AREVA

forward-looking energy

Improved PWR Simulations by Monte-Carlo Uncertainty Analysis and Bayesian Inference

E. Castro, O. Buss, A. Hoefer
PEPA1-G: Radiology & Criticality, AREVA GmbH, Germany
Universidad Politécnica de Madrid

April 15th 2015

AREVA
forward-looking energy

Motivation

- NPPs seek to improve core management
  - Power uprates, improved efficiency of fuel utilization, enhanced operational flexibility
- Knowledge of operational safety margins is crucial

➔ **Need realistic uncertainty estimates:**

1. **Base uncertainty estimations for core simulations on uncertainties of input data**
   (nuclear data uncertainties, technological parameters tolerances, …)
2. **Include operational experience** in uncertainty estimation: improved future predictions by past measurements

All rights are reserved, see liability notice.

AREVA
forward-looking energy

Outline

1. Description of the NUDUNA/MOCABA methodology applied to SEANAP core analysis:
   - SEANAP: PWR simulation system
   - NUDUNA: Nuclear Data Random Sampling
   - MOCABA: Bayesian updating
2. Application of the methodology to SEANAP core analysis
   - Direct boron letdown curve updating
   - Nuclear data library updating
3. Conclusions

All rights are reserved, see liability notice.

AREVA forward-looking energy

Chapter 1

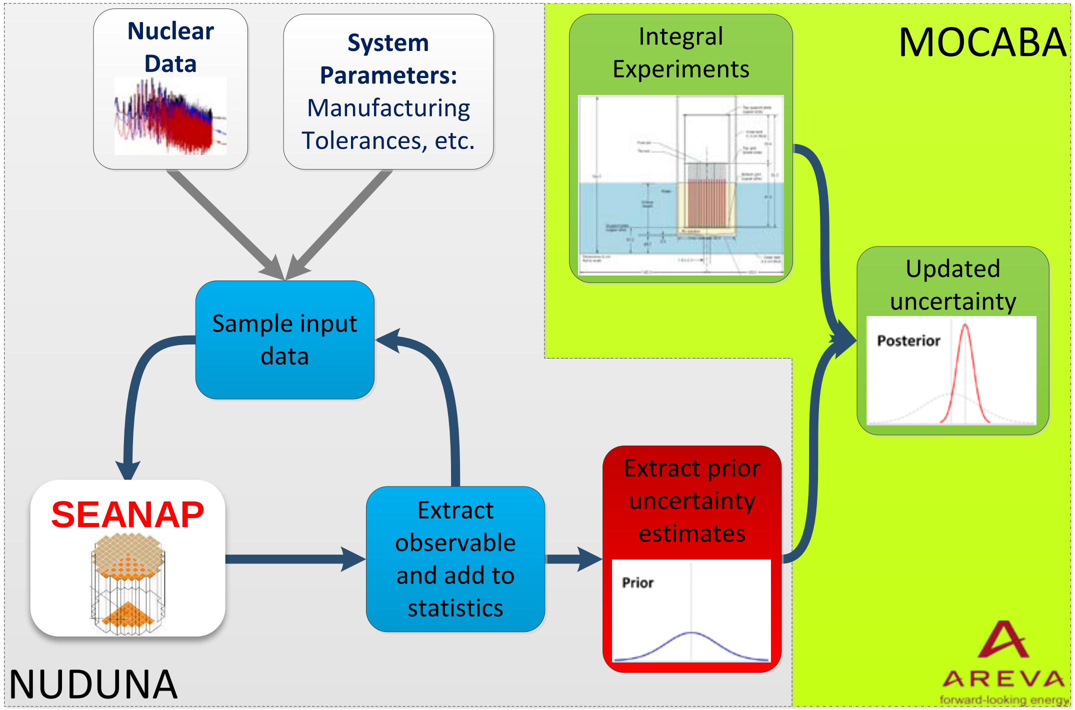
Description of the NUDUNA/MOCABA methodology applied to SEANAP core analysis

AREVA
forward-looking energy

Description of the SEANAP-NUDUNA/MOCABA methodology

- **Uncertainty assessment based on Monte Carlo methodology**
- **Improve predictions by adding measurements (Bayesian updating)**

- **Tools used:**
  - **SEANAP:**
    - PWR simulation system
  - **NUDUNA**:
    - random sampling of Evaluated Nuclear Data Files
  - **MOCABA:**
    - Bayesian updating



All rights are reserved, see liability notice.

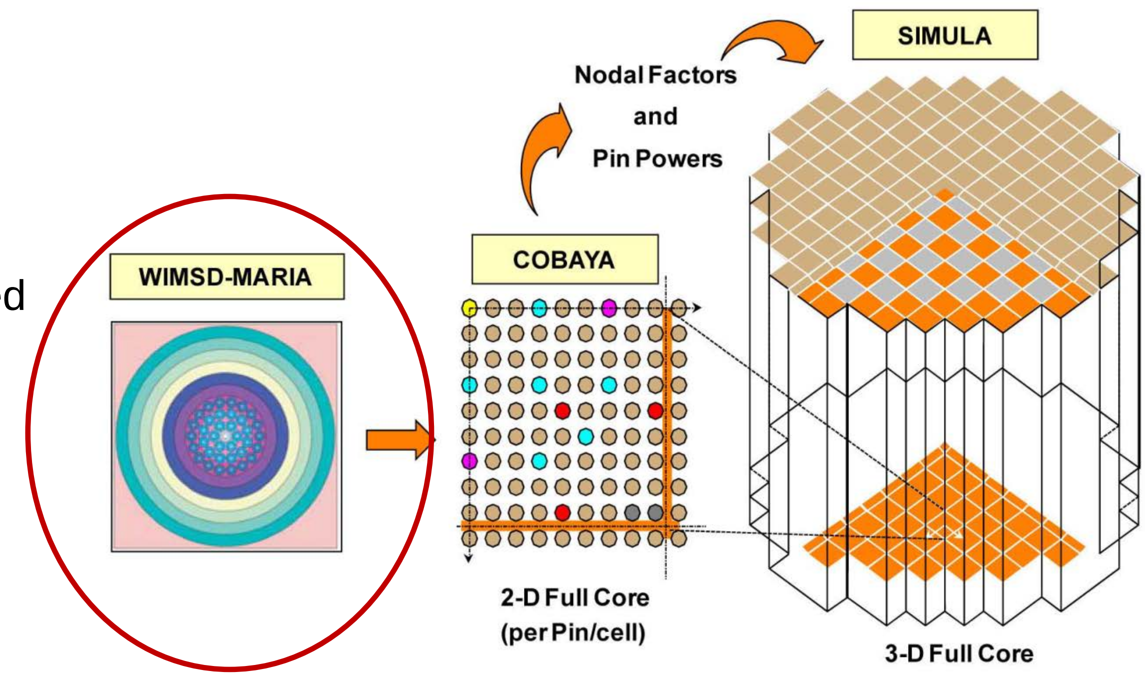
AREVA forward-looking energy

SEANAP

- **SEANAP: Sistema Español de Análisis de Núcleos de Agua a Presión. System developed at Universidad Politécnica de Madrid for the analysis of PWR reactors**
  - Applied in many cycles of Spanish PWR for the last 25 years by the facilities

WIMSD-MARIA:

- Lattice code
- 69 groups nuclear data library.
- Provides cross sections homogeneized at pin scale and whole assembly, in 2 energy groups.



All rights are reserved, see liability notice.

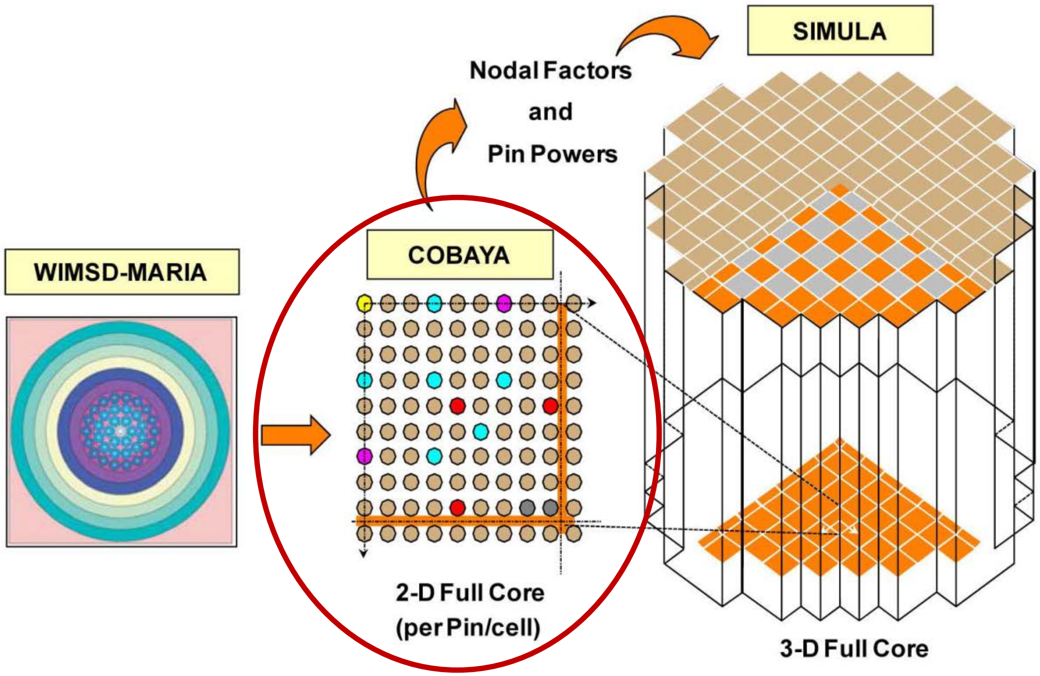
AREVA
forward-looking energy

SEANAP

- **SEANAP: Sistema Español de Análisis de Núcleos de Agua a Presión. System developed at Universidad Politécnica de Madrid for the analysis of PWR reactors**
  - Applied in many cycles of Spanish PWR for the last 25 years by the facilities

COBAYA:

- Pin by pin
- 2D
- Diffusion equation
- Finite difference, two energy groups method
- Provides:
  - Nodal discontinuity factors
  - Hot-pin to node average power ratios



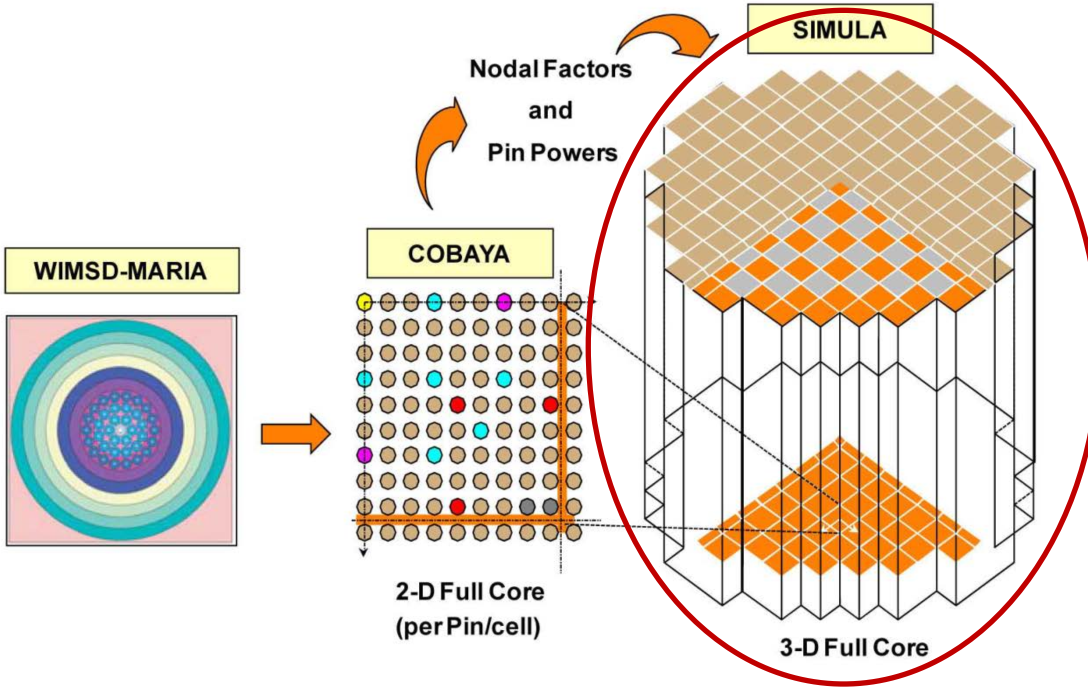
All rights are reserved, see liability notice.

AREVA
forward-looking energy

SEANAP

- **SEANAP**: Sistema Español de Análisis de Núcleos de Agua a Presión. System developed at Universidad Politécnica de Madrid for the analysis of PWR reactors
  - Applied in many cycles of Spanish PWR for the last 25 years by the facilities

- **SIMULA:**
  - Nodal core simulator
  - 3D
  - 4 nodes per Fuel Assembly
  - Solver: finite difference few group diffusion calculation
  - Uses the nodal discontinuity factors

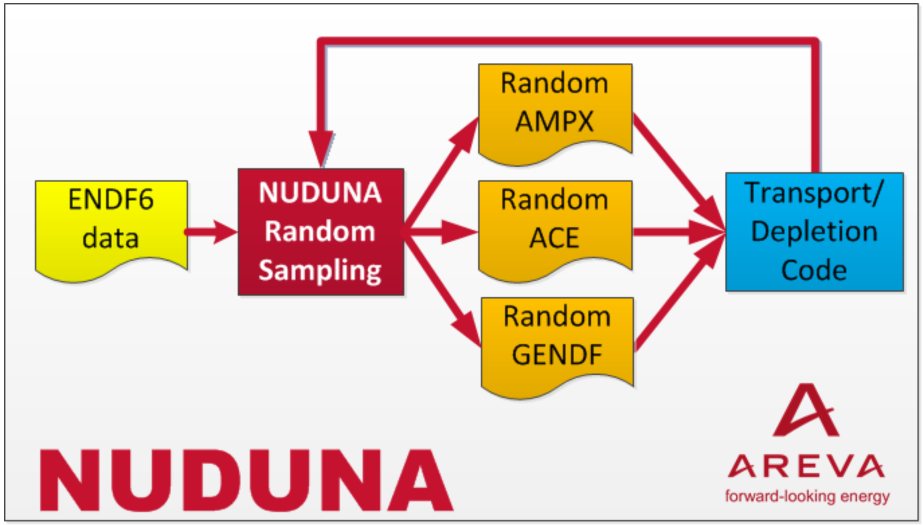


All rights are reserved, see liability notice.

AREVA
forward-looking energy

NUDUNA: nuclear data random sampling

- **Nuclear Data random sampling tool, developed at AREVA GmbH.**
- **Direct sampling of ENDF-6 data based on its covariance information**
  - Neutron multiplicities (File 1)
  - Resonance parameters (File 2)
  - Cross sections (File 3)
  - Angular distributions (File 4)
  - Decay data (File 8, Section 457)



- **Automatic creation of transport code libraries out of random ENDF6 data**
  - Based on NJOY 99, PUFF IV
  - Support for MCNP, SCALE & **WIMSD-4** (ALEPH, SERPENT, APOLLO2 in development)
  - Arbitrary temperatures and broad group structures
- **Limitations**
  - No sampling of fission spectra (χ, File 5) and no isotope-isotope correlations (in development)

 © AREVA - AL: N - ECCN: N
All rights are reserved, see liability notice.
AREVA forward-looking energy

MOCABA procedure (part I)

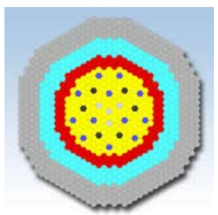
mean vector *covariance matrix*

1. MC sampling of nuclear data (*NUDUNA*): $\boldsymbol{\alpha}_{MC} \propto p(\boldsymbol{\alpha}) = N(\hat{\boldsymbol{\alpha}}, \boldsymbol{\Sigma}_{\alpha})$

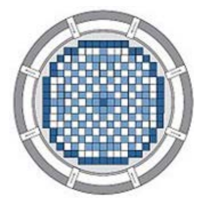
2. Calculation of integral quantities:

MC draws of application case system parameters

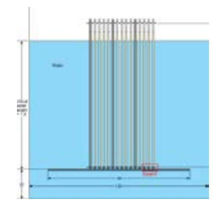
$$\mathbf{y}_{MC} := \Big(\underbrace{y_{A,1}(\boldsymbol{\alpha}_{MC}, \mathbf{x}_A^{MC}), \ldots, y_{A,n_A}(\boldsymbol{\alpha}_{MC}, \mathbf{x}_A^{MC})}_{\text{Appl. Case}} \;,\; \underbrace{y_{B,1}(\boldsymbol{\alpha}_{MC}), \ldots, y_{B,n_B}(\boldsymbol{\alpha}_{MC})}_{\text{Benchmarks}}\Big)^T$$



Appl. Case



Benchmarks



3. Calculation of prior mean and prior covariance matrix:

$$\begin{pmatrix} \Sigma_{0A} & \Sigma_{0AB} \\ \Sigma_{0AB}^T & \Sigma_{0B} \end{pmatrix}$$

$$\mathbf{y}_0 = \frac{1}{n_{MC}} \sum_i \mathbf{y}_{MC,i} \qquad \boldsymbol{\Sigma}_0 = \frac{1}{n_{MC}-1} \sum_i (\mathbf{y}_{MC,i} - \mathbf{y}_0)(\mathbf{y}_{MC,i} - \mathbf{y}_0)^T$$

→ Prior distribution: $p(\mathbf{y}) = N(\mathbf{y}_0, \boldsymbol{\Sigma}_0)$ ← *reflects uncertainty due to nuclear data uncertainty*

AREVA
forward-looking energy

All rights are reserved, see liability notice.

MOCABA procedure (part II)

4. Evaluation of likelihood function of integral measurements:

$$p(\mathbf{v_B} \mid \mathbf{y_B}) \propto N(\mathbf{v_B}, \mathbf{\Sigma_{vB}})$$

Covariance matrix of integral quantities → $\mathbf{\Sigma_{vB}} = \mathbf{S}\,\mathbf{\Sigma_{xB}}\,\mathbf{S}^T$

Measurement vector

Sensitivity matrix

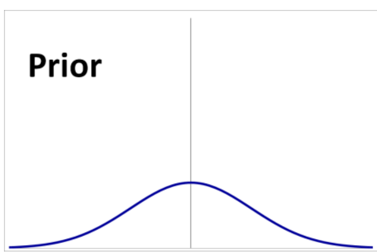
Covariance matrix of benchmark system parameters

5. Bayesian updating

Updated model parameters

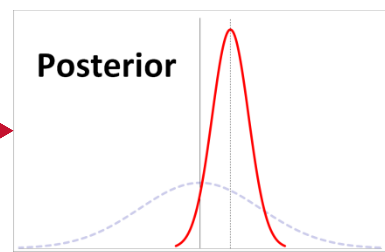
$$p(\mathbf{y} \mid \mathbf{v_B}) = p(\mathbf{v_B} \mid \mathbf{y_B})\,p(\mathbf{y}) = N(\mathbf{y}^*, \mathbf{\Sigma}^*)$$

$$\begin{bmatrix} \Sigma_{0A} & \boxed{\Sigma_{0AB}} \\ \Sigma_{0AB}^T & \Sigma_{0B} \end{bmatrix}$$



$$\mathbf{y}_{0A/B} \to \mathbf{y}^*_{A/B}$$

$$\mathbf{\Sigma}_{0A/B} \to \mathbf{\Sigma}^*_{A/B}$$



Impact of benchmark information on application case prediction determined by similarities between benchmarks and application case → correlations

AREVA
forward-looking energy

All rights are reserved, see liability notice.

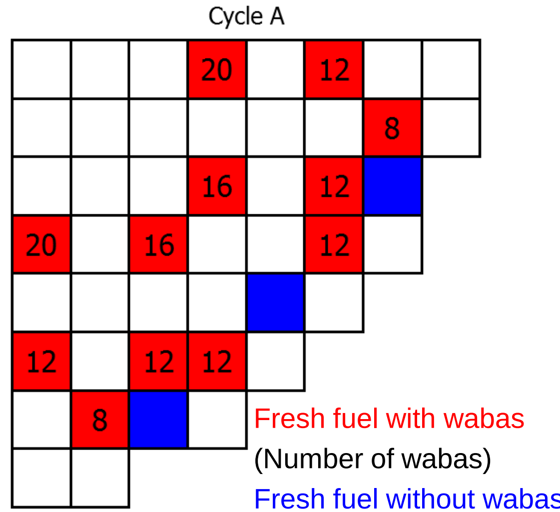
Chapter 3

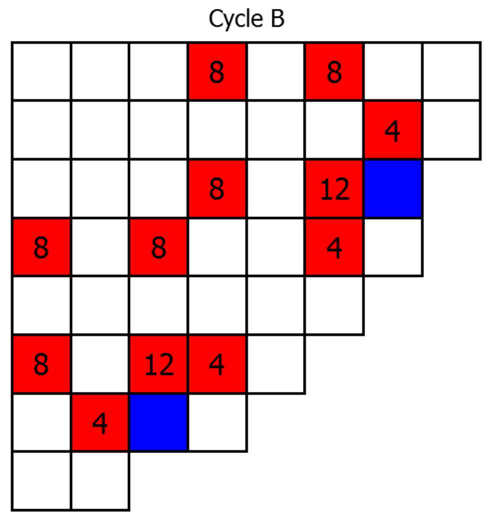
Application of the methodology to SEANAP core analysis

AREVA
forward-looking energy

Application of the NUDUNA/MOCABA methodology to SEANAP core analysis

- **Objective:**
  - **Improve the predictions of cycle B, based on the measurements and simulations of the previous cycle (cycle A)**
- **PWR core specifications:**
  - 157 Fuel Assemblies
  - 2775 MW_t
  - Fresh and used fuel
  - Wabas as burnable absorber.
- **Random libraries generated with NUDUNA from ENDF/B-VII.1:**
  - U-235 and U-238, Pu-239
  - Hydrogen, B-10, O-16

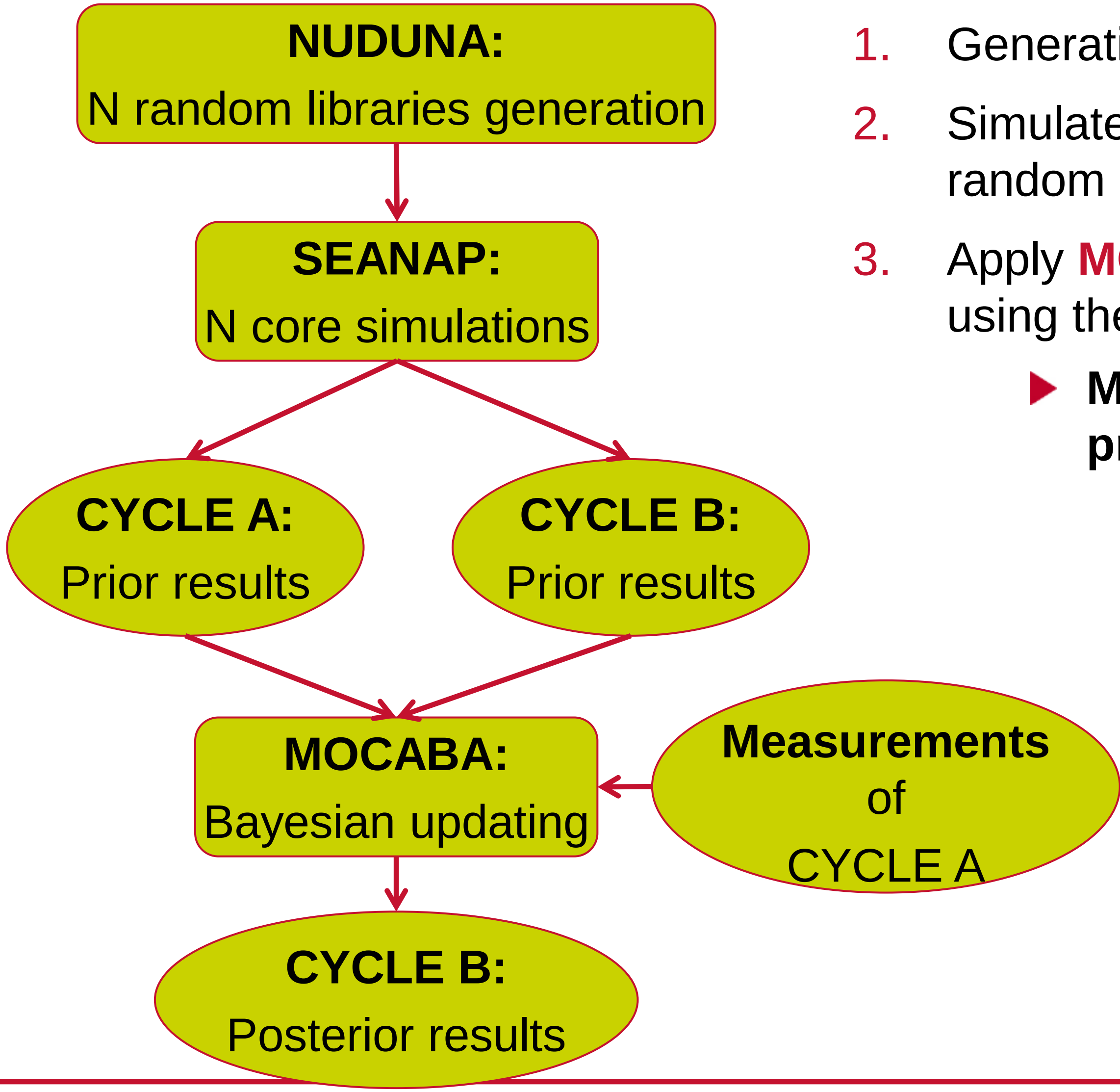




All rights are reserved, see liability notice.

AREVA
forward-looking energy

Application of the NUDUNA/MOCABA methodology to SEANAP core analysis



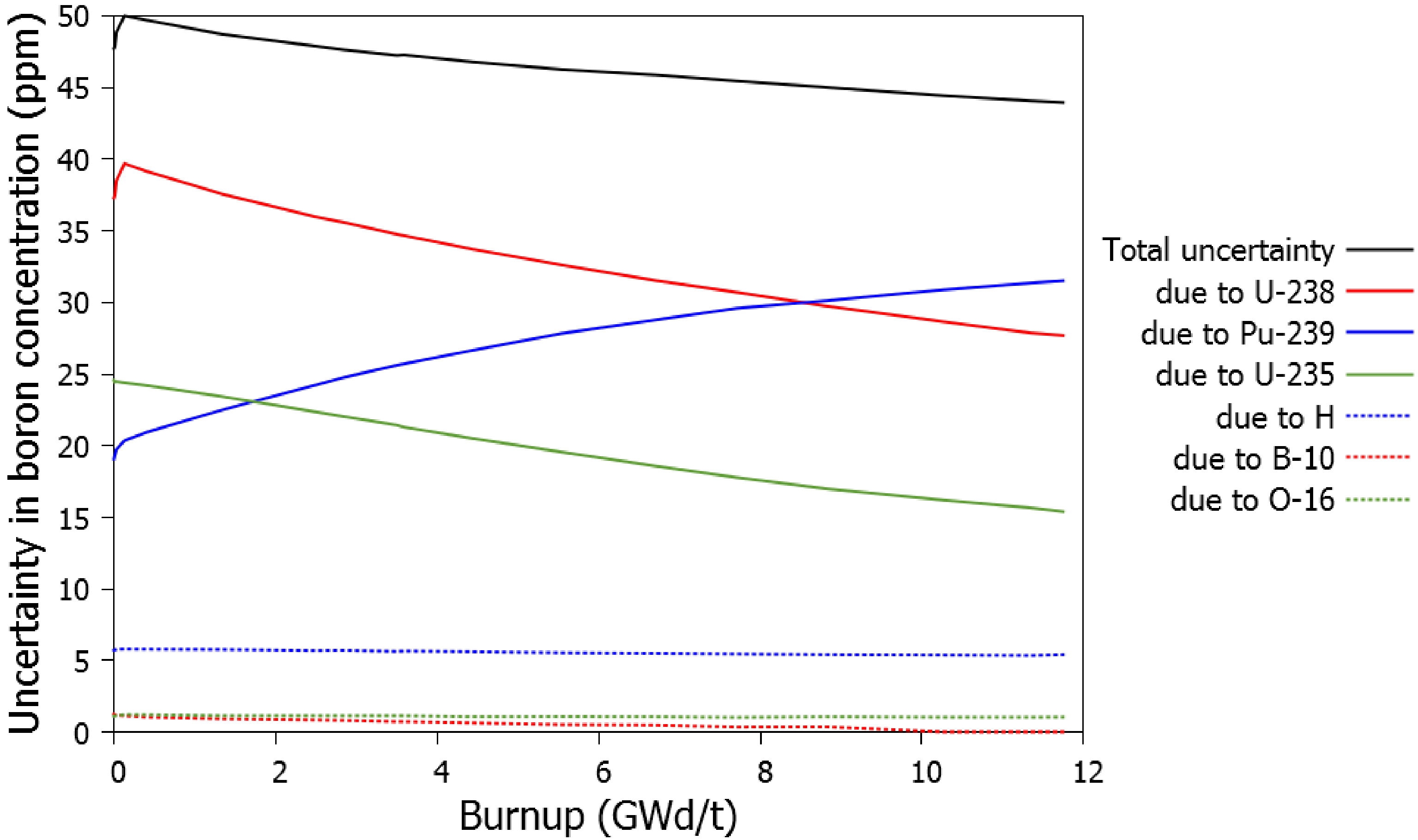
1. Generation of random libraries with **NUDUNA**
2. Simulate the burnup of cycles A and B with each random library using **SEANAP**
3. Apply **MOCABA** to update the results of cycle B using the measurements of cycle A
   - **Measurements in cycle A improve the predictions of cycle B.**
     - Applications → Current cycle (B).
     - Benchmark → Previous cycle (A).
     - Error in the measurements:
       - Boron conc.: 6 ppm (rel. error: 0.6-100%)
     - **Responses**
       - Boron curve
       - WIMS Nuclear Data Library

All rights are reserved, see liability notice.
AREVA forward-looking energy

Boron prior results for cycle B

- B = boron concentration (ppm). σ = one standard deviation (ppm)

MWd/t	B_{prior}	σ_{prior}
135	987	45
1340	867	44
2487	763	43
2842	733	43
3591	664	43
4441	590	42
5549	487	42
6692	383	42
7716	290	41
8823	197	41
10284	74	40
11351	-15	40



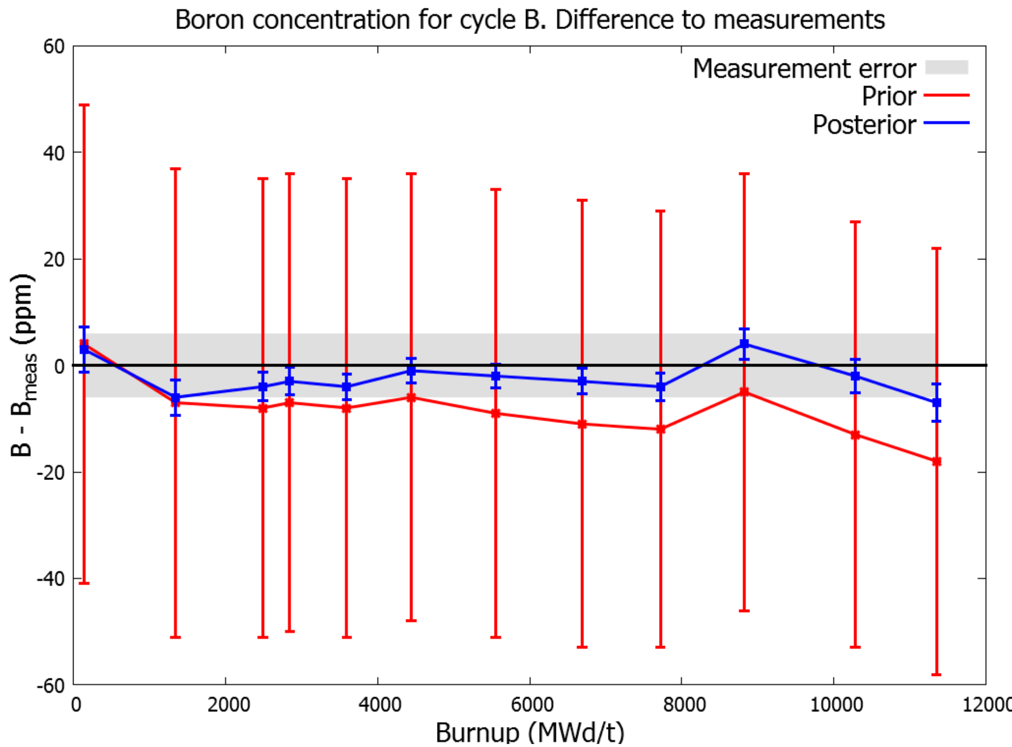
All rights are reserved, see liability notice.

AREVA forward-looking energy

Results of the MOCABA updating: Boron posterior results for cycle B

- B = boron concentration (ppm). σ = one standard deviation (ppm)

MWd/t	B_{prior}	σ_{prior}	B_{post}	σ_{post}	$\sigma_{prior} / \sigma_{post}$
135	987	45	986	4,2	10,7
1340	867	44	868	3,3	13,3
2487	763	43	767	2,7	15,9
2842	733	43	737	2,6	16,5
3591	664	43	668	2,4	17,9
4441	590	42	595	2,3	18,3
5549	487	42	494	2,2	19,1
6692	383	42	391	2,4	17,5
7716	290	41	298	2,6	15,8
8823	197	41	206	2,8	14,6
10284	74	40	85	3,2	12,5
11351	-15	40	-4	3,5	11,4



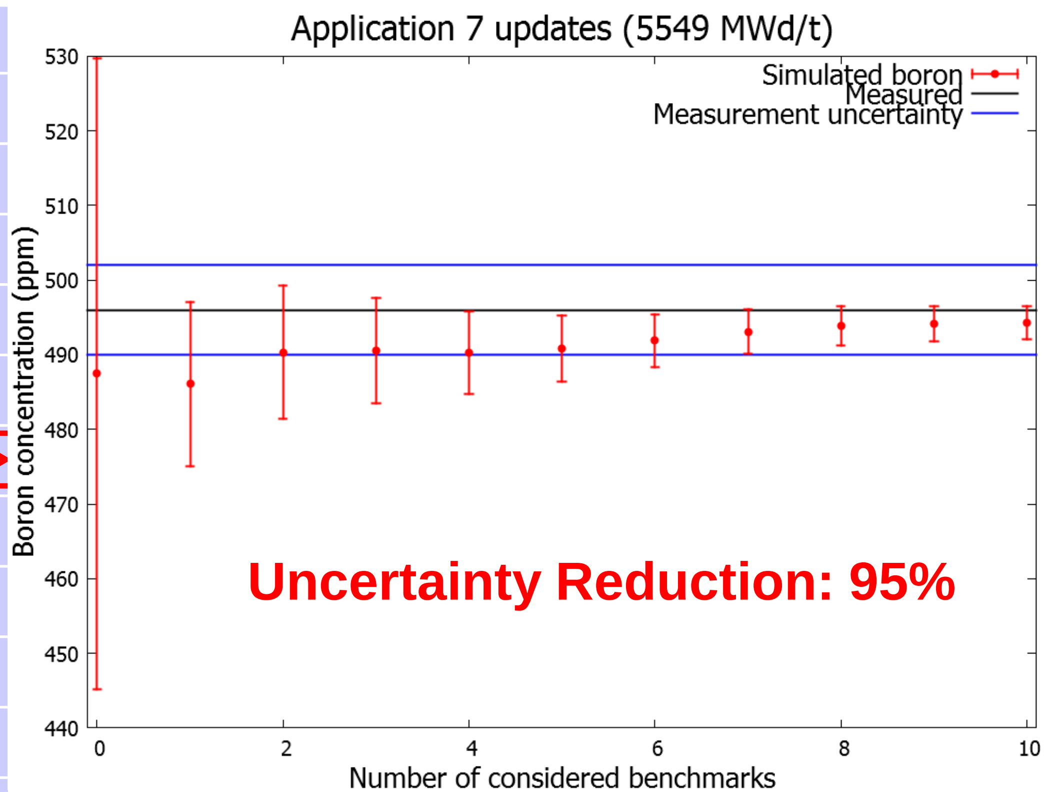
All rights are reserved, see liability notice.

AREVA forward-looking energy

Results of the MOCABA updating: Boron posterior results for cycle B

- B = boron concentration (ppm). σ = one standard deviation (ppm)

MWd/t	B_{prior}	σ_{prior}	B_{post}	σ_{post}	σ_{prior} / σ_{post}
135	987	45	986	4,2	10,7
1340	867	44	868	3,3	13,3
2487	763	43	767	2,7	15,9
2842	733	43	737	2,6	16,5
3591	664	43	668	2,4	17,9
4441	590	42	595	2,3	18,3
5549	487	42	494	2,2	19,1
6692	383	42	391	2,4	17,5
7716	290	41	298	2,6	15,8
8823	197	41	206	2,8	14,6
10284	74	40	85	3,2	12,5
11351	-15	40	-4	3,5	11,4



All rights are reserved, see liability notice.

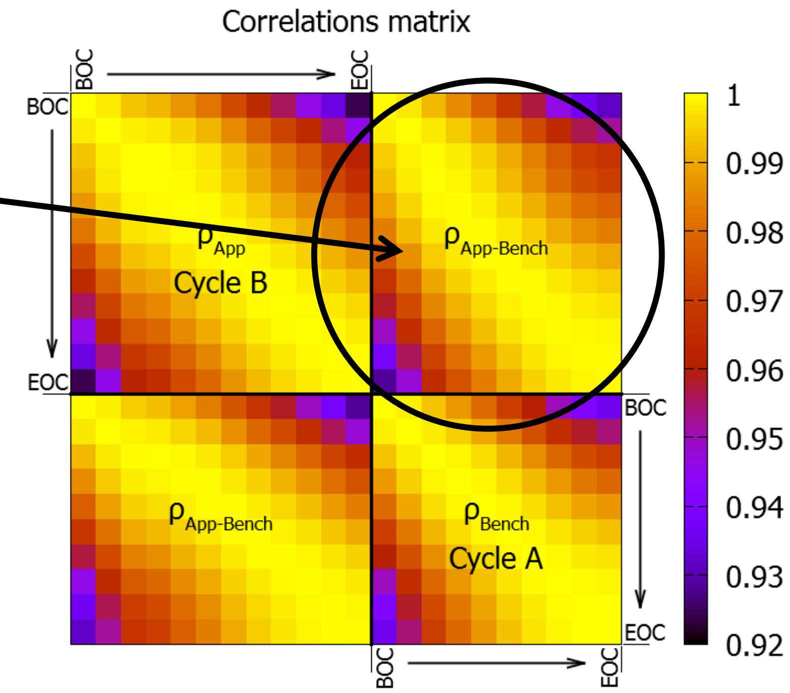
AREVA forward-looking energy

Results of the MOCABA updating: Boron posterior results for cycle B

Large correlations between cycle A and B

>0.92

Large impact of the Bayesian updating



- Posterior boron concentration improves **in all cases.**
- **Posterior uncertainty is reduced by one order of magnitude**.
- All posterior results are within the error band of the measurements

All rights are reserved, see liability notice.

AREVA forward-looking energy

Nuclear Data Library Updating with MOCABA

- **MOCABA can also be used to update nuclear data.**
- **U-235, U-238, Pu-239 and H-1** nuclear data updated for the 69 energy groups.
- Problem: huge amount of nuclear data (over 10.000 for H-1)
  → Need proper **memory management**

wims2mocaba
- Converts all random wims formatted libraries into a file for MOCABA

MOCABA
- Updates the nuclear data based on the measurements of cycle A

mocaba2wims
- Creates an updated WIMS formatted library from the output of MOCABA

Repeat for U-235, U-238, Pu-239 and H-1

Updated Nuclear Data Library

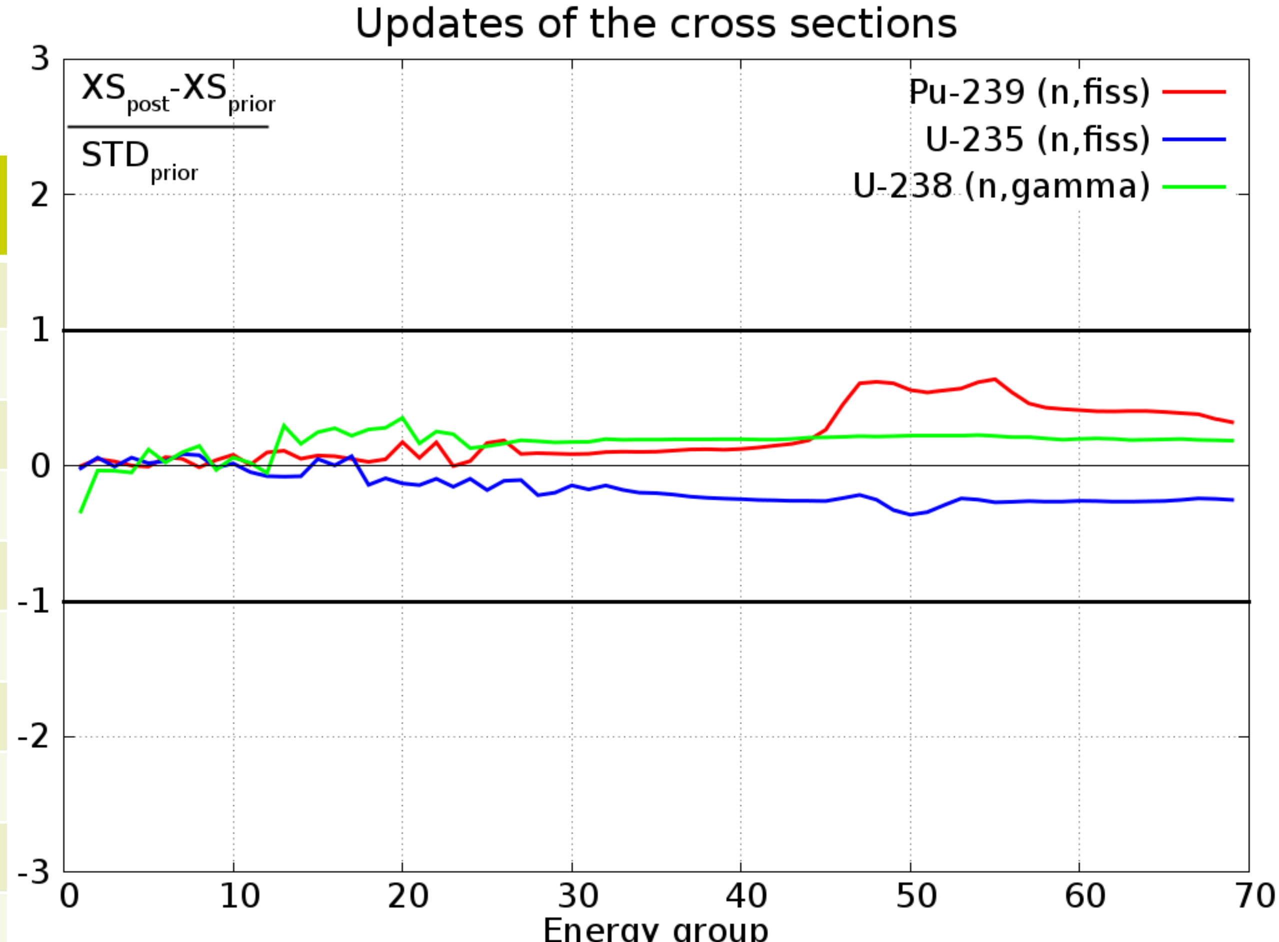
All rights are reserved, see liability notice.

AREVA forward-looking energy

Nuclear Data Library Updating: Results

- **Boron in cycle B with the updated library (ppm)**

MWd/t	B_{prior}	B_{upd}	$B_{meas}-B_{upd}$
135	987	988	-5
1340	867	870	4
2487	763	769	2
2842	733	739	1
3591	664	670	2
4441	590	597	-1
5549	487	496	0
6692	383	393	1
7716	290	300	2
8823	197	207	-5
10284	74	85	2
11351	-15	-5	8

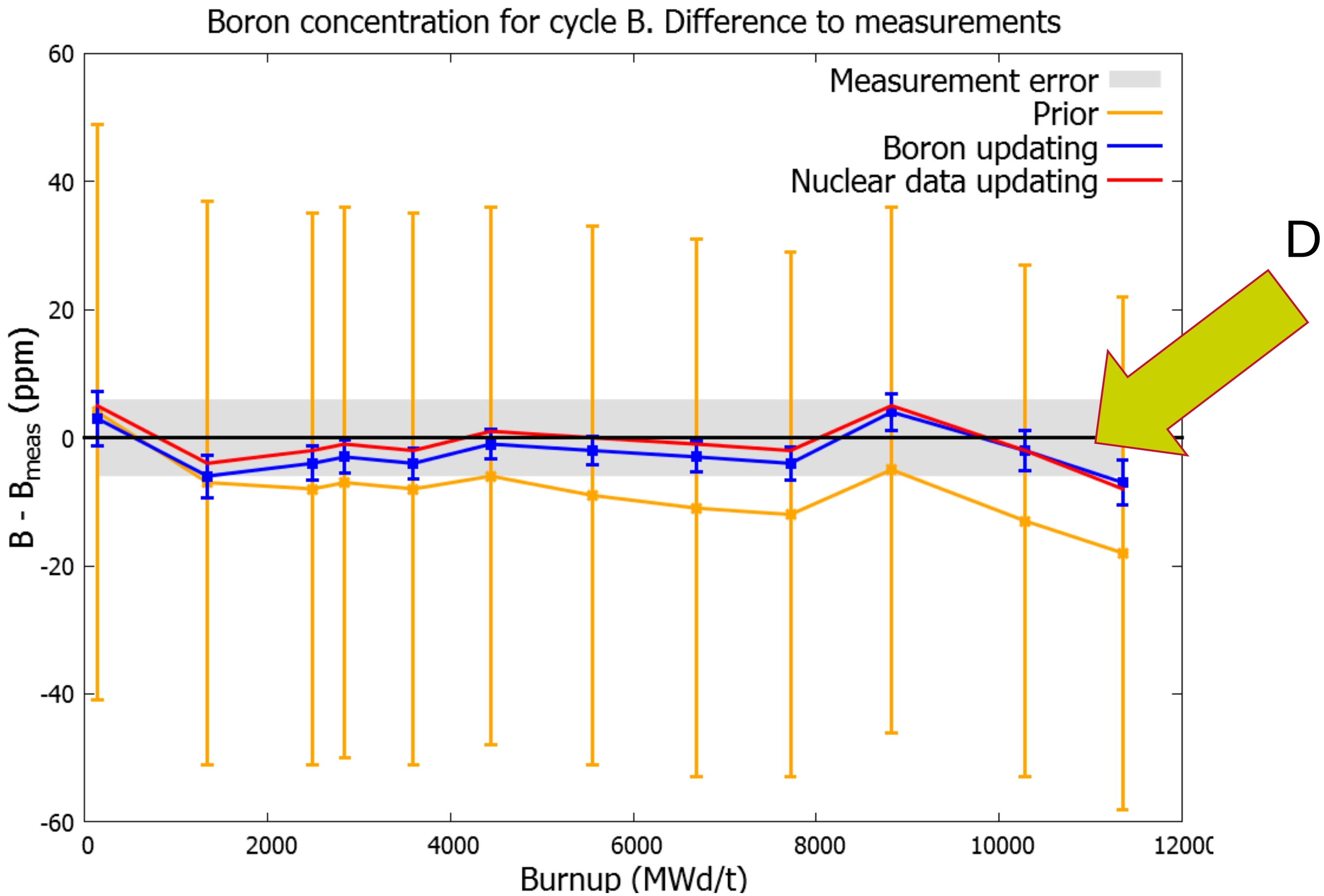


- Fast groups: 1-14
- Resonant groups: 15-27
- Thermal groups: 28-69

All rights are reserved, see liability notice.

AREVA forward-looking energy

Nuclear Data Library Updating vs. Direct Boron Curve Updating



Consistent results with both updating schemes: direct vs. nuclear data updating

All rights are reserved, see liability notice.

AREVA forward-looking energy

Chapter 5

Conclusions

AREVA
forward-looking energy

Conclusions

NUDUNA/MOCABA applied to SEANAP yields very good results:

- **Boron curve**
  - MOCABA improves mean values and leads to massive uncertainty reduction (up to 95%)
    - Update cycle by previous cycle measurements (6ppm meas. error)
    - Uncertainty=40 - 45 ppm before update ➔ 2 - 4 ppm after update
- **Nuclear data library updating**
  - Updated library provides improved predictions
  - Difference ~2ppm between results based on updated library and direct updating
  - Other applications:
    - **Evaluated Nuclear Data Libraries updating.**
    - Homogeneized Cross Sections Libraries
- **NUDUNA/MOCABA advantages:**
  - Easy to implement due to Monte Carlo methodology (Black Box approach)
  - Applicable to any integral function of nuclear data

All rights are reserved, see liability notice.

AREVA
forward-looking energy

References

[1]. Buss, O., Hoefer, A., Neuber, J., 2011. NUDUNA – nuclear data uncertainty analysis. In: Proc. International Conference on Nuclear Criticality (ICNC 2011), Edinburgh, Scotland.

[2]. Hoefer, A., Buss, O., Hennebach, M., Schmid M., Porsch D., 2015. MOCABA: A general Monte Carlo-Bayes procedure for improved predictions of integral functions of nuclear data. Annals of Nuclear Energy 77, 514-521

[3]. Cabellos, O., Castro, E., Ahnert, C., Holgado, C., 2014. Propagation of Nuclear Data Uncertainties for PWR Core Analysis. Nuclear Engineering and Technology 46 (3), 299-312

[4]. Díez, C.J., Buss, O., Hoefer, A., Porsch, D., Cabellos, O., 2015. Comparison of nuclear data uncertainty propagation methodologies for PWR burn-up simulations. Annals of Nuclear Energy 77, 101-114

All rights are reserved, see liability notice.

AREVA
forward-looking energy

Editor and Copyright [Date]: AREVA GmbH – Paul-Gossen-Straße 100 – 91052 Erlangen, Germany. It is prohibited to reproduce the present publication in its entirety or partially in whatever form without prior written consent. Legal action may be taken against any infringer and/or any person breaching the aforementioned prohibitions.

Subject to change without notice, errors excepted. Illustrations may differ from the original. The statements and information in this brochure are for advertising purposes only and do not constitute an offer of contract. They shall neither be construed as a guarantee of quality or durability, nor as warranties of merchantability or fitness for a particular purpose. These statements, even if they are future-orientated, are based on information that was available to us at the date of publication. Only the terms of individual contracts shall be authoritative for type, scope and characteristics of our products and services.

AREVA
forward-looking energy

All rights are reserved, see liability notice.

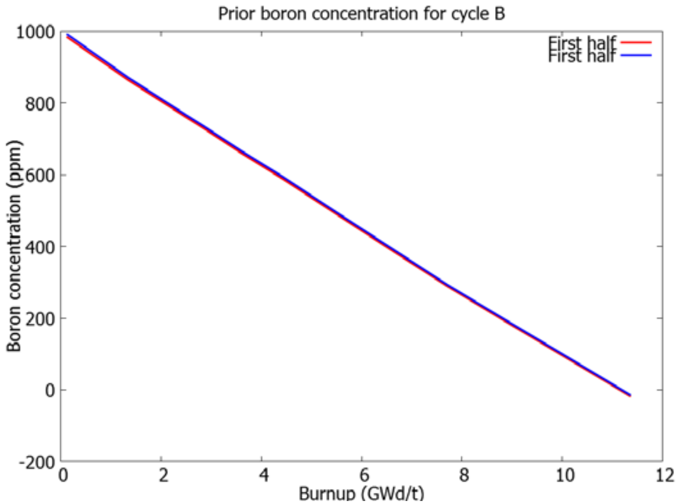
Improved PWR Simulations by Monte-Carlo Uncertainty Analysis and Bayesian Inference

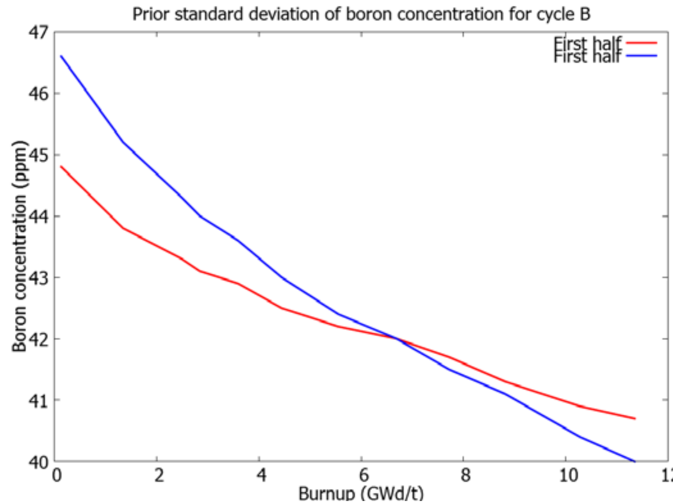
E. Castro, O. Buss, A. Hoefer
PEPA-G: Radiology & Criticality
AREBA GmbH, Germany

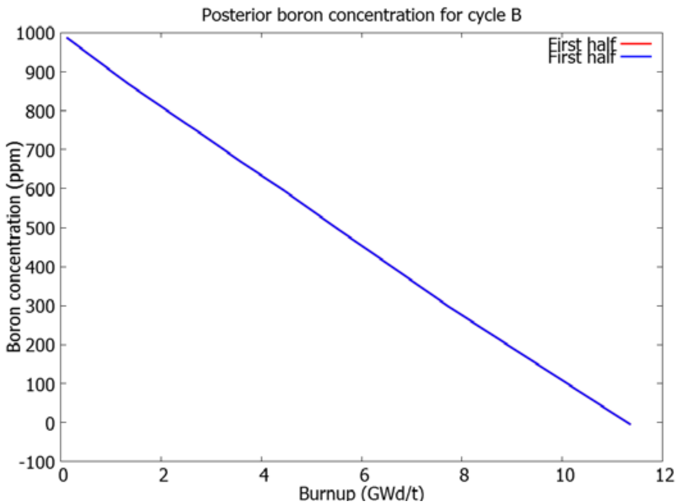
April 15th 2015

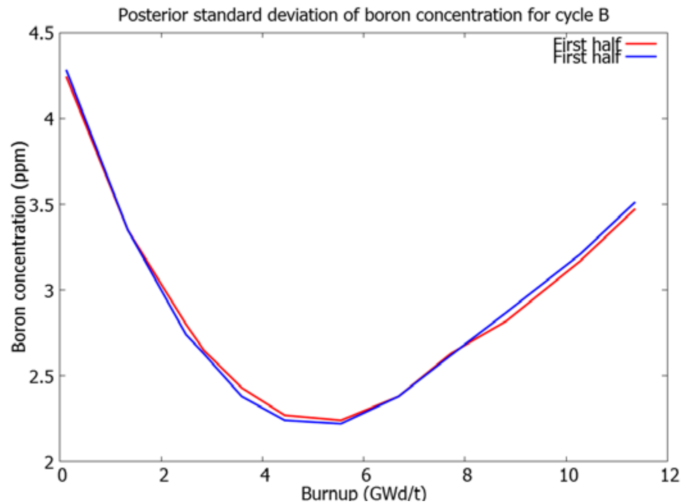
AREVA
forward-looking energy

Convergence check









All rights are reserved, see liability notice.

AREVA
forward-looking energy