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Nuclear Data Uncertainty Quantification for Operated Cycles in a Swiss PWR

WPEC-SG46, Tuesday November 26th 2019

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Outline

1. INTRODUCTION

2. METHODOLOGY

3. UNCERTAINTY ANALYSIS
   – CYCLE DEPLETION
   – SAFETY PARAMETERS

4. CONCLUSION

Introduction

– PSI, as TSO, performs calculations on the Swiss NPPs (e.g. reload licensing analysis) for the regulator (ENSI)

– In the framework of **Best-Estimate Plus Uncertainty** (BEPU) calculations, efforts are made at PSI for **Uncertainty Quantification** (UQ) on cycle depletion parameters and safety parameters of full core simulations

– Various sources of uncertainties: Technological parameters, Operating conditions, Thermal-Hydraulics, **Nuclear Data** (ND)

=> Only the ND are taken into account in this study

– Coupling the Core simulation database for the Swiss LWR (CMSYS) with the ND UQ platform (Shark-X)

➢ Assessment of ND uncertainties on cycle depletion parameters (e.g. power distributions, burnup) and on safety parameters (e.g. Doppler coefficient, rod worth)

O. LERAY et al., “Methodology for core analyses with nuclear data uncertainty quantification and application to Swiss PWR operated cycles,” Ann. Nucl. Energy 110, 547, Pergamon (2017).

Uncertainty Propagation Platform

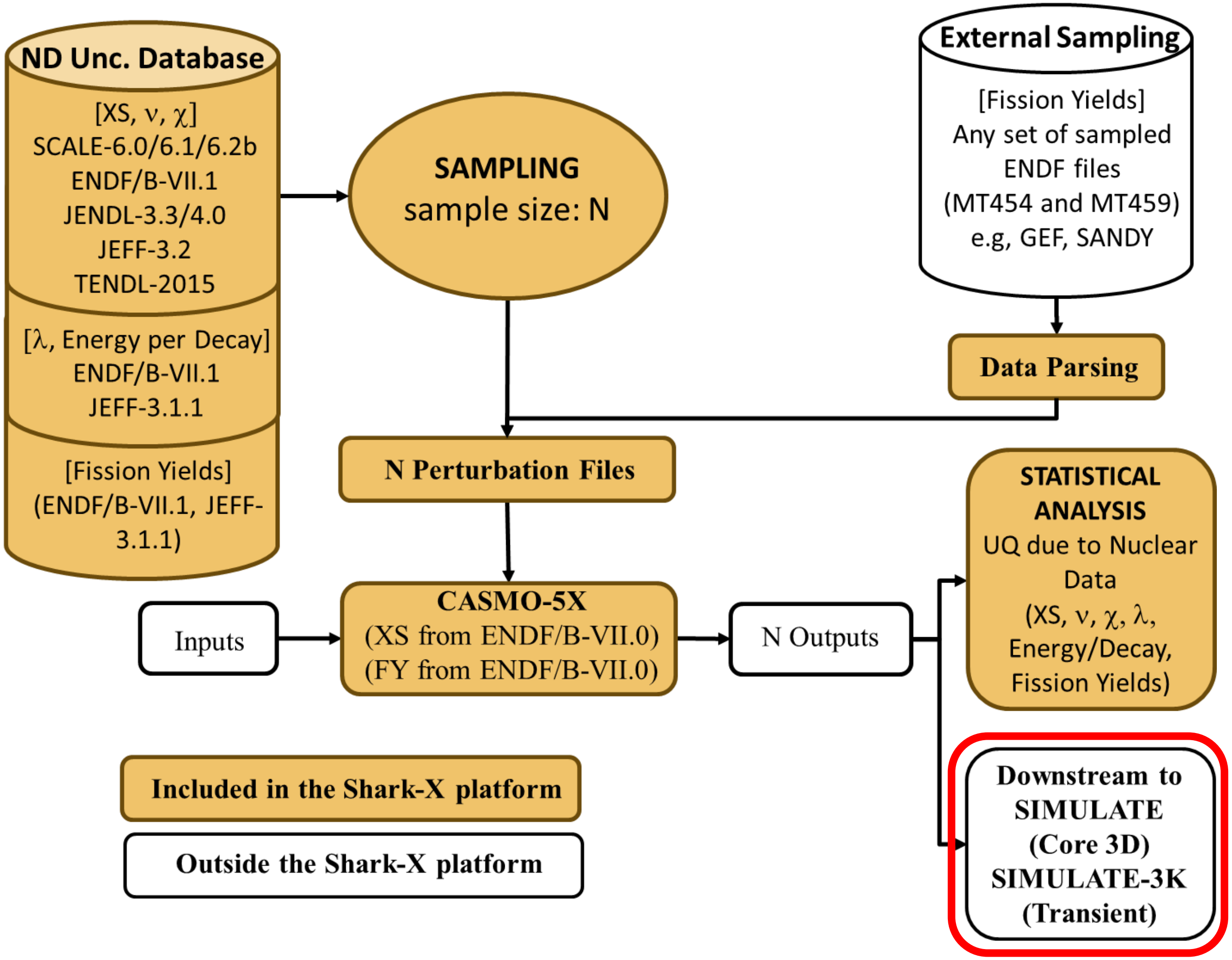
The Shark-X platform includes:

- ND Uncertainty database
- Sampling module
- The CASMO-5 code
- Statistical Analysis module

Capability for Sensitivity Analysis and Uncertainty Quantification using:

- Direct perturbation (sandwich)
- Stochastic Sampling

Shark-X Flowchart for Stochastic Sampling



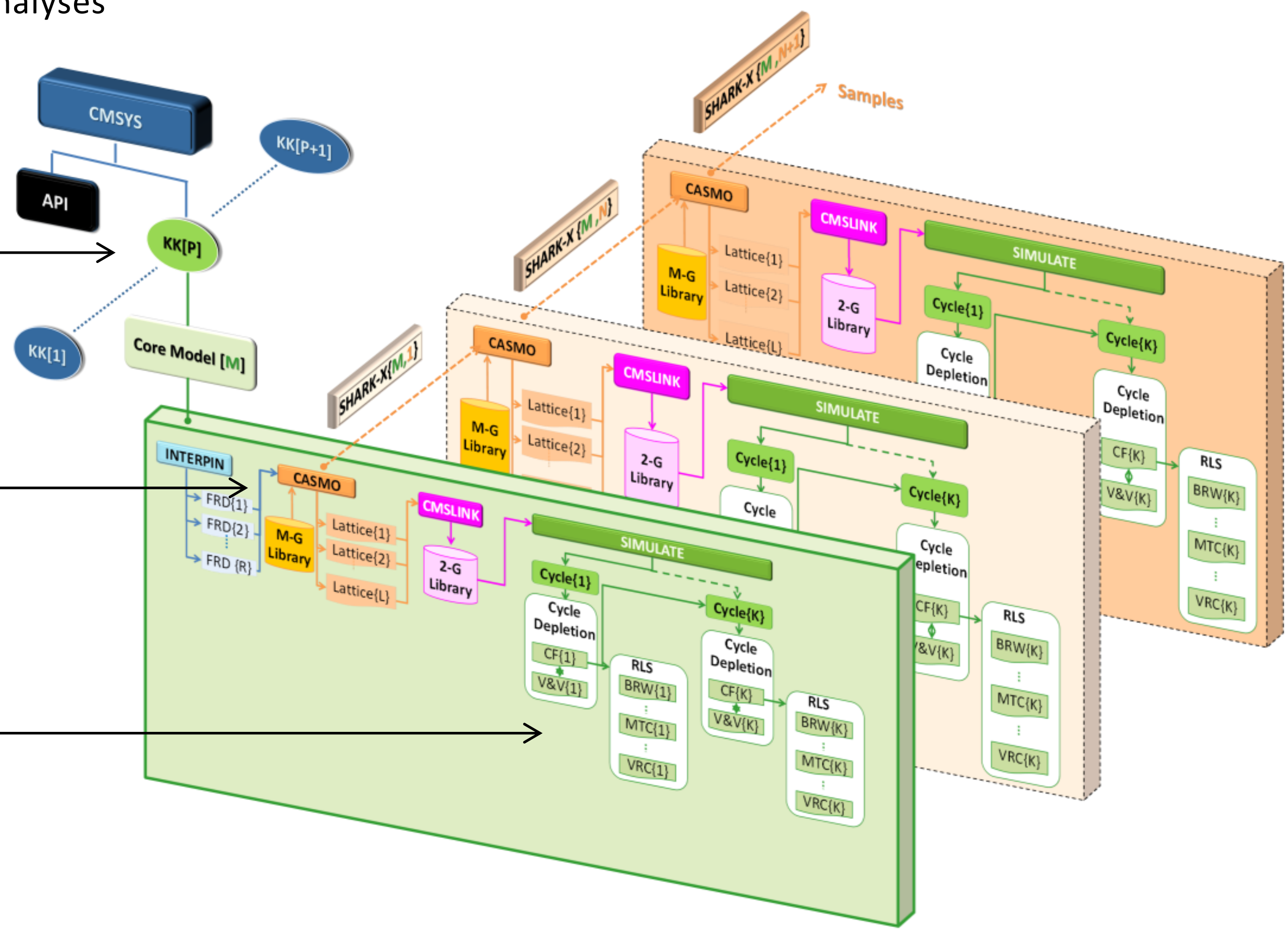
Uncertainty Propagation Platform

- CMSYS: **C**ore **M**anagement **SYS**tem for:
  - the development and the validation of the CASMO/SIMULATE Swiss reference core analysis methodologies,
  - Yearly Reload Licensing verifications of all Swiss reactors (Regulatory support)
- Coupling CMSYS with Shark-X gives the opportunity to perform integral UQ (perturbation of Nuclear Data) as part of the core analyses

Power plant

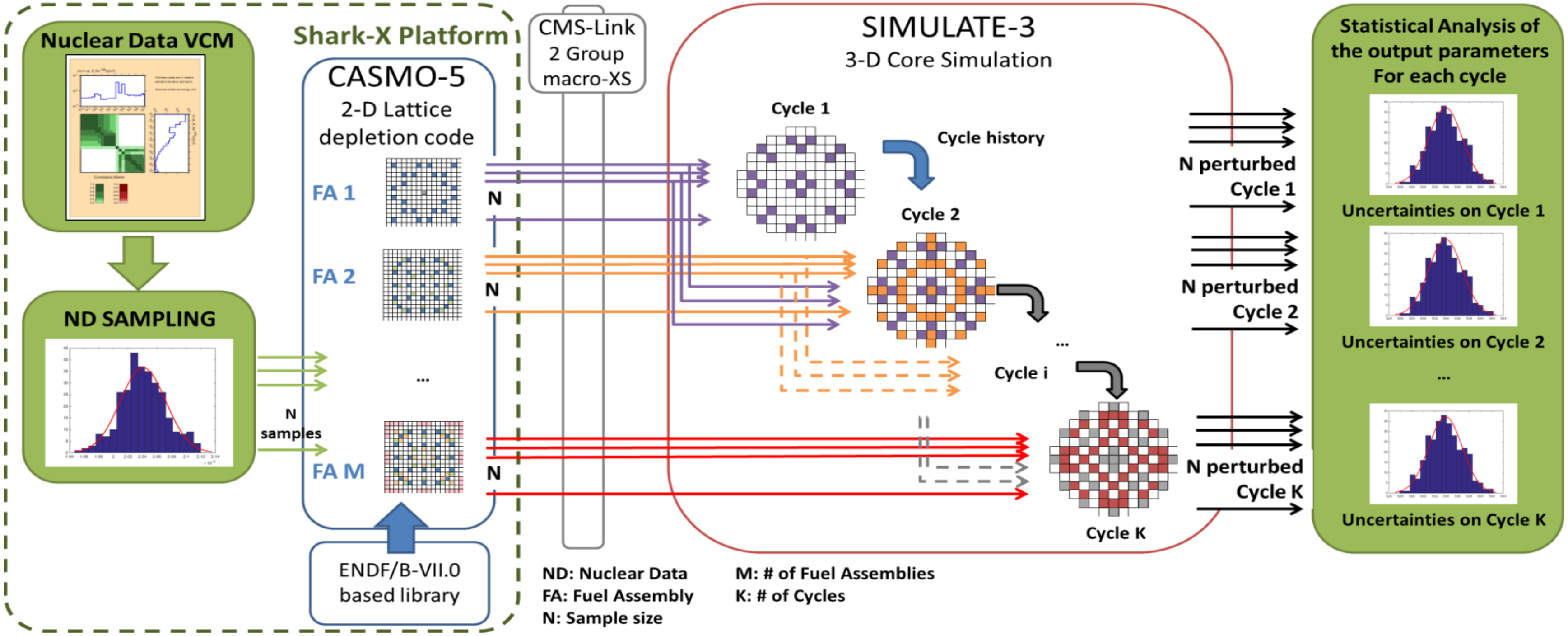
L Fuel Assemblies (CASMO-5)

K Cycles (SIMULATE-3)
Cycle depletion and safety parameters calculations



Case Description

- CASMO-5 v1.07.01 / SIMULATE-3 v6.07.17
- ENDF/B-VII.0, 586 energy groups XS library
- 2D transport solver using 19 energy groups XS
- **VCM: SCALE-6.2b4**
- Perturbation of the cross-sections, ν and χ
- **26** cycles (SIMULATE-3)
- **54** segments (CASMO-5 Fuel assemblies)
- 1 run ≈ 14 days and 2 to 4 Gb (depends on the NPP)
- **500** samples



Case Description

Type: PWR

2 Cycles under consideration: 1 MOX Cycle and 1 UOX Cycle

Cycle		MOX	UOX
Number of new Assemblies		24	20
Average core Burnup (GWd/MT)	At BOC	16.4	29.9
	At EOC	25.4	38.5
Cycle length (EFPD)		327	296

MOX Fuel Assembly
UOX Fuel Assembly
* Control/safety rods

Average Burnup of the Fuel Assemblies at BOC

CYCLE MOX

	1	2	3	4	5	6	7	8	9	10	11	12	13
A						29	34	30					
B				30	0	0 *	10	0 *	0	27			
C			30	0	8 *	32	6	32	8 *	0	30		
D		27	0	15	19	9	30	9	19	15	0	30	
E		0	8 *	19	17 *	29	10 *	28	17 *	19	8 *	0	
F	30	0 *	32	9	28	10	17	10	29	9	32	0 *	29
G	34	10	6	30	10 *	17	27 *	17	10 *	30	6	10	34
H	29	0 *	32	9	29	10	17	10	28	9	32	0 *	30
I		0	8 *	19	17 *	28	10 *	29	17 *	19	8 *	0	
J		30	0	15	19	9	30	9	19	15	0	27	
K			30	0	8 *	32	6	32	8 *	0	30		
L				27	0	0 *	10	0 *	0	30			
M						30	34	29					

CYCLE UOX

	1	2	3	4	5	6	7	8	9	10	11	12	13
A						57	55	57					
B				47	38	0 *	0	0 *	37	47			
C			55	0	11 *	47	51	47	11 *	0	55		
D		47	0	37	36	11	38	11	36	37	0	47	
E		37	11 *	36	25 *	24	25 *	24	25 *	36	11 *	38	
F	57	0 *	47	11	24	25	39	25	24	11	47	0 *	57
G	55	0	51	38	25 *	39	53 *	39	25 *	38	51	0	55
H	57	0 *	47	11	24	25	39	25	24	11	47	0 *	57
I		38	11 *	36	25 *	24	25 *	24	25 *	36	11 *	37	
J		47	0	37	36	11	38	11	36	37	0	47	
K			55	0	11 *	47	51	47	11 *	0	55		
L				47	37	0 *	0	0 *	38	47			
M						57	55	57					

Uncertainty Analysis

Mean of 500 SIMULATE-3 calculations + confidence bounds (95%, ~ 2σ)

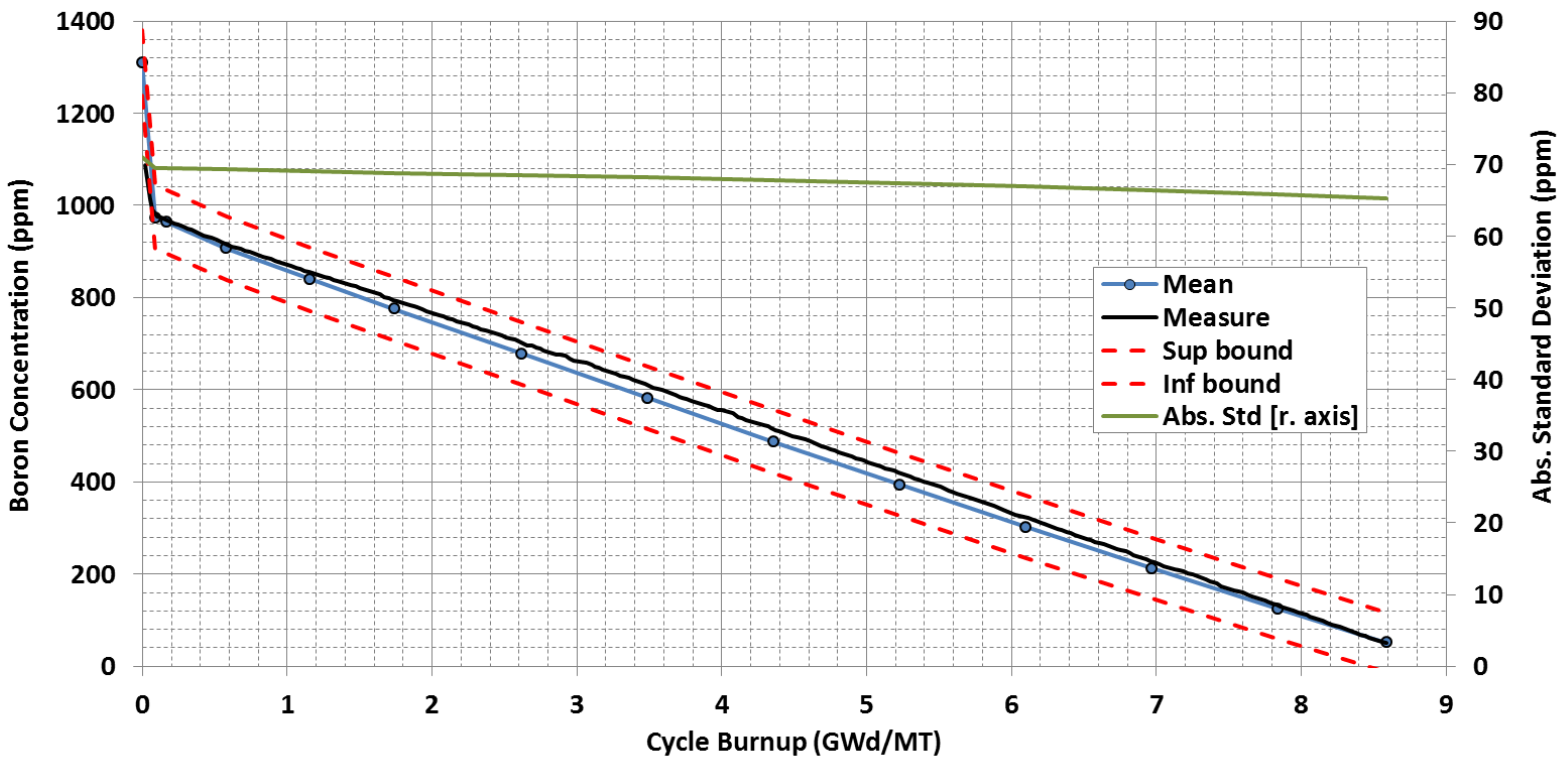
UOX Cycle boron concentration ND uncertainty:

$|C\text{-}E|_{max}$ = 33 ppm

$C\text{-}E_{average}$ = -18 ppm

Experimental uncertainty < 10 ppm

Cycle-averaged ND uncertainty: 68 ppm



Uncertainty Analysis

#1: Assembly relative power
#2: Relative uncertainty (%)

Radial Power distribution:

MOX Cycle

Higher uncertainties:

- in the center and at the periphery (fresh FA)
- At BOC (power distribution more homogeneous at EOC)

UOX Cycle

MOX – BOC (Mean / Std (%))

	1	2	3	4	5	6	7	8	9	10	11	12	13
A						0.34 / 1.8	0.35 / 1.1	0.34 / 1.5					
B				0.46 / 2.1	0.98 / 3.1	1.11 / 2.5	1.08 / 1.0	1.11 / 2.2	0.96 / 2.4	0.42 / 0.9			
C			0.52 / 0.5	1.14 / 2.0	1.28 / 1.5	1.11 / 0.4	1.31 / 0.6	1.12 / 0.2	1.22 / 0.8	1.08 / 1.0	0.52 / 0.5		
D		0.42 / 0.9	1.08 / 1.0	1.23 / 0.5	1.12 / 0.5	1.28 / 1.1	1.00 / 1.4	1.28 / 1.3	1.11 / 0.8	1.23 / 0.5	1.13 / 2.0	0.46 / 2.1	
E		0.96 / 2.4	1.22 / 0.8	1.11 / 0.8	1.22 / 1.7	1.00 / 2.1	1.25 / 1.7	1.01 / 2.1	1.22 / 1.7	1.12 / 0.5	1.28 / 1.5	0.98 / 3.1	
F	0.34 / 1.5	1.11 / 2.2	1.12 / 0.2	1.28 / 1.3	1.02 / 2.1	1.26 / 2.0	1.30 / 2.4	1.26 / 2.0	1.00 / 2.2	1.28 / 1.1	1.11 / 0.4	1.11 / 2.5	0.34 / 1.8
G	0.35 / 1.1	1.08 / 1.0	1.31 / 0.6	1.00 / 1.4	1.25 / 1.7	1.31 / 2.4	1.01 / 2.7	1.30 / 2.5	1.25 / 1.7	1.00 / 1.4	1.31 / 0.6	1.08 / 1.0	0.35 / 1.1
H	0.34 / 1.8	1.11 / 2.5	1.11 / 0.4	1.28 / 1.1	1.00 / 2.1	1.26 / 2.0	1.30 / 2.4	1.26 / 2.0	1.01 / 2.2	1.28 / 1.3	1.12 / 0.3	1.11 / 2.2	0.34 / 1.5
I		0.98 / 3.1	1.28 / 1.5	1.12 / 0.5	1.22 / 1.7	1.01 / 2.1	1.25 / 1.7	1.00 / 2.1	1.22 / 1.7	1.11 / 0.8	1.22 / 0.8	0.96 / 2.4	
J		0.46 / 2.1	1.14 / 2.0	1.23 / 0.5	1.11 / 0.8	1.28 / 1.3	1.00 / 1.4	1.28 / 1.1	1.12 / 0.5	1.23 / 0.5	1.08 / 1.0	0.42 / 0.9	
K			0.52 / 0.5	1.08 / 1.0	1.22 / 0.8	1.12 / 0.2	1.31 / 0.6	1.11 / 0.4	1.28 / 1.5	1.13 / 2.0	0.52 / 0.5		
L				0.42 / 0.8	0.96 / 2.4	1.11 / 2.2	1.08 / 1.0	1.11 / 2.5	0.98 / 3.1	0.46 / 2.1			
M						0.34 / 1.5	0.35 / 1.1	0.34 / 1.8					

Rel. Std. max 3.11% min 0.25% mean 1.45%

BOC

MOX – EOC (Mean / Std (%))

	1	2	3	4	5	6	7	8	9	10	11	12	13
A						0.41 / 0.9	0.43 / 0.5	0.40 / 0.8					
B				0.50 / 1.1	0.98 / 1.4	1.11 / 1.0	1.08 / 0.4	1.11 / 1.0	0.97 / 1.3	0.48 / 0.6			
C			0.55 / 0.2	1.11 / 0.9	1.21 / 0.5	1.09 / 0.3	1.26 / 0.2	1.10 / 0.3	1.18 / 0.3	1.06 / 0.7	0.55 / 0.2		
D		0.48 / 0.6	1.06 / 0.7	1.19 / 0.4	1.11 / 0.4	1.26 / 0.6	1.02 / 0.8	1.26 / 0.6	1.10 / 0.4	1.19 / 0.4	1.11 / 0.9	0.50 / 1.1	
E		0.97 / 1.3	1.18 / 0.3	1.11 / 0.4	1.21 / 0.8	1.03 / 0.9	1.24 / 0.4	1.04 / 0.8	1.21 / 0.8	1.11 / 0.4	1.21 / 0.5	0.98 / 1.4	
F	0.40 / 0.8	1.11 / 1.0	1.10 / 0.3	1.26 / 0.6	1.04 / 0.8	1.24 / 0.5	1.27 / 0.7	1.23 / 0.5	1.03 / 0.9	1.26 / 0.6	1.09 / 0.3	1.11 / 1.0	0.41 / 0.9
G	0.43 / 0.5	1.08 / 0.4	1.26 / 0.2	1.02 / 0.7	1.24 / 0.4	1.27 / 0.7	1.04 / 0.9	1.27 / 0.7	1.24 / 0.4	1.02 / 0.7	1.26 / 0.2	1.08 / 0.4	0.43 / 0.5
H	0.41 / 0.9	1.11 / 1.0	1.09 / 0.3	1.26 / 0.6	1.03 / 0.9	1.24 / 0.5	1.27 / 0.7	1.23 / 0.5	1.04 / 0.8	1.26 / 0.6	1.10 / 0.3	1.11 / 1.0	0.40 / 0.8
I		0.98 / 1.4	1.21 / 0.5	1.11 / 0.4	1.21 / 0.8	1.04 / 0.8	1.24 / 0.4	1.03 / 0.9	1.21 / 0.8	1.10 / 0.4	1.18 / 0.3	0.97 / 1.3	
J		0.50 / 1.1	1.11 / 0.9	1.19 / 0.4	1.10 / 0.4	1.26 / 0.6	1.02 / 0.8	1.26 / 0.6	1.11 / 0.4	1.19 / 0.4	1.06 / 0.7	0.48 / 0.6	
K			0.55 / 0.2	1.06 / 0.7	1.18 / 0.3	1.10 / 0.3	1.26 / 0.2	1.09 / 0.3	1.21 / 0.5	1.11 / 0.9	0.55 / 0.2		
L				0.48 / 0.6	0.97 / 1.3	1.11 / 1.0	1.08 / 0.4	1.11 / 1.0	0.98 / 1.4	0.50 / 1.1			
M						0.40 / 0.8	0.43 / 0.5	0.41 / 0.9					

Rel. Std. max 1.44% min 0.19% mean 0.66%

EOC

UOX – BOC (Mean / Std (%))

	1	2	3	4	5	6	7	8	9	10	11	12	13
A						0.30 / 1.7	0.37 / 1.6	0.30 / 1.5					
B				0.36 / 0.7	0.63 / 0.9	1.24 / 2.3	1.39 / 2.4	1.24 / 2.2	0.63 / 0.8	0.36 / 0.6			
C			0.41 / 0.8	1.25 / 1.7	1.32 / 0.9	0.95 / 0.4	0.88 / 0.6	0.95 / 0.4	1.32 / 0.8	1.26 / 1.7	0.41 / 0.8		
D		0.36 / 0.6	1.26 / 1.6	1.09 / 0.3	1.15 / 0.6	1.47 / 0.6	1.10 / 1.3	1.47 / 0.7	1.15 / 0.6	1.09 / 0.3	1.25 / 1.7	0.36 / 0.7	
E		0.63 / 0.8	1.32 / 0.8	1.15 / 0.6	1.33 / 1.1	1.36 / 1.5	1.28 / 1.7	1.36 / 1.5	1.33 / 1.1	1.15 / 0.6	1.32 / 0.9	0.63 / 0.9	
F	0.30 / 1.5	1.24 / 2.1	0.95 / 0.4	1.47 / 0.7	1.36 / 1.5	1.22 / 2.1	0.96 / 2.7	1.22 / 2.1	1.36 / 1.5	1.47 / 0.6	0.95 / 0.4	1.24 / 2.3	0.30 / 1.6
G	0.37 / 1.5	1.39 / 2.4	0.88 / 0.6	1.10 / 1.3	1.28 / 1.7	0.96 / 2.7	0.67 / 3.4	0.96 / 2.7	1.28 / 1.7	1.10 / 1.3	0.88 / 0.6	1.39 / 2.4	0.37 / 1.6
H	0.30 / 1.6	1.24 / 2.3	0.95 / 0.4	1.47 / 0.6	1.36 / 1.5	1.22 / 2.1	0.96 / 2.7	1.22 / 2.1	1.36 / 1.5	1.47 / 0.6	0.95 / 0.4	1.24 / 2.2	0.30 / 1.5
I		0.63 / 0.9	1.32 / 0.9	1.15 / 0.6	1.33 / 1.1	1.36 / 1.5	1.28 / 1.7	1.36 / 1.5	1.33 / 1.1	1.15 / 0.6	1.32 / 0.8	0.63 / 0.8	
J		0.36 / 0.7	1.25 / 1.7	1.09 / 0.3	1.15 / 0.6	1.47 / 0.7	1.10 / 1.3	1.47 / 0.6	1.15 / 0.6	1.09 / 0.3	1.26 / 1.7	0.36 / 0.6	
K			0.41 / 0.8	1.26 / 1.6	1.32 / 0.8	0.95 / 0.4	0.88 / 0.6	0.95 / 0.4	1.32 / 0.9	1.25 / 1.7	0.41 / 0.8		
L				0.36 / 0.6	0.63 / 0.8	1.24 / 2.2	1.39 / 2.4	1.24 / 2.3	0.63 / 0.9	0.36 / 0.7			
M						0.30 / 1.5	0.37 / 1.6	0.30 / 1.6					

Rel. Std. max 3.41% min 0.34% mean 1.24%

BOC

UOX – EOC (Mean / Std (%))

	1	2	3	4	5	6	7	8	9	10	11	12	13
A						0.35 / 0.6	0.43 / 0.4	0.35 / 0.6					
B				0.41 / 0.4	0.68 / 0.3	1.22 / 1.0	1.33 / 1.0	1.22 / 1.0	0.68 / 0.3	0.41 / 0.4			
C			0.46 / 0.5	1.23 / 0.9	1.28 / 0.4	0.97 / 0.3	0.92 / 0.6	0.98 / 0.5	1.29 / 0.4	1.23 / 0.9	0.46 / 0.5		
D		0.41 / 0.4	1.23 / 0.9	1.08 / 0.1	1.13 / 0.4	1.40 / 0.2	1.10 / 0.6	1.40 / 0.2	1.13 / 0.4	1.08 / 0.2	1.23 / 0.9	0.41 / 0.4	
E		0.68 / 0.3	1.29 / 0.4	1.13 / 0.4	1.28 / 0.4	1.30 / 0.5	1.26 / 0.6	1.30 / 0.5	1.28 / 0.4	1.13 / 0.4	1.28 / 0.4	0.68 / 0.3	
F	0.35 / 0.6	1.22 / 1.0	0.98 / 0.5	1.40 / 0.2	1.31 / 0.5	1.22 / 0.6	1.02 / 1.0	1.22 / 0.6	1.30 / 0.5	1.40 / 0.2	0.97 / 0.3	1.22 / 1.0	0.35 / 0.6
G	0.43 / 0.4	1.33 / 1.0	0.92 / 0.6	1.10 / 0.6	1.26 / 0.6	1.02 / 1.0	0.79 / 1.3	1.02 / 1.0	1.26 / 0.6	1.10 / 0.6	0.92 / 0.6	1.33 / 1.0	0.43 / 0.4
H	0.35 / 0.6	1.22 / 1.0	0.97 / 0.3	1.40 / 0.2	1.30 / 0.5	1.22 / 0.6	1.02 / 1.0	1.22 / 0.6	1.30 / 0.5	1.40 / 0.2	0.98 / 0.5	1.22 / 1.0	0.35 / 0.6
I		0.68 / 0.3	1.28 / 0.4	1.13 / 0.4	1.28 / 0.4	1.31 / 0.5	1.26 / 0.6	1.30 / 0.5	1.28 / 0.4	1.13 / 0.4	1.29 / 0.4	0.68 / 0.3	
J		0.41 / 0.4	1.23 / 0.9	1.07 / 0.2	1.13 / 0.4	1.40 / 0.2	1.10 / 0.6	1.40 / 0.2	1.13 / 0.4	1.07 / 0.2	1.23 / 0.9	0.41 / 0.4	
K			0.46 / 0.5	1.23 / 0.9	1.29 / 0.4	0.98 / 0.5	0.92 / 0.6	0.97 / 0.3	1.28 / 0.4	1.23 / 0.9	0.46 / 0.5		
L				0.41 / 0.4	0.68 / 0.3	1.22 / 1.0	1.33 / 1.0	1.22 / 1.0	0.68 / 0.3	0.41 / 0.4			
M						0.35 / 0.6	0.43 / 0.4	0.35 / 0.6					

Rel. Std. max 1.35% min 0.15% mean 0.54%

EOC

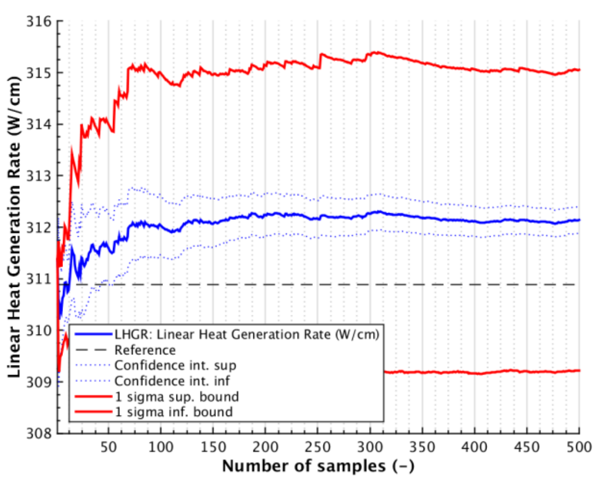
Uncertainty Analysis

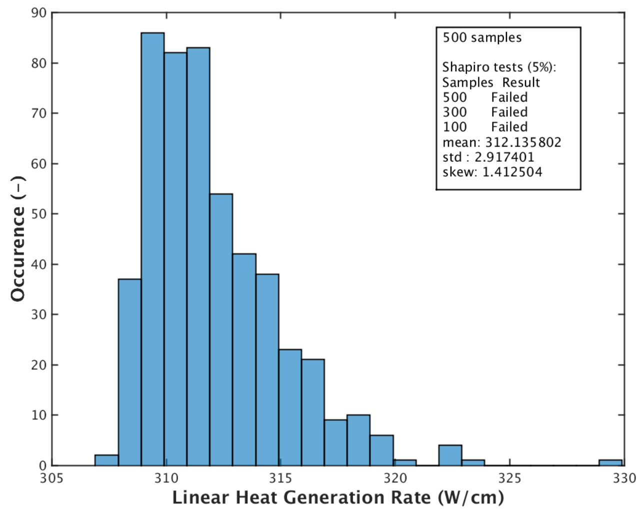
<u>Maximum</u> (during depletion) of cycle parameters and associated nuclear data uncertainties

	Cycle A (MOX)			Cycle B (UOX)		
Maximum Parameter	Average (500 samples)	abs. σ	rel. σ (%)	Average (500 samples)	abs. σ	rel. σ (%)
Linear Heat Generation Rate (W/cm)	314	5	1.5	335	6	1.6
Power Peaking Factor (-)	1.32	0.02	1.7	1.47	0.01	0.6
Axial Peaking Factor Fax (-)	1.24	0.00	0.16	1.21	0.00	0.2
Peak Pin Factor Fxy (-)	1.49	0.02	1.0	1.64	0.02	1.4
Hot Spot Factor Fq (-)	1.88	0.03	1.5	2.01	0.03	1.6
Assembly Burnup Abe (GWd/MT)	42.01	0.14	0.3	59.97	0.31	0.5
Peak Pin Burnup Axy (GWd/MT)	49.44	0.15	0.3	63.53	0.20	0.3
Peak Local Burnup Axyz (GWd/MT)	55.41	0.13	0.2	68.71	0.19	0.3

Linear Heat Generation Rate distribution not Gaussian (defined with a *max()*):

(UOX cycle **<u>at 0.6 GWd/t</u>**)

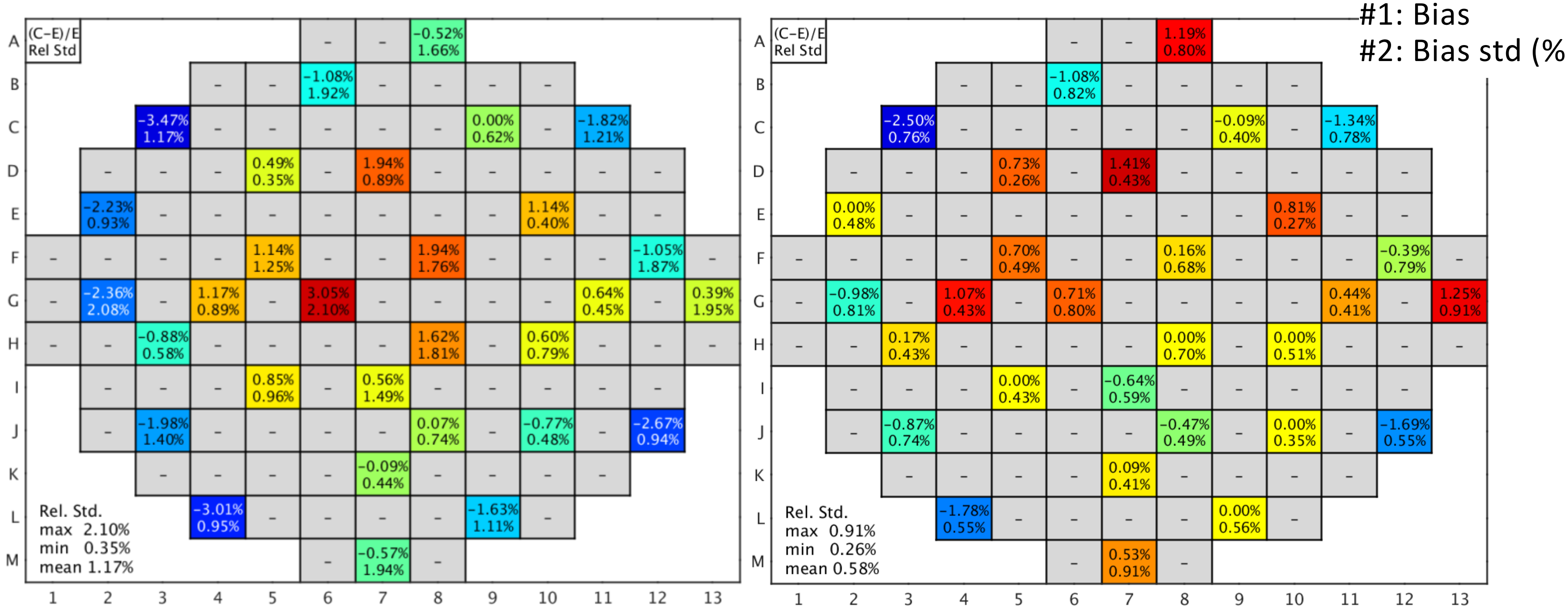




Validation of 3D Power Distribution

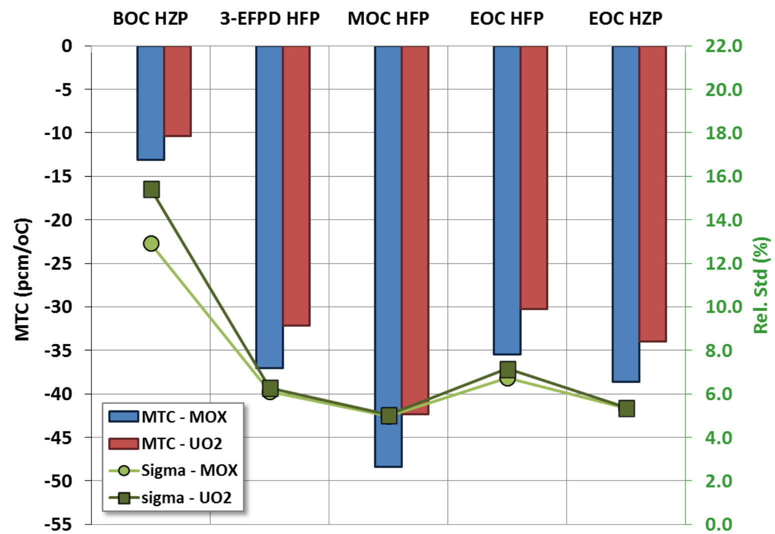
TIP measurements (U-235 fission chambers) are performed during the cycle depletion.
Comparisons with simulation are made using pin power reconstruction (SIMULATE-3) and extrapolated form functions at the detector locations (CASMO-5).
The RMS of the C/E are computed for axial, radial and nodal levels.

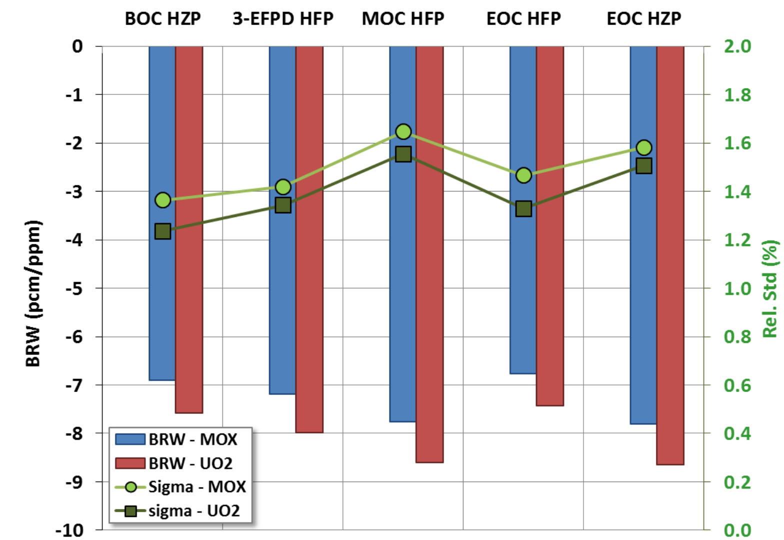
Relative discrepancies of fission rates (axial averaged) for the UOX Cycle at 2-EFPD (left) and EOC (right):

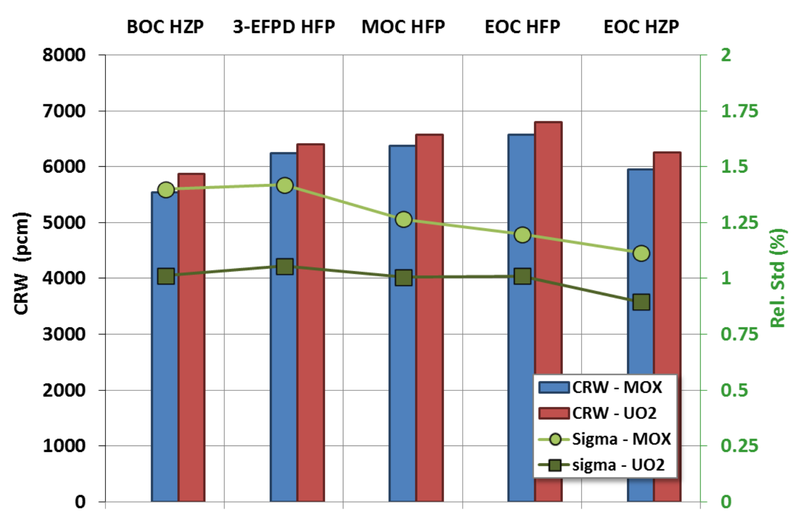


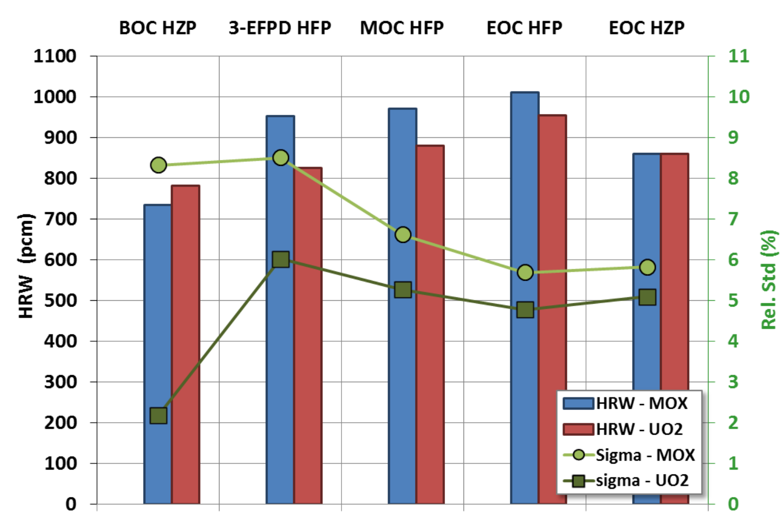
- The Biases (C-E) are almost all under 2% and the highest ones are on the periphery (under-prediction of the thermal flux close to the reflector)
- No trend concerning the uncertainties, same order of magnitude as the biases

Safety Parameters









MTC: Moderator Temperature Coefficient
BRW Boron Reactivity Worth

CRW total Control Rod Worth
HRW Highest Rod Worth

Conclusion

- Perturbation of the ND (VCM from SCALE-6.2) from the lattice code (CASMO-5) to the core depletion calculation (SIMULATE-3)

- Capability to perform UQ on cycle parameters and safety parameters of operated cycles (PWR and BWR)

- Action 6: Target Accuracy Requirements for LWR
  - Contact made with swiss PWR and BWR safety groups, code developers and TSO staff
  - No concrete answer beside “I have seen in the US what the NRC calls Nuclear Reliability & Uncertainty Factors, but these are proprietary and somewhat different from your target accuracy”

Thank you for your attention !