Analysis of severe accident scenarios in the primary circuit of a generic pressurized water reactor in the frame of plant calculations for evaluating the program system AC²

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ABSTRACT

Within the framework of the EU research project "AMHYCO", PSS performs plant calculations for the investigation of relevant in- and ex-vessel phenomena during postulated severe accidents with the program system AC² 2019.1 developed by GRS gGmbH. The calculations are carried out using a data set based on a generic 1,300 MW_{el} pressurized water reactor (PWR). The presented investigations include simulations of a small break loss-of-coolant accident (SBLOCA) and a station blackout (SBO) scenario with limited availability of primary-side safety systems which will then be used for comparative assessment with literature data for plausibility check. The focus of the comparison of these two scenarios is on the analysis of the general accident progression in the primary circuit from core degradation until reactor pressure vessel (RPV) failure. To evaluate the results, the scenarios are compared to similar simulations from the open literature, showing a good accordance with plausible differences in the hydrogen production.

INTRODUCTION

During normal power plant operation, the release of radioactive fission products to the environment is prevented by four barriers: the crystal grid of the ceramic fuel pellets, the metallic fuel rod cladding tubes, the pressurized cooling circuit and the containment [1]. In case of severe accidents (SA), the cooling system is compromised, which endangers the barriers. In both postulated scenarios, an SBO and SBLOCA, considered in this work, due to a loss of cooling inventory, the core gets uncovered which accelerates the successive core heat up. At cladding temperatures above 1,300 K in a steam atmosphere, the Zircaloy fuel claddings start to oxidize in an exothermic reaction which releases hydrogen. In addition to the Zircaloy, oxidation of further materials such as B_4C contribute to the hydrogen release [2; 3]. In this study, simulations of a SBLOCA with limited safety system operation and a SBO with primary side depressurization are conducted using the program system AC². Both postulated sequences lead to heat up of the fuel rods, core uncovery and core melt down with following RPV failure. After PRV failure, only the last barrier, the containment, remains intact before releasing fission products to the environment. The containment integrity can be jeopardized by possible ignition of combustible gases. These are e.g. H_2 which is produced during oxidation in the in-vessel phase as well as H_2 and CO in ex-vessel phase by molten corium-concrete interaction after corium discharge from the RPV [4]. To estimate the potential risk, the focus lies on in-vessel hydrogen production and corium discharge.

MODELING

To simulate the thermohydraulic processes as well as the phenomena related to core degradation, the primary and secondary coolant system sides are modeled using AC² ATHLET-CD 3.2. In Figure 1 the nodalization of the primary and secondary coolant system sides as well as the core build-up are shown. The generic 1,300 MW_{el} PWR is represented by four-loops, which are modeled by one single weighted loop connected to the pressurizer and a triple weighted loop.

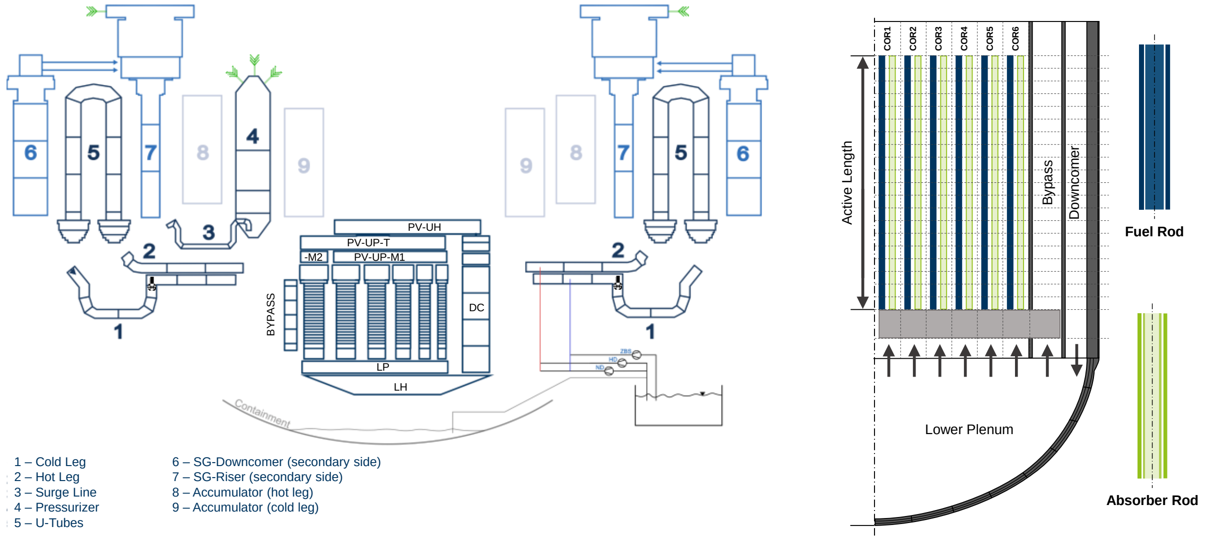

Figure 1: Primary and Secondary Circuit Nodalization (left) and Core Build-Up (right)

Inside the RPV, the core region is divided in eight radial sections, six core channels, one bypass and the downcomer. Each core channel is subdivided into 20 axial sections. In total the modeled core represents 57,900 fuel rods, consisting of UO_2-pellets and Zry-4 tubes and 1,465 control rods. In this data set, fission products are not calculated directly but taken into account by the calculated decay heat after SCRAM. During core degradation, the molten material is continuously transferred to the lower plenum. To simulate the relocated molten material behavior, the late phase module AIDA is activated. AIDA allows to calculate the thermal behavior of the corium pool, the heat transfer through the crust and RPV wall as well as the wall damage and failure. Out of four available failure models for RPV failure, the wall-ablation model is used (IDAM=1). Regarding the RPV wall integrity, the used model considers thermal and mechanical loads such as the temperature, pressure difference, remaining wall thickness, tangential/tensile stress and corium mass inside the lower plenum.

In the postulated station blackout (SBO), the failure of the electric grid, house load operation, station emergency diesel and bunkered diverse diesel is postulated. The availability of the station batteries is credited. The SBO leads to an immediate reactor SCRAM. As a consequence of the loss of power, the active injection systems including the sump recirculation are not available. The steam generator feedwater pumps are shut down, leading to a dry out of the steam generators. Following the core heat up and the rising primary pressure, steam will be released to the pressurizer relief tank through the pressurizer safety relief valve when exceeding 166 bar-abs (absolute pressure) inside the RPV. After failure of the rupture discs in the pressurizer relief tank, primary coolant is released into the containment. The safety relief valve is the one of three emergency valves with the lowest opening pressure setpoint. The valve opens and closes alternately between 166 and 160 bar-abs to limit the primary pressure. The accumulators passively inject their inventory after fulfilling the modeled emergency core cooling preparation signal (ECC signal) and at a primary pressure below 26 bar-abs. The signal takes into account a primary pressure less than 110 bar-abs, a pressure difference of 30 mbar-g (relative pressure) to the containment atmosphere and a pressurizer water level lower than 2.28 m. It is activated if two of three conditions are fulfilled. Within 500 s after reaching the ECC signal the cold side accumulators are disconnected from the primary circuit to prevent nitrogen intrusion. As a severe accident management measure, the primary side depressurization (PSD) is manually activated after reaching a core outlet temperature of 650 °C. After that, all three safety valves open permanently, causing a rapid drop of primary pressure.

The second scenario is a postulated SBLOCA with an 80 cm² leakage. The rupture is assumed to occur in the cold leg behind the main coolant pump (MCP). A failure of almost all active injection systems is postulated while preserving the total injection rate of 8 kg/s, using the extra borating system (EBS). The injection starts when the water level inside the pressurizer drops below 2.28 m. The regulation of the passive accumulator injection is identical to the SBLOCA scenario. As further pumps are postulated to fail, the sump recirculation is as well unavailable. On the secondary side the 100 K/h cool-down procedure via steam dump is activated, which is modeled by boundary conditions limited to a secondary pressure of ~3 bar-abs. In consequence of the cool-down procedure, the primary pressure follows the pressure decreasing.

RESULTS

In the following, both sequences are analyzed regarding the accident progression taking into account the most important events. The figures showed afterwards will highlight characteristic time points and results such as the mass of degraded core material and generated hydrogen. Both integrated masses will be compared to two different sources from the literature respectively, to assess these calculations. As only few publications in the field of 1,300 MW_{el} PWR plant calculations with similar boundary conditions and analysis focuses are available, the simulations and results are not identical. The varying boundary conditions moreover indicate the impact on the accident progression and thus provide a broad framework for the assessment of the results. Two of the comparison simulations are also conducted with previous AC² versions. Table 1 gives an overview on the main events and integral masses for both sequences. The values of the degraded core mass and generated H_2 are taken at 30,000 s, as afterwards no remarkable changes are noticeable. After RPV failure, the core degradation is significantly ongoing, having consequently a noticeable impact on the integral released masses to the containment.

Table 1: Characteristic In-Vessel Events and relevant Masses

	SBO	SBLOCA
SCRAM	0 s	3 s
ECC Signal	6,370 s	18 s
Start PSD	6,263 s	-
Start Accumulator Injection	6,635 s	1,747 s
Start safety injection	-	28 s
Start Core Degradation	10,909 s	19,180 s
Start Corium Relocation	12,223 s	20,663 s
RPV Failure	13,491 s	23,451 s
Degraded Core Mass	147 t	142 t
Generated H_2	617 kg	588 kg

For the SBO scenario, the initial event of total loss of AC power accompanied by reactor SCRAM starts at 0 s. In consequence to the failure of the main coolant pumps after SCRAM and the missing possibility to reduce the heat through the within approximately 2,800 s dried out steam generators, the core starts to heat up. 6,263 s after SCRAM, the core outlet temperature reaches 650 °C. At this setpoint, it is assumed that the PSD is remotely initiated by opening all three pressurizer safety valves. Contrary to regulatory requirements of an initiation at 400 °C, the 650 °C criterion is assumed to create a highly challenging scenario and on the other hand it is the highest temperature point at which a successful PSD, regarding inhibition of absorber rod meltdown, can be ensured [5]. With the ongoing core uncovery and accompanying rise of temperatures inside the vessel, the onset of H_2-release is at 10,909 s. The beginning oxidation of the cladding tubes approximately coincides with the rapid increase of the degraded material. In the following 1,300 s, 80 t of the core inventory are degraded and relocated to the lower plenum. After further 1,200 s the vessel wall fails due to temperature and weight stress.

The initiating event in the LOCA sequence is the opening of the leak at 0 s which initiates a rapid pressure drop from 158 bar-abs to 132 bar-abs within 3 s which leads to SCRAM. After further 15 s the

ECC signal is fulfilled by a pressurizer water level lower than 2.28 m and a containment pressure difference of 30 mbar-g. 1,747 s after break opening the primary pressure is decreased to 26 bar-abs. In this simulation only four of the eight accumulators inject their water inventory. The cold side accumulators are disconnected from the primary circuit 500 s after ECC signal (at 518 s). Even when half of the liquid accumulator inventory is retained, in both simulations the RPV is refilled due to a different initial water level at accumulator injection start. The safety injection via the EBS with an injection rate of 8 kg/s starts at 28 s when the pressurizer level is less than 2.28 m. In contrast to the SBO the oxidation and core degradation processes start in the SBLOCA sequence after 19,180 s. Within 1,500 s the corium relocates to the lower plenum resulting in the vessel wall ablation. At 23,451 s the vessel wall fails with 60 t of corium in the lower plenum.

The water level inside the RPV, depicted in Figure 2, lowers slower than in the SBO sequence. Regarding the SBO, after 2,250 s the primary pressure exceeds 166 bar-abs for the first time resulting in the opening of the pressurizer safety valve and steam gets released to the pressurizer relief tank. The loss of coolant results in the rapid lowering of the water level inside the RPV. The water level as well as the primary pressure drop significantly after PSD start because of the instant steam release. With reaching a primary pressure less than 26 bar-abs, the eight hydro accumulators inject their inventory.

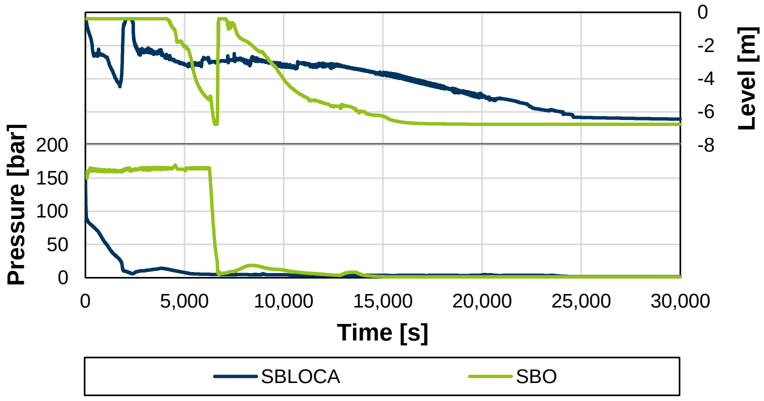

Figure 2: Water Level inside the RPV (top) and Primary Pressure (bottom)

To assess the validity of the simulations, for each sequence two similar cases from the open literature are used for comparison of the integral masses of degraded core material and produced hydrogen. The used simulations are performed with a generic 1,300 MW_{el} PWR Type KONVOI in order to provide comparability. As comparing data of alike SBO simulations with PSD the values from the references [1] and [5] are used. Reference [1] defines a comparable data set, simulated with ASTEC V2.1, the results in reference [5] are obtained with ATHLET-CD 3.0A. Both studies postulate a total loss of power and the non-availability of active injection systems. In contrast to the simulations conducted in this work, both references [1] and [5] set the PSD initiation criterion at a core outlet temperature of 400 °C.

For the postulated LOCA sequence one simulation from reference [1] and [6] is used for comparison respectively. For this sequence, the simulations to be compared have slightly differing boundary conditions. In Reference [1] a SBLOCA with a 20 cm² leakage in the cold leg is assumed and calculated with ASTEC V2.1. All active injection systems are supposed to be unavailable. The second simulation from reference [6], conducted with ATHLET-CD 3.0A, is a MBLOCA with a leak size of 200 cm² and the postulated failure of all active injection systems. The lack of the EBS reflooding in both simulations used for comparison result in a difference of 72 t of injected water, which needs to be considered during analyzing and evaluating the results.

In Figure 3 the degraded mass in the core and discharged corium to the containment for the SBLOCA and SBO are shown respectively. The integral mass of molten and thus degraded material at the time of RPV failure are given for the compared simulations. The time of RPV failure deviates from the reference cases, as LOCAs with different sizes have a deviating accident progression. Therefore, the integral masses in the figure are placed at the time of RPV failure of the reference case.

The degraded core mass of 95 t at RPV failure in the SBO reference case differ compared to 151 t in the SBO sequence of reference [1] but show good accordance with the reference [5] sequence, which led to 95 t degraded material. The higher mass in referencec [1] is attributed to the different accident progression. Overall, the values of degraded and relocated material are in a comparable range. A similar result applies to the postulated LOCA sequence in comparison with the literature. Both compared sequences of the references [1] and [6] exceed the reference case at the time of RPV failure ([1]: 145 t, [6]: 160 t). For this postulated sequence as well can be derived that the RPV failure occurs before the maximum integral value of degraded core mass is reached. However, after 30,000 s 142 t of corium have been transferred to the containment in the reference simulation. This leads to the assumption, that the deviating degraded masses in the reference simulation at RPV failure are mainly influenced by the AIDA failure criterion, as the SBO simulations from reference [1] and [5] both end with RPV failure at approximately 30,000 s in contrast to 13,492 s in the reference simulation. The deviating RPV failure times are possibly related to the different failure models in the used codes and code versions in [1; 5; 6]. Using the default criterion in ASTEC V2.1 [1], the rupture is calculated similar to the reference case. Thereby, the wall layers liquefy until failure. In [5, 6], the ASTOR method is used, where damage is accumulated linearly, depending on the ratio between the current time step length and a theoretical failure time. The comparison of the differences of a SA with differing boundary conditions shows the impact of the different assumptions. Nevertheless, the SBLOCA masses are lower than in the compared simulation which is possibly caused by the additionally assumed EBS which delays the core degradation.

In Figure 4 the produced hydrogen masses are compared. For the SBO sequence, the simulations of the references [1] and [5] calculate 745 kg and 705 kg H_2 respectively. Similar to the corium masses, the integral hydrogen mass at RPV failure is significantly lower than the comparative values. In consequence of the ongoing core degradation, the hydrogen mass rises to a total of 617 kg. In the LOCA sequences of the references [1] and [6], the range of values for hydrogen masses is simulated with 587 kg and 872 kg. The deviations could be caused by the varying leak size, as the accident progression differs regarding a 20 cm² and 200 cm² break which e.g. considerably prolongs the time until RPV rupture in the first case. Consequently the RPV in reference [1] fails after 54,000 s and in reference [6] after 21,000 s which in turn results in a good agreement with the H_2 mass of reference [6] and the reference case with 588 kg.

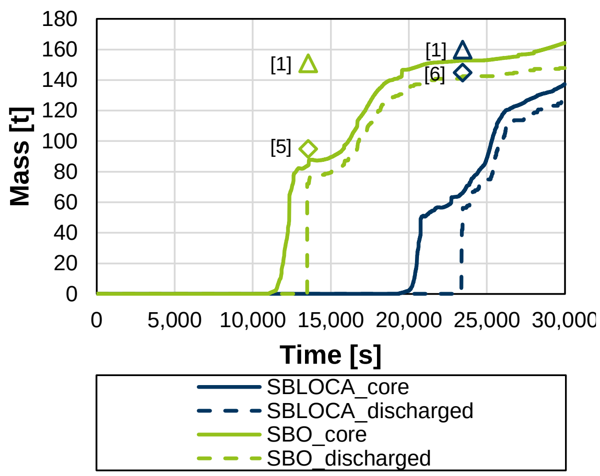

Figure 3: Molten Material in the RPV

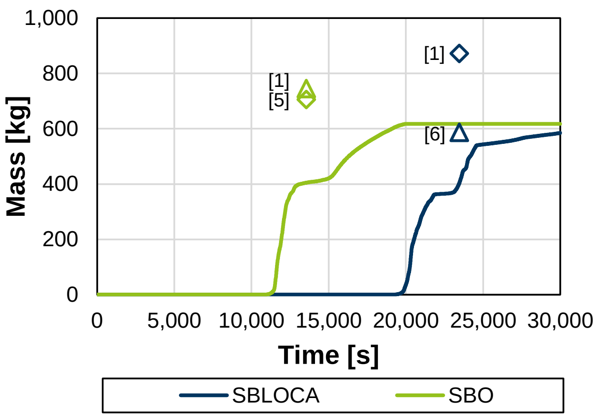

Figure 4: Generated Hydrogen Mass

CONCLUSION

The postulated accident sequences comprise on the one hand a LOCA with 80 cm² considering limited safety systems, which prolong the accident but lead to severe fuel damage as well as RPV rupture. On the other hand, a total loss of the electrical supply during a SBO with PSD. The results generated with the reference data set overall indicate a plausible accident progression for the selected SA sequence in comparison to the literature. The generated H_2 mass amounts to 617 kg in the SBO and 588 kg in the SBLOCA respectively, taken after 30,000 s. Regarding the literature comparison for the generated H_2

amount, there are differences especially in the ASTEC V2.1 simulation result [1]. Furthermore, the integral degraded mass for the SBO as well as the SBLOCA eventually amounts to approximately 140-150 t which corresponds to almost total core degradation. Each accident progression differs due to different boundary conditions but the values show good accordance to the simulations from the literature. However, uncertainties in the comparison should be considered, as there may be differences between the reference and literature values of the degraded core material and H_2 when e.g. modeling the RPV failure as well as the oxidation of the core or structural materials. The comparison of the results generated with the code version AC² 2019.1 show differences regarding the progression of the accumulated degraded material as well as the H_2 mass leading to different integral values in contrast to the literature values generated with ATHLET-CD 3.0A and ASTEC V2.1. The different hydrogen masses can possibly be attributed in part to a different course of the oxidation processes. Additional investigations are necessary to identify other influencing factors especially regarding the oxidation processes and parameters. Furthermore, the obtained results which are deemed plausible will be used in ex-vessel simulations to assess the potential combustion risk.

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