

UPM contribution to Action 6: “Revision of TAR tables”

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Action 6. **O. Cabellos, M. Hursin and A. Plompen** to circulate TAR tables to the wider community (code library developers, industry users, safety authorities), to get feedback to be finalised by the November 2019 meeting (as discussion point at the meeting).

□ Target Accuracy for PWRs ... WPEC/SG26

Table 36
Target accuracies assumed for integral parameters

	K_{eff}	Power peak	Temperature reactivity coefficient	Void reactivity coefficient	Burnup $\Delta\rho$	Transmutation
Target accuracy	$\pm 0.5\%$	$\pm 3\%$	$\pm 10\%$	$\pm 10\%$	300 pcm (fast reactors) 500 pcm (thermal reactors)	$\pm 5\%$

Ref.: G. Aliberti et al. / Annals of Nuclear Energy 33 (2006) 700–733

Table 22. PWR target accuracies (1σ)

k_{eff}	Doppler reactivity coefficient	Burn-up $\Delta\rho$	Transmutation
0.5%	10%	500 pcm	5%

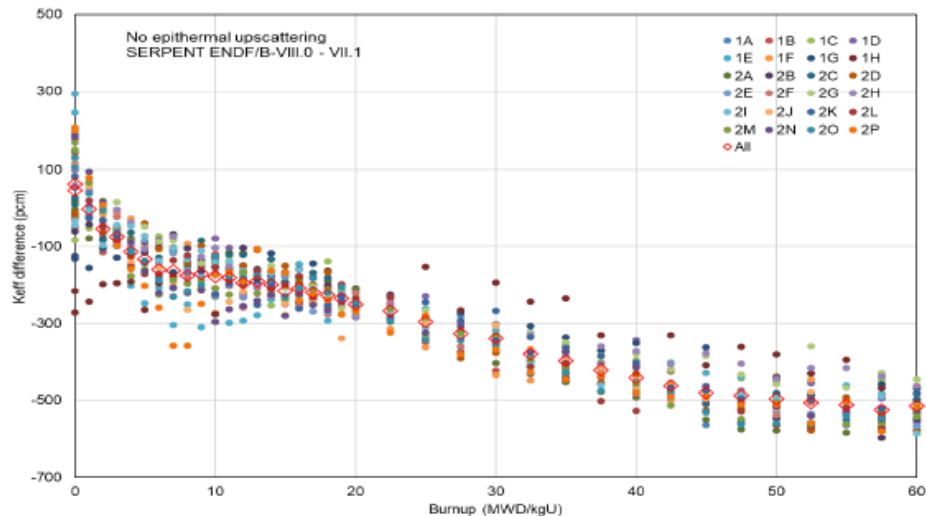
Ref.: WPEC/SG26. “Uncertainty and Target Accuracy Assessment for Innovative Systems Using Recent Covariance Data Evaluations” (2008)

Recent examples for PWRs...

ENDF/B-VII.1 vs. ENDF/B-VIII.0

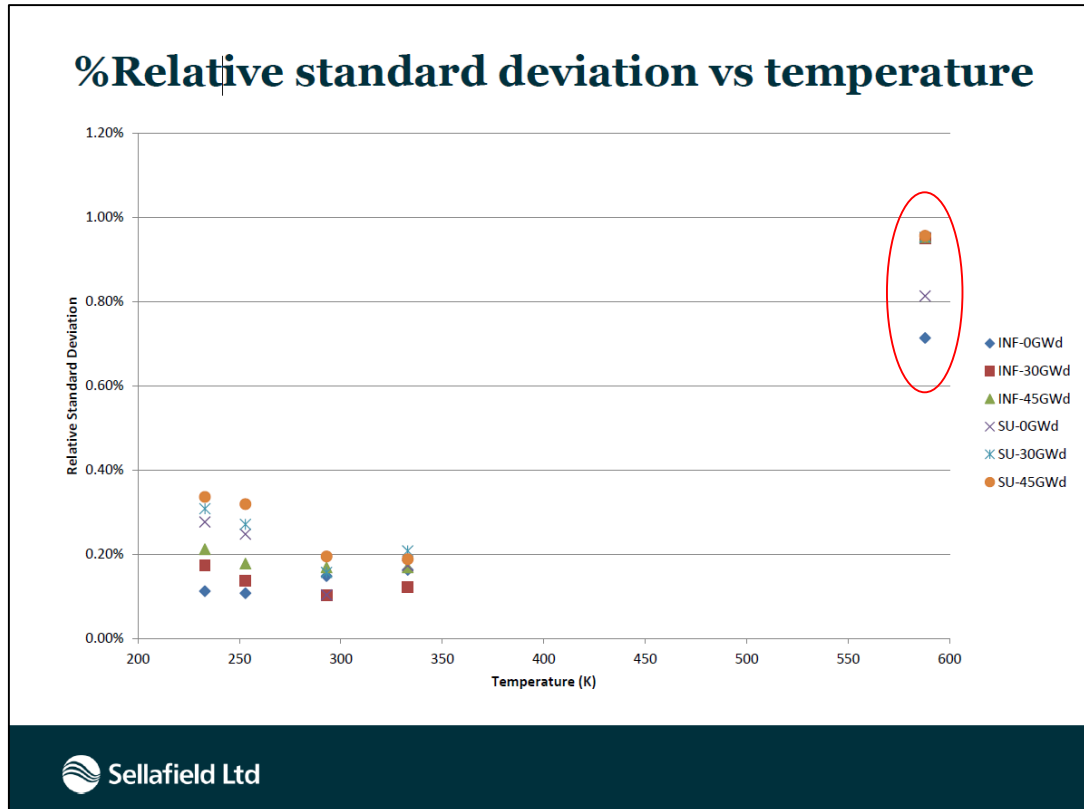
Depletion

- VERA Depletion Benchmark Problems
 - PWR single pins and assemblies
 - SERPENT2
- ENDF/B-VIII.0 reactivities are much lower



- differences in k_{eff} > 0.5% using recent evaluations!

Recent examples for PWRs...



- differences in $k_{eff} > 0.5\%$ using recent evaluations!

Table. Participants in SG3 Benchmark

ID	Participants	Institutes	Country	Code	Nuclear Data
CEA1	Yi-Kang Lee	CEA	France	TRIPOLI-4	JEFF-3.3
CEA2	Marion Tiphane			TRIPOLI-4.9	JEFF-3.3
CEA3	Coralie Carmouze			TRIPOLI-4.9	JEFF-3.1.1
EMS1	Dennis Mennerdahl	EMS	Sweden	SCALE 6.2.3	ENDF/B-VII.1
EMS2				MCNP 6.2	ENDF/B-VIII.0
EMS3				MCNP 6.2	ENDF/B-VII.1
GRS1	Fabian Sommer	GRS	Germany	SCALE-6.2.2	ENDF/B-VII.1
GRS2	Matthias Behler				ENDF/B-VII.1
GRS3	Volker Hanstein				ENDF/B-VII.1
GRS4				OpenMC	ENDF/B-VIII
GRS5				MCNP 6.1	ENDF/B-VIII
GRS6				MCNP 6.1	ENDF/B-VIII
IRSN1	Mathieu Milin	IRSN	France	MORET 5.D.1	JEFF-3.3
IRSN2	Nicolas Leclaire				JEFF-3.3
MTA1	Gabor Hordosy	MTA	Hungary	MCNP 6.1.1	ENDF/B-VIII
MTA2					ENDF/B-VII
NRA	Shigeki Shiba Toshuya Yamamoto	NRA	Japan	MVP3	JENDL-4.0
ORNL1	BJ Marshall	ORNL	United States	SCALE 6.2.3	ENDF/B-VIII
ORNL2	Bradley Rearden Douglas Bowen				ENDF/B-VIII
SL1	James Ryan	SL	United Kingdom	MONK 9A	JEFF-2.2
UJV	Radim Vocka	UJV	Czech Republic	HELIOS 2.1	ENDF/B-VII
UPM1	Oscar Cabellos	UPM	Spain	MCNP 6.1	ENDF/B-VII.1
UPM2					ENDF/B-VIII.0
UPM3					ENDF/B-VIII.0
UPM4					ENDF/B-VIII.0
UPM5					ENDF/B-VIII.0
UPM6					JEFF 3.1.1
UPM7					JEFF 3.3
UPM8					JEFF 3.3
UPM9					JEFF 3.3
UPM10					JEFF 3.3
WOOD1	David Hanlon	Wood	United Kingdom	MONK 10B	JEFF-3.1.2
WOOD2				MONK 11 (dev)	

Ref.: S. Gan, A. Wilson, The effect of temperature on the neutron multiplication factor for PWR fuel assemblies, WPNCS/SG3 Meeting. September 23, 2019

❑ Required physics characteristics to be confirmed/test criteria ... **industry!**

Test parameters	Test criteria
HZP critical boron	±50 ppm or ±500 pcm equivalent
Control rod worth Individual group or user-specified group	±15% ¹⁾ or ±100 pcm, whichever is greater (For rod swap, the reference group should be within 10%.)
Sum of groups or total integral of measured worths	±10% ¹⁾ (For DRWM, the total worth should be within 8%.)
ITC	±2 pcm/°F
Flux symmetry Deviation between the highest and lowest values in the symmetric locations	±10% ²⁾ (<i>Meas</i> versus <i>Meas</i>)
Power distribution	±0.10 RPD for each measured assembly power rms ³⁾ (radial) < 0.05
HZP to HFP reactivity measurement	±50 ppm or ±500 pcm equivalent or ±10% ¹⁾

Note:
DRWM: dynamic rod worth measurement

Note
ITC: isothermal temperature coefficient

Note:
RPD: relative power density

Note:
HZP: Hot Zero Power
HFP: Hot Full Power

¹⁾ For calculating percent differences use $(Meas - Pred) \times 100/Pred$, where *Meas* indicates the measured value and *Pred* indicates the predicted value. Having percent difference defined with *Pred* (i.e., predicted) in the denominator is consistent with comparisons of measured-versus-predicted data for safety-related purposes (e.g., total control rod worth and peaking). This definition of percent difference simply recognizes that PWR reload cores are licensed with calculated (predicted) data.

²⁾ Percent difference is $(Highest - Lowest) \times 100/Avg$, where *Highest* is the largest measured value in a particular symmetric location, *Lowest* is the smallest measured value, and *Avg* is the average of all the measured values in the same symmetric location (which could be 2, 4, or 8 values).

³⁾ The rms is defined as $\sqrt{\sum_{i=1}^N \frac{(\Delta RPD)_i^2}{N}}$.

Ref.: ANSI/ANS-19.6.1-2011. American National Standard Reload Startup Physics Tests for PWRs



□ Design and Acceptance Criteria for Start-up and Operation in PWRs

Core parameter	Design criteria	Acceptance criteria
Critical boron concentration ARO	$ (C_B)^M_{ARO} - (C_B)^C_{ARO} < 50 \text{ ppm}$	$ \alpha C_B \times \Delta(C_B)_{ARO} < 1000 \text{ pcm}$
Isothermal temperature coefficient ARO at HZP	$ (\alpha^{ISO}_T)^M_{ARO} - (\alpha^{ISO}_T)^C_{ARO} < 3.6 \text{ pcm/}^\circ\text{C}$	$ (\alpha^{ISO}_T)^M_{ARO} - (\alpha^{ISO}_T)^C_{ARO} < 6.62 \text{ pcm/}^\circ\text{C}$
Moderator temperature coefficient ARO at HZP	$(\alpha^{CTM})^{HZP}_{ARO} < 9 \text{ pcm/}^\circ\text{C}$	
Boron Worth Coefficient at HZP	$ (\alpha C_B)^M - (\alpha C_B)^C < 0.7 \text{ pcm/ppm}$	
Control banks worth for Reference Bank	$ (I^{REF})^M - (I^{REF})^C < 0.10x(I^{REF})^C$	$ (I^{REF})^M - (I^{REF})^C < 0.15x(I^{REF})^C$
Control Bank Worth value for other Banks using Rod Swap Technique	$ (I^{CBW})^M - (I^{CBW})^C < 0.15x(I^{CBW})^C \text{ or } 100 \text{ pcm}$	$ (I^{CBW})^M - (I^{CBW})^C < 0.30x(I^{CBW})^C \text{ or } 200 \text{ pcm}$
Total Control Bank Worth	$1.10 x (I^{TOT})^C > (I^{TOT})^M > 0.9x(I^{TOT})^C$	$(I^{TOT})^M > 0.9x(I^{TOT})^C$
Axial Offset	$ (AO)^M - (AO)^C < 3\%$	
Max. Relative Assembly Power (P _A)	$\% (P_A)^M - (P_A)^C / (P_A)^C \begin{cases} < 10\% \text{ if } P \geq 90\% \\ < 15\% \text{ if } P < 90\% \end{cases}$	

Note: ARO: All Rods Out

Note: According IAEA Safety Glossary, “Design limits” are used interchangeably with “safety limits” or “acceptance criteria”.

Ref.: O.Cabellos et al. Propagation of Nuclear Data Uncertainties for PWR Core Analysis. NUCLEAR ENGINEERING AND TECHNOLOGY, VOL.46 NO.3 JUNE 2014.

□ Design and Acceptance Criteria for Start-up and Operation in PWRs

Table. Start-up tests

Parameter	Calculated - Measurement		Valid range
	Mean	1 σ	
HZP			
Critical boron conc. [ppm]			
ARO	-8	25	± 50 ppm
Rod banks (global) [ppm]			
D	-15	27	
C (Din)	-21	28	
B (DCin)	-21	26	
A (DCBin)	-26	24	
Rod bank worths Δ_r [%]			
D	0.5	4.7	$\pm 10\%$
C (Din)	-1.4	4.4	$\pm 10\%$
B (DCin)	0.7	4.5	$\pm 10\%$
A (DCBin)	0.5	4.4	$\pm 10\%$
MTC [pcm/ $^{\circ}$ C]	2.4	4.6	$\pm 10\%$
MTC	-2.4	1.3	± 5 pcm/ $^{\circ}$ C
Boron worth Δ_r [%]	-2.1	4.8	$\pm 10\%$

where Δ_r denotes a relative (Calculated/Measurement -1) discrepancy

Table. Cycle depletion & 3D-distribution of neutron flux

Parameter	Calculated - Measurement		Valid range
	Mean	1 σ	
HFP			
Critical boron concent. [ppm]	-16	32	± 100 ppm
2D RRs Δ_r [%]			
Unfiltered	0.1	1.5	-
Power_gt1.00	0.0	1.3	$\pm 5\%$
UO2	0.1	1.6	-
Fresh Gd	0.6	1.4	-
3D RRs Δ_r [%]			
Without grids, unfiltered	-1.2	2.4	-
Fz _d Δ_r [%]	-1.2	1.2	-
Fz _{detp} unfiltered Δ_r [%]	-1.5	1.4	-
AO _d [%]	-0.1	1.0	-
AO _{detp} unfiltered [%]	-0.2	1.2	-
Natural cycle length [MWd/t]	-208	311	-

where Δ_r denotes a relative (Calculated/Measurement -1) discrepancy

Ref.: C.R. Schneidesch. Changing nuclear data libraries: impact on the calculation chain in industry. JEFF Stakeholder Workshop. June 6-7, 2019.

- ❑ A High-Fidelity, two cycles, PWR depletion challenge **code developers!**

Accuracy criteria


HZP	boron endpoint concentrations	± 25 ppm
	temperature coefficients	± 1 pcm/K
	rod bank worths	$\pm 5\%$
HFP	critical boron concentrations predicted with	± 25 ppm
	^{235}U fission axial integrals	$\pm 1.5\%$ rms
	^{235}U fission axial shape with	$\pm 1.0\%$ rms

□ ND Needs in LWRs?

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Nuclear Data for LWRs

- It does not seem that new measurements are needed for LWRs using UO_2 fuel
- New data needed for accident tolerant fuel (ATF) (e.g., U_3Si_2 , UN, coated cladding, etc.)
- Westinghouse observed some discrepancies between the ENDF-VII.1 and ENDF-VIII.0. libraries:
 - A standard benchmark unit assembly (a typical 17x17 Westinghouse fuel assembly with IFBA) was modeled using ENDF-VII.1 and ENDF-VIII.0. Differences were observed between the two libraries.
 - 3 cycles of a 4-loop plant were calculated and results compared to plant measured data
 - Simulations performed with ENDF-VII.1 are in a good agreement with the plant data
 - Results of the simulations with ENDF-VIII.0 are significantly different and the difference increases with depletion. Power distributions and the critical boron concentrations were investigated.
- Information/feedback on the comparison of ENDF-VII.1 and ENDF-VIII.0 and experience of other users are of interest for us



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○ No more data needed?

○ Significant differences using ENDF/B-VIII.0

Ref.: Alex Levinsky, PhD. Westinghouse Electric Co. "Nuclear Data Needs for Current and Future Nuclear Energy Systems". WANDA Nuclear Energy Roadmapping Session. January 2019

Fig. Ratio Pu239/MT18 (n,fission)
JEFF-3.3/ENDF/B-VIII.0

Incident neutron data / JEFF-3.3 / Pu239 / MT=18 : (z,fission) /
Covariances data (BOXER) MT18: <JEFF-3.3>/<ENDF/B-VIII.0>

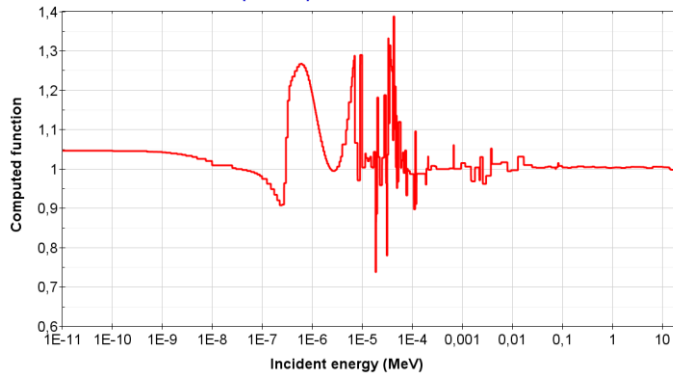


Fig. Ratio U235/MT102 (n,gamma)

Incident neutron data // U235 / MT=102 : (z,g) / Weighting : SCALE 238-group, PWR spectrum

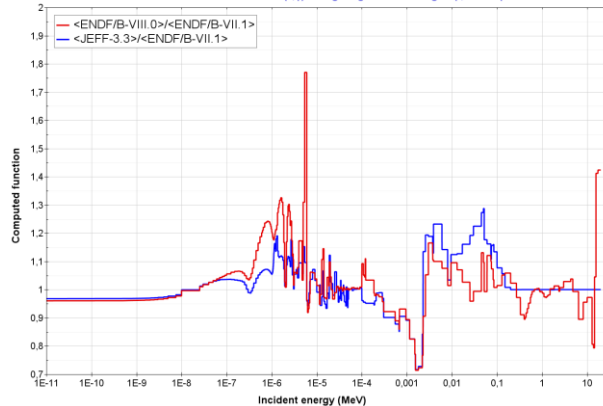
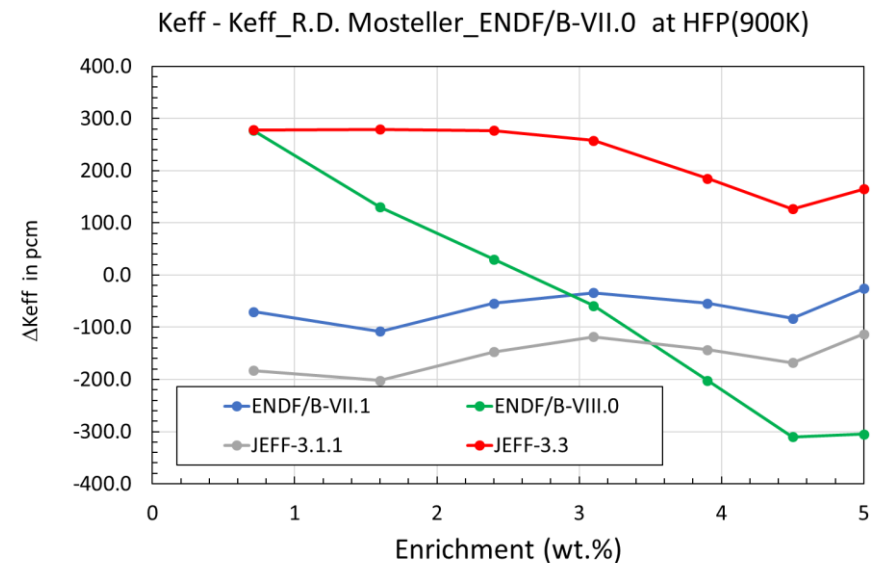
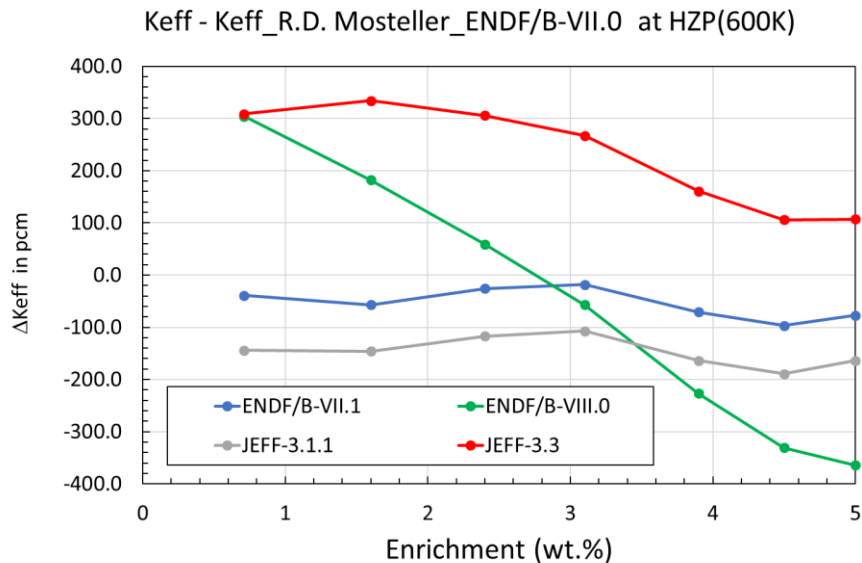
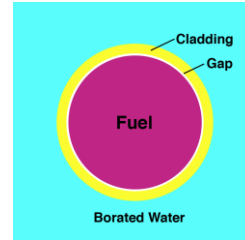


Table. PWR spectrum weighted “Average Cross-Section “ over
[1.0E-5eV - 20MeV]

	Pu239		
MTs	ENDF/B-VIII.0	JEFF-3.3	(J-E)/E*100(%)
MT18	142.79	144.88	1.5
MT102	83.67	85.49	2.1
MT452	2.92	2.90	-0.5
MT1018	0.0082	0.0082	-0.2
	U235		
MTs	ENDF/B-VIII.0	JEFF-3.3	(J-E)/E*100(%)
MT18	54.34	54.55	0.4
MT102	14.82	14.64	-1.2
MT452	2.46	2.46	0.0
MT1018	0.0082	0.0082	-0.2
	U238		
MTs	ENDF/B-VIII.0	JEFF-3.3	(J-E)/E*100(%)
MT4	0.44	0.42	-4.02
MT18	0.037	0.037	-1.3
MT102	14.98	14.97	0.0
MT452	2.47	2.43	-1.9
MT1018	0.0082	0.0082	-0.2

Comparison of keff for UO2 pin-cells

Figure. Comparison of keff values for different nuclear data libraries at HZP and HFP. Reference keff is the R.D. Mosteller calculation using ENDF/B-VII.0 (LA-UR-07-0922)



Ref.: O.Cabellos. A comparison of ENDF/B-VIII.0 to some other evaluations for different criticality calculations in thermal systems. CM INDEN "On the resonance parameters of actinides". IAEA Headquarters, Vienna, Austria. October 21-24, 2019.

□ Uncertainty Quantification (UQ) studies in PWRs

See this work: A. Alonso, E. de la Fuente, O. Cabellos et al. *Comparison of JEFF-3.3 and ENDF/B-VIII.0 in PWR simulations.* JEFDOC-1968. April 2019

- Required in **safety calculations of large scale systems ~ PWR**
- ND uncertainty propagation on the main design parameters
 - **JEFF-3.3 covariance**
 - **ENDF/B-VIII.0 covariance**
- **Decomposition of uncertainty in: ^{235}U - ^{238}U - ^{239}Pu & XS- ν -PFNS**

□ Impact of recent ND covariance in PWRs

Core parameter	Design criteria	Acceptance criteria
Critical boron concentration ARO	$ (C_B)^M_{ARO} - (C_B)^C_{ARO} < 50$ ppm Boron	$ (C_B)^M_{ARO} - (C_B)^C_{ARO} < 100$ ppm

Table. Uncertainties in Critical Boron Concentration (in ppm). PWR-V in cycle-5. Calculations performed with SEANAP and SANDY codes.

		JEFF-3.3 covariance data							TOTAL
		Pu239			U235			U238	
Power (%)	Burnup (GWd/tHM)	XS	ν	CHI	XS	ν	CHI	XS	
50	0.015	18	14	9	27	46	9	24	64
75	0.031	18	15	9	27	46	10	24	64
100	0.134	19	15	9	27	46	10	25	65
100	1.340	22	16	9	25	47	10	24	66
...
100	7.716	34	23	9	21	38	10	23	65
100	8.823	35	24	9	21	37	10	23	66
100	10.284	37	25	9	20	35	10	23	66
100	11.351	39	26	9	20	34	10	23	67

Ref.: A. Alonso, E. de la Fuente, O. Cabellos et al. *Comparison of JEFF-3.3 and ENDF/B-VIII.0 in PWR simulations*. JEFDOC-1968. April 2019

□ Impact of recent ND covariance in PWRs

Core parameter	Design criteria	Acceptance criteria
Critical boron concentration ARO	$ (C_B)^M_{ARO} - (C_B)^C_{ARO} < 50 \text{ ppm Boron}$	$ (C_B)^M_{ARO} - (C_B)^C_{ARO} < 100 \text{ ppm}$

Table. Uncertainties in Critical Boron Concentration (in ppm). PWR-V in cycle-5. Calculations performed with SEANAP and SANDY codes.

		ENDF/B-VIII.0 covariance data												
		Pu239				U235				U238				
Power (%)	Burnup (GWd/tHM)	XS	v	CHI	Ang	XS	v	CHI	Ang	XS	v	CHI	Ang	TOTAL*
50	0.015	34	9	15	0	-	31	-	0	23	11	0	1	62
75	0.031	35	9	15	0	-	31	-	0	24	11	0	1	63
100	0.134	37	10	16	0	-	31	-	0	25	11	0	1	65
100	1.340	43	11	15	0	-	29	-	0	24	11	0	1	67
...
100	7.716	66	15	15	0	-	24	-	0	22	11	0	1	81
100	8.823	69	15	15	0	-	24	-	0	22	11	0	1	83
100	10.284	73	16	15	0	-	23	-	0	21	11	0	1	86
100	11.351	76	16	15	0	-	22	-	0	21	11	0	1	88

* Note: XS and CHI uncertainties for 235U were not calculated. TOTAL uncertainty is predicted using the corresponding JEFF-3.3 values.

Ref.: A. Alonso, E. de la Fuente, O.Cabellos et al. *Comparison of JEFF-3.3 and ENDF/B-VIII.0 in PWR simulations*. JEFDOC-1968. April 2019

□ Impact of recent ND covariance in PWRs

Core parameter	Design criteria	Acceptance criteria
Axial Offset	$ (AO)^M - (AO)^C < 3\%$	

Table. Uncertainties in Uncertainties in A.O. (in %). PWR-V in cycle-5.
 Calculations performed with SEANAP and SANDY codes.

Power (%)	Burnup (GWd/tHM)	JEFF-3.3 covariance data							ENDF/B-VIII.0 covariance data											
		Pu239			U235			U238	Pu239				U235				U238			
		XS	v	c	XS	v	c	XS	XS	v	c	Ang	XS	v	c	Ang	XS	v	c	Ang
50	0.015	0.2	0.1	0.1	0.2	0.3	0.1	0.3	0.2	0.1	0.2	0	-	0.1	-	0	0.3	0.1	0	0
75	0.031	0.3	0.2	0.2	0.3	0.4	0.2	0.4	0.4	0.1	0.3	0	-	0.2	-	0	0.4	0.2	0	0
100	0.134	0.3	0.2	0.2	0.4	0.5	0.2	0.5	0.5	0.2	0.4	0	-	0.3	-	0	0.6	0.2	0	0
100	1.340	0.2	0.3	0.1	0.2	0.3	0.1	0.3	0.3	0.1	0.2	0	-	0.2	-	0	0.3	0.1	0	0
...
100	7.716	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	0	0	0	0
100	8.823	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	0	0	0	0
100	10.284	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	0	0	0	0
100	11.351	0	0	0	0	0	0	0	0	0	0	0	-	0	-	0	0	0	0	0

Ref.: A. Alonso, E. de la Fuente, O.Cabellos et al. Comparison of JEFF-3.3 and ENDF/B-VIII.0 in PWR simulations. JEFDOC-1968. April 2019



Core parameter	Design criteria	Acceptance criteria
Control banks worth for Reference Bank	$ (I^{REF})^M - (I^{REF})^C < 0.10x(I^{REF})^C$	$ (I^{REF})^M - (I^{REF})^C < 0.15x(I^{REF})^C$
Control Bank Worth value for other Banks using Rod Swap Technique	$ (ICBW)^M - (ICBW)^C < 0.15x(ICBW)^C$ or 100 pcm	$ (ICBW)^M - (ICBW)^C < 0.30x(ICBW)^C$ or 200 pcm

Table. Uncertainties in control bank worth (in ppm). PWR-V in cycle-5. Calculations performed with SEANAP and SANDY codes.

	JEFF-3.3 covariance data							ENDF/B-VIII.0 covariance data											
	Pu239			U235			U238	Pu239				U235				U238			
Control Bank Worth (in ppm)	XS	v	c	XS	v	c	XS	XS	v	c	Ang	XS	v	c	Ang	XS	v	c	Ang
D-IN (REF) ~113ppm	0.4	0.3	0.5	0.5	0.4	0.6	0.6	0.5	0.3	0.7	0	-	0.3	-	0	0.4	0.4	0	0.4
C-IN	1.5	1.3	0.8	0.8	1.3	0.8	1.0	2.8	0.9	1.1	0	-	1.0	-	0	0.5	0.5	0	0.5
B-IN	0.4	0.4	0.5	0.7	0.7	0.6	0.4	0.7	0.3	0.6	0	-	0.7	-	0	0.4	0.4	0	0.3
A-IN	2.3	1.8	0.5	1.9	3.4	0.6	1.2	4.1	1.1	0.6	0	-	2.2	-	0	0.6	0.5	0	0.4
SB-IN	1.9	1.6	1.0	1.2	2.1	1.1	1.6	3.5	1.1	1.4	0	-	1.5	-	0	0.6	0.5	0	0.6
SA-IN	1.7	1.4	0.4	1.5	2.5	0.4	0.8	3.2	0.9	0.5	0	-	1.7	-	0	0.6	0.5	0	0.5
D+C-IN	1.6	1.3	0.9	0.8	1.0	1.0	1.1	3.0	0.9	1.3	0	-	0.8	-	0	0.5	0.5	0	0.5
D+C+B-IN	2.3	1.9	1.3	1.1	1.3	1.5	1.5	4.0	1.2	1.7	0	-	0.9	-	0	0.6	0.5	0	0.5
D+C+B+A-IN	1.7	1.3	0.5	2.5	3.8	0.5	1.0	3.2	0.8	0.6	0	-	2.5	-	0	0.8	0.6	0	0.3
D+C+B+A+SB-IN	1.2	0.8	1.3	1.7	1.4	1.5	1.3	1.7	0.7	1.9	0	-	0.9	-	0	0.7	0.7	0	0.5
ARI	1.0	0.5	1.2	2.3	2.2	1.3	1.0	1.0	0.5	1.5	0	-	1.4	-	0	0.7	0.7	0	0.5

- ❑ Action 6.: **Review of Target Accuracy for PWRs**
 - Industry
 - Code Developers
- ❑ **Assessing the impact of current covariance data in PWRs**
- ❑ TO DO: Feedback from **Safety Authority** should be sought and taken into account
- ❑ Target Accuracies ...
 - **Target accuracies for Bias** (“the systematic difference between calculated results and experimental data”)
 - **¿Target accuracies for Bias Uncertainty?** (“the uncertainty that accounts for the combined effects of uncertainties in the benchmarks, the calculational models of the benchmarks, and the calculational methods”)

$$k = k_{cal} + \delta k(bias) + \sqrt{\sum [\delta k(uncert)]^2}$$