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MELCOR 2.2 Nuclear Power Plant UQ study, lesson learned

14th EMUG
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Ljubljana, Slovenia
12th – 14th April, 2023

Laboratory for Reactor Physics and Thermal-Hydraulics

Content

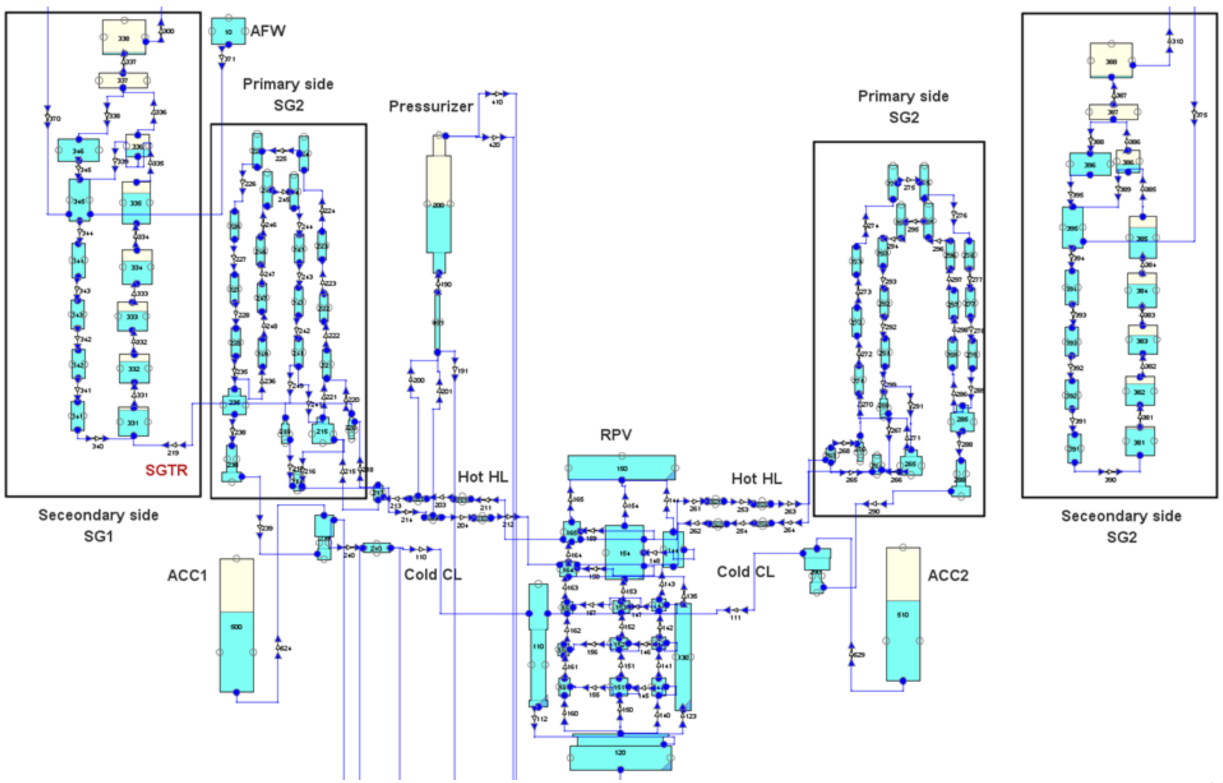
- MUSA – WP5 introduction
- NPP and Scenario description
- Uncertainty Quantification set-up
- Results
- Findings

MUSA – WP5 introduction

- The MUSA project is financed by Euratom research and training program 2014–2018 and focuses on the management and uncertainties of severe accidents.
- The project's main goal is to develop a methodology for severe accident Uncertainty Quantification (UQ).
- The MUSA WP5 aims to investigate mitigated severe accident scenarios by performing a UQ study.

NPP and Scenario description

- In Figure below nodalization of RCS of described input deck is presented
  127 CVH, 166 FL, 145 HS.
- Nodalization of the primary circuit is done to allow natural circulation during accidental conditions. SGTR is placed in the bottom part of the SG1 tube bundles, highlighted in red in Figure 1.



NPP and Scenario description

- NPP considered: PWR, 2 loop, 1000 MWth.
- Information about the selected SA sequence:
  - Scenario type; Station Black Out (SBO) + Steam Generator Tube Rupture (SGTR) (Mitigated)
  - Initial plant operational point before the start of the transient: full power
  - Initiator events; SBO
  - Main systems available; accumulators, PRessuriZer (PRZ) and Steam Generator (SG) Safety Valves (SV)
  - Rest systems considered not available;
  - Severe Accident Management actions included; reflood of damaged SG
  - Accident sequence time frame ex-vessel 220000s (61.1h)
  - SG SV on damaged SG stuck open

Uncertainty Quantification set-up

Table 1. Information on the computing environment.

Severe accident code and version	MELCOR 2.2
Uncertainty Tool and version	DACOTA 6.12.0 + Python Scripts
Computing environment (PC or HPC, operating system)	PC
CPU characteristics, RAM	INTEL i7 8700 3.2 GHz, RAM 16 GB
Wall-Clock time to perform the Reference Calculation	CPU= 4.576706E+04s ~12.7 h
Wall-Clock time to assess the database for UQ Analysis	~10 days plus re-runs
Number of calculations launched to perform the UQ	100
Number of calculations failed	~30 after re-run 0

Table 2. Partners uncertainty methodology brief description.

	Partner Choice
Uncertainty Methodology used	probabilistic method to propagate input uncertainty,
Methods used to define the required number of samples	Wilks
Sampling methods	Monte Carlo
Probability and confidence level selected	95%, 95%
Number of calculations launched to perform the UQ	100
Number of calculations failed	First iteration **30**, after relaunch **0**
Way of dealing with failed calculations	Relaunching it manually and adjusting max dt

Uncertainty Quantification set-up

- FOM1a is a % of initial inventory retained in the secondary side of damaged SG. Variable RN1-TYCLDEP is used thus **only deposited** on SG structures mass is considered.
- FOM1b is a % of initial inventory retained in the secondary side of damaged SG, RN1-TYCLT. All mass **located in SG** volume is considered.
- FOM2 is a % of initial inventory released to the environment RN1-TYCLT.
  For each relevant RN classes (Xe, Cs, I2, Mo, CsI, CsM) the variable was defined and divided by the initial inventory mass of a particular RN class.

Table 3 FOMs chosen for the study.

No	ST related FOM
1.1	Total FP1 & NG2 release (mass fraction [% ii]) into environment (time dependent or at one point in time): - from containment or in bypass scenarios from RCS for reactor scenarios - from SFP building for SFP scenarios 1 FP = Cesium and Iodine for Reactor Cases; FP = Cesium, Iodine and Ruthenium for SFP Cases 2 NG = Noble Gases
1.9	Total FP and NG (mass fraction [% ii]) into RCS or into SG secondary in case of bypass scenario (time dependent or at one point in time) - not relevant for SFP scenarios

Uncertainty Quantification set-up

Table 4:Collection of final uncertainty parameters

MELCOR Parameters	Default		min	max	Distribution
RN1_ASP	*DMIN*	*1.E-07*	*1.E-07*	*2.E-06*	*U*
RN1_MS00	*CHI*	*1*	*1*	*3.8*	*U*
	GAMMA	*1*	*1*	*4.0*	*U*
	FSLIP	*1.257*	*1.1*	*1.3*	*U*
RN1_MS01	*TKGOP*	*0.05*	*0.0002*	*0.055*	*U*
	FTHERM	*2.25*	*1.75*	*2.75*	*U*
COR_RF	*FCELA*	*0.1*	*0.1*	*0.6*	*U*
COR_LP	*VFALL*	*1.0*	*0.05*	*2.0*	*U*
COR_CMT	*FUOZR*	*0.2*	*0.1*	*1.0*	*U*
	FZXZR	*0.0*	*0.0*	*0.5*	*U*
COR_CHT – Candling Heat Transfer Coefficients	*HFRZUO*	*7500.0*	*1000.0*	*7500.0*	*U*
	HFRZZR	*7500.0*	*1000.0*	*7500.0*	*U*
	HFRZSS	*2500*	*1000.0*	*2500*	*U*
	HFRZZX	*7500.0*	*1000.0*	*7500.0*	*U*
	HFRZSX	*2500*	*1000.0*	*2500*	*U*
	HFRZCP	*2500*	*1000.0*	*2500*	*U*
COR_LHF	*HDBLH*	*1000/MODEL*	*10*	*1000*	*U*

Results FOM1a

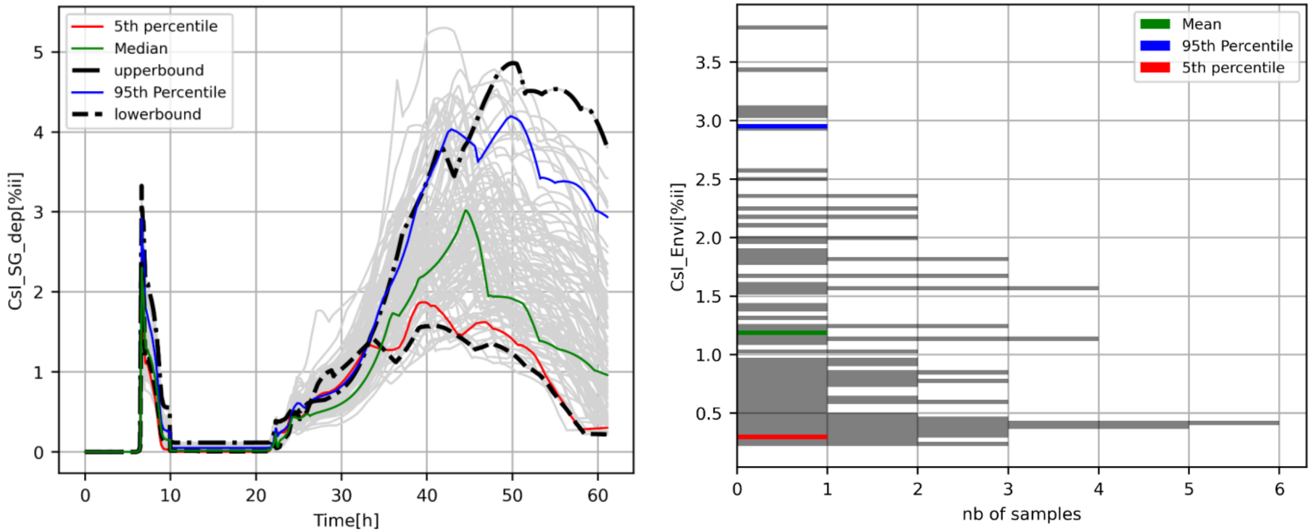


Figure 2 Dispersion and PDF figure for CsI retention in damaged SG - FOM1a

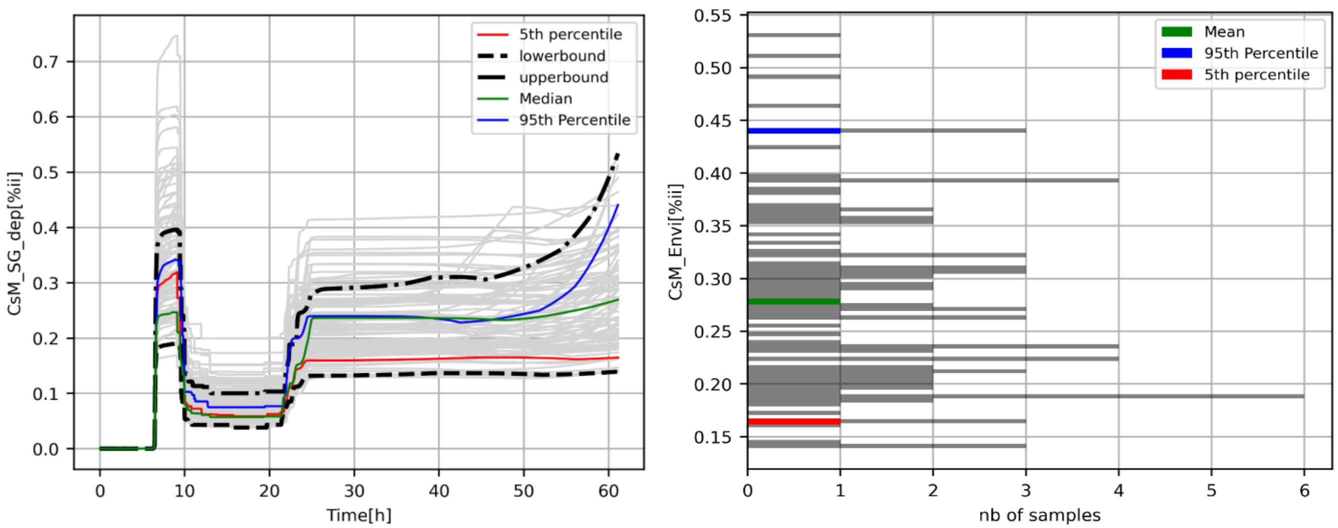
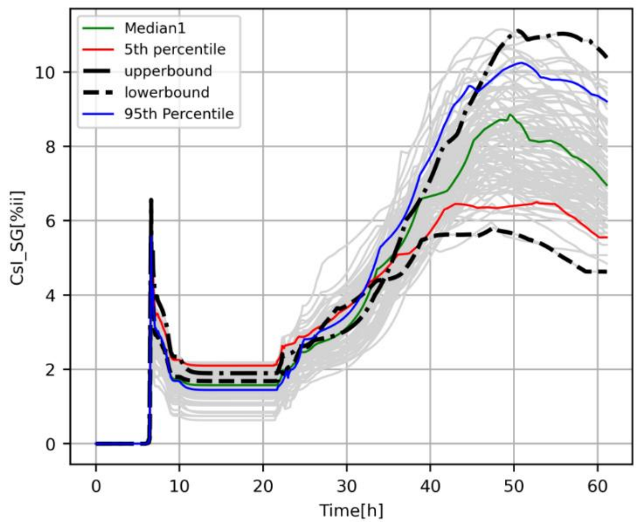


Figure 3 Dispersion and PDF (at the end of calculation) figure for CsM retention in damaged SG - FOM1a.

Results FOM1b



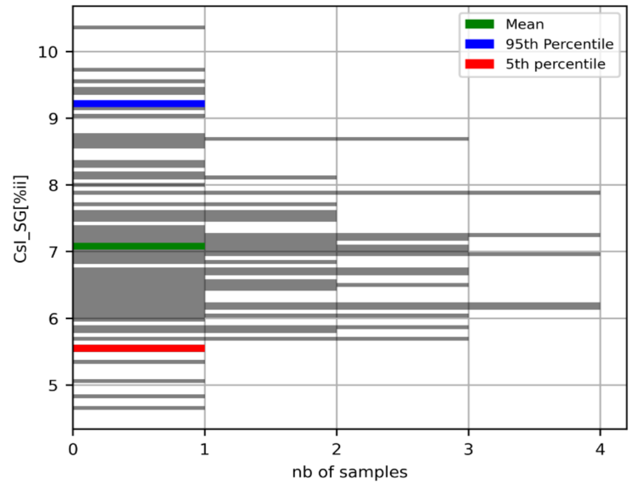
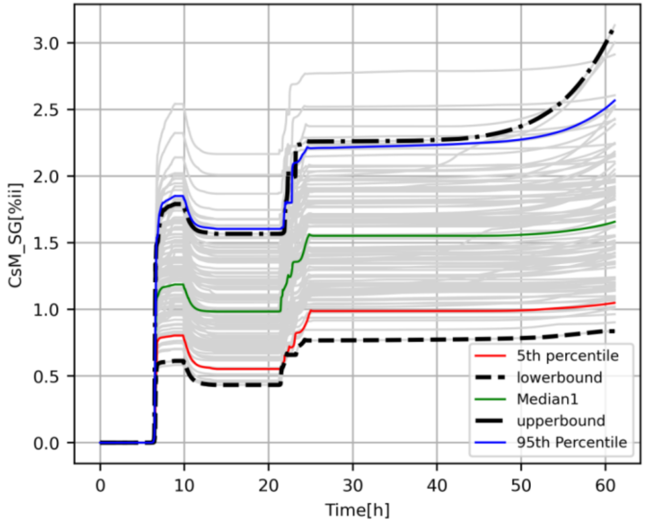


Figure 4 Dispersion and PDF figure for CsI retention in damaged SG -FOM1b



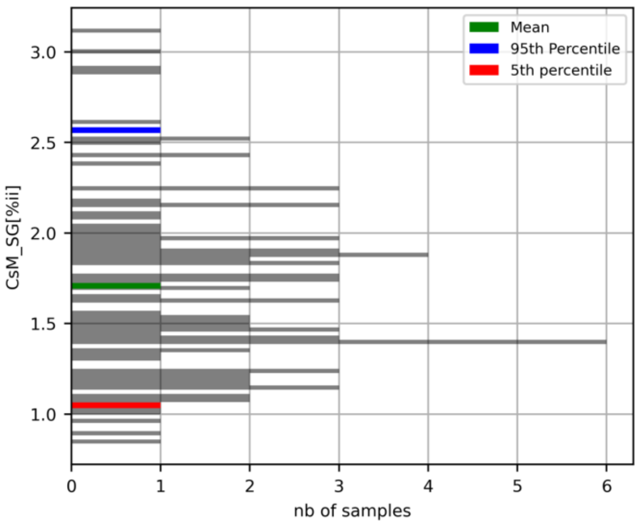


Figure 5 Dispersion and PDF (at the end of calculation) figure for CsM retention in damaged SG - FOM1b.

Results FOM2

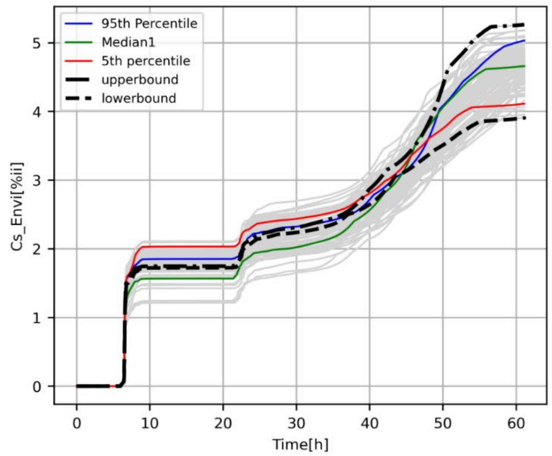


Figure 6 Dispersion figure for Cs, releases to environment, FOM2

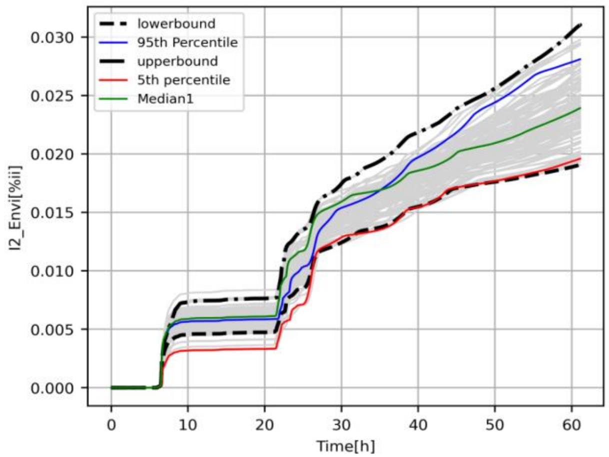


Figure 7 Dispersion figure for I2, releases to environment, FOM2

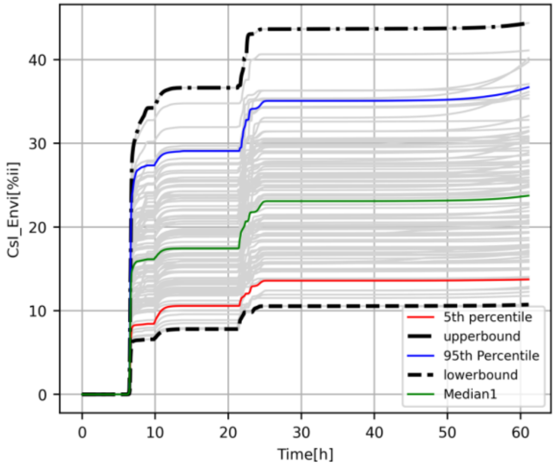


Figure 8 Dispersion figure for CsI, releases to environment, FOM2

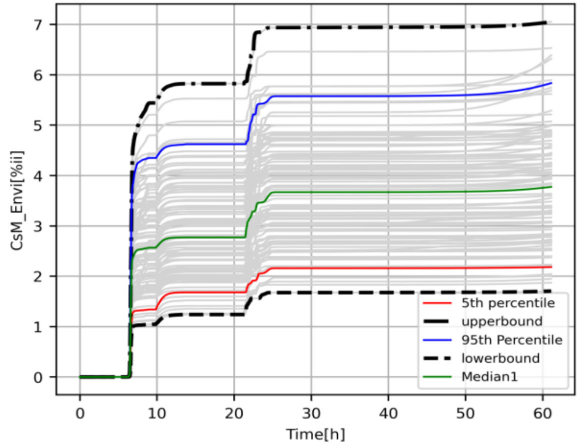


Figure 9 Dispersion figure for CsM, releases to environment, FOM2

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Results FOM1 - correlation coefficients

- It looks like some of the parameters are correlated.
- CHI and GAMMA are correlated with opposite signs which could suggest that they can be pre correlated

Table 5 Correlation coefficient for FOM1a at the end of calculation.

Uncertain Parameter	Cs_SG_dep kg]			CsI_SG_dep [kg]			CsM_SG_dep [kg]			I2_SG_dep [kg]			Mo_SG_dep [kg]			Xe_SG_dep [kg]		
	pearson	partial pearso	spearman	pearson	partial pearso	spearman	pearson	partial pearso	spearman	pearson	partial pearso	spearman	pearson	partial pearso	spearman	pearson	partial pearso	spearman
d1(DMIN)	0.038	-0.079	0.000	0.084	-0.420	0.083	0.140	-0.761	0.080	0.135	-0.814	0.131	-0.035	0.661	-0.010	nan	0.984	nan
d2(GAMMA)	0.159	0.214	0.234	0.197	0.360	0.266	-0.304	-0.466	-0.328	0.122	0.020	0.211	-0.703	-0.775	-0.805	nan	-0.018	nan
d3(CHI)	-0.593	-0.651	-0.702	-0.834	-0.859	-0.819	-0.578	-0.684	-0.636	-0.273	-0.051	-0.232	0.325	0.479	0.414	nan	0.054	nan
d4(TKGOP)	-0.014	0.024	0.002	-0.051	-0.013	-0.051	-0.017	0.030	-0.031	-0.089	0.698	-0.052	-0.105	-0.195	0.018	nan	0.690	nan
d5(FSLIP)	0.048	0.068	0.063	0.031	0.108	0.038	-0.124	-0.133	-0.115	-0.073	-0.049	-0.116	0.008	-0.057	0.041	nan	-0.049	nan
d6(FTHERM)	0.014	0.026	0.005	0.004	0.021	-0.038	0.018	0.033	0.053	0.163	-0.061	0.135	0.023	0.006	0.044	nan	-0.061	nan
d7(FCELA)	0.134	0.165	0.107	0.104	0.183	0.149	-0.247	-0.370	-0.260	0.009	-0.009	0.069	0.031	0.133	0.016	nan	0.009	nan
d8(VFALL)	0.119	0.180	0.032	0.016	0.043	0.013	0.016	0.070	0.015	-0.072	-0.013	-0.124	0.009	0.000	-0.011	nan	-0.013	nan
d9(HDBLH)	0.201	0.311	0.194	-0.029	0.034	0.028	-0.330	-0.426	-0.303	-0.080	-0.015	-0.001	0.122	0.173	0.200	nan	0.015	nan
d10(FUOZR)	-0.038	-0.037	-0.018	-0.094	-0.193	-0.048	0.092	0.169	0.085	0.064	-0.018	-0.011	0.068	0.135	0.076	nan	-0.018	nan
d11(FZXZR)	0.057	0.086	-0.001	0.013	0.041	0.042	-0.061	-0.095	-0.033	0.116	0.001	0.094	-0.110	-0.243	0.063	nan	0.010	nan
d12(HFRZUO)	-0.039	-0.085	0.031	0.030	0.024	0.032	0.070	0.094	0.049	0.055	0.017	0.121	0.059	0.088	-0.018	nan	-0.016	nan
d13(HFRZZR)	-0.052	-0.114	0.078	0.065	0.086	0.066	-0.094	-0.195	-0.107	-0.044	-0.025	0.004	0.050	0.067	0.003	nan	-0.024	nan
d14(HFRZSS)	0.001	0.000	0.033	-0.013	-0.045	0.033	-0.004	-0.030	-0.011	0.079	0.005	0.075	-0.026	-0.013	-0.070	nan	-0.005	nan
d15(HFRZZX)	0.128	0.143	0.084	0.055	0.050	0.051	-0.071	-0.142	-0.075	-0.025	0.051	-0.009	-0.074	-0.181	0.127	nan	-0.048	nan
d16(HFRZSX)	-0.030	-0.063	0.040	0.078	0.050	0.053	0.138	0.158	0.106	0.106	-0.018	0.055	-0.027	0.004	-0.057	nan	-0.018	nan
d17(HFRZCP)	-0.003	-0.015	0.027	-0.017	-0.103	-0.013	-0.026	-0.083	-0.010	0.037	-0.006	-0.047	0.010	0.018	0.012	nan	-0.006	nan

Table 6 Correlation coefficient for FOM1b at the end of calculation.

Uncertain Parameter	Cs_SGkg]			CsI_SG[kg]			CsM_SG[kg]			I2_SG[kg]			Mo_SG[kg]			Xe_SG[kg]		
	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman
d1(DMIN)	0.014	0.185	0.007	0.177	-0.294	0.187	0.012	-0.200	-0.008	0.084	0.826	0.070	-0.045	0.667	-0.025	-0.102	1.000	-0.039
d2(GAMMA	0.415	0.488	0.449	0.212	0.276	0.206	-0.627	-0.749	-0.628	0.260	-0.018	0.230	-0.699	-0.785	-0.780	-0.005	-0.005	0.189
d3(CHI)	-0.356	-0.446	-0.334	-0.591	-0.617	-0.583	0.442	0.628	0.439	-0.317	-0.061	-0.343	0.365	0.546	0.447	-0.061	0.059	-0.151
d4(TKGOP)	0.031	0.070	0.058	-0.049	-0.023	-0.078	-0.060	-0.149	-0.046	-0.121	0.999	-0.131	-0.117	-0.227	0.015	0.124	-0.998	-0.088
d5(FSLIP)	0.165	0.225	0.155	0.070	0.136	0.067	-0.062	-0.155	-0.049	-0.092	0.075	-0.105	0.023	-0.039	0.034	-0.124	0.032	0.018
d6(FTHERM	0.013	0.044	0.034	-0.114	-0.136	-0.109	-0.093	-0.199	-0.061	0.140	0.054	0.088	0.008	-0.017	0.045	0.045	0.069	0.122
d7(FCELA)	0.238	0.275	0.205	0.022	0.006	0.063	-0.246	-0.372	-0.230	-0.154	0.016	-0.123	0.017	0.114	0.008	-0.041	-0.038	-0.162
d8(VFALL)	0.027	0.045	0.059	-0.016	0.002	0.014	0.058	0.096	0.008	-0.071	0.000	-0.107	-0.023	-0.051	-0.013	-0.184	-0.190	-0.265
d9(HDBLH)	0.145	0.203	0.134	-0.193	-0.224	-0.184	-0.101	-0.204	-0.102	-0.189	-0.009	-0.180	0.142	0.210	0.200	-0.187	-0.213	-0.267
d10(FUOZR	-0.090	-0.109	-0.077	-0.129	-0.170	-0.111	0.043	0.092	0.017	-0.027	0.015	-0.085	0.071	0.152	0.066	0.057	0.081	0.046
d11(FZXZR)	0.023	0.053	0.015	-0.026	-0.003	-0.002	-0.030	-0.081	-0.003	0.021	-0.016	0.004	-0.111	-0.254	0.067	0.051	0.052	0.004
d12(HFRZU	-0.109	-0.151	-0.107	-0.014	-0.010	0.016	0.045	0.084	0.064	0.143	0.006	0.078	0.044	0.072	-0.023	-0.035	-0.005	-0.058
d13(HFRZZ	-0.026	-0.037	0.038	0.040	0.052	0.011	-0.067	-0.113	-0.046	-0.120	0.032	-0.134	0.018	0.016	-0.008	-0.194	-0.197	0.007
d14(HFRZS	0.031	0.032	0.007	0.032	0.027	0.073	-0.005	0.029	-0.005	0.010	0.013	-0.010	-0.051	-0.062	-0.074	-0.272	-0.013	-0.104
d15(HFRZZ	0.115	0.154	0.085	0.030	0.022	0.020	-0.006	-0.038	0.009	-0.093	0.038	-0.102	-0.069	-0.174	0.110	-0.059	-0.039	-0.042
d16(HFRZS	-0.048	-0.077	-0.013	0.050	0.009	-0.001	0.018	0.093	0.009	-0.116	0.006	-0.106	-0.036	0.008	-0.069	-0.200	-0.006	-0.178
d17(HFRZC	0.003	0.005	0.032	-0.015	-0.056	0.004	-0.080	-0.141	-0.066	-0.002	-0.008	0.038	-0.007	-0.006	0.010	-0.006	0.009	-0.147

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Results FOM1 - correlation coefficients

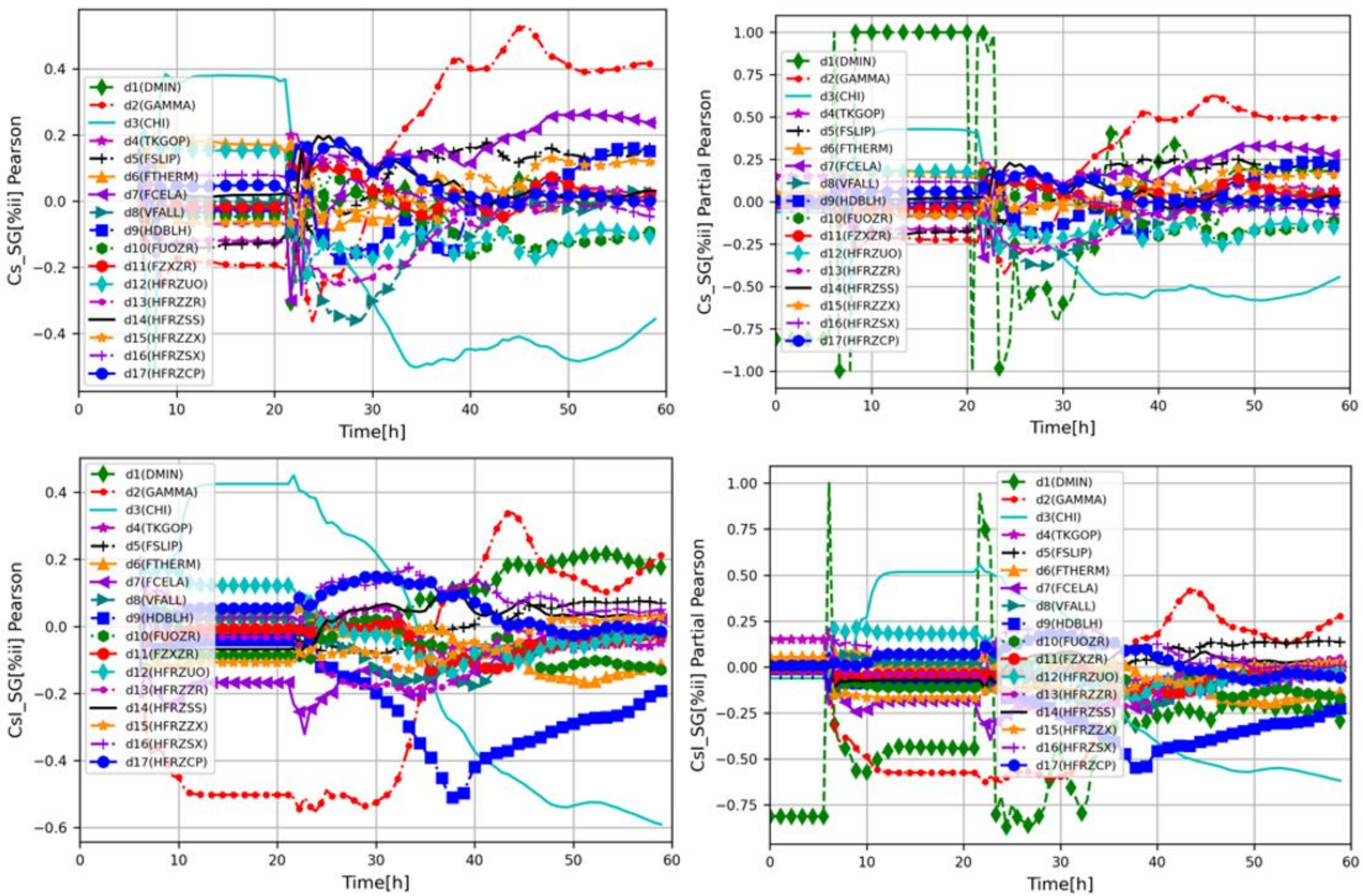

Figure 10 Pearson and Partial Person correlation coefficients for Cs and CsI in FOM1b.

Results FOM2 - correlation coefficients

Table 7 Correlation coefficient for FOM2 at the end of calculation.

Uncertain Parameter	Cs_Envi[kg]			CsI_Envi[kg]			CsM_Envi[kg]			I2_Envi[kg]			Mo_Envi[kg]			Xe_Envi[kg]		
	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman	pearson	partial pearson	spearman
d1(DMIN)	-0.192	0.189	-0.175	-0.024	-0.222	-0.029	-0.024	-0.222	-0.029	0.191	-1.000	0.205	0.090	-0.114	0.104	0.018	-0.229	0.016
d2(GAMMA	-0.498	-0.596	-0.485	-0.628	-0.764	-0.621	-0.628	-0.764	-0.621	-0.170	-0.183	-0.162	-0.328	-0.363	-0.353	-0.063	-0.059	-0.052
d3(CHI)	0.399	0.521	0.412	0.522	0.706	0.519	0.522	0.706	0.519	-0.080	-0.079	-0.076	0.261	0.314	0.237	0.130	0.199	0.042
d4(TKGOP)	0.051	0.060	0.065	-0.072	-0.185	-0.048	-0.072	-0.185	-0.048	-0.081	-0.093	-0.094	-0.064	-0.094	-0.124	-0.060	-0.098	-0.136
d5(FSLIP)	0.010	-0.056	-0.007	-0.042	-0.150	-0.022	-0.042	-0.150	-0.022	0.064	0.090	0.099	-0.006	-0.017	0.020	-0.114	-0.154	-0.083
d6(FTHERM	0.122	0.188	0.125	-0.085	-0.198	-0.066	-0.085	-0.198	-0.066	-0.116	-0.137	-0.132	-0.051	-0.075	-0.038	0.035	0.006	0.023
d7(FCELA)	0.154	0.281	0.132	-0.179	-0.278	-0.176	-0.179	-0.278	-0.176	-0.322	-0.352	-0.286	-0.243	-0.265	-0.221	-0.648	-0.678	-0.686
d8(VFALL)	-0.203	-0.325	-0.196	0.061	0.095	0.018	0.061	0.095	0.018	-0.066	-0.058	-0.057	-0.023	-0.031	-0.034	0.093	0.141	0.052
d9(HDBLH)	0.119	0.143	0.100	-0.004	-0.044	-0.025	-0.004	-0.044	-0.025	-0.299	-0.332	-0.305	-0.215	-0.258	-0.187	-0.122	-0.167	-0.105
d10(FUOZR	-0.179	-0.258	-0.168	0.007	0.024	-0.001	0.007	0.024	-0.001	-0.085	-0.089	-0.094	-0.037	-0.041	-0.054	-0.081	-0.105	-0.105
d11(FZXZR)	0.029	-0.001	0.038	-0.002	-0.038	0.002	-0.002	-0.038	0.002	-0.016	0.000	-0.038	-0.045	-0.058	-0.047	-0.114	-0.126	-0.086
d12(HFRZU	-0.033	-0.052	-0.009	0.046	0.090	0.053	0.046	0.090	0.053	-0.026	-0.020	-0.033	0.072	0.095	0.082	0.095	0.143	0.063
d13(HFRZZ	0.044	0.089	0.007	-0.034	-0.057	-0.031	-0.034	-0.057	-0.031	-0.062	-0.051	-0.050	-0.068	-0.067	-0.082	-0.040	-0.078	-0.019
d14(HFRZS	0.009	0.039	-0.031	-0.016	0.017	0.005	-0.016	0.017	0.005	0.054	0.073	0.071	-0.010	-0.003	-0.010	-0.046	-0.051	-0.057
d15(HFRZZ)	-0.006	-0.025	0.010	0.019	0.003	0.047	0.019	0.003	0.047	-0.077	-0.095	-0.093	-0.055	-0.072	-0.051	-0.059	-0.073	-0.043
d16(HFRZS)	0.021	0.087	-0.013	0.011	0.103	0.011	0.011	0.103	0.011	0.005	-0.014	-0.009	0.079	0.108	0.077	0.117	0.185	0.115
d17(HFRZC	0.069	0.060	0.040	-0.073	-0.136	-0.067	-0.073	-0.136	-0.067	-0.027	-0.055	0.008	-0.037	-0.056	-0.044	0.005	-0.012	-0.008

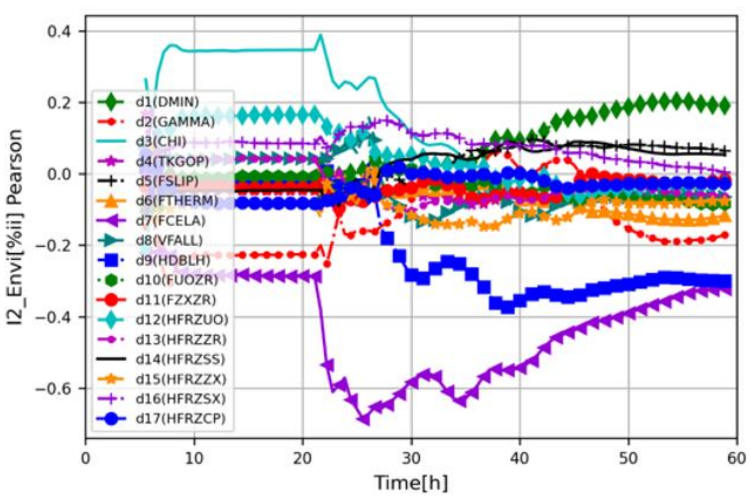

Figure 11 Pearson correlation coefficients for I_2 in FOM2.

Results FOM2 - correlation coefficients

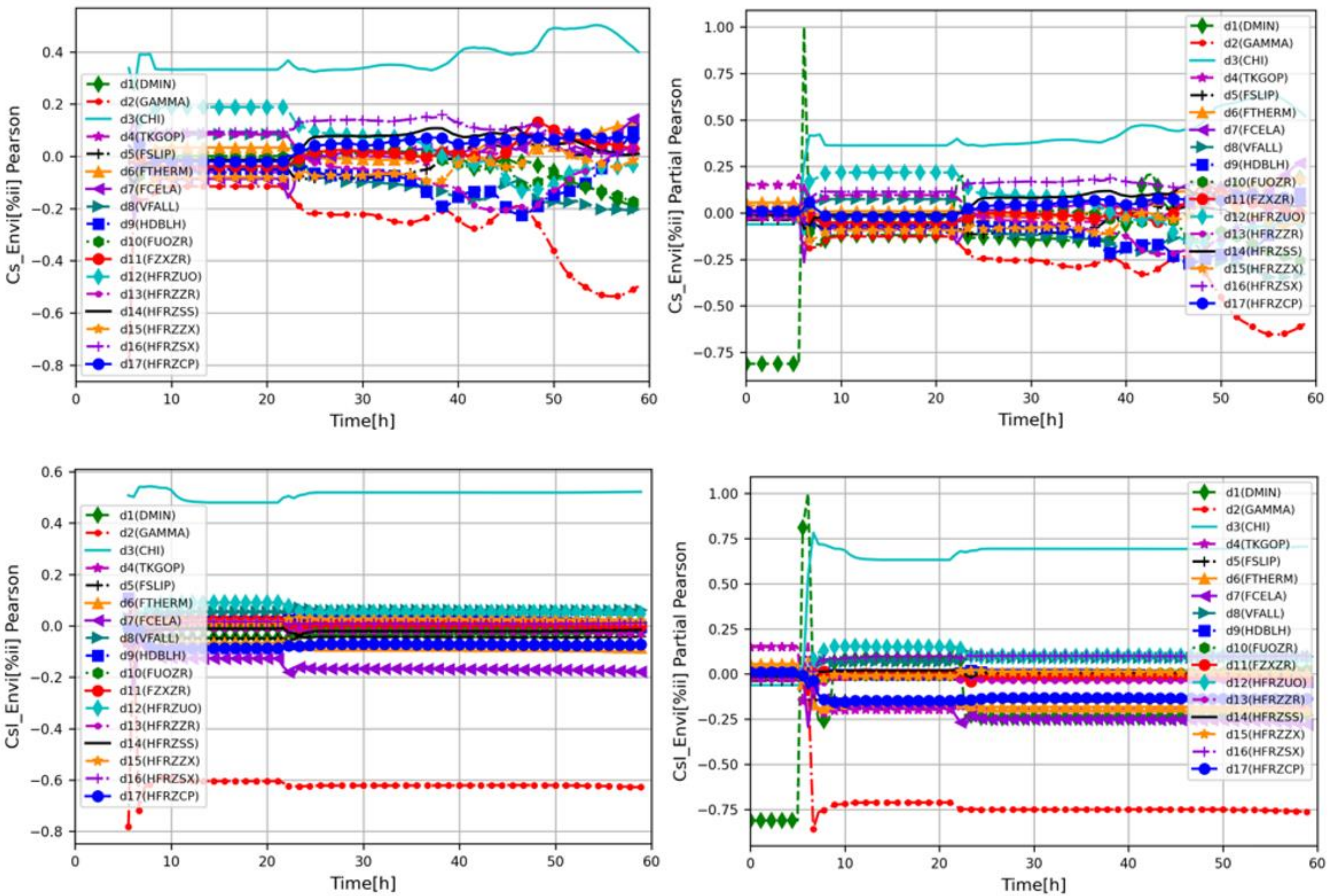

Figure 12 Pearson and Partial Person correlation coefficients for Cs and CsI in FOM2.

Findings - UQ launch

- We used SNAP/MELCOR/DAKOTA coupling for UQ calculations, and we reached ~**70% of successful calculations**, which means around 30 calculations crashed.
- We found out that simple **relaunching using Launchpad** helps in around 20 (out of 30) cases. The rest (~10) crashed again, but when we adapted time step (decreased maximum time step at the moment it crashed), they were also able to finalize the calculation.
- This raises a question and the remark, if **time step adaptation impacts** the results and we should try to develop algorithms or features within SNAP to re-run the failed calculation, and if it's not enough, then try to adapt time step.

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Findings – UQ analyses

- Based only on this study's results, just a few parameters strongly impact the ST,
  - radiation heat exchange factor – **FCELA** in the COR package,
  - Aerosol agglomeration shape factor - **GAMMA** in RN package
  - Aerosol dynamic shape factor - **CHI** in RN package.
- A deep understanding of these parameters and setting up the most accurate values could help reduce uncertainty; however, we are not sure if it will increase the accuracy of the results.
- Introducing these parameters as dynamic, instead of static, variables in the code could be another solution, but this demands extended review and a new version of the codes.
  - Maybe, defining different aerosol groups for various shape factors will decrease uncertainty and keep/increase the accuracy of the results.

Findings

- Nevertheless, in ST study the leakage path is still a major uncertainty.
- It should be noted that another uncertainty comes from water leakages which are far less known / not really modeled in SA codes than releases to the atmosphere.
- The abovementioned parameter **pre-correlation (e.g. CHI and GAMMA)**, identifying the **most influential parameters** which affect ST, and trying to **narrow down** the input value space for those parameters is a good first step to increase the certainty of the SA codes.

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Wir schaffen Wissen – heute für morgen

My thanks go to

- **Stephan BRUMM – WP5 coordinator**
- **All MUSA coordinators and partners**

THANK YOU!

MUSA project has received funding from the Euratom research and training program 2014–2018 under grant agreement No. 847441.

MUSA