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In vessel corium propagation sensitivity study of reactor pressure vessel rupture time with PROCOR platform

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Abstract

The problem of corium propagation for PWRs in the Reactor Pressure Vessel (RPV) and the timing of RPV failure is one of the main issues of study in the area of severe accidents. The PROCOR numerical platform created by the CEA severe accident laboratory is modelling corium propagation for LWRs, its relocation to the Lower Plenum and RPV failure. The idea behind the platform was to provide a tool that is fast enough to be able to perform numerous calculations within a reasonable time frame in order to deliver a statistical study. Work on the development of models that describe in-vessel issues is being pursued through simplified phenomena modelling, their verification and sensitivity studies. Recent activities related to PROCOR development involved cooperation between French CEA experts and Polish PhD students, who were engaged in the topics of core support plate modelling and analysis of the phenomena occurring in a thin metallic layer on top of the corium pool. Those issues were identified as strongly influencing the course of severe accidents and the timing of RPV failure. In some sensitivity studies performed on a given generic high power Light Water Reactor with heavy reflector, two groups of RPV ruptures were distinguished related to the two issues, which provided motivation for further work on these topics. The paper will present a sensitivity study of corium propagation in order to identify the relevance of those two issues for the timing of RPV rupture.

Keywords: Sensitivity study, PROCOR Platform, IVMR strategy

1. Introduction

This work is related to the study of severe accidents in Light Water Reactors (LWR) aimed at enhanced prevention and/or mitigation. In order to illustrate the importance of the two modelling topics that we are working on, the motivating study that we will present in this paper is in the context of the current Severe Accident Management Strategy. The concept of the Severe Accident Management response is the In-Vessel Melt Retention (IVMR) strategy. This concept is being investigated in a European Commission funded project under Horizon 2020: In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs [1].The concept is that melted core material can be contained inside the RPV, by removing the risk of vessel failure. This is important, as the RPV wall is a key safety feature for nuclear power plants. To ensure the ability of RPV to preserve its integrity, heat transfer needs to be studied on both sides of the vessel walls.

The IVMR strategy is a severe accident management strategy that incorporates flooding the external vessel to remove the heat from the in-vessel molten pool material.

Heat is transferred from the molten pool to the external coolant through the vessel wall. This severely impacts the structure of the vessel due to the high temperature and interaction between the corium and the steel walls (ablation).

IVMR seeks to contain the solid debris and liquid corium (relocated after core degradation and melting) in the the lower plenum. For existing reactor design the concept was considered feasible for small power reactors. The strategy has already been adopted for the VVER 440 type 213 based on thorough research work for the Finnish Loviisa NPP and Hungarian Paks NPP [2]. The concept is interesting from the safety point of view and there is a suggestion that it could be adopted for high power reactors with power of about 1000 MW or more. This is a challenge, because the power density in such reactor types is higher and the feasibility of the method is not evident. The calculation and experiments, proving the efficiency of external vessel cooling for lower

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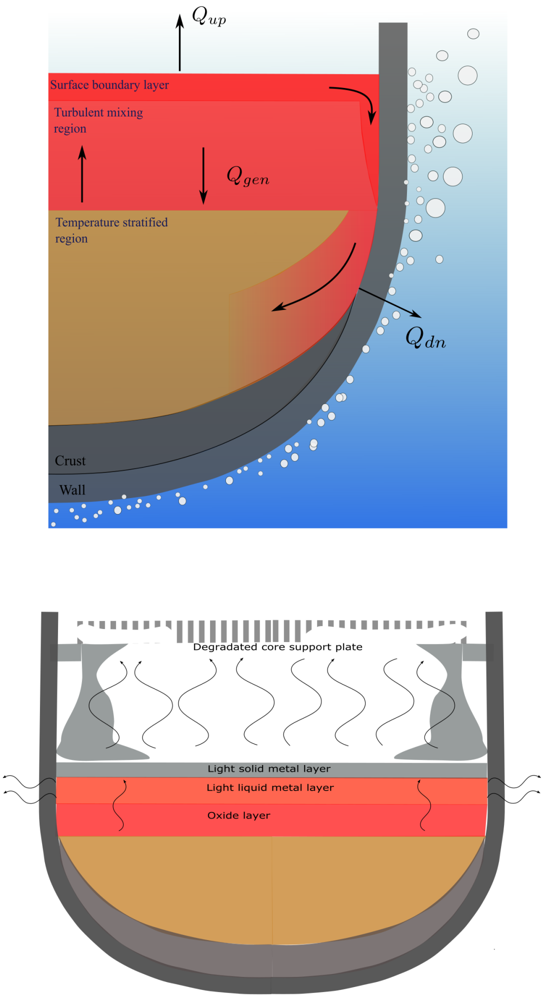

Figure 1: Heat transfer during IVMR strategy. Focusing effect

power reactors, were demonstrated by application of conservative assumptions. With such assumptions heat removal at the vessel outer wall cannot be guaranteed, which indicates that best-estimate methods need to be applied [3].

It is crucial for the purposes of evaluating the IVMR strategy for high power reactors to study how the corium behaves in the RPV. The study indicates the areas which strongly influence RPV failure time and determines possible failure modes. This paper focuses on results from a sensitivity study on corium propagation in the context of the IVMR strategy and especially on the phenomena that directly impact vessel wall rupture—the behavior of the thin metallic layer on top of the corium pool—"focusing effect" and the relocation of the corium from the core to the lower plenum—particularly "core support plate failure mode", which will be described in more detail.

2. Tools

To perform the calculations of reactor corium pool propagation in the core and the timing of the vessel rupture, PROCOR platform [4–6] software was used, which uses URANIE software [7], both developed in CEA. Before discussing the result of the computations, the tools will be briefly described in the following sections.

The PROCOR platform is a tool that is used to perform the sensitivity study of corium propagation and all transient phenomena in the core region, as well as vessel rupture. Features and capabilities of the platform are contained in packages, which are later gathered into different applications. The distributions of the PROCOR differ by the applications, whose functionalities are specific to the reactor design. The main advantage and characteristics of PROCOR is its two part construction, consisting of a set of simplified models and numerical tools, which are gathered as a library and a Monte-Carlo code launcher for the purposes of the sensitivity/uncertainty study [4].

2.1. Physical part—simplified modelling

The physical part is composed of all simplified models to describe corium propagation in the core region and lower head together with its behavior. It contains functionalities to deal with the model and parameters. It takes the form of a library, which is written in Java under object-oriented paradigm [8] and contains different packages. The important models, which are relevant for the study, are presented later on in this paper. One is the corium pool thermal and stratification model, describing corium pool behavior in the core region and lower head. The other model is the debris bed model, treated as porous media, which deals with the coolability of the debris and its melting (upper and lower debris bed). In terms of the internal solid structures of the RPV, the steel structures ablation models represent the vessel wall or core baffle/reflector as 1D slabs. These models deal with the melting and melt-through of the heavy reflector in the core and RPV rupture in the lower head [4–6] . Melt-through of the steel structure is possible due to the presence of decay heat, which is calculated by a separate model in the PROCOR platform. This model evaluates the power density in a single material or set of materials and associates it to the U or (U, Zr) elements according to their mass fractions after reading the decay curve from the integrated code calculations.

2.2. Statistics based on URANIE

The Monte Carlo method is currently used to perform sensitivity and uncertainty analysis. The statistical part of the PROCOR platform consists of two parts. The first part is a C++ executable based on URANIE, which provides the PROCOR dedicated coupling with the functionalities for parameter sampling and code launching. URANIE is a sensitivity and uncertainty analysis tool based on the ROOT framework [9]. It is a piece of software developed at CEA [7]and provides various tools for data analysis, sampling, statistical modelling, optimization, sensitivity analysis, uncertainty analysis and running code on high performance computers, etc. The second part is a set of CINT scripts for post-calculations uncertainty/sensitivity analysis [4].

3. Calculations

To investigate the propagation of the corium pool in the Reactor Pressure Vessel and most important parameters influencing the RPV rupture time, a sensitivity study was performed. This study highlights how the uncertainty in the output of the model, in terms of its distribution, is dependent upon the uncertainty of some input parameters. This study is not a full statistical analysis of the IVMR strategy, but seeks instead to illustrate the importance of two modelling issues which form part of the work involved in the authors' Ph.D. theses. Two issues – the focusing effect and massive corium draining through the core support plate – which were identified as important for the course of severe accidents at high power PWR reactors are characterized by different probabilities of occurrence during specific accident sequences. In the literature [10] and related studies the probability of RPV failure lies in the range of 83–86% with associated probability of the corium retention in the lower plenum of 10-13% depending on the methodology of the Probability Safety Analysis. As is shown in the later sensitivity study presented, the two phenomena—focusing effect and core support plate failure – are representative accident paths for RPV failure and non-failure modes for the analyzed reactor sequence.

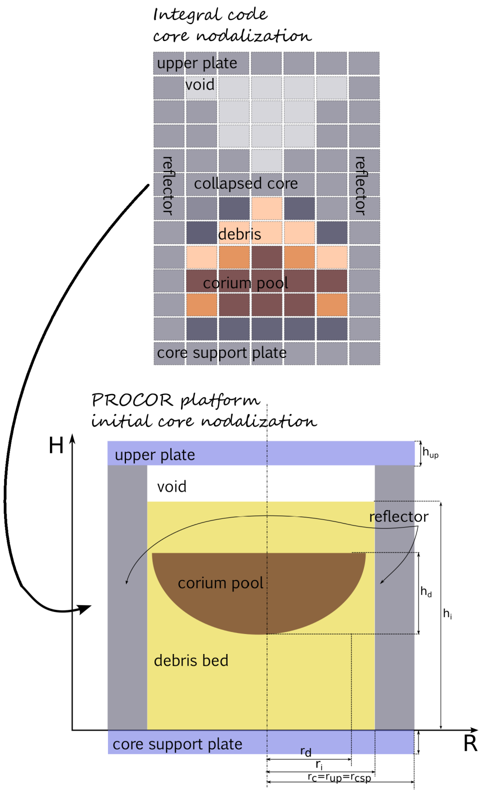

Figure 2: In-vessel core region initial configuration defined for the PROCOR platform

3.1. Calculations

The calculations are performed for a 1650 MW PWR type reactor. This is a generic reactor with the specific feature of a heavy reactor surrounding the core, which was used for the purpose of our study. The study is done for the Station Black Out—SBO [11] scenario without safety injection. This accident sequence is not the fastest one, compared to the Large Break Loss of Coolant Accident—LBLOCA [12], but it is an example of a scenario comparable to the Fukushima events, which led to core melt and probable RPV rupture. The PROCOR platform calculation starting point corresponds to the formation of the corium pool in the core, but the degradation of the core is not computed itself by the code. This starting point is deduced from another integral type severe accident code—MAAP. MAAP4 calculations were used for the analyses performed in the study, which gave the initial core state with corium pool for the SBO sequence before the initiation of the core melt propagation. The sequence itself is the accident scenario, where the external and internal power sources needed for operation of the active cooling safety systems are cut off and no portable power sources are available (Diesel Generators or Emergency Diesel Generators). This leads to the progressing core region dry-out and melting of the core structures.

In the Fig. 2 the general view of the initial core and pool definition in the PROCOR code is shown and the translations based on the physical criteria of the corium state from integral type severe accident code into the platform. Later during the simulation starting from the point of the corium presence in the core [5], the corium pool with spherical and/or cylindrical shape is formed and this results in the corium pool coming into contact with the peripheral core reflector and/or lower core support plate.

Table 1 presents a limited set of uncertain parameters and two changed manually (nb. 7 and 8), that were used in the PROCOR simulations to perform a sensitivity analysis for the purpose of this study. All of them will be defined in the following sections. To have clear overview on the parameters that influence the RPV rupture mode and time, the ones concerning corium pool creation inside the vessel were chosen, both in the core and lower plenum.

One parameter that greatly influences the phenomena of vessel rupture is Uranium diffusivity—D_U. Diffusivity is used in the thermochemical model and determines the stratification of the corium pool into separate layers of top metallic, oxide and heavy metal layer using a simplified kinetic model [6]. D_U influences mass transfer coefficient on the basis of a heat-mass transfer analogy that relates the thickness of the mass transfer boundary layer δ_m to the thermal boundary layer δ_m and it is written as [13]:

Table 1: Parameters investigated during the sensitivity study

nb	Model	Sensitivity study parameter
1	In-core thermochemistry kinetic 0D model	Uranium molecular diffusivity—D_U
2	Lower head thermochemistry kinetic 0D model	Uranium molecular diffusivity—D_U
3	Corium pool in lower head model	Boundary condition emissivity factor for debris -$f_{e,d}$
4	Lower debris bed in lower head model	Porosity -ε_{ld}
5	Upper debris bed in lower head model	Porosity -ε_{ud}
6	Corium pool	Corium expansion coefficient -V_{exp}
7	Main	Corium draining through core support plate model
8	Vessel ablation model	Critical heat flux factor—f_ϕ

$$\frac{\delta_t}{\delta_m} = \frac{Sh}{Nu} = (Gr)^{1/12}\left(\frac{Sc}{Pr}\right)^{1/3} \tag{1}$$

with the Sherwood number Sh related to the mass transfer coefficient by $\frac{h_m H}{D_U}$. The Uranium diffusion is present in the core and in the lower head of the RPV and the parameters of them are taken to the study with the same probability density function distribution. The nominal value is taken as equal to the Stokes-Einstein formula value [6]:

$$D_U = \frac{k_B T}{6\pi\eta r}, \tag{2}$$

where k_B—Boltzmann's constant, T—absolute temperature, η—dynamic viscosity and r—radius of the spherical particle.

The emissivity factor for debris—$f_{e,d}$—is used in the top boundary condition of the corium pool (also in the lower head) and the equation for the radiative heat transfer evaluation (3). It is a dimensionless factor, applied to upper layer emissivity in the presence of debris. This way the top boundary heat transfer is modified and the lower value of the factor will limit the top radiative heat transfer and increase the power transmitted laterally to the vessel wall. The formula of the heat flux is:

$$\phi_{rad} = f_{e,d}\sigma(T^4_{surf} - T^4_\infty), \tag{3}$$

where ϕ_{rad}—radiative heat flux, σ—Stefan Boltzmann constant, T_{surf}—body surface temperature and T_∞—surrounding temperature.

Another parameter investigated during this sensitivity study was vessel rupture depending on debris bed porosity—ϵ_{ld} and ϵ_{ud}, as lower and upper, respectively. This parameter influences the position of the corium pool in the lower head. With its higher value, the corium pool is higher and can cause core support plate melting. Apart from this, the parameter influences the critical heat flux associated with debris bed coolability due to residual water presence in the lower head for our study:

$$\phi^{crit}_{debris} = 1.21\frac{\mathcal{H}_v}{((0.095 + (\frac{\rho_w}{\rho_v})^{0.19}))^{2.63}}\sqrt{\frac{\epsilon^3 d \cdot g\Delta\rho \cdot \rho_v}{6(1-\epsilon)}}, \tag{4}$$

where g is the gravity, d—particle diameter,ρ_w (resp. ρ_v) corresponds to the water density (resp. vapor density), $\mathcal{H}_v$ means the vaporization enthalpy [14] . When the critical heat flux is reached it will result in the melting of the debris. So while changing the porosity value—ϵ_{ld} and ϵ_{ud} the ϕ^{crit}_{debris} will increase with porosity growth and the debris bed will be cooled more easily with larger ϵ_{ld} and ϵ_{ud} value.

The parameter investigated during our study is corium pool expansion coefficient—V_{exp}, which for a spherical cap determine the corium shape modification by the following relation:

$$\Delta h_{pool} = \alpha\Delta r^+_{pool} + \beta \tag{5}$$

h_{pool}—pool height, r^+_{pool}—top pool radius, α,β—expansion coefficients.

There are two possible choices for the expansion coefficients sets (α,β)—"Ratio" and "Sum" option. For "Ratio" option, the ratio of the ablation velocity v_{abl} on the top z^+_{pool} and bottom z^-_{pool} of the corium pool shape, where deformation is proportional to the local ablation speed:

$$\alpha = \frac{v_{abl}(z^+_{pool})}{v_{abl}(z^-_{pool})} = \frac{\phi^+_{pool}}{\phi^-_{pool}} \qquad \beta = 0 \tag{6}$$

ϕ_{pool}—corium heat flux at the top and bottom.

For the second choice—"Sum" option, the difference of ablation velocity of the lateral ablated component on the top and bottom of the associated corium pool shape:

$$\alpha = 1 \qquad \beta = (v_{abl}(z^+_{pool}) - v_{abl}(z^-_{pool}))\Delta t = \frac{\Delta t(\phi^+_{pool} - \phi^-_{pool})}{\rho_c H_c(1-\epsilon_c)} \tag{7}$$

ρ_c—density, H_c—fusion enthalpy, ϵ_c—porosity [5].

The next two parameters—mode of corium draining to the lower head and critical heat flux factor—f_ϕ , were investigated during the study, but were not treated as random variables. They were changed for the sets of calculations as constant values for the purpose of further analysis.

For corium draining, the two cases regarding the behavior of the core support plate and possible axial transfer from the core to the lower head were considered. The "no axial draining" model through the core support plate involves the corium slumping to the lower head only through the lateral direction. This approach is justified from a thermal-only analysis of the in-core corium pool interaction with the core support plate: indeed, thermal stationary computations show that the flux at the bottom of the corium pool in the core is low and consequently the crust on the bottom of the corium in the core becomes thick and does not break. The other case is the "axial draining" model, in which the corium pool when coming into contact with the core support plate goes through the plate porosity or causes the structure to fail, the assumption being that the crust surrounding the plate is not stable and directly breaks causing corium transfer to the lower head.

The second parameter was the critical heat flux factor—f_ϕ. Critical Heat Flux (CHF) is computed with the ULPU correlation and is multiplied by $f_\phi = 1.933$, so that the maximum CHF is about 3 MW/m^2. This high value was selected in order to give more visible results of different vessel failure modes. The factor indicates the heat flux that leads to the dryout of the vessel surface and consequently influences the time of vessel rupture. Use of the flux factor changes the wall critical heat flux value by the formula:

$$\phi^{crit}_{wall,i} = \begin{cases} f_\phi \Phi^{crit}(\theta_i)\ if\ z_i \leq z_{water}\ and\ z_i \leq h_s \\ f_\phi \Phi^{crit}(0)\ if\ z_i \geq z_{water}\ and\ z_i \geq h_s \\ 0\ otherwise \end{cases}, \quad (8)$$

where i is the mesh of the vessel wall and the vessel wall is the spherical bottom and cylindrical part,θ_i is the local angle of the surface and Φ^{crit} is taken from the ULPU experiments [15] .

Table 2: Parameters taken to the statistical analysis

	Parameters	Law	Min value	Nominal value	Max value	Standard deviation
1	Uranium molecular diffusivity in core	Logtriangular	1.81E-9	1.81E-8	1.81E-7	-
2	Uranium molecular diffusivity in lower head	Logtriangular	1.81E-9	1.81E-8	1.81E-7	-
3	Emissivity factor for lower and upper debris in lower head	equiprobable (Bernoulli law $p = \frac{1}{3}$)	0.0	0.25	0.5	-
4	Porosity for lower and upper debris bed in lower head model	Normal	0.3	0.4	0.5	0.1
5	Volume anisotropic expansion option	equiprobable (Bernoulli law $p = \frac{1}{2}$, "Sum" and "Ratio" [5]	0.0		1.0	-

The probability functions of parameters described above are presented in the Table 2.

3.2. Results

The Figs 3 and 4 show the results of the study for the reactor case, in which the core damage propagated until formation of the pool. The previous studies in [6] and other studies classified the possible accident propagations into three groups: early, late and no vessel failure cases. The parameters for our study differ from [6] and the choice of parameters was done to maximize the number of early rupture modes in order to highlight the work on the thin metallic layer and core support plate.

With the "no axial draining" model, in most cases the focusing effect occurs quickly during the top steel layer formation due to structures ablation and leads to an early vessel rupture. In the "axial draining" case, there is a distinctive group of "no failure of the RPV" cases, which indicates corium pool stabilization and its cooldown (7% probability). It is related to a massive addition of corium to the lower head and a very large steel layer, whose presence results in no focusing effect (upper Fig. 3, blue group).

The earlier failure mode (first group of failure in red color in the lower Fig. 3) is directly connected to the appearance of the early focusing effect and the heat transfer model in the thin metallic layer. This phenomenon of the focusing effect is present in the top steel layer formed in the corium pool, during the first melting of the vessel and of the steel structures in the RPV.

The first slumps of molten material from the core region that lead to the RPV break range from t=23,800 s (6 h 36 min 40 s) with around 30,000 kg of molten corium pool (heavy metal, oxide pool and light metallic layer) created.

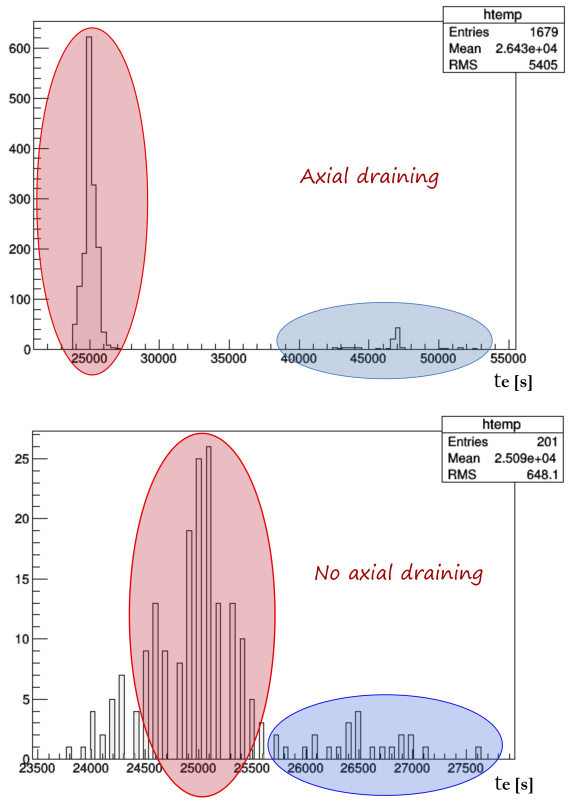

Figure 3: Rupture and stabilization time groups for "no draining" and "massive draining" through the core support plate model, te—end of calculation time

The later ruptures (right Fig. 3, blue group) correspond to the thermochemical effects, the mass transfer of steel during the achievement of stratification equilibrium, which is responsible for the decrease in thickness of the metallic layer. In our study (Fig. 3) the early rupture mode occurs more often than the later rupture mode.

The high value of the heat flux to the walls results in failures with the lower masses of the formed pool (**mev**$_{\mathbf{hm}}$—heavy metal mass, **mev**$_{\mathbf{ox}}$—oxide mass) and especially molten metal (**mev**$_{\mathbf{lm}}$—light metal mass) presented in the Fig. 4. The model used in the calculations overestimates the lateral heat flux for a very thin layer. In the PROCOR platform, to define the heat fluxes the transient 0D energy conservation equation is solved with the following heat transfer correlations: top Globe and Dropkin [16] , lateral Churchill and Chu [17] or Chawla and Chan [18] and bottom Bali [19] . These correlations are questionable for layer thickness below 10 cm and do not take into account the time delay for the establishment of natural convection. This suggests the need for introduction of new modelling enabling less conservative **tvr** estimation. The studies planned for that issue will focus on the liquid phase of the metallic layer. In particular, they will include studies to investigate the heat transfer regimes in the metallic layer—the time delay of convection establishment and description of the thermal-hydraulics in the metallic layer, with the goal being to propose a simplified realistic model that could be incorporated into the PROCOR platform.

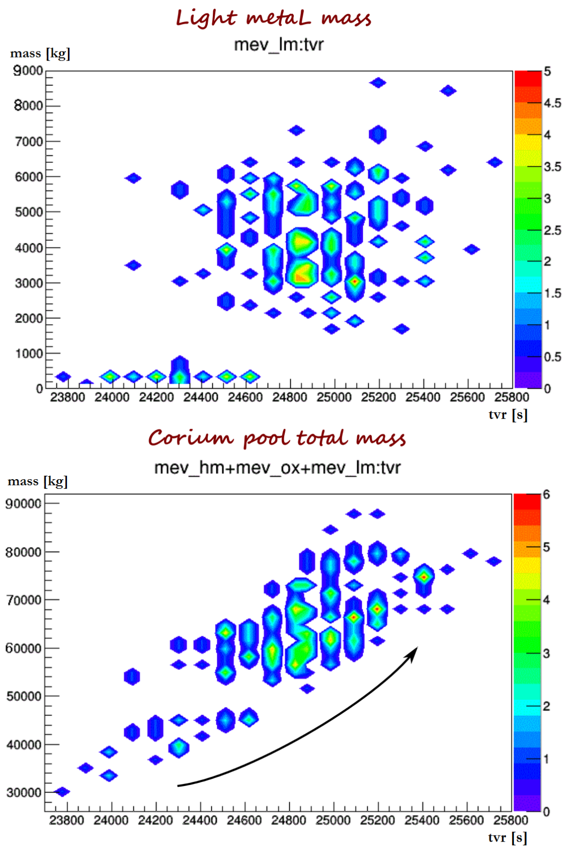

Figure 4: Relation of the RPV time of rupture (tvr) and light metal, heavy metal and oxide layer in the pool mass—"no axial draining" model

Another group of the accident course is stabilization of the corium pool in the lower head. For the performed study this is an option with the "axial draining" model through the use of the core support plate.

In the simulations presented, for the SBO sequence as determined by the PROCOR code, core support plate failure occurs around 25,000 s (6 h 56 min and 40 s). The modelling shows the high impact of the core support plate on the time of vessel failure, as can be seen in the Fig. 5.

From this figure the conclusion can be drawn that the time of vessel rupture—**tvr** is delayed in the cases where the contact with the core support plate was present and massive draining through the plate took place. In the cases with the "axial draining" model through the core support plate, the way of pool formation was found to be influencing the possible **tvr**, which is presented in the Fig. . The V_{exp} parameter is related to the geometrical modelling of the corium expansion [5] in the RPV core region, when the value is above 0.5 ("Ratio" modelling option) the pool is hemispherical and larger. With the "Sum" modelling option (V_{exp} below 0.5) we have earlier heavy reflector failure and consequently an earlier appearance of the corium pool in the lower head. The result is that vessel rupture occurs earlier than core support plate rupture. The contact of the core support plate with the molten corium pool induces higher mass transfers of the molten materials to the lower head, which results in lower thermal loads of the vessel walls (lower lateral heat flux).

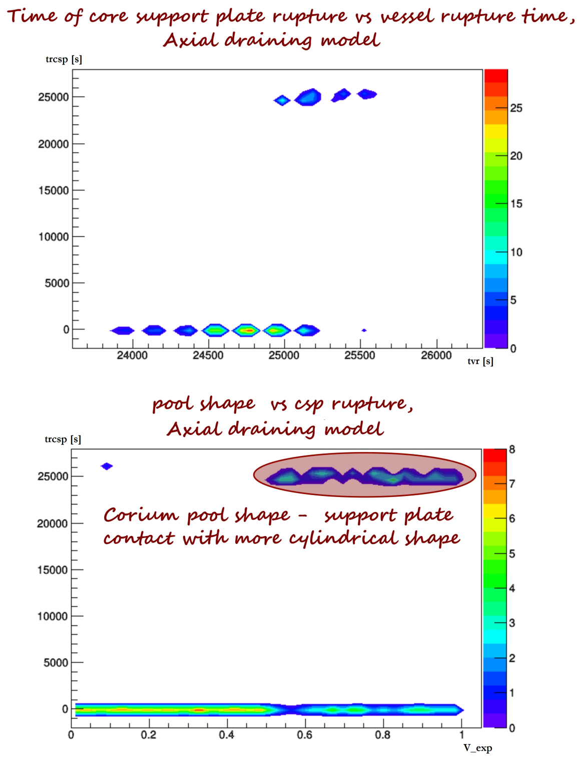

Figure 5: Relation of the RPV rupture time (tvr) and way of core support modelling ($trcsp$—time of core support plate rupture)—"axial draining" model $trcsp = 0$ means no contact between core support plate and corium

The results with the axial draining model in the Fig. 5 show we have fewer cases corresponding to RPV rupture when massive draining through the plate occurs. At present, the "axial' and "no axial" draining models in PROCOR are two extreme cases and we have to introduce a simplified thermal--mechanical model to have a realistic evaluation of the corium that can drain through the plate. In this part the work will be done with the use of additional software—mechanical detailed code (Finite Element Code), i.e., ANSYS. The objective is to validate our model with ANSYS, based on detailed modelling—better thermomechanical coupling and using this modelling to build a set of reference cases that could be used for further validation or for introducing a better simplified model, for example a response surface.

4. Conclusion

The results of the limited sensitivity analysis with PROCOR for SBO sequence have highlighted the ongoing need to improve the modelling of the two phenomena. The first one related to modelling the focusing effect responsible for early vessel failures. More precisely, it deals with modelling natural convection for the thin metallic layer. Work will be performed to find a simplified model for the thin steel layer and perturbation analysis of the top boundary condition. The second issue is related to modelling the core support plate, which influences vessel failures. To addess this problem, actions are needed to develop accurate thermomechanical modelling of the core support plate and this will form part of the upcoming development of the PROCOR platform. These aspects of improvements in the modelling will lend insight to the use of the In-Vessel Melt Retention strategy in nuclear reactors.

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