IMPACT OF THE FISSION YIELD COVARIANCE DATA IN BURN-UP CALCULATIONS

O. Cabellos, D. Piedra, Carlos J. Diez

Department of Nuclear Engineering, Universidad Politécnica de Madrid, Spain

E-mail: oscar.cabellos@upm.es

Outline

1. Introduction: “Burnup Credit”

- 1.1 “Pin-cell Burn-up UAM Benchmark”
- 1.2 Propagation of FY Uncertainties in “pin-cell burn-up Benchmark”
- 1.3 State-of-art FY Covariance Data
  - 1.3.1 Bayesian Methodology by Katakura

2. Methodology to propagate ND Uncertainties

- 2.1 Monte Carlo Methodology: “Number Density Uncertainty”
  - 2.1.1 Monte Carlo Methodology: “Number Density Uncertainty” for ^{148}Nd, ^{137}Cs and ^{139}La
  - 2.1.2 Monte Carlo Methodology:“Number Density Uncertainty” for ^{109}Ag and ^{129}I
  - 2.1.3 Low correction for ^{109}Ag using Katakura correlation matrix
- 2.2 S/U Methodology: “Number Density Uncertainty”
  - 2.2.1 S/U Methodology: ^{148}Nd, ^{139}La and ^{137}Cs (burnup indicators)
  - 2.2.2 S/U Methodology: ^{109}Ag and ^{129}I

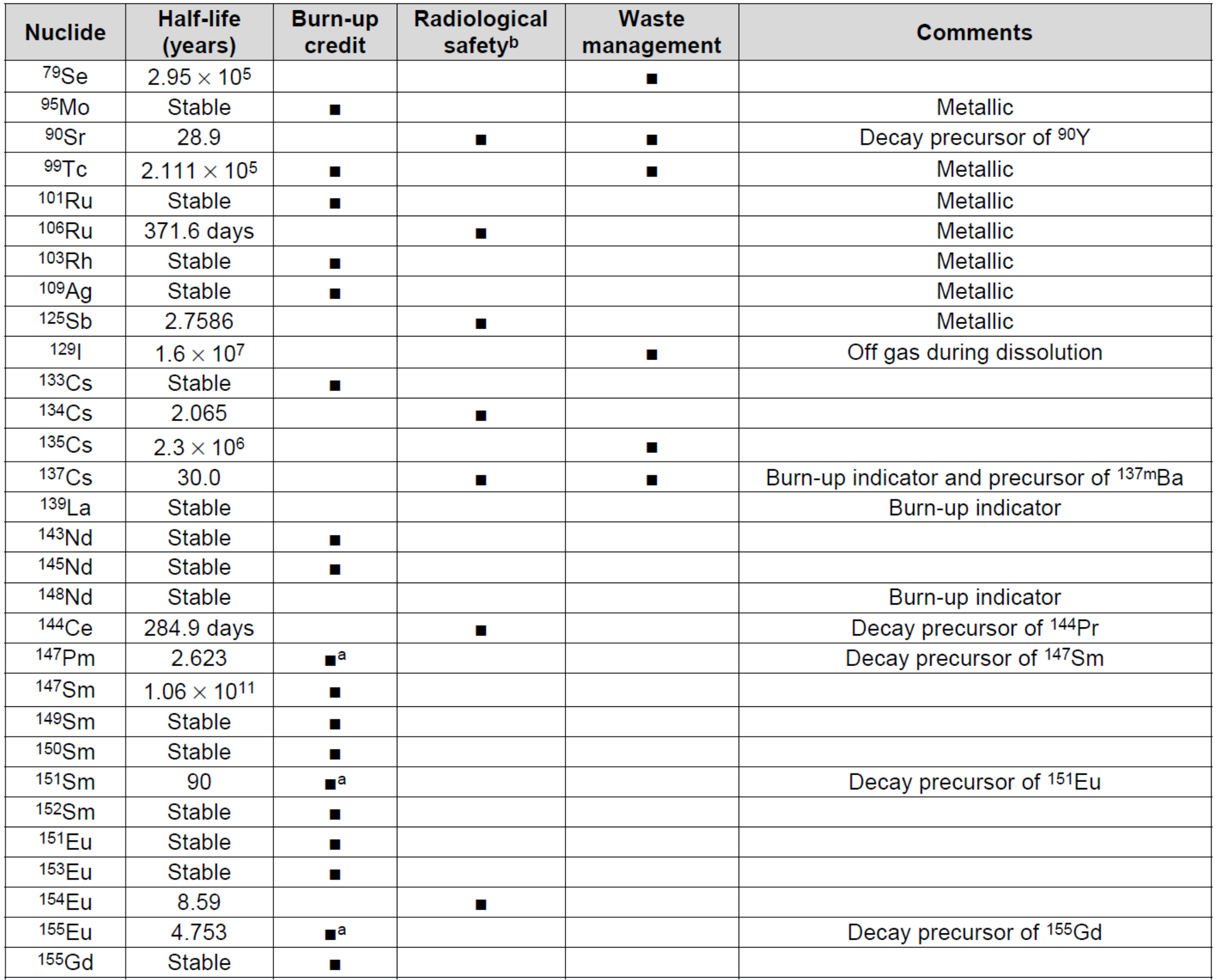
3. Uncertainty Propagation: “Criticality Uncertainty”

Summary and conclusions

1. Introduction: “Burnup Credit”

*“In nuclear criticality safety studies involving spent fuel, **<u>burn-up credit</u>** is being pursued and has been implemented in many countries as a means of more accurately and realistically determining the system reactivity by taking into account a decrease in the reactivity of spent fuel during irradiation*”.

Table 1. Commonly measured **Fission Products** of importance to different safety-related fuel applications.



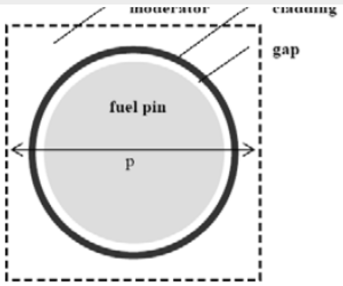
Nuclide	Half-life (years)	Burn-up credit	Radiological safety^b	Waste management	Comments
^{79}Se	2.95×10^5			■	
^{95}Mo	Stable	■			Metallic
^{90}Sr	28.9		■	■	Decay precursor of ^{90}Y
^{99}Tc	2.111×10^5	■		■	Metallic
^{101}Ru	Stable	■			Metallic
^{106}Ru	371.6 days		■		Metallic
^{103}Rh	Stable	■			Metallic
^{109}Ag	Stable	■			Metallic
^{125}Sb	2.7586		■		Metallic
^{129}I	1.6×10^7			■	Off gas during dissolution
^{133}Cs	Stable	■			
^{134}Cs	2.065		■		
^{135}Cs	2.3×10^6			■	
^{137}Cs	30.0		■	■	Burn-up indicator and precursor of ^{137m}Ba
^{139}La	Stable				Burn-up indicator
^{143}Nd	Stable	■			
^{145}Nd	Stable	■			
^{148}Nd	Stable				Burn-up indicator
^{144}Ce	284.9 days		■		Decay precursor of ^{144}Pr
^{147}Pm	2.623	■^{a}			Decay precursor of ^{147}Sm
^{147}Sm	1.06×10^{11}	■			
^{149}Sm	Stable	■			
^{150}Sm	Stable	■			
^{151}Sm	90	■^{a}			Decay precursor of ^{151}Eu
^{152}Sm	Stable	■			
^{151}Eu	Stable	■			
^{153}Eu	Stable	■			
^{154}Eu	8.59		■		
^{155}Eu	4.753	■^{a}			Decay precursor of ^{155}Gd
^{155}Gd	Stable	■			

`Ref.: “Spent Nuclear Fuel Assay Data for Isotopic Validation State-of-the-art Report”, NEA/NSC/WPNCS/DOC(2011)5`

`Expert Group on Assay Data of Spent Nuclear Fuel (EGADSNF)`

1.1 “Pin-cell Burn-up UAM Benchmark”

Table A.10: Hot Full Power (HFP) conditions for fuel pin-cell test problem	
Fuel temperature (K)	900.0
Cladding Temperature (K)	600.0
Moderator (coolant) temperature (K)	562.0
Moderator (coolant) density (g/cm3)	0.7484
Reactor Power (MWt)	2772.0
Total number of fuel assemblies in the reactor core	177
Number of fuel rods per fuel assembly	208
Active core length (mm)	3571.20



p – pitch of the unit cell

Ref.: Benchmarks for Uncertainty Analysis in Modelling (UAM) for the Design, Operation and Safety Analysis of LWRs, Volume I: Specification and Support Data for Neutronics Cases(Phase I), NEA/NSC/DOC(2013)7 May 2013

Expert Group on “Uncertainty Analysis in Modelling”

Table A11: Configuration of pin-cell test problem	
Unit cell pitch (mm)	14.427
Fuel pellet diameter (mm)	9.391
Fuel pellet material	UO2
Fuel density (g/cm3)	10.283
Fuel enrichment (w/o)	4.85
Cladding outside diameter (mm)	10.928
Cladding thickness (mm)	0.673
Cladding material	Zircaloy-4
Cladding density (g/cm3)	6.55
Gap material	He
Moderator material	H2O

Table A12: Simplified operating history data for benchmark problem pin-cell calculation and specific power	
Operating cycle	1
Burn time (days)	1825.0
Final Burnup (GWd/MTU)	61.28
Downtime (days)	1870.0
Specific power (kW/kgU)	33.58

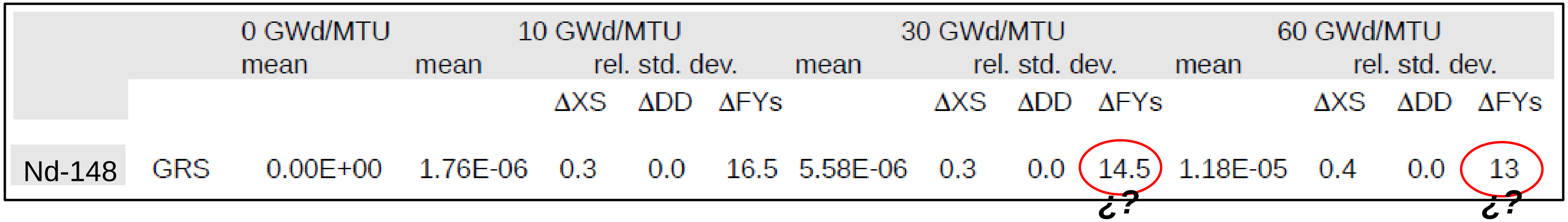
INDUSTRIALES
ETSII | UPM

1.2 Propagation of FY Uncertainties in “pin-cell burn-up Benchmark”

➢ References on FY uncertainty calculations:

❑ *J.S. Martínez et al., “GRS Results for the Burnup Pin-cell Benchmark Propagation of Cross-Section, Fission Yields and Decay Data Uncertainties”, 7th Int. Workshop on Uncertainty Analysis in Modeling, OECD/NEA, Paris, France. 10-12 April 2013.*

- *Implemented in XSUSA Methodology (Monte Carlo) using FY-ENDF/B-VII.1*



		0 GWd/MTU	10 GWd/MTU				30 GWd/MTU				60 GWd/MTU			
		mean	mean	rel. std. dev.			mean	rel. std. dev.			mean	rel. std. dev.		
				ΔXS	ΔDD	ΔFYs		ΔXS	ΔDD	ΔFYs		ΔXS	ΔDD	ΔFYs
Nd-148	GRS	0.00E+00	1.76E-06	0.3	0.0	16.5	5.58E-06	0.3	0.0	14.5 ¿?	1.18E-05	0.4	0.0	13 ¿?

➢ Justification of FY covariance generation methodologies

$$\begin{cases} \dfrac{dN_7(t)}{dt} = (-\lambda_7 - \sigma_c^7\phi)N_7 + \Sigma_f\phi \cdot y_{cum}^7 \\ \dfrac{dN_8(t)}{dt} = -\sigma_c^8\phi N_8 + \sigma_c^7\phi N_7 + \Sigma_f\phi \cdot y_{cum}^8 \end{cases}$$

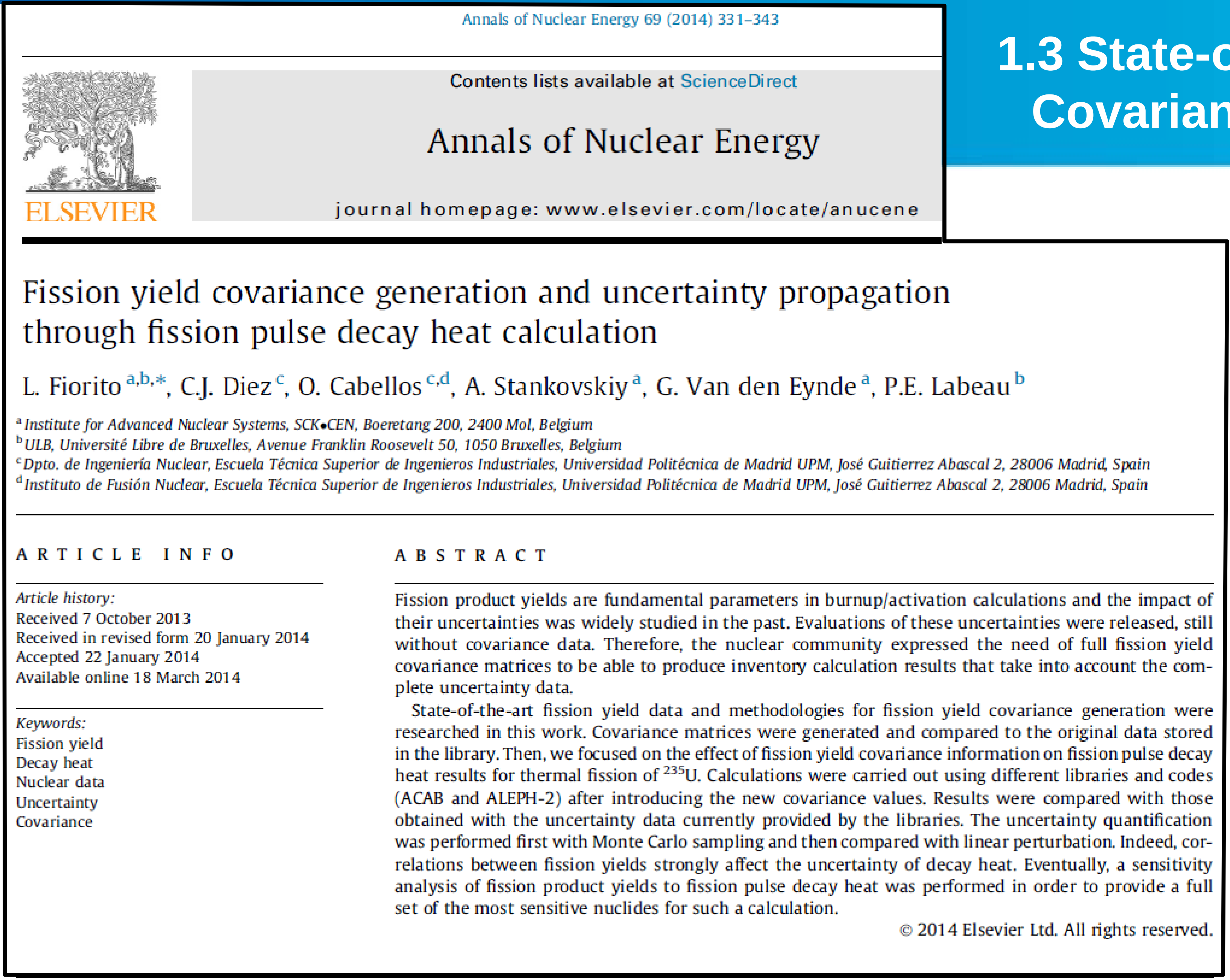
$$N_8(t) \approx \frac{\Sigma_f\phi \cdot y_{cum}^8}{\sigma_c^8\phi}\left(1 - e^{-\sigma_c^8\phi t}\right)$$

$$\frac{\Delta N_8}{N_8} \approx \frac{\Delta y_{cum}^8}{y_{cum}^8} \quad < 1\%$$

Table 2. Cumulative fission yield uncertainty value by fission in ^{235}U and ^{239}Pu with thermal neutrons. Data processed from ENDF/B-VII.1 Fission Yield Data Library.

CFY: Rel. err. (in%)	By neutron thermal fission in: ^{235}U	^{239}Pu	CFY: Rel. err. (in%)	By neutron thermal fission in: ^{235}U	^{239}Pu
^{148}Nd	0.35	0.50	**^{129}I**	1.0	4.0
^{137}Cs	0.50	0.50	**^{109}Ag**	64.0	64.0
^{139}La	0.70	2.80	**-**	-	-

1.3 State-of-art FY Covariance Data



Annals of Nuclear Energy 69 (2014) 331–343

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Fission yield covariance generation and uncertainty propagation through fission pulse decay heat calculation

L. Fiorito [a,b,*], C.J. Diez [c], O. Cabellos [c,d], A. Stankovskiy [a], G. Van den Eynde [a], P.E. Labeau [b]

[a] Institute for Advanced Nuclear Systems, SCK•CEN, Boeretang 200, 2400 Mol, Belgium
[b] ULB, Université Libre de Bruxelles, Avenue Franklin Roosevelt 50, 1050 Bruxelles, Belgium
[c] Dpto. de Ingeniería Nuclear, Escuela Técnica Superior de Ingenieros Industriales, Universidad Politécnica de Madrid UPM, José Guitierrez Abascal 2, 28006 Madrid, Spain
[d] Instituto de Fusión Nuclear, Escuela Técnica Superior de Ingenieros Industriales, Universidad Politécnica de Madrid UPM, José Guitierrez Abascal 2, 28006 Madrid, Spain

ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form 20 January 2014
Accepted 22 January 2014
Available online 18 March 2014

Keywords:
Fission yield
Decay heat
Nuclear data
Uncertainty
Covariance

ABSTRACT

Fission product yields are fundamental parameters in burnup/activation calculations and the impact of their uncertainties was widely studied in the past. Evaluations of these uncertainties were released, still without covariance data. Therefore, the nuclear community expressed the need of full fission yield covariance matrices to be able to produce inventory calculation results that take into account the complete uncertainty data.

State-of-the-art fission yield data and methodologies for fission yield covariance generation were researched in this work. Covariance matrices were generated and compared to the original data stored in the library. Then, we focused on the effect of fission yield covariance information on fission pulse decay heat results for thermal fission of ^{235}U. Calculations were carried out using different libraries and codes (ACAB and ALEPH-2) after introducing the new covariance values. Results were compared with those obtained with the uncertainty data currently provided by the libraries. The uncertainty quantification was performed first with Monte Carlo sampling and then compared with linear perturbation. Indeed, correlations between fission yields strongly affect the uncertainty of decay heat. Eventually, a sensitivity analysis of fission product yields to fission pulse decay heat was performed in order to provide a full set of the most sensitive nuclides for such a calculation.

1.3 State-of-art FY Covariance Data

FY covariance data generation:

- ❑ Great efforts have been committed to develop methodologies for correlation generation (full covariance matrices) for FY data.

- ❑ This task is in the scope of the framework of WPEC-SG37.

  Methodologies proposed at the kick-off meeting of WPEC-SG37 (May 2013), based on:

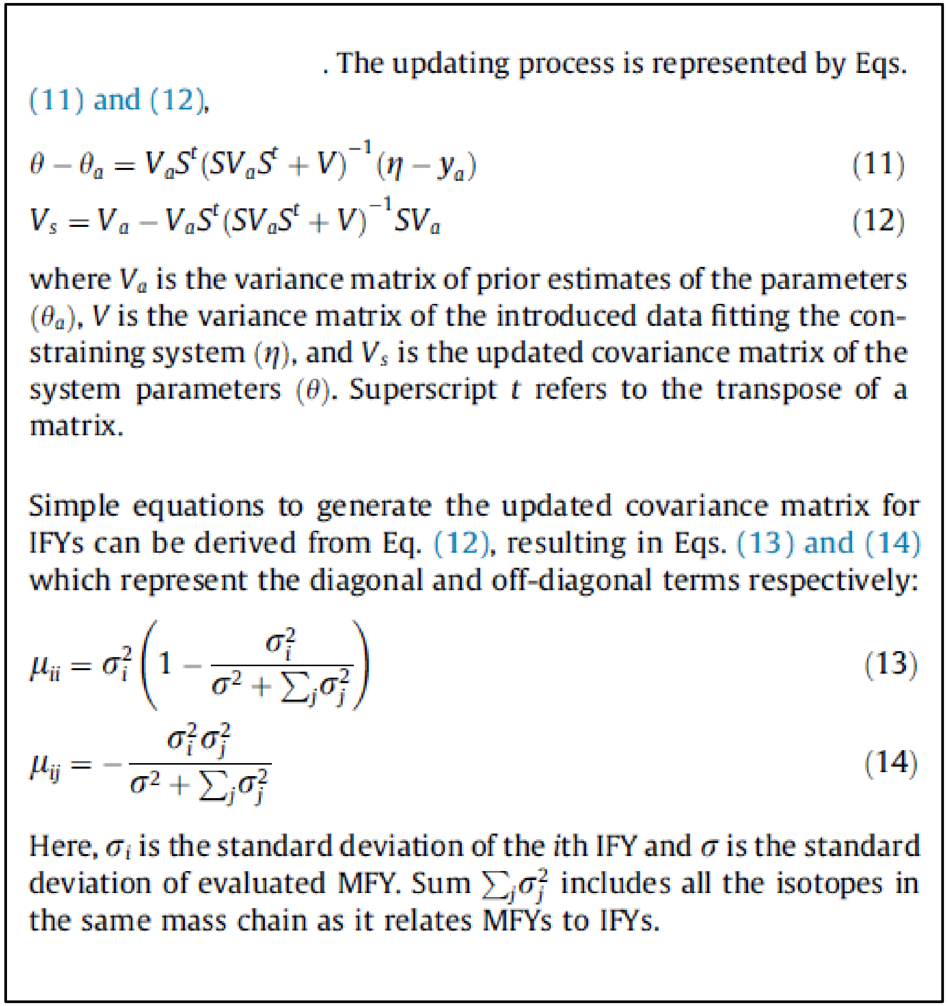
  - o **Perturbation theory** applied to the ‘‘Five Gaussians and Wahl’s models’’ (*Musgrove et al., 1973; Wahl, 1988*), proposed by *Pigni et al. (2013).*

  - o **Monte Carlo parameter perturbation** using the GEF code (*Schmidt and Jurado, 2010*), presented by Schmidt (*2013*).

  - o **Bayesian/general least-squares (GLS) method**, where the IFY covariance matrix is updated with information on the chain yields as proposed by *Kawano and Chadwick (2013)*, and previously applied by *Katakura (2012)*.

    - ▪ A variation of this proposal, with IFYs covariance matrix updated with CFYs ones is described and reported by UPM/SCK (*L. Fiorito et al., 2014*)

1.3.1 Bayesian Methodology by Katakura



. The updating process is represented by Eqs. (11) and (12),

$$\theta - \theta_a = V_a S^t (S V_a S^t + V)^{-1} (\eta - y_a) \quad (11)$$

$$V_s = V_a - V_a S^t (S V_a S^t + V)^{-1} S V_a \quad (12)$$

where V_a is the variance matrix of prior estimates of the parameters (θ_a), V is the variance matrix of the introduced data fitting the constraining system (η), and V_s is the updated covariance matrix of the system parameters (θ). Superscript t refers to the transpose of a matrix.

Simple equations to generate the updated covariance matrix for IFYs can be derived from Eq. (12), resulting in Eqs. (13) and (14) which represent the diagonal and off-diagonal terms respectively:

$$\mu_{ii} = \sigma_i^2 \left(1 - \frac{\sigma_i^2}{\sigma^2 + \sum_j \sigma_j^2} \right) \quad (13)$$

$$\mu_{ij} = - \frac{\sigma_i^2 \sigma_j^2}{\sigma^2 + \sum_j \sigma_j^2} \quad (14)$$

Here, σ_i is the standard deviation of the ith IFY and σ is the standard deviation of evaluated MFY. Sum $\sum_j \sigma_j^2$ includes all the isotopes in the same mass chain as it relates MFYs to IFYs.

Ref. : "Fission Yield Covariance generation …", L. Fiorito et al. Annals of Nuclear Energy, 2014

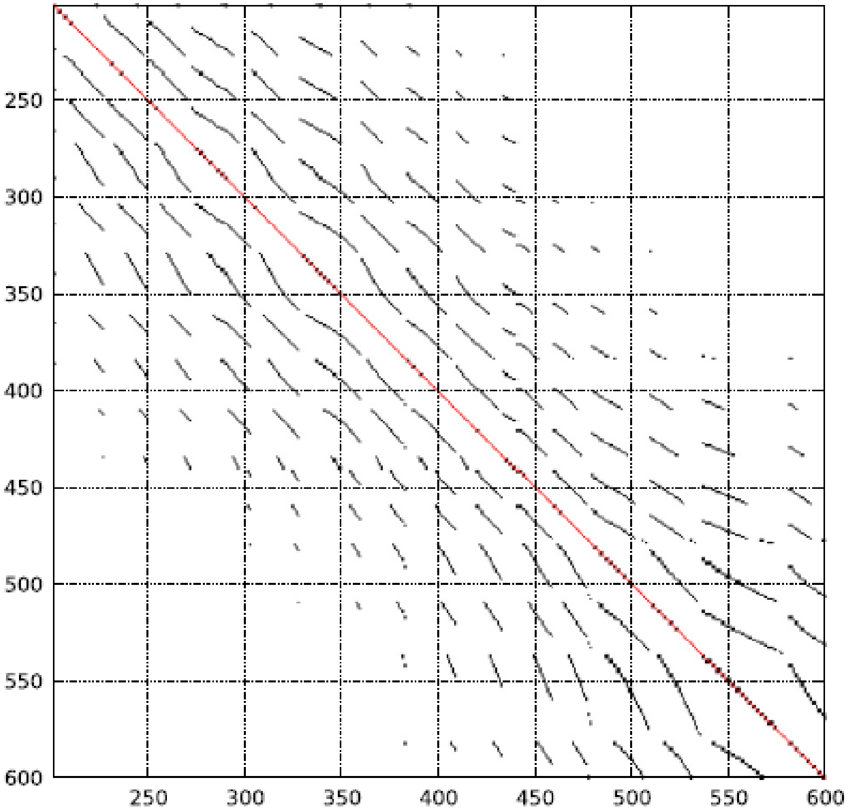


Fig. 2. Section of the IFY correlation matrix of ^{235}U thermal fission for ENDF/B-VII.1 obtained by updating with MFY uncertainties. Red dots are positive correlations and black dots are negative correlations, otherwise no correlation exists. Each matrix index refers to one FP of the studied fissionable system, once the FPs are sorted by ZZZAAAM (Z, charge; A, mass; M, isomeric state) in increasing order (e.g. index 1 refers to the lowest ZZZAAAM value). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methodology to propagate ND Uncertainties

- **Monte Carlo burnup calculation SCALE6.1.2/TRITON**
  - Generation of a set of 1000 FY random libraries for U^{235} and Pu^{239}

"No-correlation". FY uncertainty is the <u>standard deviation</u> of ENDF/B-VII.1	"Correlation" matrix using Katakura methodology
$V_U = \begin{bmatrix} \left(\Delta\gamma_1/\gamma_1\right)^2 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \left(\Delta\gamma_k/\gamma_K\right)^2 \end{bmatrix}$	$V_U = \begin{bmatrix} \left(\Delta\gamma_1/\gamma_1\right)^2 & \left(\mathrm{cov}(\gamma_1,\gamma_2)/\gamma_1\gamma_2\right)\cdots & \left(\mathrm{cov}(\gamma_1,\gamma_K)/\gamma_1\gamma_K\right) \\ \vdots & \ddots & \vdots \\ \left(\mathrm{cov}(\gamma_K,\gamma_1)/\gamma_K\gamma_1\right) & \cdots & \left(\Delta\gamma_k/\gamma_K\right)^2 \end{bmatrix}$

  - PDF: Normal distribution, with "zero" for negative values.

- **Sensitivity/Uncertainty calculation SCALE6.1.2/TRITON**
  - Calculation of Sensitivity coefficients: $S^{U}_{FYi,j} = (\Delta N_i/N_i) / (\Delta FY^{U}_{i,j}/FY^{U}_{i,j})$
  - S/U: 1st Order Approximation, "Sandwinch Formula"

$$\frac{\mathrm{var}(Ni)}{N_i^2} = \begin{pmatrix} S^{U235}_{FYi} & S^{Pu239}_{FYi} & \cdots \end{pmatrix} \begin{bmatrix} V_{U235} & 0 & 0 \\ 0 & V_{Pu239} & 0 \\ 0 & 0 & \ddots \end{bmatrix} \begin{pmatrix} S^{U235}_{FYi} \\ S^{Pu239}_{FYi} \\ \vdots \end{pmatrix}$$

2.1 Monte Carlo Methodology: "Number Density Uncertainty"

Table 3. Uncertainty in number density (in %) for some important fission products at 60 GWd/MTU. Fission Yield source of uncertainty (standard deviation) is taken from ENDF/B-VII.1.

Nuclide	Corr.	No corr.	GRS XSUSA	Nuclide	Corr.	No corr.	GRS XSUSA
^{79}Se	3.5	16.0	-	**^{142}Nd**	0.8	3.5	-
^{90}Sr	0.8	6.2	-	**^{143}Nd**	0.4	6.5	5.9
^{95}Mo	0.5	8.4	7.9	**^{144}Nd**	0.2	3.9	-
^{99}Tc	0.8	10.0	9.5	**^{145}Nd**	0.4	7.1	6.7
^{101}Ru	0.7	4.6	-	**^{146}Nd**	0.7	10.8	-
^{106}Ru	1.2	13.7	-	**^{148}Nd**	0.8	13.7	13.0
^{103}Rh	1.1	12.1	-	**^{147}Pm**	0.6	10.3	-
^{109}Ag	10.9	17.8	-	**^{147}Sm**	0.5	9.4	-
^{125}Sb	4.2	19.1	-	**^{149}Sm**	0.6	12.2	10.6
^{129}I	2.7	20.7	-	**^{150}Sm**	0.6	10.3	-
^{135}I	2.8	4.3	-	**^{151}Sm**	0.7	11.7	-
^{131}Xe	0.4	6.9	-	**^{152}Sm**	0.6	11.3	8.8
^{135}Xe	0.4	5.1	-	**^{151}Eu**	0.7	12.1	-
^{133}Cs	0.3	3.4	1.7	**^{153}Eu**	0.8	9.9	-
^{134}Cs	0.3	3.0	-	**^{154}Eu**	0.8	10.4	-
^{135}Cs	0.3	3.4	-	**^{155}Eu**	1.0	9.5	-
^{137}Cs	0.5	1.5	1.7	**^{155}Gd**	1.0	10.5	8.8
^{139}La	0.9	3.2	-	**^{156}Gd**	1.2	9.0	-
^{144}Ce	0.2	8.0	-	**^{157}Gd**	1.3	9.5	-
				^{158}Gd	2.3	11.3	-

i) No correlation between fission products (ΔFYs/No corr.)

ii) FYs including correlations for ^{235}U and ^{239}Pu taken from Katakura methodology (ΔFYs/Corr.)

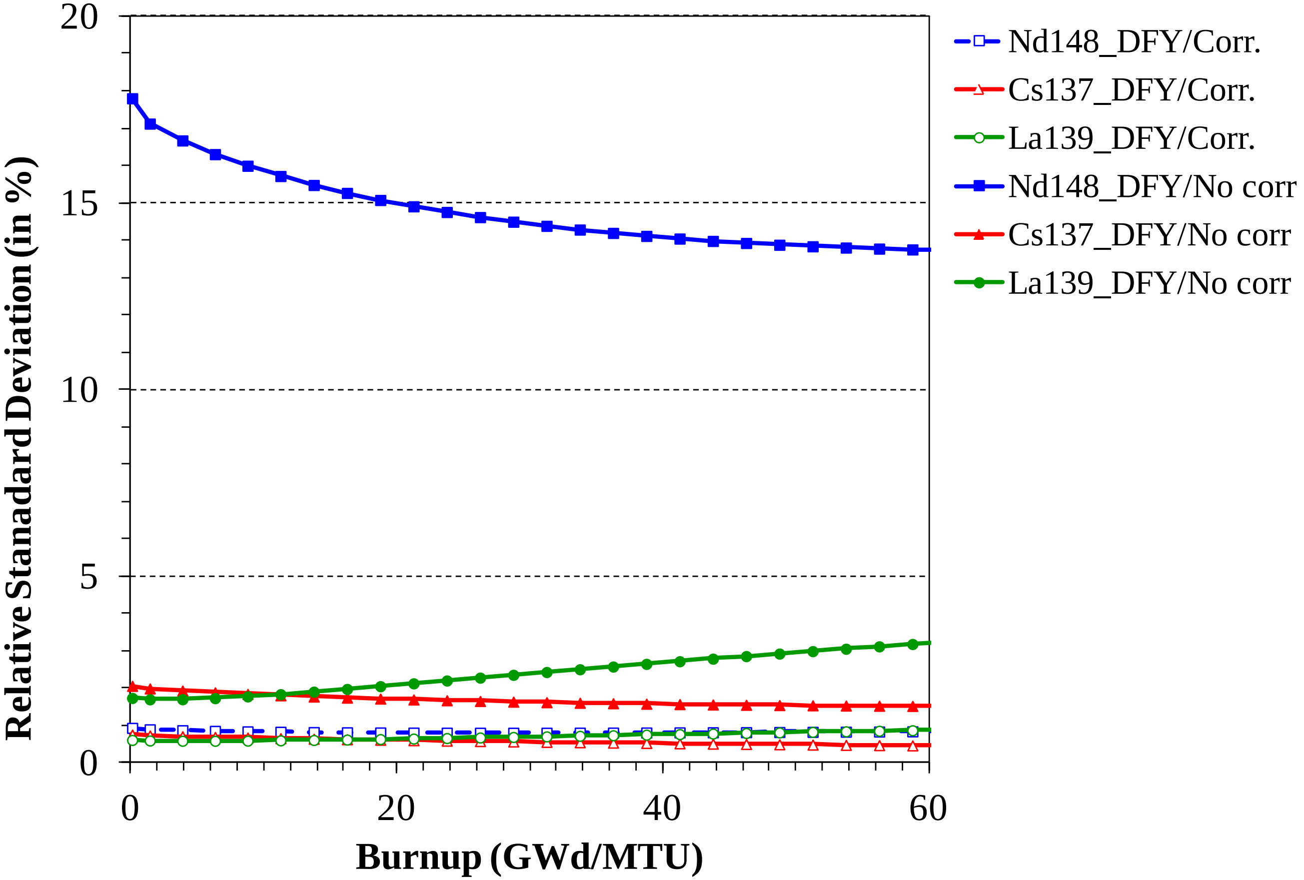
iii) GRS calculation

2.1.1 Monte Carlo Methodology: "Number Density Uncertainty" for ^{148}Nd, ^{137}Cs and ^{139}La

Figure 1. Relative standard deviations (in %) of ^{148}Nd, ^{137}Cs and ^{139}La (**burnup indicators**). Calculations performed with SCALE6.1.2, a set of 1000 random fission yield libraries based on ENDF/B-VII.1.

i) "*No corr.*" case, no-correlation between FYs

ii) "*Corr.*" case where fission yield correlation matrices supplied for ^{235}U and ^{239}Pu using Katakura methodology.

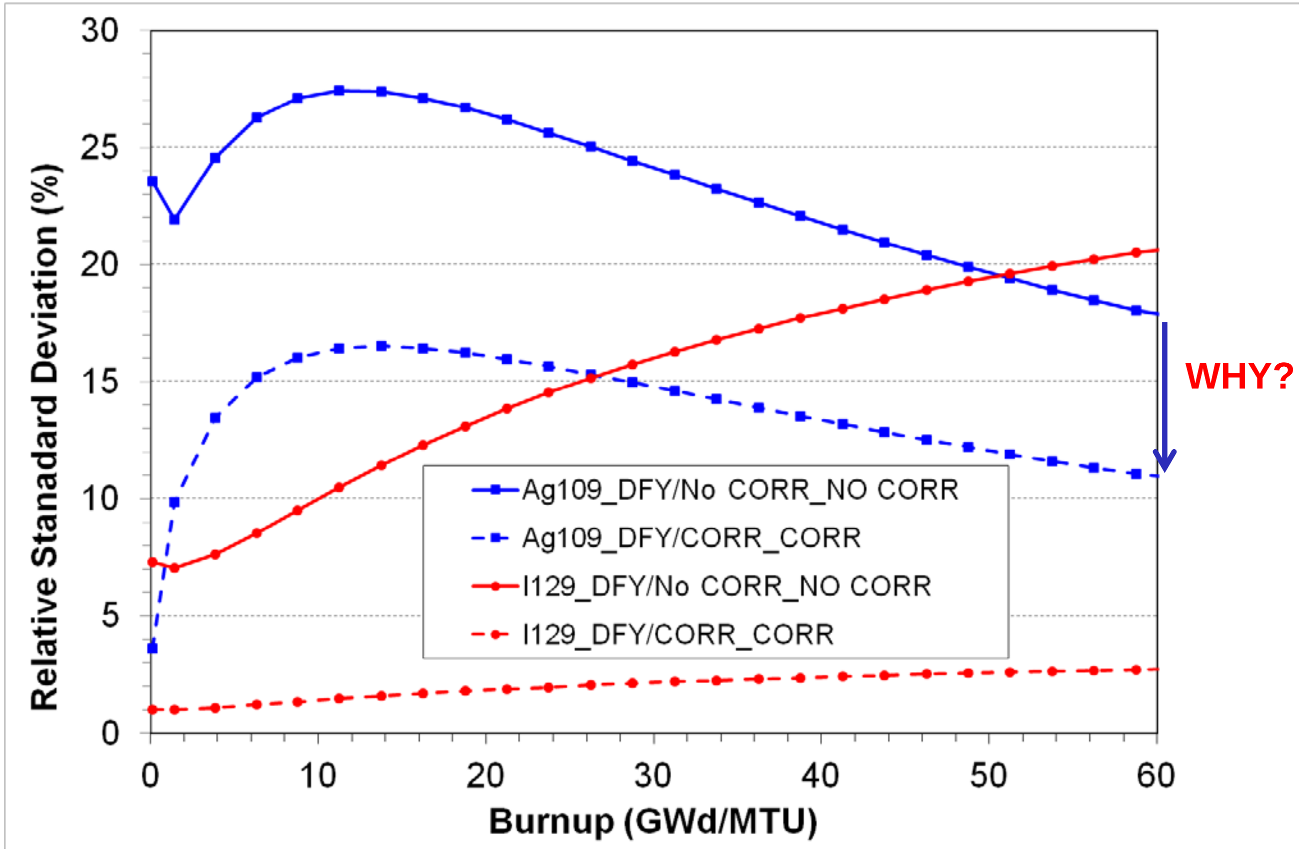


2.1.2 Monte Carlo Methodology: "Number Density Uncertainty" for ^{109}Ag and ^{129}I

Figure 2. Relative standard deviations (in %) of ^{109}Ag (**burn-up credit**) and ^{129}I (**waste management**). Calculations performed with SCALE6.1.2, a set of 1000 random fission yield libraries based on ENDF/B-VII.1.

i) "*No corr.*" case, no-correlation between FYs

ii) "*Corr.*" case where fission yield correlation matrices supplied for ^{235}U and ^{239}Pu using Katakura methodology.



2.1.3 Low correction for ^{109}Ag using Katakura correlation matrix

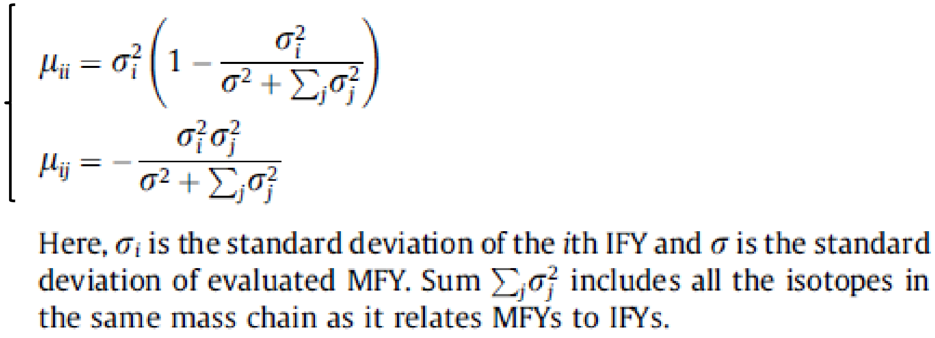
➢ Mass Yield Data

Table 4. Range of mass chain yield uncertainties (in %) reported by England (1993) by fission in ^{235}U and ^{239}Pu with thermal neutrons.

A mass	^{235}U	^{239}Pu	A mass	^{235}U	^{239}Pu
109	4-6	2.8-4	**137**	0.35-0.5	0.35-0.5
129	0.7-1.0	2-2.8	**139**	0.5-0.7	2-2.8
-	-	-	**148**	<0.35	.35-0.5

`Ref.: England T., Rider B., “`*`1993. Evaluation and Compilation of Fission Technical Report, LA-UR-94-3106`*`”, LANL (1993)`

➢ Mass Yield Data



$$\left\{\begin{aligned} \mu_{ii} &= \sigma_i^2\left(1-\frac{\sigma_i^2}{\sigma^2+\sum_j\sigma_j^2}\right)\\ \mu_{ij} &= -\frac{\sigma_i^2\sigma_j^2}{\sigma^2+\sum_j\sigma_j^2}\end{aligned}\right.$$

Here, σ_i is the standard deviation of the ith IFY and σ is the standard deviation of evaluated MFY. Sum $\sum_j\sigma_j^2$ includes all the isotopes in the same mass chain as it relates MFYs to IFYs.

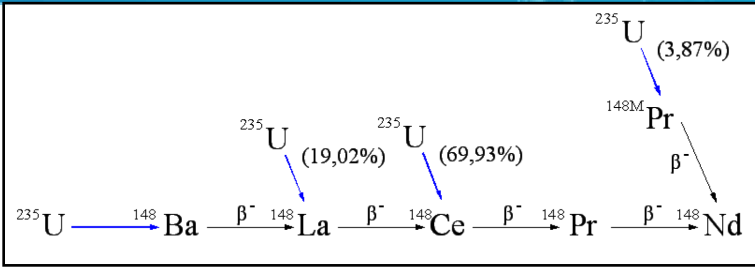
Deficiencies for ^{109}Ag:

- High value of MFY “standard deviation”
- Only takes into account correction for IFY for the same “A”

  (exception for Ru108)

INDUSTRIALES
ETSII | UPM

2.2 S/U Methodology: "Number Density Uncertainty"



➢ Calculation of Sensitivity Coefficients:

$$S^{U}_{FYi,j} = (\Delta N_i/N_i) / (\Delta FY^{U}_{i,j}/FY^{U}_{i,j})$$

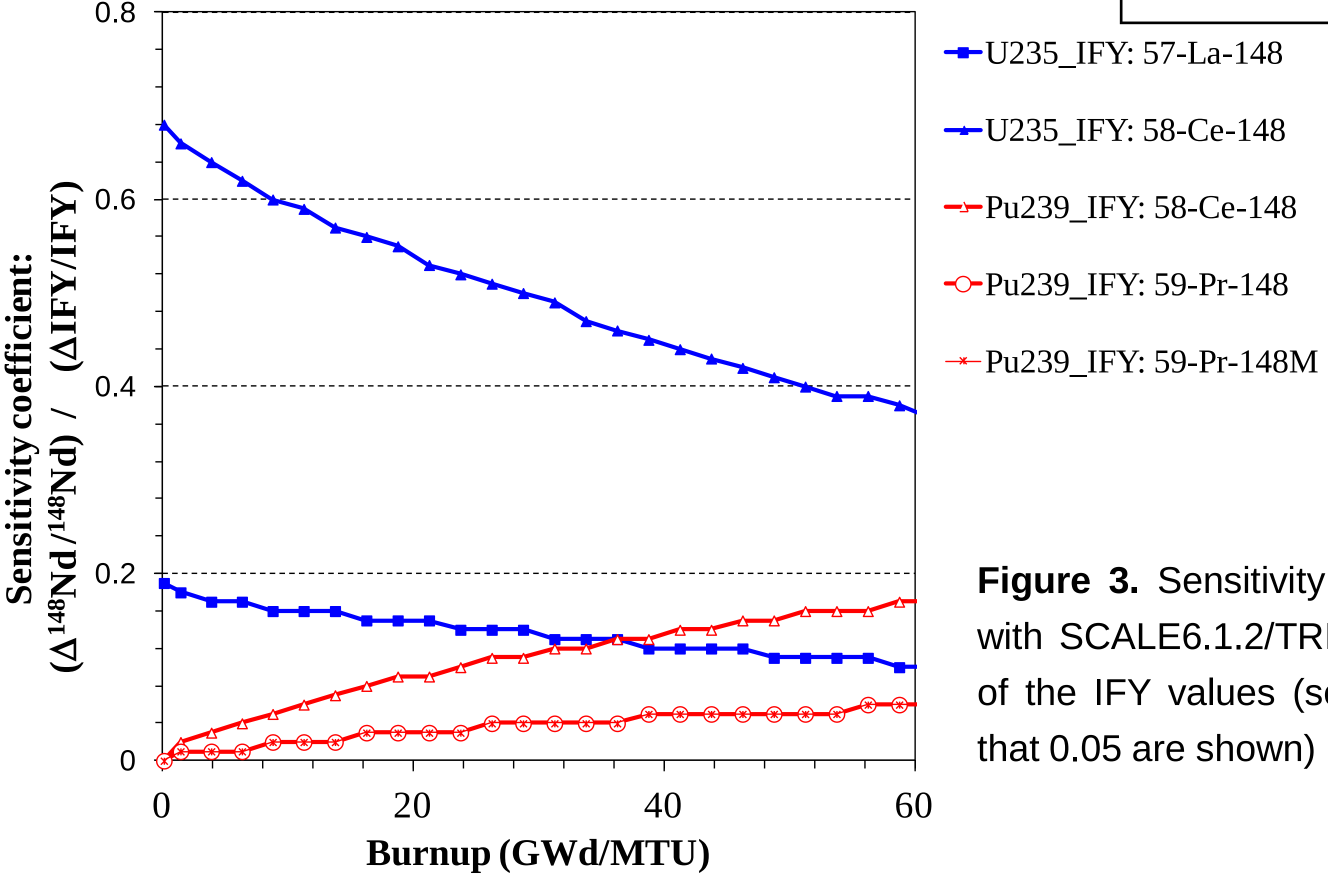


Figure 3. Sensitivity **Nd^{148}** coefficients calculated with SCALE6.1.2/TRITON by a linear perturbation of the IFY values (sensitivities with values higher that 0.05 are shown)

2.2.1 S/U Methodology: ^{148}Nd, ^{139}La and ^{137}Cs (burnup indicators)

Table 5. Uncertainty of the main independent fission yield contributors to the generation of **^{137}Cs, ^{137}La and ^{148}Nd** by fission in ^{235}U and ^{239}Pu with thermal neutrons. Data processed from ENDF/B-VII.1 Fission Yield Data Library.

IFY: Rel. err. (in%)	Generation of ^{137}Cs by fission in:		IFY: Rel. err. (in%)	Generation of ^{139}La by fission in:		IFY: Rel. err. (in%)	Generation of ^{148}Nd by fission in:	
	^{235}U	^{239}Pu		^{235}U	^{239}Pu		^{235}U	^{239}Pu
^{137}Te	8.0	64.0	^{139}I	8.0	23.0	^{148}La	64.0	64.0
^{137}I	4.0	6.0	^{139}Xe	2.0	4.0	^{148}Ce	23.0	45.0
^{137}Xe	2.8	4.0	^{139}Cs	4.0	23.0	^{148}Pr	64.0	64.0
-	-	-	-	-	-	^{148M}Pr	64.0	64.0

S/U, Applying "Sandwich Formula":

$$\frac{var(N_i)}{N_i^2} = \left(S^{U235}_{FYi} \quad S^{Pu239}_{FYi} \quad \dots\right) \begin{bmatrix} V_{U235} & 0 & 0 \\ 0 & V_{Pu239} & 0 \\ 0 & 0 & \ddots \end{bmatrix} \begin{pmatrix} S^{U235}_{FYi} \\ S^{Pu239}_{FYi} \\ \vdots \end{pmatrix}$$

Table 6. Comparison of S/U and Monte Carlo uncertainty prediction at 60 GWd/TMU. FY uncertainty with "No corr."

Nuclide	S/U	Monte Carlo
^{148}Nd	14.2	13.7
^{137}Cs	1.50	1.50
^{139}La	3.20	3.20

2.2.2 S/U Methodology: ^{109}Ag and ^{129}I

- **Calculation of Sensitivity Coefficients:**

$$S^{U}_{FYi,j} = (\Delta N_i/N_i) / (\Delta FY^{U}_{i,j}/FY^{U}_{i,j})$$

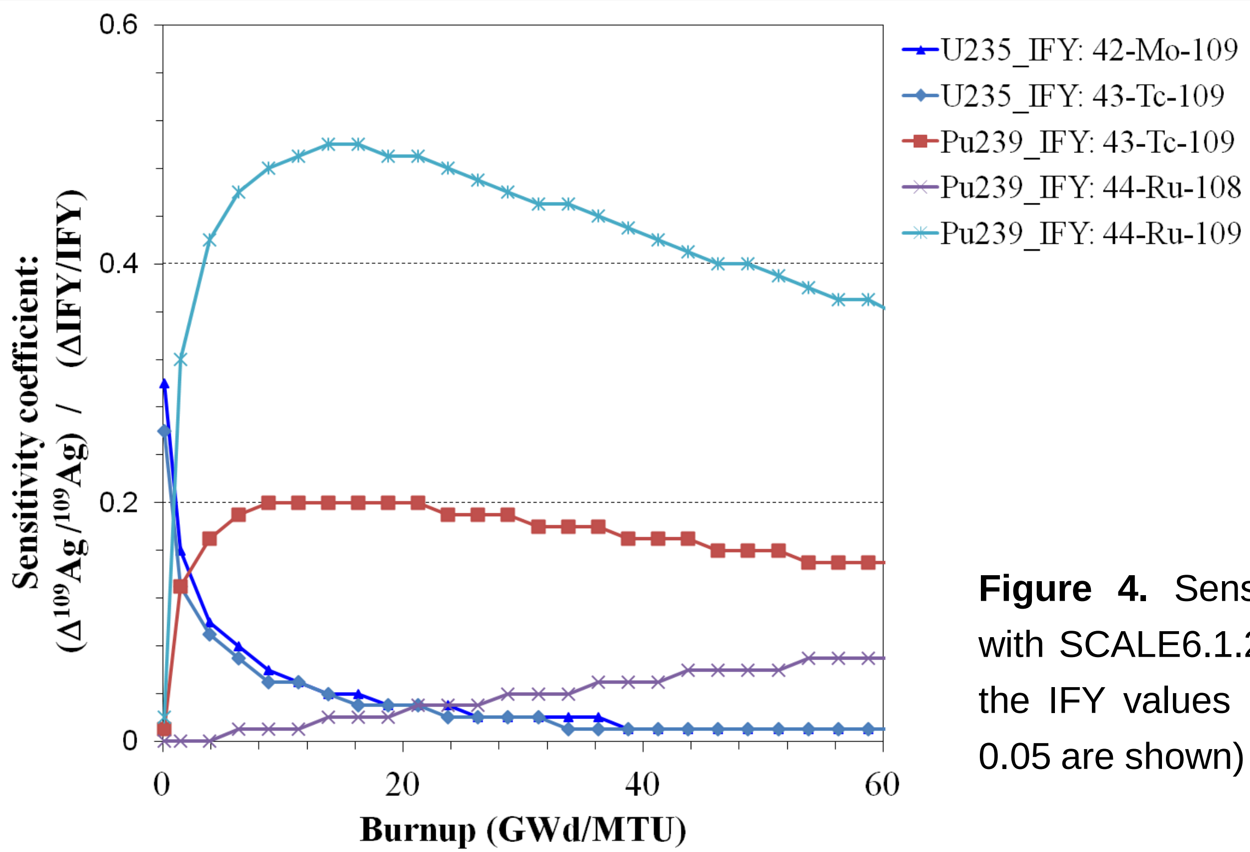


Figure 4. Sensitivity **Ag^{109}** coefficients calculated with SCALE6.1.2/TRITON by a linear perturbation of the IFY values (sensitivities with values higher that 0.05 are shown)

2.2.2 S/U Methodology: ^{109}Ag and ^{129}I

Table 7. Uncertainty of the main independent fission yield contributors to the generation of ^{109}Ag and ^{129}I by fission in ^{235}U and ^{239}Pu with thermal neutrons. Data processed from ENDF/B-VII.1 Fission Yield Data Library.

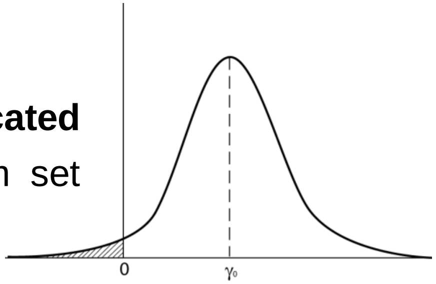
IFY: Rel. err. (in%)	Generation of ^{109}Ag by fission in: ^{235}U	^{239}Pu	IFY: Rel. err. (in%)	Generation of ^{129}I by fission in: ^{235}U	^{239}Pu
^{109}Mo	64.0	64.0	**^{129M}Sn**	6.0	64.0
^{109}Tc	64.0	64.0	**^{129}Sn**	11.0	64.0
^{109}Ru	64.0	64.0	**^{129}Sb**	45.0	64.0
^{108}Ru	64.0	64.0	**-**	-	-

Table 8. Comparison of S/U and Monte Carlo uncertainty prediction at 60 GWd/TMU. FY uncertainty with "No corr."

Nuclide	S/U	Monte Carlo
^{109}Ag	25.0	17.8
^{129}I	20.3	20.7

⬅ **WHY?**

- Our Monte Carlo method uses a "**truncated Normal PDF**". Then, the new random set yields a reduced uncertainty.



3. Uncertainty Propagation: "Criticality Uncertainty"

Figure 5. Relative standard deviation in k_{eff} (in %):

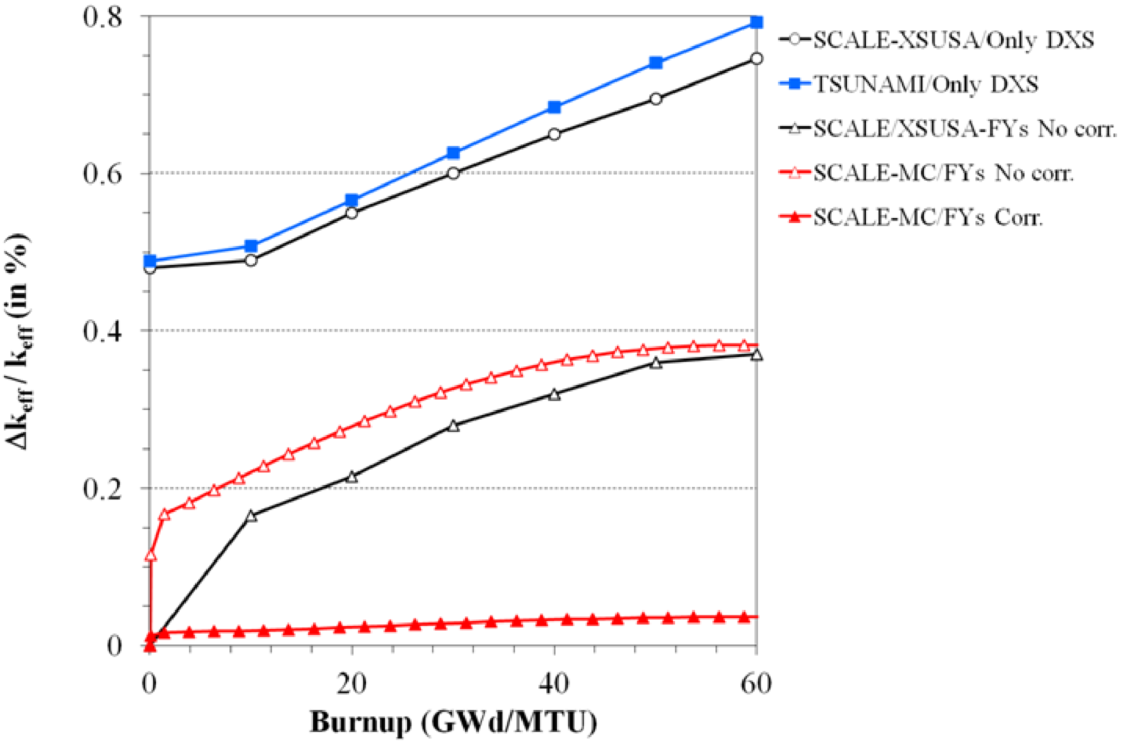
i) SCALE/XSUSA calculation performed by GRS [7] only uncertainties in cross-section data,

ii) SCALE/TSUNAMI calculation [2] only uncertainties in cross-section data,

iii) SCALE/XUSA calculation by GRS with uncertainties only in fission yield data taken from ENDF/B-VII.1/FY data library,

iv) Monte Carlo with a set of 1000 different fission yield data libraries based on ENDF/B-VII.1 with no-correlation between fission yields ("*No corr.*")

v) Monte Carlo with correlations generated by Katakura method in ^{235}U and ^{239}Pu ("*Corr.*").



$$\mathrm{var}(k) = (S_\sigma \quad S_N)\begin{bmatrix} V_\sigma & \mathrm{cov}(\sigma,N) \\ \mathrm{cov}(\sigma,N) & V_N \end{bmatrix}\begin{pmatrix} S_\sigma^t \\ S_N^t \end{pmatrix} = \mathrm{var}(k_\sigma) + \mathrm{var}(k_N) + \mathrm{cov}(k_\sigma, k_N)$$

Summary and conclusions

- The present study has demonstrated **the importance of covariance terms if fission yield data libraries to improve estimations of uncertainties in burn-up applications**

- Results in a LWR **pin-cell burnup** benchmark

- It has been proved that **non-correlated independent fission yields data bring to overestimated uncertainties in the number density and criticality predictions**

- Comparison between **S/U and Monte Carlo** shows good agreement (except for ^{109}Ag)

- **Assessment of the methodology to generate fission yield covariance data** based on Katakura model using information of experimental mass fission yield data

    - ☐ Covariance fission yield data for ^{235}U and ^{239}Pu fissile nuclides were processed

    - ☐ Covariance for isotopes in the same mass chain are modified

    - ☐ Covariance data (by Katakura) changes the criticality and number density uncertainties, reducing its variance to almost a negligible effect (except for ^{109}Ag)

Acknowledgements

This work is supported by:

- Agreement between CSN & UPM in the area of “Uncertainty Propagation for Neutronic Calculations” (2012-16)