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Investigation of IVMR Strategy with External Vessel Water Cooling in VVER1000 Reactor Type with ASTECv2.1.1.0 Computer Code

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Abstract. It is investigated the applicability of In-Vessel Melt Retention (IVMR) strategy with external vessel water cooling for the VVER-1000 reactor type. The investigation concerns a calculation made with ICARE and CESAR module of ASTECv2.1.1.0 computer code. ASTEC computer code was developed by IRSN (France) and GRS (Germany) to be a European computational tool for simulation of severe accidents in the different reactor designs.

The selected reference nuclear power plant for this analysis is Units 5 and 6 of the Kozloduy NPP equipped with VVER-1000 reactor. This type of reactor is a pressurized water reactor with 3000 MW thermal power and 1000 MW electric power. A LB-LOCA (double ended guillotine break of the cold leg: 2×850 mm) simultaneously with SBO at VVER-1000 reactor design was the postulated SA transient chosen as the most challenging for this type of reactor.

The purpose of this calculation is to compute a realistic heat flux profile on the inner side of the vessel and from the vessel to the external water. The periods of maximal heat input from the corium to the vessel steel wall were also accounted.

Keywords: In-Vessel Melt Retention, Severe accident, VVER-1000, ASTEC v2.1.1.0 computer code.

1 Introduction

This work discusses the progress in the development of an ASTEC computational model for investigation of molten corium pool behaviour in the lower head of a VVER-1000 reactor in case of a hypothetical accident with core degradation. The analysis is performed in support to the numerical investigations realized within the frames of the EU HORIZON2020 IVMR project (grant agreement number 662157).

This study aims to investigate some aspects related to the implementation of an IVMR strategy for VVER1000 reactor type [1]. ASTEC computer code [2–4], which was developed by IRSN and GRS, has been used in this investigation as a computational tool for severe accident simulation. The applied IVMR strategy is with external water vessel bottom cooling with temperature 60°C. It is a continuation of the previous investigations made with ASTECv2.1.0.3 [5] in the frame of the IVMR project where the in-vessel phase of a severe accident after the LB LOCA with double ended guillotine break on the cold leg simultaneously with SBO is the initiated event [6,7]. The passive systems (forth Hydro-accumulators) are not available at that time. This is the most challenging scenario because the accident progresses very fast from core coolant depletion, core overheating and melting to molten pool formation at the bottom of the vessel.

The calculation presented hereafter describe processes after a great amount of molten corium that consists of core fuel and melted in-vessel structures is poured in the reactor vessel bottom head. It happens when the core barrel is destroyed and melt-through. The previous integral calculations done with previous versions of ASTEC computer code show that core barrel failure appears at 4910 s during the transient time. After that time 188.44 tons corium with temperature 2500 K pours in the vessel bottom head. There are no water and internals modelled in the calculations. The constituent parts of the corium are UO_2, ZrO_2, Zr and Stainless Steel. The masses of the corium components are accounted from the previous ASTEC calculations. The changes in the decay heat during the calculation time also are taken from these previous calculations. For more realistic investigation the table of the decay heat power was reduced by 20% (fission products power). The elliptical part of the vessel is realistically modelled as in the VVER1000 reactor sited in the Kozloduy NPP. It is used CESAR and ICARE modules [8] of the new version of ASTECv2.1.1.0 to simulate the processes after corium pouring in the reactor vessel bottom head.

2 The ASTECv2.1.1.0 VVER-1000 Input Model

The new ASTEC model is prepared in accordance with the requirements of the new version of ASTECv2.1.1.0. For this type of investigation CESAR and ICARE modules work in a coupled mode to represent in-vessel events phenomenology. CESAR models the thermo-hydraulics in the only modelled channel in the reactor vessel (CHAN1). The channel is modelled without water ($x_{\text{alpha}} = 1.0$) and without internals. The initial water level is assumed to be zero ($z_{\text{wat 1}} = 0.0$). ICARE module computes the thermochemical phase separation and stratification of the pool and the melting of the vessel lower head. The model nodalization scheme used in the calculation is shown in Figure 1.

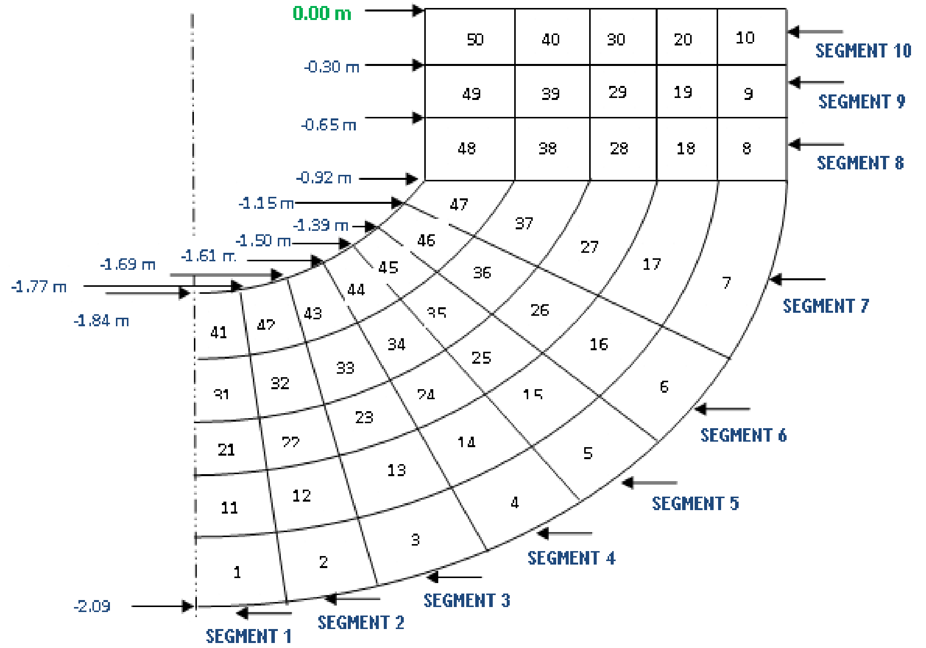

Figure 1. Segmentation of the vessel lower head for the ASTECv2.1.1.0 code modelling (elliptical section: segments 1-7, cylindrical section: segments 8-10).

Table 1. Initial masses of the main corium components

Material	Mass, t	Source
UO_2	85.9	CORE
Zr	15.6	CORE
ZrO_2	17.1	CORE
	34.4	CORE
	12.2	elliptic part of barrel
Steel	9.0	melted cylindrical part of barrel
	12.3	FA-supports
	1.94	support grid

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

The calculations start at 4910 s that is the time of barrel melt-through. At that time the reactor pit is flooded by

Table 2. Decay heat

Time, s	Decay heat, W (per 1 kg of UO_2)	Time, s	Decay heat, W (per 1 kg of UO_2)
4910	373.44	50000	190.16
5000	371.04	60000	182.24
6000	350.00	70000	175.12
7000	333.28	80000	168.96
8000	319.12	90000	162.4
9000	307.52	100000	155.92
10000	297.28	200000	133.20
20000	240.08	300000	117.04
30000	215.12	400000	102.88
40000	200.40		

water with temperature 333 K (60°C). The pressure outside the vessel is assumed 1.5 bars. Certain presence of a homogeneous corium in the vessel bottom is assumed. The initial corium composition is shown in Table 1. During the calculation the corium stratified in two layers: heavier oxidic layer at the bottom and laughter metallic layer at the top. Stratification is ensure in the model by activation of phase separation model (SEPA_ACT = 1).

The decay heat parameter implemented in the model is presented in Table 2.

Thickness of the vessel is 25 cm. For the vessel rupture the 'MECHANIC' and 'FUSION' criteria have been used.

```
STRU RUPTURE
    CRIT 'FUSION'
    CRIT 'MECHANIC'
END
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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

3 Discussion of the Simulation Results

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

Figure 2 presents heat fluxes (HF) from the pool to the internal surface of the lower head vessel for each one of the segments. The internal heat fluxes are determined for each internal element (mesh) that is in contact with the molten pool. The equation that have been used is: $\varphi = P_{\text{exchange}}/S_{\text{int\_mesh}}$, where: P_{exchange} (W) represents the power exchanged on the internal face of the mesh but $S_{\text{int\_mesh}}$ is internal surface of the mesh in contact with the

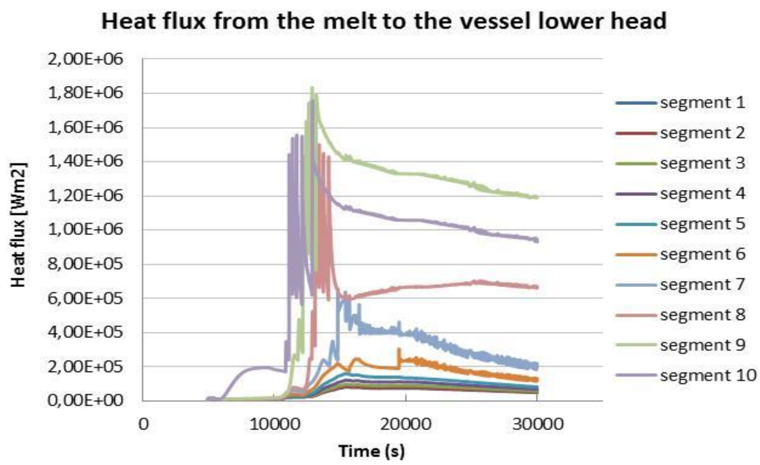

Figure 2. Internal heat flux distribution (ASTECv2.1.1.0 calculation).

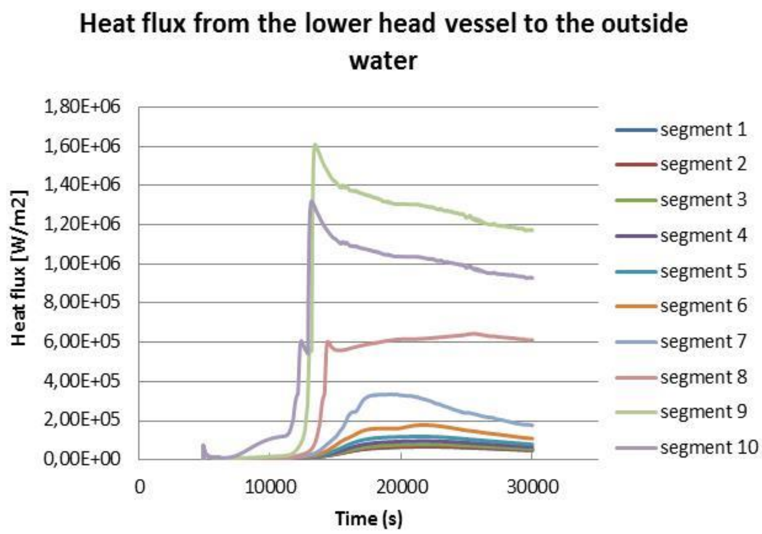

Figure 3. External heat flux distribution (ASTECv2.1.1.0 calculation).

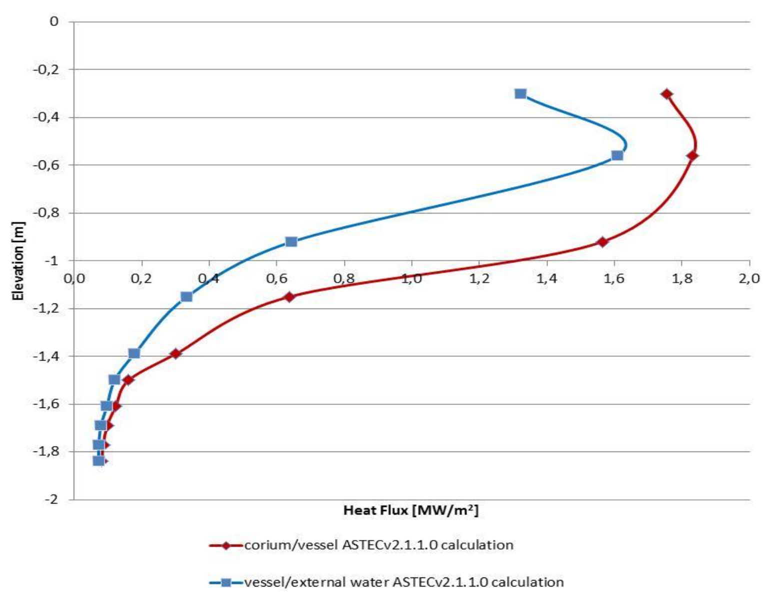

Figure 4. Bounding curves of maximal heat fluxes (ASTECv2.1.1.0 calculation).

molten pool. In the same way were calculated the heat fluxes from the vessel to the water for each one of the external surfaces of the segments. The maximal heat flux of 1.83 MW/m^2 has been accounted at 12890 s (segment 9) between elevations -0.65 m and -0.30 m.

In Figure 3 are given the heat fluxes (HF) from the vessel external surface to the water for each one of the segments. The external heat fluxes from the vessel to the water are calculated in the same way as the internal feat fluxes for each one of the external surfaces of the meshes from 1 to 10. The curves indicate higher heat flux to the water at segment 9. The maximal value of 1.61 MW/m^2 has been accounted at approximately 13400 s.

In Figure 4 are presented the curves of maximal internal and external heat fluxes registered for each one of the segments (from 1 to 10) during the calculations. The maximal HF for each segment defines these bounding curves. The maximal HF axial profiles are given looking at each external and internal point during the whole time at all elevations.

4 Conclusion

The calculation prolongs till 30000 sec. The results show that the vessel bottom head failure doesn't occur till the end of the calculation. This indicates that the IVMR strategy with external water vessel cooling could be a successful strategy to prevent vessel failure and corium relies in the containment. Nevertheless that the calculations indicate some differences in the heat flux values there are similar results for the HF axial distribution. The maximal values of the internal (1.83 MW/m^2) and the external (1.61 MW/m^2) heat fluxes are reached at segment 9 at the time interval approximately from 12890 s to 13400 s.

Acknowledgements

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