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Investigation of IVMR Strategy with External Vessel Bottom Head Water Cooling in VVER1000/v320 Reactor Design with ASTECv2.1.0.3 Computer Code

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Abstract. During a severe accident a large quantity of molten core material may relocate to the lower plenum of the reactor pressure vessel, where it starts to interact with the stainless steel of the vessel. This causes heat up of the lower head vessel and its eventual failure.

In-vessel melt retention strategy through external cooling of the reactor vessel is one of the essential Severe Accident Management (SAM) measures at nuclear power plants. The aim is to terminate the progress of a core melt accident and to ensure the final coolability of the reactor pressure vessel.

The reference power plant for this investigation is VVER-1000/v320 reactor sited at Units 5 and 6 of Kozloduy NPP. In the calculation external water cooling of the vessel lower head was simulated during a severe accident: Large Break LOCA (2×850 mm) with full Station blackout (SBO).

Calculation has been performed with ICARE and CESAR module of ASTECv2.1.0.3 computer code and input model for VVER-1000 reactor design. ASTECv2.1.0.3 computer code was used to predict the heat fluxes from the corium to the vessel and the heat fluxes from the vessel to the outside coolant. It highlighted key periods of maximum heat input to the vessel steel wall that the steel wall has to be capable of sustaining.

Keywords: In-Vessel Melt Retention, Severe accident, VVER-1000, ASTEC v2.1.0.3 computer code

1 Introduction

This paper aims to enrich the knowledge on the applicability of the In-Vessel Melt Retention (IVMR) strategy with external vessel water cooling to the reactors of VVER-1000/v320 type [6]. The selected reference nuclear power plant for this analysis is Units 5 and 6 of the Kozloduy NPP equipped with VVER-1000 reactor model v320. This type of reactor is a pressurized water reactor with 3000 MW thermal power and 1000 MW electric power.

IVMR strategy is one of the feasible solutions to mitigate reactor vessel failure and further fission products release to the containment and to the environment outside. The investigation concerns a calculation made with ICARE and CESAR module of ASTECv2.1.0.3 computer code. ASTEC computer code [1,2] was developed by IRSN (France) and GRS (Germany) to be a European computational tool for simulation of severe accidents in the different reactor designs. Significant attention was paid on the applicability of ASTEC [3] to the VVER reactor types.

A LB-LOCA (double ended guillotine break of the cold leg: 2×850 mm) simultaneously with SBO at VVER-1000/v320 reactor design was the postulated SA transient chosen as the most challenging for this type of reactor and the IVMR strategy. Some investigations of this scenario and IVMR strategy have been done with previous versions of ASTEC [4,5]. In this scenario, the accident evolution is the fastest and the decay heat of the molten corium is the highest. Melting and relocation of fuel elements and reactor internals into the lower head vessel comes sooner. The broken loop is assumed to be at the loop with the pressurizer and the break is located near the reactor inlet.

One calculation was done with ICARE coupled with CESAR modules of ASTECv2.1.0.3. For this purpose it was developed a model of the bottom vessel head where an adequate external boundary conditions simulating external lower head vessel water cooling were implemented. In the calculation ICARE module of ASTECv2.1.0.3 is used to predict the in-vessel phase of the event (LB-LOCA plus SBO). The purpose of this calculation is to compute a realistic flux profile on the inner side of the vessel and from the vessel to the external water. The periods of maximum heat input from the corium to the vessel steel wall were also accounted.

2 Description of ASTECv2.1.0.3 VVER-1000 Input Model

In the ASTECv2.1.0.3 integral code, ICARE module is used to calculate in-vessel core degradation and CESAR module is used to calculate thermal-hydraulics during severe accident of a reactor. The coupled modules compute the behavior of in-vessel structures, thermal-hydraulics for water, steam and non-condensable gases as well as chemical reactions between materials.

In the input model it was modeled just the elliptical and the cylindrical vessel bottom head, which is shown in Figure 1. The elliptical part of the lower head vessel has been divided into 5 radial rings and 7 axial segments (summary

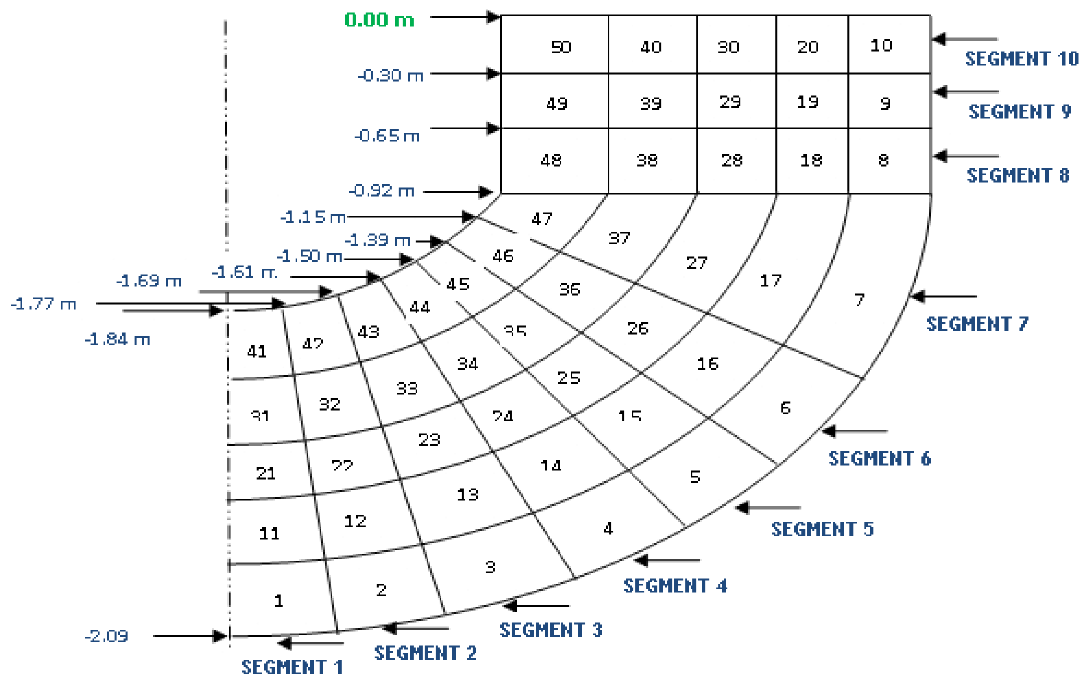

Figure 1. Segmentation of the vessel lower head for the ASTECv2.1.0.3 code modelling (elliptical section: segments 1-7, cylindrical section: segments 8-10).

35 meshes). The cylindrical part of the lower plenum has been modeled as 5 rings and 3 axial segments (summary 15 meshes). The elevation 0.00 is assumed to be between the cylindrical part of the vessel and the cylindrical part of the lower head in the input, as can be seen from Figure 1.

The lower head vessel is modeled with one channel without the in-vessel internal structures and water. The initial and boundary conditions are modeled using the structure CONNECTY. The calculation starts when a corium with a certain composition and initial temperature is poured in the lower bottom head of the vessel. The quantity and the composition of the corium are defined so that to be realistic input for the investigated event. The water cooling simulation starts at the beginning of the calculation.

3 Basic Modelling Assumptions

The calculation starts at $t = 4910$ s of overall transient assuming core barrel melt-trough followed by corium relocation into dry lower reactor head. The relocation phase was not modelled. Sudden presence of corium in lower head was assumed instead. The transient than continues with formation of volumetrically heated molten pool, reactor wall heat up and ablation. At that time the reactor pit is flooded by water with temperature 60°C.

The initial corium composition is shown in Table 1. The corium is composed by UO_2, ZrO_2, Zr and Stainless Steel.

The instant parameter is the decay heat power. The decay heat time dependence is presented in Table 2.

Vessel is modeled with one channel named "CHAN1" without internals.

The void fraction in the fluid channel is assumed to be: $x_\alpha = 1.0$;

Table 1. Initial corium composition

Material	Mass, [t]	Source
UO_2	85.9	CORE
Zr	15.6	CORE
ZrO_2	17.1	CORE
Steel	34.4	CORE
	12.2	elliptic part of barrel
	19.0	melted cylindrical part of barrel
	12.3	FA-supports
	1.94	support grid

Table 2. Decay heat history

Time [s]	Decay heat [W per 1 kg of UO_2]	Time [s]	Decay heat [W per 1 kg of UO_2]
1000	585.28	30000	215.12
2000	487.52	40000	200.4
3000	433.92	50000	190.16
4000	397.68	60000	182.24
4910	**373.44**	70000	175.12
5000	371.04	80000	168.96
6000	350	90000	162.4
7000	333.28	100000	155.92
8000	319.12	200000	133.2
9000	307.52	300000	117.04
10000	297.28	400000	102.88
20000	240.08		

The initial water level in the channel is assumed to be: $z_{\text{wat1}} = 0.0$;

Initial inside pressure in the channel is assumed to be 15.7 MPa and the fluid initial temperature is assumed to be 593 K (320°C).

Initial corium is modelled as one layer.

For the vessel rupture have been used ’MECHANIC’ and ’FUSION’ criteria:

STRU RUPTURE

CRIT ’FUSION’

CRIT ’MECHANIC’

END

The Rayleigh-Taylor instability model is activated in the input model: RTI_ACT 1

Phase separation model is activated in the input model: SEPA_ACT 1

4 Analysis of the Results

The calculation continues till 30000 s. Up to this time the lower head vessel failure doesn’t occur.

In Figures 2 to 9 below, the temperature field and the temperature diagrams of the different rings versus vessel elevation are given at early ($t = 7032$ s), mid ($t = 15082$ s and 20122 s) and late ($t = 30000$ s) stages.

The figures show that the maximum temperatures are observed at -0.65 m after approximately 12000 s. The maximum temperatures reached at this point are from 1700 K to 1750 K. Most of the inner wall of the cylindrical part of the lower vessel and the upper part of the elliptical part of the lower vessel has relocated to the vessel bottom. The outer cooled wall of the vessel has remained unmelted.

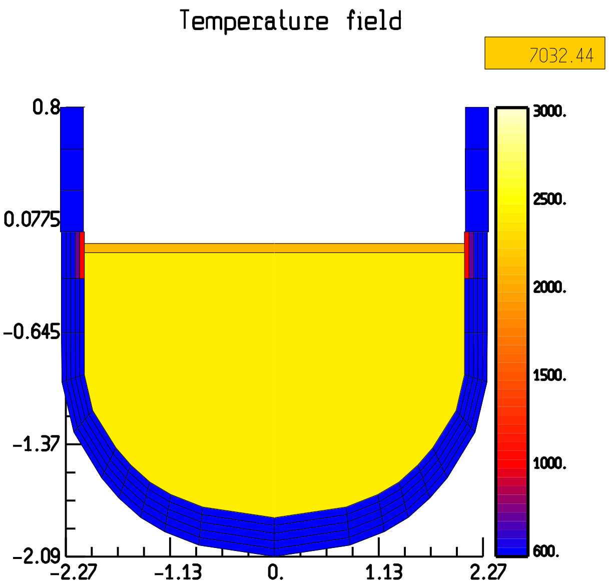

Figure 2. Temperature field at 7032 s.

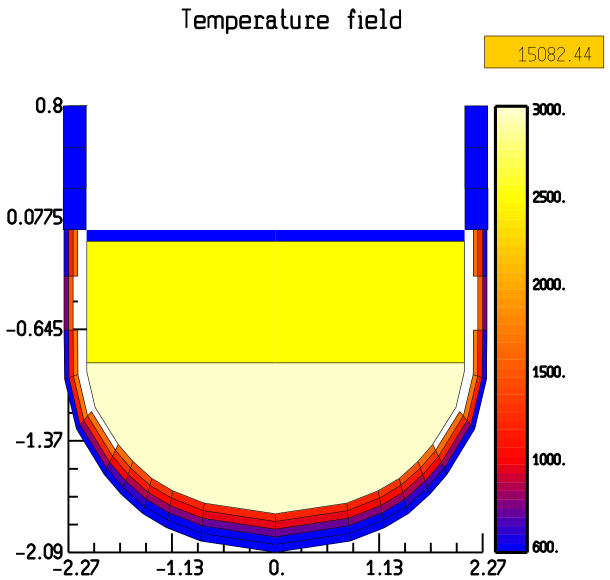

Figure 4. Temperature field at 15082 s.

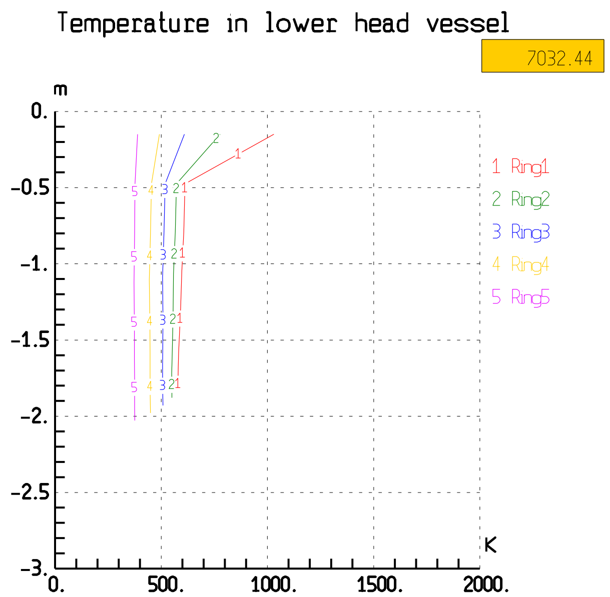

Figure 3. Rings temperature diagram at 7032 s.

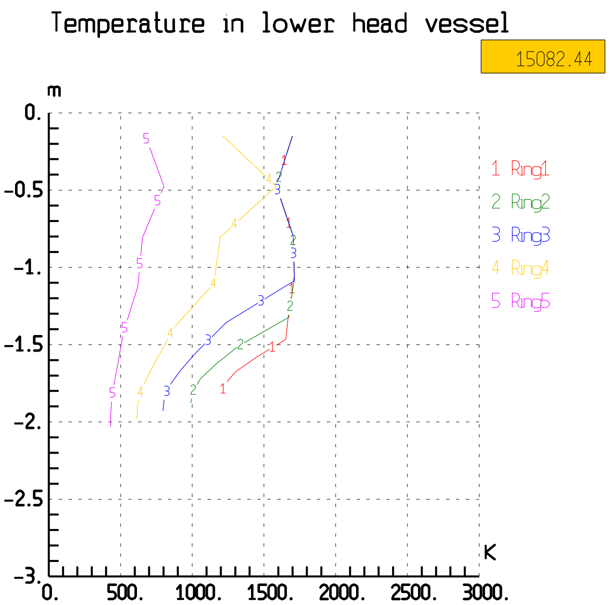

Figure 5. Rings temperature diagram at 15082 s.

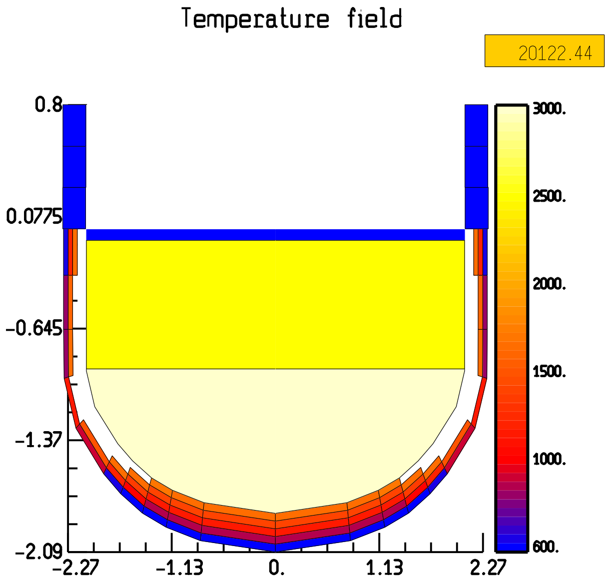

Figure 6. Temperature field at 20122 s.

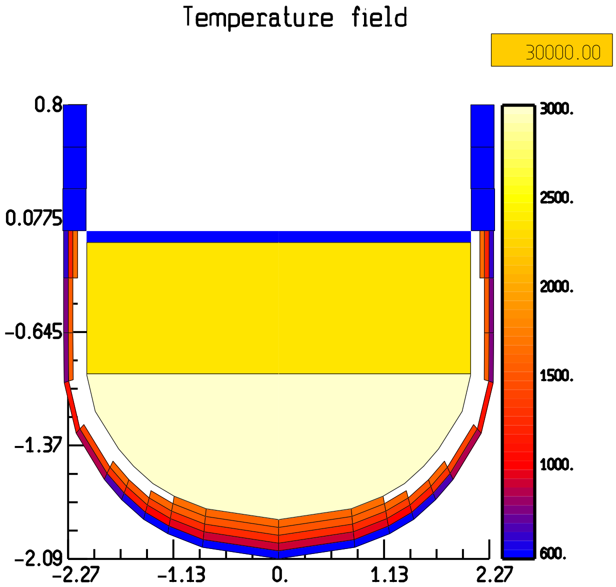

Figure 8. Temperature field at 30000 s.

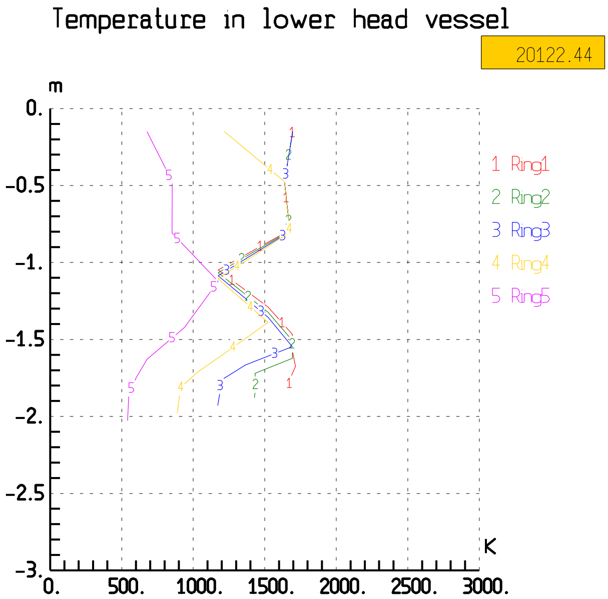

Figure 7. Rings temperature diagram at 20122 s.

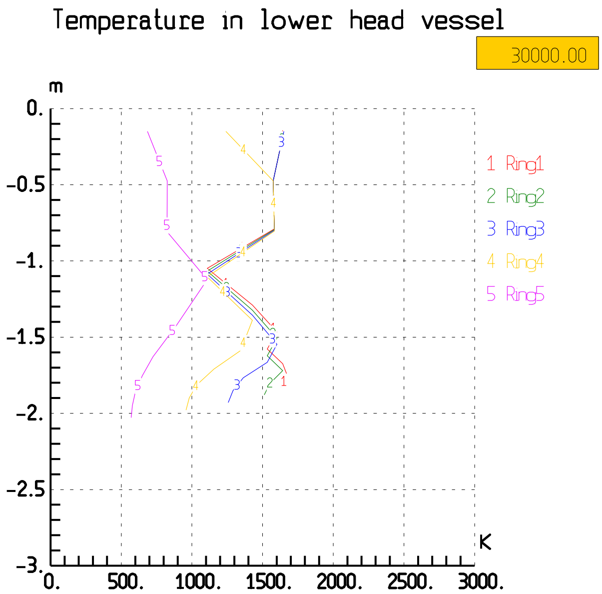

Figure 9. Temperature field at 30000 s.

The internal and external heat fluxes distribution in height (for the segments from 1 to 10) is presented in Figures 10 and 11. Heat fluxes correspond to the inner surface of the internal lower head vessel meshes. The meshes were considered as being in contact with the pool. Once the mesh melts, it disappears and the heat flux corresponds then to that of the neighboring mesh from the respective segment. As was explained above, the lower head vessel was axially divided in 10 segments: 7 in the elliptical part and 3 in the cylindrical part of lower head (see Figure 1). Each segment is divided in 5 rings called meshes.

In Figure 10 the heat fluxes (HF) from the vessel external surfaces to the water between two elevations are given. These correspond to the heat fluxes from the outer surface of the external lower head vessel meshes. They indicate notably higher outward heat fluxes to the water at segment 7 (elevations from -1.15 m to -0.92 m). The maximal value of 0.9 MW/m^2 has been accounted at approximately 20300 s.

The heat fluxes are determined for each internal mesh by the equation:

$$\varphi = P_{\text{exchange}}/S_{\text{int\_mesh}},$$

where:

- P_{exchange} (W) represents the power exchanged on the internal face of the mesh;
- $S_{\text{int\_mesh}}$ is the internal surface of the mesh in contact with the pool.

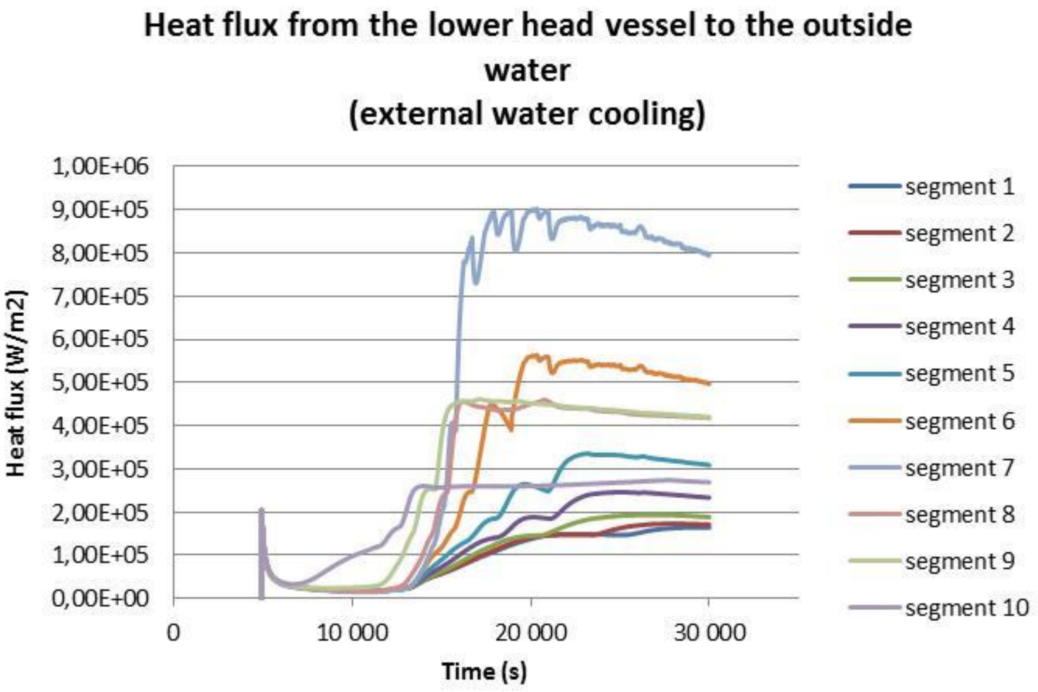

Figure 10. External heat flux distribution (ASTECv2.1.0.3 calculation.

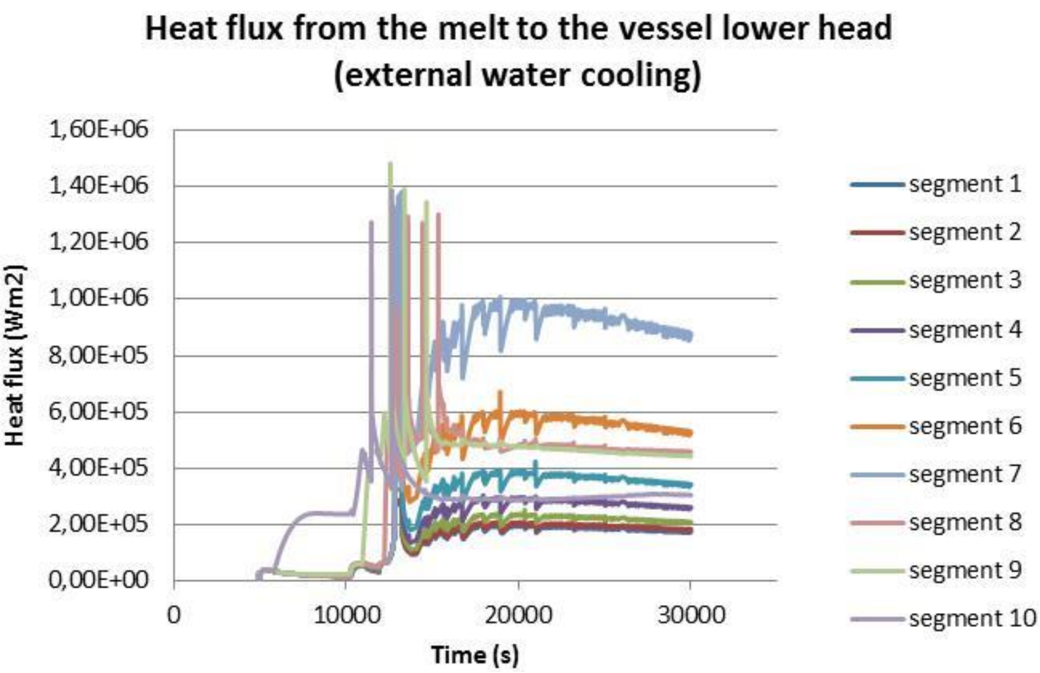

Figure 11. Internal heat flux distribution (ASTECv2.1.0.3 calculation).

Figure 11 presents heat fluxes from the melt pool to the lower head vessel internal surfaces in height. The maximal heat flux of 1.48 MW/m^2 has been accounted at 12552 s (segment 9) between elevation -0.65 m and -0.30 m.

The bounding curves of maximal heat fluxes registered at each point and each elevation are presented in Figure 12. The maximal values for each segment define these bounding curves. The maximum HF axial profiles are given looking at each external and internal point during the whole time at all elevations.

Looking at Figures 10 and 11, we can determine the maximal HF values for each internal and external segmental surface of the lower head vessel. Figure 12 presents the HF maximal values obtained from the curves in Figures 10 and 11.

Looking at Figure 12, we ascertained that the absolute heat flux maximum of 1.48 MW/m^2 happens at segment 9 (12552 s) and corresponds to the area between elevations -0.65 m and -0.30 m. This is the maximal heat flux given looking at each external and internal point during the whole time at all elevations and corresponds to the most difficult situation.

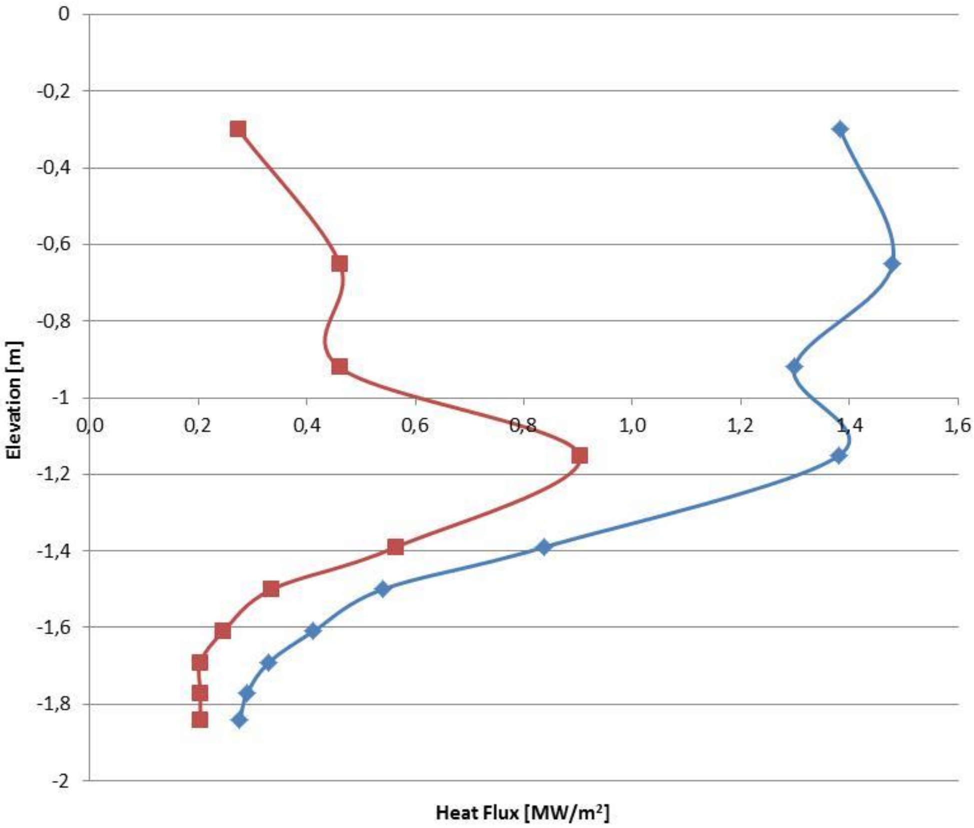

Figure 12. Bounding curves of maximal heat fluxes.

5 Conclusion

The calculation shows that the IVMR strategy with external water cooling could be a successful strategy for mitigation of a severe accident in VVER-1000 reactor types. This means that under certain conditions the vessel of VVER-1000/v320 could be saved from failure using the outside water cooling. In the calculation the heat flux from the vessel wall to the water outside obviously exceeds the heat flux from the melted pool to the vessel wall.

The results considered in this paper have identified the most demanding points for the heat fluxes for the VVER-1000/v320 reactor design. The highest detected value of the heat fluxes of 1.48 MW/m^2 occurs at segment 9 (between elevations -0.65 m and -0.30 m) at 12552 s.

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