Analiza wrażliwości propagacji stopionego rdzenia oraz czasu rozerwania zbiornika ciśnieniowego przy użyciu platformy PROCOR.

In Vessel Corium Propagation Sensitivity Study Of Reactor Pressure Vessel Rupture Time With PROCOR Platform

M.Skrzypek[1], E.Skrzypek[1] , R.Le Tellier[2], L.Saas[2]

[1]National Centre for Nuclear Research, NCBJ/DUZ/UZ3

[2]CEA Cadarache, DEN/DTN/SMTA/LPMA

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Abstrakt

Problem propagacji stopionego rdzenia w reaktorach PWR wewnątrz zbiornika ciśnieniowego i czas jego rozerwania jest jednym z bardziej interesujących aspektów w obszarze analiz ciężkich awarii.
Platforma numeryczna PROCOR, stworzona przez ekspertów z laboratorium ciężkich awarii CEA, pozwala na modelowanie propagacji stopionego rdzenia, przemieszczenie go do dolnej części zbiornika oraz określenie czasu rozerwania RPV.
Główna idea platformy to zapewnienie narzędzia obliczeniowego, które będzie odpowiednio szybkie aby móc wykonać obliczenia w rozsądnych ramach czasowych.
W celu opisania jak najdokładniej powyższych aspektów, konieczne jest tworzenie wielu modeli ich weryfikacja i analiza wrażliwościowa.

Introduction

Severe accident treatment
This work is related to the study of severe accidents in Light Water Reactors (LWR) for the improvement of their prevention and/or mitigation.

- for example concept of the Severe Accident Management response is the In-Vessel Melt Retention (IVMR) strategy.
- the concept is being investigated under European Commission funded project from the Horizon 2020 - In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs [**?**].
- major idea: the melted core material can be kept inside of the Reactor Pressure Vessel.

The aim is to present results from a sensitivity study on the corium propagation and the phenomena that are directly impacting vessel wall rupture:

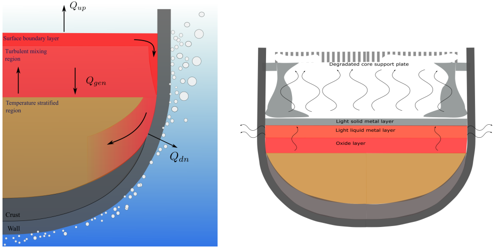
1. behaviour of the **thin metallic layer on the top of the corium pool** - "focusing effect" and
2. the **relocation of corium from the core to the lower plenum** - especially "core support plate failure mode", which will be described in more details.

This is an introductive work to two research topics starting at NCBJ in collaboration with CEA.

The melt retention in the RPV

IVMR strategy:

The In Vessel Melt Retention strategy is a severe accident management strategy that incorporates the external vessel flooding to remove the heat from the in-vessel molten pool material. For this method, the heat is transferred from the molten pool to the external environment (atmosphere or coolant) through the vessel wall. This impacts highly the structure of the vessel due to high temperature and interaction between corium and steel walls (ablation).



Heat transfer during IVMR strategy. Focusing effect.

At present:

- RPV integrity preservation, the study of the heat transfer at each side of the vessel walls needs to be performed.
- for the existing reactor design, the concept was considered feasible for the small power reactors
- strategy is already adopted for the **VVER 440 type 213** based on thorough research work for the **Finnish Loviisa NPP and Hungarian Paks NPP** [?].
- interesting from the safety point of view and there is a suggestion that it could be adopted for the high power reactors with power of about 1000 MW or more (H2020).

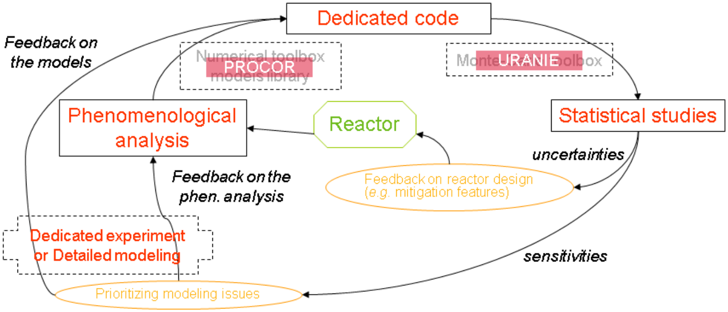
Numerical calculations. Tools

Used tools

To perform the calculations of the reactor corium pool propagation in core and the timing of the vessel rupture, the **PROCOR platform and URANIE software** were used, both developed in CEA.

The main advantage and characteristics of PROCOR is its **two part construction**, which consists in a set of simplified models and numerical tools - gathered as a library and a Monte-Carlo code launcher for the purposes of the sensitivity/uncertainty study [**?**].

Figure: Methodology for the PROCOR work circle



In the following slides the important models will be presented with the parameters relative to the study.

Input data for our study

- the calculations for a 1650 MW PWR reactor type (generic reactor for our study), with heavy reflector surrounding the core
- sequence the Station BlackOut (SBO) [?] scenario without safety injection - external and internal power sources are cut off, no portable power sources are available (DG and EDG)
- leads to the progressing core region dry-out and melting of the core structures.
- PROCOR platform calculation starting point corresponds to the formation of the corium pool in the core (degradation of the core is not computed).
- the PROCOR starting point is deduced from integral type severe accident code calculation - MAAP (the initial core state with corium pool for the SBO sequence [?] in our studies).

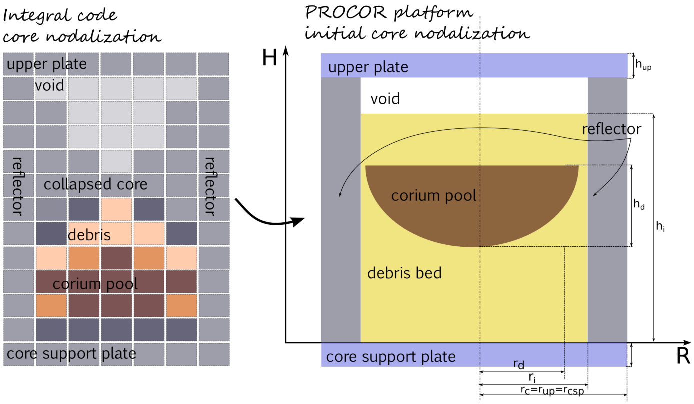


Figure: In-vessel core region initial configuration defined for the PROCOR platform.

Tools - PROCOR

Important models, which are relevant for our study:

1. the corium pool thermal and stratification transient model, describing the corium pool behaviour in the core region and lower head.
2. the debris bed model, as porous media, which is dealing with the coolability of the debris and its melting (upper and lower debris bed).
3. the steel structures ablation models are representing the vessel wall or core baffle/reflector (1D slabs) - the model is dealing with the melting and melt-through of the heavy reflector in the core and RPV rupture in the lower head. [?], [?], [?]

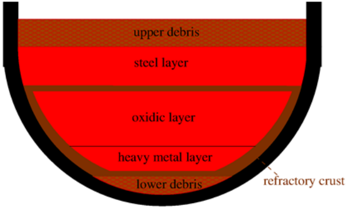


Figure: Set of layers that are embedded in a refractory crust and a steel layer above the crust - PROCOR pool model.

Sensitivity parameters - parameters of models and their probability functions laws.

We choose this parameters in order to show the needs of further modelling. These parameters are:

Table: Parameters investigated during 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	Vessel ablation model	Critical heat flux factor - f_ϕ
8	Main	Corium draining through core support plate model

Table: 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" [?])	0.0		1.0	-

Sensitivity parameters

Uranium diffusivity - D_U

- used in thermochemical model to determine stratification of the corium pool.
- D_U influences mass transfer coefficient - (heat-mass transfers analogy that relates the thickness of the mass transfer boundary layer δ_m to the thermal boundary layer δ_t), it is written as ([?])

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

  with the Sherwood number Sh related to the mass transfer coefficient by $\frac{h_m H}{D_U}$
- used to determine the stratification of the corium pool into separate layers of top metallic, oxide and heavy metal layer using a simplified kinetic model [?].

The nominal value is taken as equal to the Stokes-Einstein formula value [?]:

$$D_U = \frac{k_B T}{6\pi\eta r}, \tag{1}$$

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

Sensitivity parameters cd.

Emissivity factor for debris - $f_{e,d}$

- used in top boundary condition of the corium pool (also in the lower head),
- used in the equation for the radiative heat transfer evaluation - equation **??**,
- is the dimensionless factor, which is applied to the upper layer emissivity in presence of debris
- top boundary heat transfer is modified - lower value of the factor will limit the top radiative heat transfer and increase the power transmitted laterally to the vessel wall.

$$\phi_{rad} = f_{e,d}\sigma(T_{surf}^4 - T_{\infty}^4), \tag{2}$$

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

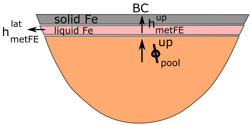


Figure: In-vessel core region initial configuration defined for the PROCOR platform.

When fe,d=0, the top boundary condition is adiabatic and, at steady state, all the power goes to the vessel wall.

Sensitivity parameters cd.

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

Debris bed porosity

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

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 [**?**].

- **when the critical heat flux is reached it will result in the melting of the debris**.
- while changing the porosity value - ϵ_{ld} and ϵ_{ud} the ϕ^{crit}_{debris} will **increase with the porosity growth**, the debris bed will be cooled easier with larger ϵ_{ld} and ϵ_{ud} value.

Sensitivity parameters cd.

Corium pool expansion coefficient - V_{exp}

For a spherical cap, the expansion coefficients determine the corium shape modification by the following relation:

$$\Delta h_{pool} = \alpha \Delta r^{+}_{pool} + \beta \tag{4}$$

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

The two choices for the expansion coefficients are:

- The ratio of the ablation velocity v_{abl} on the top z^{+}_{pool} and bottom z^{-}_{pool} of the corium pool shape (called "Ratio" option, the shape deformation is proportional the local ablation speed):

$$\alpha = \frac{v_{abl}(z^{+}_{pool})}{v_{abl}(z^{-}_{pool})} = \frac{\phi^{+}_{pool}}{\phi^{-}_{pool}} \tag{5}$$

$$\beta = 0 \tag{6}$$

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

- The difference of ablation velocity of the lateral ablated component on the top and bottom of the associated corium pool shape(called "Sum" option):

$$\alpha = 1$$

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

  ρ_c - density, H_c - fusion enthalpy, ϵ_c - porosity.

The radial propagation is slower for the "Sum" expansion coefficients and consequently the corium pool at the reflector melting is bigger - corium pool looks like a hemisphere. [?]

Additional important parameters

2 parameters (not treated as random variables) - mode of corium draining to the lower head and critical heat flux factor - f_Φ

1. corium draining - corium transfer from the core to the lower head
   - "no axial draining" model through the core support plate (CSP) - corium is slumping to the lower head only through the lateral direction: thermal-only analysis of the in-core corium pool interaction with CSP, the flux at the bottom is low and the crust on the bottom of the corium in the core becomes thick and does not break
   - "axial draining" model - corium pool when entering into contact with the core support plate goes through the plate porosity or is causing the structure to fail, the assumption is that the crust surrounding the plate is not stable and directly breaks (opposite to the "no axial draining" model) - transferred to the lower head.
2. critical heat flux
   - critical heat flux is computed with ULPU correlation multiplied by $f_\Phi = 1.933$ so that the maximum CHF is about 3 $\frac{MW}{m^2}$,
   - this high value was selected in order to give more visible results of different vessel failure modes.

Rupture time of vessel

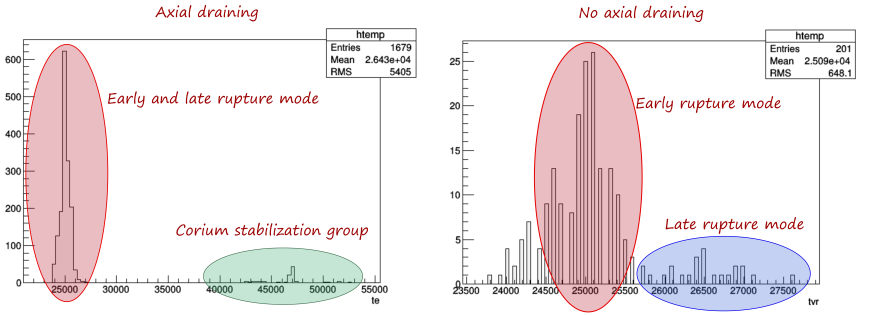


Figure: Rupture and stabilization time groups for "no draining" and "massive draining" through the core support plate model, *tvr* - vessel rupture time, *te* - end of calculation time

- The previous studies in [?] and other studies have classified the possible accident propagations into three groups: early, late and no vessel failure cases.
- The choice of parameters was done to maximize the number of early rupture mode in order to highlight the work on the thin metallic layer and core support plate.
- With the "no axial draining" model, in most cases, focusing effect occurs quickly during the top steel layer formation (structures ablation) and leads to an early vessel rupture.
- In the "axial draining" case, there is a distinctive group of the "no failure of the RPV" cases, that indicates the corium pool stabilization and its cooldown (7% of probability). It is related to massive addition of corium to lower head and very large steel layer (no focusing effect).

Light metal, heavy metal and oxide mass in the vessel vs time of rupture

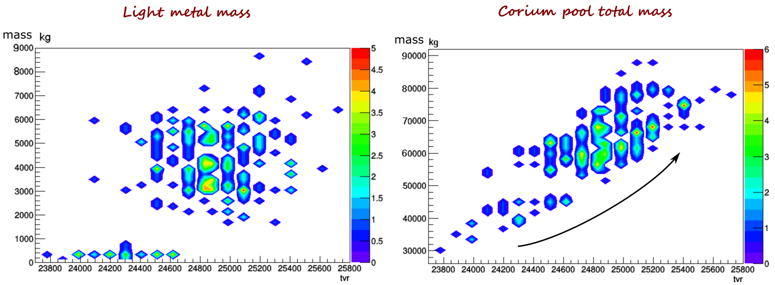


Figure: Relation of the RPV time of rupture (tvr) and light metal, heavy metal and oxide layer in the pool mass - "no axial draining" model.

- The high value of the heat flux to the wall is resulting in failures with low 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)
- the model used in the calculations overestimates the lateral heat flux for very thin layer. Transient 0D energy conservation equation with the following correlations: top h-t Globe and Dropkin [?], lateral h-t Churchill and Chu [?] or Chawla and Chan [?], bottom h-t Bali [?]: questionable for layer thickness < 10cm and does not take into account the time delay for the natural convection establishment.
- this suggest the need for introduction of the new modelling enabling less conservative **tvr** estimation (will probably reduce the number of early failure).

Contact time of corium with core support plate

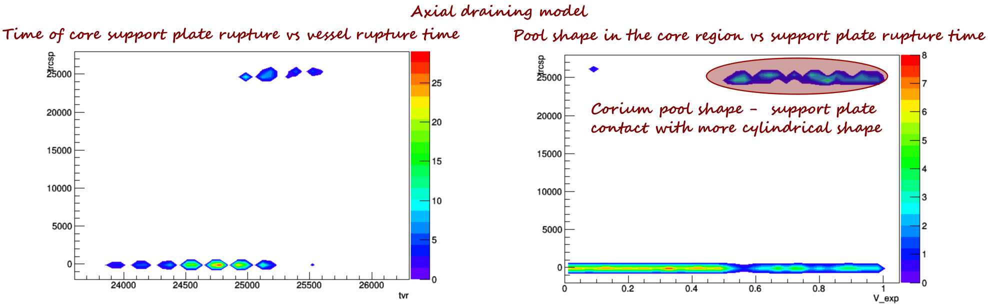


Figure: Relation of the RPV rupture time (tvr) and way of the core support modelling (*trcsp* - time of core support plate rupture) - "axial draining" model. $trcsp = 0$ means no contact between core support plate and corium

- The V_{exp} parameter is related to the geometrical modelling of the **corium expansion** [?] in the RPV core region, when the value is above 0.5 ("Ratio" modelling option) the pool is hemispherical and larger.
- With "Sum" modelling option (*Vexp* below the 0.5) we have earlier heavy reflector failure and consequently earlier appearance of the corium pool in the lower head. The rupture of the vessel occurs earlier than the core support plate rupture.
- The contact of the core support plate with the molten corium pool induce **higher mass transfers** of the molten materials to the lower head, which result in **lower vessel walls thermal loads** (lower lateral heat flux).

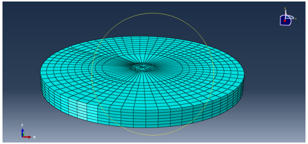
Future core support plate modelling

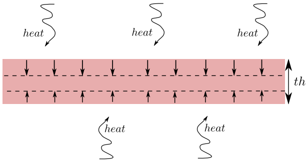
The results with axial draining model in the previous slides show we have less cases corresponding to RPV rupture when massive draining through the plate occurs.
At present, the axial and no axial draining models in PROCOR are two extreme cases and we have to introduce a **simplified** thermal–mechanical model to have a realistic evaluation of the corium that can drain through the plate.
In this part of work, is done with the use of additional software:

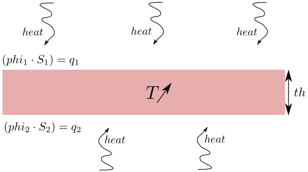
- Usage of mechanical detailed code (Finite Element Code) i.e.ABAQUS, ANSYS, ASTER

Objective

- Validation of our model with FEM Code, based on detailed modelling, better thermal-mechanical coupling,
- Using the FEM Code modelling to build a set of reference cases that could be used for further validation or for introducing a better simplified model (for ex. response surface).







Conclusion and summary

The results for the limited sensitivity analysis with PROCOR for SBO sequence have highlighted the further need for the improvement of the modelling of the two phenomena.

- The first one related to the modelling the focusing effect responsible for the early vessel failures, more precisely, it deals with modelling of the natural convection for thin metallic layer. The work will be performed to find a simplified model for thin steel layer and perturbation analysis of the top boundary condition
- The second issue is related to the core support plate modelling, which influences the vessel failures. For this problem the action are to develop an accurate thermomechanical modelling of the core support plate that is needed in upcoming PROCOR platform development.
- There are optimistic and pessimistic model, "axial draining" and "no axial draining" model respectively. First one is assuming the instantaneous CSP fail, while the second one assumes total core support plate - CSP resistance.
- These aspects improvement in the modelling will give help to have better understanding of the IVMR strategy utilization for nuclear reactors.

Thank you for your attention today.

maciej.skrzypek@ncbj.gov.pl

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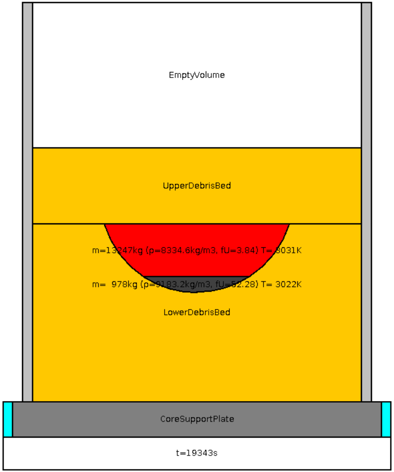
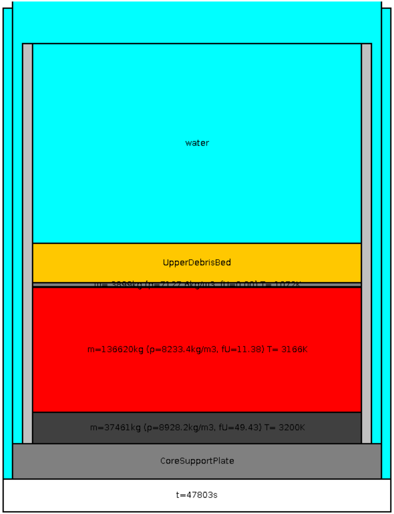
Wizualizacja przebiegu awarii



Axial draining, no reflooding, loop650



No-axial draining, reflooding, LOCA