DE LA RECHERCHE À L'INDUSTRIE

Needs of reliable nuclear data and covariance matrices for Burnup Credit in JEFF-3 library

WONDER 2012 | A. CHAMBON[1], A. SANTAMARINA[1], C. RIFFARD[1], F. LAVAUD[2], D. LECARPENTIER[2]

[1] CEA, DEN, DER, SPRC, Cadarache Center, F-13108 Saint-Paul-lez-Durance, France

[2] EDF, 1, avenue du Général de Gaulle, BP 408, F-92141 Clamart, France

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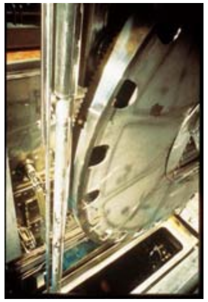
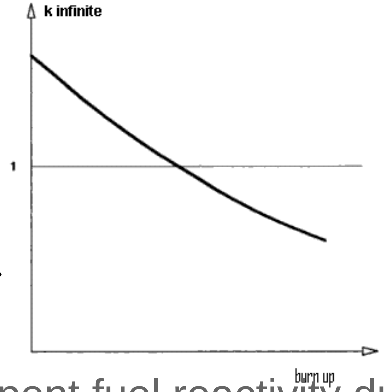
Burnup Credit concept





- Context : spent fuel storage, transport and reprocessing
- In general, spent fuel is considered as fresh in criticality-safety studies => significant conservatism in the calculated value of the system reactivity

Linearity of k_{inf} in function of Burnup



- ***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)
  - Industrial interest : downstream fuel cycle activities optimization
  - 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

Overview of the Presentation

Which purpose ?

- Recent publications and discussions within the French Burnup Credit (BUC) Working Group highlight the current interest of BUC for PWR-MOx spent nuclear fuel for transport and storage
- The consideration of full BUC including fission products would enable a load increase in several fuel devices

Main lines

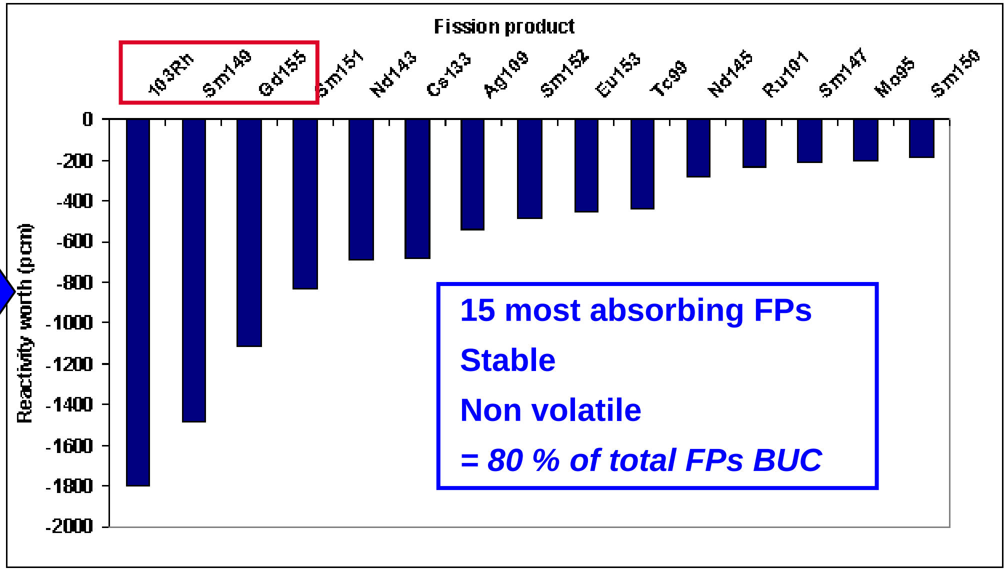
- Burnup Credit concept and PWR-MOx BUC particularities
- Assessment of inventory biases – methodology
- Individual reactivity worth bias : separated FPs oscillations in MINERVE reactor, interpretation with the dedicated scheme PIMS
- Taking into account the individual reactivity worth in criticality-safety studies

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



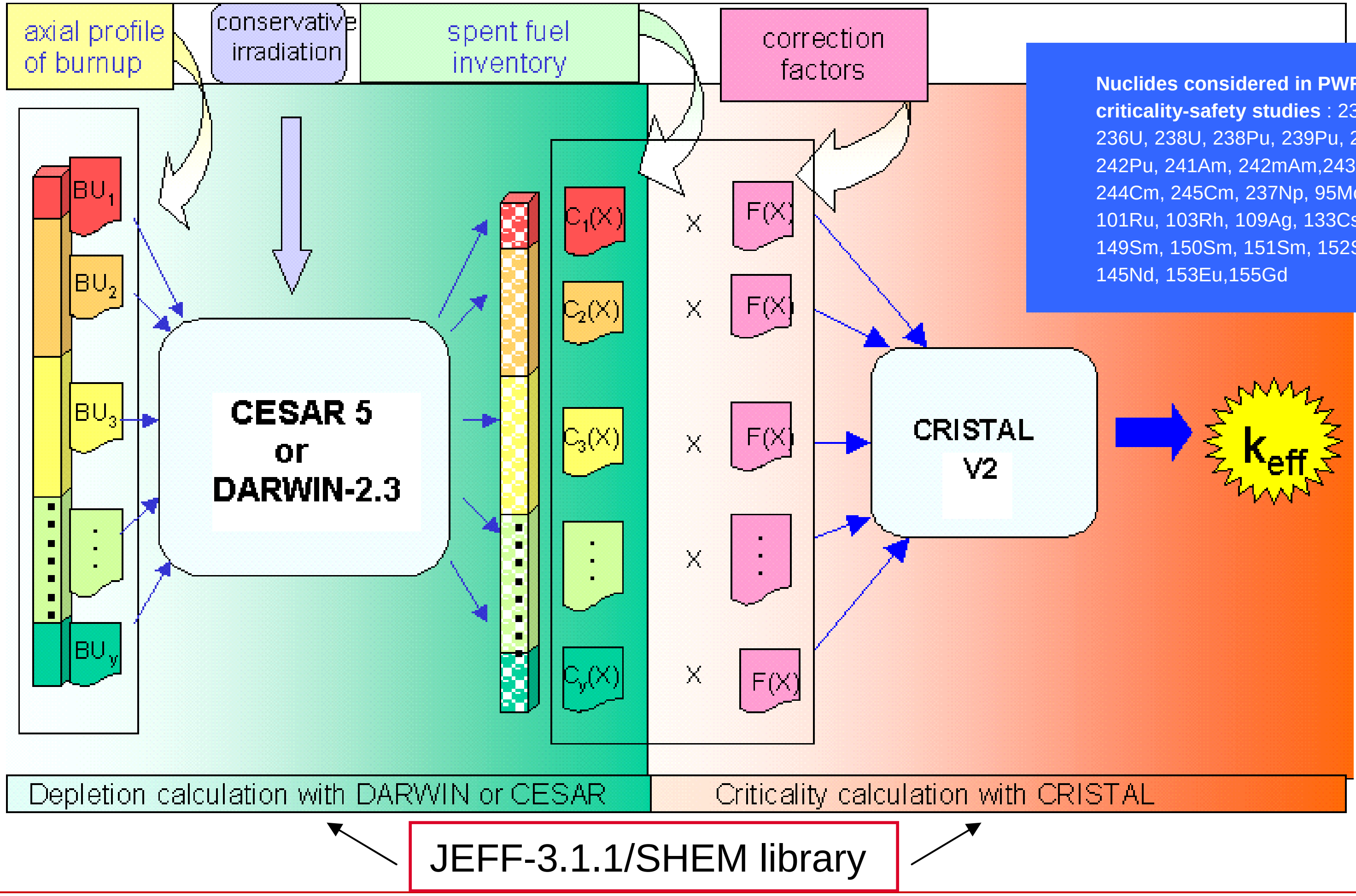
- In order to get a conservative and physically realistic value of k_{eff} and meet the USL constraint, calculation biases on FPs inventory and individual reactivity worth should be considered in criticality studies

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)

French BUC calculation route



Nuclides considered in PWR-MOx criticality-safety studies : 234U, 235U, 236U, 238U, 238Pu, 239Pu, 240Pu, 241Pu, 242Pu, 241Am, 242mAm,243Am, 243Cm, 244Cm, 245Cm, 237Np, 95Mo, 99Tc, 101Ru, 103Rh, 109Ag, 133Cs, 147Sm, 149Sm, 150Sm, 151Sm, 152Sm, 143Nd, 145Nd, 153Eu,155Gd

References

A. Santamarina, "The JEFF-3.1.1 library for accurate Criticality-Safety calculations", Proc. Of Int. Conf. ICNC 2011, Edinburgh, UK, September 19-22 (2011)

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)

Inventory and individual reactivity worth biases evaluation

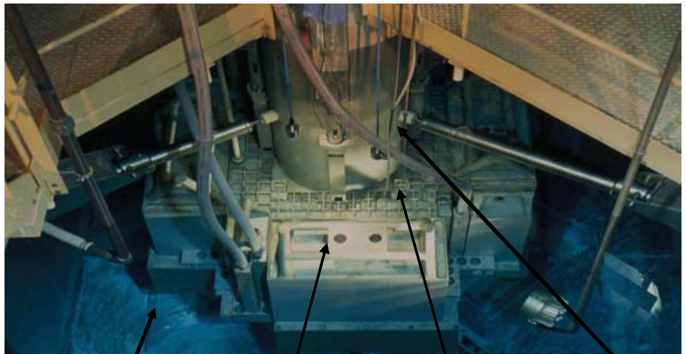
- In support of BUC studies, a **specific experimental programme** has been developed at Cadarache Center in the framework of CERES CEA-UKAEA co-operation, and within the CEA-AREVA collaboration.

- It is composed of **two kinds of experiments** :
  - *Post Irradiation Experiments (PIE) for Spent Fuel Inventory Calculation*
    - Destructive analysis of fuel rods cuts of PWR-MOx assemblies
    - Accurate measurements of isotopic content with mass-spectrometry techniques

Reference
B. Roque & al., "The French Post Irradiation Examination Database for validation of depletion calculation tools", Proc. Of Int. Conf. ICNC 2003, Oct. 20-24, Tokai, Japan

  - *Oscillation experiments in the MINERVE reactor : reactivity worth of individual BUC isotopes*

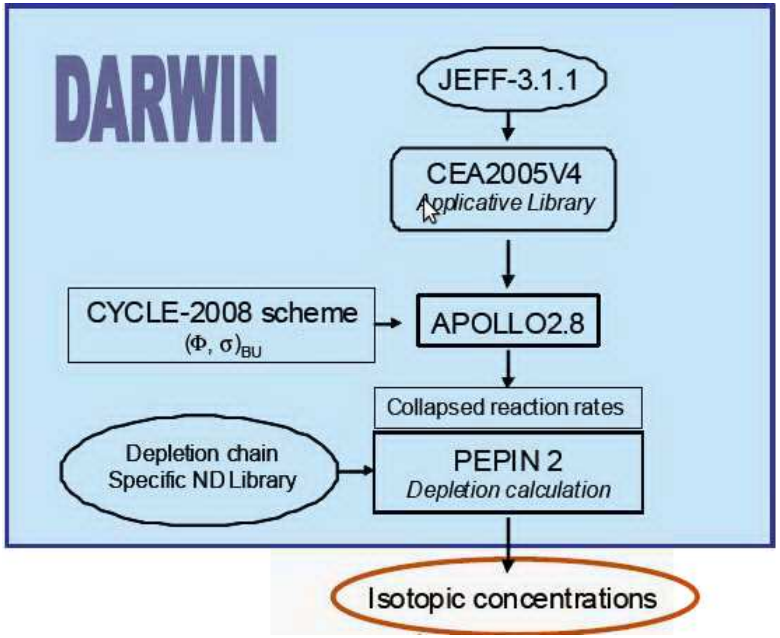
Minerve core



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

Reference
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)

Assessment of inventory biases (1/3)



- Trends in function of the burnup can be derived from the DARWIN-2.3 package qualification using the JEFF-3.1.1 library and the refined SHEM energy mesh
- Using JEFF-3.1.1, concentrations of actinides and main BUC FPs are accurately calculated

Isotopic ratio	C/E-1 (%)±σ(%) DP2 5 cycles J08-57 GWd/t_{HM}
$^{239}Pu/^{238}U$	1.3 ± 1.1
$^{241}Pu/^{238}U$	-1.5 ± 1.2
$^{149}Sm/^{238}U$	1.6 ± 5.1
$^{133}Cs/^{238}U$	0.9 ± 1.5
$^{143}Nd/^{238}U$	-0.7 ± 1.5

PWR-MOx PIE data base

	Burnup Range (GWd/t_{HM})	Measurements	Number of central fuel rods samples
SLB1	30	U, Pu, Nd, Np, Am, Cm, Cs, Sm, Eu, Gd	9
Dampierre 2	10-58	U, Pu, Nd, Np, Am, Cm, Cs, Sm, Eu, Gd, metallics	6

Reference
L. San Felice & al., "Experimental validation of the DARWIN-2.3 package for fuel cycle applications", Proc. Of Int. Conf PHYSOR 2012, Knoxville, USA, April 15-20, 2012

Assessment of inventory biases (2/3)

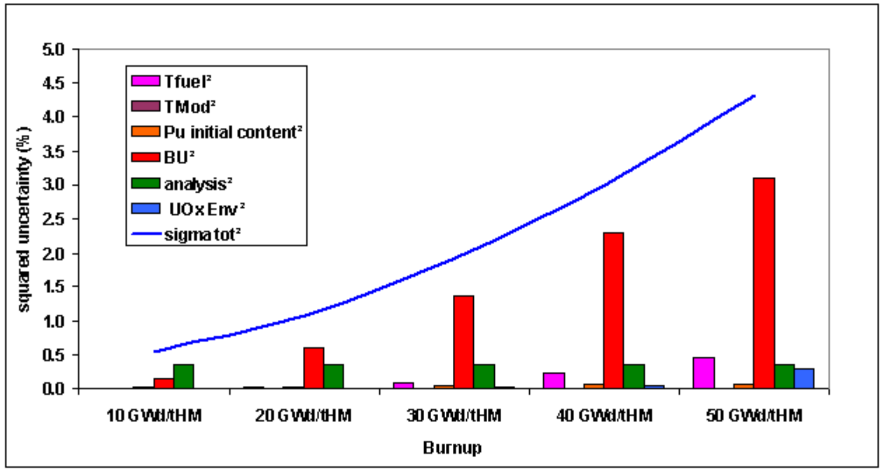
Isotopic Correction Factors applied to BUC isotopic concentrations Methodology

- Determination of a linear trend of relative Calculation/Experiment discrepancies (C-E)/E in function of the Burnup for each isotope

- Determination of the total experiment uncertainty by combining the various uncertainty components
  - Fuel and coolant temperature ;
  - Initial Pu content ;
  - Chemical assays ;
  - Local burnup estimation ;
  - Follow-up.

Quadratic components of the total uncertainty (1σ)

Example of the ^{239}Pu



- Penalization of the (C-E)/E bias at each burnup by the one sided 95% confidence interval
  - Penalized bias for fissile isotopes $\Delta = (C-E)/E - 1.65\sigma$
  - Penalized bias for absorbant isotopes $\Delta = (C-E)/E + 1.65\sigma$

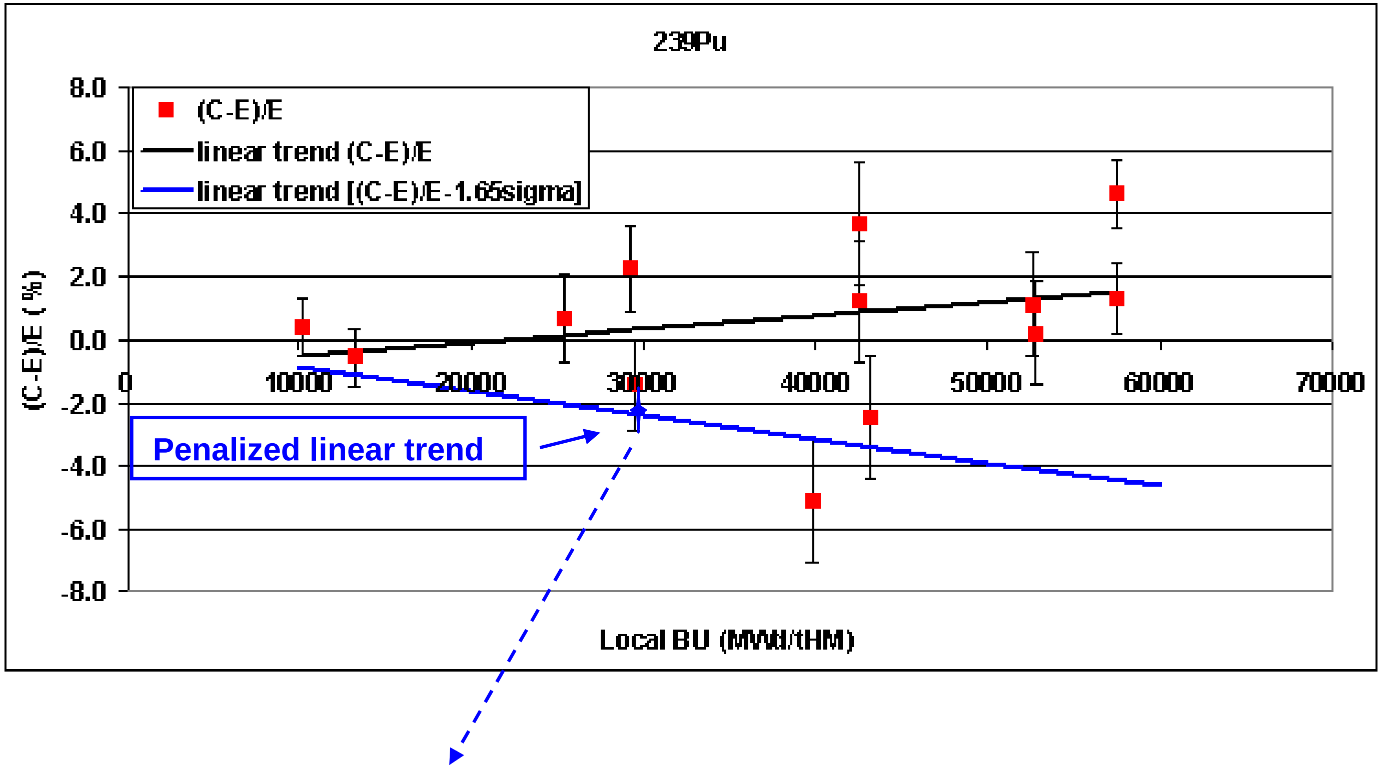
- Application of the ICFs = $1/(1+\Delta)$ to the calculated concentrations

Reference
C. Riffard, A. Santamarina, J.F Thro, « Correction facors applied to isotopic concentrations in Burnup Credit implementation with the recent JEFF-3.1.1/SHEM library », Proc. Of Int. Conf. ICNC 2011, Edinburgh, UK, September 19-22 (2011)

Assessment of inventory biases (3/3)

Detailed example : ^{239}Pu

Penalized bias trend [C-E]/E -1.65σ vs bumup



-2.5% at 30GWd/t_{HM} ⇒ ICF = 1.03 at 30 GWd/t_{HM}

Individual reactivity worth bias

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

Programme	Nuclides	Technique	Organizing Country	Status	Access
Appareillage B	FPs	criticals	France	completed	restricted
OSMOSE	Actinides	oscillation	France	completed	restricted
CERES	FPs	oscillation	France/UK	completed	restricted
MINERVE LWR UOx & MOx	Spent fuel	oscillation	France	completed	restricted
REBUS-P-B	Spent fuel	criticals	Belgium	completed	restricted
PROTEUS	Spent fuel	criticals	Switzerland	completed	restricted
SANDIA	^{103}Rh	foils	USA	completed	open

- 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

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)

Individual reactivity worth bias : MINERVE BUC programme

- PWR-MOx BUC programme in the MINERVE reactor
  - Carried on in 1998, recent development of an accurate interpretation scheme and work on good command of the experimental uncertainties
  - Samples of 12 separated FPs and 5 natural elements (Ag, Mo, Nd, Sm, Ru) oscillated in the R1MOX lattice (PWR-MOx spectrum)

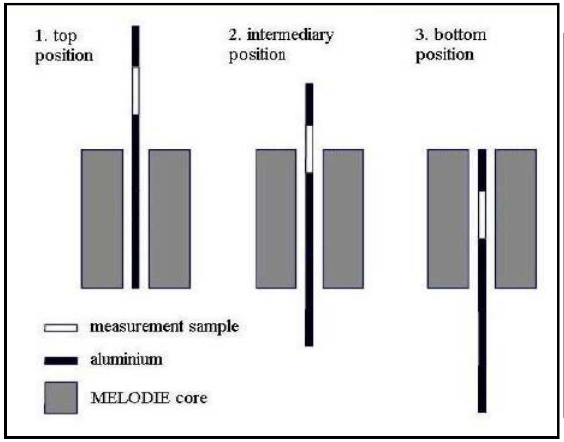
Ocillated Sample	Doping Isotope
Sm9	**^{149}Sm**
Sm7	^{147}Sm
Sm2	^{152}Sm
Sm	SmNAT
Nd3	**^{143}Nd**
Nd5	^{145}Nd
Nd	NdNAT
CsC1	**^{133}Cs**
CsC2	**^{133}Cs**
ACs1	**^{133}Cs**
ACs2	^{133}Cs
Ag9C1	^{109}Ag
Ag9C2	^{109}Ag
AAg	AgNAT
Mo5	^{95}Mo
AMo	MoNAT
ARu	RuNAT
Eu3	^{153}Eu
Tc99C	^{99}Tc
Gd5	**^{155}Gd**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

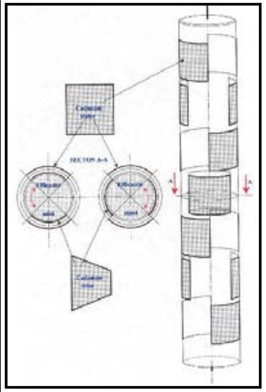
- Oscillation technique

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



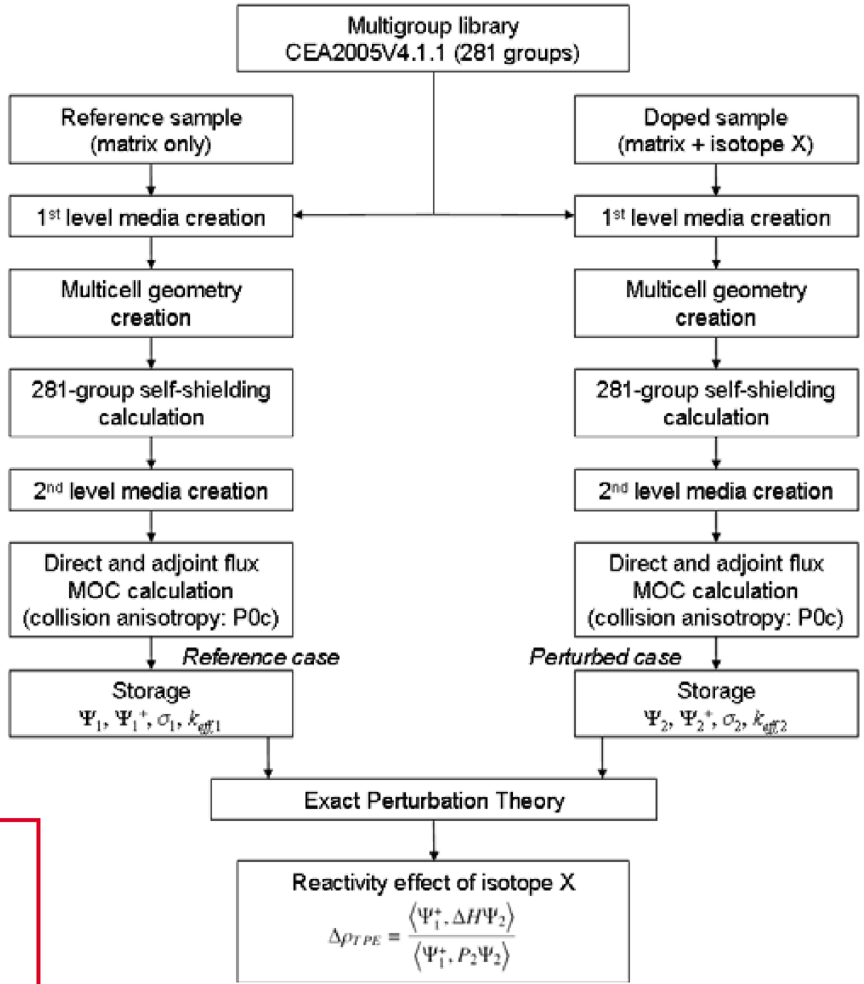


Reference
A. Santamarina & al., " Experimental validation of Burnup Credit calculation by Reactivity Worth Measurements in MINERVE reactor", Proc Int. Conf. ICNC'95, Albuquerque, New Mexico, USA, September 17-21 (1995)

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



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

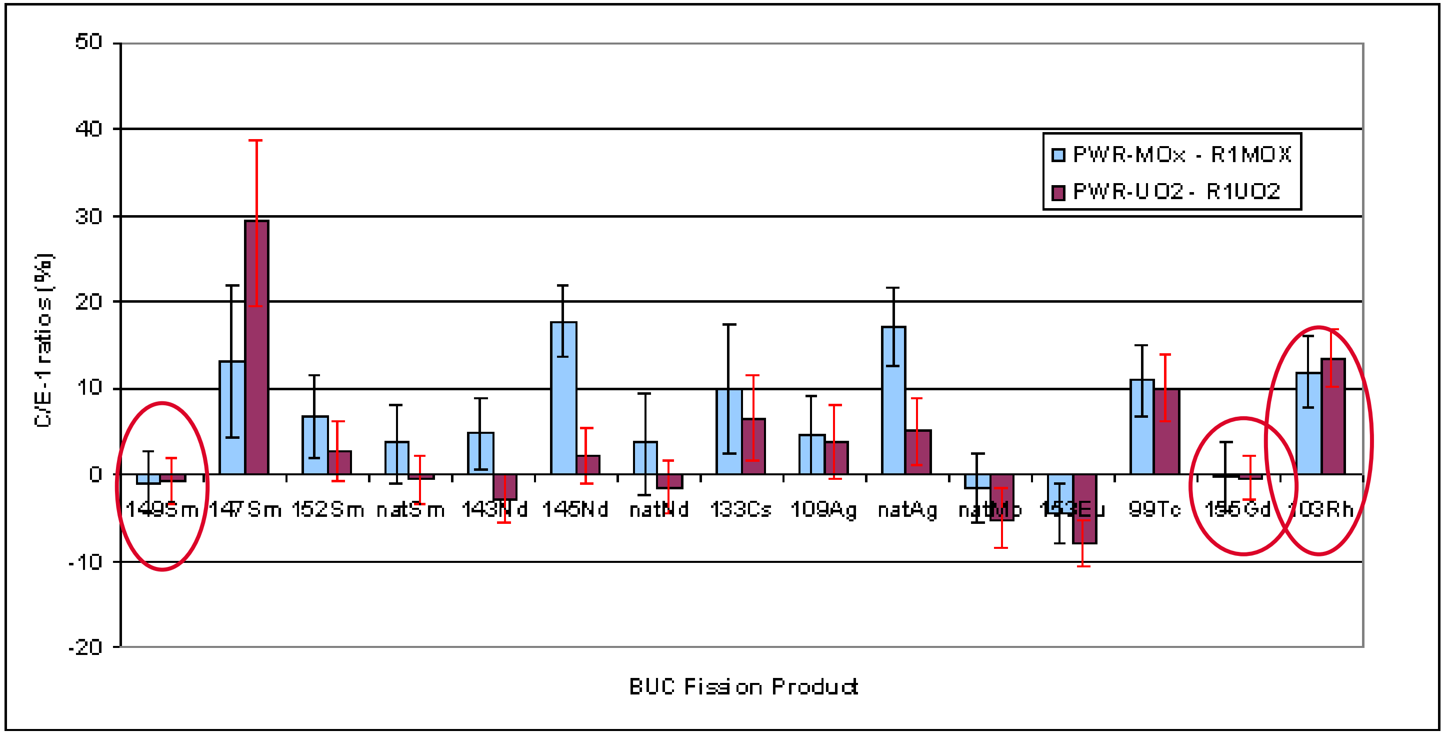
References

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, ^{103}Rh to correct the overestimation of their resonance integral

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.

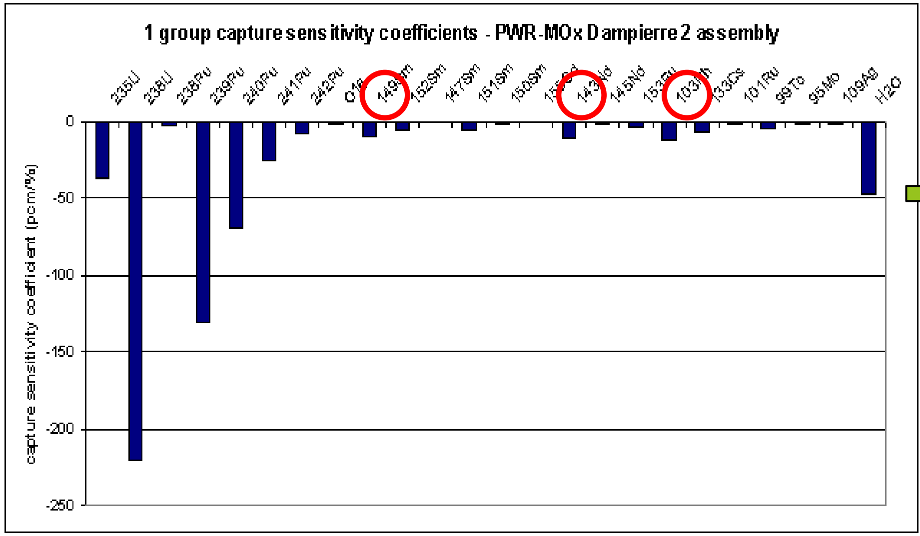
=> The use of such a methodology requires the elaboration and introduction in JEFF-3.1.1 evaluation of the missing covariance matrices for actinides and each of the 15 BUC FPs

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, Richland, Washington, USA, September 13-17 (2009)

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

Preliminary study on the basis of APOLLO-2.8 Pij sensitivity calculation

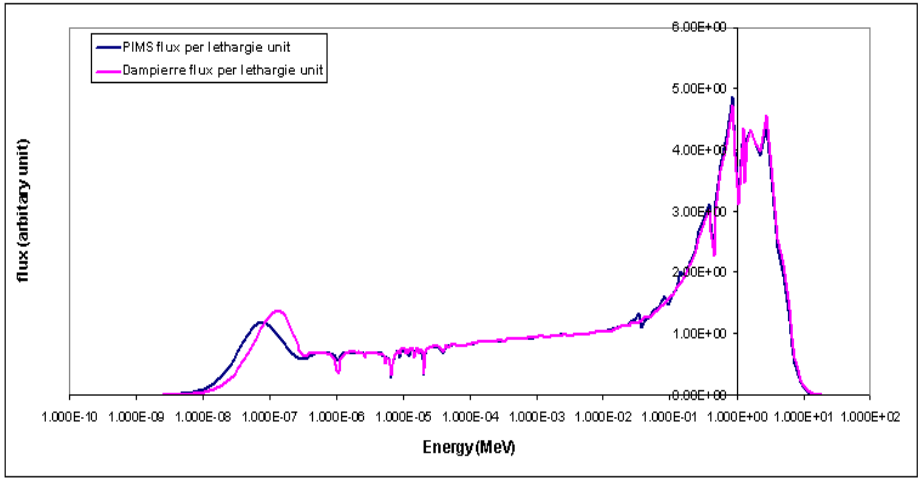
- Chosen application : DAMPIERRE 2 PWR-MOx assembly
- Sensitivity coefficients (pcm/%) to the cross sections are obtained from the first order perturbation theory and derived on the European JEF15-group structure



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

A preliminary study with RIB gives a representativity factor r_{AE}=0.94 of the MINERVE ^{155}Gd worth with respect to FP-BUC poisoning in a PWR-MOx assembly



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

Prior covariance matrices available for BUC FPs

- Available cross sections covariance obtained from ND differential measurements and expert advice :

BUC FP	Covariance matrices database						
	COMAC	BOLNA	COMMARA 2.0	TENDL	SCALE-6	ENDF BVII	JENDL
^{95}Mo			X	X	X	X	
^{99}Tc			X	X	X	X	
^{101}Ru			X	X	X	X	
^{103}Rh			X	X	X	X	
^{109}Ag			X	X	X	X	
^{133}Cs			X	X	X	X	
^{143}Nd			X	X	X	X	
^{145}Nd			X	X	X	X	
^{147}Sm				X	X		
^{149}Sm			X	X	X	X	
^{150}Sm				X	X		
^{151}Sm			X	X	X	X	
^{152}Sm			X	X	X	X	
^{153}Eu			X	X	X	X	
^{155}Gd	X (JEFF-3.1.1)	X	X	X	X	X	

- Available tools for interpolation of cross sections covariance data : (a 15 groups mesh is used in RIB)
  - **ANGELO2** : adapted for SCALE 6 cvx. format matrices
  - **CADTOOL** (SPRC/LEPh) : adapted for ENDF format matrices

References

M. Herman & al., "COMMARA-2.0 Neutron Cross Section Covariance Library", BNL-94830-2011, 2011

S. Hobli & al., "Neutron Cross Section Covariances for Structural Materials and Fission Products", in Nuclear Data Sheets 112 (2011) 3075-3097

A.J Koning, D Rochman, "TENDL-2009 : consistent TALYS-based Evaluated Nuclear Data Library including covariance data", JEF-DOC 1310, 2009

I. Kodeli, "Manual for ANGELO2 and LAMBDA codes", NEA-1264/05 package (2003)

G. Noguere, J. Ch Sublet, "A nuclear data oriented interface code for processing applications", in Annals of Nuclear Energy 35 (2008) 2259-2269

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

Needs of reliable covariance matrices for BUC FPs in JEFF-3.1.1 evaluation

- The actual ^{235}U covariance matrix associated with JEFF-3.1.1 has already been derived from targeted clean integral experiments

⇒In order to obtain reliable covariance matrices

Ongoing studies : ^{149}Sm and ^{103}Rh covariance matrices

- Covariance matrices, obtained from ND differential measurements and expert advice are already available for BUC nuclides (in particular in ENDF BVII ND evaluation). Thanks to the **RDN process of nuclear data re-evaluation** (rigourous non-linear regression method), we are using the MINERVE integral measurements in order to infer realistic JEFF-3.1.1 covariance matrices for BUC FPs.

References
A. Santamarina, D. Bernard, N. Dos Santos, O. Leray, C. Vaglio, L. Leal, "Re-estimation of Nuclear Data and JEFF3.1.1 Uncertianty Calculation", Proc. Of Int. Conf PHYSOR 2012, Knoxville, Tennese, USA, April 15-20,2012
C. De Saint-Jean, P. Archier, G. Noguere, O. Litaize, C. Vaglio, D. Bernard, O. Leray, " Estimation of multi-group cross section covariances of $^{238,235}U$, ^{239}Pu, ^{241}Am, ^{56}Fe, ^{23}Na", Proc. Of Int. Conf. PHYSOR 2012, Knoxville, USA, April 15-20 (2012)

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 programs were carried out by CEA
  - Chemical analyses and microprobe measurements of LWR-MOx spent fuel rods

    => Recent trends in function of the burnup can be derived from the DARWIN-2.3 package qualification
  - BUC oscillation program 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%)

    => some improvements may be needed to correct the overestimation of ^{145}Nd, ^{133}Cs, and ^{103}Rh resonance integral

- The use of the Integral Experiment Methodology confirms the good representativity of the MINERVE experiments for BUC industrial application *(r_{AE} = 0.94 for ^{155}Gd)*
- On the basis of existing best estimate covariance matrices and MINERVE experimental results, missing JEFF-3.1.1 covariance matrices will be introduced in the RIB tool

THANK YOU FOR YOUR ATTENTION !

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint Paul lez Durance
T. +33 (0)4 42 25 31 30 | F. +33 (0)4 42 25 48 49

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