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NUCLEAR REACTOR PRESSURE THERMAL SHOCK SIMULATION

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Abstract. The article describes a multistage modelling methodology proposed by the author for the modelling of emergency core cooling processes. The methodology is based on the best practice guidelines presented by the IAEA, it is applied to a specific scenario of emergency core cooling during a loss of coolant accident [1] with an effective break diameter of 20mm. A 3D thermohydraulic analysis was performed as the first step in the solution process, where the transient changes in the pressure, velocity and temperature fields within the reactor pressure vessel were studied [2]. The primary knowledge learned when processing the results of the first step, was the presence of an oscillating cold coolant stripe in close proximity to the pressure vessel wall. The next step in the methodology consisted of a three-dimensional thermo-mechanical analysis of the reactor pressure vessel [3]. In this step, pressure thermal shock induced critical zones of mechanical loading were identified and the influence of the oscillatory character of the cold stripe on the pressure vessel was studied.

1 INTRODUCTION

The reactor pressure vessel is considered the most reliable component of pressurized water reactors [1]. The target of concurrent research is the extension of operating life of existing power plants and their components [2, 3, 4]. The condition of the reactor pressure vessel (RPV) is a major limiting factor for the operating life of a power plant [2]. The pressure vessel is exposed to thermo-hydraulic transients and the embrittlement effect caused by long time exposure to fast neutron radiation [4]. The coupled impact of these effects increases the risk of structural damage to the pressure vessel during pressure thermal shock (PTS) transients [3]. Thermal shock damage within solid materials represents high risk of structural weakening or in severe cases total structural failure and its elimination represents a significant engineering challenge.

2 PROBLEM DEFINITION

Loss of coolant accidents (LOCA) represent highly transient processes within the reactor pressure vessel. The two loading conditions that influence the vessel wall are pressure and temperature, both experience rapid changes during a thermo-hydraulic transient. This makes it necessary to perform a time transient thermo-hydraulic analysis to be able to capture the dynamic loading of the RPV in sufficient quality[2]. Given the unstable and non symmetrical nature of the coolant flow, the analysis must also include a model without symmetrical reductions that describes the RPV and the governing coolant flow characteristics within [3].

The initial transient thermo-hydraulic analysis [5] simulated the initiation of high pressure coolant injection into the primary circuit cold leg. In the beginning of the simulation, the primary circuit was in nominal operational state. Water was pumped through the cold leg into the downcomer region by the main coolant pump. Cold water injection was initiated by pressure decrease at the beginning of the simulation caused by a SB- LOCA.

Specific parameters of the SB-LOCA case were:

- initial condition was standard operating state
- equivalent break with a diameter of 20 mm located in Loop 1 (outside of the modeled domains)
- all other Loops were considered undamaged
- single high pressure injection pump active on CL2
- main coolant pumps and reactor shut down at t = 0 s
- no coolant phase change (water-steam) during event, no water level decrease in RPV

Boundary conditions were set up based on the specific case parameters and based on data acquired from a system level thermo-hydraulic analysis:

- On undamaged loops (e.g. 2,3,4,5,6) inlet mass flows on CL were equal to the outlet mass flow on HL and are specified based on data from system code simulation (not analyzed in this paper)
- CL1 defined as pressure inlet (provided pressure information and also represented the leak), HL1 set up as mass flow according to data
- Inlet temperatures on all CLs defined based on data
- Decay heat defined from data

The above described analysis was performed using Ansys CFX on a High-performance computing (HPC) cluster. The main results of the above described analysis were pressure and temperature conditions on the reactor pressure vessel. These conditions are shown in figure 1.

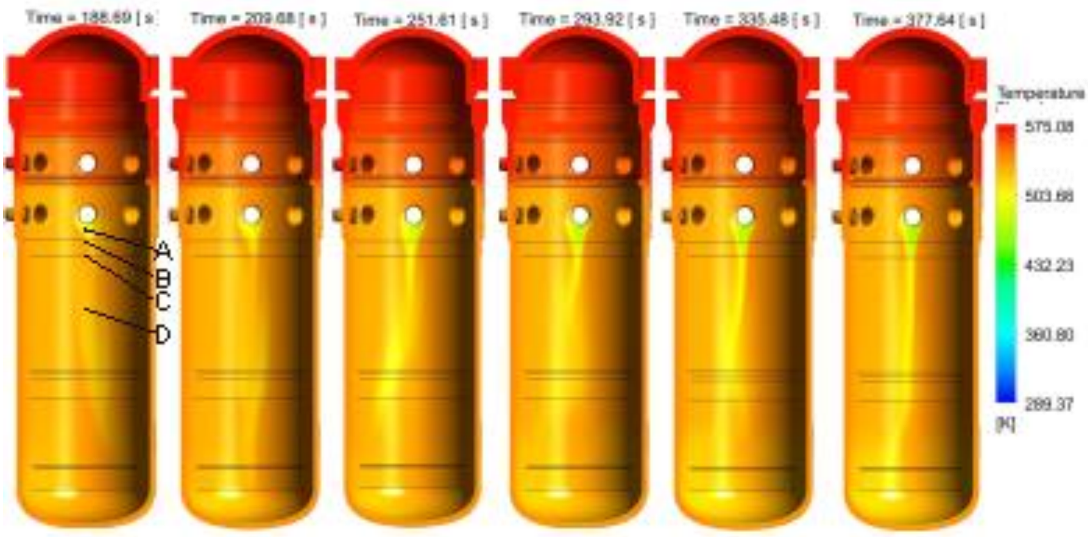

Figure 1: Temperature distribution on the RPV inner surface at several time marks

Fig. 1 shows the overtime development and change in the temperature distribution of the RPV wall inner surface. Fluid flow and mixing creates a strip cooling effect, the RPV is cooled in a long thin strip under the nozzle. Results show that this strip is also unstable and has a slight oscillation. Sample points located on the inner surface of the RPV at different heights A(below CL2), B(Belt line weld), C (top of Core) and D(middle mark of Core) marked on figure 2 were used to plot the overtime development of the wall temperature.

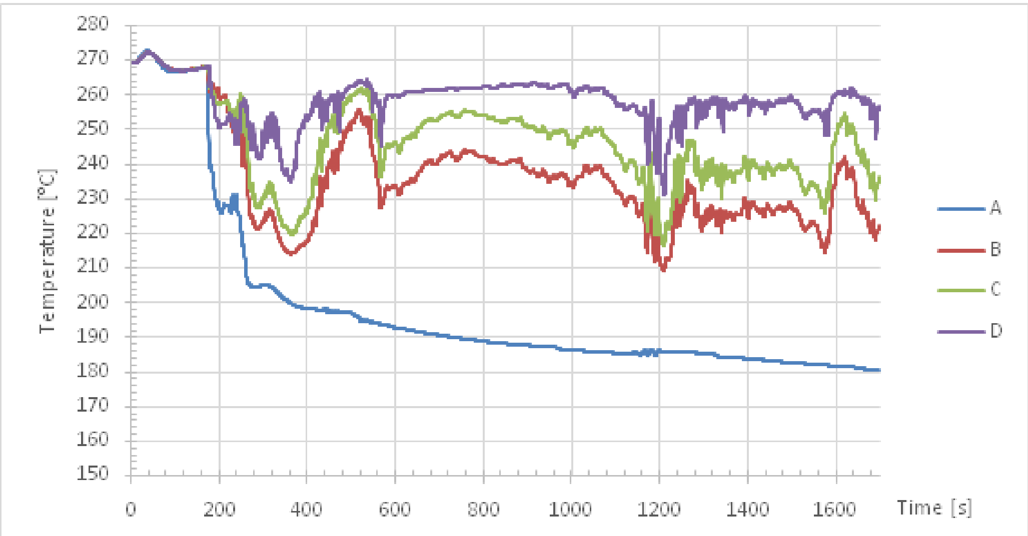

Figure 2: Temperature development on the RPV inner surface at sample points

These results were subsequently used in a thermo-mechanical analysis and a fracture mechanics analysis as loading and boundary conditions.

3 THERMO-MECHANICAL ANALYSIS

The model represents the reactor pressure vessel and the solid domain of the RPV itself. Although, the RPV and fluid layers directly in contact with it are modeled in detail, internal structures and components have been significantly simplified. The larger internal structural components (i.e. cladding, welds, control rods etc.) are not directly modeled, only their shape is defined in the fluid domain [4].

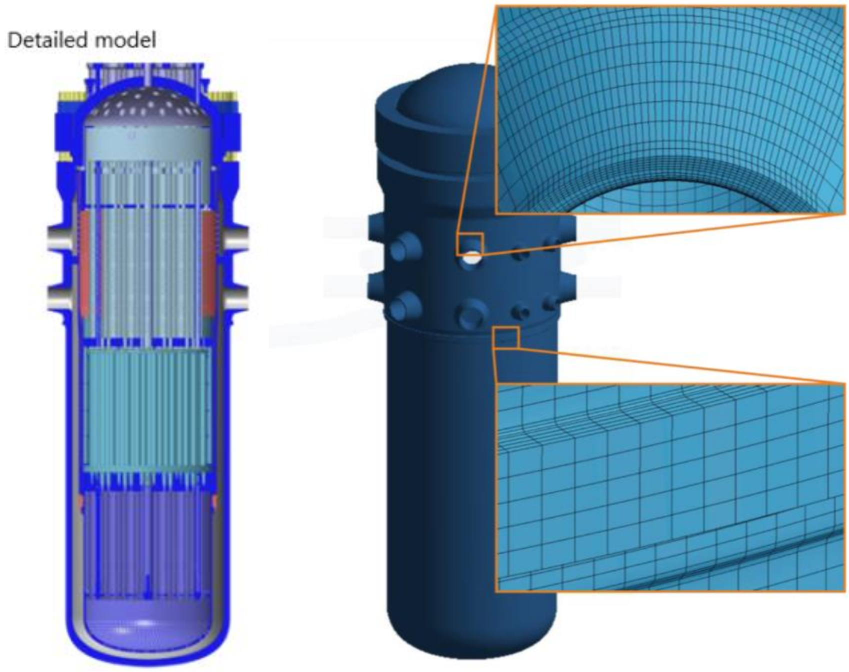

Figure 3: Computational model with indexed bodies compared to the detailed Reactor model

The structure of more complex components (i.e. fuel assemblies, perforations of reactor shaft and bottom etc.) were modeled as parameters of porous regions. The fully assembled model is shown in Fig. 3.

Basic parameters of the computational model and solver parameters used in simulations:

- model created using ICEM CFD, analysis performed in ANSYS APDL [6, 7] through ANSYS Workbench interface

- the final computational model contains 3,7 million nodes and 3,5 million elements

- the mesh is assembled from 20 node quadratic hexahedral elements

- RPV modelled with homogenous isotropic material, 15Cr2MoVA steel. Linear elastic material model with temperature dependent material properties.

- model assembled as a single solid domain

Figure 4 shows the mechanical boundary conditions defined for the thermo-mechanical analysis. The individual conditions are:

- A – RPV seating lip, fixed vertical degree of freedom

- B and C – cold leg connections, fixed translational degree of freedom in the axial direction, required for numerical stability.

- D – pressure conditions applied on all internal faces of the RPV, mapped from the results of the thermo-hydraulic analysis

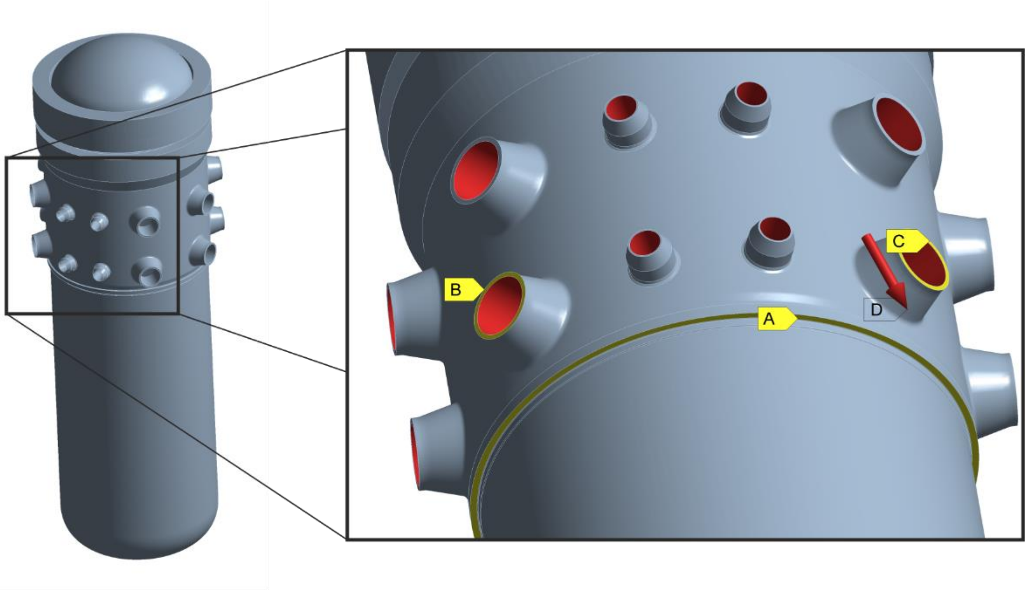

Figure 4: Boundary conditions

Imported data with temperature conditions were mapped on the whole model volume of the RPV. Temperature and pressure conditions were mapped on the RPV for three different timepoints.

4 ANALYSIS RESULTS

The thermo-mechanical analysis consisted of three steady-state simulations representing the three chosen timepoints. The individual simulations represent loading state snapshots at given timepoints of the loading scenario.

Figures 5, 6 and 7 show the imported and mapped temperature (left), mechanical strain (middle) and equivalent mechanical stress (right) in a longitudinal section showing the internal wall faces.

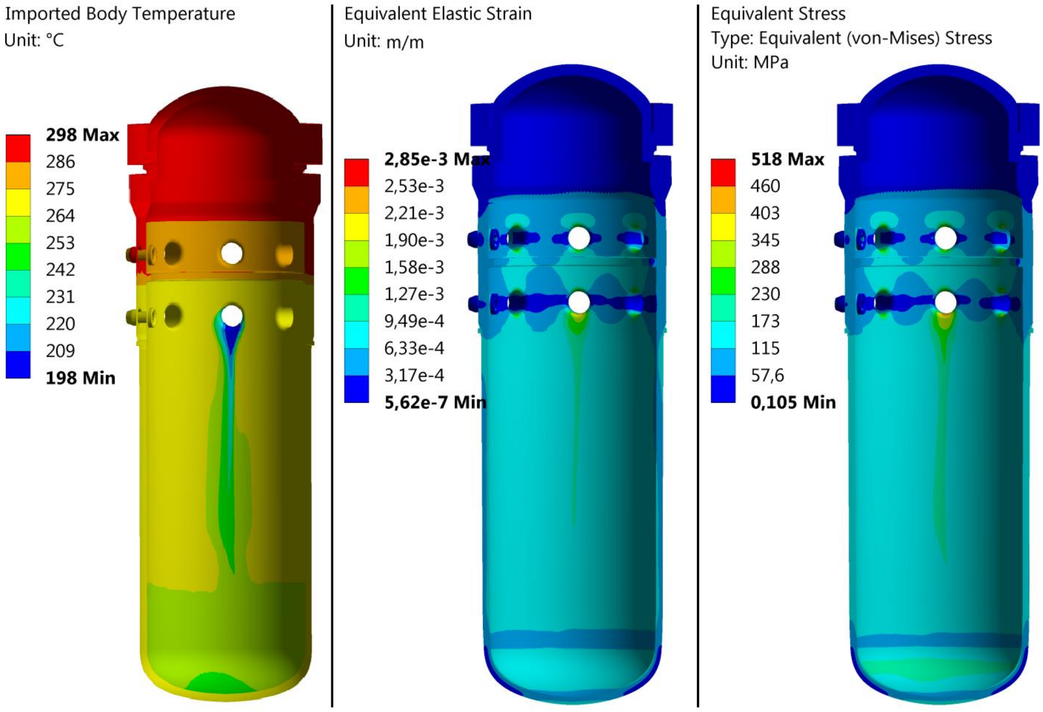

Figure 5: Results of thermo-mechanical analysis for timepoint 360s

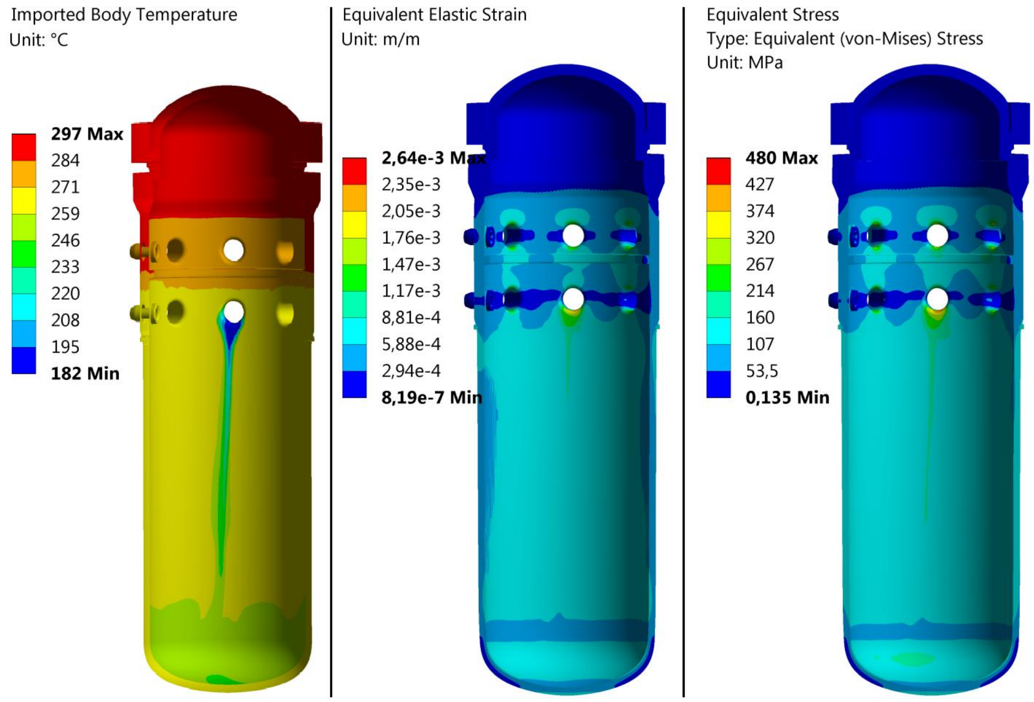

Figure 6: Results of thermo-mechanical analysis for timepoint 1053s

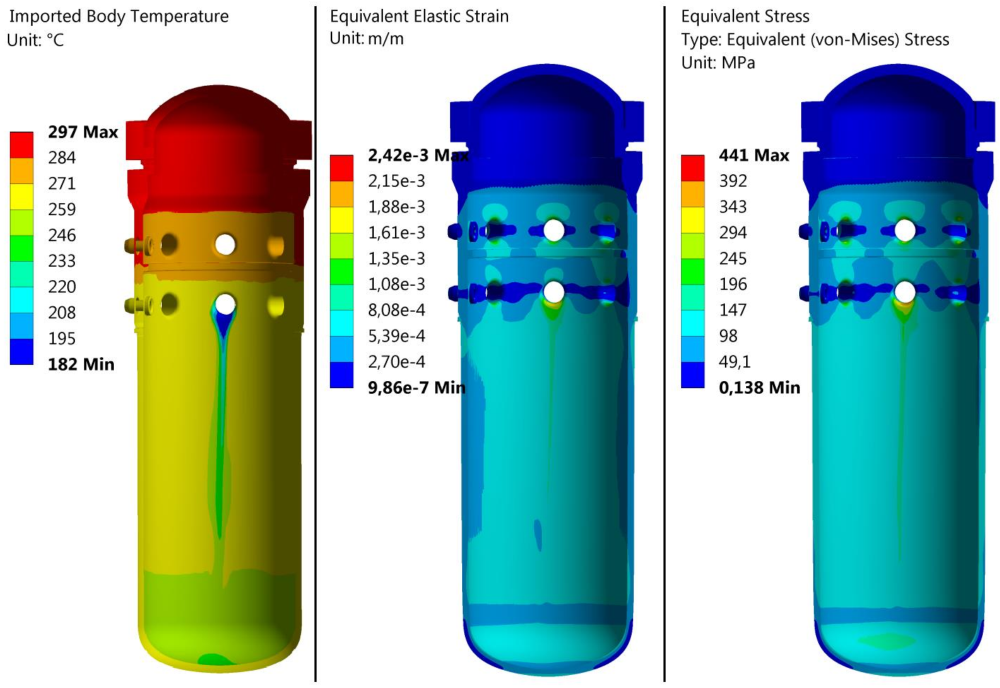

Figure 7: Results of thermo-mechanical analysis for timepoint 1218s

5 CONCLUSIONS

The acquired results show relatively high maximal stresses. However, these extremes are located in a relatively small region and represent a thin surface layer. Additionally, stress values are overestimated by the linear elastic material model. In reality, these regions would undergo local plastic deformation thereby lowering stress intensity.

Considering that these extremes are located on the internal surface of the cold leg nozzles, with relatively small surface area, the results have been deemed acceptable. [1]

ACKNOWLEDGEMENT

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