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Feedback on nuclear data for separated Burnup Credit fission products oscillations in the MINERVE reactor with JEFF-3 library in PWR-MOx fuel criticality-safety studies

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Overview of the Presentation

- Burnup Credit concept

  Context : **spent fuel storage, transport**

Burnup-Credit (BUC) : taking credit for the reduction of the spent fuel reactivity due to its burnup (reduction of net fissile content, actinides build-up, increase of fission products concentration)

Actual regulatory status in France : « Actinide only » for PWR-UOx fuel at La Hague reprocessing plant

Reference
A. Santamarina, " Burnup credit implementation in spent fuel management", FJSS'98, CEA, Cadarache, France, August 17-26, 1998

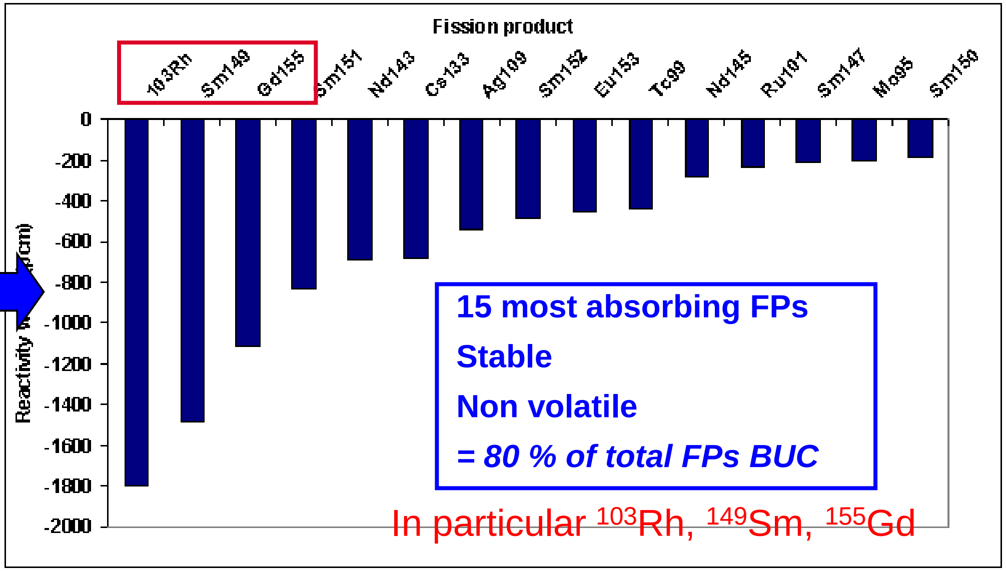
- Main lines
  - Burnup Credit concept and PWR-MOx BUC particularities
  - Individual reactivity worth bias : separated FPs oscillations in MINERVE reactor, interpretation with the dedicated scheme PIMS
  - Taking into account the individual reactivity worth in criticality-safety studies
    - Integral Experiment Methodology (RIB Tool)
    - Sensitivity and representativity study : PWR-MOx assembly
    - Determination of covariance matrices associated with the JEFF-3.1.1 for two main BUC FP : ^{149}**Sm** et ^{103}Rh.

Importance of fission products in PWR-MOx BUC

- *The MOx fuel BUC is lower than the one of PWR-UOx fuel because of the conversion factor improvement due to the high ^{240}Pu content. The contribution of the 15 most absorbing, stable and non-volatile FPs selected to the credit is as important as the one of the actinides.*

	PWR-UOx	PWR-MOx
Actinide BUC	19000 pcm	7550 pcm
15 FPs BUC	8400 pcm	8330 pcm
Total BUC	**27400 pcm**	**15880 pcm**

BU = 40 GWd/t$_{HM}$ Cooling time 1 year



- In order to get a conservative and physically realistic value of k_{eff} and meet the USL constraint, calculation biases on **FPs** inventory and **individual reactivity worth** should be considered in criticality studies.
- Inventory biases (depletion code DARWIN) already treated with CEA methodology *(ICNC 2011)*.

References
B. Roque, A. Santamarina, "Burnup credit in LWR-MOx assemblies", Proc. of Int. Conf. on Nuclear Criticality Safety (ICNC'95), Albuquerque, New Mexico, USA, September 17-21 (1995)
A. Barreau & al. , "Recent advances in French validation program and derivation of the acceptance criteria", Technical meeting on advances on Burnup Credit , IAEA-TECDOC-CD-1547, London, August 29-Sept 2 (2005)

Separated FP Oscillation Programmes in the MINERVE reactor

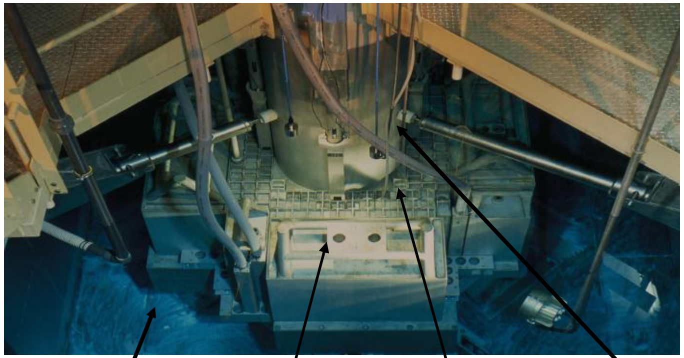
- In support of BUC studies, **specific experimental programme** has been developed at Cadarache Center in the framework of CERES CEA-UKAEA co-operation, and within the CEA-EDF-AREVA collaboration.

  - Experimental validation of the BUC FP individual reactivity worth in representative spectrum for PWR applications : trends due to nuclear data in JEFF-3.1.1 evaluation

- *The dedicated BUC programme (R1UO2 and R1MOX lattices) :*
  - Carried on in 1998, recent development of an accurate interpretation scheme and work on good command of the experimental uncertainties

- *The MAESTRO Phase-I programme (R1UO2 lattice) :*
  - *Validation of the capture cross sections for structural, detection and absorbing materials for GEN-III+ applications ;*
  - Validation of JEFF-3.1.1 capture cross sections for Co, Mn, V and **Rh.**

Minerve core



References
A. Santamarina, N. Thiollay, C. Heulin, J.P Chauvin, "The French Experimental programme on Burnup Credit", Proc. Top. Meeting on criticality challenges, Chelan (WA), USA, September 7-11 (1997)
P. LECONTE, The MAESTRO Experimental Program in MINERVE : Validation of JEFF-3.1.1 capture crosssections for Co, Mn, V and Rh, Proc of JEFF Meeting, NEA, Issy-les-Moulineaux, November 27th, 2012

Individual reactivity worth bias : MINERVE BUC physical principle

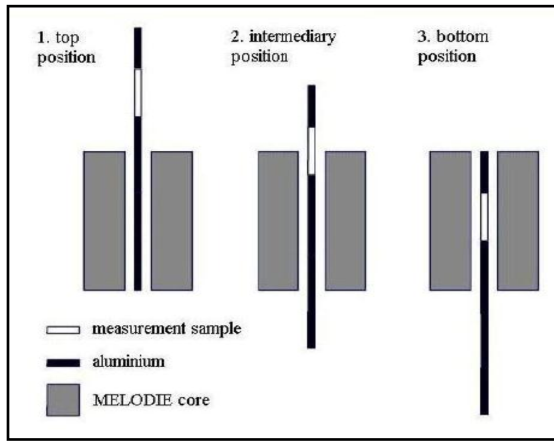
- The oscillation technique is well adapted to measure with accuracy low reactivity effects (10 pcm ± 0.02 pcm)
- Samples of 12 separated FPs and 5 natural elements (Ag, Mo, Nd, Sm, Ru) oscillated in the R1MOX lattice (PWR-MOx spectrum)
- Allows the transposition of the observed tendencies on their integral cross-sections

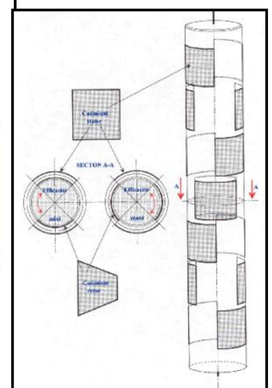
Ocillated Sample	Doping Isotope
Sm9	^{149}**Sm**
Sm7	^{147}Sm
Sm2	^{152}Sm
Sm	SmNAT
Nd3	^{143}**Nd**
Nd5	^{145}Nd
Nd	NdNAT
CsC1	^{133}**Cs**
CsC2	^{133}**Cs**
ACs1	^{133}**Cs**
ACs2	^{133}Cs
Ag9C1	^{109}Ag
Ag9C2	^{109}Ag
AAg	AgNAT
Mo5	^{95}Mo
AMo	MoNAT
ARu	RuNAT
Eu3	^{153}Eu
Tc99C	^{99}Tc
Gd5	^{155}**Gd**
Rh	^{103}Rh
RhC1	^{103}**Rh**
X	^{150}Sm
X	^{151}Sm
X	^{101}Ru

Oscillation technique

1 -Introduction of a doped sample at the center of the MINERVE core

2 - Flux variation detected by a boron chamber linked to a pilot rod





3 -The pilot rod compensates the variation : its rotation angle is proportional to the reactivity of the inserted sample

=> The reactivity variation due to the substitution of a reference sample by a separated FP (ie the perturbed sample) is estimated through the measurement

Reference
A. Santamarina & al., " Experimental validation of Burnup Credit calculation by Reactivity Worth Measurements in MINERVE reactor", Proc Int. Conf. ICNC'95, Albuquerque, New Mexico, USA, September 17-21 (1995)

Individual reactivity worth bias : oscillation interpretation

Based on the dedicated tool PIMS V1 (Pile-oscillation analysis tool for the IMprovement of cross Sections) developed at CEA (D. Bernard, P. Leconte)

- Reference modular scheme for oscillation experiments
- Based on APOLLO-2.8 deterministic code and on the recommendations from the reference SHEM-MOC calculation scheme for LWR applications
- Fully validated against stochastic calculations
- Reactivity variation calculation by Exact Perturbation Theory

Multigroup library JEFF-3.1.1 / SHEM

Data / input
- Isotopic concentrations
- Sample and lattice geometry

SHEM-MOC
- Self-shielded multigroup cross sections
- Flux calculation (MOC)

Exact Perturbation Theory
- Reactivity difference $\Delta\rho$ between separated FP sample and a reference sample (only the effect of UO2 support)

Calibration
- Measured effect in MINERVE converted in (C-E)/E bias (pcm)

=> Thanks to PIMS, the calculation biases are well quantified and reduced to get precise information on nuclear data

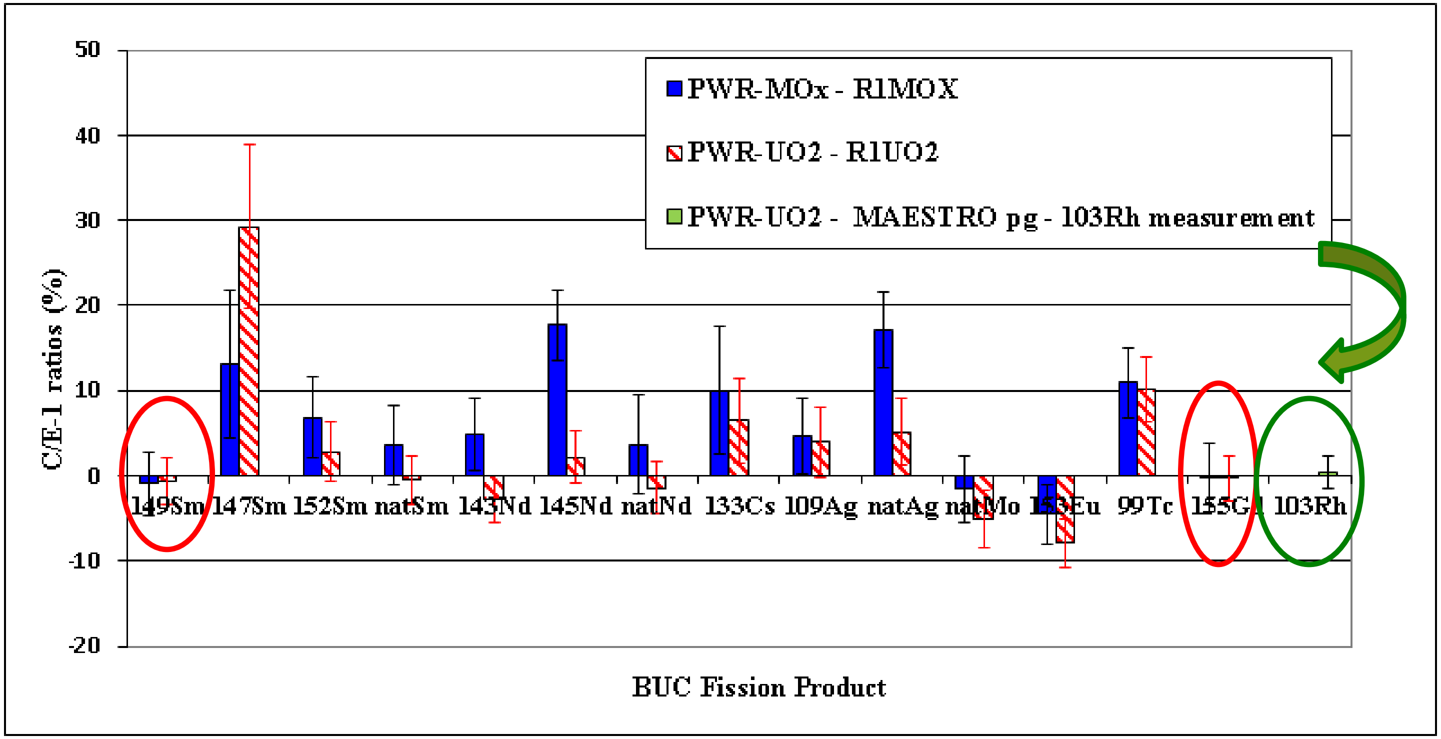
References

A. Gruel, P. Leconte, D. Bernard, P. Archier, G. Noguère, " Interpretation of Fission Product Oscillations in the MINERVE reactor, from Thermal to Epithermal Spectra ", Nucl. Sci. and Eng., 169, 229-224 (2011)

A. Santamarina, D. Bernard, P. Blaise, L. Erradi, R. Letellier, C. Vaglio, J.F Vidal, "APOLLO2.8, a validated code package for PWR calculation ", Proc. of Int. Conf. Advances in Nuclear Fuel Management, ANFM-IV, Hilton Head Island (SC), USA, April, 12-15 (2009)

Individual reactivity worth bias : oscillation interpretation

Interpretation results obtained with PIMS



- In a PWR-MOx spectrum, ^{109}Ag, ^{155}Gd, ^{143}Nd, ^{149,152}Sm are well predicted with the European JEFF-3.1.1 library (C/E biases less than 5%).
- Improvements may be needed in particular for ^{145}Nd, ^{133}Cs to correct the overestimation of their resonance integral. The MAESTRO programme confirms that ^{103}Rh is also well predicted with JEFF-3.1.1 (C/E biases less than 1%).

Taking into account the individual reactivity worth in criticality-safety study

Methodology proposed to determine the calculation biases and associated uncertainty due to nuclear data

- Integral Experiment Methodology
  - Allows the assessment of the calculation bias and the posterior uncertainty on the calculated integral parameters thanks to the information transfer from the integral experiment to the nuclear data
  - Based on : the re-estimation of nuclear data
    Experiment Representativity →
    $$r_{AE} = \frac{S_A^{+} \cdot D_{\sigma} \cdot S_E}{\varepsilon_A \cdot \varepsilon_E}$$
  - **Implemented in the dedicated tool RIB** (Representativity Uncertainty Bias) of the CRISTAL Criticality-Safety package to select representative experiments of an application and to determine the calculation biases and associated uncertainty due to ND after the experimental interpretation
- Transposition
  - The experiment representative coefficient and the experimental C/E-1 allow to determine computational k_{eff} bias due to the nuclear data to apply to the application integral parameter and its posteriori associated uncertainty.

=> The use of such a methodology requires the elaboration and introduction in JEFF-3.1.1 evaluation of the missing covariance matrices for actinides and each of the 15 BUC FPs

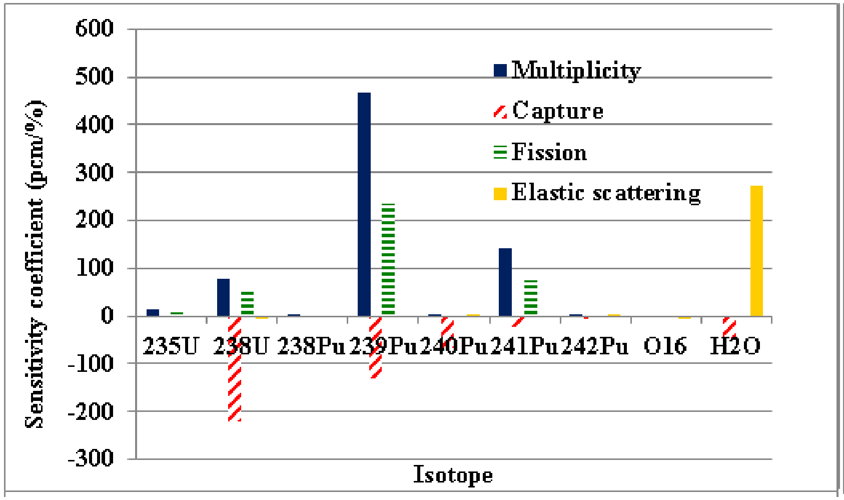
Reference
C. Venard, A. Santamarina, A. Leclainche, C. Mounier, "The RIB tool for the determination of computational bias and associated uncertainty in the CRISTAL criticality-safety package ", NSCD 2009

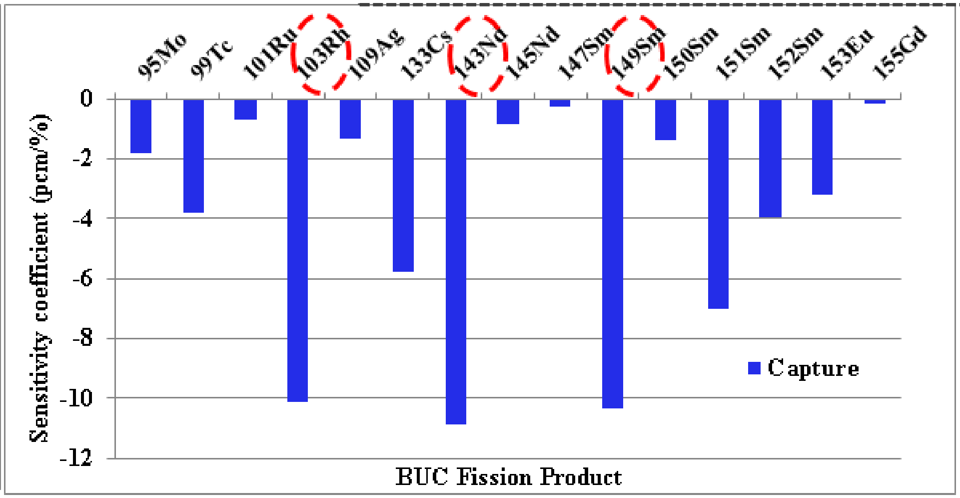
Taking into account the individual reactivity worth in criticality-safety study

Sensitivity and representativity study on the basis of APOLLO-2.8 P_{ij} calculation

- Chosen application : DAMPIERRE 2 PWR-MOx assembly ;
- Sensitivity coefficients (pcm/%) to the cross sections are obtained from the first order perturbation theory and derived on the European JEF15-group structure.

^{149}Sm, ^{103}Rh, ^{143}Nd *(perspective)*



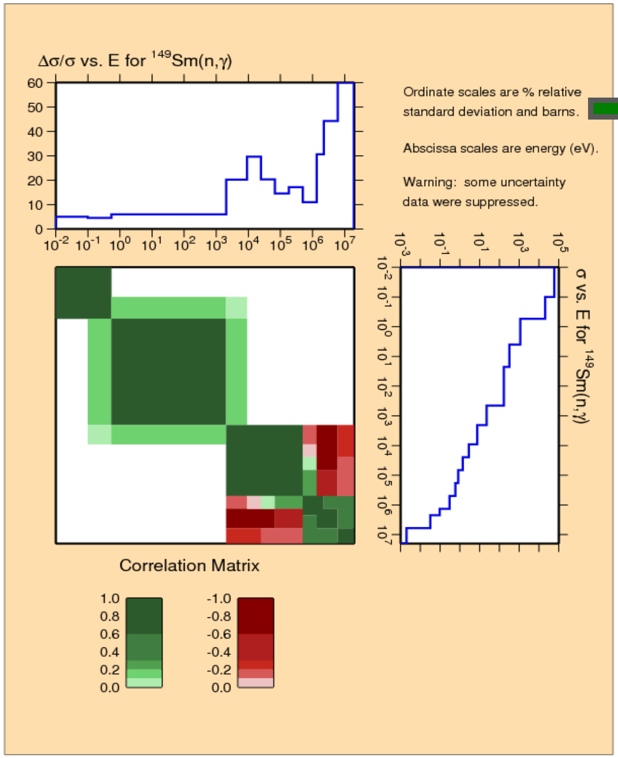


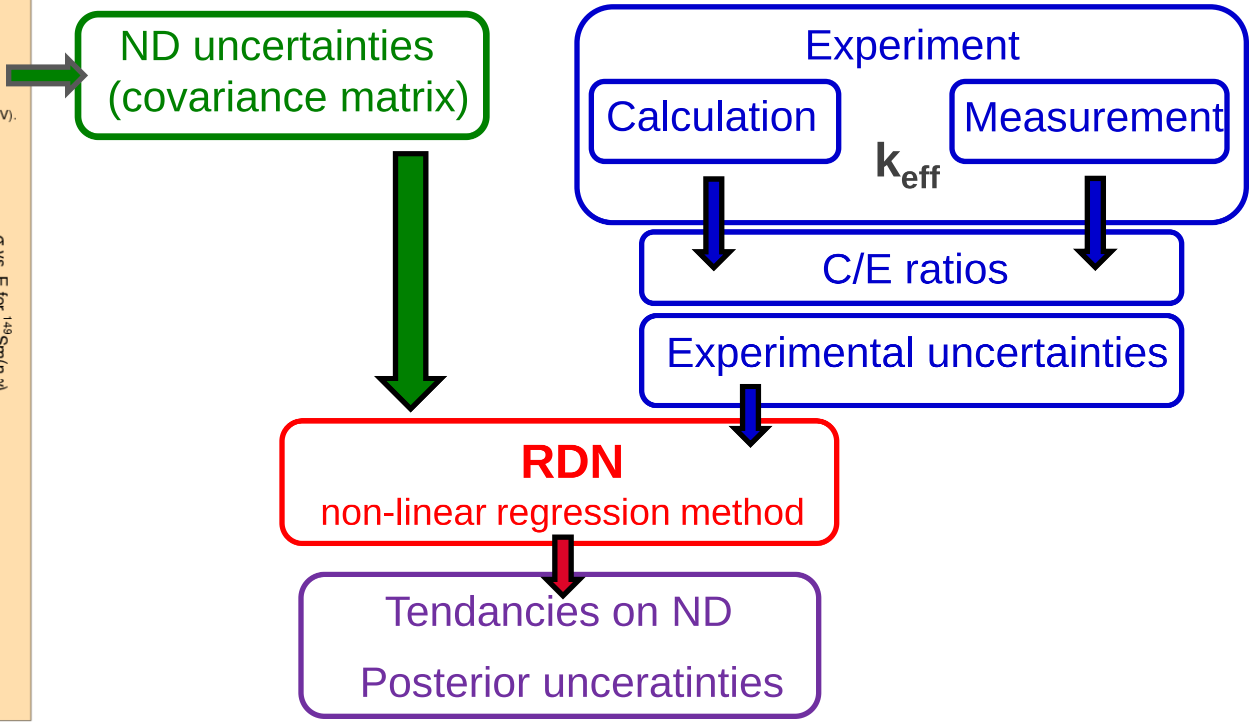
- k_{eff} particularly sensitive to ^{239}Pu, ^{241}Pu, ^{240}Pu ND and to the resonant capture of ^{238}U
- FPs : k_{eff} sensitive to ^{149}Sm, ^{103}Rh, ^{143}Nd ND (≈ 10 pcm/%)

Sample oscillated	Sm9	SmNAT	RH - MAESTRO	RhC1	Gd5
Lattice	R1MOX	R1MOX	R1UO2	R1MOX	R1MOX
Representativity factor	0,99968	0,99971	0,72716	0,99703	0,99974

DETERMINATION OF A COVARIANCE MATRIX FOR ^{149}SM : METHOD

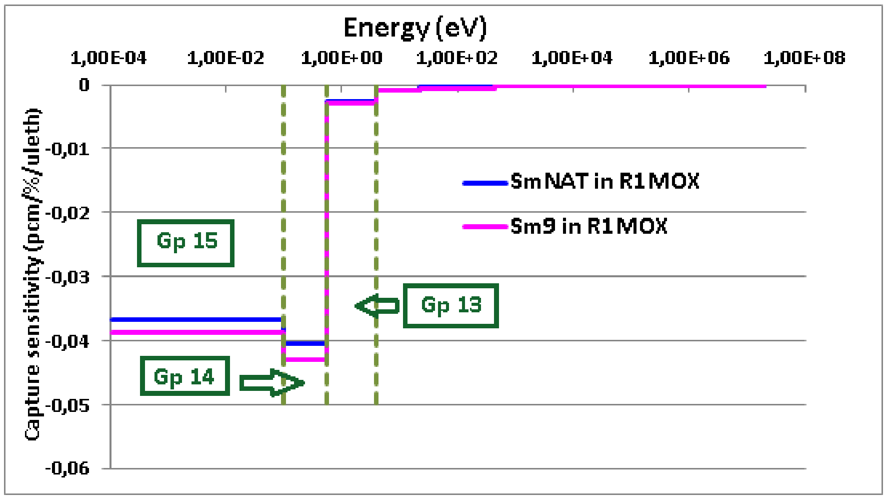
- Reactivity worth well predicted with JEFF-3.1.1 for ^{149}Sm (interpretation of the BUC programme) => associated C/E and uncertainties can be used for a nuclear data reestimation ;
- **RDN code** used for nuclear data re-estimation to produce prior covariance matrices (rigorous non-linear regression method using an iterative technique) ;
- **A priori covariance matrix from ENDF/B-VII** (expert advice), interpolated on the European JEF15-group structure using the CADTui Tool developed at CEA.

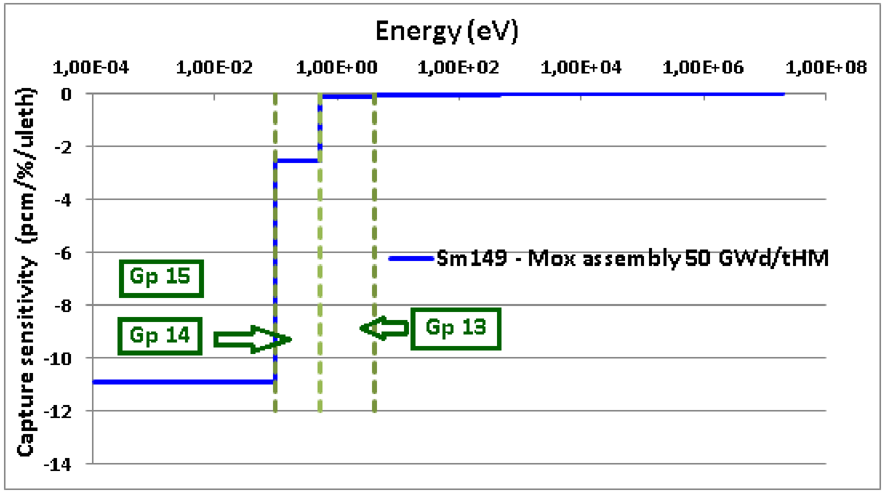




RESULTS – UNCERTAINTY REDUCTION IN THE THERMAL RANGE

- ^{149}Sm capture cross-section the Sm9 and SmNAT MINERVE samples are both taken into account ;





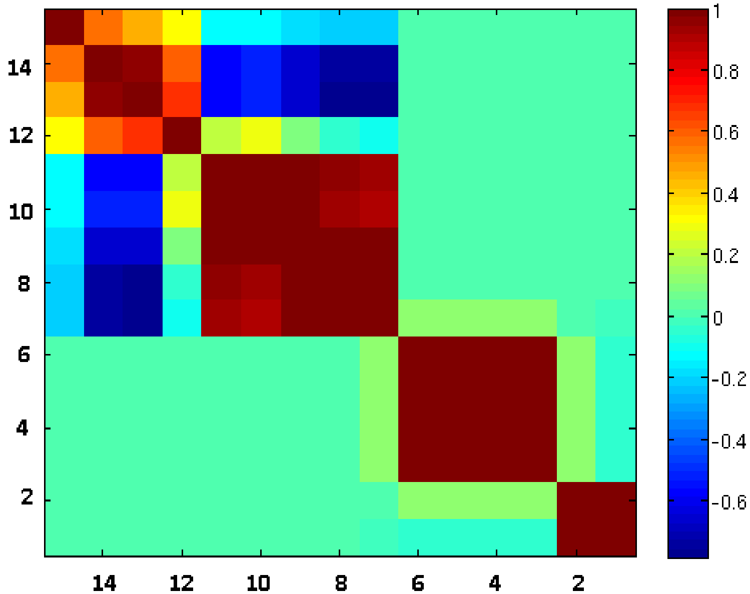
^{149}Sm capture cross section sensitivity profiles – Sm9 sample oscillated in R1MOX and in PWR-MOX assembly (50 GWd/t_{HM} – CT = 0)

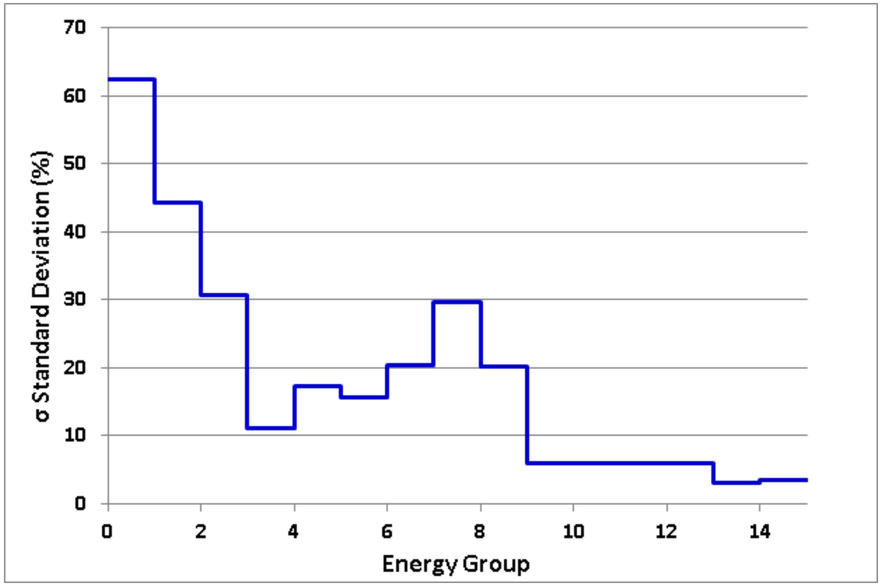
- **^{149}Sm** is **pure thermal poison** ;
- **K_{eff} is sensitive to its capture cross section variation** only into the **14th** (1.0 10^{-1} – 5.4 10^{-1} eV) and **15th** (1.0 10^{-4} - 1.0 10^{-1} eV) **energy groups** ;
- Cross-section modifications and the associated uncertainties recommended by the RDN code only concern these two thermal groups.

JEF-15 Energy Group	Prior Uncertainty (1σ) %	Posterior Uncertainty (1σ) %
14 (0,1<E<0,5 eV)	4,58	3,09
15 (E<0,1 eV)	5,00	3,38

^{149}SM PROPOSED COVARIANCE MATRIX

- The same three-blocs structure is observed for the new covariance matrix provided by RDN ;
- Integral information on ND taking into account => Reduction of the correlation between the **13th , 14th** and **15th energy groups (** 0.1 eV < E < 4 eV**)** => Reduction in the link between these groups and the rest of the spectrum.





- Implementation into the RIB tool.

Significant uncertainty reduction in the thermal range = > independance from prior data used.

Conclusion

- The evaluation and the way of taking into account the biases on FPs inventory and individual reactivity worth calculation in criticality-safety studies is an important issue of LWR-MOx BUC methodology .

- In support of the implantation of such a methodology, specific experimental programmes were carried out by CEA, in particular : BUC oscillation programme of separated FPs in MINERVE reactor

  => reactivity worth well predicted with JEFF-3.1.1 for ^{149}Sm, ^{155}Gd (<2%), ^{143}Nd, ^{152}Sm, ^{109}Ag, ^{153}Eu (<5%) ^{103}Rh (MAESTRO) ; some improvements may be needed to correct the overestimation of ^{145}Nd and ^{133}Cs resonance integral ;

  => feedback on nuclear data to produce covariance matrices to complete the JEFF library.

- The use of the Integral Experiment Methodology confirms the good representativity of the MINERVE experiments for BUC industrial application with respect to the FP BUC poisoning in a PWR-MOx assembly *(r_{AE} = 0.99 for ^{155}Gd and ^{149}Sm).*
- On the basis of existing best estimate covariance matrices and MINERVE experimental results, missing JEFF-3.1.1 covariance matrices are evaluated and proposed.

- ***Perspectives***

Apply the Integral Experiment Methodology to transport and pool storage applications for Mox cases using the proposed matrices and taking into account FPs (new in France) - evaluation of FP penalties (inventory, reactivity worth).

THANK YOU FOR YOUR ATTENTION !

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Evaluation of individual FP reactivity worth bias

- BUC FPs in PWR-MOx spectrum :
  - Not many experimental programs avalaible
  - Access to their results often restricted

Programme	Organizing country	Nuclides	Spectrum	Technique
Appareil B	France	FPs	PWR-UOx lattice	Criticals
CERES	France/UK	FPs	PWR-UOx/MOx lattice	Oscillation
MINERVE CBU	France	FPs	WR-UOx/MOx lattice	Oscillation
SANDIA	USA	^{103}Rh	PWR-UOx lattice	Foils
STACY	Japan	FPs	PWR-UOx lattice	Criticals
MINERVE MAESTRO	France	^{103}Rh	PWR-UOx lattice	Oscillation

- Thanks to the BUC oscillation programme of separated FPs in the MINERVE reactor, calculation over experiment ratios can be accurately transposed to tendencies on the FPs integral cross sections

- The oscillation technique is well adapted to measure with accuracy low reactivity effects (10 pcm ± 0.02 pcm)

Reference
"Advances in Application of Burnup Credit to enhance spent fuel transportation, storage, reprocessing and disposition " , Proceedings of a technical meeting held in London, August 29– Sept 2, IAEA-TECDOC-CD-1547 (2005)