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MELCOR Simulations of the SBO in Gen III PWR with EVMR

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ABSTRACT

The paper presents simulations of a Station Blackout accident in a large generic PWR reactor with Ex-Vessel Melt Retention (EVMR) strategy. The nuclear power plant is equipped with core melt stabilisation device (core-catcher), which plays an essential role in its severe accident mitigation strategy. The plant model and simulations were prepared with the MELCOR 2.2.9541 computer code for in-vessel and ex-vessel phases. The analysis covered thermal-hydraulics, core degradation, MCCI and containment response. Conclusions were found about the core catcher modelling with MELCOR. It was found that the current LHC model cannot be directly used to assess the core catcher performance for the studied design. The mixed corium was studied for old and new (SOARCA based) MELCOR default setup and four parametric cases. It was observed that the corium conductivity multipliers have an impact on the assessment of the core catcher and containment response.

1 INTRODUCTION

In the case of a Pressurized Water Reactor (PWR) with a capacity higher than 1000 MWe, it cannot be guaranteed that it is possible to efficiently utilise In-Vessel Melt Retention (IVMR) strategy during a hypothetical severe accident. In consequence, Ex-Vessel Melt Retention (EVMR) can be adopted to mitigate consequences of a meltdown [1], [2].

This paper reports the MELCOR 2.2 model of a high power PWR reactor and simulations of in-vessel and ex-vessel phases of a Station Blackout (SBO) with no power recovery. The scenario was selected as it is one of the essential sequences considered in PSA studies [1], [3], [4].

A studied plant is a generic four-loop unit considered to be a representative for the Generation III European NPP fleet. It was defined and is being developed in the framework of the NARSIS (New Approach to Reactor Safety Improvements) H2020 research project [5], [6]. The primary motivation of this work was to develop and test the full-plant model to be used in further studies. The second motivation was to evaluate MELCOR's EVMR simulation capabilities.

2 MELCOR MODEL

Figure 1(L) presents RPV nodalization for thermal-hydraulics (CVH) package, core modelling (COR) package and heat structures package (HS). The COR model has nineteen axial levels and six rings, and it is connected with five control volumes, one per ring and additional bypass volume. The RPV has single downcomer, lower plenum, upper plenum and upper head volumes. Reactor Coolant System (RCS) has two loops, one is a single loop with pressurizer, and the second is a combination of three other loops (Figure 1(R)).

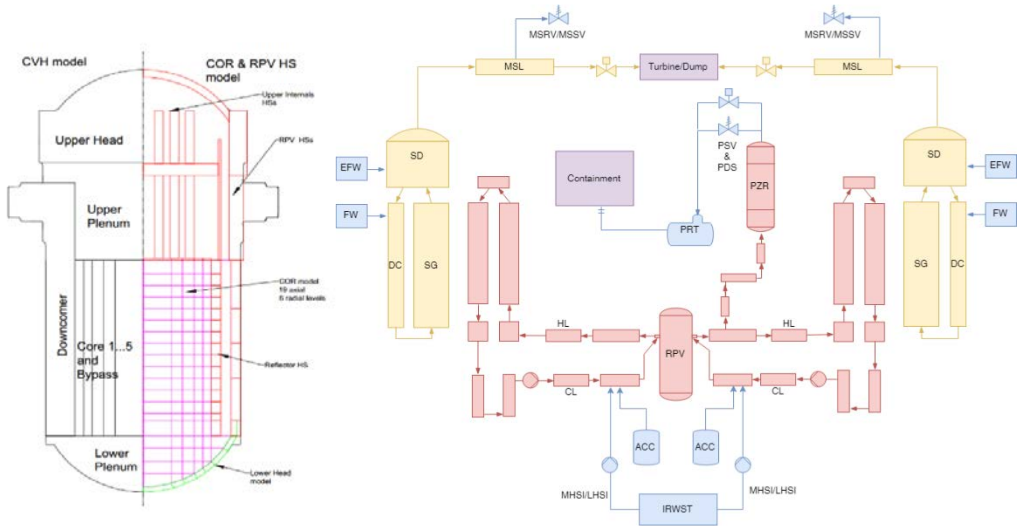

Figure 1: Left - RPV and core nodalization for CVH and COR, HS package. Right - Reactor Coolant System nodalization.

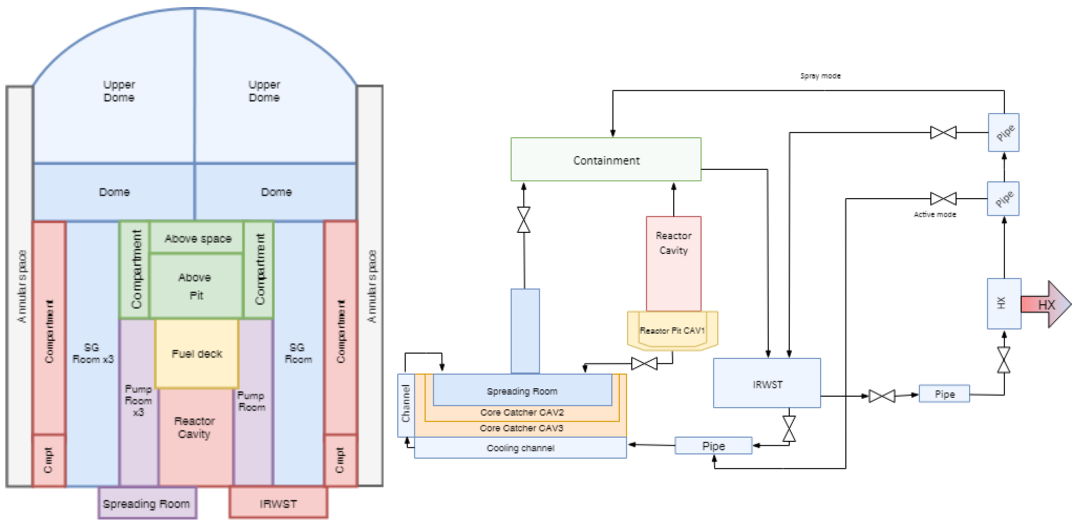

Figure 2: Left - Containment nodalization. Right – Containment heat removal system.

The model of the large dry containment with ~80000m^3 volume is presented in Figure 2(L). It is composed of 24 CVs, ~100 HS and ~50 Passive Autocatalytic Recombiners (PARs).

The model allows simulating passive and active corium cooling with core catcher, containment spraying system and heat exchangers (Figure 3(R)). For both operation modes, water is transferred from the IRWST tank.

Containment has three cavities (CAV package) dedicated to model ex-vessel corium phenomena. The first is the reactor pit made of concrete which has melt-plug with ~0.5m thickness. After plug failure corium is transferred by TP functions to the second cavity, which is made of a sacrificial concrete and simulates core catcher device, it is ~10 cm thick. The third cavity is dedicated to arresting melt after sacrificial concrete erosion, and its ablation functionality is turned off. Otherwise, only the heat transfer between the top of the corium surface and spreading room CV is simulated. Due to the nature of the CAV package, there is no possibility to recover heat from the bottom of a cavity model using a standard modelling approach. In consequence, cooling channels below the core catcher plate are not able to remove heat, and they work only as a coolant transferring volumes. Developments are in progress to propose a solution with control functions.

An attempt was made to prepare the core catcher model with new MELCOR LHC (Lower Head Containment) package [7], [8]. The studied plant, under the RPV, has a concrete pit and it demands MCCI modelling. The MELCOR code allows transferring fuel debris from COR to the LHC and then to the CAV package. Unfortunately, according to the code's manual [7], [8], it is not allowed to transfer material from COR to CAV and then to LHC package. Hence, it was impossible to simulate corium interaction with core catcher's metal plate using LHC package. The first idea to resolve this problem was to use the LHC package stand-alone mode with initial and boundary conditions given by plant simulations. This approach was tested, but the LHC package can accept only eight materials for initial melt: AL2O3, SSOX, UO2, ZRO2, AL, SS, U and ZR. Unfortunately, no concrete type materials are allowed, and reliable simulations are not directly possible. In consequence, results are not reported here.

As it is a preliminary study, only six cases were calculated (see Table 1) with different modelling options for CAV package. The first case (#1) is based on the older M2.1 default setup [8], case #2 is based on SOARCA best practices – new M2.2 defaults [9]. Four cases are based on SOARCA with modified oxide/metal conductivites in core catcher. All cases were calculated with enforced mixing (ENFOR) with debris forming a single layer.

Table 1: CAV modelling options varied in parametric calculations. All parameters are in CAVnnaak (CAV_U) MELCOR field. All simulations with default CORCON-Mod3. For cases #3-#6, multipliers were modified only for core catcher CAVities.

Parameter	Variable	Base Case#1 Old Defaults	Case#2 New Defaults	Case#3	Case#4	Case#5	Case#6
CAV package emissivity of oxide/metallic/surrounding	EMISS.OX EMISS.MET EMISS.SUR	0.6/0.6/0.6	0.9/0.9/0.9				
Multipliers for surface boiling heat transfer and oxide/metallic thermal conductivity	BOILING COND.OX COND.MET	1.0 1.0 1.0	10.0 5.0 5.0	10.0 10.0 10.0	10.0 50.0 50.0	10.0 100.0 100.0	10.0 200.0 200.0
Mixing between metallic and oxidic components of the debris	MIXING	ENFOR, enforce mixing (all debris forms a single mixed layer)					

3 SCENARIO AND ASSUMPTIONS

Acceptable and stable steady-state conditions were obtained a priori to the accident, and they were in agreement with plant definition. Steady-state covered full power operation for ~1200 seconds before the event with accelerated steady-state option. The initiating event (IE) is a loss of offsite power (LOOP). The MSIV closure, pump coast-down and reactor SCRAM are activated immediately. It is assumed that all emergency diesel generators and SBO dedicated diesels are not available due to combined failure. Main feed water and Emergency Feedwater system are not operational. Accumulators are available, and there is no activation of low-head and high-head safety injections. Moreover, it is assumed that there are no creep induced ruptures during the event, and there are no seal-LOCA type events.

4 RESULTS AND DISCUSSION

Results presented in this section are for base case #1, results for cases #2-#6 are presented for selected parameters for which relevant differences were observed. Figure 3(L) depicts water inventory in the RCS and SGs. The bleed of steam generators with SG relief valves allows delaying accident progression for ~2h. Later, due to the lack of water makeup, SGs are emptied, and RCS heat transfer to the secondary side is lost. Figure 3(R) shows pressures in the RPV and SGs. Two hours after IE, pressurizer safety valves start cycling and dumping steam to the relief tank (PRT). In the time-frame of minutes, PRT diaphragm ruptures and steam is released to the containment (Figure 4(R)). After about 3.5h RCS depressurisation procedure starts when core exit temperature reaches 650°C as core heat-up is progressing (Figure 4(L)). During depressurisation accumulators pressure set-point, ~4bar, is reached, and flooding is initiated, (Figure 3). The core is covered with water, and it leads to the fuel temperature (Figure 4(L)) decrease and delays progression for ~1h.

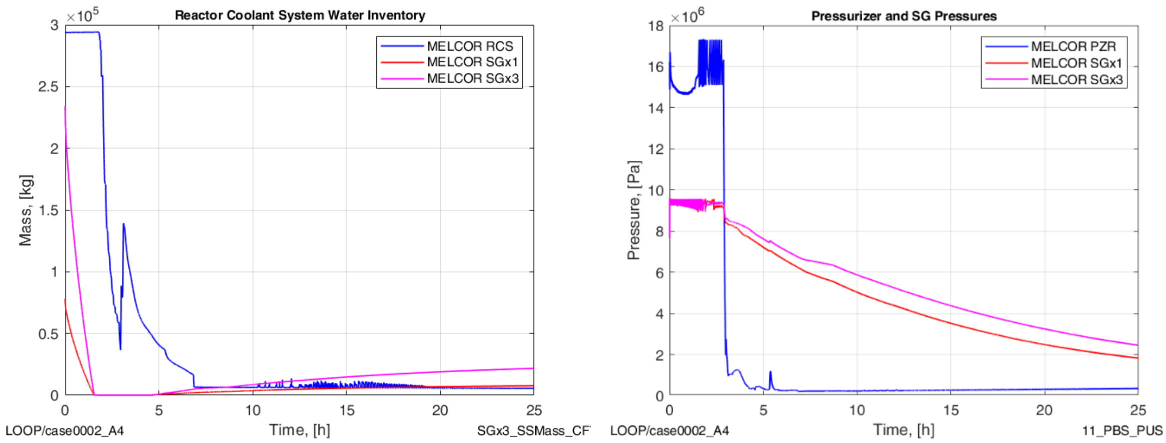

Figure 3: Left – RCS and SGs water inventory. Right – PZR and SGs pressures.

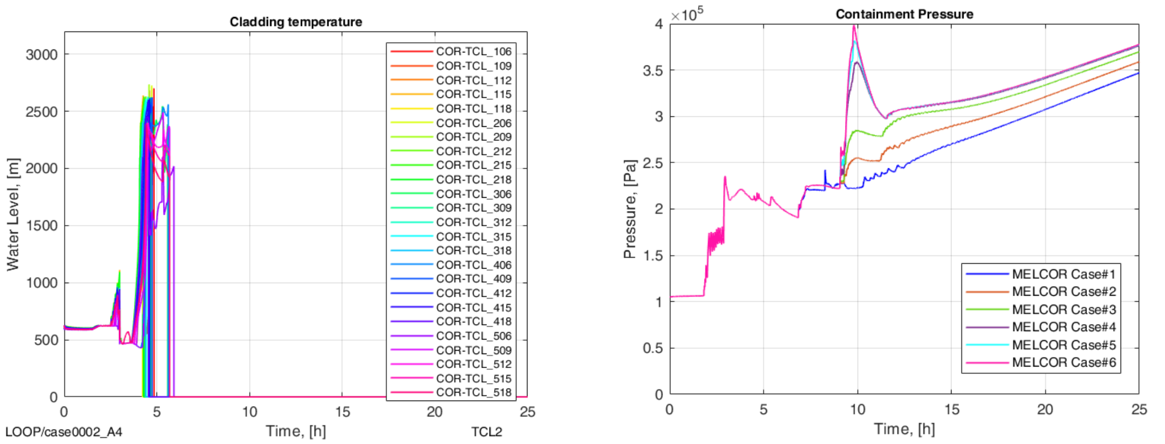

Figure 4: Left – Cladding temperature in the central part of the core. Right – Containment pressure. Case #1-#6, conductivity 1.0,5.0,10.0,50.0, 100.0, 200.0, respectively.

Decay heat vaporises water (Figure 3(L)), and the core is slowly uncovering. In consequence, fuel temperature increases (Figure 4(L)). It leads to the intensive exothermic cladding oxidation (Figure 6) and enhances the core degradation process (Figure 5). During the in-vessel phase of the accident, ~570 kg of H2 is produced (Figure 6) and released to the containment through the PRT tank. Passive recombiners are activated and consume hydrogen (see Figure 6(L)).

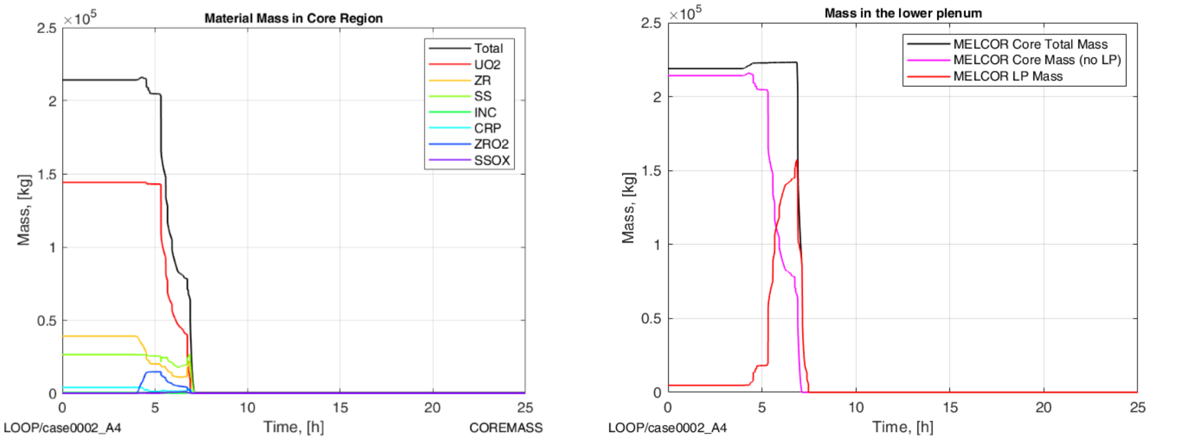

Figure 5: Left – Masses in the core region. Right – Total mass in the core and LP.

Core debris is relocated gradually to the lower support plate and partly to the lower plenum. After ~6h massive core plate failure occurs, transferring a large portion of the debris mass to the lower plenum (Figure 5). The lower head attack is initiated, and ~7h after the scenario initiation, a rupture occurs ejecting mass to the reactor pit (Figure 6(R)).

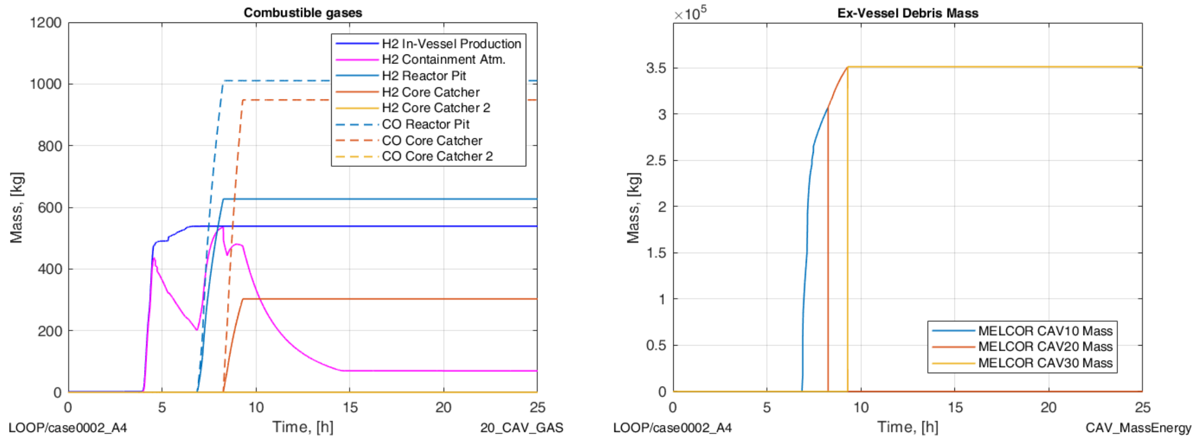

Figure 6: Left – Combustible gases. Right – Ex-vessel corium mass. CAV10 – reactor pit, CAV20,30 – core catcher.

In the reactor pit, MCCI reactions take place, releasing additional H2 and CO to the containment (Figure 6(L)) and causing a slight pressure increase (Figure 4(R)). After ~8.5h corium consumes melt plug (Figure 7(L)), and mass is transferred to the spreading room. After ten minutes, the passive corium flooding starts and about 500 tons of water are transferred from the IRWST tank (Figure 8(L)). The containment pressure quenching peak due to vaporisation was observed for cases #2-#6 with enhanced corium heat transfer (Figure 4(R)). The peak value increases with the increase of the corium conductivity values. In the case of base case MELCOR setup, there was no peak.

Molten corium consumes sacrificial concrete in ~1h (Figure 6 and Figure 7(R)) producing additional H2 and CO. No substantial difference was observed for case #1 and case #2 for ex-vessel hydrogen production. Later, the third cavity is activated, and in this simulation, ablation is assumed to stop. Corium mass settles (Figure 6(R)) on the metal plate and is being cooled by convection, conduction and steaming phenomena. Flooded corium, in the long term, leads to the water vaporisation, and containment pressure increase (Figure 4(R)). In the considered period (25h) the maximum pressure is ~3.5bar, and it is substantially below ultimate containment strength. With no active cooling and no venting, the containment will fail in the time frame of days. The total ex-vessel hydrogen and carbon oxide production is presented in Figure 6(L); the significant deflagration events with substantial pressure peaks were not predicted by MELCOR. The produced non-condensable gases H2, CO, CO2 are influencing the containment pressure, but the steam is the most essential for pressure build-up.

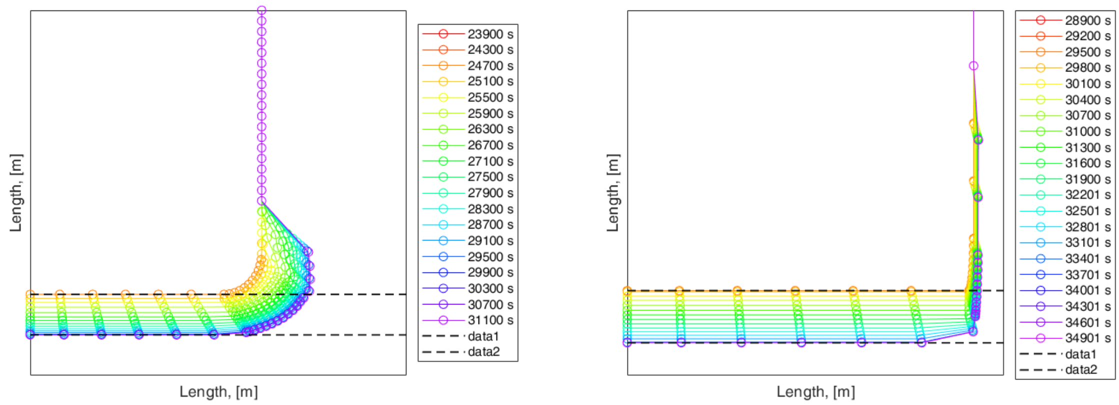

Figure 7: Case #1. Left – MCCI history for reactor pit. Right – MCCI history for CC.

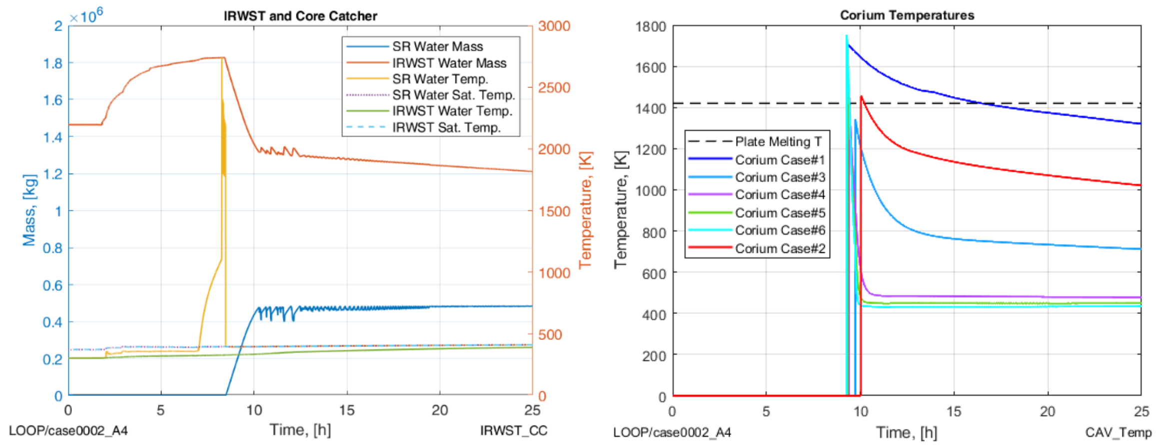

Figure 8: Left – IRWST and CC water inventory and temperatures (case #1). Right – mixed corium temperature after sacrificial concrete failure for cases #1-#6. CC- Core Catcher, SR – Spreading Room.

The plate has a melting temperature of ~1420K. The best-estimate (new MELCOR defaults), case #2, corium-concrete mixture temperature has ~1450K at the moment of corium transfer to the core catcher. It is rapidly cooled below plate melting temperature. The same issue is for cases #3-#6 with the rate of cooling increasing with conductivity. It is worth to mention that in cases #2-#6, corium temperature is well below the estimated solidus temperature for the corium mixture. What is important, MELCOR predicts efficient corium cooldown even without modelling of a bottom cooling mechanism. In the case of old defaults (Case#1), corium temperature is ~1750K, and it takes ~6h for average temperature to be below plate melting point and it may potentially pose a risk to the plate. In principle, in all cases it is speculative to conclude about the plate survivability. We can recommend the simulations of the plate-corium interactions for future studies.

Nevertheless, these cases directly show the role of corium heat transfer modelling. Worth to mention that similar conclusions were drawn by Gauntt et al. [10]. They argued that for flooded corium in a cavity, heat transfer enhancement is expected as (old) default setup assumes that the crust is impenetrable.

5 CONCLUSIONS

The simulations of the SBO accident without power recovery for large PWR with Ex-Vessel Melt Retention were presented. The main phenomena were described, including the core degradation, RCS, MCCI and containment responses during the in-vessel and ex-vessel phases. Simulations show that during the considered 25 hours period after the accident initiation, there is a small risk of the containment breach, thanks to the corium arrest, hydrogen removal by PARs and RCS depressurisation. In the case of no power recovery or no alternative water injections, the containment is expected to pressurise up to the point of the containment breach in several days.

The corium-water interaction, especially metal and oxide conductivity multipliers and boiling multiplier for heat transfer modelling in the spreading room have a substantial impact on results of core catcher operation. It is impossible to assess core catcher's plate survivability with current MELCOR LHC model. It shows that the reactor pit and sacrificial material allow corium to reach properties which are close to the state with an average temperature below plate melting temperature. In the case of CORCON default setup (MELCOR2.1 default), the mixed corium temperature is larger than the plate melting point for a long-time period, and it poses a risk for it. Otherwise, it is considered to be more conservative result. For the SOARCA SNL recommendations (new MELCOR 2.2 defaults) mixed temperature is higher than melting for very short time and corium cooling is very efficient. What is essential, model does not take into account fact that the considered design provides cooling of the plate. Hence, the presented calculations have an additional level of conservatism. In consequence, it is likely that the top surface of the plate has temperature substantially lower than melting and its survival is probable.

Finally, it can be concluded that for the studied design, MELCOR 2.2 with (new) default setup for MCCI modelling, predicts corium arrest even without bottom cooling and core catcher device fulfil its role.

Worth to mention that the presented NPP model developments are ongoing. Authors are convinced that the developed containment model demands improvements as the containment pressure are believed to be underpredicted. The model uses the RN package and predicts source term, but it was note reported in this paper.

Further research will aim to resolve the issue of the core catcher modelling after ablation of the sacrificial concrete and will aim to assess metallic plate survivability. It will be fascinating to perform sensitivity and uncertainty analysis to study the response of this device.

In the frame of the NARSIS project, it is planned to implement ageing effects for different components. Alternative scenarios will be considered to take into account seal-LOCA, surge line break, loss of ultimate heat sink and other scenarios. Source term will be assessed. Comparison with representative Gen II PWR, uncertainty and sensitivity studies are also envisioned to be performed.

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