D5.7. Report on reactor and shielding C/E validation and nuclear data trends

Linked to WP5/T5.2/ST5.2.2 – C/E validation and trends

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SANDA Meeting, February 5 2024

Proposed structure for D5.7

1. Introduction
2. Methodologies for Nuclear Data Validation
3. Fast Reactors C/E validation and nuclear data trends
4. Thermal Reactors C/E validation and nuclear data trends
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HORIZON 2020

HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

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1. Introduction

- **Objective: C/E validation to contribute to the improvement of JEFF nuclear data files**
- **JEFF-based C/E biases are analyzed to identify needs for nuclear data improvement**

1. Reactor physics experiments:
   1. IRPhE
   2. Partner's own databases: CEA/DES - LWR
   3. Other legacy experiments: SEFOR, Almaraz NPP (IAEA)
2. Shielding benchmarks: SINBAD

Experiments from different facilities, neutron spectra, and integral quantities of interest

2. Methodologies for ND validation

- **Different validation strategies applied, all of them based on calculating C/E**
- **But differing in how they use C/E ratios to assess the quality of the library and identify needs for ND improvement**

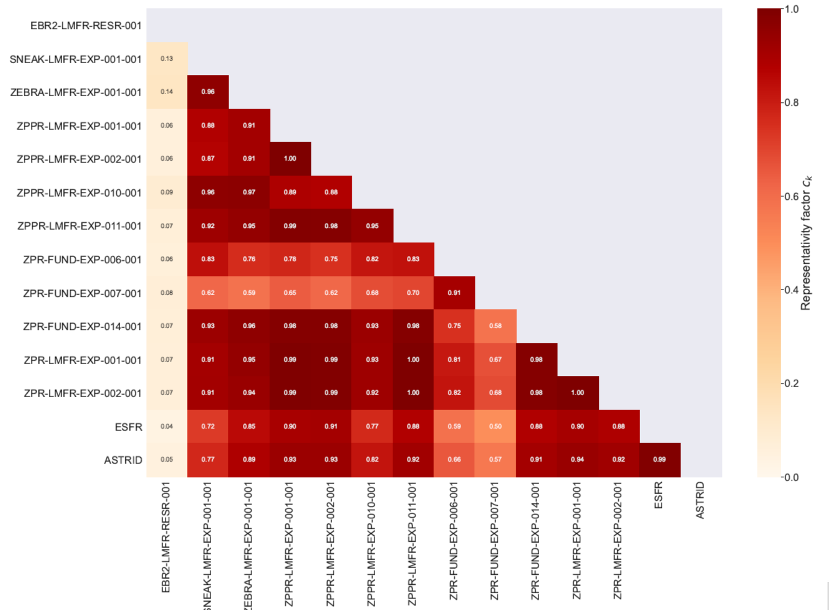
Mean bias or weighted mean bias	Perturbation analysis	Trending analysis	Bayesian-based analysis
• Different metrics applied	• Impact of ND perturbations with respect to data from other libraries	• Comparisons with trending parameters	• GLLS method

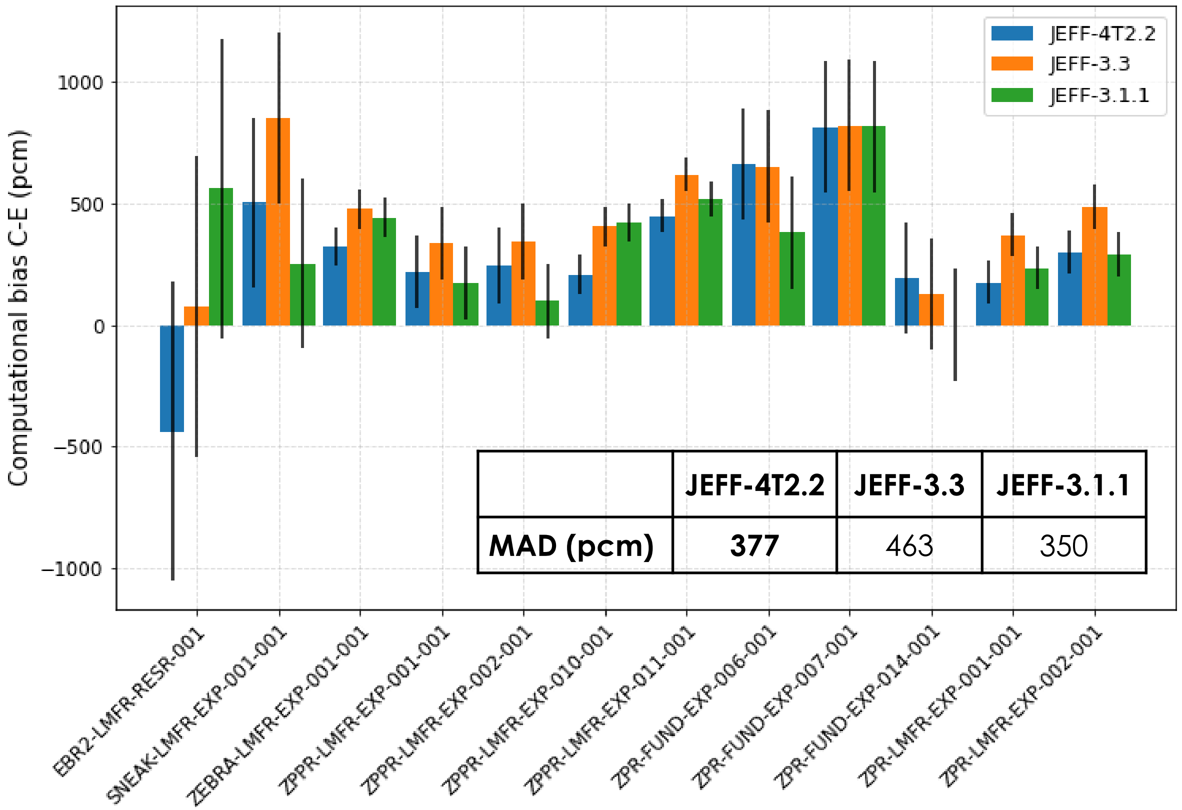
3. Fast Reactors C/E validation and nuclear data trends

Reactor physics benchmarks useful for ND validation (of SFR) have been identified and C/E assessed (UPM)

Multiplication factor: set of experiments from IRPhE (12 experiments) with a high similarity to SFR

Benchmark identifier in IRPhEP	Fuel/Other	Experimental facility	Institution
EBR2-LMFR-RESR-001	UO_2/Sodium	EBR-II	ANL, USA
SNEAK-LMFR-EXP-001	MOX/Sodium	SNEAK 7A	KFK, Germany
ZEBRA-LMFR-EXP-001	Pu metal-UO_2/Sodium	ZEBRA 22	AEEW, UK
ZPPR-LMFR-EXP-001	MOX/Sodium	ZPPR-10A	ANL, USA
ZPPR-LMFR-EXP-002	MOX/Sodium	ZPPR-9	ANL, USA
ZPPR-LMFR-EXP-010	MOX/Sodium	ZPPR-12	ANL, USA
ZPPR-LMFR-EXP-011	MOX/Sodium	ZPPR-2	ANL, USA
ZPR-FUND-EXP-006	Pu-U alloys/Graphite	ZPR-3/53	ANL, USA
ZPR-FUND-EXP-007	Pu-U alloys/Graphite	ZPR-3/54	ANL, USA
ZPR-FUND-EXP-014	Pu-U carbide/Sodium	ZPR-9/31	ANL, USA
ZPR-LMFR-EXP-001	MOX/Sodium	ZPR-6/7	ANL, USA
ZPR-LMFR-EXP-002	MOX/Sodium	ZPR-6/7	ANL, USA





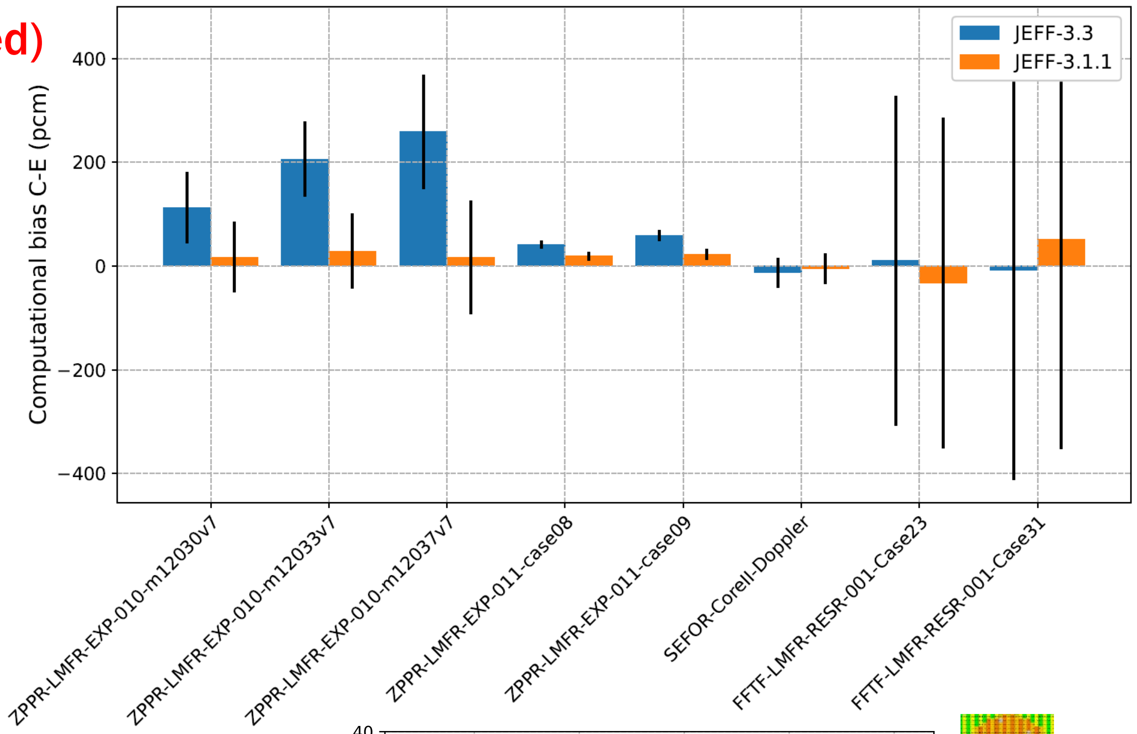
	JEFF-4T2.2	JEFF-3.3	JEFF-3.1.1
MAD (pcm)	377	463	350

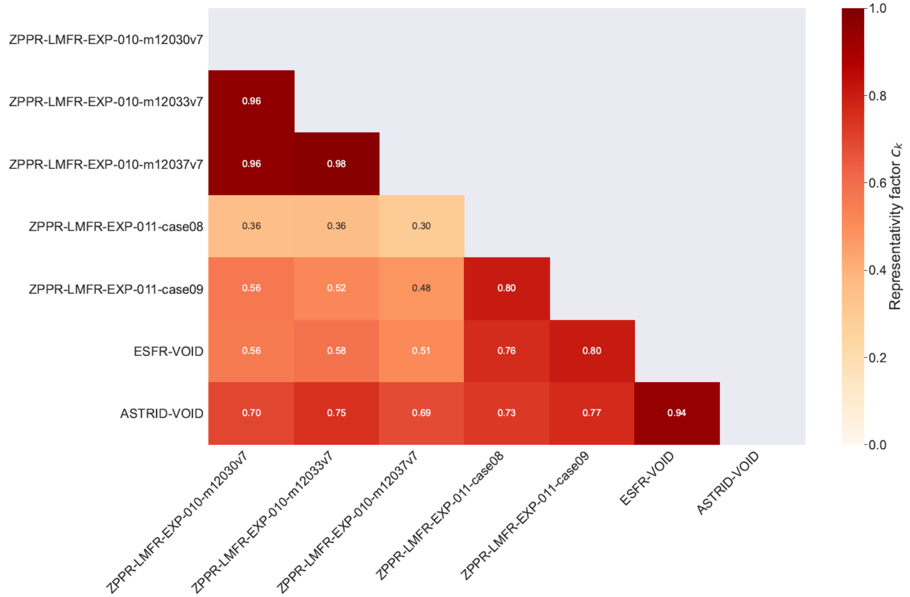
Perturbation with NDaST and GLLS for biases analysis

3. Fast Reactors C/E validation and nuclear data trends

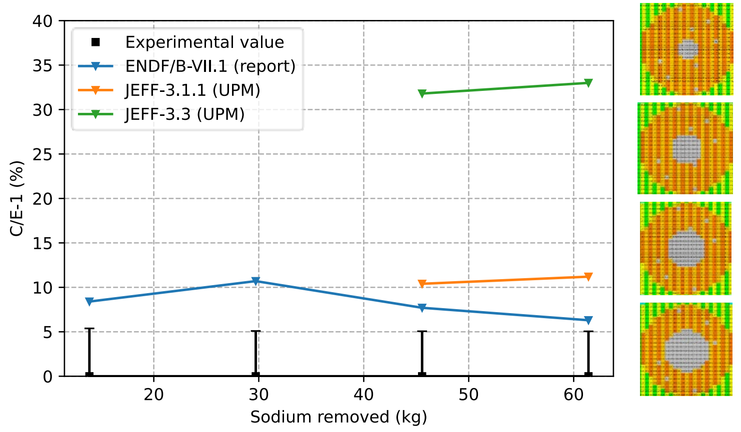
Sodium void reactivity effect: IRPhE (5 experiments selected)

Benchmark identifier	Experimental facility	Core Loading
ZPPR-LMFR-EXP-010-m12030	ZPPR-12	Loading 30
ZPPR-LMFR-EXP-010-m12033	ZPPR-12	Loading 33
ZPPR-LMFR-EXP-010-m12037	ZPPR-12	Loading 37
ZPPR-LMFR-EXP-011-case08	ZPPR-2	Loading 184
ZPPR-LMFR-EXP-011-case09	ZPPR-2	Loading 185





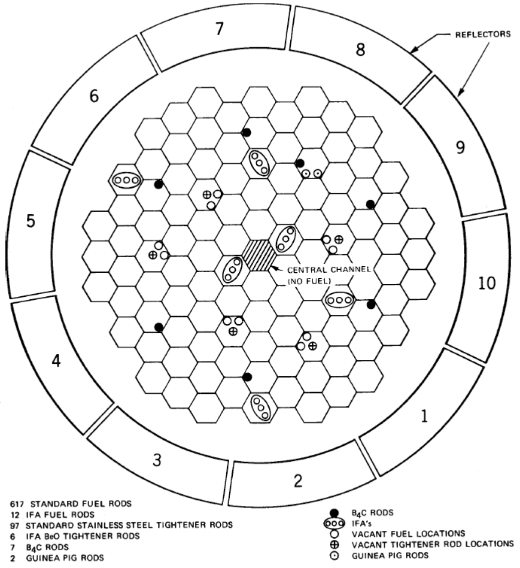
Trending analysis for ZPPR-2



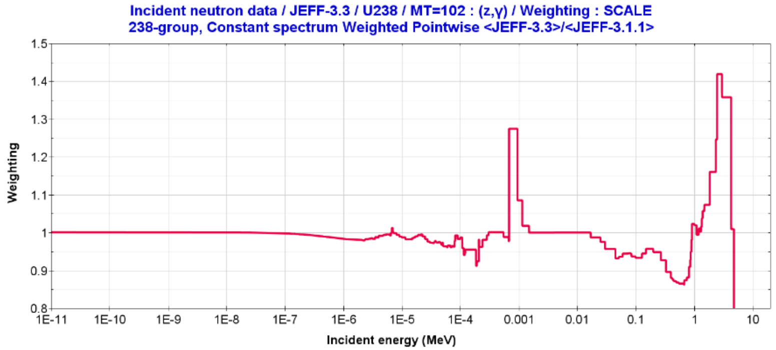
3. Fast Reactors C/E validation and nuclear data trends

Doppler reactivity effect: lack of experiments in IRPhE; SEFOR experiments from SFR-UAM

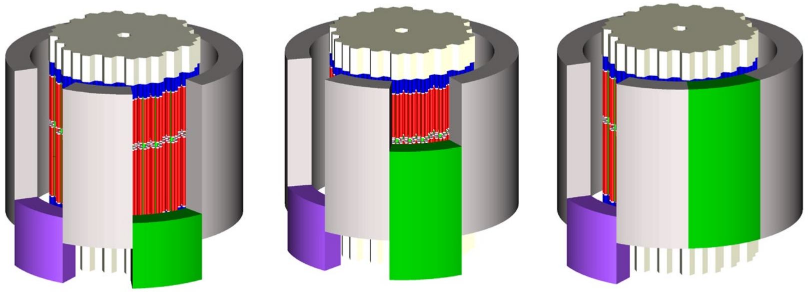
Reflector worth: potential of SEFOR calibration curves for ND validation of ^{239}Pu, ^{56}Fe, ^{58}Ni

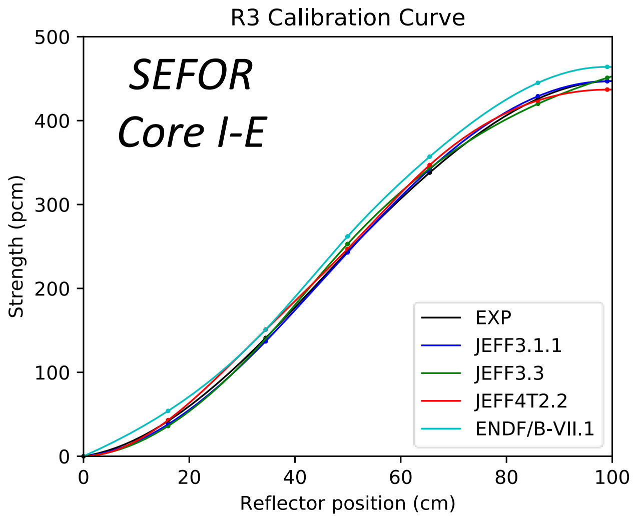


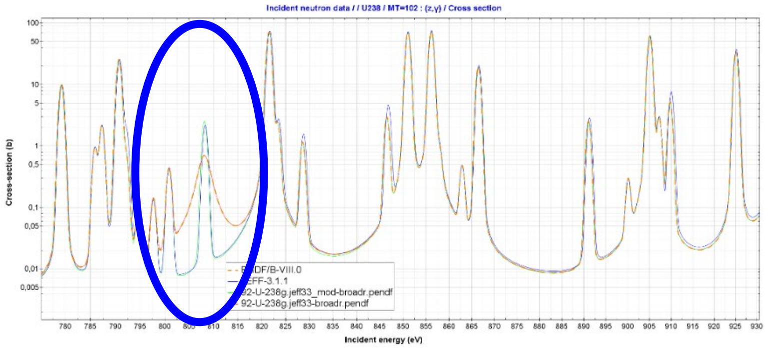
SEFOR Core II	Calculated at UPM SCALE-6.2.3 (R-Z model)		
	JEFF-3.1.1	JEFF-3.3	Corrected JEFF-3.3
Doppler constant	**-676.6**	**-708.9**	**-688.7**
Core II C/E	**1.010**	**1.058**	**1.028**



U-238 (n,γ) ratio JEFF-3.3/JEFF-3.1.1





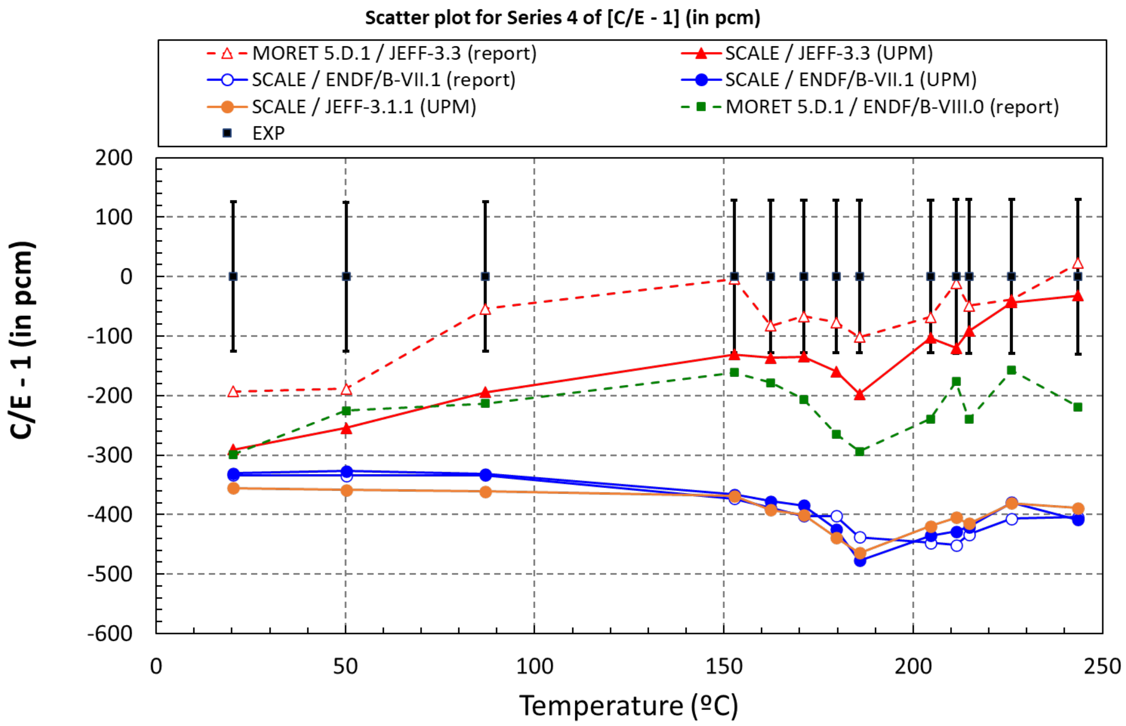


This allowed to identify a typo for the 808 eV p-wave Γ_γ parameter

4. Thermal Reactors C/E validation and nuclear data trends

4.1 Thermal Reactor Physics benchmarks from IRPHE

- UPM analyzed C/E in KRITZ benchmarks (LWR lattices at KRITZ reactor in Studsvik) and trends with Tª



JEFF-3.3, the trend with temperature becomes stronger

Perturbation analysis using NDaST showed biases probably due to ^{235}U(n,fission) ~ 0.01 eV –1eV

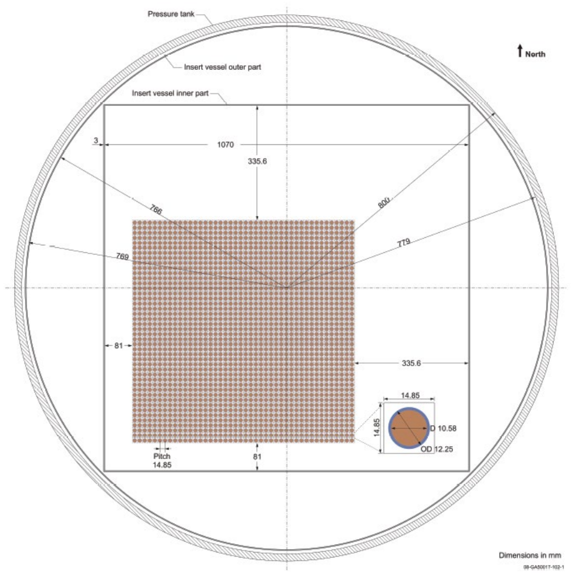


Figure 1.5 Schematic Top View of the Core.

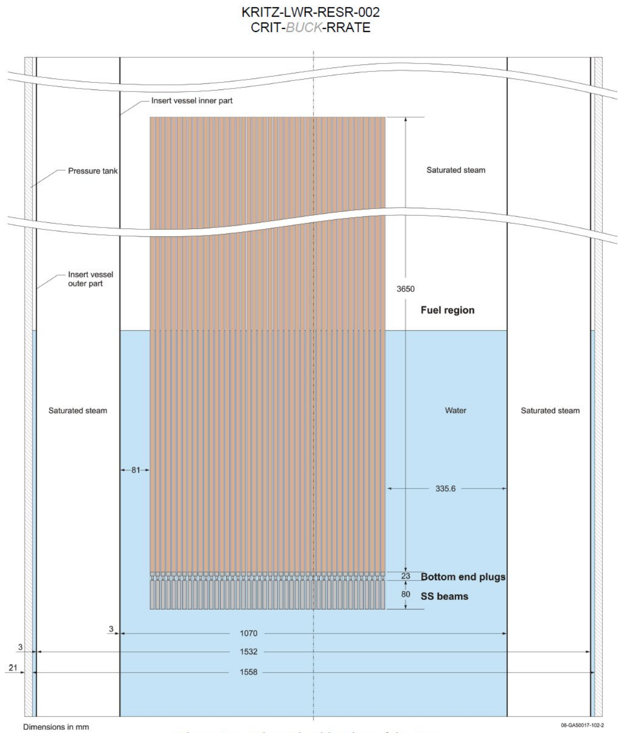
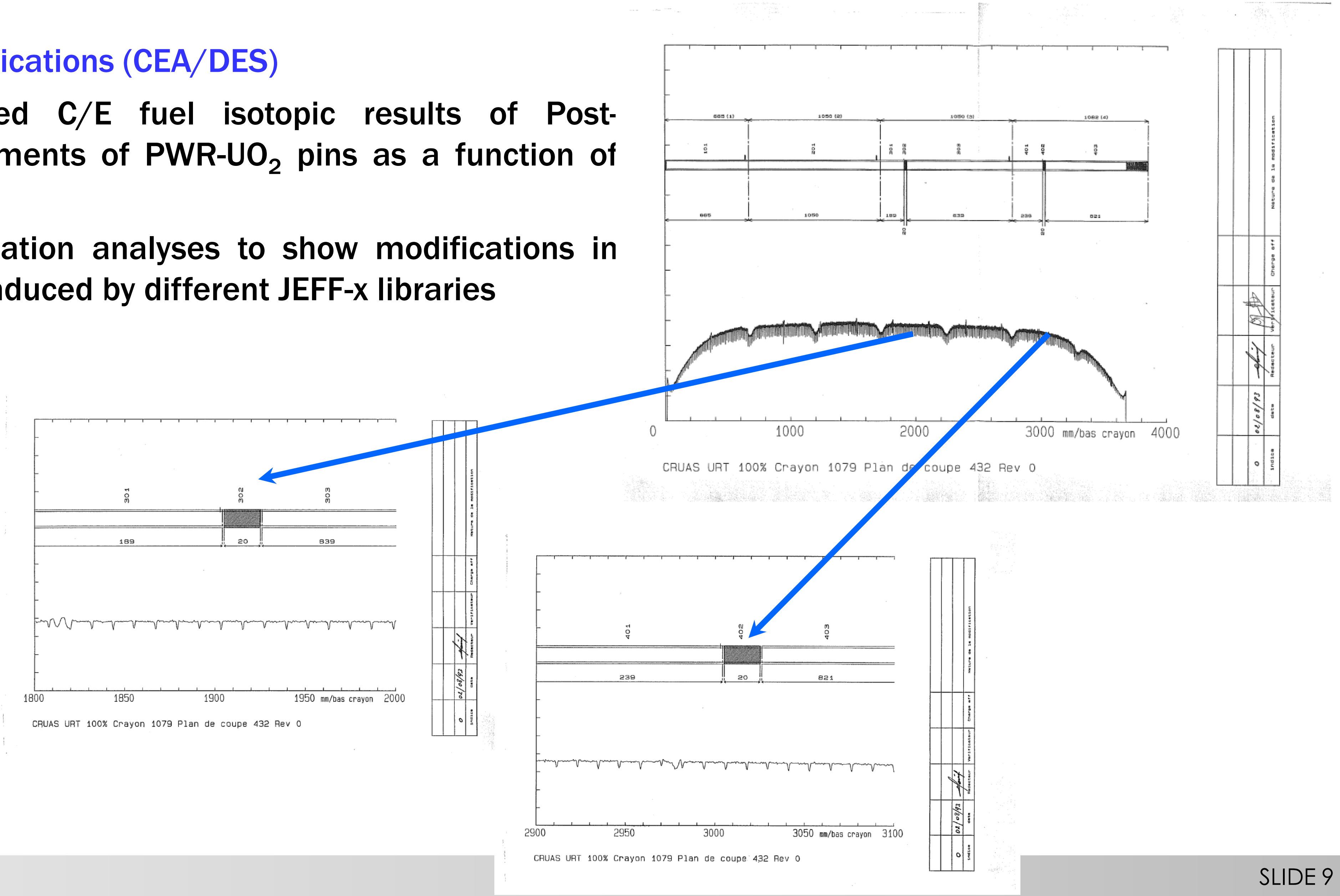


Figure 1.6. Schematic Side View of the Core.

***Ref.:** Kodeli et al. Analysis of the KRITZ Critical Benchmark Experiments, NENE2009*

4.2 Commercial LWR applications (CEA/DES)

- **CEA/DES analyzed C/E fuel isotopic results of Post-Irradiation Experiments of PWR-UO_2 pins as a function of burnup**
- **APOLLO2 perturbation analyses to show modifications in isotopic content induced by different JEFF-x libraries**



4. Thermal Reactors C/E validation and nuclear data trends

JEFF-3.1.1

REL2005	Cycle 1	Cycle 2	Cycle 3
	(C/E-1) ± ΔE/E [%]	(C/E-1) ± ΔE/E [%]	(C/E-1) ± ΔE/E [%]
$^{234}U/^{238}U$	1.0 ± 0.3	1.2 ± 0.4	1.4 ± 0.5
$^{235}U/^{238}U$	0.3 ± 0.4	1.3 ± 0.7	1.6 ± 1.3
$^{236}U/^{238}U$	0.0 ± 0.2	0.5 ± 0.2	0.3 ± 0.2
$^{237}Np/^{238}U$	-7.7 ± 2.9	-3.3 ± 2.9	-2.0 ± 2.0
$^{238}Pu/^{238}U$	-5.6 ± 1.9	-4.0 ± 2.0	-3.4 ± 1.8
$^{239}Pu/^{238}U$	0.6 ± 0.7	0.7 ± 0.9	2.2 ± 1.2
$^{240}Pu/^{238}U$	-1.3 ± 1.2	0.3 ± 0.9	0.5 ± 0.7
$^{241}Pu/^{238}U$	-2.5 ± 2.1	-1.6 ± 1.4	0.0 ± 2.0
$^{242}Pu/^{238}U$	-2.5 ± 3.3	-0.8 ± 2.1	-0.2 ± 1.6
$^{241}Am/^{238}U$	•	•	-0.1 ± 3.2
$^{241}Am/^{238}U$ EOC			± 5.4
$^{242m}Am/^{238}U$			8.9 ± 7.0
$^{243}Am/^{238}U$			-0.1 ± 4.1
$^{243}Cm/^{238}U$			-5.0 ± 15.0
$^{244}Cm/^{238}U$	•	•	1.0 ± 5.6
$^{245}Cm/^{238}U$	•	•	3.5 ± 7.5
$^{246}Cm/^{238}U$	•	•	-15.2 ± 8.2
$^{247}Cm/^{238}U$	•	•	1.8 ± 29.7
$^{143}Nd/^{238}U$	-0.8 ± 0.6	-0.6 ± 0.6	-0.5 ± 0.5
$^{144}Nd/^{238}U$	-1.3 ± 0.8	-1.5 ± 0.8	-1.6 ± 0.9
$^{145}Nd/^{238}U$	0.0 ± 0.7	-0.1 ± 0.7	-0.5 ± 0.6
$^{146}Nd/^{238}U$	-0.3 ± 0.8	-0.4 ± 0.8	-0.1 ± 0.8
$^{148}Nd/^{238}U$	0.5 ± 0.8	0.5 ± 0.7	0.6 ± 0.8
$^{150}Nd/^{238}U$	-0.4 ± 0.9	-0.1 ± 0.8	0.0 ± 0.8
$\Sigma^{i}Nd/^{238}U$	0.0 ± 1.0	0.0 ± 1.0	0.0 ± 1.0
BU Cray. [GWjj/t]]	13.6	22.0	35.2

JEFF-3.3

REL2005	Cycle 1	Cycle 2	Cycle 3
	(C/E-1) ± ΔE/E [%]	(C/E-1) ± ΔE/E [%]	(C/E-1) ± ΔE/E [%]
$^{234}U/^{238}U$	1.1 ± 0.3	1.4 ± 0.4	1.7 ± 0.5
$^{235}U/^{238}U$	-0.2 ± 0.4	0.1 ± 0.7	-1.0 ± 1.3
$^{236}U/^{238}U$	0.1 ± 0.2	0.7 ± 0.2	0.5 ± 0.2
$^{237}Np/^{238}U$	-6.5 ± 2.9	-2.4 ± 2.9	-0.7 ± 2.0
$^{238}Pu/^{238}U$	-3.6 ± 1.9	-0.3 ± 2.0	3.7 ± 1.8
$^{239}Pu/^{238}U$	0.5 ± 0.7	-0.5 ± 0.9	0.5 ± 1.2
$^{240}Pu/^{238}U$	-0.5 ± 1.2	0.6 ± 0.9	1.1 ± 0.7
$^{241}Pu/^{238}U$	-2.1 ± 2.1	-1.5 ± 1.4	0.0 ± 2.0
$^{242}Pu/^{238}U$	-2.6 ± 3.3	-0.8 ± 2.1	0.6 ± 1.6
$^{241}Am/^{238}U$	•	•	-1.2 ± 3.2
$^{241}Am/^{238}U$ EOC			± 5.4
$^{242m}Am/^{238}U$			11.9 ± 7.0
$^{243}Am/^{238}U$			-2.6 ± 4.1
$^{243}Cm/^{238}U$			24.6 ± 15.0
$^{244}Cm/^{238}U$	•	•	11.8 ± 5.6
$^{245}Cm/^{238}U$	•	•	25.3 ± 7.5
$^{246}Cm/^{238}U$	•	•	-1.3 ± 8.2
$^{247}Cm/^{238}U$	•	•	11.5 ± 29.7
$^{143}Nd/^{238}U$	-0.1 ± 0.6	0.1 ± 0.6	0.2 ± 0.5
$^{144}Nd/^{238}U$	-1.2 ± 0.8	-1.6 ± 0.8	-1.9 ± 0.9
$^{145}Nd/^{238}U$	0.3 ± 0.7	0.0 ± 0.7	-0.7 ± 0.6
$^{146}Nd/^{238}U$	0.6 ± 0.8	0.7 ± 0.8	1.1 ± 0.8
$^{148}Nd/^{238}U$	1.5 ± 0.8	1.5 ± 0.7	1.6 ± 0.8
$^{150}Nd/^{238}U$	-0.1 ± 0.9	0.0 ± 0.8	0.1 ± 0.8
$\Sigma^{i}Nd/^{238}U$	0.7 ± 1.0	0.6 ± 1.0	0.6 ± 1.0
BU Cray. [GWjj/t]]	13.6	22.0	35.2

JEFF-4.0t0

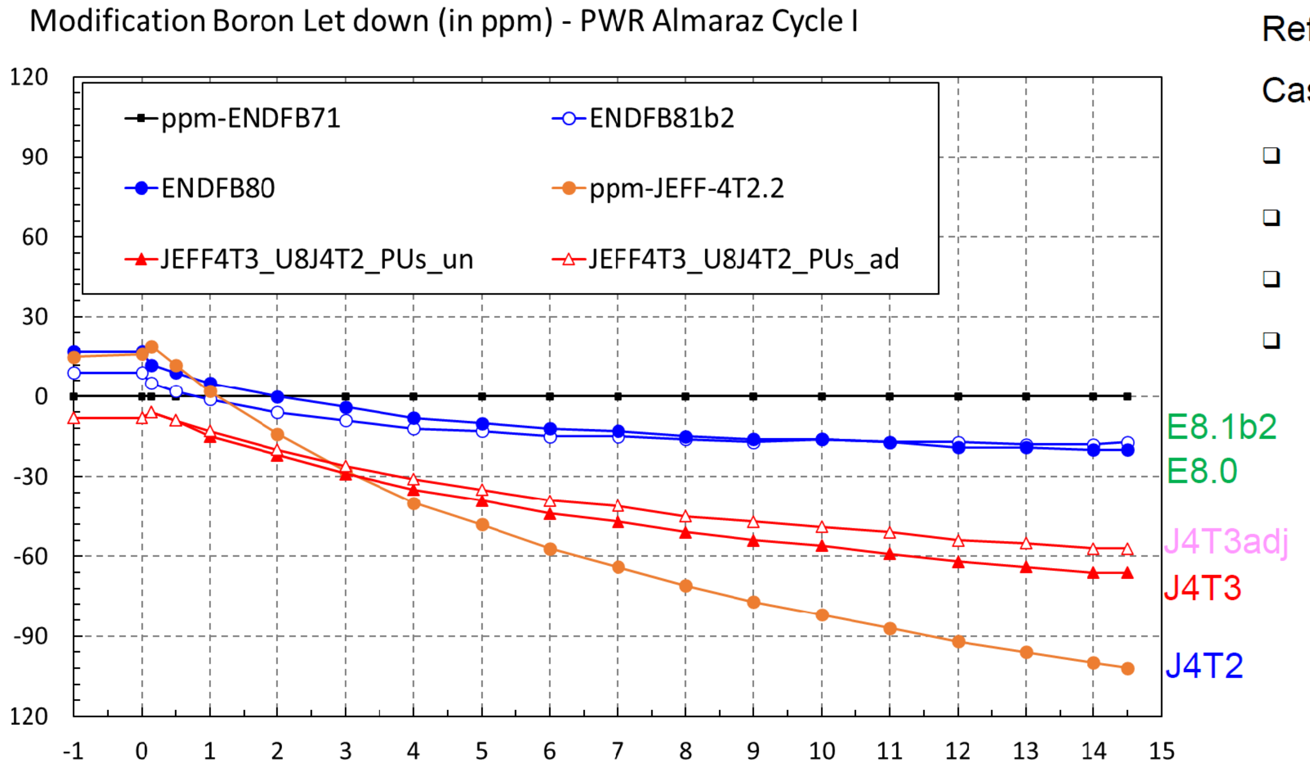
REL2005	Cycle 1	Cycle 2	Cycle 3
	(C/E-1) ± ΔE/E [%]	(C/E-1) ± ΔE/E [%]	(C/E-1) ± ΔE/E [%]
$^{234}U/^{238}U$	1.1 ± 0.3	1.4 ± 0.4	1.6 ± 0.5
$^{235}U/^{238}U$	-0.2 ± 0.4	0.1 ± 0.7	-0.9 ± 1.3
$^{236}U/^{238}U$	0.1 ± 0.2	0.6 ± 0.2	0.4 ± 0.2
$^{237}Np/^{238}U$	-6.7 ± 2.9	-2.7 ± 2.9	-1.1 ± 2.0
$^{238}Pu/^{238}U$	-6.2 ± 1.9	-4.5 ± 2.0	-3.4 ± 1.8
$^{239}Pu/^{238}U$	0.7 ± 0.7	0.0 ± 0.9	1.3 ± 1.2
$^{240}Pu/^{238}U$	-2.2 ± 1.2	-1.3 ± 0.9	-0.9 ± 0.7
$^{241}Pu/^{238}U$	-2.5 ± 2.1	-1.8 ± 1.4	0.0 ± 2.0
$^{242}Pu/^{238}U$	-3.7 ± 3.3	-2.0 ± 2.1	-0.9 ± 1.6
$^{241}Am/^{238}U$	•	•	-1.1 ± 3.2
$^{241}Am/^{238}U$ EOC			± 5.4
$^{242m}Am/^{238}U$			12.3 ± 7.0
$^{243}Am/^{238}U$			-0.4 ± 4.1
$^{243}Cm/^{238}U$			23.4 ± 15.0
$^{244}Cm/^{238}U$	•	•	14.2 ± 5.6
$^{245}Cm/^{238}U$	•	•	28.0 ± 7.5
$^{246}Cm/^{238}U$	•	•	0.5 ± 8.2
$^{247}Cm/^{238}U$	•	•	13.5 ± 29.7
$^{143}Nd/^{238}U$	-0.1 ± 0.6	0.1 ± 0.6	0.3 ± 0.5
$^{144}Nd/^{238}U$	-1.1 ± 0.8	-1.6 ± 0.8	-1.8 ± 0.9
$^{145}Nd/^{238}U$	0.5 ± 0.7	0.4 ± 0.7	0.0 ± 0.6
$^{146}Nd/^{238}U$	0.3 ± 0.8	0.2 ± 0.8	0.3 ± 0.8
$^{148}Nd/^{238}U$	1.0 ± 0.8	0.9 ± 0.7	1.0 ± 0.8
$^{150}Nd/^{238}U$	-0.1 ± 0.9	0.1 ± 0.8	0.2 ± 0.8
$\Sigma^{i}Nd/^{238}U$	0.5 ± 1.0	0.4 ± 1.0	0.4 ± 1.0
BU Cray. [GWjj/t]]	13.6	22.0	35.2

While C/E results are consistent with experimental uncertainties, they show different trends with burnup, suggesting that some cross sections should be revised: ^{236}U and ^{239}Pu radiative capture and ^{238}Pu production

4. Thermal Reactors C/E validation and nuclear data trends

4.3 Commercial LWR applications (UPM)

- **UPM analyzed C/E for PWR Critical Boron Letdown Curve Almaraz II NPP – Cycle I (IAEA-TECDOC-815, 1995)**



Nuclear Data:

Reference: ENDF/B-VII.1

Case **JEFF-4T3_U8J4T2**

- XS/JEFF-4T3 + U8/JEFF-4T2
- TSL /JEFF-4T3
- DD/JEFF-3.3
- FY_U5_PU9/JEFF-4/CON

Full core simulations expensive to be used in ND validation

Many compensating effects, no clean benchmarks

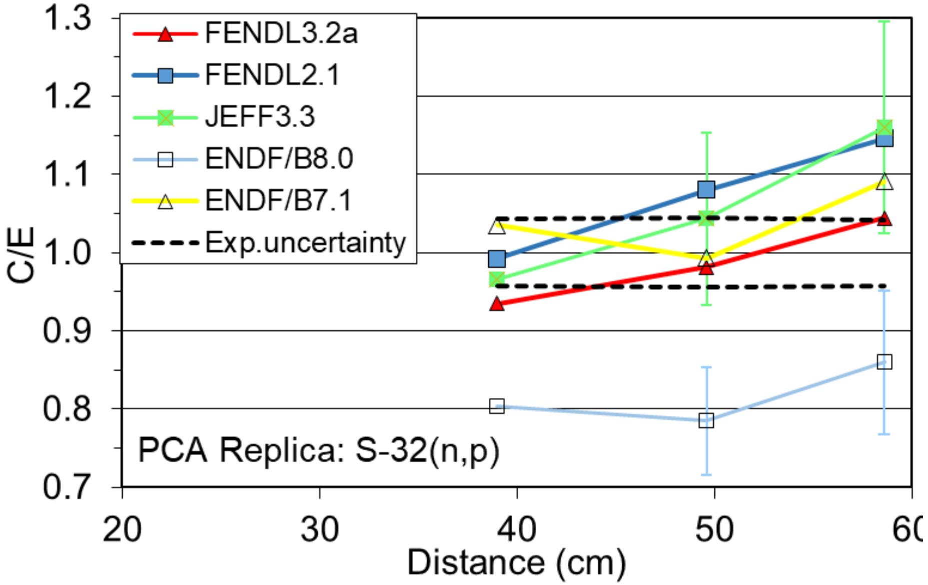
But able to identify general trends due to ND

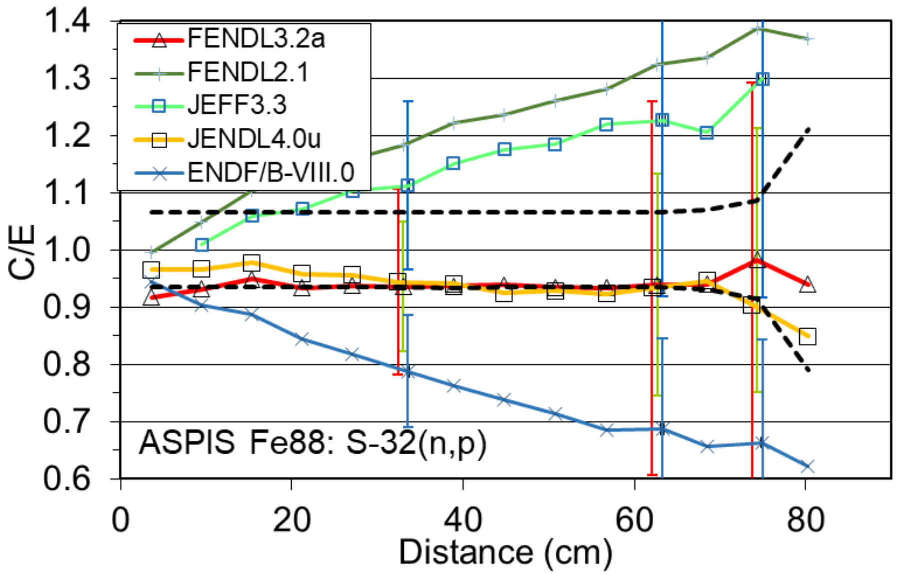
5. Shielding benchmarks C/E validation and nuclear data trends

5.1. SINBAD benchmarks for validation of recent Fe evaluations (ENDF/B-VIII.0, JEFF-3.3 and FENDL-3.2)

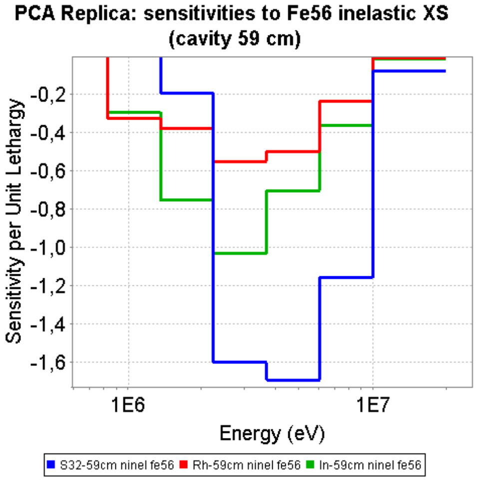
Benchmark / quality	Additional information needed on:
ASPIS Iron-88 ~ ♦♦♦ Analyses by UKAEA (I.Kodeli)	Review: new MCNP model. Additional information needed on: - detectors arrangement (e.g. stacking) - gaps between the slabs - absolute calibration of neutron source & dilution factor - effect of the cave walls
ORNL PCA Pool Critical Assembly - PV Benchmark (1980) Analyses by NRG (S.v.d. Marck)	- approximate modelling of neutron source (material test reactor (MTR) with a 93% ^{235}U fuel elements) - SINBAD quality evaluations to be performed
ASPIS PCA REPLICA - Winfrith Water/Steel ♦♦♦ Analyses by UKAEA (I.Kodeli)	Supplementary information received from David Hanlon (Jacobs) on (available from WPEC SG47 Githab): - geometrical arrangement of the fission plate and ASPIS cave; - geometry and material of the detectors; - measurement arrangement and background contribution - availability of ^{235}U fission chamber measurements
CIAE Iron slab 14 MeV benchmark Analyses by UKAEA (I.Kodeli)	- Ongoing SINBAD evaluation (presented at WPEC SG47) - TOA neutron spectra measured from 5, 10 and 15 cm Fe slabs at 60^0 and 120^0 (~2016)

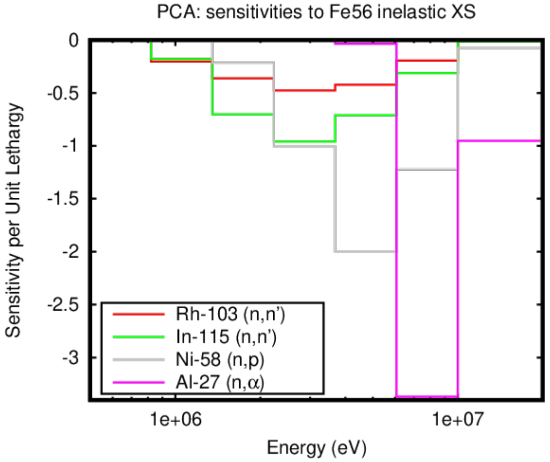
5. Shielding benchmarks C/E validation and nuclear data trends

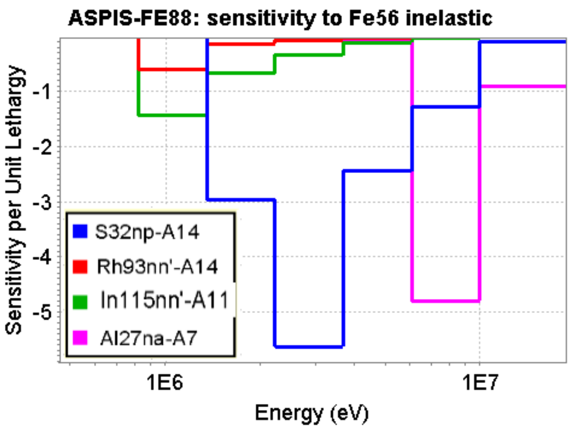




C/E for S(n,p) and Al(n,α) using ASPIS-Fe88, PCA & PCA Replica





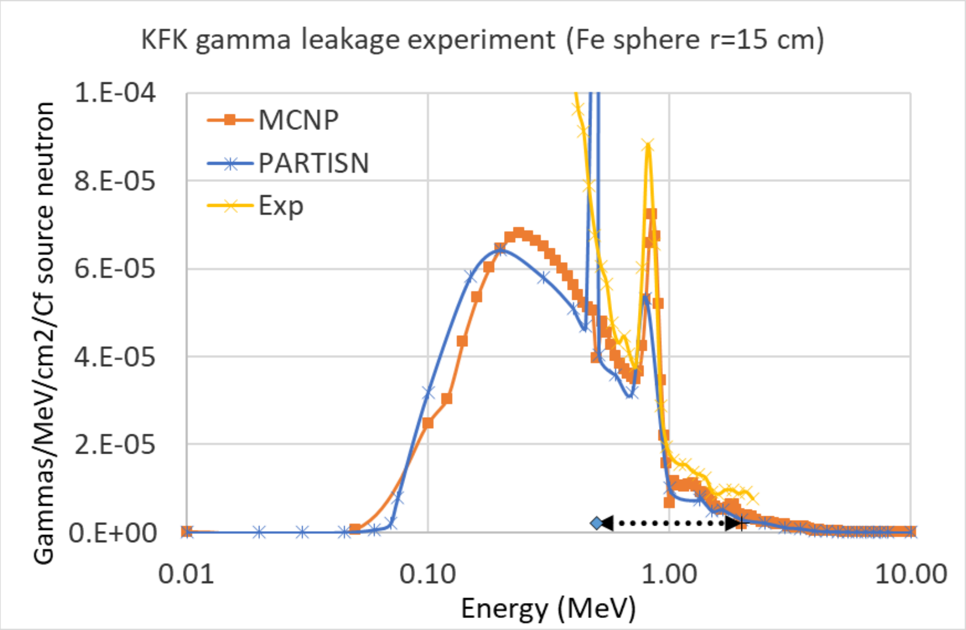


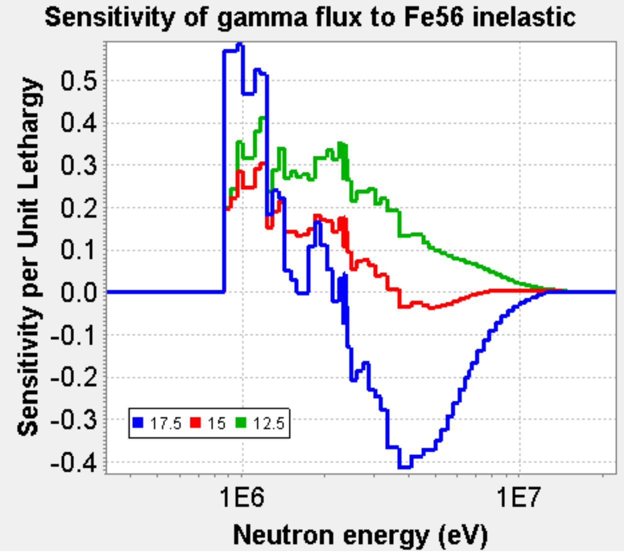
Sensitivity profiles to ^{56}Fe(n,n') in deepest positions for PCA, PCA Replica vs. ASPIS Fe88

5. Shielding benchmarks C/E validation and nuclear data trends

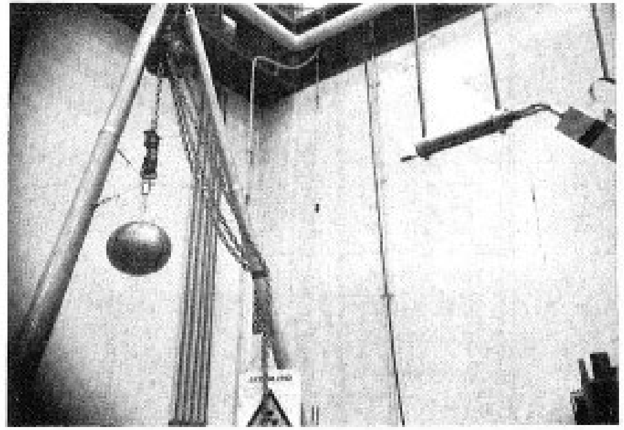
5.2. KFK-1977 γ-ray leakage benchmark

- **New SINBAD evaluation by Stanislav Simakov: KFK-1977 measured gamma from bare 252Cf(s.f.) source and from Ø25, 30 and 35 cm Fe spheres was prepared within WPEC SG47**

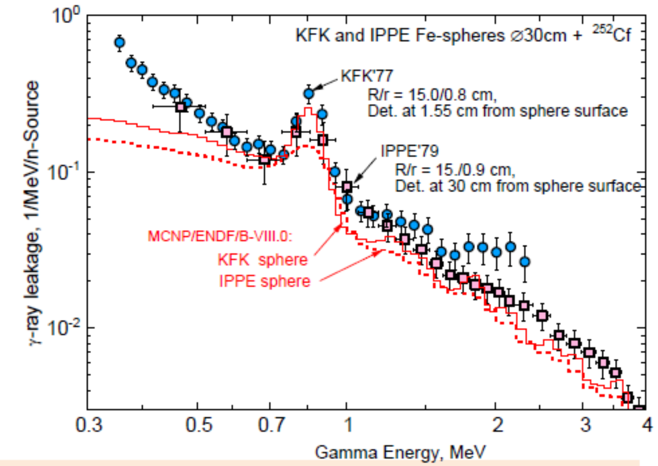




KFK set-up:



KFK vs. IPPE: γ-ray leakage spectra from Fe Ø30cm with Cf-source

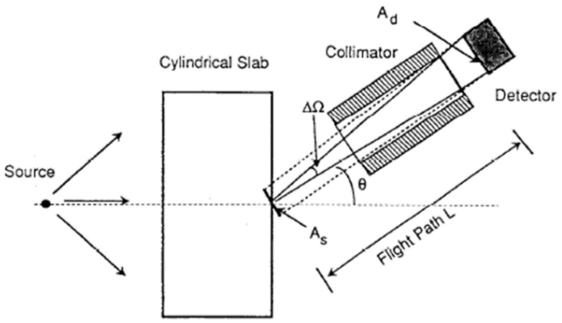


5. Shielding benchmarks C/E validation and nuclear data trends

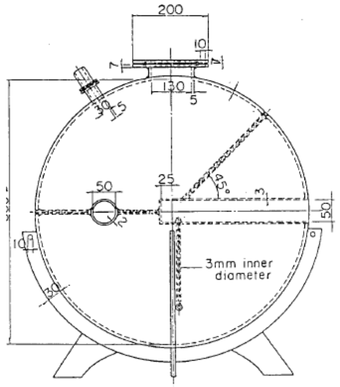
5.3. TOF Shielding Benchmarks in SINBAD

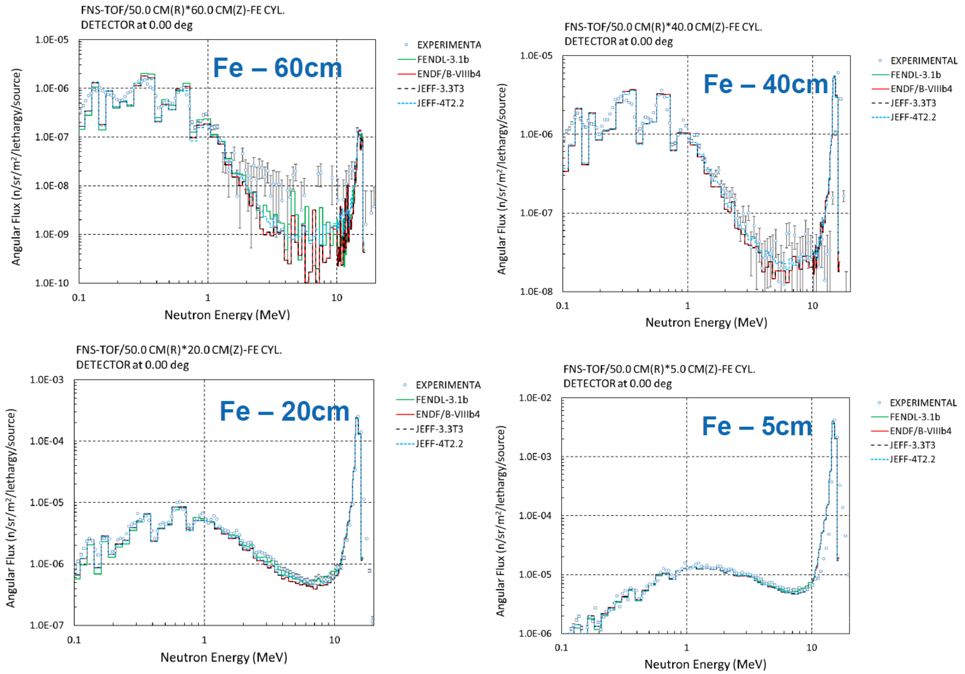
- FNS - TOP (17 cases x 5 angles)
- Oktavian (15 cases)
- MCNP6 shielding suite (14 cases)

FNS/TOF

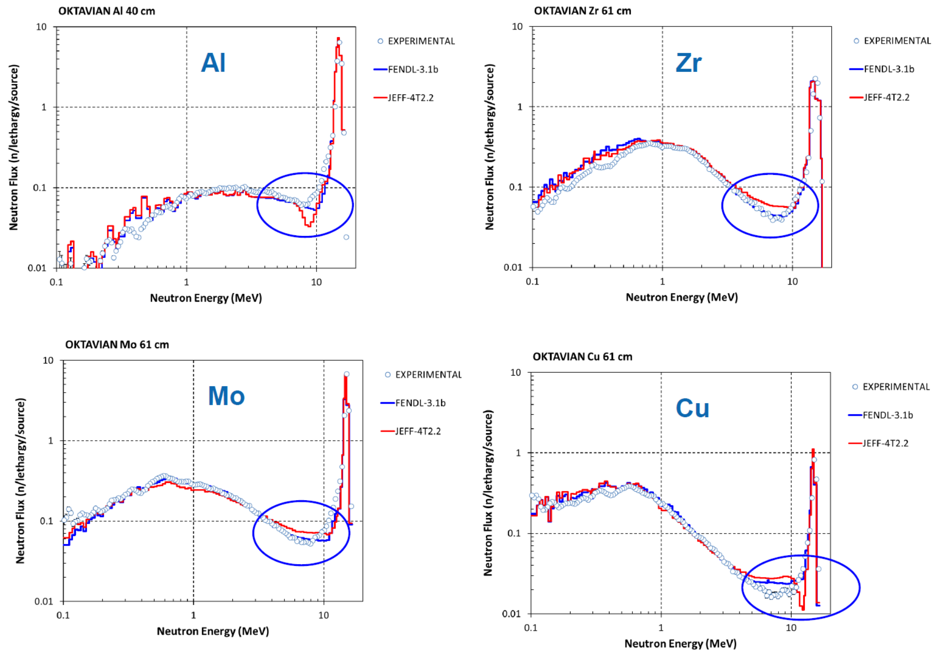


Oktavian pulsed sphere





FNS/TOF results



Oktavian results

Deliverable D5.7 – Status summary

- ✓ Significant number of sets of reactor physics & shielding benchmarks, as planned
- ✓ Extensive use of JEFF-3.3 and JEFF-4Tx for C/E estimates and trends identified
- ✓ Deliverable structure already shared with all contributors (January 2024)
- ✓ Pending to send a draft so that contributors can include additional updated results/analysis
- ✓ Estimated date to send a 1st draft to contributors: March 2024
- ✓ Estimated date for completion: April 2024