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Radiological Consequences of severe accident scenarios in a generic KONVOI NPP

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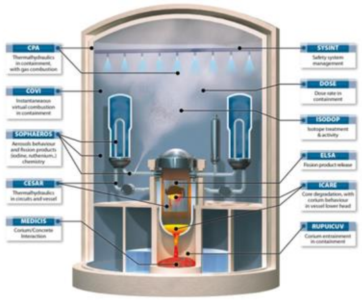
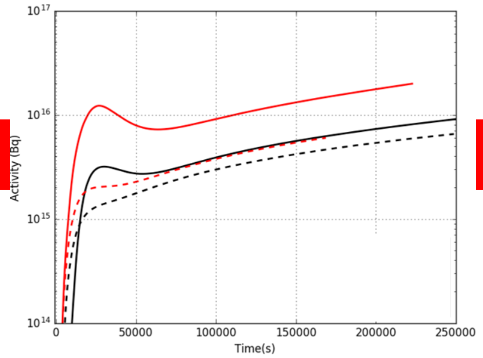
Motivation

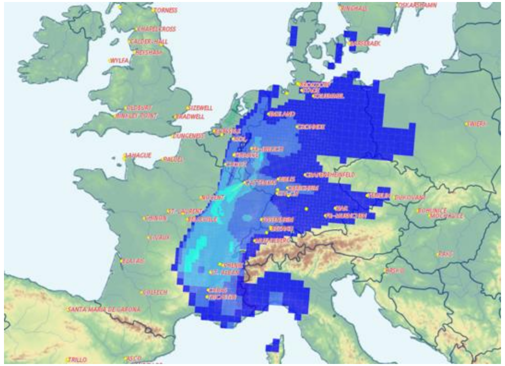
- Evaluation of source term (ST) and fission product (FP) dispersion during a severe accident (SA) in current and innovative NPPs is one of the major objectives of the nuclear reactor safety research program at KIT.
- **Main goal** → supporting the emergency and management teams during such abnormal events → **a reliable evaluation of the source term is mandatory**.
- **ASTEC plays a central role in the KIT strategy for SA analyses.**
- **ASCOM Project** → WP4-RUNPLANT (see ppt from A. K. Mercan), WP5-EXTEND (see ppt from O. Murat)
- **EU Management and Uncertainties of Severe Accidents (MUSA, CIEMAT) and German WAME projects (KIT/Framatome collaboration)** (see ppt from A. Stakhanova)
- **IAEA CRP** ‘Advancing the State-of-Practice in Uncertainty and Sensitivity Methodologies for Severe Accident Analysis in Water-Cooled Reactors’
- **Accident Tolerant Fuels**: IAEA CRP ATF-TS and OECD-NEA QUENCH-ATF
- **Coming EU SASPAM-SA (ENEA) and EU ASSAS (IRSN) projects**

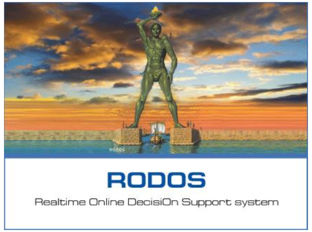
KIT Strategy for Source Term Analyses (1/2)

- 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 (KATUSA, FSTC), FP dispersion (JRODOS).









- 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)**.

A. K. Mercan, et al., 2022, Source term estimation and dispersion analysis of VVER-1000 reactor in case of LBLOCA along with SBO, ERMSAR2022, May 19-22, Karlsruhe.
O. Murat, et al., 2022, Extending Capabilities of the ASTEC Severe Accident Code to Simulate Accident Sequences of Generic BWR4 Mark I, ERMSAR2022, May 19-22, Karlsruhe.

KIT Strategy for Source Term Analyses (2/2)

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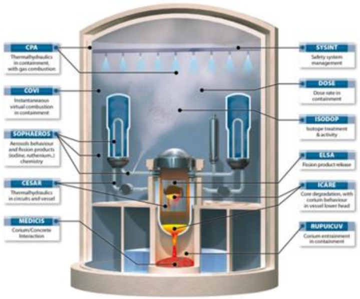
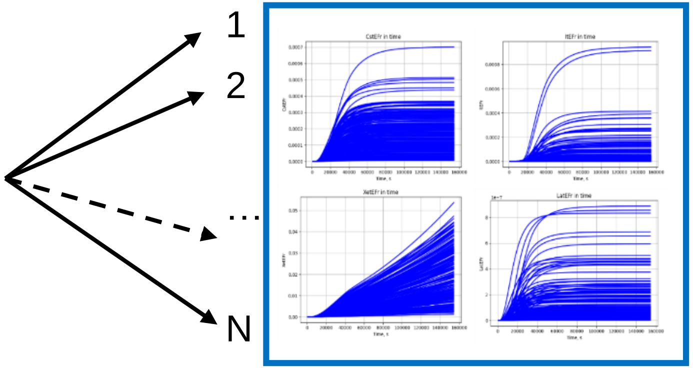
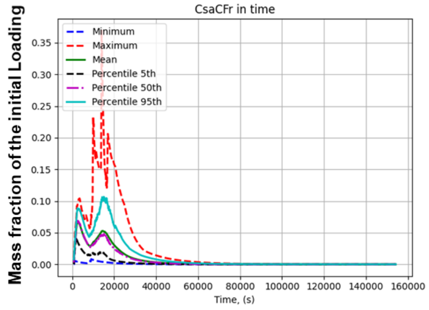
- Development of in-house **KArlsruhe Tool for Uncertainty and Sensitivity Analyses (KATUSA)** → UQ of the ASTEC ST results + **training database** for
- **Source Term prediction** → Monte Carlo-based Bayesian inference model (**MOCABA** algorithm from Framatome GmbH embedded)

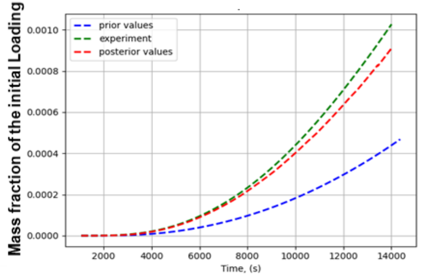


ST Training Database



ASTEC/KATUSA





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 (v2.2.0.1) Model of a Generic KONVOI NPP

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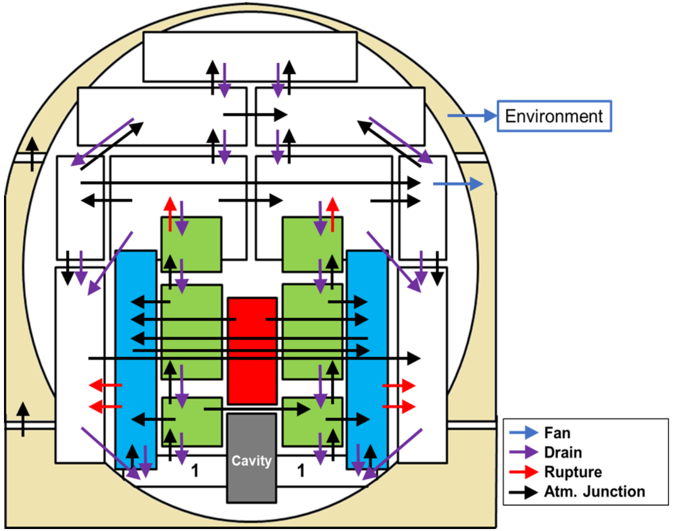
- All the calculation modules activated.
- SOPHAEROS: Optimization of the RCSMESH nodalization based on parametric analyses for the STRU LOOP.
- Auxiliary building model assessed (not shown here).
- Containment Leakage from design.
- Heat exchange (convection, conduction, and radiation) and oxidation 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)

ASTEC (v2.2.0.1) Model of a Generic KONVOI NPP

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- FPEVOL (of course) and SMEVOL
- Heat Exchange: Radiation (RADR, RADCAV), Fluids/LP (CONVLOW), Corium layers/vessel (EXCHLOWE)
- Chemical Interactions: Oxidation (Zr, SS, magma), Fuel/Zr dissolution by molten Zr, Zr liquefaction by liquid Ag-In-Cd, SS, and grid materials
- Magma movement: 2D-relocation, Corium slump in the LP and Jet fragmentation, Decanting, Separation and mixing in the LP (default model employed)
- Cavity
  - The original wall thickness (EWALL=2.35 m) has been increased to 4.0 m base on PWR 900 case*
  - MODE OPENCAVI employed
- PWR 900 input deck employed for the calculation parameters for the RUPUICUV, MEDICIS, COVI, and CORIUM calculation modules.
- DCH connections Vessel → Cavity → Containment
- FPs transport activated in each connection

*K. Chevalier-Jabet, et al., 2015. Iodine source term computations with ASTEC, link with PSA2-tools and fast running source term tools for emergency organization, OECD-NEA/NUGENIA-SARNET Workshop, March 30, April 1, Marseille, France.

ASTEC (v2.2.0.1) Model of a Generic KONVOI NPP

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- Library of fuel inventories for an equilibrium cycle with 328 effective full power days computed (30 days time step).
- 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.

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

Scenarios

- **MBLOCA (12”) and SBLOCA (2”)**
  - Medium (12’’) and small (2’’) break of the cold leg at t=0 s
  - Reactor scram, if the primary pressure < 132 bar or containment overpressure > 30 mbar
  - Admission to turbine and closure of the main feed water pumps into the steam generator;
  - 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
  - Main Coolant Pumps are coasted down and the pressure regulation in the pressurizer is switched off
  - Activation of the Emergency Feed Water System (EFWS) when the liquid level of one SG falls <4.50 m
  - HPIS (SBLOCA) and LPIS (MBLOCA) activated (T_gas in the primary > 650 °C) up to the tanks are empty → severe accident
  - Activation of the Extra Borating System when the pressurizer water level <2.30 m
  - 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

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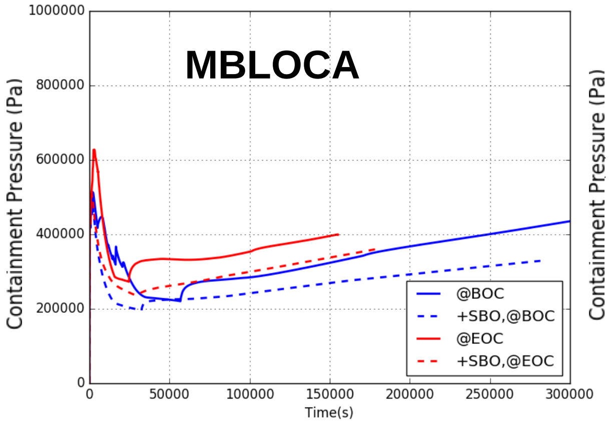
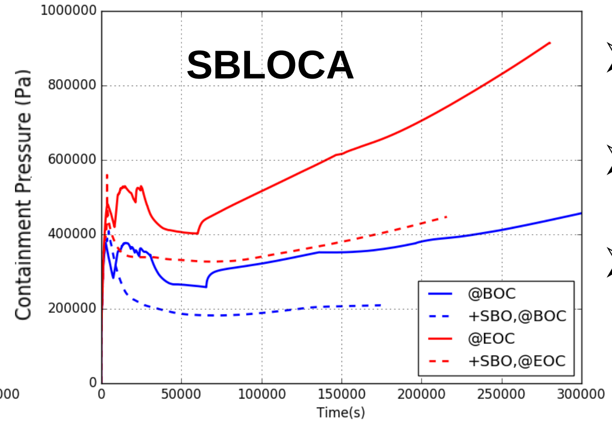
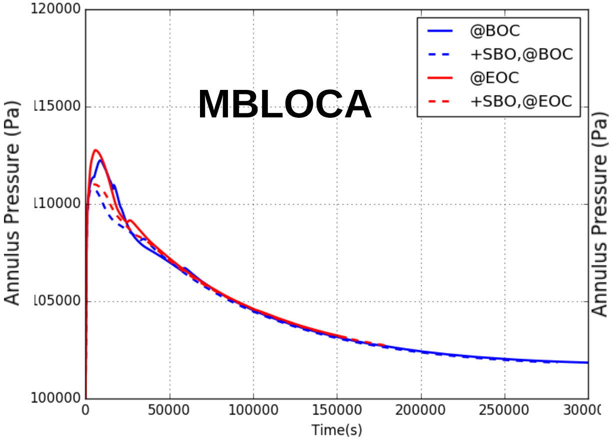
	BOC		EOC	
Phenomenon	**SBLOCA**	**SBLOCA+SBO**	**SBLOCA**	**SBLOCA+SBO**
FPs Release (s)	11056	1133	10619	1426
20/50 tons relocated to the LP (h)	6.6	0.5/0.7	6.0	0.5
70/90 tons relocated to the LP (h)	6.6	-/-	6.0	-/-
LPV Failure (h)	**8.5**	**1.3**	**6.8**	**1.0**
Basemate Rupt. (h)	102.2	48.5	77.8	6.0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

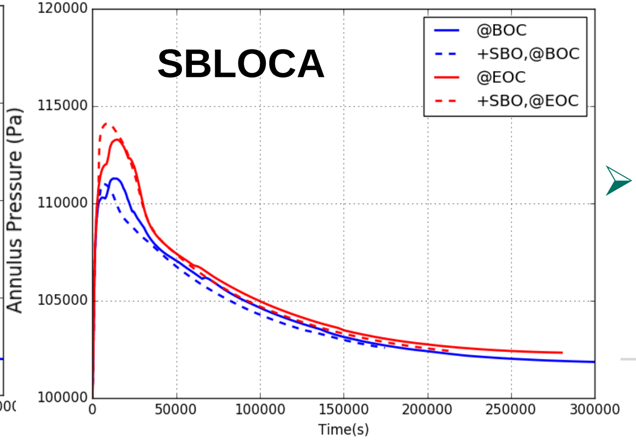
- Significant effect of the composition of the fuel inventory on the accident progression.
- By comparison with MBLOCA results, huge effect of scenarios on the mass of aerosols in the containment.

Containment and Annulus Pressure





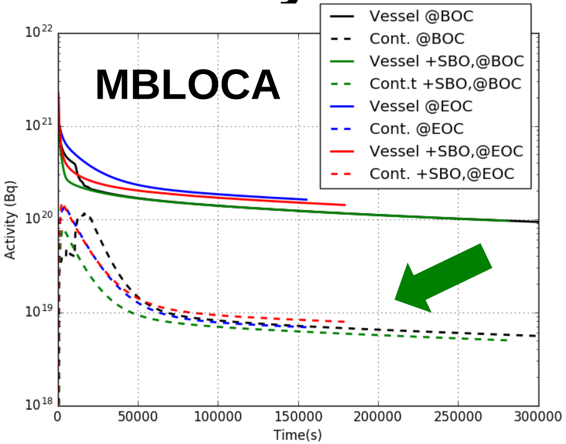


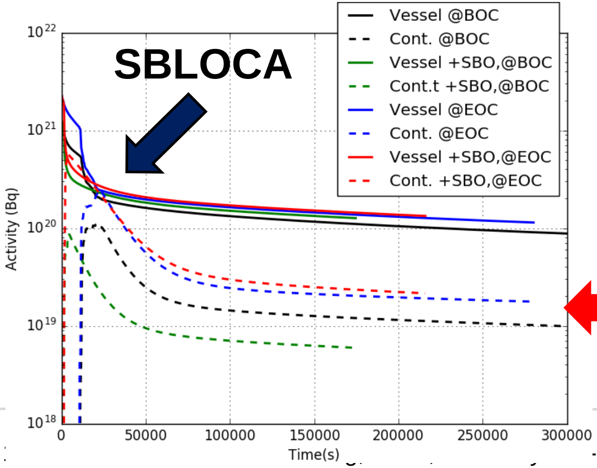


- Higher pressures in EOC conditions.
- Long term higher pressures w/o SBO.
- In SBLOCA (EOC), pressure containment up to about 9 bar
  - No containment rupture modeled (WAME project) .

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

Total activity in the Plant



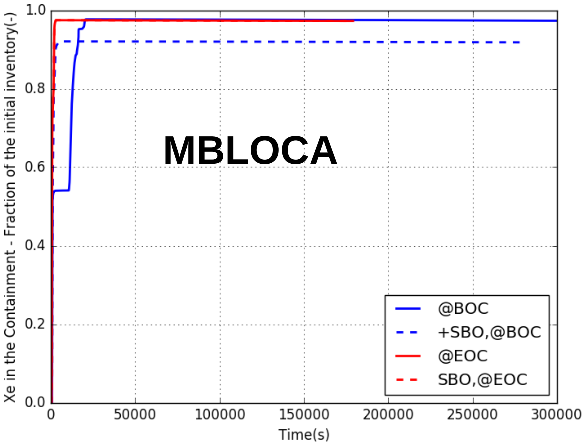


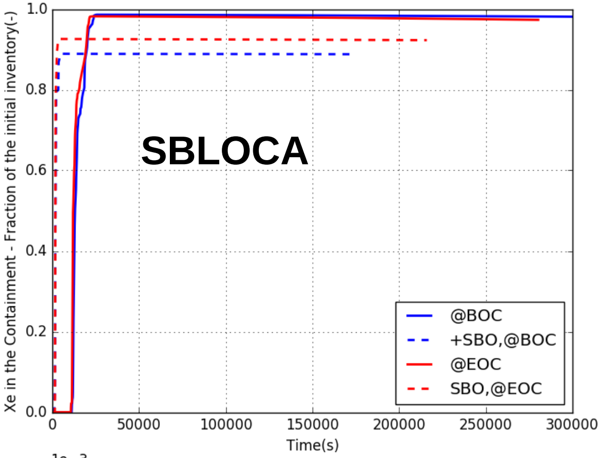
- **MBLOCA scenarios →** **about 1% of the initial activity of the fuel inventory transported to the containment.**

- **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

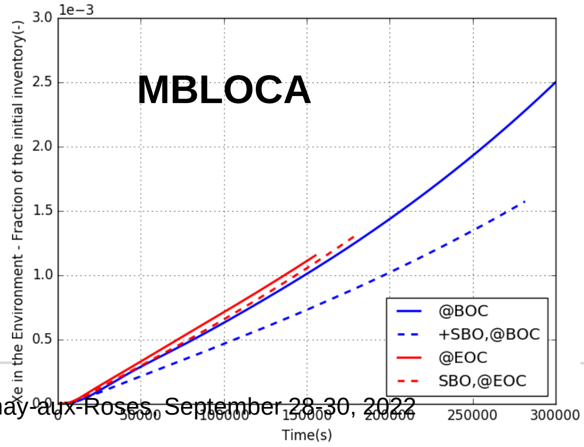
- Noble gases almost completely transported to the containment.

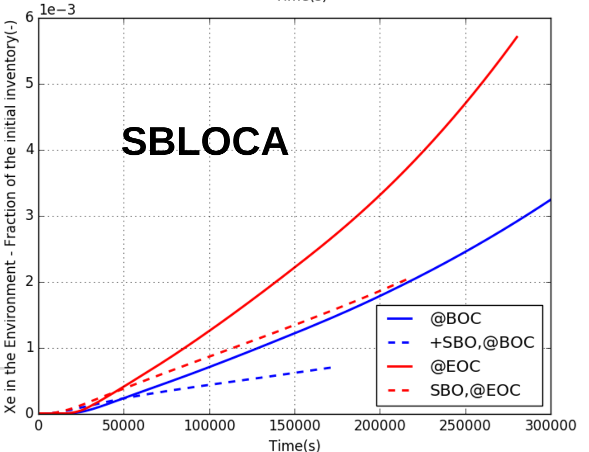




Release to the Env.

- Larger release:
  - **at higher fuel burn-up**
  - **in SBLOCA scenarios**





I Mass in the containment: Total and Aerosols

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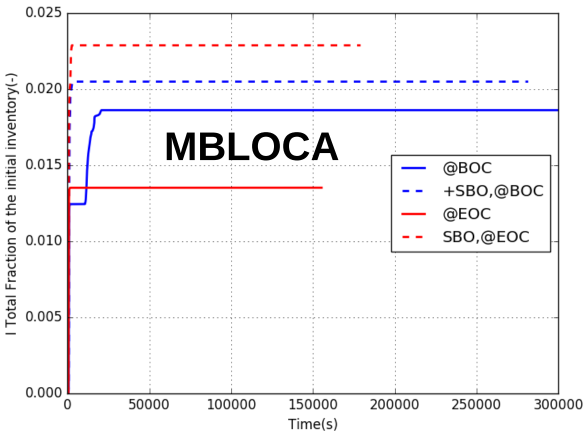
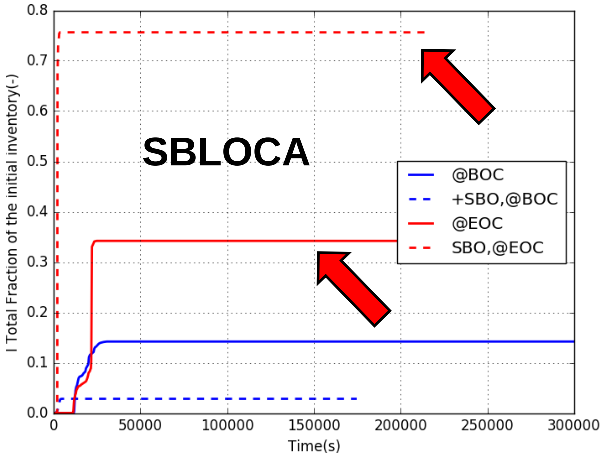
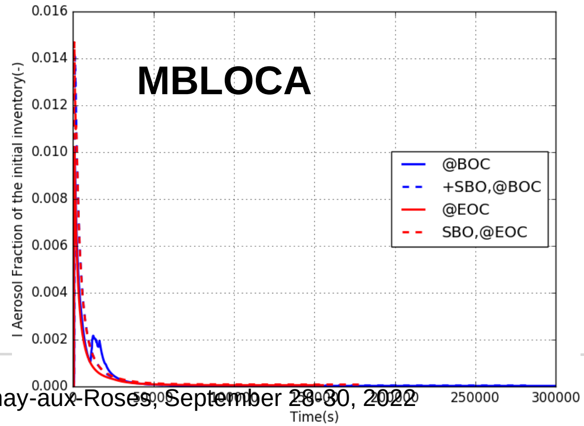
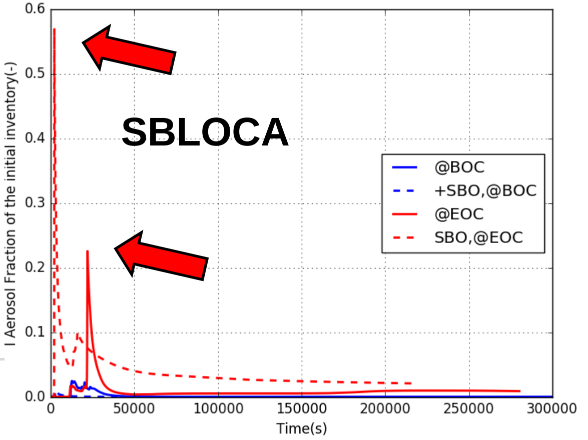
- Release strongly dependent on:
  - Scenario
  - Initial core inventory

- SBLOCA+SBO (@EOC)
- Total: Up to 75% of the initial inventory
- Aerosols: up to 60% of the initial inventory





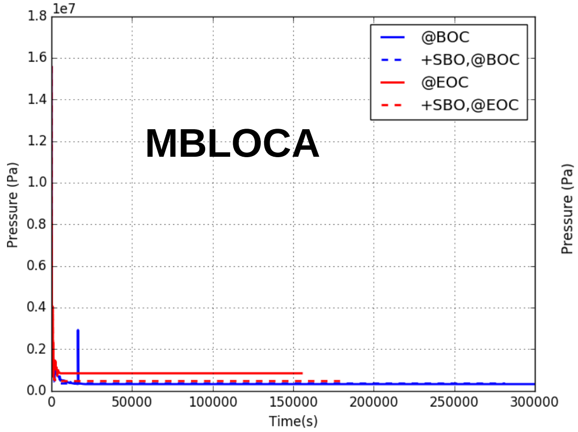


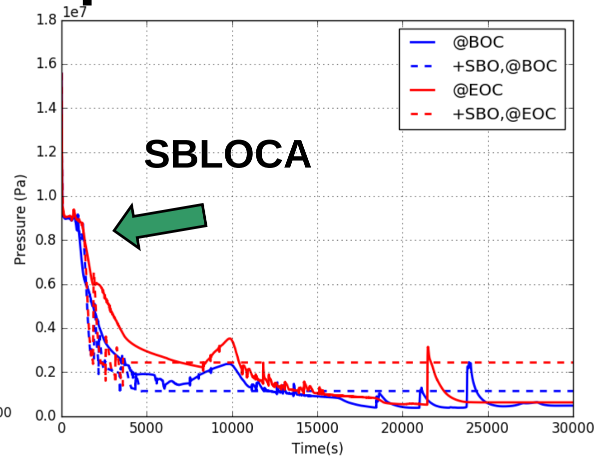


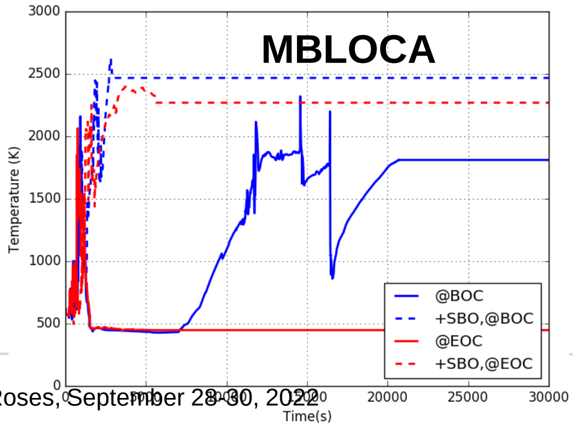
Accident Progression and FP release/transport

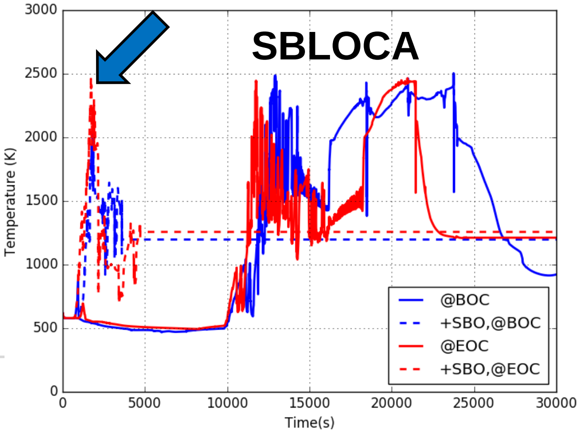
- Primary Pressure and gas temperature at the core outlet in focus.

- SBLOCA vs. MBLOCA
- Larger pressure in the primary for longer time
- Higher temperature escalation in SBLOCA+SBO (@EOC) → Lower retention in the circuit





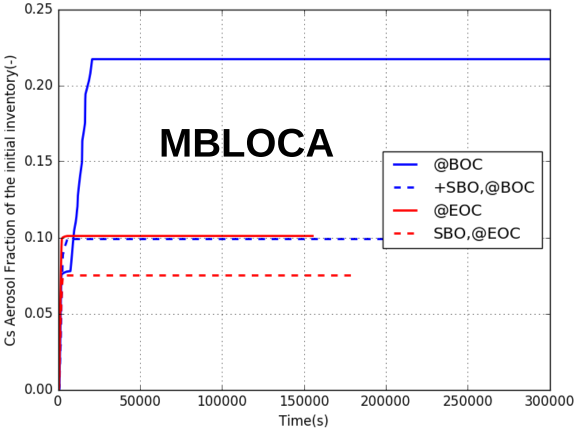


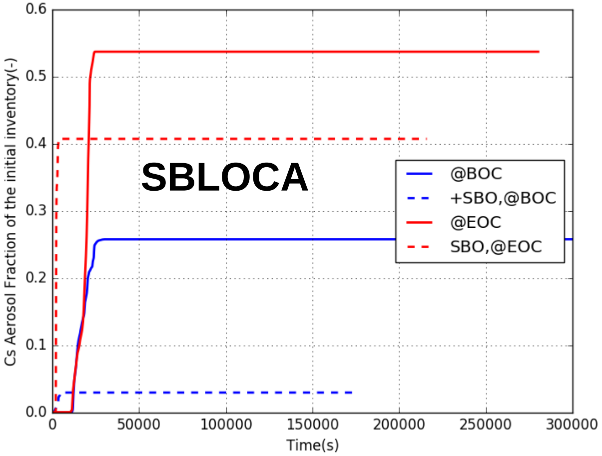


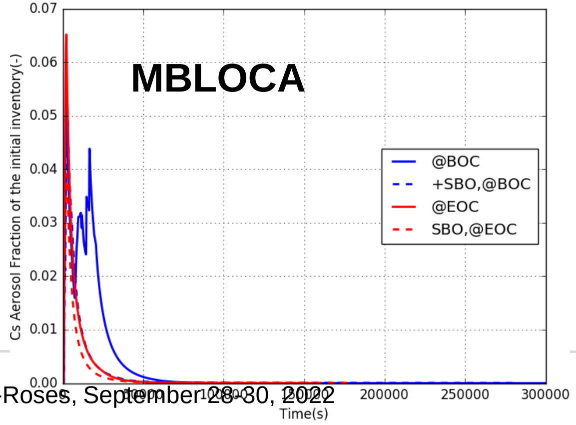
Cs Mass in the containment: Total and Aerosols

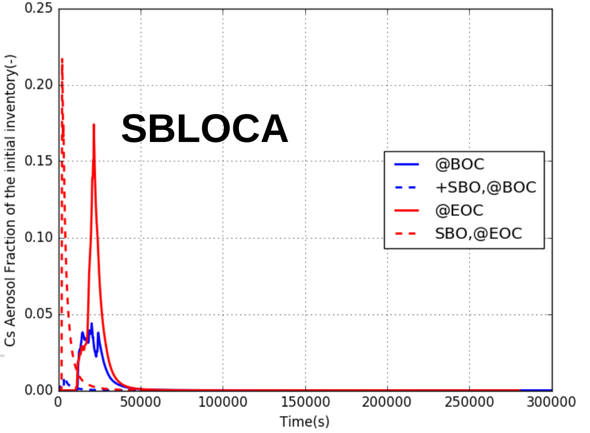
- ➢ Release strongly dependent on:
  - ➢ Scenario
  - ➢ Initial core inventory

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



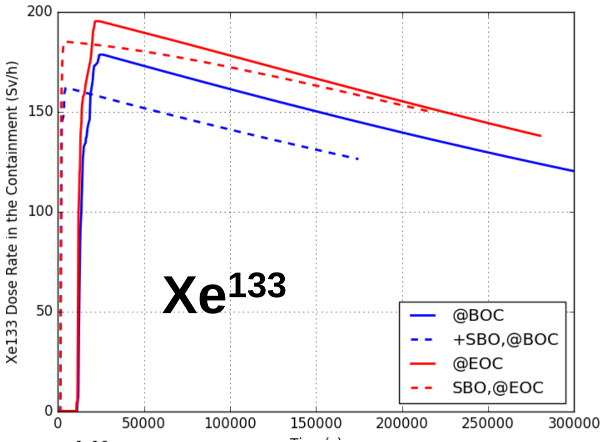


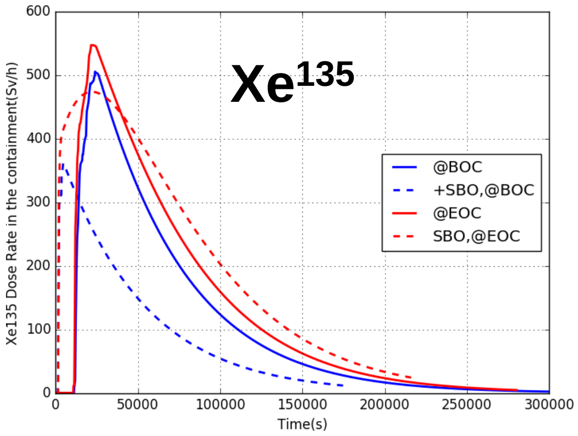


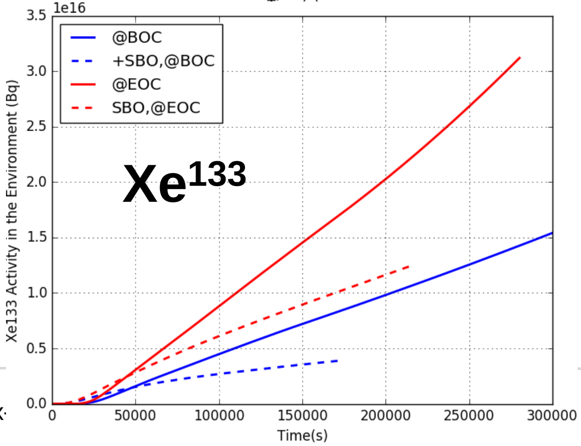


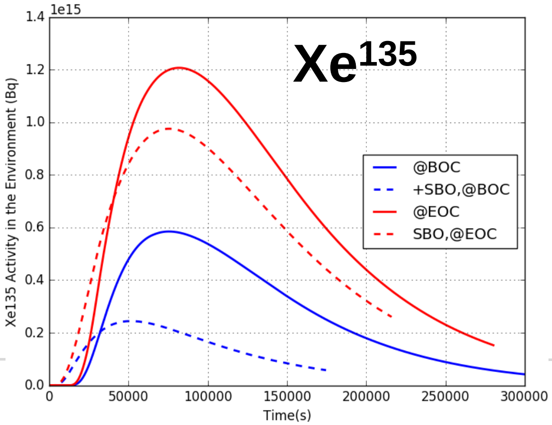
Xe-wise isotopes in the Containment and Environment

- 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

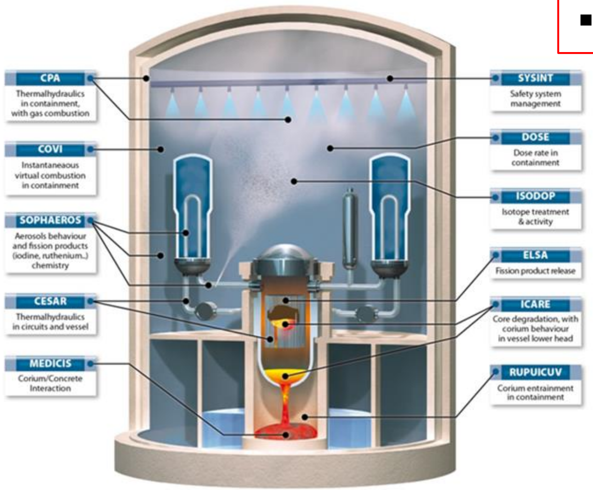




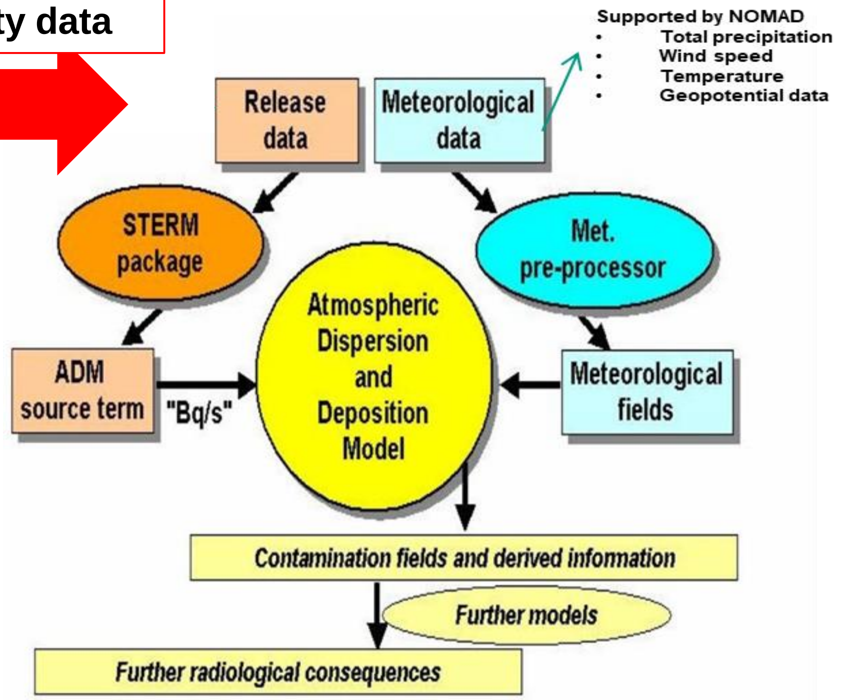




The ASTEC/JRODOS Platform



- Isotope-wise mass data
- Isotope-wise activity data



- ASTEC/JRODOS coupling assessed at INR → **first-of-its-kind**
- Employed for radiological consequences of SAs in generic VVER-1000 plants (PhD work, A. K. Mercan)

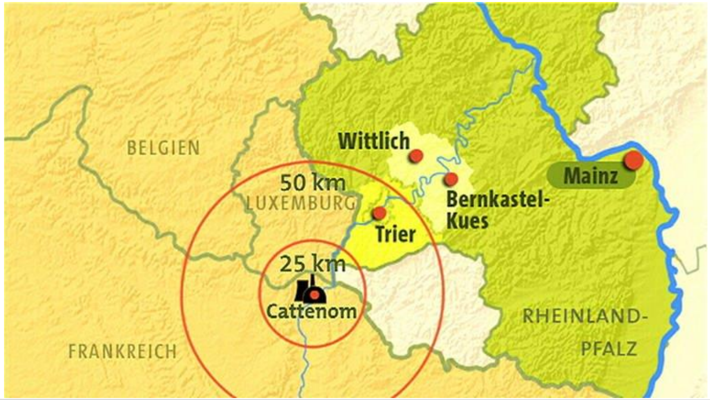
A.K. Mercan, et al., 2022. Source term estimation and dispersion analysis of VVER-1000 reactor in case of LBLOCA along with SBO, ERMSAR, Karlsruhe, May 16-19.

W. Raskob, 2012. Radiological consequences to the environment resulting from Severe Accidents, Course on Severe Accident Phenomenology and Management, KIT, July 10th -11th.

Example of Calculation

- The consequences of a MBLOCA severe accident in a generic KONVOI-1300 have been evaluated.
- The plant has been located in JRODOS in Cattenom (France).
- In Cattenom, 4 PWR-1300 Units (built between 1979 and 1991) are in operation.
- The effect on the environment in winter and summer time have been evaluated.

https://de.wikipedia.org/wiki/Kernkraftwerk_Cattenom



Courtesy from A. K. Mercan

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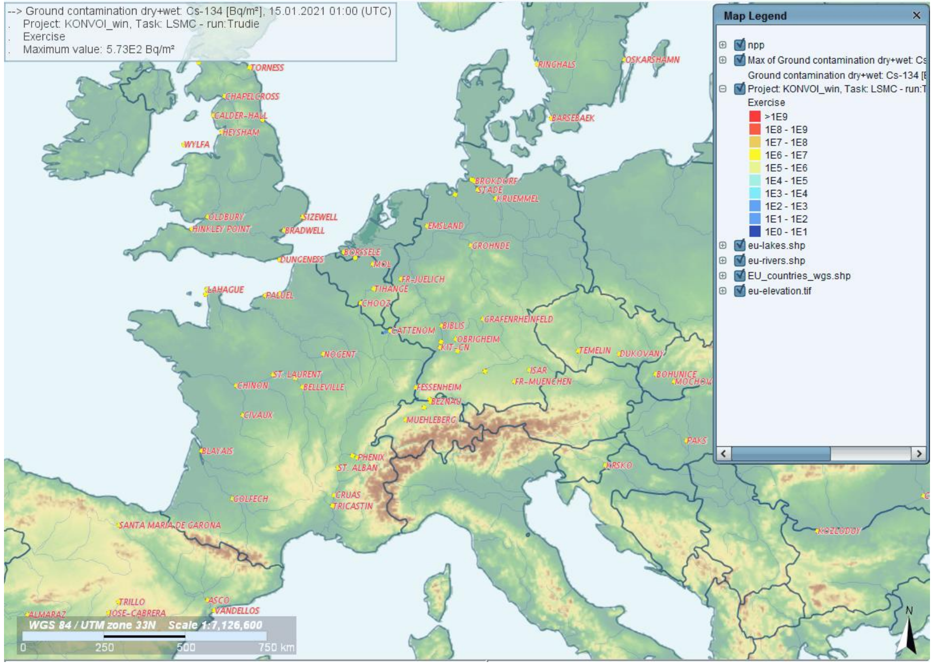
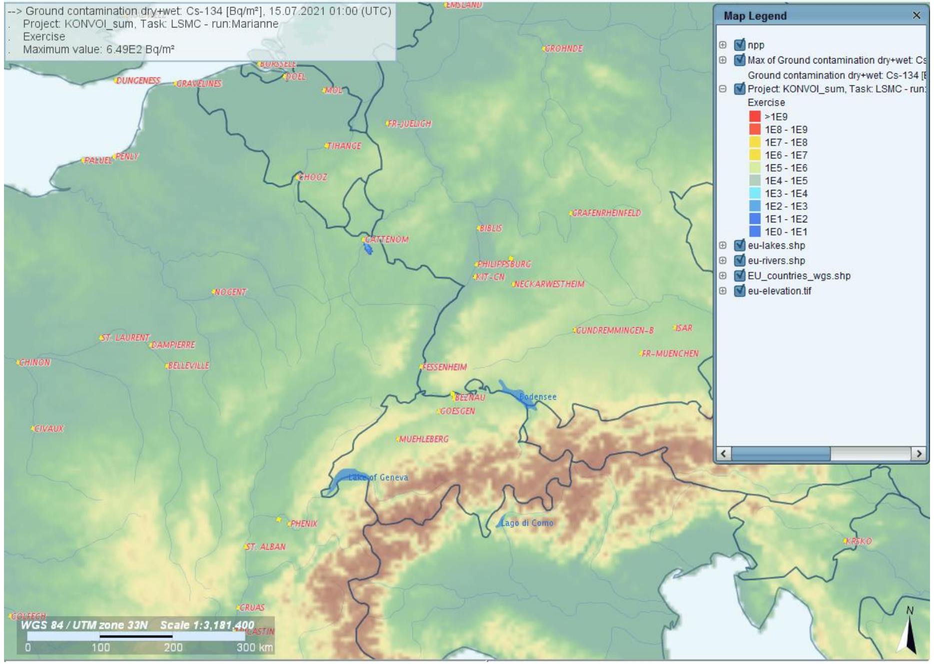
Winter and Summer results: Cs^{134} contamination

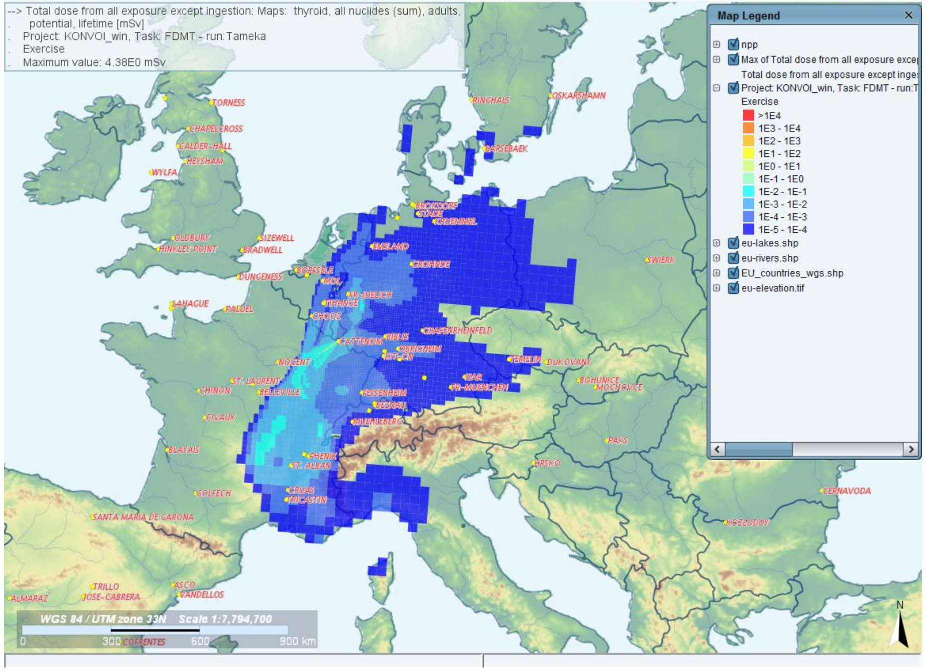


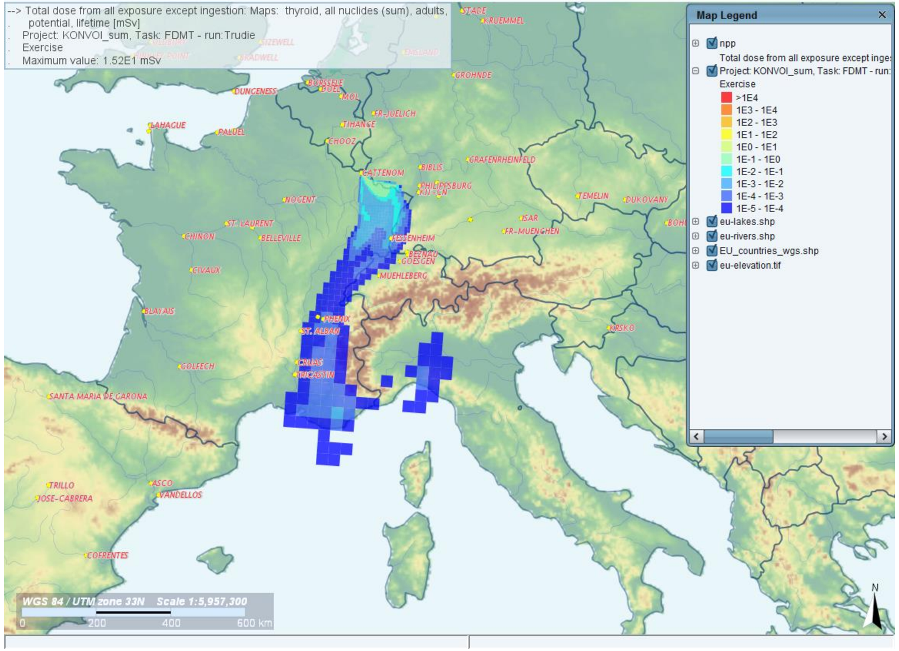


- Larger area involved during the Winter time.
- Maximum value larger during the summer time ($6.32 \cdot 10^4$ Bq/m2) than in the wintertime ($1.57 \cdot 10^4$ Bq/m2).

Courtesy from A. K. Mercan

Winter and Summer results: Thyroid dose lifetime adult





- Maximum values 15.2 mSv (Summer) and 4.38 mSv (Winter).
- Larger I^{131} wet and dry ground contamination during the summer time ($7.96 \cdot 10^4$ Bq/m^2) than in the wintertime ($2.55 \cdot 10^4$ Bq/m^2).

Conclusion

- The generic input deck (v2.2.0.1) of the PWR KONVOI 1300 has been further extended to evaluate the ST for different SA scenarios.
- **Platform of reference codes (ASTEC, KATUSA, JRODOS) for the analysis of the radiological impact of severe accidents assessed at KIT.**
- Source term database from ASTEC results + UQ currently under assessment for generic KONVOI NPP.
- **The code show a rather high stability (i.e. no hot restarts).**
- ASTEC-JRODOS analyses show that the codes are able to estimate the contamination and the short- and long-term exposure to the radiological sources → multi-interactive code calculation could help decision makers, regulators, and TSO.
- **Outlook:**
  - **Evaluating the uncertainty band for the JRODOS results by providing the results of the ASTEC source term UQ from the database.**