KERNTECHNIK 2022

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

F. Gabrielli[1], A. Stakhanova[1], V.-H. Sanchez-Espinoza[1],
E.-M. Pauli[2], A. Hoefer[2], H. Feldmann[2]

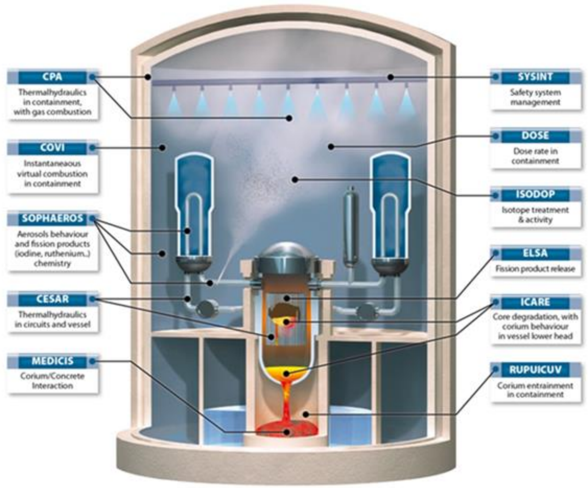
[1] Karlsruhe Institute of Technology
[2] Framatome GmbH

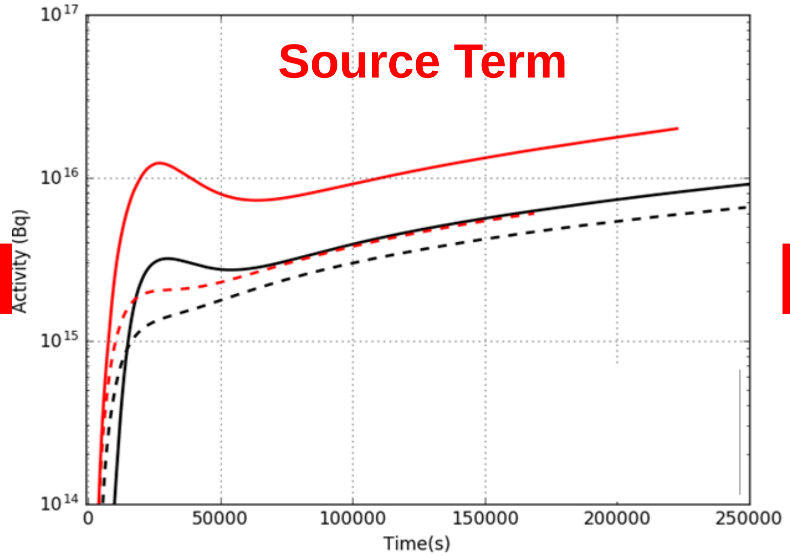
KernD KTG

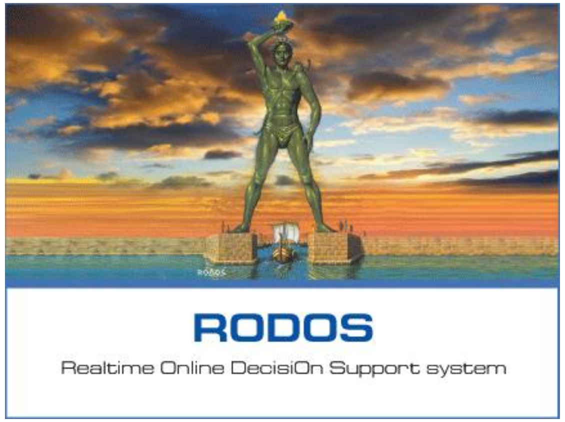
Motivation

- Evaluation of source term (ST) and fission product (FP) dispersion during a severe accident (SA) in NPPs is one of the major objectives of the nuclear reactor safety research program at KIT.
- Main goal → supporting the emergency and management teams during such abnormal events → **a reliable evaluation of the source term is mandatory**.
- **Reference** codes to be employed for assessing a database of STs during SA scenarios for different NPPs → Realistic fuel inventories, ST evaluation (ASTEC), U&S and ST prediction (FSTC+MOCABA algorithm), FP dispersion (JRODOS).
- Activities triggered by the KIT/Framatome joint participation to the EU H2020 MUSA and German WAME projects.
- **The amount of FPs 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.**
- Large mass of FPs loaded → larger decay power → larger in-vessel degradation → larger FP release from the vessel to the containment and then to the environment.

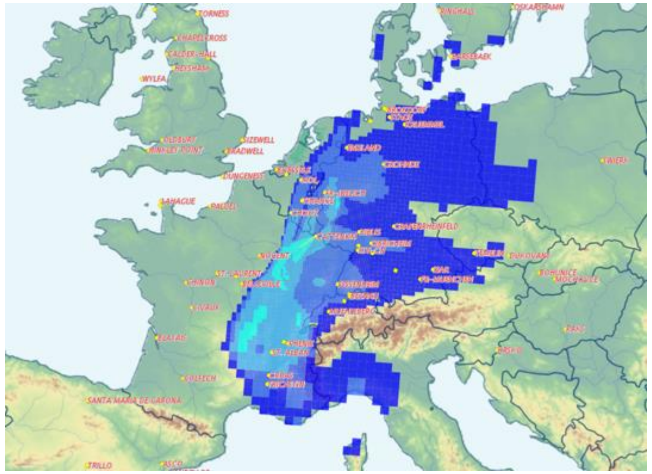
KIT Strategy for Source Term Analyses (1/2)







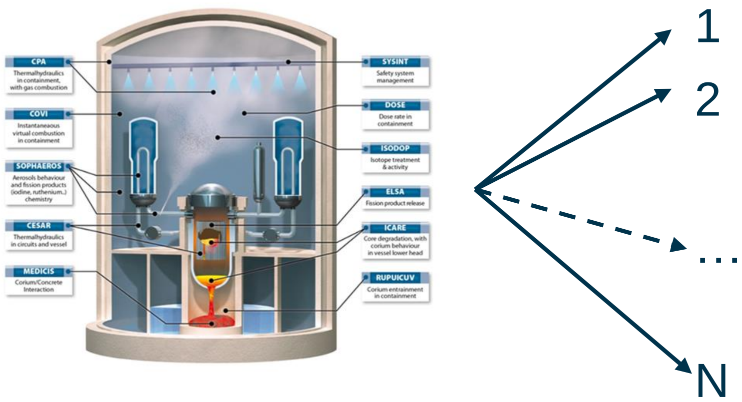
https://www.ites.kit.edu/english/294.php



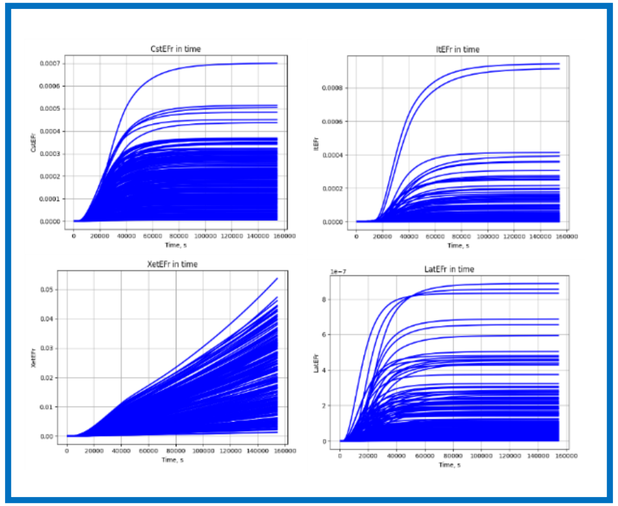
- **European reference Accident Source Term Evaluation Code (ASTEC)**, developed by IRSN and co-developed by KIT since 2020 → SA scenario analyses and ST evaluations.
- ASTEC results employed to analyze the FP dispersion in the environment by means of the **Java based Real-Time On-Line Decision Support system (JRODOS, KIT).**

KIT Strategy for Source Term Analyses (2/2)

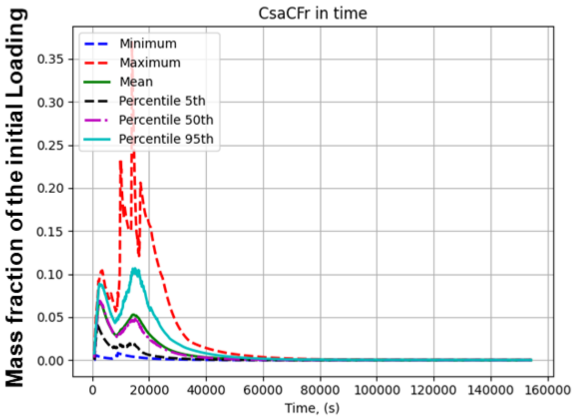
- Development of in-house **Fast Source Term Code (FSTC)** → **Uncertainty Quantification (UQ) of the ASTEC ST results** + **training database** for
- **Source Term prediction** → Monte Carlo-based Bayesian inference model (**MOCABA** algorithm from Framatome GmbH embedded)



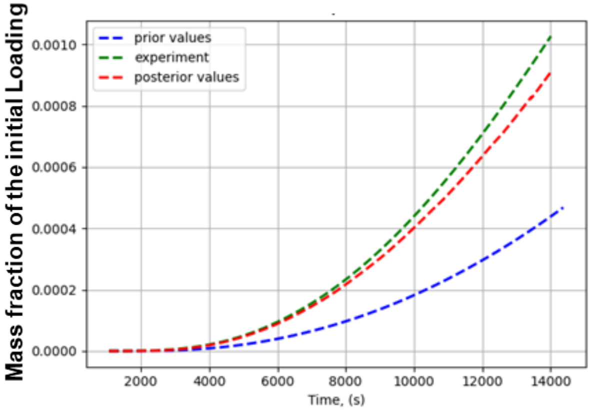
ST Training Database



ASTEC+UQ



ASTEC+UQ +MOCABA

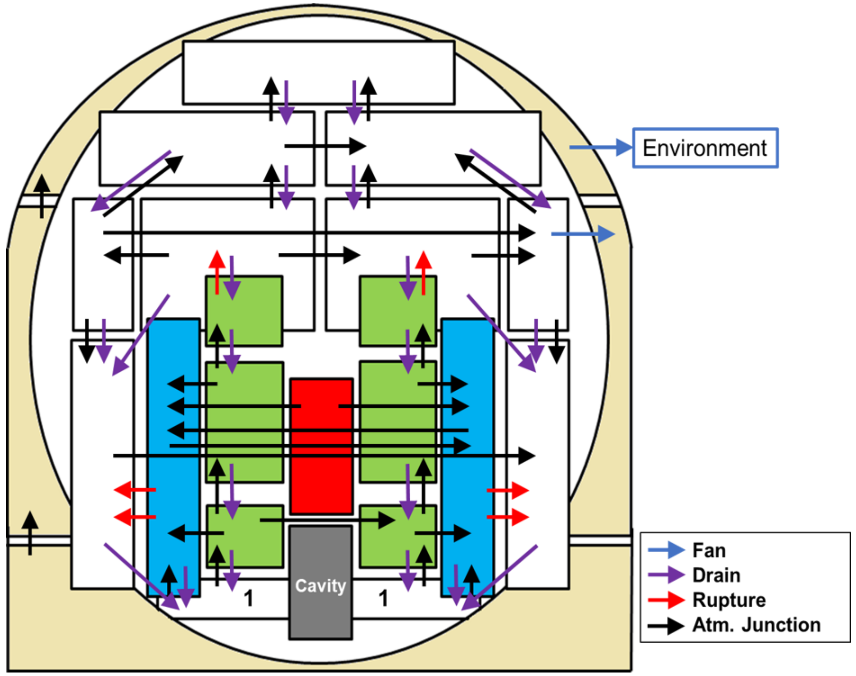


A. Stakhanova, et al., 2022, Uncertainty and Sensitivity Analysis of the ASTEC Simulation Results of a MBLOCA Scenario in a Generic KONVOI Plant Using the FSTC Tool, ERMSAR2022, May 19-22, Karlsruhe.

E.-M. Pauli, et al, 2022, Prediction of the Radiological Consequences of a Severe Accident Scenario in a Generic KONVOI Nuclear Power Plant, ERMSAR2022, May 19-22, Karlsruhe.

ASTEC Model of a Generic KONVOI NPP

- Significant improvement and extension of the original generic ASTEC input deck available in the code release.
- All the calculation modules activated → analysis of the SA scenario from the initiation up to the basemat rupture.
- SOPHAEROS module for element- and isotope-wise FP transport and behavior from the core to the environment.
- Heat exchange (convection, conduction, and radiation) and oxidation models.
- Main models governing the in-vessel and ex-vessel (relocation to the cavity after the lower head vessel rupture+MCCI) behaviour of the molten material.



Plant rooms (11 volumes)
Operating rooms (9 volumes, white)
Annulus (3 volumes, light yellow)

A. Stakhanova, et al., 2022, Uncertainty and Sensitivity Analysis of the ASTEC Simulation Results of a MBLOCA Scenario in a Generic KONVOI Plant Using the FSTC Tool, ERMSAR2022, May 19-22, Karlsruhe.

Fuel Inventory

- Library of fuel inventories for an equilibrium cycle with 328 effective full power days computed.
- Core is loaded with 193 Fuel Assemblies (48 U FAs, 6 batches; 81 U-Gd FAs, 6 batches; 64 MOX FAs, 4 batches).
- 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.
- Two initial fuel inventories employed:
  - Beginning of Cycle (BOC)
  - End of Cycle (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

Scenarios

- **MBLOCA (12”) and SBLOCA (2”)**

  1. Medium (12’’) and small (2’’) break of the cold leg at t=0 s
  2. Reactor scram, if the primary pressure < 132 bar or containment overpressure > 30 mbar
  3. Admission to turbine and closure of the main feed water pumps into the steam generator;
  4. Emergency Core Cooling System (ECCS) activated if two of the following three conditions are fulfilled containment overpressure >30 mbar, RCS pressure <110 bar or pressurizer liquid level< 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 <4.50 m
  7. HPIS (SBLOCA) and LPIS (MBLOCA) activated (T_gas in the primary > 650 °C) up to the tanks are empty → **severe accident**
  8. Activation of the Extra Borating System when the pressurizer water level <2.30 m
  9. When the horizontal erosion reaches 4.4 m radius, water from SUMPF flows into the cavity and the spalt

- **MBLOCA (12”) and SBLOCA (2”) + Station Black Out (SBO)**

  - AC loss @t=0 s
  - As above but no 4 – 8 actions (namely only accumulator discharge available)

MBLOCA Scenarios: Quicklook

	BOC		EOC	
Phenomenon	**MBLOCA**	**MBLOCA+SBO**	**MBLOCA**	**MBLOCA+SBO**
FPs Release (s)	644	644	434	444
20/50 tons relocated to the LP (h)	4.6	0.5	-/-	0.2/0.4
70/90 tons relocated to the LP (h)	4.6	0.8/0.9	-/-	0.5/0.6
LPV 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

- Significant effect of the composition of the fuel inventory on the accident progression.
- Significant effect of scenarios on the mass of aerosols in the containment.

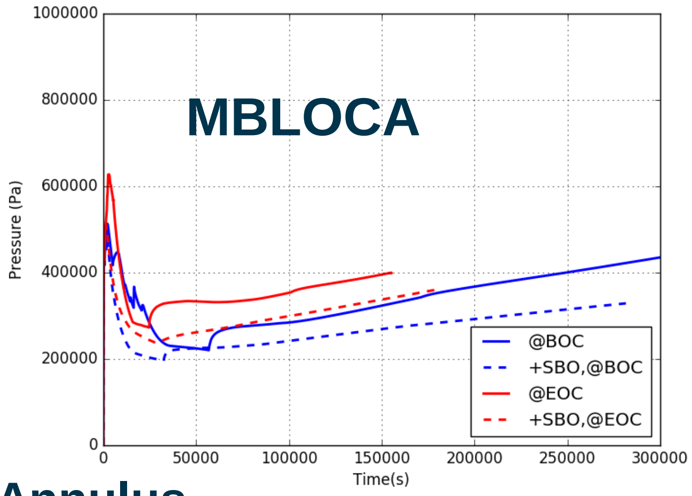
SBLOCA Scenarios: Quicklook

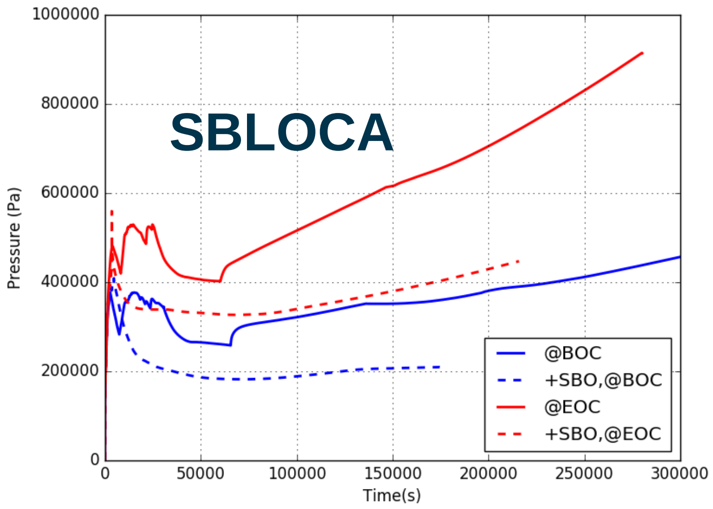
	BOC		EOC	
Phenomenon	**SBLOCA**	**SBLOCA+SBO**	**SBLOCA**	**SBLOCA+SBO**
FPs Release (s)	11056	1133	10619	1426
20/50 tons relocated to the LP (h)	6.6	0.5/0.7	6.0	0.5
70/90 tons relocated to the LP (h)	6.6	-/-	6.0	-/-
LPV Failure (h)	**8.5**	**1.3**	**6.8**	**1.0**
Basemate Rupt. (h)	102.2	48.5	77.8	6.0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

- Significant effect of the composition of the fuel inventory on the accident progression.
- By comparison with MBLOCA results, huge effect of scenarios on the mass of aerosols in the containment.

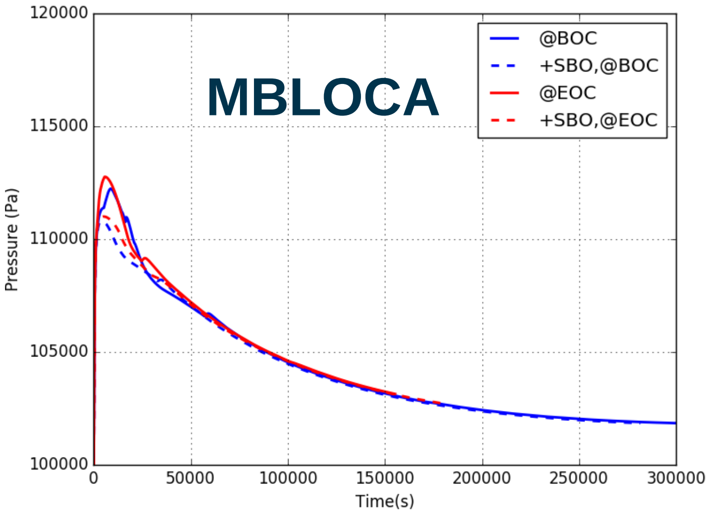
Containment and Annulus Pressure

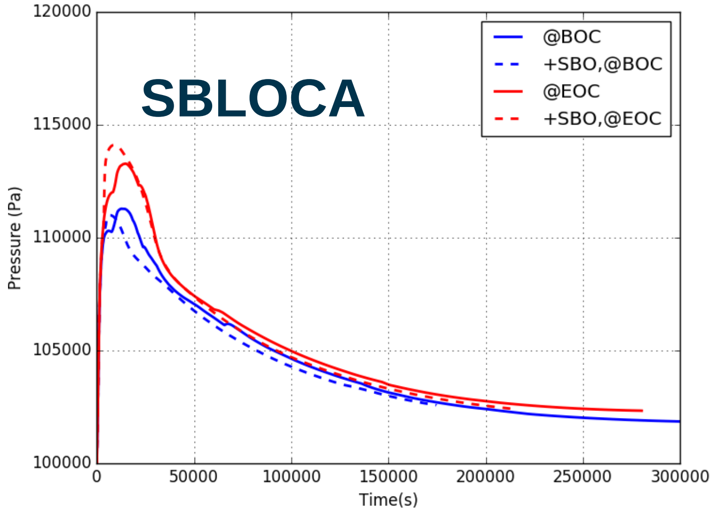
Containment





Annulus

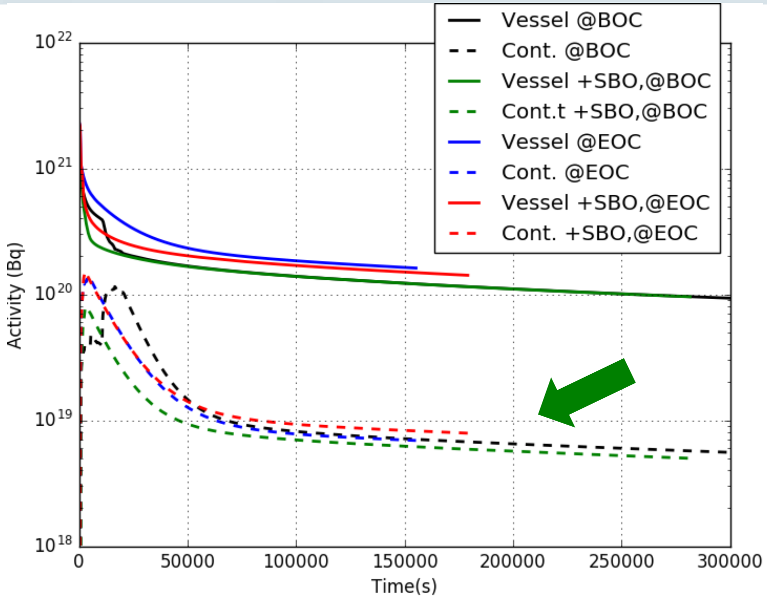


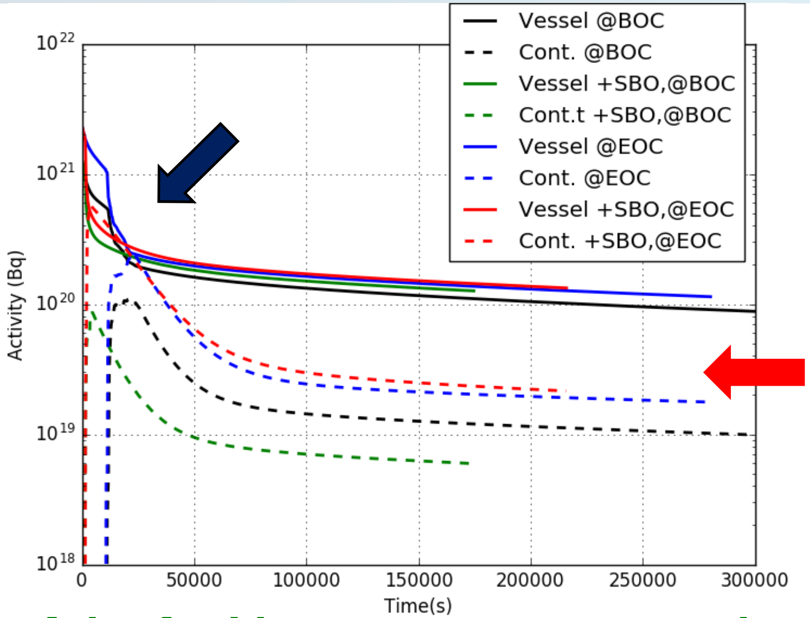


- **Containment**
- Higher pressures in EOC conditions.
- Long term higher pressures w/o SBO.
- In SBLOCA (EOC), pressure containment up to about 9 bar
- No containment rupture modeled (WAME project).

- **Annulus**
- Pressure in the annulus decreases due to the release to the environment

Total activity in the Plant

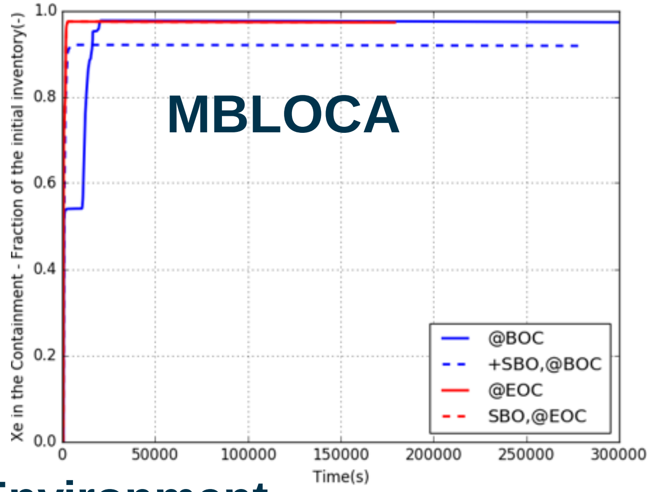


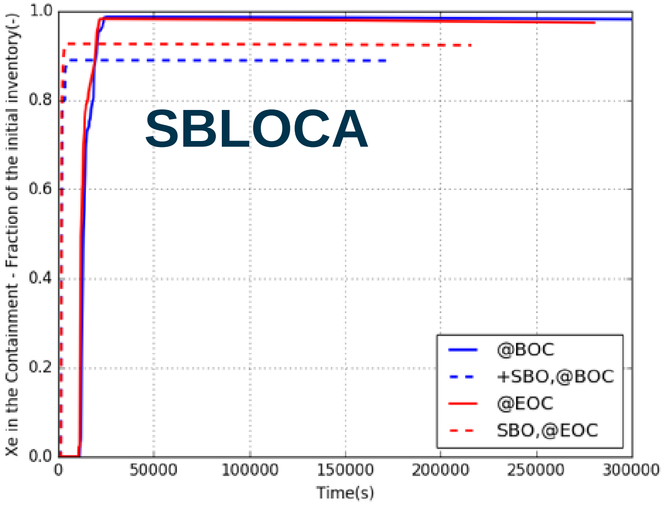


- **MBLOCA scenarios → about 1% of the initial activity of the fuel inventory transported to the containment.**
- **SBLOCA scenarios more severe**
  - SBLOCA+SBO (@EOC) → about 3% of the initial activity in the vessel transported to the containment in the long term.
  - SBLOCA @EOC → **max. activity release to the containment about 15-20% (no SBO) and 70% (+SBO) of the initial activity.**
  - **The release to the containment is almost twice as high for a fuel inventory at EOC as for a fuel inventory at BOC.**

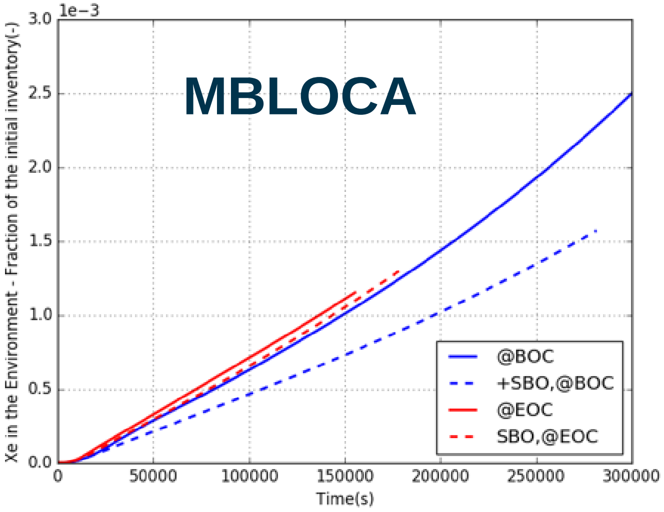
Xe Mass in Containment and Environment

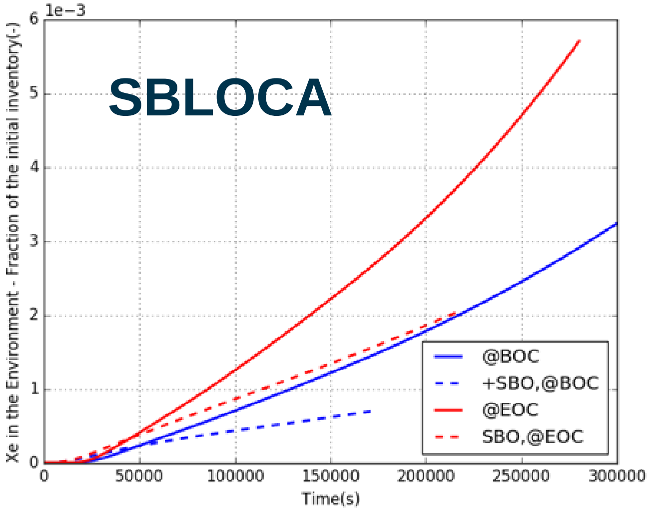
Containment





Environment



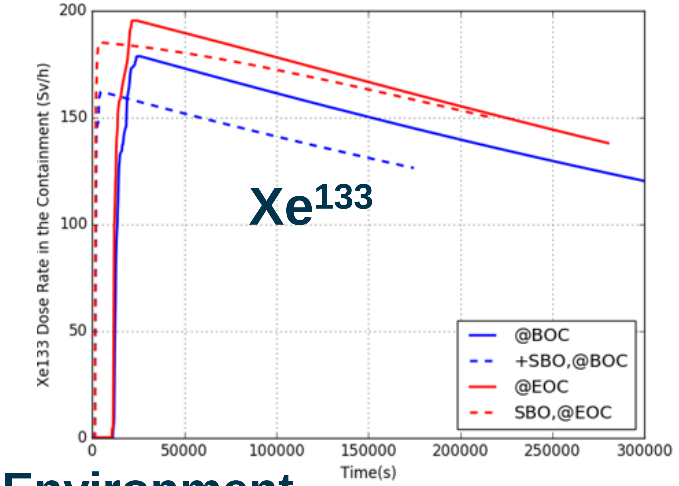


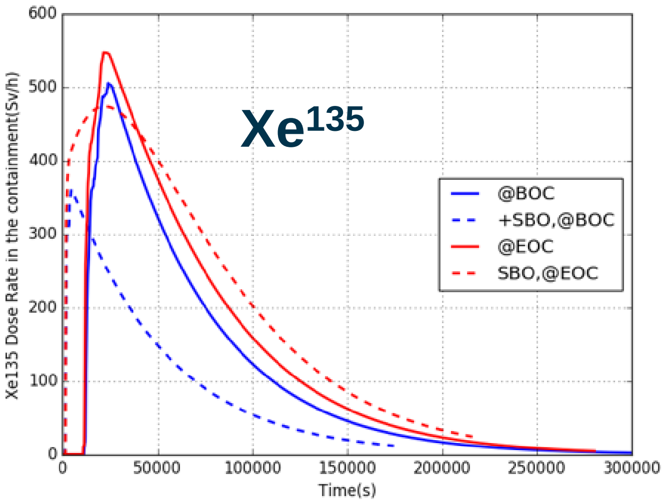
- Noble gases almost completely transported to the containment.

- Largest release at higher fuel burn-up in SBLOCA scenarios.
- (SBLOCAs and MBLOCA+SBO) Release with fuel at EOC is about twice than at BOC

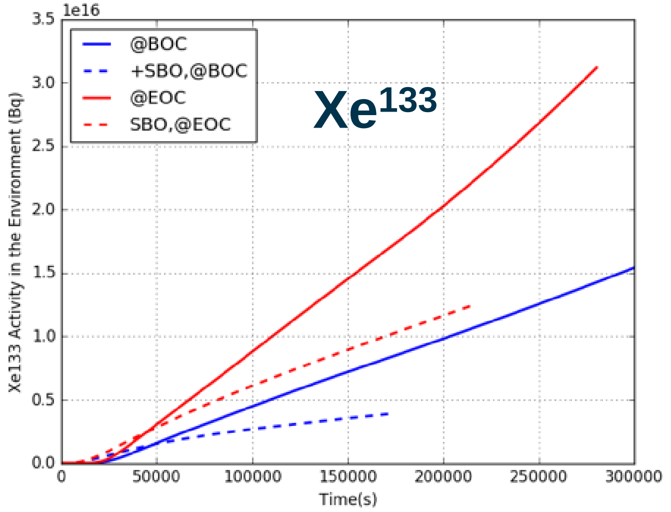
Xe-wise isotopes in the Containment and Environment

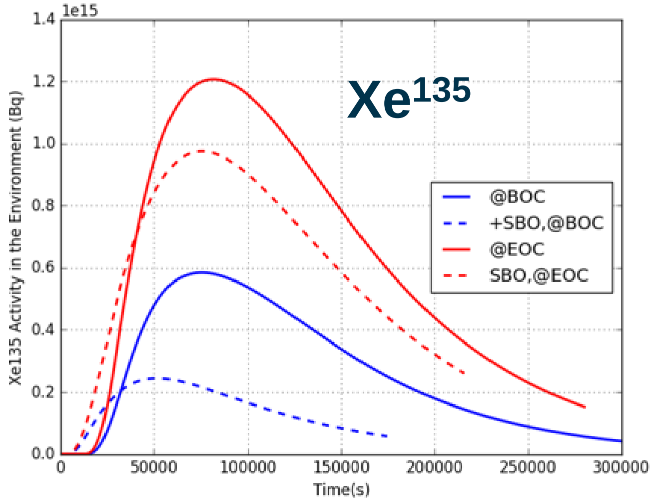
Containment





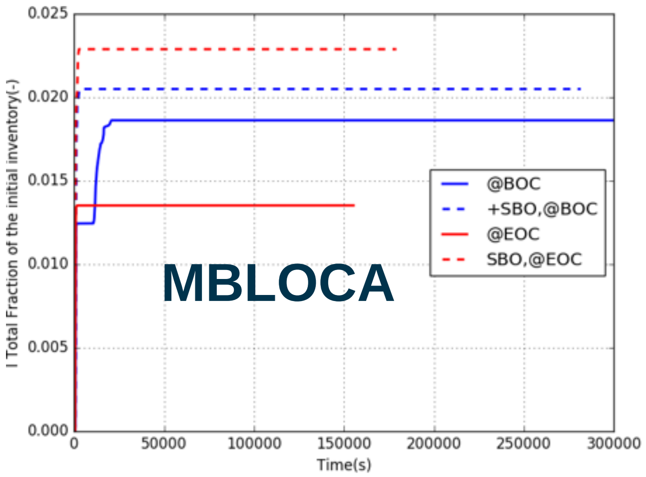
Environment

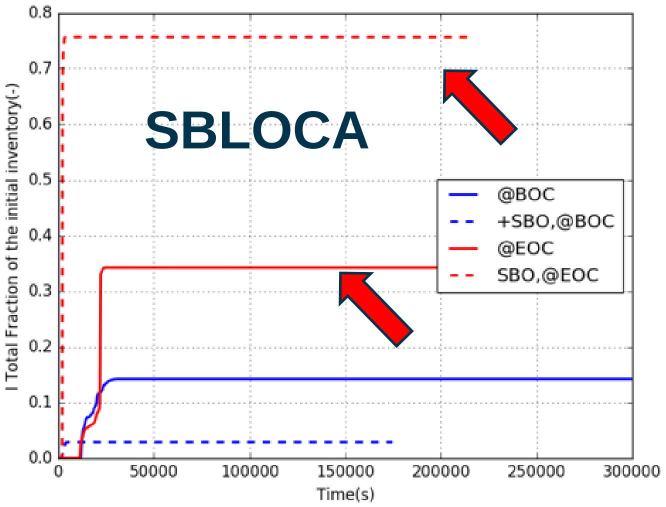


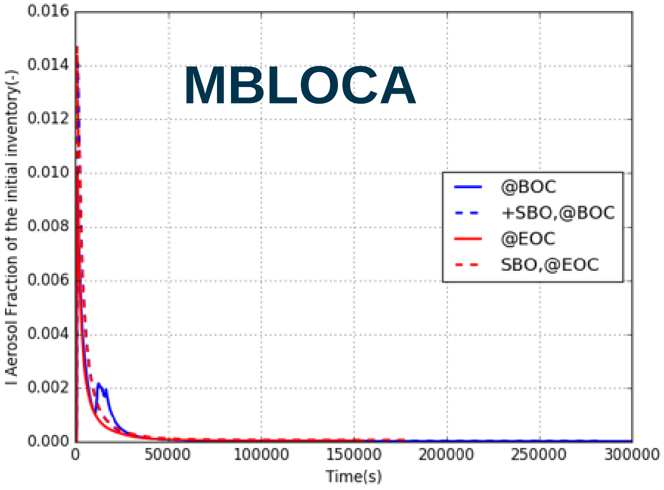


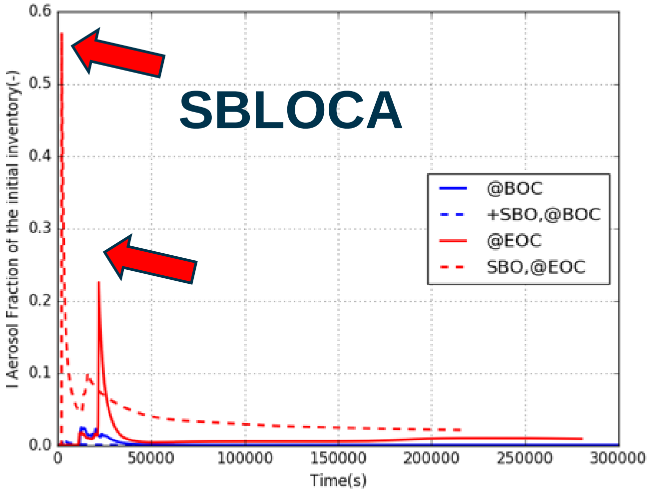
- SBLOCA results shown
- Element- and isotope wise results stored in the database:
  - Dose rates in Containment and Annulus
  - Activity in the containment, annulus, and environment

I Mass in the containment: Total and Aerosols



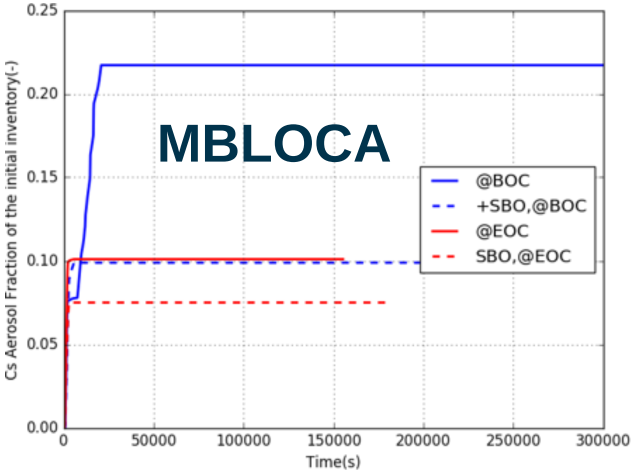


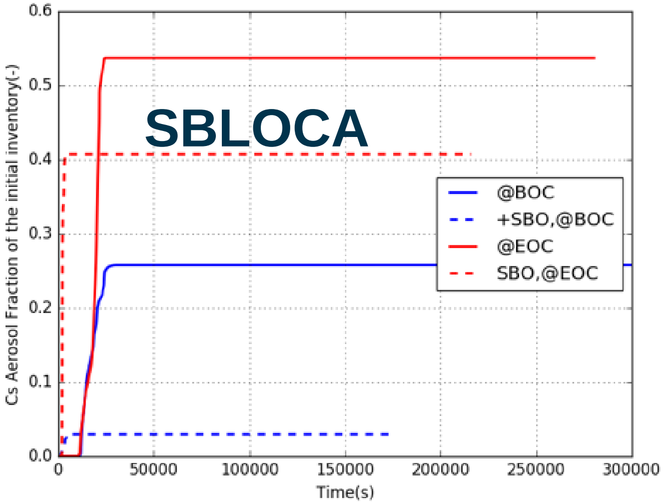


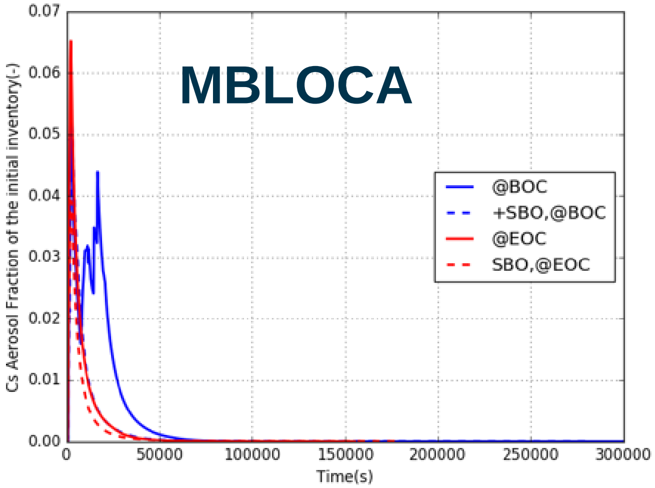


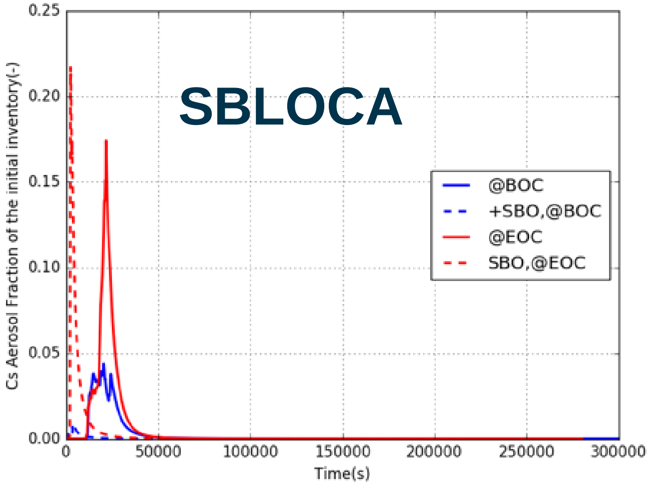
- Release strongly dependent on:
  - Scenario
  - Initial core inventory
- SBLOCA+SBO (@EOC)
- Total: Up to 75% of the initial inventory
- Aerosols: up to 60% of the initial inventory

Cs Mass in the containment: Total and Aerosols









- Release strongly dependent on:
  - Scenario
  - Initial core inventory

- SBLOCA+SBO (@EOC)
  - Total: Up to 55% of the initial inventory
  - Aerosols: up to 20% of the initial inventory

Conclusion and Outlook

- Platform of reference codes (ASTEC, FSTC, JRODOS) for the analysis of the radiological impact of severe accidents assessed at KIT, triggered by the KIT/Framatome joint participation to EU and National projects.
- ASTEC results for selected SA scenarios in a generic KONVOI NPP showed large effect of the initial amount of FPs in the core both on the accident progression and on the ST.
- Evaluation of realistic fuel inventories and employment in integral codes modelling is mandatory to perform reliable evaluations ST evaluations → final goal: supporting the emergency and decision teams during severe accidents.
- **Source term databases from ASTEC results + UQ currently under assessment for generic KONVOI and VVER-1000 NPPs.**
- Rather solid basis of understanding in view of the planned ASTEC analyses at KIT of SA scenarios in generic **Small Modular Reactors (SMRs)**.
    - Evaluation of the fuel inventories challenging because of the rather heterogeneous core arrangements in these systems → insights from the EU H2020 McSAFER project
    - Employment of innovative materials, e.g. Accident Tolerant Fuels (ATFs)