heat transfer equations consisted with differential equations and boundary conditions can be referred to the manual of CORQUENCH 3.03. Finally, it should be realized that the key phenomenology is that the water overlayer could not penetrate through the crust to fill the gap, owing to the gas from MCCI continuously purge the gap. Thus, quenching process will be terminated effectively by crust anchoring through invalidating the upper water cooling.
Figure 2.4 A Framework of Physical Models in CORQUENCH 3.03.
3. Validation calculations

As one part of the CORQUENCH developmental activities, a series of validation calculations have been carried out. Such results and relative detailed parameters can be found in the code manual of CORQUENCH (only the input file for CCI-2 test). Prior to the plant scenario analysis, the verification of the code was performed based on the CCI-2, CCI-3, CCI-4 and CCI-5 tests (OECD/MCCI Program) in order to understand the code well. Moreover, the validation calculation on the integral experiments (CCI-6) was also carried out for comparative analysis.

It is reasonable to choose such CCI-2, CCI-3, CCI-4 and CCI-5 tests as optimal scenarios. The characteristics of these tests are shown in Table 3.1. Firstly, all the cases were conducted under the OECD/MCCI Program. The integral effect Core Concrete Interaction (CCI) tests replicated as close as possible the conditions at a plant scale, thereby the data and results are suitable for verifying and validating the codes directly. As shown in Table 3.1, two of them are conducted with LCS concrete and the other two are siliceous. Both types of concrete are most used for the containment construction in current nuclear power plant. And it has been proved that the concrete type can significantly affect the power split and melt eruption phenomena during MCCI. Besides, the cavity conditions include two phases, dry and late flooding, and the cavity configurations range from 0.25 m$^2$ to 0.79 m$^2$. All these tests conditions almost cover the important input parameters in the code.

According to the specifications for the tests, the calculations were carried out by following the instructions in Code Manual. Detailed parameters for code verification of such tests are accessible in the final reports of the OECD/MCCI project 1 and 2 (Farmer, 2006 and 2010). The results of the verification are exactly coincident with the validation performed by Farmer (2011).

Meanwhile, the validation of CCI-6 test was done in a different way. Different with the previous four calculations, the CCI-6 test was carried out by setting the input parameters exactly according to the experimental results instead of setting the parameters same as Farmer’s work. So the result of the CCI-6 test simulation is not as same as the result presented by Farmer. Actually, the CCI-6 is a more interesting test. The conditions and process of the CCI-6 test are also very different from the other four tests. Firstly, the CCI-
6 test is a single large scale integral test which was initially conducted to provide data for validation of severe accident codes under the conditions of early cavity flooding. Actually, since the melt-through of the main steamline during the experiment, the earlier cavity flooding was activated at about 40 seconds after the melt pool formed. But it originally was planned to flood after cavity ablation was established. And the successful quenching was achieved in the end of the experiment. Though the experiment was conducted with siliceous concrete, substantial melt eruptions were observed during the process while it did not occur in the previous tests. So in the validation, eruption is also calculated using Rico-Spalding correlation with the proportionality constant set at E=0.08. All value of input parameters used in this case can be referred to appendix A.

A comparison is calculated by comparing the end-of-test ablation depth and melt temperatures with the experimental data. The discrepancy between calculations and experiments are summarized in Table 3.2. Errors in ablation depth predictions range from -19.1% to +56.1%. Similarly, variations in melt temperature predictions range from -11.6% to +5%. For the case of CCI-3, it produced the worst prediction with 56.1% error. That is because the experiment shows a large power split on the sidewall and basemat. Unfortunately, the code cannot capture the phenomenon.

For the CCI-6, the calculation result on the ablation also does not show a good agreement with the experimental data. The temperature evolution comparison is plotted in Figure 3.1.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Concrete Type</th>
<th>Cavity Configuration</th>
<th>Corium</th>
<th>Initial Melt Mass (depth)</th>
<th>Cavity Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCI-2</td>
<td>LCS</td>
<td>50 cm × 50 cm</td>
<td>100% oxidized PWR + 8 wt% LCS</td>
<td>400 kg (25 cm)</td>
<td>Dry, late flooding</td>
</tr>
<tr>
<td>CCI-3</td>
<td>Siliceous (EU-type)</td>
<td>50 cm × 50 cm</td>
<td>100% oxidized PWR + 15 wt% SIL</td>
<td>375 kg (25 cm)</td>
<td>Dry, late flooding</td>
</tr>
<tr>
<td>CCI-4</td>
<td>LCS</td>
<td>50 cm × 40 cm</td>
<td>78% oxidized BWR + 7.7 wt% SS +10 wt% LCS</td>
<td>300 kg (25 cm)</td>
<td>Dry</td>
</tr>
<tr>
<td>CCI-5</td>
<td>Siliceous (EU-type)</td>
<td>50 cm × 79 cm (one insulating wall)</td>
<td>100% oxidized PWR + 15 wt% SIL</td>
<td>590 kg (25 cm)</td>
<td>Dry</td>
</tr>
<tr>
<td>CCI-6</td>
<td>Siliceous (CEA-type)</td>
<td>70 cm × 70 cm</td>
<td>100% oxidized PWR + 6 wt % SIL</td>
<td>900 kg (28 cm)</td>
<td>Wet</td>
</tr>
</tbody>
</table>

Table 3.1 Tests Characteristics for Code Verification and Validation.
The coolability is overestimated in this case. In contrast to the experiment, only half time is estimated to cool down the corium totally. Anyway, the predictions for CCI-2, CCI-4 and CCI-5 have a good agreement with the experiments. And a fine tuning on parameters should be able to get a better agreement with the experiments.

Table 3.2 Comparison of Validation Calculations.

<table>
<thead>
<tr>
<th>Test</th>
<th>Maximum Ablation Depth (cm)</th>
<th>Melt Temperature in the end (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Prediction</td>
</tr>
<tr>
<td>CCI-2</td>
<td>30</td>
<td>27.5</td>
</tr>
<tr>
<td>CCI-3</td>
<td>33.3</td>
<td>14.6</td>
</tr>
<tr>
<td>CCI-4</td>
<td>35</td>
<td>41.7</td>
</tr>
<tr>
<td>CCI-5</td>
<td>30</td>
<td>26.4</td>
</tr>
<tr>
<td>CCI-6</td>
<td>16</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Figure 3.1 Melt Temperature Predictions on CCI-6 Test.
4. Plant scale analysis

4.1. Models specific setup

Following the verification and validation on the large scale integral experiment (CCI-6), a simulation was carried out to predict the MCCI behavior in a reactor scale. A 3100 MWt nuclear power plant designed by Westinghouse is chosen as the prototypic model in the base scenario. The original cavity configuration is a combination of two cylinders, as shown in Figure 4.1. Since only simple 2-D geometry is available in current CORQUENCH code, the geometry is modeled as a cylinder with a diameter of 8.444 m. The thicknesses of concrete walls at radial direction and axial direction are 2 m and 2.56 m, respectively. The initial melt compositions data is based on the normal scenario analysis of reactor failure, shown in Table 4.1. The initial melt temperature is set as 3000 K and the upper structure temperature (i.e., the atmosphere temperature) is set as 750 K. The density of corium is calculated by inner subroutine within CORQUENCH. The common LCS type is selected for the concrete type. The initial concrete temperature is 300 K, which is used in the evaluation of the concrete decomposition specific enthalpy, and the concrete decomposition temperature is 1500 K. All gases arising from concrete decomposition are assumed to travel up through the melt. The cavity absolute pressure is 0.3 MPa. The decay heat during the calculation is evaluated from an interpolation table which is based on the typical data about 24 hours after the reactor shutdown. In terms of the crust and particle bed formation, the decay heat is delivered according to their mass, i.e., same mass can produce same decay power.

For water injection conditions, it is dry cavity during the first 20 minutes, and then water will be injected from the top and maintained with a constant depth during the whole MCCI process. The water saturation temperature is set as 372 K and same value is held for the upper water all along, which is same as the normal plant operating condition following cavity flooding.

The other miscellaneous modeling assumptions are summarized as follows. The concrete ablation model includes the initial transient crust growth and remelting phase. The crust freezing temperature is based on the melt composition. The crust is assumed to be permeable and fail when the thickness falls below the mechanical stability limit under the
applied hydrostatic load of the melt. For melt upper surface heat transfer, both melt eruption and water ingestion are activated. The Rico-Spalding correlation is used to calculate the melt entrainment rate. Water ingestion is calculated by using the modified Lister-Epstein model, with the empirical constant C=0.9 in the crust dryout heat flux model. The crust anchoring is not applicable due to the large scale. In addition, in respect of that unoxidized Zr cladding was present in the melt (Table 4.1), Zr was assumed to be solution with the core oxide phase, and condensed phase chemical reactions between metallic Zr and SiO$_2$ were considered. Finally, the calculation was run with a time step of 0.03 second to achieve a converged solution.

![Figure 4.1 Cavity Geometry in Reactor-Scale Scenario.](image)

Table 4.1 Corium Compositions for Base Case Analysis.

<table>
<thead>
<tr>
<th>Corium Composition (kg)</th>
<th>ZrO$_2$</th>
<th>Zr</th>
<th>UO$_2$</th>
<th>Stainless Steel</th>
<th>FeOx</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6500</td>
<td>14000</td>
<td>73050</td>
<td>32700</td>
<td>550</td>
<td>126800</td>
</tr>
</tbody>
</table>

4.2. Results

The calculation results of evolution versus time are presented in Figure 4.2~Figure 4.7, and the final outcomes are listed in the Table 4.2. The simulations predict that the
quenching will be achieved at 145 minutes, thus both basemat and sidewall erosion will be arrested. Here, the criteria of debris stabilization in the code are that: i) basemat erosion has been arrested, ii) melt temperature has fallen below the concrete liquidus temperature, or iii) melt depth is below a minimum thickness which was set as 0.005 m. As shown in Figure 4.2, the calculation was terminated at 8687 seconds (144.8 minutes), where the melt depth had been reduced to the minimum thickness. At the same time, the temperature also declined to 1492 K which is blow the concrete decomposition temperature (1500 K) and just a little higher than the concrete liquids temperature (see Figure 4.3). The relative low temperature is exactly the reason for that the ablation rate approached to zero during the last 20 minutes. Here one thing should be noted that even the ablation is zero, the heat-up of concrete still be able to continue and cause the release of the gases from concrete which has lower gas decomposition temperature than the average concrete decomposition temperature.

The time evolution of the heat flux is shown in Figure 4.4. It can be found that there are three peaks in the curve of the heat flux on the upper surface (heat flux to water/air), which exactly reflects the important cooling phenomena during the whole MCCI process. In the beginning, there is no water existed on the top and the melt temperature is very high, which results in the radiant heat transfer is still relatively high. At that time, both the very high heat flux to concrete and a severe concrete ablation, up to 100 mm/minute, are caused by the high temperature. The sparging gas with very high velocity also contributes to the well cooling. After 20 minutes, the second heat flux peak happened as the result of the top water flooding was initiated. Then, the heat flux declined as the melt temperature decreased. In the following about 20 minutes, the thermal condition for crust formation did not be satisfied, even though the superficial gas velocity has reduced to about 2 cm/sec (Figure 4.7). Until 41.9 minutes, the temperature at melt/water interface finally was reduced to the crust freezing temperature and the stable floating crust formed, as shown in Figure 4.5. But the melt eruption phenomenon happened as well at the same time (see Figure 4.6), which caused the third heat flux spike. Soon after that, at 42.3 minutes, water ingression into the crust was initiated since the heat flux from the crust upper surface fell below the crust dryout limit. Afterward, the heat flux to the upper structure approached a constant of 690 kW/m² to the end.

During the whole process, the prediction shows that stable crust cannot form on the melt/concrete interface since the high temperature and gas velocity. Furthermore, the very high initial melt temperature also leads to the failure of the transient concrete dryout
model. Instead, the fully developed ablation model was used to calculate the long-term interaction with melt pool in direct contact with concrete, i.e., Phase 4 in Figure 2.3. The totally same erosion behaviors on basemat and sidewall were predicted since the homogenous characteristic of the melt pool. In the end, the ablation depth reached to 38.1 cm. So the integrity of the cavity is completely kept by the top water flooding as the code prediction.

Figure 4.2 Ablation Front Location Predictions for Base Case.
Figure 4.3 Melt Temperature Prediction for Base Case.

Figure 4.4 Melt-Atmosphere Heat Flux Prediction for Base Case.
Figure 4.5 Surface Elevation Predictions for Base Case.

Figure 4.6 Average Melt Entrainment Coefficient Prediction for Base Case.
Figure 4.7 Superficial Gas Velocity Predictions for Base Case.

Table 4.2 Key Parameters Outcome from Base Case Simulation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching Time</td>
<td>145 minutes</td>
</tr>
<tr>
<td>Final Melt Temperature</td>
<td>1493 K</td>
</tr>
<tr>
<td>Axial Ablation Depth</td>
<td>38.1 cm</td>
</tr>
<tr>
<td>Radial Ablation Depth</td>
<td>38.1 cm</td>
</tr>
<tr>
<td>Upper Crust Depth/Mass</td>
<td>46.89 cm / $1.6889 \times 10^5$ kg</td>
</tr>
<tr>
<td>Particle Bed Depth/Mass</td>
<td>7.8 cm / 16966 kg</td>
</tr>
<tr>
<td>Crust Permeability</td>
<td>$0.50014 \times 10^{-9}$ m$^2$</td>
</tr>
<tr>
<td>Cumulative Gas Release</td>
<td>0.7105E6 moles</td>
</tr>
</tbody>
</table>
5. Sensitivity analysis

Since the principles behind the complex phenomena have not understood very well for MCCI, it is a good way to recognize the impacts of different factors through the code sensitivity analysis. In addition, the validity and the code applicable range can also be identified by analyzing whether the results from the code are sensible. Based on the cooling models analysis described above, total ten parameters have been selected to carry out the sensitivity analysis in the present study, i.e., concrete composition (concrete type), corium composition, water flooding time, atmosphere pressure, concrete ablation temperature, initial temperature, decay power, cavity geometry, concrete decomposition model and melt upper heat transfer model. The values were also set in a reasonable range, which listed in Table 5.2 in the end of this section. The other non-varied parameters are same as the base case simulation described in the last section. All the calculations were conducted during a period of 81 hours (3 days after SCRAM), which is considered as the most important period for MCCI. The simulation results about the ablation depths are summarized in Table 5.2 too. Meanwhile, an attempt is done to explain the variation trends based on the physical models.

5.1. Concrete type

In general, there are three types of concrete used in MCCI analysis. And the characteristics of concrete may significantly impact the MCCI behavior include: 1) the gas content, which is a key factor for the gas superficial velocity from the concrete decomposition; 2) the thermophysical properties, which determine the heat transfer coefficient; 3) different solidus/liquidus temperatures, here 1393/1568 K is set for LCS concrete, 1403/1523 K for siliceous concrete and 1495/2577 K for limestone/limestone concrete. As well, the different concrete decomposition temperature has to be selected for different concrete, i.e., 1500 K for siliceous and 1750 K for limestone/limestone.

Figure 5.1 illustrates melt-atmosphere heat flux predictions for different concretes and the results show that the siliceous concrete will lead to the most severe concrete erosion while limestone/limestone cause the best erosion resistance. That is due to the eruption cooling mechanism will rarely occur for the siliceous concrete, which has a good reflection by the experimental results from Farmer (2005). It is also reflected in the time
evolution of the heat flux to upper water (Figure 5.1). After the water ingression into crust, the heat flux of the siliceous concrete declines to the crust dryout limit. For the other two kinds of concrete, eruptions enhance the heat flux further. Besides, although the different power splits (in radial direction and axial direction) were observed for siliceous in OECD/MCCI programs, it is not reflected in the predictions. Further investigations about the mechanisms behind that are needed to simulate the phenomenon.

![Figure 5.1 Melt-Atmosphere Heat Flux Predictions for Different Concretes.](image)

5.2. Initial corium compositions

Although the reactor core compositions are considered as similar for the same reactor type, the corium compositions will still vary with the previous reactor failure process. Here the compositions of unoxidized Zr cladding and Cr which is main part of stainless steel are changed to study the effect of chemical oxidation reaction by metals during MCCI. The initial corium compositions for different cases are shown in Table 5.1.
Table 5.1 Corium Compositions for Simulations.

<table>
<thead>
<tr>
<th>Case</th>
<th>ZrO\textsubscript{2}</th>
<th>Zr</th>
<th>UO\textsubscript{2}</th>
<th>Stainless Steel</th>
<th>FeO\textsubscript{x}</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(base) 1</td>
<td>6500</td>
<td>14000</td>
<td>73050</td>
<td>32700</td>
<td>550</td>
<td>126800</td>
</tr>
<tr>
<td>2</td>
<td>13750</td>
<td>10150</td>
<td>82910</td>
<td>32700</td>
<td>550</td>
<td>140060</td>
</tr>
<tr>
<td>3</td>
<td>27450</td>
<td>0</td>
<td>82910</td>
<td>32700</td>
<td>550</td>
<td>143610</td>
</tr>
<tr>
<td>4</td>
<td>13750</td>
<td>10150</td>
<td>82910</td>
<td>16000</td>
<td>550</td>
<td>123360</td>
</tr>
</tbody>
</table>

As shown in Figure 5.2, the ablations for the four cases are divided into two groups. The first group including the base case and case 2 has about 20% more ablation than the other group. Since the base case and case 2 have high portion of unoxidized Zr and stainless steel, the ablation will be relatively higher as a result of more heat source from chemical reactions. Though the mass of Zr in case 4 is same as case 2, the reduced portion of Cr results in a less ablation. But by overall analysis, they all reflect the same erosion trends with time.

Figure 5.2 Ablation Front Location Predictions for Corium with Different Compositions.
5.3. Water flooding time

For the sensitivity study of water flooding time, the calculations were carried out with the four different starting point of water injection. Firstly, the time of 10 seconds after corium arrives at the cavity is employed to simulate the condition of immediate water injection after the corium/concrete fully contact. In addition, the infinite time equally simulate the dry cavity condition.

Figure 5.3 shows the results during the early 300 minutes and it predicts that the corium can be quenched more easily in the earlier water injection. The ablation depths increase greatly if water flooding is delayed longer time. It is explicit that if water injects later, the melt with high temperature may cause more severe erosion before it can be cooled down. Moreover, the permeability of the final status increases with the decreasing of the flooding time. It may be explained by the eruptions and gas content in melt, since the mass of particle bed has the same tendency as the permeability. As the time of flooding increases, the concrete content in the melt will increase owing to the ablations. It should be noted that the concrete employed here is LCS. That means larger potential of gas production can be caused by the larger portion of concrete in the melt. And the gas will cause higher porosity in the crust which is a key parameter for the following water ingress and eruptions.

For the dry cavity condition, complete quenching cannot be achieved during the calculating time. But the concrete ablation rate has been reduced to zero temporarily during the last 500 minutes (see Figure 5.4). In the following long period, it is reasonable to predict that the decay heat can be transferred out by both upper surface and concrete. But as the crust growing, the heat transfer coefficient of the upper crust will decrease. And then the melt temperature will increase again, owing to the insufficient heat removal. Therefore, crust may remelt and concrete ablation will occur again if the decay power is high enough. The dynamic crust growth should be terminated as the decay heat power declining.

Therefore, it can be concluded that faster quenching can be achieved relatively easily for the immediate flooding condition, only ~28 minutes after flooding as shown in Figure 5.3.
Figure 5.3 Ablation Front Location Prediction for Different Flooding Time.

Figure 5.4 Ablation Front Location Prediction for Dry cavity.
5.4. Atmosphere pressure

It is obvious that the atmosphere pressure above the upper structure can affect the superficial gas velocity from the concrete decomposition. And it has been mentioned above that both water ingresson and eruptions depend on the superficial gas velocity greatly. The predictive gas velocities under the different operative pressures are shown in Figure 5.5. The higher pressure may restrain the gas velocity and results in the poor cooling but more severe ablation as seen in Figure 5.6. Meanwhile, Figure 5.7 indicates that eruptions at standard atmosphere pressure occur very earlier than those of the other three higher pressure cases. Then one may conclude that the stable crust can form more easily under the high superficial gas velocity. It is against that the higher gas velocity will break up the crust more easily. However, we need to consider two criteria for the stable floating crust formation, thermodynamic and mechanical conditions. In this study, it is found that the mechanical condition, i.e., the gas velocity is less than the critical velocity which precludes the stable crust formation, can be met for all cases in the early period. Whether a stable crust can form or not mainly depends on the thermodynamic conditions, i.e., the heat removal by water should be larger than the convective heat transfer into the crust from melt zone, which will initiate the incipient crust formation. When the system pressure is 1 bar, the heat transfer coefficient to overlying water is significantly larger than the other cases. The reason is the area enhancement as the gas bubbles pass through the melt-water interface. A simplified model implemented within the code is expressed in Equation 5-1.

\[ A_\ast = 1 + 4.5 \frac{j}{U} \]  

Here \( A_\ast \) is the enhanced area; \( j \) is gas velocity and \( U \) is the bubble terminal rise velocity evaluated by the Peebles and Garber correlation (Peebles, 1953).

Since the water-side heat transfer coefficient is proportional to the contact area, the thermodynamic condition is predicted to be satisfied earlier with a high gas velocity.

However, according to the Ricou-Spalding correlation (Ricou, 1961), the larger melt entrainment coefficients are obtained under the higher pressure. The correlation is of the form:

\[ K_{ent} = E \left( \frac{p_g}{\rho_m} \right)^{1/2} \]  

(5-2)
where $K_{ent}$ is melt entrainment coefficient; $\rho_g$, $\rho_m$ are densities of gas and melt, respectively. $E$ is proportionality constant which was set as 0.08 during the calculations. Hence, the high pressure leads to high gas density and large entrainment coefficient.

Furthermore, the results show that the complete quenching time vary inversely with the pressures (Figure 5.6). It is caused by the larger portion of concrete ablation. When concrete is eroded into the melt, the average melt temperature will be reduced by mixing the concrete with low temperature.

![Figure 5.5 Superficial Gas Velocity Predictions for Different Atmosphere Pressures.](image-url)
Figure 5.6 Ablation Front Location Predictions for Different Atmosphere Pressures.

Figure 5.7 Melt Entrainment Coefficient Predictions for Different Atmosphere Pressures.
5.5. Concrete ablation temperature and decay power

The concrete ablation temperature has been modified to study the sensitivity for the ablation. As listed in Table 5.2, as the ablation temperature is modified from 1400 K to 1560 K, the ablation depth is enlarged about 20 cm and additional 17 minutes are needed for quenching. The same trends of ablation evolution are hold for all these concrete ablation temperatures, as plotted in Figure 5.8.

The decay power is also shifted to higher level to investigate the possible results. In the new scenario, the decay heat power is treated as a nuclear power plant with 3100 MWth has continuously run for 2 years before SCRAM, and the time of core melt relocation into the cavity is 2 hours. The Todreas and Kazimi equation (Todreas 1990) is used for the estimation of the approximate decay power. The final quenching still can be achieved by the calculations. Comparing with the base case, it results in more concrete ablation, about 21%, and longer time to cool down (Figure 5.9).

The results from the two scenarios show the same trend as expected. The higher ablation temperature can effectively resist melt erosion, but longer quenching time is required. Although the corium is still quenched with the double decay power in this scenario, the decay power cannot be simply regarded as less important to the sensitivity analysis.

![Figure 5.8 Ablation Front Location Predictions for Different Concrete Decomposition Temperatures.](image)
5.6. Melt initial temperature

A large range, from 2200 K to 4000 K, is changed for the sensitivity analysis of the initial melt temperature. Figure 5.10 shows the results that if the initial melt temperature increases 1000 K, about 10 cm additional ablation will be caused and much less ablation for the case with initial temperature of 2200 K. And it is explicit that the lower melt temperature is more easily to achieve the complete quenching. From the heat flux evolution (Figure 5.11), the heat flux at upper surface of 2200 K case does not decrease as the other two cases before the water flooding. And water ingestion is initiated immediately after water flooding. Moreover, the crust dryout heat flux reaches to 2 MW/m², it is much higher than the others. Actually, for the case with initial temperature of 2200 K, the transient concrete dryout model is available for calculating and the stable crust is able to form and grow on both axial and radial direction, as Figure 5.12. Apparently, compared with the other cases, the relative lower initial temperature involves the different calculating models within the code. Meanwhile, by modifying the value from 2200 K to 2800 K, it has been found that when the initial melt temperature is lower
than 2400 K, the transient concrete dryout model is able to be applied and significant effect will be reflected on the final ablation depth. At last, the ablation rates for 2200 K case does not decline to zero before it achieves complete quenching, but the thickness of melt has already met the criterion of terminating calculation, less than 0.005 m.

Figure 5.10 Ablation Front Location Predictions for Different Melt Initial Temperatures.
Figure 5.11 Melt-Atmosphere Heat Flux Predictions for Different Melt Initial Temperatures.

Figure 5.12 Crust Growth on Concrete/melt Interface Predictions for Different Melt Initial Temperatures.
5.7. Cavity geometry

The shorter diameters of the cavity (4 m and 6 m) with the same mass of corium are used to check the effects of the cavity geometry. The ablation evolutions are shown in Figure 5.13. Three curves show the same variation trends with time. The larger cavity has more sufficient cooling ability, because the large spreading area increases the heat removal. For the cavity with diameter of 4 m, the ablation is up to more than 1 m but the quenching time is dramatically longer than the other cases. However, it should be noted that the crust anchoring is not validated for all three cases due to the phenomenon of crust anchoring is believed to be impossible in a cavity with a large span, generally 6 meters. But it is not clear that whether a stable crust can attach to the sidewall or not for the cavity with diameter of 4 m. And in fact the large basemat size of 120 cm × 120 cm experiment MACE M3b has been done and the crust was indeed observed to anchor to the sidewalls successfully (Farmer et al., 1997).

![Ablation Front Location Predictions for Different Cavity Geometries.](image)

Figure 5.13 Ablation Front Location Predictions for Different Cavity Geometries.
5.8. Melt upper heat transfer model

Different cooling mechanisms are chosen respectively to compare the cooling capacities. When the option of eruption model is nullified, the prediction is almost same as that of the base case. Only the quenching time is about 13 minutes longer. The difference of heat flux can be seen in Figure 5.14. Without eruptions, the dryout heat flux is a little smaller after water ingestion. But for the case without water ingestion, extra 12 cm ablation will be produced and the complete quenching cannot be achieved during the calculating period (81 hours). As shown in Figure 5.15, the heat flux will decline to 200 kW/m² after stable floating crust formation. Although eruptions occur after a stable crust formation, the heat flux to the overlying water pool is still much smaller than the crust dryout limit of water ingestion. Then as the crust growing, the melt under the crust layer is very difficult to cool down and freeze without water infiltration through the crust. Nevertheless, the eruption mechanism still reduces 38 cm concrete ablation by better cooling, as illustrated in Figure 5.16.

In respect of crust anchoring condition, the unexpected result is obtained, shown in Figure 5.17. When crust anchoring option is set on in the scenario, the crust anchoring really occurs at 7188 seconds. The concrete erosion is same as that of the base case but the complete quenching cannot be obtained in the end. Regardless of whether crust anchoring is able to occur in real conditions, the predictive results are not sensible in respect of that the melt temperature continues declining without concrete ablation after melt/crust separation. Actually, due to the anchoring crust model involves a secondary crust formation, it most likely is caused by one bug about mass conservation within the code. If the secondary crust forms over the melt pool while the upper bridge crust acts as a thermal insulator, one assumption is made about that the secondary crust is thin enough to be neglected. As a result, the mass of the lower crust is not taken into account for the mass conservation. However, the evidences from the prediction show that the lower crust is growing but the total mass of crust still keeps constant.
Figure 5.14 Melt-Atmosphere Heat Flux Predictions for No Eruption Model.

Figure 5.15 Melt-Atmosphere Heat Flux Predictions for No Water Ingression Model.
Figure 5.16 Ablation Front Location Predictions for Different Models Applied.

Figure 5.17 Melt Temperature Prediction for Crust Anchoring.
5.9. Concrete decomposition model

Although there are three concrete decomposition models offered by the code, the transient concrete dryout model cannot be performed due to the initial temperature at the melt/concrete interfacial is higher than the melt freezing temperature. So the crust formation will not be considered, and the calculation is changed automatically to the fully developed ablation model without crust formation. Finally, only the concrete decomposition model is modified to quasi-steady model to compare with the fully developed ablation model. From Figure 5.18, it is clear that the ablation depth from quasi-steady is larger than that of the fully developed ablation model. It is due to the quasi-steady model does not take into account the heat conduction into the concrete. Concrete ablation will continue once the melt temperature is higher than the concrete decomposition temperature. But for fully developed ablation model, higher melt temperature is required to initiate the concrete erosion.

![Figure 5.18 Ablation Front Location Predictions for Quai-Steady Concrete Ablation Model.](image)
Table 5.2 Maximum Ablations and Quenching Time for Sensitivity Study.

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5.10. Discussion

As known from the code instruction, it is assumed that melt eruption will not occur for siliceous concrete, which is based on the experimental observations. Indeed, it is reflected in the previous sensitivity analysis of different concrete. The melt entrainment coefficient is zero during the whole process for siliceous. But the calculations for melt upper heat transfer models indicate that eruption cooling mechanism is less important for the LCS concrete. Actually, it has been observed that eruption can increase the heat flux effectively in the CCI tests. Also, eruption phenomenon is proved to be a key factor for the porosity formation in the crust. However, the calculations indicate that a high crust dryout limit due to water ingress can be obtained even without eruptions, which leads to better coolability of LCS than that of siliceous. So a clear relevance between eruption and water ingress cannot be seen only from the calculations above.

From the pressure sensitivity analysis, the results show that reduction in pressure will increase the efficiency of the melt eruption cooling mechanism. Meanwhile, we can also deduce a decreasing effectiveness of the water ingestion mechanism should be obtained for the same physics models. If the same assumption is hold, i.e., water ingestion is more important than eruption, the inverse trends would be expected to be observed in the pressure sensitivity calculation. Thus, more complex relationship between the two mechanisms should exist behind the phenomenon.

Finally, both the mass of the overlying water pool and temperature are constant from beginning to end. It may result in the unexpected coolability for example the result in earlier water flooding. It is due to the ways to evaluate the thermophysical properties and models are based on the experimental data rather than the universal physical models. So if the assumption is far out of the experimental range, the wrong prediction will be obtained. Further fine parameters tuning and models corrections should be used to make the calculations more reliable.
6. Comparison of different codes

A further investigation is performed with the comparisons of different codes. Two codes have been used for the simulation, i.e., ASTEC V2.0 and FinCCI, respectively. The possible parameters in the base case for CORQUENCH are used in both codes. For the parameters unenclosed in CORQUENCH but needed in the ASTEC or FinCCI, the values are chosen as close as the real reactor conditions by following their instructions. In order to do the better comparison, the maximum calculating time is set same as CORQUENCH, 292000 seconds. The final comparisons results are mainly focused on the ablations and melt temperature. A brief analysis for the results from both codes is presented below.

6.1. Comparison with FinCCI

The FinCCI also originated from the OECD/MCCI project. In the CCI experiments, Sevón (2008a) developed a new method for evaluating heat transfer and gas release rates for MCCI. It takes into account the heat conduction in the concrete. The FinCCI was developed as an Excel macro for testing the empirical heat transfer correlation (Sevón, 2008b). Currently, it has been updated to use the latest version of the correlations. Compared with the other MCCI codes, the main advantage of FinCCI is that it solves the heat conduction equation in the concrete which is proofed to be important in the concrete erosion. More information about the code and the source code can be found in the report (Sevón, 2011).

Since the FinCCI is a simple macro, many phenomena were modeled in a very simplified way or ignored completely. So some parameters in the code can only be set as an approximate value, but it may cause great difference. The key parameters used for the simulation are given in appendix C.

The results of the concrete ablation are presented in the Figure 6.1. The complete quenching is not achieved by the maximum calculating time. The ablation depths on basemat and sidewall finally converge in the end. The maximum erosion is about 90 cm, which is much larger than that of CORQUENCH prediction. In addition, though the same ablation depth on both directions in the end, great discrepancy is predicted in the early period. The sidewall ablation seems have been hugely overestimated, about 67 cm in the very beginning. And the ablations jump dramatically in the first calculating time step on
both direction. It is due to the heat flux limited is neglected in FinCCI code. As opposed to the ablation jump, the melt temperature drops more quickly and then almost approaches to a constant of 1670 K (Figure 6.2). Such great immediate erosion is not acceptable under the real conditions. Also, the superficial gas velocity from the sidewall reaches as high as 5.5 m/s from beginning. This is far outside the validity range of the heat transfer correlations (Sevón, 2011). So the calculation results by FinCCI for the reactor-scale are doubted, at least in this scenario.

Figure 6.1 Ablation Front Location Predictions for Base Case by FinCCI.
6.2. Comparison with ASTEC

As an integral code, ASTEC is more complex than the CORQUENCH and FinCCI. Almost all severe accident phenomena are covered in the code, except steam explosion and containment mechanical integrity. Such a code, which is originally developed for classical plant applications, should be able to predict the reliable result in a reactor-scale scenario. Another main advantage of the code is that more validation work and continuous improvements are being done all the time. Just recently, the code has been updated to the first V2.0 version. The CCI and VULCAO tests simulations have been conducted by MEDICIS which is the module about MCCI in ASTEC. Moreover, the ability of coupling with the other model can do the more complex scenario for the severe accident analysis.

One main feature of the MEDICIS code is both homogeneous and stratified pools are applicable for the simulation, even the way to stratify the pool is simplified. Meanwhile, the pool configuration evolution is available between homogeneous and stratified
configuration determined by criteria fitted on BALISE experiments (Tourniaire, 2003, 2004). Also regarding the cavity, its shape can be axisymmetric or non-axisymmetric. Furthermore, heat flux due to both water ingress and corium eruption can be included in the calculation. The decay power can be appointed to be a variable distribution according to different elements. The main parameters are set almost same as CORQUENCH simulation (see appendix B), except the pool configuration evolution is activated and more precise decay power distribution is employed.

The prediction from ASTEC also shows a large difference compared with the results of CORQUENCH. The cavity profiles and ablation evolutions are presented in Figure 6.3 and Figure 6.4. The final erosion on basemat reaches 151.7 cm and 62.6 cm on the sidewall. A complete quenching cannot be obtained after 3 days. The average melt temperature still has a relative value about 2000 K in the end. Therefore, although the ablation rates seems approach to zero during the last period, a sharp raise still be possible due to the high temperature melt driven by decay heat. It actually happens to the sidewall ablation at about 1100 minutes, as seen from Figure 6.4. In addition, a large ablation difference is predicted on the sidewall and basemat. More than twice ablation depth on the basemat may be caused in the scenario. As the evidence from CCI tests, the phenomenon is unexpected for the LCS concrete (Farmer, et al., 2006). However, it may be explained as the water atop will migrate into the concrete porosity which can effectively suppressed the concrete ablation (Maruyama et al., 2006).
Figure 6.3 Cavity Profile Predictions for Base Case by ASTEC.

Figure 6.4 Ablation Front Location Predictions for Base Case by ASTEC.
7. Conclusions

The coolability of ex-vessel melt pools by top water flooding is studied by simulations with various computer codes, especially CORQUENCH. A series of experiments were reviewed to learn the newly developed cooling mechanisms. Prior to the reactor-scale analysis by the code, verifications and validations were performed to understand how to develop a proper calculating model and check the applicability of the code in integral experiments. The same results on the tests CCI-2, CCI-3, CCI-4 and CCI-5 are obtained as the previous calculations independently carried out by the code developer, but a discrepancy is found on the last integral test CCI-6. A good agreement is obtained for the three of CCI tests (i.e. CCI-2, CCI-4 and CCI-5) and the main trends can be also captured for the remaining tests (CCI-3 and CCI-6).

A reactor-scale simulation is carried out to predict the MCCI behavior in a plant scenario. Fast quenching and complete solidification of melt is achieved by top water flooding for LCS concrete. Only 38 cm concrete were eroded on both axial and radial directions at 145 minutes. The optimistic prediction shows if water penetration into the upper crust is allowed, much larger amount of heat can be removed from melt only by top flooding. But as a blind calculation, uncertainties are difficult to assess since no such experimental data is available so far.

Moreover, several important parameters identified by experiments are selected for the purpose of sensitivity study. The atmosphere pressure, starting point of flooding and water ingression show the greater impacts on the quenching behavior. To assure the code gives sensible results, simple explanations are made for the results on the basis of the physical models. However, exact sensitivity ranking is not given owing to the complex dependency among the models.

Since CORQUENCH is developed on the basis of experiment data, it has incorporated all the recent identified cooling mechanisms. The calculations basically show the relevance of the set of models and assumptions. But as the limitation of the State of the Art, it still cannot capture all the phenomena about MCCI. According to the experience achieved during the MSc thesis project, some limitations of the code are found and corresponding suggestions are proposed for the code improvement:
i) In the anchoring phase of crust, if a secondary crust forms successfully, the mass conservation of the total system is violated because the crust is assumed to be very thin. It will lead to the prediction that the secondary crust can grow to the infinite thickness.

ii) The concrete ablation caused by upper crust should be considered, especially in a scenario with large melt height in a small cavity. If the ablation indeed occurs at the interface between concrete and crust, the crust anchoring should fail immediately due to the failure of support edge.

iii) Since conduction heat transfer into the concrete is factored into the analysis, the concrete heat-up phase should be considered, which can lead to a sharp increase in ablation rate after crust failure.

Finally, the simple comparisons of CORQUENCH calculation with those of the ASTEC and FinCCI code are presented. The predictions by different codes show a large scatter of the effect of top flooding. It is mainly due to the varied modeling approaches and thermophysical and thermochemical properties data used by the three codes. This reflects that a consistent understanding of MCCI phenomena is not achieved yet.

In summary, the coolability of ex-vessel corium by top flooding is predicted to have a great enhancement when incorporating the several cooling mechanisms found or proposed in OECD/MCCI projects and elsewhere. But for the purpose of applying the code to safety analysis of a LWR, more work is needed in this field, both concerning experiments and models.
Reference


Farmer M. T., 1992. Modeling and Database for Melt-Water Interfacial Heat Transfer. 2nd CSNI Specialist Meeting on Core Debris-Concrete Interactions, Karlsruhe, Germany, 1-3 April.


Spindler B., Dimov D., Foit J., Sevon T., Cranga M., Atkhen K., Martin M. G., Schmidt W., Spengler C., 2008. Simulation of corium concrete interaction in a 2D geometry: recent benchmarking activities concerning experiment and reactor
cases. The 3\textsuperscript{rd} European Review Meeting on Severe Accident Research (ERMSAR-2008), Nesseber, Bulgaria, 23-25 September.


APPENDIX A: INPUT FILE OF CORQUEENCH

Mod 3.03, Test CCI-6 performed by Huaqiang Zhong, 2011

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<td>0.321E+05</td>
</tr>
<tr>
<td>0.746E+04</td>
<td>0.307E+05</td>
</tr>
<tr>
<td>0.756E+04</td>
<td>0.301E+05</td>
</tr>
<tr>
<td>0.766E+04</td>
<td>0.292E+05</td>
</tr>
<tr>
<td>0.776E+04</td>
<td>0.279E+05</td>
</tr>
<tr>
<td>0.786E+04</td>
<td>0.185E+05</td>
</tr>
<tr>
<td>0.796E+04</td>
<td>0.161E+05</td>
</tr>
<tr>
<td>0.806E+04</td>
<td>0.128E+05</td>
</tr>
<tr>
<td>0.816E+04</td>
<td>0.106E+05</td>
</tr>
<tr>
<td>Value 1</td>
<td>Value 2</td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>0.826E+04</td>
<td>0.865E+04</td>
</tr>
<tr>
<td>0.846E+04</td>
<td>0.638E+04</td>
</tr>
<tr>
<td>0.866E+04</td>
<td>0.432E+04</td>
</tr>
<tr>
<td>0.886E+04</td>
<td>0.242E+04</td>
</tr>
<tr>
<td>1.000E+05</td>
<td>0.000E+04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value 5</th>
<th>Value 6</th>
<th>Value 7</th>
<th>Value 8</th>
</tr>
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<tbody>
<tr>
<td>3.73E+02</td>
<td>4.20E+01</td>
<td>0.00E-02</td>
<td>2.45E+02</td>
</tr>
<tr>
<td>0.10E+00</td>
<td>0.30E+00</td>
<td>7.50E+02</td>
<td>1000</td>
</tr>
<tr>
<td>0.00E+03</td>
<td>0.1E+00</td>
<td>1.02E+04</td>
<td>0.00E+00</td>
</tr>
</tbody>
</table>
APPENDIX B: INPUT FILE OF ASTEC V2.02

!----------------------------------------------------------------------------------
! Reactor-Scale Scenario with Atop Flooding Simulation
! performed by Huaqiang Zhong, 28MAY2011
!----------------------------------------------------------------------------------
! Calculation options

! Fliq mass <Fliqvol at a given temperature (higher density of refractory oxides)
(name="REALMCCI") ! gamma= 0.2
(compute=GETENV(computer))
!
!
! STRU SEQUENCE
! initial and final calculation times
TINI 0.
TIMA 292000. !
TMCC 0. !
! ASTEC Macro timestep
STRU MACR
   MINI 500. !
   MAXI 500. !
END
END
!
!
CALL menu.visu
CALL cavity_shape.visu
CALL cavity_temperatures.visu
CALL cavity_erosion.visu

!CALL CCI2.visu

STRU SAVE
FILE (name//'.bin')
FORM DIRECTOR
FREQ 1000.
END

STRU PLOT
   FILE (name//'_mnt_''/compute//'.plot')
   FREQ 5.
   DATA "VERO =BASE:CAVITY:GEOMETRY:VERO"
DATA "RMAX =BASE:CAVITY:GEOMETRY:RMAX"
DATA "MEROD=BASE:CAVITY:CONCRETE:MEROD"
! DATA "TLAYER=BASE:CAVITY:LAYER 'NAME' OXIDE:THER:T"
! DATA "TMETAL=BASE:CAVITY:LAYER 'NAME' METAL:THER:T"
END
!
!STRU VISU
! FILE "menu.vis"
! PAUS NO
!END
!STRU VISU
! FILE "evol.vis"
! TITL "VERO"
! STIT (stit)
!LABX "time (s)"
!LABY "(m)"
! SFIL "VERO.eps"
!STRU VARI
! PATH "BASE:CAVITY:GEOMETRY:VERO"
! NAME "VERO"
END
!END

STRU CALC_OPT
SC1 MODULIST MEDICIS TERM ! list of active modules
STRU MEDICIS
STRU OUTPUT TYPE CURVES
    FILE (name/.'cur')
    FREQ 1000.
END
STRU OUTPUT TYPE CAVITY
    FILE (name/.'cav')
    FREQ 1000.
END
STRU OUTPUT TYPE LISTING
    FILE (name/.'lst')
    FREQ 1000.
END
EROSION 1 ! activation of concrete erosion (default=1)
POWERUP 1 ! activation of loss of power through the upper surface (default=1)
GASRISE 1 ! activation of gas rise (default=1)
SPECTRANS 1 ! activation of species transfer between layer (default=1)
POWERLAY 1 ! activation of exchange of power between layer (default=1)
PDECAY 2 ! variable distribution of power between oxides and metals (default=1)
UPPCRUST 1 ! activation of the upper crust formation (default=0)
MIXTURE 0 ! deltal solidification = hpool(Tpool) -hsol(Tsold) is increased default=1)
ERUPTION 1 ! activation of the melt eruption through the upper crust
RATIOCAV 5.D-2 ! ratio = displacement of the node / length of the segment (default=1.d-1)
RATIOTEMP 5.D-3 ! maximal evolution of the layer temperature -deltaT/T- (default=1.d-2%)
NCRIT 1.D-5 ! Newton criterium for temperature (default=1.D-5)
DTMIN 1.D-4 ! minimum time step (s)
DTMAX 100. ! maximum time step (s)
PRECIS 0.00001 ! Zero numérique 0.00001
FMAX 0.5 ! Holes/corners correction factor 0.5
IDIM 2 ! 2=calcul 2D ; 11=calcul 1D complet ; 12=calcul 1D partiel
VMPREC 1. ! precision on the metal volume in order to find the point nmet (1. means 1%)
DTX 100. ! maximum temperature increment during Newton iteration (K) (default=5.)

CONFIG 2
PARACONF JG
  a_SH 0.
  b_SH 1.
  a_HS 0.
  b_HS 0.054

SRG ATOMPOWE
  U 1.21379
Zr 0.41438
Fe 0.0
Ni 0.41438
Cr 0.41438
TERM
TRED 1
END END
!---------------------------------------------------------------
! Updating material properties
!
STRUCTURE MDB

STRUCTURE SET
NAME Corium
! addition of Mg, MgO !
SC1 atoms Al C Ca Cr Fe H Mg Ni O Si U Zr TERM
SC1 species CO Al2O3 CaOMgO O2U O2Zr O2Si Cr203 NiOFeO CO2 H2O H2 O2 Cr Fe Ni Si U Zr Al Ca Mg TERM
SC1 low Al2O3 CaOMgO O2Si Cr203 NiOFeO TERM
SC1 high O2U O2Zr TERM
!
CALL REACTOREVOL.includethermodata_2.dat

STRU PROPERTY
  LAW 'ETAL'
  NAME "eta_i(T)"

63
VARIABLE 'T'
RUNLOW  2.731500000000000E+02
RUNUPP  4.000000000000000E+03
MVISCO  0
END
STRU PROPERTY
  LAW  'ETASL'
  NAME  "eta(T)"
  VARIABLE 'T'
RUNLOW  2.731500000000000E+02
RUNUPP  4.000000000000000E+03
NVI SCO  0                                   ! NVISCO (nvisco) choice of model (Stedman=0,Thomas=1,Ramac=2,Weschl=3)
  ! RAMACIOT  3.                              ! FLIQMIN for Stedman and RAMACIOT for Ramaciotti
  FLIQMIN  0.35
END
END END
!
!--------------------------------------------------------------------------
!
! Corium properties
!
!
!!coupl: STRU CORIUM => STRU CAVITY
!
STRU CAVITY
  FRAD   0.5 ! 0. 0.5 1.    ! fraction of power radiated used for ablation
  NRAD   0.5 ! 2.          ! Exponent for distance from point over corium pool / upper corium interface
      ! crashes if NRAD=2 !
  FSOLIDIV  0.8
!
! 4 hours after shut-down

SR1 PRESID

1.  16138000.
  5100.  15505000.
 10500.  15095000.
 15900.  14648000.
 21300.  14223000.
 26700.  13861000.
 32100.  15374000.
 37500.  13291000.
 42900.  13020000.
 48300.  12748000.
 59100.  12205000.
 75300.  11391000.
TERM

STRU LAYER
! NCOREL ! Choice of correlation: =1 : Kutateladzestd,
! =2 : Bali, =3 : Blottner, =4 : Konsetov, =5 : Kuta modif
!
STRU HEAT_TRANSFER
STRU ANGLE VALUE -90. NCOREL 2 FKU 1. HSLAG 1000. END!
STRU ANGLE VALUE 0. NCOREL 2 FKU 1. HSLAG 1000. END
STRU ANGLE VALUE 90. NCOREL 2 FKU 1. HSLAG 1000. END
END
! threshold value for solidification
! mass liquid fraction
! TSOLIDIF FSOL
! volumetric liquid fraction
! TSOLIDIF FSOLIV
! no use of gamma parameter
TSOLIDIF GAMMA
GAMMA 0.2 ! T solidification = gamma.Tsolidus + (1-gamma).Tliquidus
!
BETA 0. ! coefficient for Teff=beta*Tinterf+(1-beta)*Tbain
! for corium viscosity evaluation

ERUPTION 0.08 ! advise valued between 0.06 and 0.12 (default 0. <= no melt eruption)
LCRUST 3. ! Conductivity of the crust (W/(m.K))
EMISS 1. ! emissivity of oxide pool
NAME OXIDE
TEMP 3000. ! temperature (K)
FGREEN 1.0

SRG MASS
O2U 73050.
O2Zr 6500.
O2Si 10.6
CaO 9.7
MgO 3.6
AI2O3 1.2
Cr2O3 29.2
TERM
END

STRU LAYER

   NAME METAL
   TEMP  3000.
   HSLAG 1000.
   FGREEN 1.0
   GAMMA 0.
   FKU  1.
   LCRUST 30.
   NCOREL 2
   EMISS 0.7
   SRG MASS
Fe 26710.
   Cr 6540.
   Ni 4000.
Zr 14000.
   TERM

STRU LAYER

NAME CRUST
FKU  1.
HSLAG 1000.               ! Convection coefficient corium/slag layer (W/(m2.K))
!STRU HEAT_TRANSFER
   !STRU ANGLE VALUE -90.  NCOREL 2  FKU  1.  HSLAG 1000. END! hconv up =hconv lat= hconv bot !
   !STRU ANGLE VALUE  0.  NCOREL 2  FKU  1.  HSLAG 1000. END
   !STRU ANGLE VALUE  90.  NCOREL 2  FKU  1.  HSLAG 1000. END
!END
FGREEN 1.
PERMEABILITY 3.D-11
TEMP 3000.
EMISS  1.             ! emissivity of oxide pool
END

! Cavity properties

STRU GEOMETRY

! TYPE AXI ! NONAXI = nonaxisymmetric cavity ; AXI = axisymmetric cavity (default)
NPTS 1500 ! Initial number of points
HRAD 2. ! Basemat thickness (m)
HCAV 2.6 ! Cavity height (m) ! 0.5 0.3
RCAV 4.222
EWALL 2. ! Lateral wall thickness (m)
RAY 0.3
WUP 0.5 ! upper width of the cavity (m):
WDOWN 0.5 ! lower width of the cavity (m)
LENGTH 0.5 ! cavity length (m): distance between non ablatable walls
TNONABLA 298. ! temperature of the 2 non ablatable sides (K)
STRU MODIF
  SUP 1 ! Suppression of nodes
  COEFDMIN 0.8 ! Coef pour distance mini
  ADD 1 ! Addition of nodes
  COEFDMAX 1.2 ! Coef pour distance maxi
END

END

! Concrete properties

STRU CONCRETE

RHOSOL 2320. ! Solid concrete density (kg/m3) !
DHBET 2380000. ! Ablation enthalpy of the concrete (J/kg)
TABLA 1500. ! ablation temperature (K)
SRG SPECIES ! mass fraction
  O2Si 0.23
  CaO 0.275
  MgO 0.122
  Al2O3 0.027 ! 0.026 => 0.027 to get a sum equal to 1
  H2O 0.044
  CO2 0.302
TERM
END

!
! Gas properties
!
!
!
STRU GAS
SR1 PRES ! gas pressure (s, Pa)
  0. 3.0bar !
  1.E7 3.0bar
TERM
! XXWATER: no water injection !
SR1 WATER ! water (kg)
  0. 0.kg !
  1200. 0.kg
  1210. 28000.kg
  5200. 28000.kg
  300000. 28000.kg
    ! water mass flow rate = 2.kg/s
TERM
SR1 TEMP ! surrounding temperature (s, K)
  0. 1500. ! equal to Tablation
  1000. 1500.
  300000. 1500.
TERM
EMISS 0.8 ! gas emissivity
END
!
END
!---------------------------------------------------------------
!
END
!!!!!!!!!!!!!!!!!!!!!!!!!!
APPENDIX C: KEY PARAMETERS FOR FinCCI

' FinCCI - a code for simulating molten core - concrete interactions

Option Explicit

Const DELTA_T As Single = 1 ' Time step in seconds. Make sure that DELTA_T < DELTA_X^2/(2*CONCR_ALPHA)
Const END_TIME As Single = 292000 ' End time of calculation in seconds
Const PLOT_INTERVAL As Single = 100 ' Plot interval in seconds
Const DELTA_X As Single = 0.002 ' Mesh size in meters
Const NODES As Integer = 1000 ' Number of nodes

Const POOL_WIDTH0 As Single = 8.444 ' Initial melt pool width in meters
Const CORIUM_MASS As Single = 126800 ' Corium mass in melt pool (kg)
Const SLAG_MASS0 As Single = 0 ' Initial concrete mass in melt pool (kg)

Const HEATING As Single = 15000000 ' Heating power in watts
Const HTC_UP As Single = 750 ' Heat transfer coefficient upwards from melt to crust (W/m2 K)

Const CONCR_K As Single = 0.71 ' Concrete thermal conductivity (W/m K)
Const CONCR_RHO As Single = 2432 ' Concrete density (kg/m3)
Const CONCR_CP As Single = 1137 ' Concrete specific heat (J/kg K)
Const CONCR_ALPHA As Single = CONCR_K / (CONCR_RHO * CONCR_CP) ' Concrete thermal diffusivity (m2/s)
Const CONCR_T0 As Single = 300.01 ' Initial concrete temperature in kelvins
Const ABL_TEMP As Single = 1500.01 ' Concrete ablation temperature in kelvins

Const CORIUM_RHO As Single = 6640 ' Corium density (kg/m3)
Const CORIUM_CP As Single = 617 ' Corium specific heat (J/kg K)
Const SLAG_RHO As Single = 2330 ' Molten concrete density (kg/m3)
Const SLAG_CP As Single = 1405 ' Molten concrete specific heat (J/kg K)
Const MELT_T0 As Single = 3000 ' Initial melt temperature in kelvins

Const H2O_FREE As Single = 0.0325 ' Weight fraction of free water in concrete
Const H2O_CHEM As Single = 0.0111 ' Weight fraction of chemically bound water in concrete
Const CO2 As Single = 0.2971 ' Weight fraction of CO2 in concrete
Const H2O_FREE_RELEASE As Single = 399.15 ' Release temperature of free water
Const H2O_CHEM_RELEASE As Single = 713.15 ' Release temperature of chemically bound water
Const CO2_RELEASE As Single = 893.15 ' Release temperature of CO2
Const STEAM_RHO As Single = 0.144 ' Steam density at concrete ablation temperature
Const CO2_RHO As Single = 0.353 ' CO2 density at concrete ablation temperature