ANALYSIS OF PWR SEVERE ACCIDENT SEQUENCES INCLUDING MITIGATIVE MEASURES TO PREVENT OR DELAY THE FAILURE OF SAFETY BARRIERS WITH THE SEVERE ACCIDENT CODE ASTEC

V. H. SANCHEZ ESPINOZA
Karlsruhe Institute of Technology (KIT), Germany
Email: victor.sanchez@kit.edu

I. GÓMEZ-GARCÍA-TORAÑO
Karlsruhe Institute of Technology (KIT), Germany
Email: ignacio.torano@kit.edu

Abstract

After the Fukushima accident, several international research initiatives started to investigate all safety-relevant phenomena occurring during severe accidents. In this frame, a re-evaluation of the safety features of operating nuclear power plants was performed to identify the strengths /weaknesses of different designs. As a consequence, severe accident cooperative research was worldwide intensified and the Fukushima accidents are being evaluated. The obtained data will be of paramount importance for code validation. In Germany, the WASA-BOSS Project started in 2013 to evaluate the capability of severe accident codes for LWR-severe accidental sequences including accident management measures. Similarly, the European CESAM project that gathered many European research institutions has been launched to enhance the simulation capability of the European Reference Code ASTEC to simulate the behaviour of different plant designs e.g. PWR, BWR, VVER and PHWR in case of severe accidents. At KIT, investigations have been performed in the frame of the CESAM Project to evaluate the ASTEC capabilities to describe PWR severe accident sequences e.g. MBLOCA, SBLOCA and SBO including SAM measures. For this purpose, ASTEC was firstly validated using experimental data and later on applied to analyse different accidental sequences e.g. SB-LOCA including SAM measures. In this paper, the influence of several SAM measures on the in-vessel accident progression and on the integrity of the reactor pressure vessel (RPV) investigated with ASTEC for a Small Break LOCA and for a Station Black-out (SBO) sequences will be presented and discussed in detail.

1. INTRODUCTION

In the last two decades, a significant progress on Severe Accident Management strategies through the elaboration of plant specific SAM Guidelines (SAMGs) has been observed. Despite of this significant progress, the severe accidents at Fukushima (2011) have highlighted that further improvements of SAMGs are still necessary. For the development and optimization of SAMGs, a solid basis of risk-relevant analyses must be produced using severe accident simulation tools. The ASTEC code, developed by the *Institut de Radioprotection et de Sûreté Nucléaire* (*IRSN*) and the *Gesellschaft für Anlagen und Reaktorsicherheit (GRS)*, is becoming the reference integral SA code in Europe. The code is able to simulate the progression of a SA from the initiating event till the release of radioactive material from the containment. Within the European CESAM project [1], ASTEC capabilities regarding the assessment of SAM measures are being extended through model development, code validation and reactor calculations. In the frame of such project, KIT-INR is devoted to the verification and extension of SAM measures in a German Konvoi PWR using ASTEC, considering the lessons learnt from the Fukushima accidents [2].

Within this work, the ASTECV2.0 (rev3) is used to investigate the impact of selected SAM measures (e.g. secondary and primary bleed and feed procedures) on the progression of postulated SBLOCA (with SBO) and SBO sequences, which are relevant for the risk of core damage and containment failure according to the outcomes of the Probabilistic Safety Analysis (PSA) for the Konvoi PWR [3]. First of all, the ASTECV2.0 model of the Konvoi PWR is introduced. Then, the reference SBLOCA and SBO sequences are analysed. Finally, the influence of SAM measures is discussed and general recommendations concerning SAM are proposed.

2. THE ASTEC CODE

The ASTEC code simulates complete severe accident sequences for water-cooled nuclear reactors. The structure of ASTEC is modular, each module representing a zone of the reactor (primary loop, secondary loop, safety systems, vessel, etc.) or a set of physical phenomena. Two modules are of interest for the current work: CESAR and ICARE. Further details about all ASTECV2.0 modules and their modelling features can be found in [4]. The CESAR module calculates the thermal-hydraulics in the core region up to the beginning of core degradation, and in the rest of the primary and the secondary circuit. CESAR makes use of a 5-equation approach to solve the thermal-hydraulics in 1-D. ICARE describes the thermal-hydraulics in the core region after the onset of core degradation. For this purpose, the module uses the same approach to solve the thermal-hydraulics as CESAR. The 1-D approach is valid as long as the axial velocities are predominant over the radial ones. However, when significant blockages have been formed in the core region, a 2-D resolution of the thermal-hydraulics is necessary. The reflooding model used in the current work is devoted to bottom reflooding assuming that the core geometry is sufficiently intact so that it can be treated with a 1-D approach.

3. GENERIC ASTEC MODEL FOR A KONVOI PWR

The reference plant is the four loop German Konvoi PWR. The ASTECV2.0 model of a generic German Konvoi PWR used in the current work has been derived from a more detailed one used by GRS in previous studies [5]. The geometry of the reactor domains, the physical phenomena considered during the in-vessel phase, the automatic actions taken by the Reactor Control Protection System and the most relevant safety systems are identical to the ones described in [6,7]. In the following, a description of additional safety systems and key information from the aforementioned reference is given.

The four loop PWR is represented by two loops: the loop B (containing the pressurizer) and the loop A (containing the other three loops). Simplified sketches of the primary and secondary circuits of the loop B and the RPV are depicted in *FIG. 1*. The RPV is divided in six rings for the core region, the bypass and the downcomer. The pressurizer is equipped with a Pilot Operated Relief Valve (PORV) and two Safety Valves (SV1 and SV2). Each SG is equipped with a Safety Valve. The Emergency Core Cooling System (ECCS) consists of accumulators, the High Pressure Injection System (HPIS) and Low Pressure Injection System (LPIS). The last two take water from four borated tanks or from the sump. Mobile pumps have been included in the model to simulate an external injection into the primary or the secondary side.

Regarding the SAM procedures used in a German Konvoi PWR, secondary bleed and feed (SBF) is initiated when the liquid level of all SGs is lower than 4 m or when the plant has been for more than 20 min without any AC power supply [8]. The action is modelled through the opening of the SV SG-B and the injection by means of mobile pumps upon the fulfilment of such criteria. Primary bleed and feed, also named Primary Side Depressurization (PSD), is initiated when the Core Exit Temperature (CET) exceeds 400 °C or the core liquid level falls below *min3* [8]. This action is modelled through the opening of all pressurizer valves upon the fulfilment of the first condition (CET > 400 °C).

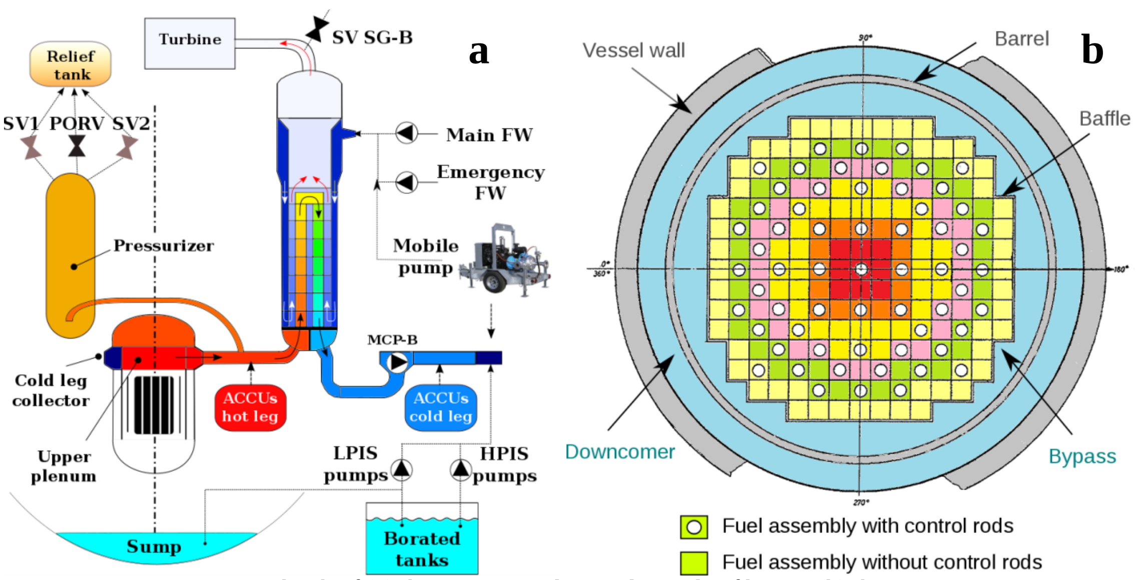

FIG. 1: Sketch of (a) the primary and secondary side of loop B (b) the RPV for a generic German Konvoi PWR by ASTECV2.0 [6].

4. SEQUENCES WITHOUT SEVERE ACCIDENT MANAGEMENT

The current section describes the behaviour of the risk-relevant sequences in a German Konvoi PWR [3] by means of ASTECV2.0 simulations. In particular, a Small Break LOCA in the main coolant line, which is relevant for the risk of core damage (PSA-1), and the total Station Blackout, which is relevant for the risk of fission product release to the environment (PSA-2), have been considered. For both sequences, an automatic intervention of the systems introduced in section 2 is assumed. Additionally, the following assumptions are made: (1) No failure of the surge line due to high temperatures; (2) No seal LOCA in the Main Coolant Pumps, (3) No thermal-induced SG Tube Rupture and (4) No automatic 100 K/h cooldown of the reactor through the SGs. The calculations are limited to the in-vessel phase and hence, they are terminated when RPV failure is calculated.

Concerning SBLOCA, it is considered that a 10 cm^2 break occurs in the cold leg of the pressurizer loop at 0.00 h. Furthermore, the sequence assumes the total loss of AC power supply 1 h after SCRAM and the availability of 3 out of 4 trains of the HPIS. On the other hand, the Station Blackout sequence postulates the total loss of AC power supply at 0.0 h without any kind of break in the main coolant line. The pressure evolution in the primary circuit as a function of the time after SCRAM is depicted in *FIG. 2*.

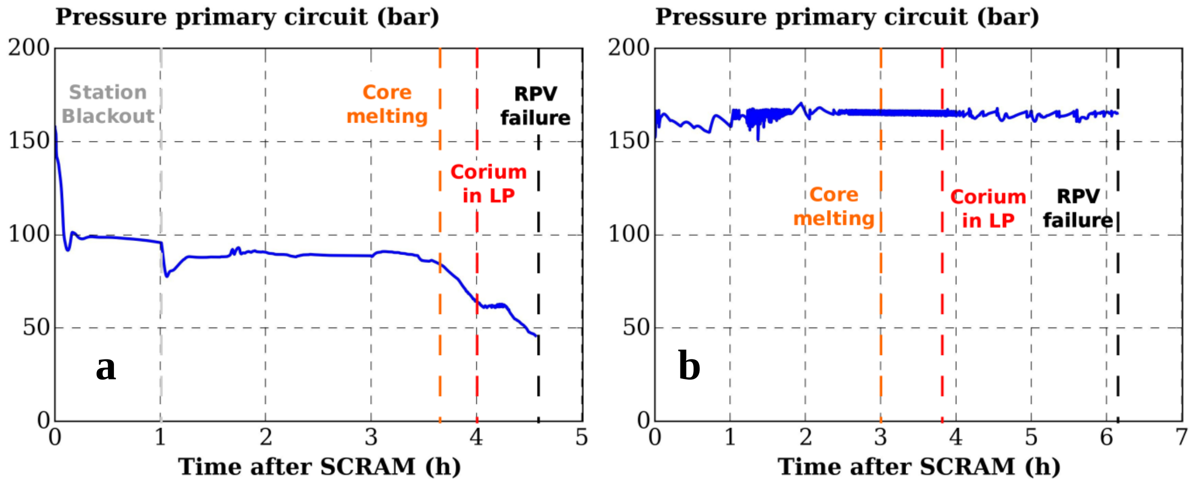

FIG. 2: Evolution of the primary pressure during the postulated (a) SBLOCA (b) SBO sequences as a function of the time after SCRAM in hours. Vertical lines mark the occurrence times of major events in each simulation.

For the considered SBLOCA sequence (*FIG. 2*-a), the pressure falls down at the beginning of the transient, since the water is leaving through the break. A few seconds later, when the pressure falls below 110 bars, the HPIS injects the inventory of the borated water tanks into the circuit. Consequently, the pressure remains at about 100 bars up to 1 h after SCRAM. At that time, there is a total loss of AC power, which automatically cuts off the HPIS. Afterwards, no active system can provide coolant to the reactor. Initially, the pressure decreases because the water is leaving the circuit at the cold leg. However, after some minutes, the water in the hot leg reaches saturation and starts to evaporate, which contributes to the increase of the pressure. This pressure balance is kept up to about 3.50 h, when the steam evacuation from the circuit compensates the overpressure of the gases exiting the circuit. In contrast to SBLOCA, where RPV failure occurs at medium pressures, the SBO sequence (*FIG. 2*-b) leads to high pressure sequences just after the loss of AC power. This happens because the water inventory of the SGs is rapidly depleted (in about 1.20 h) and hence, the heat sink of the primary side is lost. As a result, the temperature of the water and the pressure in the primary circuit starts to increase up to the set point of the pressurizer safety valves, where it remains until RPV failure.

5. SEQUENCES WITH SEVERE ACCIDENT MANAGEMENT

In the previous section it was that, if no Accident Management measures are considered, the postulated accidents lead to core melting, corium relocation to the lower plenum and, eventually, RPV failure, which also occurs at medium-high pressures. Within this section, several accident management measures are put in place to prevent, mitigate or delay core melting and the failure of the RPV. In this context, primary bleed and feed is investigated as a mean to stop the progression of the SBLOCA, whereas secondary bleed and feed is the selected measure to stop the progression of the SBO. The influence of both actions is shown in separated diagrams (FIG. 3 and FIG.4) in the form of timelines. The bar located at the top represents the timeline of the sequence without any accident management, whereas the vertical dashed lines mark the occurrence times of other relevant events of that simulation.

As far as the SBLOCA sequence is concerned, FIG. 3 shows that PSD significantly delays core melting and vessel failure if it is performed with a maximum delay of 20 min after the detection of a CET = 400 °C. On the other hand, a 60-min delayed PSD cannot delay RPV failure with respect to the reference sequence. This happens because at least 20 tons of corium has been heating up the upper metallic layer in the lower plenum and the vessel walls component in contact with it. Therefore, the water supplied by the accumulators cannot cool down the metallic layer, this eventually leading to vessel failure. In between, the 40-min delayed offers the longest grace time to vessel failure. This occurs because the water inventory from the accumulators covers the corium in the core region and hence, ASTECV2.0 shifts the corium relocation to a later time point. However, the validity of this finding should remain in question until further analyses with the ASTECV2.1 version [9], which incorporates new models for degraded core reflooding, would be performed.

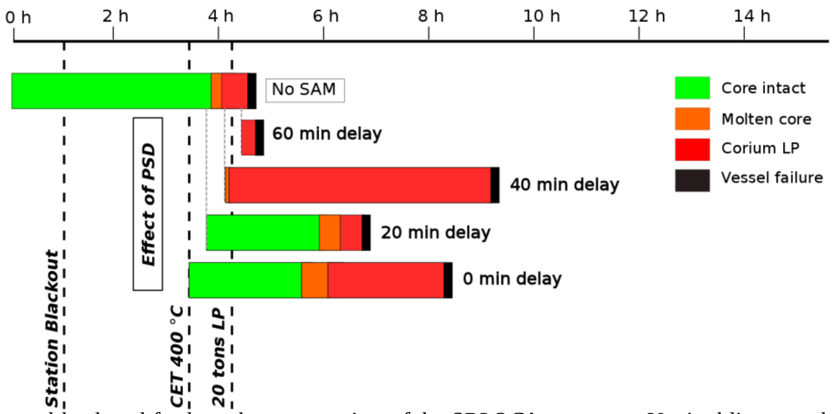

FIG. 3: Impact of primary bleed and feed on the progression of the SBLOCA sequence. Vertical lines mark the occurrence times of major events for the SBLOCA sequence without any SAM measure.

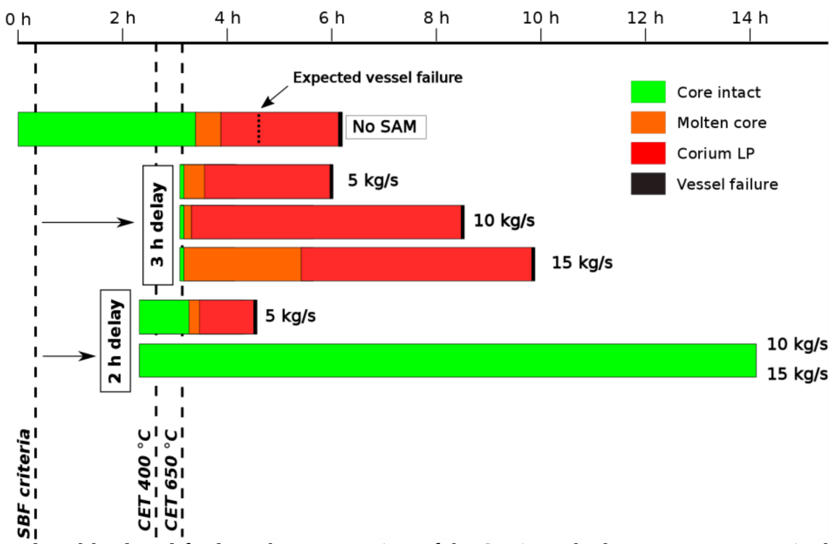

FIG. 4: Impact of secondary bleed and feed on the progression of the Station Blackout sequence. Vertical lines mark the occurrence times of major events for the SBO sequence without any SAM measure. Flow rates are referred to the injection rates into the depressurized SG i.e. SGB.

The timelines associated to the SBO sequence (*FIG. 4*) differ with respect to the ones of SBLOCA in certain aspects: first of all, the delay of the measure is evaluated after the secondary bleed and feed conditions are fulfilled; second, each bar (except the one located at the top) has two attributes: the mass flow rate injected by the mobile equipment into the depressurized SGB and the aforementioned delay in the performance of secondary bleed and feed. It can be observed that SBF is effective regarding the prevention of core melting if it is performed before the detection of CET = 400 °C providing that a mass flow rate higher than 10 kg/s is provided into the depressurized SGB. Beyond such time, SBF cannot prevent vessel failure, but may delay it if the supplied mass flow rates are above 10 kg/s. For all cases, an injection rate below 5 kg/s does not affect the time of vessel failure, which occurs at similar times as the reference case without SAM actions.

6. CONCLUSIONS

The elaboration of SAMGs requires a solid database of deterministic analysis performed with validated severe accident codes. Within the EU CESAM project, KIT-INR is involved in the extension of the technical basis for the verification, improvement and development of SAM measures for a German Konvoi PWR using ASTEC. The analyses are based on the findings of the PSA for the German Konvoi PWR and the lessons learned from the Fukushima accidents. Within this work, the impact of selected SAM measures (e.g. primary and secondary bleed and feed) on the progression of the risk-relevant SBLOCA and SBO sequences was studied. The results show that secondary bleed and feed should be initiated before detecting a CET=400 °C with an injection rate of at least 10 kg/s to prevent core degradation (according to SBO), and that primary bleed and feed should be initiated with a maximum delay of 20 min after the detection of CET=400°C in order to significantly delay core melting and vessel failure. Future investigations will deepen in the parametrization of the aforementioned measures, with a special attention to the reflooding of overheated cores during SBO conditions, similarly to the analysis performed in [6]. The verification of the findings concerning degraded core reflooding will be also addressed with the new ASTECV2.1 version [9].

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