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Detailed Thermal-Mechanical Modelling of Cylindrical Core Support Plate During Severe Accident in PWR

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[1]National Centre for Nuclear Research

Otwock, Świerk, 25 kwietnia 2017

The core support plate modelling. Literature overview and phenomenological background

Development philosophy

The core plate model is present in few of the commercial codes ([1], [2], [3]) There are several modelling options identified on the basis of the SCDAP/RELAP code developent strategy [4]:

1. utilize the existing lower plenum debris model
2. modify the existing upper plenum structure model, or
3. develop a completely new core plate model.

Development of a new model is usually eliminated because it is considered to be too costly.

Issues during anticipated accident sequence (without core recovery):

1. **Debris Interaction With Core Plate**
   Three potential sources of molten or partially molten material below the active core, that can reach CSP:
   - molten core structures,
   - in-core molten pool,
   - upper plenum molten structures,
2. **Heat Transfer**
   The tracking of the **pool formation** above the CSP is needed, while the heat transfer in the pool is established and the amount of heat is transferred to the solid core support plate. The solution of the conduction problem through the crust around the corium pool into the CSP is characterized by **nondimensional numbers**: surface-averaged Nusselt number, Nu, a modified Rayleigh number, Ra, and the fluid Prandtl number, Pr.

Figure: SBO sequence - MELCOR, CSP failure [5]

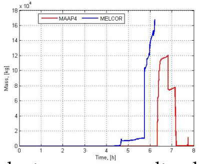


Table: TMLB accident sequence results - different break sizes for PWR type reactor. Range of debris and molten material formed below the core. [4]

Core Plate Debris Characterization	MIN	MAX
Ag-In-Cd [kg]	200	2350
UO2 [kg]	61040	82550
Zr [kg]	0	452
ZrO2 [kg]	15770	20860
Maximum Temperature [K]	3775	4108
Average molten temperature [K]	3415	3794
Molten Fraction	0.8	1.0

The questions appearing around Fukushima events about the progression of the severe accident (in this case BWR reactor type) led to investigations found in [6], [7].

Sequence and resulting possibilities of the corium relocation

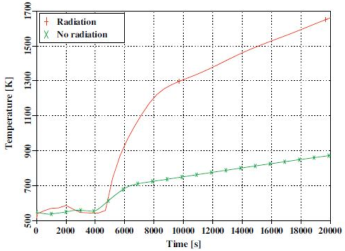
Typical BWR (similarly PWR) sequence:

- core uncovering - the core degradation of the Unit 1, assumption: the control rod liquefaction and downward relocation of the B_4C and stainless steel, and fuel debris, in the lower core region.
- partial fuel melting - first corium pool in the centre of the core [7].

Possibilities of in-vessel melt progression, i.e.:

- **axial progression of the debris and the molten fuel through the lower support plate** and/or;
- lateral progression of the molten fuel through the shroud.

Figure: Temperature of the lower surface of the core support plate before and after the inclusion of the radiation model for the SCDAP/RELAP code [8]. Possibility of the CSP melting due to radiation - change of the accident sequence.



Sum up for the contact of the corium with CSP:

1. relocation, PWR or BWR core, in **two stages**,
2. first metallic debris with a total mass on the order of **1-14 metric tons** at it's **melting point**
3. second - composite (ceramic of UO2, ZrO2, and metals), and may have a total mass in the range from of **80 to 130 metric tons**, non-homogeneous (70% molten,additionally solids), up to $T_{av,molten} = 3900 - 4000K$. [4]

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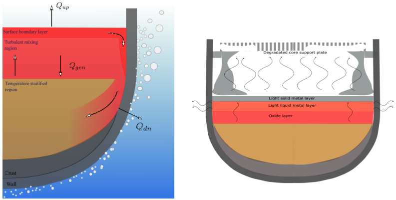
The melt retention in the RPV

IVMR strategy:

The In Vessel Melt Retention strategy is a severe accident management strategy that incorporates the internal or 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).

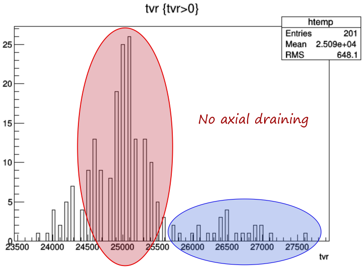


Heat transfer during IVMR strategy. Focusing effect.

At present the strategy:

- 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** [9].
- 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.
- 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

The melt retention in the RPV



Distribution of cases for statistical analysis, where pink corresponds with early and blue with late rupture

Motivation:

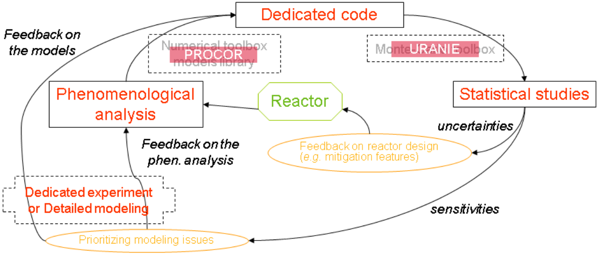
- To investigate the possibility of in-vessel melt retention success, sensitivity analyzes where performed for PWR reactor. [10]
- Analyzes have shown that the time of the vessel rupture can vary in time and we can distinguish early and later rupture cases.
- The vessel fails in most cases by phenomena called focusing effect, when thin metal layer on the top of corium corresponds with the highest heat flux on the vessel.
- Later vessel ruptures are occurring when the corium pool touches the core support plate.
- These analysis shows the need for more detailed modeling of the core support plate in the PROCOR code.

Numerical calculations. Tools

In the study regarding mechanical core support plate model during severe accident for pressurized water reactor, few important issues will be analyzed. To perform such analyzes the PROCOR platform, developed by CEA will be used, as also URANIE platform for statistical part (done) and Finite Element Code for detailed core support plate behavior analysis under severe accident conditions. To develop the core support plate which represents reality the following actions will be undertaken:

- the study of **later rupture cases** for in-vessel corium propagation in the PROCOR framework due to contact with core support plate,
- the more accurate evaluation of the corium flow from the core to the lower head (by lateral and axial draining),
- in particular study of the core support plate rupture and the massive draining that will occur due to plate rupture.

Figure: Methodology for this study is shown on the PROCOR work circle [11]



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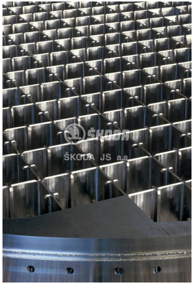
Core support plates in LWR

Core support plate in typical Pressurized and Boiling Water Reactor

Core support plate

- This is 'simple machine' - plate but if we look more into detail we see that it is complex plate, consisting a lot of wholes, porous plate (egg-crate)
- It supports all fuel assemblies in right places and has to withstand all loads which come from reflector and fuel assemblies.
- The average mass for LWR is around 30 tons of steel.



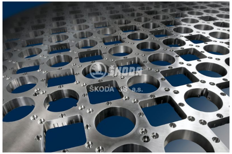


Figure: Examples of core support plates [12]

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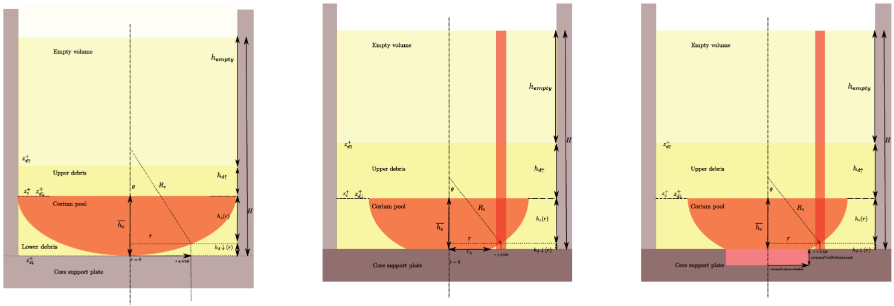
Figure: Possible configuration of core support plate during severe accident



- Cylinder radius - 2.145m
- Cylinder height- 0.415m
- Material mass 32.4 t
- Used materials: FE 0.73 CR 0.19 NI 0.07
- Stainless steel density- 7890 kg/m3, Young Modulus- 200GPa, Poisson ratio-0.3
- Positioned 1.59m above lower vessel head

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Second step = 2^{nd} round PROCOR work cycle

Thermal model– ODE Model

- ablation model (adopted from PROCOR platform)
- heating model

Figure: Only ablation model

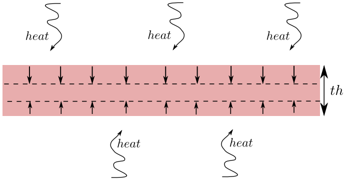


Figure: Only heating model

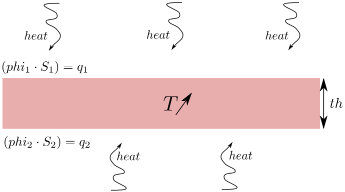


Figure: Only ablation model

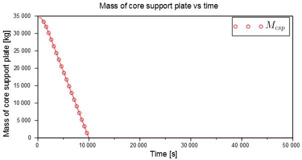
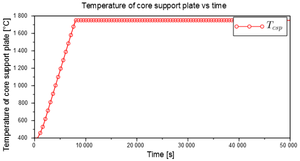


Figure: Only heating model



Second step = 2^{nd} round PROCOR work cycle

Stress model– mechanical

- circular plate with clamped edges

Assuming uniformly loaded,circular plate [13]:

$$\frac{d}{dr}\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right)\right] = \frac{qr}{2D}$$

integrating the equation and finding constants we have deflections:

$$w = \frac{q}{64D}\cdot(a^2 - r^2)^2$$

and slope:

$$\phi = \frac{-dw}{dr} = \frac{qr}{16D}\cdot(a^2 - r^2)$$

Radial moment:

$$M_r = \frac{q}{16}\cdot(a^2(1+\nu) - r^2(3+\nu))$$

Radial stress:

$$\sigma_{r(max)} = -\frac{6\cdot M_r}{h^2}$$

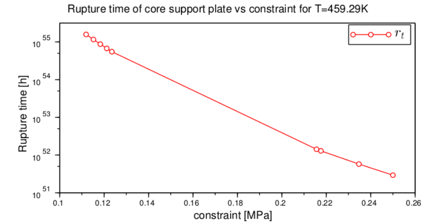
Second step = 2^{nd} round PROCOR work cycle

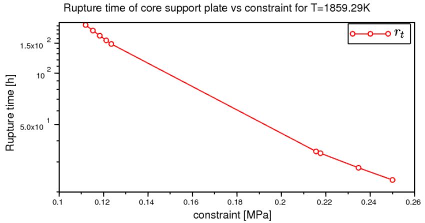
Rupture time model

- based on the Larson Miller Parameter

$$\frac{T(K)}{1000} \cdot (C + \log_{10} t_R) = A - B \log_{10} \sigma$$

where:
t_R time of plate rupture [h],
σ stress [MPa],
T-temperature [K],
A,B,C - coefficients for given material.





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Third step = 3^{rd} round PROCOR work cycle

ABAQUS as a Finite Element Tool allows to conduct mechanical calculation

1. fatigue clalculation
2. stress calculation
3. coupled thermal and mechanical

Figure: Screen shoot of ABAQUS CAE

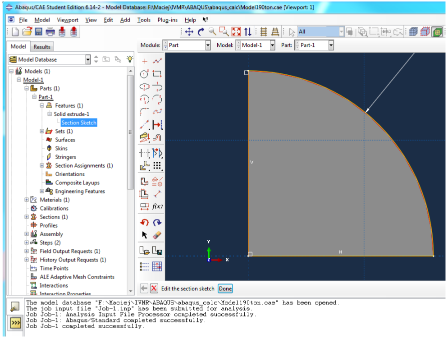
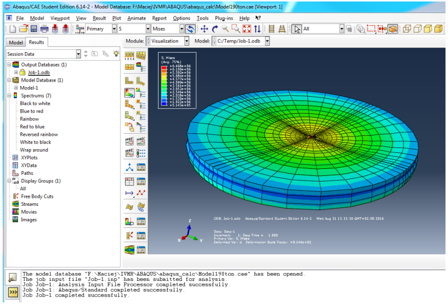


Figure: Screen shoot of ABAQUS CAE



ABAQUS/CAE Student Edition 6.14-2, Dassault Systemes, 2014

1. Complete solution for Abaqus finite element modeling, visualisation and process automation
2. Limitation up to 1000 nodes in Student Edition, neccessary to extend license for commercial

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1. Model of the part of the plate created using ABAQUS/CAE
2. It consists 987 nodes which corresponds with 720 elements (6 layers and 20 rows)
3. Type of the mesh: sweep technique using medial axis algorithm, with hex-dominated element shape

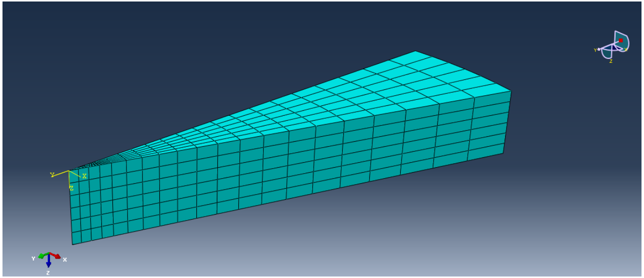


Figure: Final mesh of the part of core support plate

Model represents only part of the plate. Symmetry boundary condition implemented on lateral walls.
Uniform pressure implemented to upper surface represents mass of the core p=131640Pa
Radial surface with "encastre" BC represents clamped edges on the plate

Results

Deflection

- Model based on uniformely loaded circular plate assumption [13] is reflecting deflections in good agreement comparing to FEM results.

Figure: Simplified model

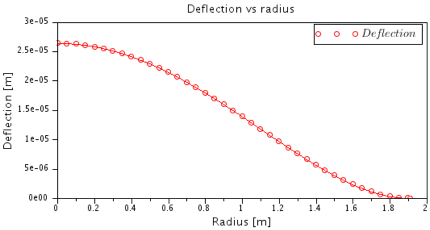
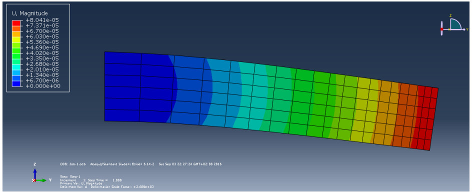


Figure: ABAQUS calculation



Sum up of the values: the range of deflection of the core support plate under the uniform load is:

1. 0.0 m to $8.04 \cdot 10^{-}5$ m for the FEM calculation,
2. 0.0 m to $2.61 \cdot 10^{-}5$ m for the 2D calculation.

The deflection is higher for simple load calculations than the FEM code.

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Failure criteria which predict failure based on different mechanisms

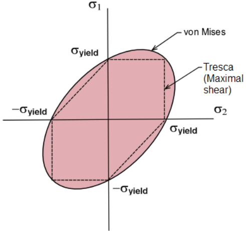
Basically all the failure theories provide some "scalar" equivalent of the stress “tensor” that can be compared with the design stress(strength) for the design purpose.

- Maximum Principle Stress Theory - According to this theory failure will occur when the maximum principal stress in a system reaches the value of the maximum stress at elastic limit in simple tension.
- Distortion Energy Theory (or Shear Strain Energy Theory) This theory proposes that the total strain energy can be separated into two components: the **volumetric** (hydrostatic) strain energy and the **shape** (distortion or shear) strain energy.
  - Mises criterion [14]
- Maximum Shear Stress Theory. This theory states that failure occurs when the maximum shear stress in the component being designed equals the maximum shear stress in a uniaxial tensile test at the yield stress.
  - Tresca criterion [15]

Applicability of the Theories:

- Mises stress is widely used, because it is suitable for the situation where the material is ductile and the failure mode corresponds to a normal stress.
- The maximum shear stress criterion (Tresca) is bit more conservative than von Mises criterion.

Figure: Mises and Tresca criterion comparison



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Failure criteria which predict failure based on different mechanisms

- Maximum Principle Stress Theory - This theory is usually associated with Rankine. According to this theory failure will occur when the maximum principal stress in a system reaches the value of the maximum stress at elastic limit in simple tension ($\sigma_{max} < \sigma_{ultimate}$).
- $\sigma_{max} = (\sigma_x + \sigma_y)/2 + \sqrt{[(\sigma_x - \sigma_y)/2]^2 + T_{xy}^2}$
  - σ_{max} - maximum principal stress
  - σ_x, σ_y normal stresses in X and Y direction
  - T_{xy} - shear stress in XY plane

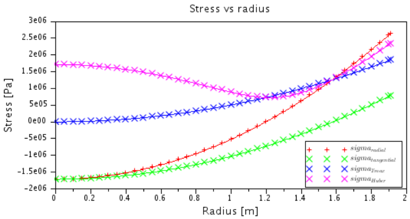

Figure: Simplified model

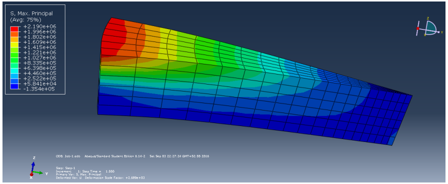

Figure: ABAQUS calculation- Stress Max Principle

Sum up of the values: the range of stress on the core support plate under the uniform load is:

1. -1.35 MPa to 2.19 MPa for the FEM calculation,
2. -1.42 MPa to 2.46 MPa for the 2D calculation.

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Failure criteria which predict failure based on different mechanisms

- Distortion Energy Theory and Maximal Shear Stress Theory, on the example of Mises and Tresca criterion.
  This theories propose that the total strain energy can be separated into two components: the **volumetric** (hydrostatic) strain energy and the **shape** (distortion or shear) strain energy ($\sigma_{red} < \sigma_{ultimate}$).

Figure: ABAQUS calculation-Mises Criterion

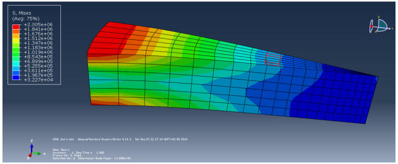
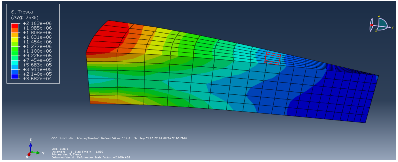


Figure: ABAQUS calculation- Tresca Criterion



Sum up of the values: the range of stress on the core support plate under the uniform load is:

1. 2.005 MPa to 0.035 MPa for the FEM calculation (Mises),
2. 2.163 MPa to 0.037 MPa for the FEM calculation (Tresca),

Conclusion and summary

The results for modelling of core support plate highlighted the further need for the improvement of the modelling

- Performed analysis with ABAQUS code gave indications of influential parameters, which have been neglected in the simplified modelling: the geometry effect, wholes/egg-crate porosity of plate, material, criteria of rupture or equation of state and conservation law.
- Important issue is coupling mechanical model with thermal impact, due to the fact that temperature will have big influence on the elastic limit of the steel. It could lead to the core support plate melting and failure adding the metallic molten material to the lower plenum and changing the established heat transfer in the lower head.
- Mechanical modelling of the core support plate is needed in upcoming PROCOR development. It allows to extend present "no axial draining" model for more reliable, which could influence vessel failures and overall accident sequence.
- These aspects improvement in the modelling will give help to have better understanding of the IVMR strategy utilization for high power nuclear reactors.

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Thank you for your attention today.

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Narodowe Centrum Badań Jądrowych
Świerk

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- Ex-vessel corium interactions and coolability
- Containment behaviour incl. H_2 explosion risk
- Source term issues
- Severe accident scenarios
- Emergency management and severe accidents impact on the environment

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