IMPACT OF REALISTIC FUEL INVENTORIES ON THE RADIOLOGICAL CONSEQUENCES OF A SEVERE ACCIDENT SCENARIO IN A GENERIC KONVOI PLANT BY MEANS OF THE ASTEC CODE

Fabrizio Gabrielli
Karlsruhe Institute of Technology
Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, Germany
fabrizio.gabrielli@kit.edu

Anastasia Stakhanova, Victor-Hugo Sanchez-Espinoza
Karlsruhe Institute of Technology
Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, Germany
anastasia.stakhanova@kit.edu, victor.sanchez@kit.edu

Eva-Maria Pauli[1], Axel Hoefer[2], Harald Feldmann[2]
Framatome GmbH
[1] Paul Gossen Strasse 100, 91052 Erlangen, Germany
[2] Seligenstädter Strasse 100, 63791 Karlstein am Main, Germany
Eva-Maria.PAULI@framatome.com, Axel.Hoefer@framatome.com, harald.feldmann@framatome.com

ABSTRACT

The amount of fission products in the core is one of the key parameters driving the progression and the radiological consequences of a severe accident (SA) in a NPP. Therefore, the role of the fuel inventory should be considered while evaluating the radiological consequences of a SA by means of integral codes and decision support systems, in order to provide a valid support to the emergency teams in such severe accident events. The current paper provides a quantitative analysis of such effect on the Source Term (ST) of different SA scenarios in a generic KONVOI NPP. Having this in mind, realistic fuel inventories computed by using the reference ORIGEN-ARP code are employed in the SA simulations, which are performed by means of the European reference ASTEC code, developed by IRSN.

INTRODUCTION

The evaluation of the radiological consequences of severe accident (SA) scenarios in light water cooled nuclear power plants (NPP) is one of the major objectives of the nuclear reactor safety research program at the Karlsruhe Institute of Technology (KIT). One of the main goals is providing a valuable support to the emergency and management teams during such abnormal events. In this framework, a reliable evaluation of the source term (ST) during a SA scenario plays a central role.

In line with the KIT strategy, a database of STs during SA scenarios for different NPPs is under assessment. With this goal, a platform of reference codes and methods has been assessed at KIT to analyze SA scenarios and to evaluate and characterize the corresponding STs in different NPPs from the initiation up to the fission product (FP) release and dispersion in the environment [1]. In this framework, the European Accident Source Term Evaluation Code (ASTEC) [2], developed by IRSN and co-developed by KIT since 2020, is employed for the ST prediction during a SA scenario in a NPP. The ASTEC results are then employed to analyze the behavior of the FP released in the environment by means of the the Java based Real-Time On-Line Decision Support system (JRODOS, developed by KIT) [3][4], which is employed in several countries worldwide to assist in the management of nuclear and radiological emergencies and the subsequent rehabilitation of contaminated environments. Furthermore, in order to assess the database, large efforts have been started in recent years on performing the uncertainty quantification (UQ) of the ASTEC ST results as well as ST preditions by means of the in-house Fast Source Term Code (FSTC) developed at KIT [5]. Such research activity, triggered by the KIT/Framatome joint participation to the German WAME project [6] and to the currently running EU Management and Uncertainties of Severe Accidents (MUSA) project [7], aims at quantifying the uncertainty range of the ASTEC ST results as well as identifying the parameters and physical phenomena, which mainly affect such uncertainty [8][9][10].

For a given SA scenario, the amount of FPs in the fuel inventory initially loaded in the core is one of the main parameters affecting the in-vessel and ex-vessel accident progression as well as the ST. The larger the mass of FPs loaded, the larger is the decay power, which triggers the accident after the reactor scram. As a result, larger portions of in-vessel materials degrade faster, triggered by the higher temperatures in the core also in conjunction with the loss of in-vessel cooling. Such scenarios lead to larger FP release from the vessel to the containment and then to the environment, also due to the higher pressure conditions reached in the containment zones. Having this in mind, the assessment of a plant model in SA codes should employ realistic fuel inventories for a reliable evaluation of the ST during a SA scenario.

The current paper focuses, therefore, on the analysis of the ST during selected SA scenarios in a generic KONVOI-1300 NPP by means of the latest version of the ASTEC code (v2.2.0.1, November 2021), where realistic fuel inventories have been employed. In particular, a library of fuel inventories for an equilibrium cycle with 328 effective full power days have been computed for performing the ASTEC analyses. For such evaluations, the core is loaded with 193 Fuel Assemblies (48 U FAs, 6 batches; 81 U-Gd FAs, 6 batches; 64 MOX FAs, 4 batches). For the depletion calculations, the ORIGEN-ARP tool has been used, employing the ORIGEN reactor libraries for an 18x18 FA design embedded in SCALE 6.2.3 [11].

In the paper, the Medium (12'') and Small (2'') Break Loss Of Coolant Accidents, MBLOCA and SBLOCA respectively, are considered also in conjunction with a Station Black Out (SBO). For each scenario, two initial fuel inventories at the Beginning (0 Effective Full Power Days, EFPD) and at the End (328 EFPD) of the equilibrium cyle, begin-of-cycle (BOC) and end-of-cycle (EOC) repectively, are considered in the ASTEC model. In order to quantify the effect of the scenarios, as well as of the initial amount of FPs loaded in the core on the ST, the behavior of the ASTEC preditions about the mass fraction of the intial inventory for Xe, Cs, and I in the containment and in the environment are considered and the corresponding results are discussed.

THE ASTEC MODEL OF A GENERIC KONVOI-1300 NPP

NODALIZATION AND FUEL INVENTORIES

The original generic input deck available in the ASTEC release has been significantly improved in view of the ST evaluations. All the calculation modules are activated, allowing the analysis of the SA scenario from the intiation up to the basemat rupture, as well as the evaluation of the FP release from the vessel to the environment. In particular, the modelling of the FP transport (SOPHAEROS module) has been assessed to take into account all the physical phenomena, which may affect the FP behavior. Note that such quite sophisticated module allows monitoring the element- and isotope-wise transport of the FPs in the plant.

In the assessent of the ASTEC input deck, heat exchange (convection, conduction, and radiation) and oxidation models have been employed. In particular, the Best-Fit correlation is employed for clads, spacer grids, and guide tubes, while stainless steel oxidation has been used for control rod clads, plates, barrel, baffle and vessel, as well as the B4C oxidation model. Furthermore, the main models governing the the in-vessel and ex-vessel (relocation to the cavity after the lower head vessel rupture) behaviour of the molten material have been employed. Finally, the Molten Corium Concrete Interation (MCCI) modelling has been assessed.

The containment and core nodalization of the ASTEC model of a generic KONVOI NPP is shown in Figure 1. The containment is divided into two nearly symmetrical halves. Exceptions concern the centrally located spaces such as sump, cavity, reactor room and dome. Smaller rooms and staircases are combined and joined to the adjacent rooms. The plant rooms, labeled by green, red, gray, and light blue boxes in Figure 1, are nodalized with eleven volumes and the operating rooms (white boxes in

Figure 1) with nine volumes. The annulus is subdivided into three zones (light yellow boxes in Figure 1). A fan connects the containment and the annulus, as well as the annulus and the environment, the corresponding flow areas depending of the relative pressure differences in these zones based on plant data.

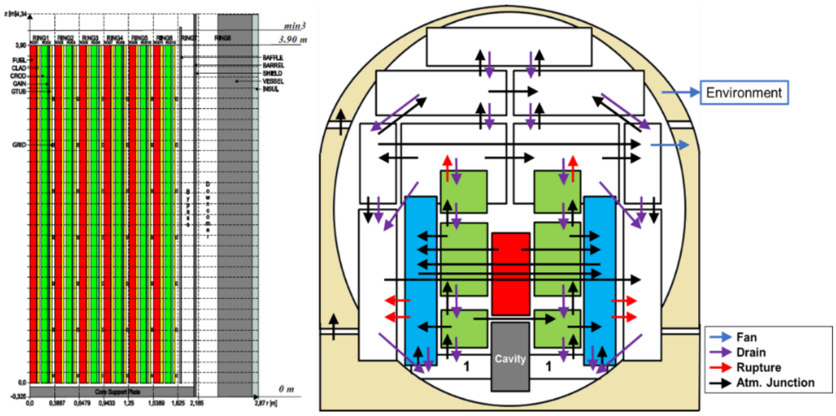

Figure 1: Core (left) and containment (right) nodalization in the ASTEC model of a generic KONVOI NPP.

The activity of key elements in the fuel inventory computed at BOC and EOC by ORIGEN-ARP employed in the ASTEC modeling are shown in Table 1.

Table 1: Activity in Bq of the initial fuel inventories at BOC and EOC

Element	Volatility	Activity @BOC (Bq)	Activity @EOC (Bq)
Xe	Noble Gas	1.502E+19	1.678E+19
Kr	Noble Gas	4.323E+18	4.576E+18
I	Very Volatile	4.311E+19	4.726E+19
Cs	Very Volatile	3.718E+19	7.702E+20
Te	Moderately Volatile	2.258E+19	2.547E+19
Sr	Moderately Volatile	1.104E+19	1.393E+19
Ba	Moderately Volatile	5.492E+20	6.913E+20
Ru	Less Volatile	1.298E+19	1.541E+19
La	Less Volatile	2.236E+19	2.465E+19
Ce	Less Volatile	1.662E+19	1.895E+19

DESCRIPTION OF THE SCENARIOS

The progression of the events of the MBLOCA (+SBO) and SBLOCA (+SBO) scenarios have been modeled in the ASTEC input deck as follows:

1. Break of the cold leg at t=0 s;
2. Reactor scram, if the primary pressure is lower than 132 bar or containment overpressure is larger than 30 mbar;
3. Admission to turbine and closure of the main feed water pumps into the steam generator;
4. Emergency Core Cooling System (ECCS) are activated if two of the following three conditions are fulfilled: containment overpressure larger than 30 mbar; pressure of the Reactor Coolant System (RCS) lower than 110 bar; pressurizer liquid level lower than 2.30 m;
5. Main Coolant Pumps are coasted down and the pressure regulation in the pressurizer is switched off;

6. Activation of the Emergency Feed Water System (EFWS) when the liquid level of one SG falls below 4.50 m;
7. High pressure injection system (for SBLOCA) and low pressure injection system (for MBLOCA) activated when the temperature of the gas in the primary exeeds 650 °C, until the tanks are empty. In this condition, the severe accident occurs;
8. Activation of the Extra Borating System when the pressurizer water level is lower than 2.30 m;
9. When the horizontal erosion reaches 4.4 m radius, water from the sump flows into the cavity.

In case of SBO, the alternating current is lost at t=0 s, and the actions 4-8 in the list above do not occur, namely only the accumulator discharge is available.

RESULTS

ACCIDENT PROGRESSION: MAIN EVENTS

The main events during the MBLOCA (+SBO) and SBLOCA (+SBO) scenarios are shown in Table II and Table III, respectively. Concerning the MBLOCA scenarios, the results in Table II reveal the significant effect of the composition of the fuel inventory on the accident progression. In particular, the core melting and material relocation to the lower plenum (LP) is faster when the fuel at EOC is employed than in the case of an initial fuel inventory at BOC. Consequently, the reactor pressure vessel (RPV) failure as well as the basemat rupture occurs earlier when EOC fuel is employed. One may also observe that the SBO sequence further accelerates the core degradation in the BOC case.

Table II: Main events during MBLOCA (+SBO) scenarios

Phenomenon	BOC MBLOCA	BOC MBLOCA+SBO	EOC MBLOCA	EOC MBLOCA+SBO
FP Release (s)	644	644	434	444
20/50 tons to the LP (h)	4.6	0.5	-/-	0.2/0.4
70/90 tons to the LP (h)	4.6	0.8/0.9	-/-	0.5/0.6
RPV Failure (h)	5.7	1.6	1.5	0.8
Basemate Rupt. (h)	93.2	7.8	4.3	5.0
Total H2 In-vessel/Containm. (kg)	938/1820	731/2124	638/1987	825/2270
Final Aerosols in Cont. (kg)	184	135	100	145

Concerning the total amount of hydrogen in the vessel and in the containment, the results show that the SBO event leads to larger values of such parameter. In these scenarios, the absence of ECCS systems in operation leads to the fast and violent oxidation of the vessel components leading to larger releases to the containment, also in conjunction with the higher temperature reached during such scenarios.

Table III: Main events during SBLOCA (+SBO) scenarios

Phenomenon	BOC SBLOCA	BOC SBLOCA+SBO	EOC SBLOCA	EOC SBLOCA+SBO
FP Release (s)	11056	1133	10619	1426
20/50 tons to the LP (h)	6.6	0.5/0.7	6.0	0.5
70/90 tons to the LP (h)	6.6	-/-	6.0	-/-
RPV Failure (h)	8.5	1.3	6.8	1.0
Basemate Rupt. (h)	102.2	48.5	77.8	6.0
Total H2 In-vessel/Containm. (kg)	865/2241	741/2790	862/2095	546/1652
Final Aerosols in Cont. (kg)	1159	144	1032	544

The results concerning the SBLOCAs scenarios in Table II show, as expected, the strong dependence of the scenarios on the initial fuel core loading, as observed for the MBLOCAs as well as a much faster degradation progress in case of SBO. Furthermore, by comparison with MBLOCA results, one may observe the huge effects of the SBO event on the mass of aerosols in the containment. In particular, when the SBO does not occur, the final mass of aerosols in the containment is about 10 times larger than in the case of a SBO event.

The different in-vessel accident progressions clearly trigger the behaviour of the containment pressure during the scenarios shown in Figure 2. One may observe that higher pressures peaks occur under EOC conditions (dotted lines) as well as higher values are observed in the long term in the scenarios not involving SBO events, which are also triggered by the hydrogen production during the flooding of the cavity. As expected, the SBLOCA scenarios, in particular at EOC, are characterized by larger and increasing pressures in the long term, up to about 9 bar. Note that no containment rupture is modelled in the ASTEC input deck.

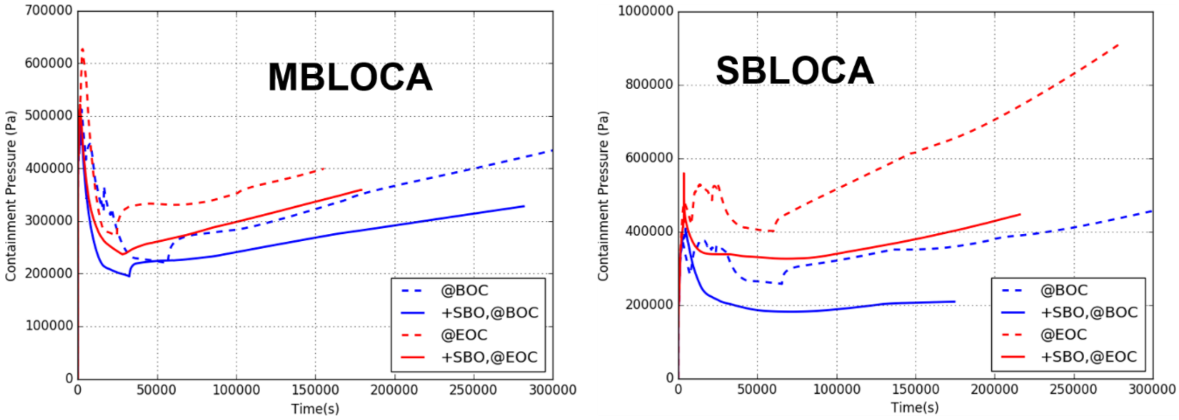

Figure 2: Containment pressure during MBLOCA (+SBO) and SBLOCA (+SBO) scenarios.

SOURCE TERM

The behavior of the total activity in the vessel and in the containment computed by ASTEC in the different parts of the NPP for the scenarios analyzed are shown in Figure 3.

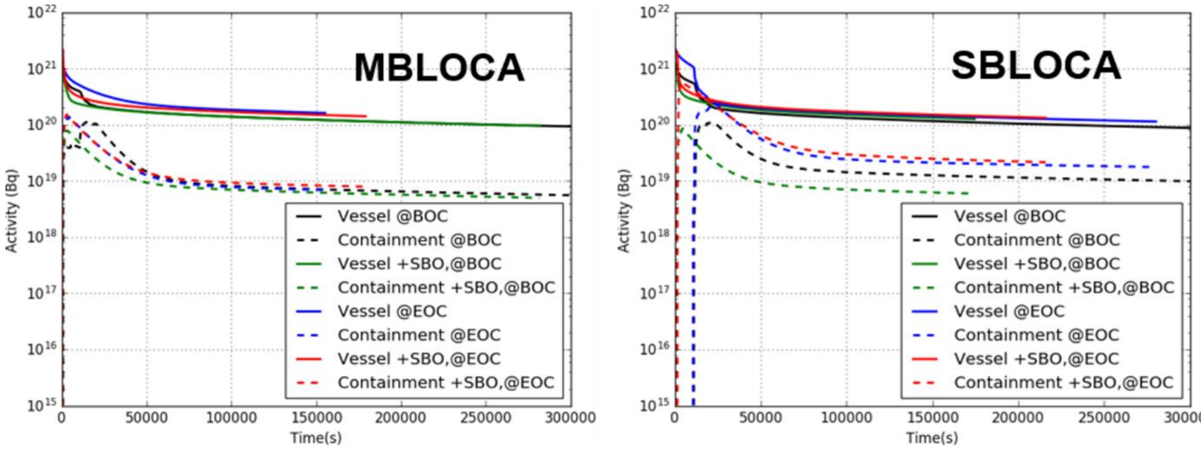

Figure 3: Total activity in the vessel and in the containment during the selected scenarios.

One may observe that during the MBLOCA scenarios about 1% of the initial activity of the fuel inventory is transported from the vessel to the containment (dashed lines). In particular, the results show that for the same scenario a larger amount of FPs is transported to the containment when the fuel inventory at EOC is employed than at BOC, i.e. dashed green and red lines. The comparison of the results show that the SBLOCA scenarios look more severe with respect to activity release . The results on the right hand-side of Figure 3 show that up to about 3% of the initial activity in the vessel is transported to the containment in the long term during SBLOCA+SBO (@EOC). In case of SBLOCA @EOC the activity release to the containment reaches about 15-20% and 70% of the initial activity at the beginning of the FP release from the vessel for the cases without and with SBO, labelled by dash blue and red lines respectively. One may observe that the release to the containment is almost twice as high for a fuel inventory at EOC as for a fuel inventory at BOC.

Concerning the behavior of the noble gases, the amount of Xe in the containment and its release to the environment are shown Figure 4.Note that the results are provided as fraction of the intial mass loaded in the core. As expected, the noble gases are almost completely transported to the containment and, therfore, only small differences are observed between the results for the different scenarios. These differences are related to the different timing of the release from the primary circuit, which, as discussed above, strongly depend on the initial amount of FPs in the core.

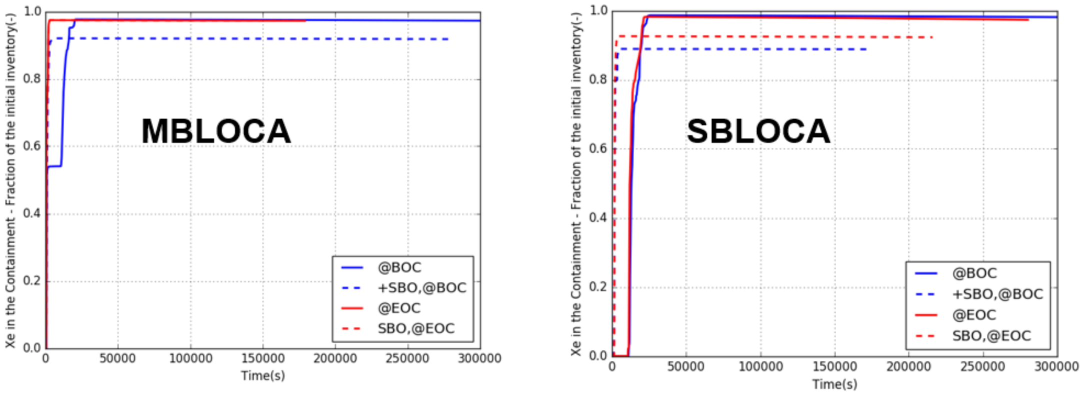

Figure 4: Amount of Xe in the containment during the selected scenarios.

Nevertheless, such conclusion changes when one considers the relase to the environment are analyzed. The results in Figure 5 show that the Xe release to the environment increases with the increase of the amount of FPs in the fuel, with the exeption of the MBLOCA+SBO scenarios. In particular, the fraction of Xe released to the environment with the fuel at EOC is about twice than at BOC (red curves vs. blue curves). Furthermore, for the same kind of fuel employed, such release during SBLOCAs is almost twice than in the MBLOCAs, due to the larger pressures in the containment (Figure 2).

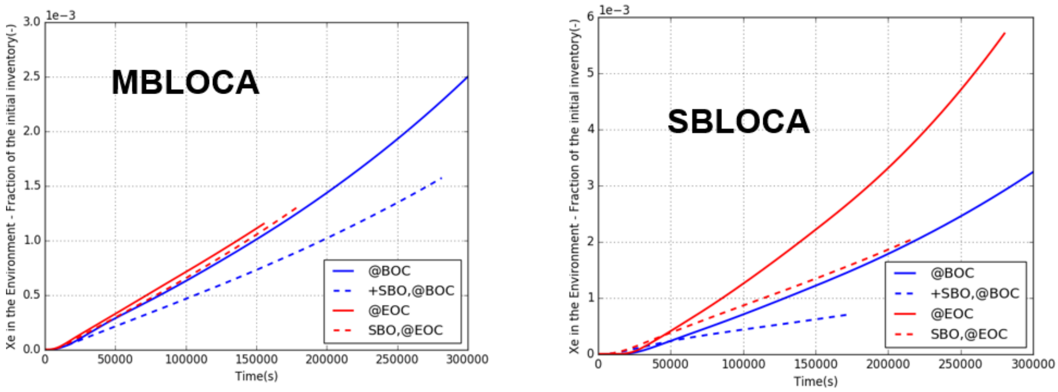

Figure 5: Amount of Xe released to the environment during the selected scenarios.

As mentioned above, the ASTEC code also allows evaluating the isotope-wise contribution to the source term by employing dedicated libraries as well as an internal engine for computing the decay of the nuclides. The activity of Xe^{133} and Xe^{135} released to the environment during the SBLOCA scenarios are shown in Figure 6. Concerning Xe^{133}, it can be observed that the results at EOC fuel condition are about a factor 2 larger that at BOC. Such deviation becomes further larger, up to a factor 5, for the Xe^{135} during a SBLOCA+SBO scenario.

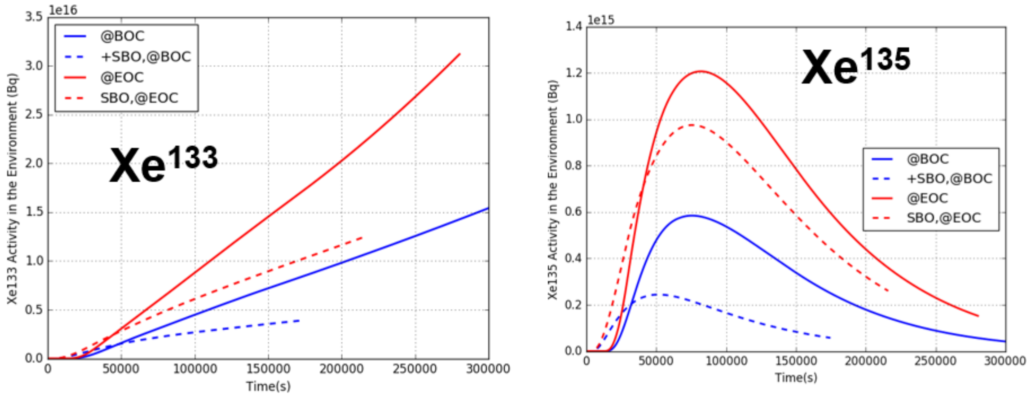

Figure 6: Activity of Xe^{133} and Xe^{135} released to the environment during the SBLOCAs.

As other Figures-of-Merit of the current analysis, the ASTEC results concerning the amount of Cs and I aerosols in the containment are shown in Figure 7 and Figure 8, respectively. The MBLOCA results show that for the same scenario, the released amount of Cs is about 30% largerfor EOC fuel than for BOC fuel, while no meaningful deviations can be observed for I. Furthermore, the results show that the SBLOCAs (+SBO) lead to larger releases of aerosols than the MBLOCAs (+SBO).

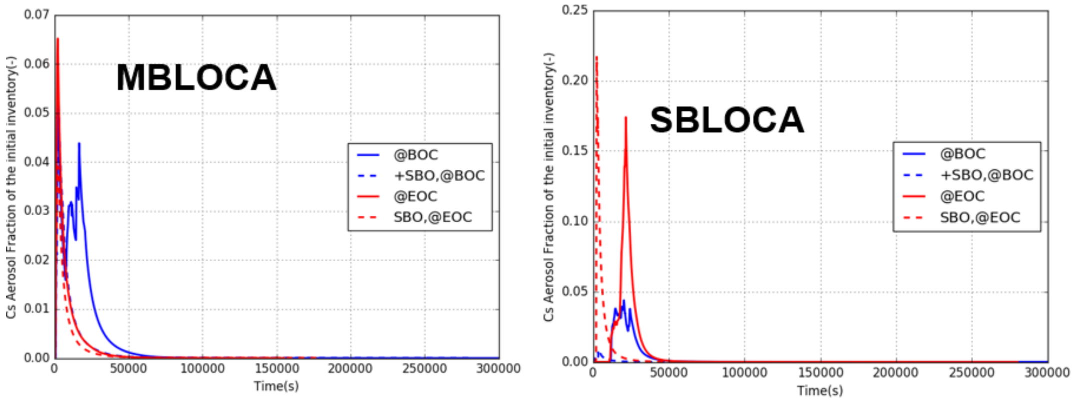

Figure 7: Amount of Cs aerosols in the containment during the selected scenarios.

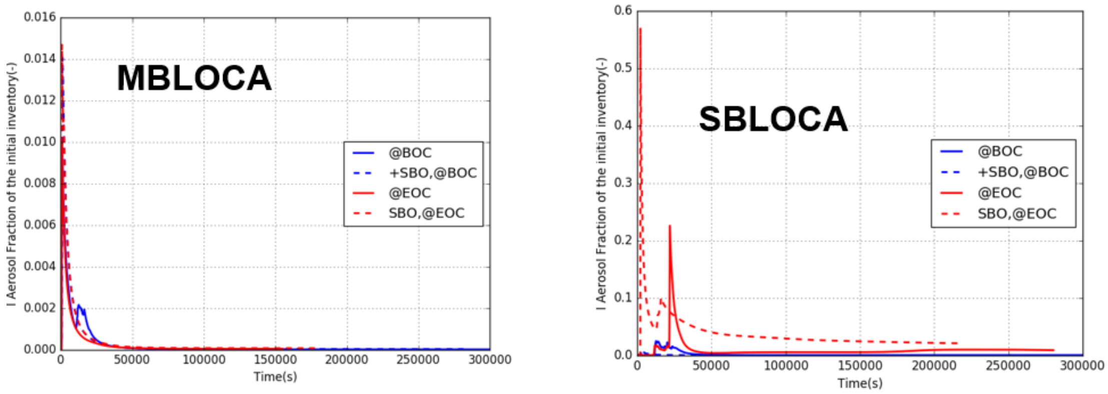

Figure 8: Amount of I aerosols in the containment during the selected scenarios.

The ASTEC results show that the fraction of mass of aerosols is larger when the fuel inventory at EOC is employed than at BOC (red lines). Such deviation becomes rather huge when moving from the analysis of the results for MBLOCA to SBLOCA scenarios. In fact, one may observe that in the SBLOCA cases, rather small amounts of aerosols are transported to the containment with the fuel at BOC, while these amounts reach about 22% and 60% of the initial fuel inventory for Cs and I at EOC, respectively.

CONCLUSION

For selected SA scenarios at a generic KONVOI-1300 nuclear power plant, the impact of the initial fuel inventory in the core on SA progression and the ST has been studied. For this purpose, ASTEC calculations have been carried out both for BOC and EOC core inventories. The obtained results show a quite large effect of the initial amount of FPs in the core both on SA progression and on the ST.

Larger amounts of FPs in the fuel lead to faster and more severe core degradation. Furthermore, larger amounts of FPs are released from the vessel and transported to the containment and then to the environment, also triggered by the larger pressure values reached during the transient in the containment. In particular, the ASTEC analyses of the MBLOCA (+SBO) and SBLOCA (+SBO) scenarios show that the employment of a fuel inventory characterized by a larger amount of FPs leads to larger releases of Xe in the environment up to a factor two. Similarly, the results for the Cs and I aerosols in the containment show an increase of about 30% for MBLOCAs. Finally, the SBLOCA results for EOC fuel show that up to 20% and about 60% of the initial mass loaded in the core of Cs and I aerosols, respectively. On the contrary, for BOC fuel rather small amounts of such quantities are transported to the containment.

Therefore, the employment of realistic fuel inventories loaded in a reactor core in the simulations of SAs by means of integral reference codes is mandatory to perform a reliable evaluation of the ST and to provide a valuable support to the emergency and decision teams during such events. Having this in mind, similar ASTEC analyses are currently performed for further scenarios both for a generic KONVOI NPP and for a VVER-1000 NPP in the framework of the assessment of a ST database at KIT.

These research activities also provide a rather solid basis of understanding in view of the planned ASTEC analyses at KIT of SA scenarios in generic Small Modular Reactors (SMRs). Since such systems are characterized by rather heterogeneous core arrangements and are envisaged to employ innovative materials, e.g. Accident Tolerant Fuels (ATFs), the evaluation of the fuel inventories as well as the analyses of their effects of the SA progression and ST in SMRs is expected to represent a key and challenging issue. With this respect, the lessons learned from dedicated projects on the topic, e.g. the EU H2020 High-performance advanced methods and experimental investigations for the safety evaluation of generic Small Modular Reactors (McSAFER) coordinated by KIT, will provide important insights.

REFERENCES

[1] F. Gabrielli, et al., 2021, Employment of the ASTEC Code in the Severe Accidents Research Activities at KIT, Proc. of NENE, September 6-9, Bled, Slovenia, ISBN 978-961-6207-51-5.
[2] P. Chatelard, at al., 2016, Main modelling features of the ASTEC V2.1 major version, Ann. Nucl. Energy 93, 83–93. https://doi.org/10.1016/j.anucene.2015.12.026.
[3] W. Raskob, et al., 2011, JRODOS: Platform for improved long term countermeasures modelling and management", Radioprotection, vol. 46, n° 6 S731-S736.
[4] A.K. Mercan, et al., 2022, Source term estimation and dispersion analysis of VVER-1000 reactor in case of LBLOCA along with SBO, Proc. of ERMSAR2022, May 16-19, Karlsruhe, Germany.
[5] A. Stakhanova, et al., 2022, Uncertainty and sensitivity analysis of the QUENCH-08 experiment using the FSTC tool, Ann. Nucl. Energy, 169, https://doi.org/10.1016/j.anucene.2022.108968.
[6] WAME Project, German Federal Ministry of Economic Affairs and Energy, FZK 1501582.
[7] L.E. Herranz, at al., 2021, The EC MUSA Project on Management and Uncertainty of Severe Accidents: Main Pillars and Status, Energies, 14.
[8] A. Stakhanova, et al., 2022, Preliminary Uncertainty and Sensitivity Analysis of the ASTEC simulations results of a MBLOCA scenario at a Generic KONVOI Plant using FSTC tool, Proc. of ERMSAR, May 16-19, Karlsruhe, Germany.
[9] E. Pauli, et al., 2022, Prediction of the Radiological Consequences of a Severe Accident Scenario in a Generic KONVOI Nuclear Power Plant, Proc. of ERMSAR, May 16-19, Karlsruhe, Germany.
[10] F. Gabrielli, et al., 2021, Source Term Evaluation following MBLOCA and SBLOCA Scenarios in a generic KONVOI-1300 NPP by means of the ASTEC Code, Proc. of EUROSAFE, November 22-23, Paris, France.
[11] B.T. Bearden, M.A. Jessee, 2018, SCALE Code System, ORNL/TM-2005/39, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.