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MODELLING THE EFFECTS OF OSCILLATING STRIPE COOLING DURING A LOCA EVENT IN A VVER440/213 REACTOR PRESSURE VESSEL

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Abstract. A Loss of Coolant Accident (LOCA) is initiated by damage in the primary circuit and subsequent coolant leak of a pressurised water reactor (PWR). The loss of coolant is then compensated by the Emergency Core Cooling System (ECCS) [1]. This system supplies the primary circuit with cold high pressure coolant during emergencies. The mixing of this cold coolant results in stripe cooling of the RPV wall. This article focuses on the modelling of the mixing processes of this cooling stripe and their effects on the RPV wall in a VVER440/213 Russian type PWR. The mixing processes are modelled in a transient thermo-hydraulic analysis which models the mixing of the coolant flows in the reactor pressure vessel and results in the overtime temperature and pressure fields within the RPV [2]. The analysis results show that the cooling stripe is not stationary. The turbulent mixing causes an unstable oscillatory motion of the cold stripe which has a notable effect on the RPV wall temperature distribution. Selected results were subsequently transferred into a thermo-mechanical analysis via one way coupling method. This analysis was performed to evaluate the PRV loading state during the LOCA transient. Where the loading stresses were shown to correspond to the oscillatory nature of the cooling strip. In conclusion, an oscillating cooling strip can result in multiple loading cycles [3,4] of the reactor pressure vessel wall during a single LOCA transient or ECCS high pressure coolant injection.

1 INTRODUCTION

The reactor pressure vessel is considered the most reliable component of pressurised water reactors. The target of concurrent research is the extension of operating life of existing power plants and their components. The condition of the reactor pressure vessel (RPV) is a major limiting factor for the operating life of a power plant. The pressure vessel is exposed to thermo-hydraulic transients and the embrittlement effect caused by long time exposure to fast neutron radiation. The coupled impact of these effects increases the risk of structural damage to the pressure vessel during pressure thermal shock (PTS) transients. 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 PRESSURE THERMAL SHOCK ANALYSIS

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[4]. 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 [5].

As described above, a transient thermo-hydraulic analysis is necessary to capture the dynamic loading of the RPV during a Small-break LOCA event (SB-LOCA). The transient thermo-hydraulic simulation was set up to calculate coolant flow and mixing in the fluid domain and to calculate heat transfer at the RPV inner wall and the temperature field within its solid domain.

The CFD model represents the fluid domain within the RPV and the solid domain of the RPV itself. Although, the RPV and fluid layers directly in contact with it are modelled in detail, internal structures and components have been significantly simplified. The larger structural components (i.e. reactor shaft, core barrel, reactor bottom etc.) are not directly modelled, only their shape is defined in the fluid domain [6].

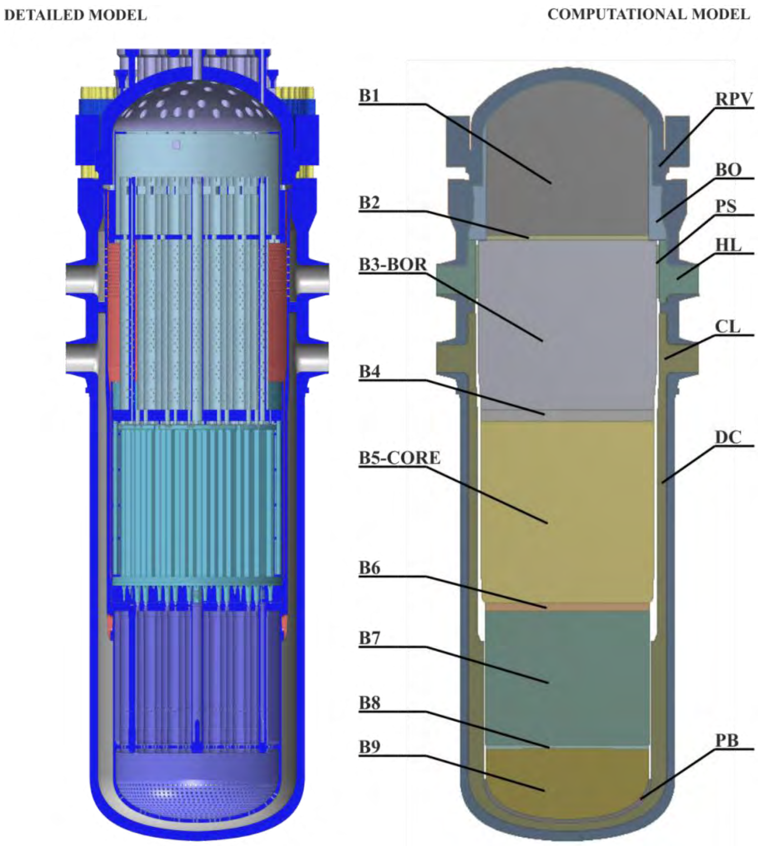

Figure 1: Computational model with indexed bodies compared to the detailed Reactor model

The structure of more complex components (i.e. fuel assemblies, perforations of reactor shaft and bottom etc.) were modelled as parameters of porous regions. The fully assembled model is shown in figure 1.

3 THERMO-HYDRAULIC ANALYSIS

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

Specific parameters of the SB-LOCA case:

- initial condition is standard operating state
- equivalent breakwith a diamater of 20 mm located in Loop 1 (outside of the modelled domains)
- all other Loops are 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 are 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 (provides pressure information and also represents 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 total solution time for a single 1700 s transient equalled 7days and 14 hours. The final solution contains 270 GBs of data. As such a large database cannot be fully included in this article the following figures represent some of the most relevant result data. As the source data did not include the temperature of the ECC injected coolant, a parametric study had to be performed. Figure 2 shows the different temperature histories for the different ECC injected coolant temperature variants.

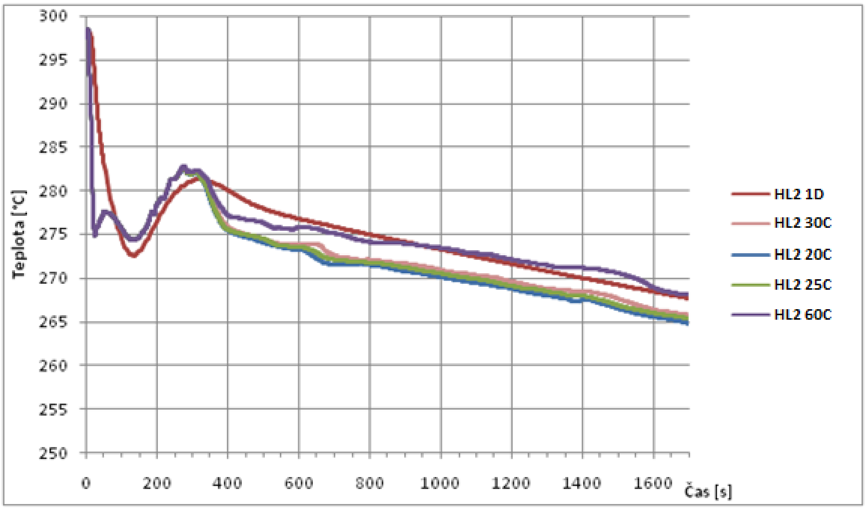

Figure 2: Outlet coolant temperature histories on HL2 for different ECC injected coolant temperatures

Variant 60C was choosen as the best fitting one, which represented ECC coolant injected at 60 °C. This variant was then used in all follow up analyses.

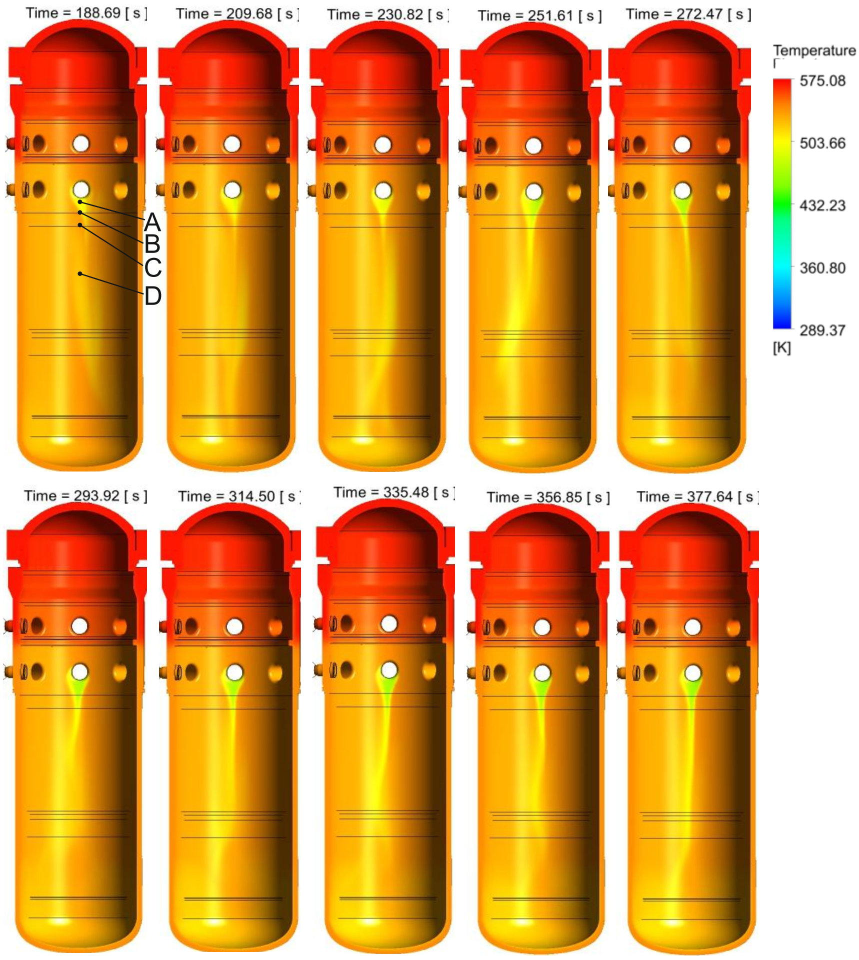

Figure 3: Temperature distribution on the RPV inner surface at several time marks

Figure 3 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 3 were used to plot the overtime development of the wall temperature.

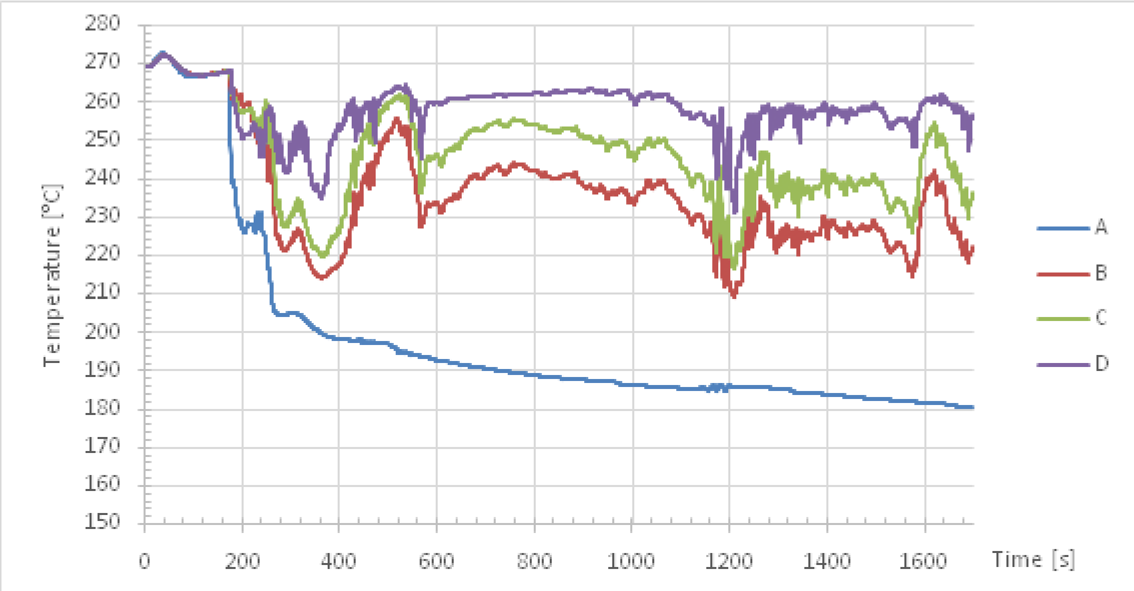

Figure 4: Temperature development on the RPV inner surface at sample points

Figure 4 shows the over time temperature at the given sample points. These temperatures represent the behaviour of the cooling stripe under the cold leg. The shown temperatures represent the oscillatory nature of the cooling stripe and its effects on the inner surface temperature of the RPV wall. However the cooling is not only superficial. Figure 5 shows the cooling effects on subsurface layers of the RPV wall. The overtime transient temperatures shown in figure 5 represent the temperatures at the given depths under sample points B and C. Where depth 0mm is identical with the sample point and its time transient temperature shown in figure 4 and depth 140mm represents the time transient temperature on the outer surface of the RPV wall (wall thickness is 140mm).

As shown in figure 5, temperatures within the thickness of the wall follow and copy the inner surface temperatures and its oscillations caused by the cooling stripe. Thereby creating time transient temperature gradients in the RPV wall.

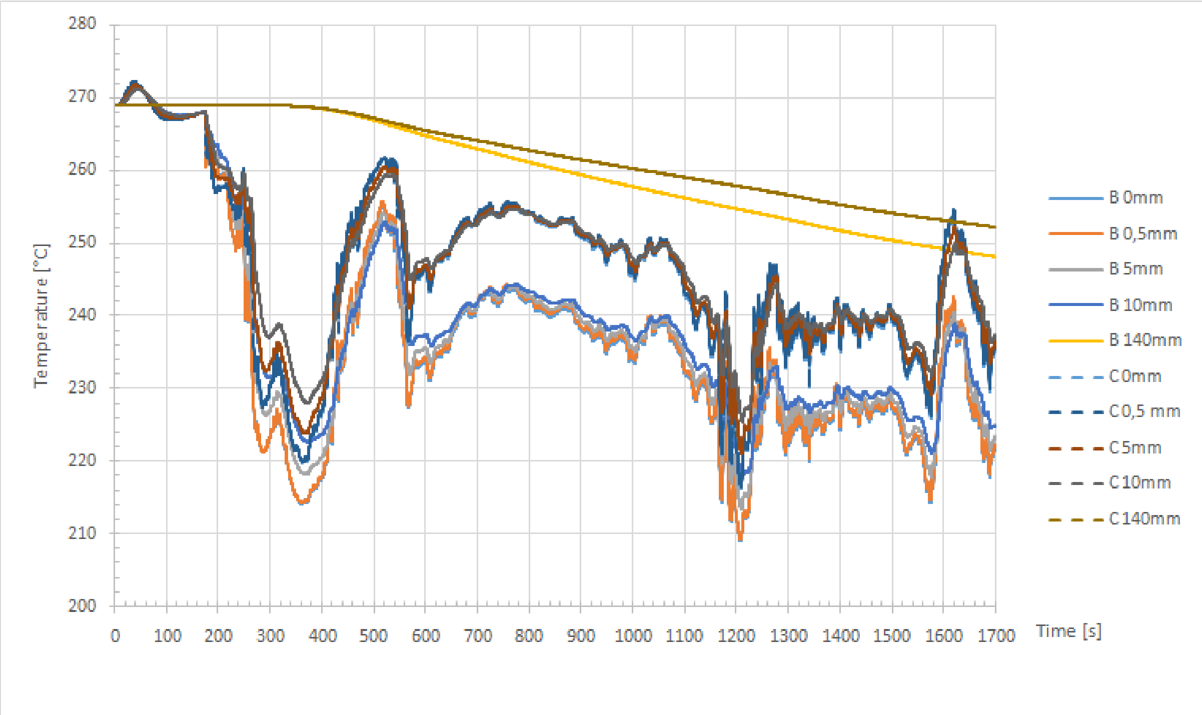

Figure 5: Temperature distribution in subsurface layers under sample points B and C

4 THERMO-MECHANICAL ANALYSIS

As shown in the previous chapter, coolant mixing during the SB-LOCA event creates highly non-uniform temperature fields within the reactor pressure vessel. Therefore, a structural analysis is required to evaluate the severity of the loading forces within the RPV. As the SB-LOCA transient is characterised by relatively slow pressure and temperature changes compared to the dynamic properties of the RPV, the Structural Analysis can be performed as a static structural problem. The structural model represents the volume and shape of the Reactor Pressure Vessel and utilises the model and element mesh already prepared for the thermo-hydraulic analysis as shown in figure 1 designated as "RPV".

However, the RPV model contains some significant simplifications compared to its real counterpart:

- Reactor Head and Closure Flange modelled as a single part together with the RPV. The model omits the effects of bolt pretension and the friction between their contact surfaces.
- The Austenitic cladding layer is not represented, it was modelled as if made from the same Bulk material. No significant difference between the relevant Material properties to merit the additional computational resources required to model the Austenitic layer.
- Material properties describing the 15Cr2MoV Steel, represent the properties of the bulk material after RPV manufacturing. The material properties do not include the effects of chemical and radiation exposure after long term operation. (These properties were unavailable in sufficient detail)
- The model does not include weld lines or residual stresses from welding.

- Reaction forces from pipelines are not included in the loading.

The RPV is the only "fixed" component in the primary circuit, other components in the individual coolant loops (i.e. Steam Generators, Main coolant pumps etc.) are all mounted on flexible supports to allow the free thermal expansion of pipelines. Therefore, their reaction forces were considered negligible.

Because the model does not contain the whole primary circuit, only the RPV is represented, multiple boundary conditions have to be applied to correctly support and prevent the rigid movement of the RPV.

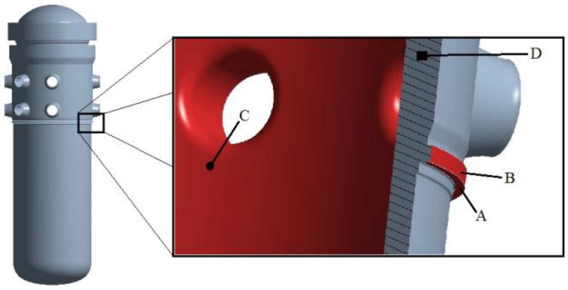

Figure 6: Boundary conditions and imported loads for thermo-mechanical analysis

Boundary conditions are shown in figure 6 where:

A - RPV support pad - Defined as Displacement BC where vertical DOF has been set to zero

B - Outer surface of the RPV support pad - Defined as Elastic Support, implemented to prevent sideways rigid motion, but it allows thermal expansion without significant interference. The elasticity represents the friction of the RPV seating surfaces.

C - Internal surfaces of RPV - Imported Pressure loads from the Transient Thermo hydraulic analysis

D - RPV volume - Imported Temperature Distribution from Transient CFD analysis, CHT solid domain RPV.

The loads were imported for a single time point of the transient CFD results.The static structural analysis is used to calculate the state of the RPV for a given loading time point, imported from the transient CFD results.

The structural analysis was performed for a chosen time point of t=206.947 s. At this time index HPI of cold coolant is already operational and coolant mixing created stripe cooling is at its beginning.

Figure 7 shows the calculated Equivalent Strain for the given loading state at time t=206.947 s, as is evident from these results, the highest stress is located just below the cold leg nozzle. This local stress distribution is shown in a detail view in figure 7.

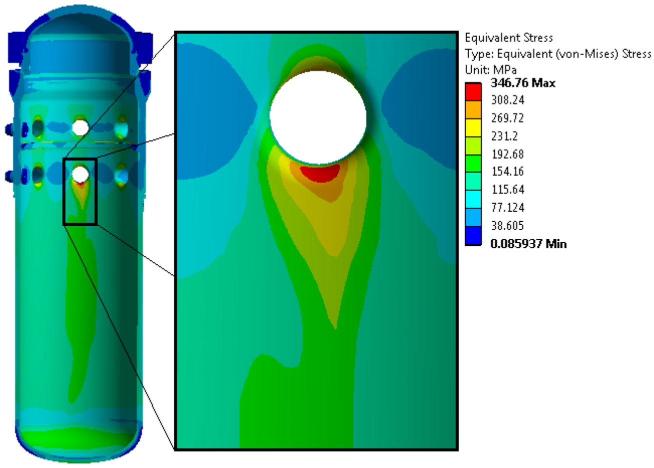

Figure 7: Equivalent stress on the internal surface of RPV
(Time= 206.947s; Viewpoint: Internal surface, axial view of Cold leg 2)

The highest stress region is located at CL2 with a value of 346.76 MPa. Although, the calculated stress values are relatively high, it is still within the elastic region of the modelled material with a Yield Strength of 395 MPa at 350 °C. However, all surfaces were modelled as perfectly smooth, whereas surface irregularities or cracks could create singularities that would increase stress magnitudes.

5 CONCLUSIONS

As the results show the SB-LOCA event causes strip cooling of the RPV as expected. However, the cooling strip was shown to be unstable and to oscillate over time. This oscillation could result in cyclical loading of the RPV wall and its fractures. Continued investigation into the cause of this instability and into its effects is needed. The analysis has shown that the temperature oscillations are not only superficial but propagate into the thickness of the RPV wall. Relatively high stress values calculated during the static structural analysis present an incentive to perform a fracture mechanics study to determine the loading intensity of possible initialisation fractures in the RPV, which will require a sub-modelling approach to determine localised crack loading.

ACKNOWLEDGEMENT

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