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Modelling issues related to molten pool behaviour in case of In-Vessel Retention Strategy

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Abstract

The In-Vessel Retention (IVR) strategy for Light Water Reactors (LWR) intends to stabilize and retain the core melt in the reactor pressure vessel. This type of Severe Accident Management (SAM) strategy has already been incorporated in the SAM guidance (SAMG) of several operating small size LWR (reactors below 500MWe, like VVER440) and is part of the SAMG strategies for some Gen III+ PWRs of higher power like the AP1000.

The demonstration of IVR feasibility for high power reactors requires using less conservative models as the margins are reduced.

In this paper modelling issues related to molten pool behaviour in case of IVR are highlighted based on sensitivity studies performed with the severe accident integral code ASTEC (Accident Source Term Evaluation Code) for a typical PWR reactor. In particular, the following physical processes are addressed:

- Heat transfer coefficients in thin light metal layer and in heavy metal layer
- Kinetics of corium stratification and thermal exchanges between oxide and metal phases during inversion of stratification
- Relocation of steel coming from ablated vessel wall
- Characteristics of oxide crust

Analyses based on a simple configuration of corium in the lower head allow identifying potential impact of each modelling assumption on the heat flux distribution along the vessel wall, especially in transient situations.

This work is performed in the frame of the European project IVMR (In-Vessel Melt Retention) coordinated by IRSN. This project has been launched in 2015 and gathers 23 organizations with as main objective, the evaluation of feasibility of IVR strategy for LWR (PWR, VVER, BWR) of total power 1,000MWe or higher.

Keywords: Corium pool modelling, In-Vessel Retention, ASTEC code

1. Introduction

During a severe accident in Light Water Reactor (LWR), the lack of fuel cooling in the reactor vessel leads to core heat up and then melting of materials. The melt flows down to the lower plenum of the vessel. Consequently, the main part of the power generated by the fuel is not produced in the core zone anymore but relocates and accumulates in the bottom of the reactor pressure vessel (RPV). In this situation a strategy of external cooling of the vessel wall (ERVC) to maintain the integrity of the vessel and to stabilize the corium inside the RPV may be used. This would reduce significantly the threats to the last barrier (the containment) and therefore reduce the risk of large release of radioactive products to the environment. In order to demonstrate the feasibility of such a strategy and to assess the vessel integrity, one of the main difficulties lies in the evaluation of the thermal loads applied on the vessel wall.

In current methodologies, both bounding case and probabilistic approaches are used based on stabilized corium configurations. This is the case, for example, in the demonstration performed for VVER440 reactor of Loviisa power plant (Kymäläinen et al. (1997)), for AP1000 reactor design (Esmaili and Khatib-Rahbar (2005)) or for new Korean reactor design APR1400 (Jung et al. (2015)). Complex phenomena involved during transient situations, due mainly to thermo-chemistry in the quaternary system U-O-Zr-Fe which leads to metal and oxide phases separation, are not considered in these evaluations. Up to now, there is a lack of experimental data, due to the difficulties associated to the use of UO₂ at large scale, which prevents complete understanding of all the processes involved and their impact on heat flux distribution to the vessel wall.

In this paper, modelling issues related to molten pool behaviour in the lower head are investigated. In the first part, stabilized corium configurations are considered. Then, the main issues associated to transient situations and their deterministic evaluation using the integral severe accident code like ASTEC are discussed.

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2. Stabilized corium configurations

In the first studies of In-Vessel Retention (IVR) (Henry and Fauske (1993), Tuomisto and Theofanous (1994), Theofanous et al. (1997)), a steady-state configuration with a complete fill-up of the lower plenum with stratified oxidic and metallic melt was considered. It was based on the idea that this configuration would provide the largest (bounding) thermal load to be used as the basis for the analysis, since in this situation all the decay heat is dissipated through the vessel wall because there is no more debris or structure to melt and no more water to evaporate. Even if it is true that high heat fluxes can be transmitted to the vessel wall only when the oxide pool is liquid, the OECD MASCA program (Bechta et al. (2008)) identified the possibility of transient corium stratifications in 3-layers, with a part of the metallic melt below and the other above the oxide layer. Such configurations modify the thermal load applied to the RPV and may lead to more critical situations due to increase of the so-called focusing effect, which corresponds to the heat flux concentration on the RPV walls adjacent to the top metal layer. Due to these thermo-chemical effects, the bounding corium configuration to consider is more difficult to define. In the following sections, issues regarding heat transfer evaluation in a stabilized configuration are discussed considering successively the oxide layer, the light metal layer and then the heavy metal layer.

2.1. Heat transfers in corium pool

The thermal behaviour of oxide pool was investigated thanks to many experimental studies, such as COPO, ACOPO, BALI, RASPLAV-SALT and SIMECO. They have allowed defining correlations for heat transfer coefficients at each interface of the volumetrically heated pool. However, some inconsistency in empirical results may be pointed out, especially at high Rayleigh number and can be related to the influence of boundary conditions (cooled or adiabatic) and of crust formation (Gauss-Liu et al. (2016)). Regarding the thermal behaviour of the top metal layer, available experiments are limited (MELAD, BALI-metal) and general correlations for heat transfers between two horizontal or vertical plates are used (Churchill&Chu or Chawla&Chan for the lateral heat transfer and Globe&Dropkin for the axial one). The validity of those correlations for the top metal layer is discussed in section 2.2.

In this section, a sensitivity study on correlations used for heat transfer in the oxide pool is performed considering a steady state configuration of stratified corium pool with a light metal layer above the oxide, as shown in Figure 1. The volumetric power inside the oxide pool is taken equal to 19MW at the beginning and a power law is considered to simulate the residual power decrease with time. This value represents the residual power 2h after reactor scram for a typical PWR reactor of 1000MWe, considering release of volatile Fission Products (FP). In this situation, the internal Rayleigh number (Rai) of the oxide pool is around 10^{15} .

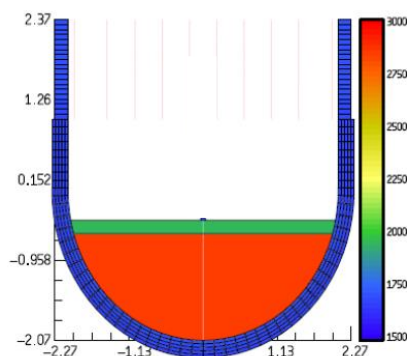


Figure 1 Stratified corium pool configuration simulated with ASTEC code

Four different sets of correlations have been selected for the oxide pool in this study and implemented in a test version of ASTEC V2.1 code for sensitivity calculations. They are summarized in Table 1 and referred to as follows:

- “Reineke” for the first correlations established in the seventies,
- “ACOPO” for the correlations derived from ACOPO experiments,

- “INEEL-ACOPO”, which also refers to ACOPO experiments but with the correlations established in a conservative way by Rempe et al. (1997),
- “COPO/BALI” for the correlations established based on COPO and BALI tests. They are those used in standard version of ASTEC code.

Table 1 Correlations considered for Nusselt number evaluation in oxide pool

Name	Upper surface	Surface in contact with the vessel
Reineke (Steinberner and Reineke (1978), Jahn and Reineke (1974))	$0,345 \cdot Ra_i^{0,233}$ $8 \cdot 10^{12} < Ra_i < 4 \cdot 10^{13}$	$0,54 \cdot Ra_i^{0,18} (H/R)^{0,26}$ $10^7 < Ra_i < 5 \cdot 10^{10}$
ACOPO (Theofanous et al. (1997))	$1,95 \cdot Ra_i^{0,18}$ $8 \cdot 10^{12} < Ra_i < 4 \cdot 10^{13}$	$0,3 \cdot Ra_i^{0,22}$ $8 \cdot 10^{12} < Ra_i < 4 \cdot 10^{13}$
INEEL_ACOPO (Rempe et al. (1997))	$2,4415 \cdot Ra_i^{0,1722}$ $10^{12} < Ra_i < 10^{16}$	$0,1857 \cdot Ra_i^{0,2304} (H/R)^{0,25}$ $10^{10} < Ra_i < 3 \cdot 10^{16}$
COPO/BALI (Bonnet and Seiler (2000))	$0,381 \cdot Ra_i^{0,234}$ $10^{13} < Ra_i < 10^{17}$	$0,131 \cdot Ra_i^{0,25} (H/R)^{0,19}$ $10^{13} < Ra_i < 10^{17}$

In this study, the impact of the correlations in the oxide pool on the value of the maximum heat flux transmitted to the vessel wall by the top metal layer is evaluated for different metal layer heights. To do this, the heating and melting of the vessel wall is not simulated and the liquidus temperature of steel (1700K) is taken as a temperature boundary condition. Adiabatic condition on the top surface of the pool is also considered. Results obtained are presented in Figure 2, defining the concentration factor as the ratio between the maximum heat flux applied to the vessel wall by the metal layer to the one applied by the oxide layer if there were no metal layer on the top (estimated at 1.6MW/m² in this case). For the four correlations considered, the tendencies are similar. As expected, INEEL_ACOPO correlations are the most conservative. On the contrary, Reineke correlations lead to lower concentration factors, since they are validated for lower Rayleigh numbers (cf. Table 1). Discrepancies between other correlations (COPO/BALI and ACOPO) are limited and independent on the metal layer height. **It appears that uncertainties on heat transfer correlations in the oxide pool have a limited impact (+/- 10%) on the focusing effect and do not constitute a significant issue for models in severe accident integral codes.**

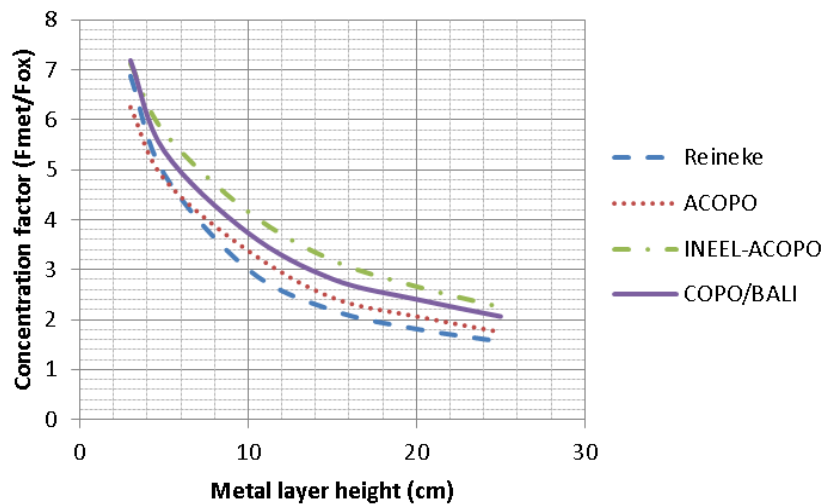


Figure 2 Concentration factor depending on heat transfer correlation and metal layer height

2.2. Top thin metal layer

For the light metal layer, responsible of the focusing effect phenomenon, heat transfer evaluations are typically based on Theofanous et al. (1996) methodology which considered that axial and radial heat transfers may be evaluated based on correlations valid respectively for top and side cold boundaries. Interaction between

the two processes is expected to occur in the bulk of the layer and manifest itself, for a sufficiently small aspect ratio, as a radial temperature gradient in the bulk. Thanks to the MELAD experiment it was checked that the assumption of a well-mixed bulk is conservative in producing higher thermal loads to the side. However, it should be noted that the experiment was performed for a layer aspect ratio (H/R) of 0.2, which corresponds to a metal layer height of 40cm considering a typical PWR vessel radius of 2m. Thus, conclusions are not validated for thin metal layers and heat fluxes to the vessel wall evaluated with those correlations (as it is done in ASTEC code) are overestimated for thin metal layers (typically below 20 cm), as confirmed by BALI-Metal experiments and illustrated in Figure 3.

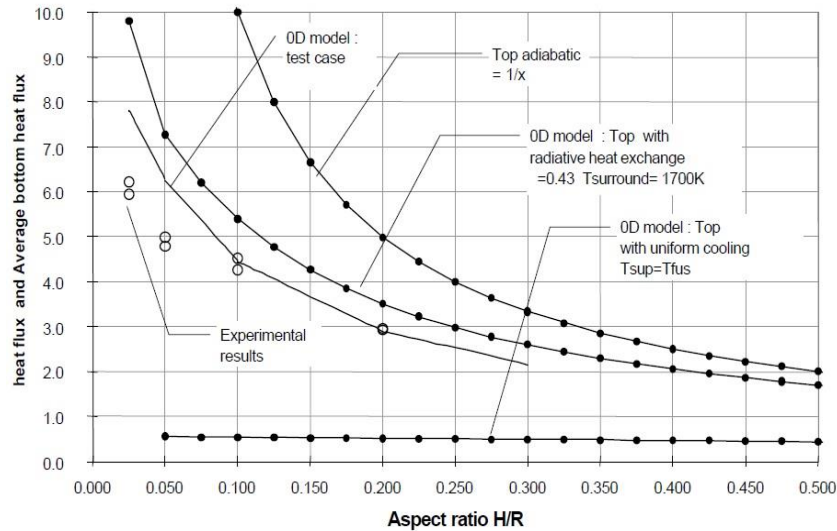
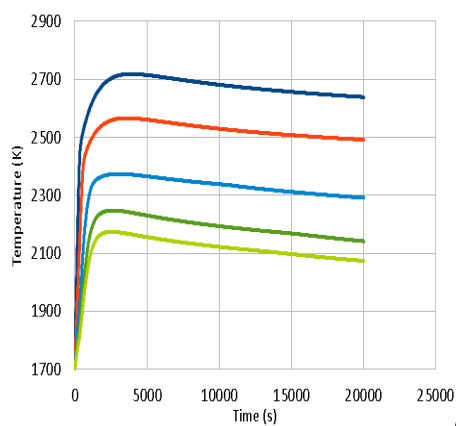


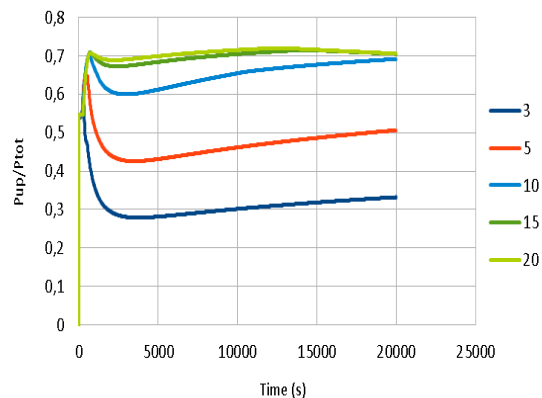
Figure 3 Ratio between lateral and bottom heat flux for a layer heated from below evaluated using OD model (standard correlations for radial and axial heat transfers) and compared to BALI-Metal experimental results (from Bonnet et al. (1999))

Thus, there is a need for new correlations adapted to thin layers to accurately model the focusing effect for these situations.

In addition, in order to study the thermal behaviour of the thin top metal layer, an issue lies in the determination of the right boundary conditions corresponding to reactor situation. In curves presented in Figure 3, the average bottom heat flux does not depend on the height of the layer. However, as illustrated by ASTEC simulations in Figure 4, when the height of the metal layer decreases, its temperature increases. This leads to oxide crust melting at the interface with the oxide. This modification of oxide top boundary condition leads to modify the partition of power in the pool and to an increase of the heat flux to the vessel wall (see Figure 4 b): The axial temperature gradient is reduced whereas the lateral one is kept constant. **Consequently, the melting of the crust between metal and oxide significantly decreases the intensity of the focusing effect comparing with models in which a constant heat flux is imposed at the bottom of the metal layer.**



(a)



(b)

Figure 4 Influence of top metal layer height in cm (INEEL-ACOPO correlation) on (a) Temperatures evolutions of top metal layer (melting temperature of the oxide is considered equal to 2600K) and (b) Power partition between upper and lateral surfaces of oxide pool

Furthermore, the boundary condition on the upper surface of the metal layer also has to be determined. On one hand, the assumption of adiabatic surface may be considered in order to be conservative. On the other hand, the most probable situation in reactor case is a radiative transfer with surrounding structures. To investigate the impact of such assumption on the thermal behaviour of the metal layer, ASTEC calculations were performed with the stratified corium configuration presented in the previous section, to evaluate the concentration factor depending on the metal layer height and depending on the top boundary condition: adiabatic or with radiation considering that the metal layer exchanges by radiation with steel structures at melting temperature. Results are presented in Figure 5. They show that for metal layers around 15cm or above the heat flux dissipated by radiative heat transfers is reduced and therefore the adiabatic assumption is acceptable. In contrast, for a thin metal layer, since metal heats up, the effect of radiation becomes significant and cannot be neglected any more.

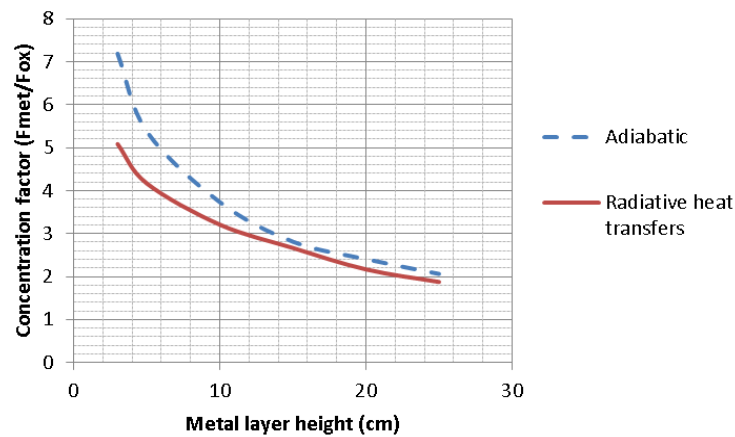


Figure 5 Concentration factor in the metal layer depending on top boundary condition

Thus, the boundary condition at the top surface of the metal layer plays a significant role in its thermal behaviour when the layer is thin. **For codes and experiments, radiative heat transfers from the top surface of the metal layer should be considered when studying the thermal behaviour of the thin top metal layer.**

2.3. Heavy metal layer

Shortly after corium relocation in the lower head, the most probable configuration is a heavy metal layer below the oxide pool. Indeed, the small amount of molten steel associated to incomplete oxidation of Zirconium leads to form, at thermo-chemical equilibrium, a metal phase whose density is heavier than the oxide as illustrated in Figure 6.

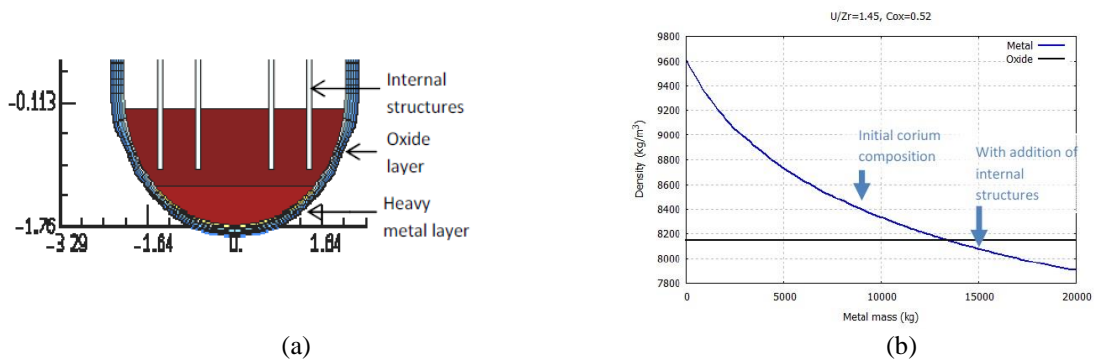


Figure 6 (a) Corium stratification after relocation in the lower head evaluated by ASTEC code and (b) Evolution of the density of the metal phase compared to the oxide with addition of steel

The issue regarding this configuration, which may last for more than 15min depending on the kinetics of metal incorporation (see section 3.2.1), is the heat flux transmitted by the heavy metal layer to the vessel wall. Indeed, up to 15% of residual power may be concentrated in this layer due to fission products having affinities with metal phase such as U, Zr, Mo (Asmolov et al. (2004)). For example, in a LBLOCA scenario in a PWR 1000MWe reactor, the ASTEC simulation evaluates an oxidation degree of Zirconium of 0.52 and 9 t of steel already incorporated in the pool at corium relocation. The heavy metal layer formed is about 40 cm high with an

internal power close to 3 MW. Thus, considering heat flux profile along the vessel wall due only to wall inclination and no heat flux coming from the oxide layer above, the maximal value of heat flux applied on the vessel wall at the top of the heavy metal layer is about 1.2 MW/m². At such elevation (37°) standard CHF values are lower: about 1 MW/m² as measured in ULPU configuration III experiments (Theofanous et al. (1996)). **Thus, improved designs for ERVC may be necessary to prevent vessel failure in front of the heavy metal layer. In addition, it is important to consider in models the distribution of FP in oxide and metal phases depending on their affinities.**

3. Modelling of transient situations

As mentioned in section 2, the relative position of the two phases (metal and oxide) depends on the density of the metal phase, which is related to its composition (mainly its content in U metal) and evolves after corium relocation from a heavy to a light metal layer. During this process two stages have been identified (Fichot and Carénini (2015)) as critical: the first one is the thinning of the top metal layer due to heavy metal formation (configuration (a) in Figure 7) and the second one occurs at stratification inversion when the heavy metal becomes lighter and progressively relocates at the top (configuration (b) in Figure 7).

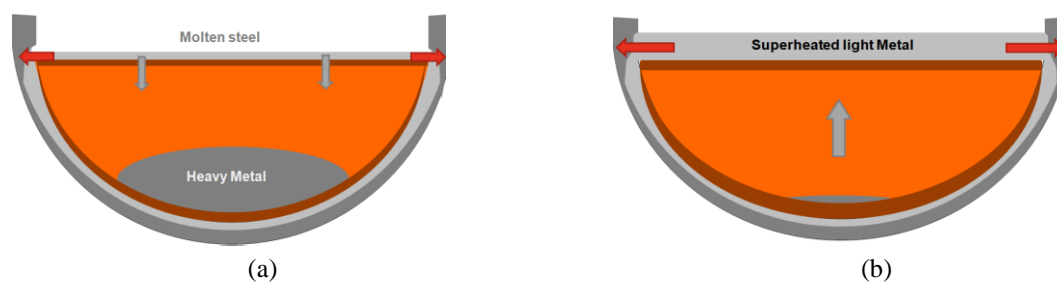


Figure 7 (a) Critical stages during transient situations: formation of heavy metal layer and (b) Stratification inversion

Issues associated to such transients and identification of poorly known phenomena which are of high importance for code modelling are discussed in the following sections.

3.1. Kinetics of corium stratification

Knowing the maximum heat flux imposed to the vessel wall during transient states is not sufficient to conclude on the vessel integrity. Indeed, this heat flux would first heat up and melt a part of the wall before being transferred to the water at the external surface of the vessel. Furthermore, even if the thermal behaviour of a thin metal layer heated from below is still under investigation (see section 2.2), it can be evaluated that the level of heat flux which is reached for a thin layer is too high to be withstood by the vessel. As an example, for high power reactors (about 1,000 MWe), the heat flux transmitted by the oxide at its upper surface is around 1 MW/m² for fast scenarios such as LBLOCA. In this case, even a ratio 3 between the heat flux transmitted to the wall and the imposed heat flux at the bottom (which is below values obtained experimentally in BALI-Metal experiments) leads to vessel failure in stabilized configurations since the associated vessel thickness is less than 1 cm. **Consequently, it is of primary importance to be able to evaluate the duration of these high heat fluxes.**

The first issue concerns the evaluation of the kinetics to reach the global thermochemical equilibrium in the whole pool, i.e. the time needed to stabilize the corium in a 2 layers configuration. Some models are available (Le Tellier et al. (2015) and Fichot & Carénini (2015)) and allow estimating this kinetics. However, up to now, there are not enough experimental data to validate those models and, depending on the value chosen for species diffusion coefficient for example, kinetics may change significantly. This is illustrated in Figure 8 that shows the effect of iron diffusion coefficient (D) across the two phases interaction zone on the kinetics of first top metal layer thinning and then on its growth after stratification inversion. Depending on the value of D , critical situations (i.e. situations when metal layer height is small during a significant time) are identified: during the first phase when metal layer is created (case of slow kinetics $D=10^{-9}$ m²/s), at stratification inversion (average case with $D=10^{-8}$ m²/s) or may be almost excluded (case of high kinetics $D=10^{-7}$ m²/s).

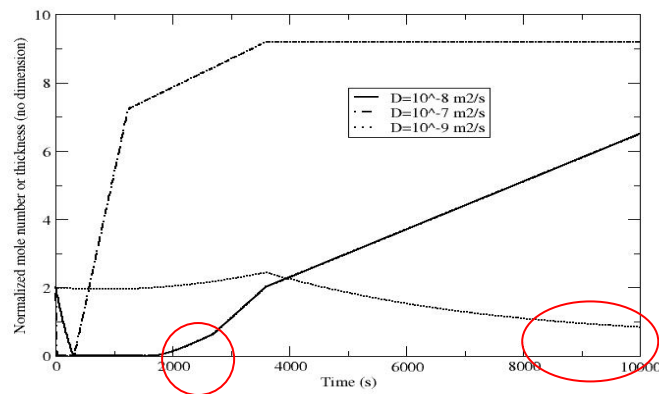


Figure 8 Effect of iron diffusion coefficient D on kinetics of top metal layer thickness (from Fichot & Carénini (2015))

Then, as the thermochemical equilibrium depends on steel and oxygen proportions, the kinetics of pool oxidation and molten steel addition also play an important role in the transient evolution of the corium and consequently on the heat flux distribution to the vessel wall. Modelling issues regarding kinetics of steel incorporation in the pool are detailed in the following section 3.2 as their impact is of first order. Oxidation process, on the other hand, appears to become significant only in a longer term or when reflooding the vessel. Modelling issues associated to stratified molten pool oxidation are not investigated in the paper.

Finally, another element has to be considered when modelling kinetics of corium pool stratification. It is the presence of an oxidic crust all around the oxide pool. This solid phase makes the situation more complex. Associated issues are discussed in section 3.3.

3.2. Molten steel addition

3.2.1. Phenomena description

Several sources of molten steel addition have to be identified: from the melting of internal structures present in the lower head, from the core part (structures such as the core support plate melt by radiative heat transfers) and from the vessel wall melting. All of these sources have their own kinetics of incorporation, which can be evaluated in the codes as illustrated in Figure 9. But they also differ by the path for interaction with oxide pool. The way the molten steel relocates inside the pool has never been investigated and consequently different modelling assumptions can be found in the codes. Such assumptions have a major impact on the evaluation of transient configurations. For example, in the ASTEC code, the molten steel from the vessel is incorporated in the corium phase just in contact (oxide or metal phases) whereas it is considered to be pushed upwards to the top of the pool in some other models. This directly impacts the kinetics of the top metal layer growth but also the temperature of this molten metal as it will be discussed in the following section.

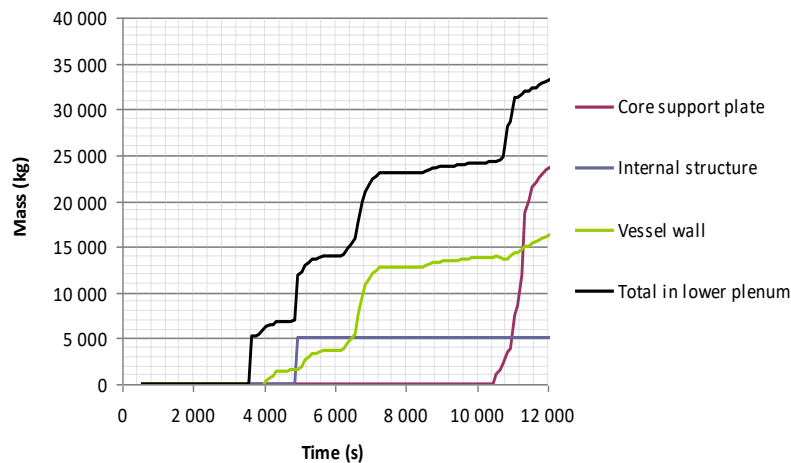


Figure 9 Example of kinetics of molten steel incorporation in the pool depending on its origin

Differences in assumption on molten steel relocation are linked to the representation of the oxide crust as a physical barrier for the species or not, as illustrated in Figure 10. Effects of such unknown on the simulation will be evaluated in section 3.3.

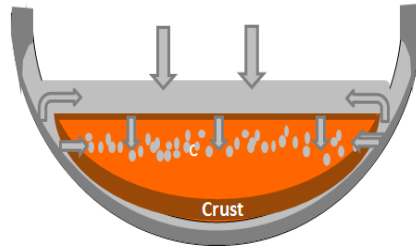


Figure 10 Path for molten steel interaction with the oxide

3.2.2. Metal super-heat

Here, the effect of the temperature of the light metal layer, when it is formed, is investigated. Two types of scenarios are possible when stratification inversion occurs: either the metal layer may separate from the oxide pool at its own temperature and mix with melting steel from vessel wall or structures leading to a layer temperature close to the melting one (1700 K), or the metal phase relocates above the oxide pool at a temperature close to the oxide one (taken in the present study at 2500K). This last assumption is the one made currently in ASTEC models. Consequences of those modelling choices depending on the height of the metal layer after relocation at the top of the oxide are investigated. In Figure 11 and Figure 12, the impact of considering or not super-heat of the top metal layer just after stratification inversion on respectively heat fluxes to the vessel wall and metal temperature evolutions is illustrated.

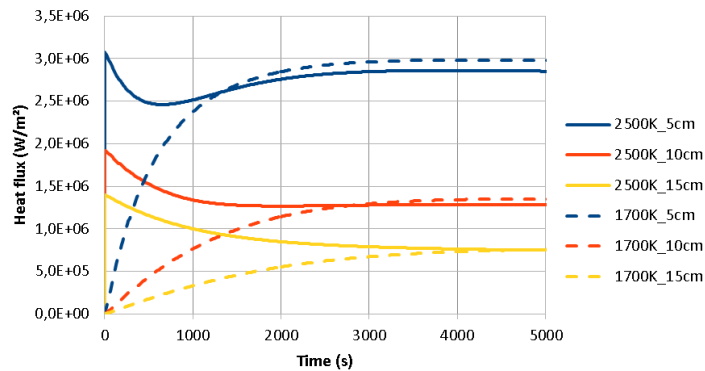


Figure 11 – Heat flux transmitted by the metal layer to the vessel considering metal initially at 1700 K or 2500 K

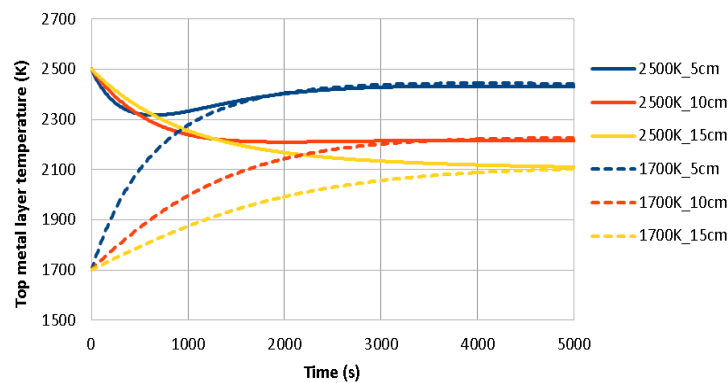


Figure 12 – Metal layer temperature evolution depending on its initial temperature after stratification inversion

As expected, there is almost no impact on the value reached in steady state. However, a strong initial peak is calculated. This maximal heat flux decreases with the increase of the layer height, whereas the duration of super-heat dissipation and the ratio between the transient heat flux and the one in steady state configuration increase (see Table 2). Depending on the duration of this first phase, this may be sufficient to significantly ablate the vessel wall. Indeed, considering stainless steel, the ablation rate for a heat flux applied of 1MW/m^2 is close to 1cm/min . The characteristic thickness of the vessel wall being between 15cm and 20cm , the time needed to significantly ablate it under such high heat flux is around $15\text{-}20\text{min}$. As summarized in Table 2, the duration of the metal super-heat dissipation is in the same order of magnitude and may consequently lead to the vessel failure.

Table 2 Transient increase factor of the heat flux applied to the vessel wall due to metal super-heat

Metal layer height	5cm	10cm	15cm
Time for super-heat dissipation	8min (500s)	15min (1000s)	25min (1500s)
Maximum heat flux to final heat flux ratio	1.1	1.5	2

In the sensitivity study, performed by Phillipov et al. (2016), on the essential factors defining the RPV thermal loading for VVER1000 reactor case, the initial temperature of the metallic phase after melt stratification is considered and also identified as a key parameter. Due to the metal super-heat and high decay-heat power in the oxide, transient heat fluxes up to 3.5MW/m^2 are evaluated for 50cm metal layer height. **Thus, super-heat of metal layer may threaten the vessel integrity at stratification inversion.**

Last but not least, it should be noted that in the ASTEC code, as in all severe accident scenario codes, steady-state correlations are used for the heat transfers (cf. section 2). Those correlations are not able to properly capture the transient evolution of natural convection flows, especially in case of rapid change in the configuration as it is the case for the metal layer relocation with significant super-heat. Further investigations would be necessary to evaluate the impact of transient establishment of heat transfers.

3.3. Oxide crust behaviour

As mentioned before, kinetics of corium stratification and paths for molten steel interaction with the oxide depend on the characteristics of the oxide crust which is formed due to thermal gradients around the oxide pool. However, there is a lack of data concerning the oxide crusts behaviour, which are at the same time subjected to thermal and mechanical stresses, as well as chemical interactions. It should be noted that the crust characteristics and behaviour depend on its location, thus the horizontal crust between the oxide and the metal layer and the crust with the vessel wall have to be distinguished. In addition, regarding heat flux to vessel wall, those crusts play two different roles, which have to be considered for modelling: they behave as a thermal resistance and may also prevent or slow down mass transfers, acting then as a physical barrier. Regarding the horizontal crust between oxide and metal layers, it may be postulated that it is fragmented and then cannot prevent direct species transfers between metal and oxide. Indeed, when the heat flux transmitted from the oxide to the metal is high, the crust thickness is small (few millimetres). In addition, the surface of the pool is large and turbulent mixing occurs in the oxide pool. Thus, it seems justified to consider that cracks are formed in this crust, allowing direct mass transfers. However, its thermal role is maintained. For the lateral crust in contact with the vessel wall, here again, its thickness is small at the top of the oxide pool where the heat flux is maximum and its impact on molten steel mass transfers is uncertain. The CORDEB experimental program was conducted by the Alexandrov Research Institute of Technology (NITI) in Russia between 2012 and 2015 and funded by CEA, AREVA, EDF and IRSN. Among tests performed using prototypical material in a cold crucible, the interaction between oxide crust and molten steel was in particular studied. Results show that transfer of molten steel through the oxide crust due to chemical interaction occurs, as illustrated in Figure 13. Thus, after an initial period necessary for chemical interactions, the oxide crust does not constitute a physical barrier for the molten steel. **However, oxide crust has an impact on the kinetics of mass transfer which should be considered in models and additional experimental results are still needed to better characterize it.** This issue, in particular, is studied in CORDEB2 experimental program conducted in the frame of the IVMR project.

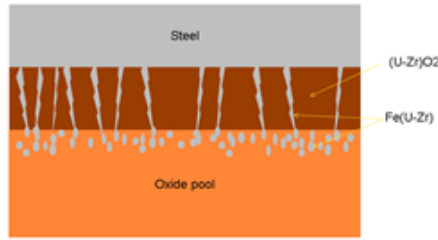


Figure 13 – Schematic representation of molten steel mass transfers through oxide crust due to chemical interactions

In order to investigate the effect of these unknowns and associated modelling assumptions on the thermal load evaluated for the vessel wall, a simple evaluation is proposed considering the two configurations for the corium after stratification inversion illustrated in Figure 14. The issue is whether, when the metal phase becomes lighter and relocates above the oxide pool, the oxide crust remains stable and surrounds the top metal layer (configuration (a) in Figure 14) or not (configuration (b) in Figure 14).

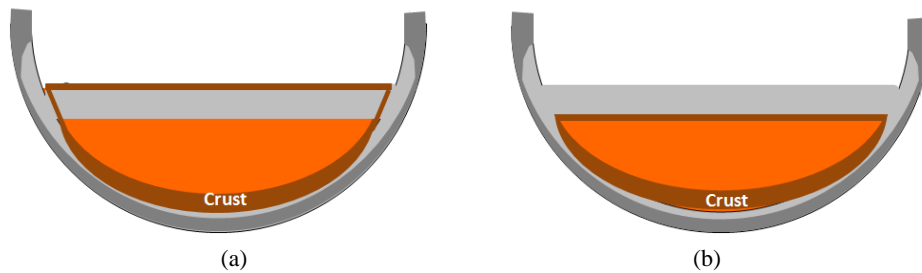


Figure 14 – Corium configuration after stratification inversion considering stability (a) or not (b) of the oxide crust along the lateral part of the metal layer

The presence of the oxide crust between the vessel and the top metal layer adds a thermal resistance which reduces the heat flux transmitted to the vessel. In order of magnitude, if we consider a metal layer of 15cm, in a steady state, the heat flux transmitted to the vessel wall is reduced by a factor 3 due to the presence of a thin oxide crust of 5mm. In Table 3, the influence of metal super-heat is also illustrated. It appears that both assumptions have a significant impact and the maximum heat flux reached may threaten the vessel integrity as observed in ASTEC simulations.

Table 3 Heat flux applied by the top metal layer to the vessel wall depending on the presence of an oxide crust and on the metal super-heat

Metal super-heat	With crust	Without crust
1100K	0.8MW/m ²	2.8MW/m ²
200K	0.15MW/m ²	0.5MW/m ²

4. Conclusions

In this paper, the main issues related to molten pool behaviour in the vessel lower head have been addressed. Based on sensitivity studies and considerations from models implemented in the ASTEC code, the issues with large impact on the heat flux distribution to the vessel wall have been highlighted. In particular, the following points, whose modelling is already available in ASTEC, are identified:

- For the calculation of situations where a thin metal layer is formed at the top of the oxide, the possible melting of the crust between metal and oxide due to metal temperature increase should be modelled as well as consequences on the intensity of the focusing effect.
- The radiative heat transfers from the top metal layer play a significant role in power dissipation when the height of the top metal layer decreases.
- The distribution of FP in oxide and metal phases depending on their affinities has to be considered for evaluation of the maximum heat flux applied to the vessel wall, in particular at low elevations, if a heavy metal is formed.

Then, additional issues are identified, for which models implemented in ASTEC suffer from a lack of validation:

- The heat transfer correlations in the top metal layer when its height is below 20cm.
- The transient establishment of natural convection and associated heat fluxes.
- The kinetics of corium stratification and the consequences on the duration of situations with thin metal layer on the top of the oxide.
- The possible super-heat of the metal layer at stratification inversion and the behaviour of the oxide crust.

Sensitivity evaluations performed for a reactor of power around 1,000 MWe show that such uncertainties on transient situations lead to evaluate high heat fluxes which are likely to challenge the success of the IVR strategy. Within the IVMR project, progress in the determination of the probability of occurrence of critical transient situations and in the evaluation of the associated heat fluxes should be done. In particular, new experimental results, needed to cover all possible configurations of corium in the lower plenum, are expected. In addition to CORDEB2 tests already mentioned in this paper, KIT and KTH are working on the design of experiments on stratified pools to be performed at KTH using the SIMECO-2 facility and at KIT with LIVE facility. Outside IVMR project, experimental results are also expected from ALISA European project, with the COPRA facility dealing with stratified pool at XJTU (China).

5. Nomenclature

Latin letters

D	Diffusion coefficient [m ² /s]
F	Heat flux [W/m ²]
H	Layer height [m]
R	Vessel radius [m]

Dimensionless numbers

Ra _i	Internal Rayleigh number [-], $Ra_i = (g \cdot \beta \cdot \omega \cdot \rho \cdot H^5) / (\alpha \cdot \lambda \cdot \mu)$
With g	Standard gravity [m/s ²]
α	Thermal diffusivity [m ² /s]
β	Thermal expansion coefficient [K ⁻¹]
ω	Volumetric power [W/m ³]
λ	Thermal conductivity [W/m/K]
μ	Dynamic viscosity [Pa.s]

Subscripts, superscripts

ox	Oxide layer
met	Metal layer

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