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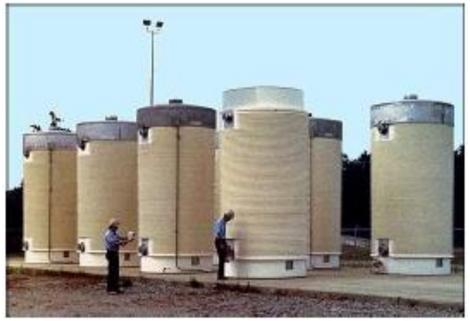
Nuclear data requirements for an accurate estimation of the neutron production rate of spent nuclear fuel

P. Schillebeeckx, M. Verwerft, **P. Romojaro**, G. Žerovnik, N. Messaoudi, G. Alaerts, L. Fiorito, K. Govers, J. Paepen, Y. Parthoens , B. Pedersen, A. Stankovskiy, G. Van den Eynde and R. Wynants

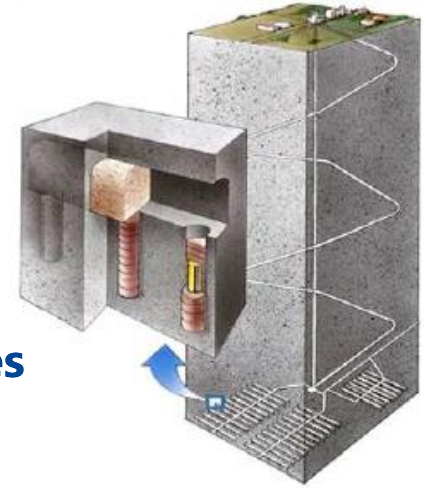
Workshop on *"Impact of recent nuclear data evaluations on energy and non-energy nuclear applications"*, UPM, Madrid (Spain), May 23rd, 2023

Introduction

- **Spent Fuel Characterisation**
  - Pool storage
  - Transport
  - Interim storage
  - Repository systems



- **Observables:** DH, n and γ emission, reactivity, fissile material, long-lived radionuclides



- Isotopic content determined with **fuel depletion codes**

Experimental programs

ARIANE
(1994 – 2000)

MALIBU
(2004 – 2013)

REGAL
(2016 - …)

Radiochemical analyses (pellet average)
- Std. BU UO_2 and low BU $(U,Gd)O_2$ (~50 & ~12 GWd/tHM)
- PWR commercial reactor, advanced assemblies

Local investigations (radial profile)
- SIMS & EPMA

Radiochemical analyses (pellet average)
- Ultra high BU UO_2 and MOX fuels (75 GWd/tHM)
- PWR & BWR commercial reactors, standard assemblies

Local investigations (radial profile)
- none

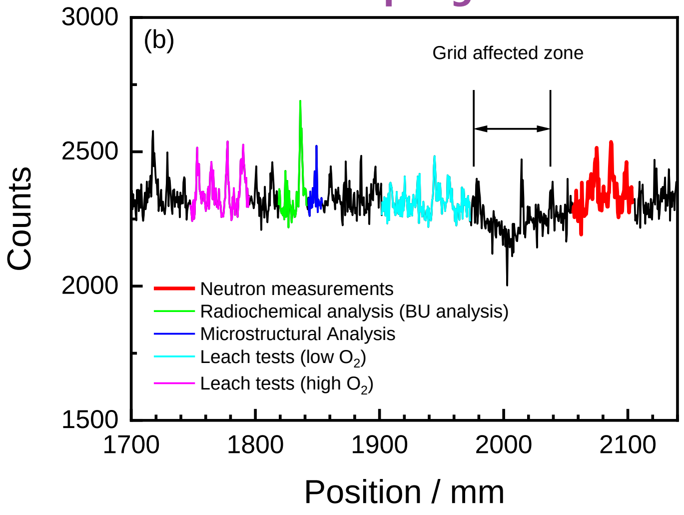
Radiochemical analyses (pellet average)
- Medium to high BU UO_2 and MOX fuels (30-60 GWd/t_{HM})
- PWR (commercial) & BWR (prototype) reactors

Local investigations (radial profile)
- SIMS & EPMA

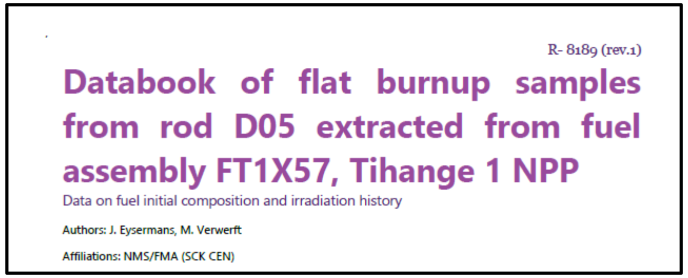
Representative and validated data
- **Code validation** (core reactivity, transport, storage)
- Source term studies (back-end)
- …

Radiochemical analysis

Sampling



Detailed databook


R- 8189 (rev.1)

Databook of flat burnup samples from rod D05 extracted from fuel assembly FT1X57, Tihange 1 NPP

Data on fuel initial composition and irradiation history

Authors: J. Eysermans, M. Verwerft

Affiliations: NMS/FMA (SCK CEN)

RCA results

BU indicator	Analysis date	Nuclide Inventory N_X/N_U	BU MWd/kg
^{137}Cs	21/10/2013	2.539 (55) x 10^{-3}	52.6 (11)
$^{143+144}Nd$	05/02/2014	5.701 (60) x 10^{-3}	53.95 (56)
$^{145+146}Nd$	05/02/2014	3.643 (38) x 10^{-3}	53.05 (56)
^{148}Nd	05/02/2014	0.974 (21) x 10^{-3}	53.3 (12)
^{150}Nd	05/02/2014	0.463 (21) x 10^{-3}	52.2 (23)
			Average: 52.78 (37)

Operator-based BU: 54.30 MWd/kg

Source: P. Schillebeeckx *et al. An absolute measurement of the neutron production rate of a spent nuclear fuel sample used for depletion code validation.* Front. Energy Res. 11 (2023) 1162367

Neutron measurements

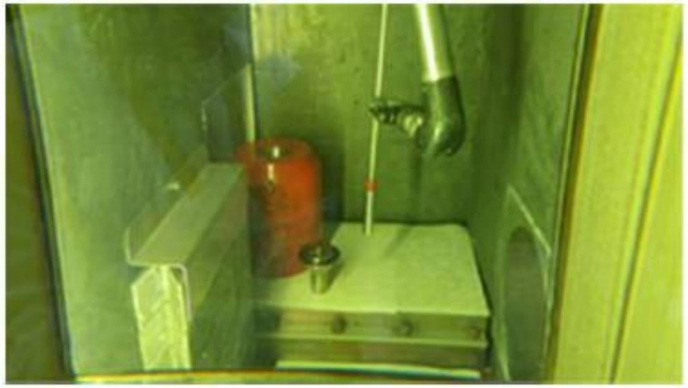
- Provide experimental data to **validate depletion codes**
  - ^{244}Cm inventory: reduced uncertainty compared to radiochemical analysis

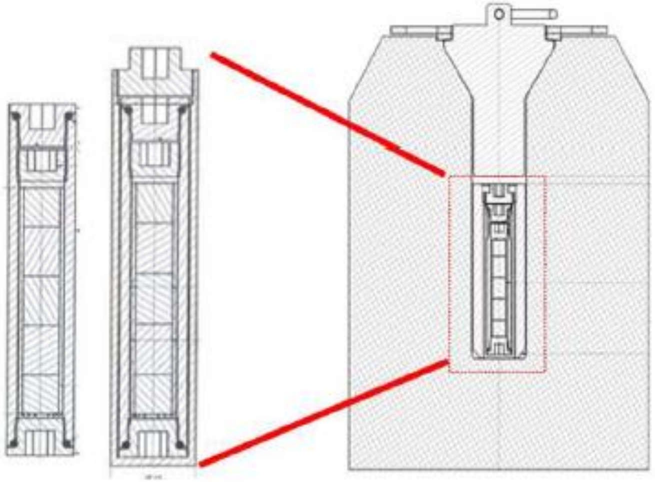
- Experimental method to **verify declared burnup**
  - Extremely sensitive to BU
  - Axial BU profiles

- Important for the **validation of any characterisation scheme based on depletion calculations**
  - Support nuclear safeguards verification by e.g. FORK, DDSI, PNAR measurements
  - Support nuclear criticality safety procedures relying on loading curves
  - Support decay heat estimates based on depletion calculations

Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

Neutron measurements





Source: P. Schillebeeckx. *Neutrons as a signature for the characterization of spent nuclear fuel*. EURAD Annual Event 2021

SNF segment sample: characteristics

Parameter	Value
Segment length	52.01 (4) mm
Segment weight	42.616 (1) g
Cladding weight	6.71 (4) g
Net fuel weight	35.91 (4) g

$$\mathbf{S_{sf} = 678\ (12)\ s^{-1}g^{-1}}$$

$$S_{\alpha n} / S_{sf} = 0.039\ (\mathbf{18})$$

Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

Depletion calculations

- ALEPH2, SCALE and Serpent 2.2.0
  - Calculations normalized to ^{148}Nd inventory

- Nuclear data libraries:
  - ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0
  - JEFF-3.1.2, JEFF-3.3, JEFF-4T1 and JEFF-4T2
  - JENDL-4.0u and JENDL-5
  - Recommended SFY from Santi and Miller (2008)* and DD from DDEP

***Source**: P. Santi and M. Miller. *Reevaluation of prompt neutron emission multiplicity distributions for spontaneous fission*. Nucl. Sci. Eng. 160 (2008) 190–199

Impact of nuclear data

^{137}Cs, ^{244}Cm and BU

Code	Library	^{137}Cs	^{137}Cs	^{244}Cm	BU	^{137}Cs	^{244}Cm	BU
		$N_X/N_U \times 10^{-3}$	C/E	$N_X/N_U \times 10^{-5}$	MWd/kg			
ALEPH2	JEFF-3.3	2.225	0.982	6.290	53.25	**0.990**	0.981	**0.983**
SCALE	ENDF/B-VII.0	2.241	0.990	6.380	54.01	0.997	0.995	0.997
Serpent2	ENDF/B-VII.0	2.285	1.009	6.633	54.37	1.016	1.035	1.004
	ENDF/B-VII.1	2.274	1.004	6.710	54.39	1.012	1.047	1.004
	ENDF/B-VIII.0	2.274	1.004	6.701	54.38	1.012	1.045	1.004
	JEFF-3.1.2	2.248	0.993	6.110	54.18	1.000	**0.953**	1.000
	JEFF-3.3	2.225	0.982	6.354	53.37	**0.990**	0.991	0.985
	JEFF-3.3 (1)	2.290	1.011	7.149	55.24	1.019	1.115	**1.020**
	JEFF-3.3 (2)	2.249	0.993	6.644	54.21	1.000	1.037	1.001
	JEFF-3.3 (3)	2.246	0.992	6.599	54.12	0.999	1.029	0.999
	JEFF-4T1	2.248	0.993	6.410	54.16	1	1	1
	JENDL-4.0u	2.301	1.016	7.009	55.07	**1.024**	1.093	1.017
	JENDL-5.0	2.253	0.995	7.194	54.97	1.002	**1.122**	1.015

(1) $\sigma(n,\gamma) = 0$ for ^{147}Nd
(2) $\sigma(n,\gamma)$ for ^{147}Nd from JENDL-4.0u
(3) $\sigma(n,\gamma)$ for ^{147}Nd from JEFF-4T1

Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

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Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

Impact of nuclear data

S_{sf}

S_{sf} = 678 (12) $s^{-1}\,g^{-1}$

Code	Library	Ssf/ (1/sg)	Ssf/ (1/sg)	C/E	C/E		
		LIB	REC	LIB	REC		LIB/REC
ALEPH2	JEFF-3.3	640.1	642.4	0.944	0.947		0.996
SCALE	ENDF/B-VII.0	653	652.1	0.963	0.962		1.001
Serpent2	ENDF/B-VII.0	683.7	678.1	1.008	1.000		1.008
	ENDF/B-VII.1	689.4	685.3	1.017	1.011		1.006
	ENDF/B-VIII.0	688.5	684.3	1.015	1.009		1.006
	JEFF-3.1.2	632.5	623.8	0.933	0.920		1.014
	JEFF-3.3	656.8	648.9	0.969	0.957		1.012
	JEFF-3.3 (1)	739.4	730.5	1.091	1.077		1.012
	JEFF-3.3 (2)	686.8	678.6	1.013	1.001		1.012
	JEFF-3.3 (3)	682.2	673.9	1.006	0.994		1.012
	JEFF-4T1	662.6	654.6	0.977	0.965		1.012
	JEFF-4T2	676.4	668.3	0.998	0.986		1.012
	JENDL-4.0u (4)		715.9		1.056		0.000
	JENDL-5.0	738.4	733.9	1.089	1.082		1.006

(1) $\sigma(n,\gamma) = 0$ for ^{147}Nd
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(3) $\sigma(n,\gamma)$ for ^{147}Nd from JEFF-4T1

(4) No data available to calculate S_{sf}

Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

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Impact of nuclear data

S_{sf}

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S_{sf} = 678 (12) $s^{-1}\,g^{-1}$

Calculated from RCA with REC:
S_{sf} = 699 (28) $s^{-1}\,g^{-1}$

(1) $\sigma(n,\gamma) = 0$ for ^{147}Nd
(2) $\sigma(n,\gamma)$ for ^{147}Nd from JENDL-4.0u
(3) $\sigma(n,\gamma)$ for ^{147}Nd from JEFF-4T1

(4) No data available to calculate S_{sf}

Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

Conclusions

- Recommended decay and neutron emission data not always adopted in evaluated data libraries
- ^{147}Nd(n,γ) cross section in JEFF-3.3 and ENDF/B-VIII.0 are too high (important for normalisation of PIE data)
- Fission yields for ^{148}Nd in JENDL-5.0 are too low
- ^{242}Pu(n,γ) and ^{243}Am(n,γ) cross sections require a re-evaluation (use of available experimental data)

Source: P. Schillebeeckx *et al. Task 2.2 Neutron measurements on REGAL sample*. EURAD Task 2 Workshop, KIT, Karlsruhe (Germany), May 10-12,2023

Acknowledgements

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