DE LA RECHERCHE À L'INDUSTRIE

Nuclear data feedback on structural, moderating and absorbing materials through the MAESTRO experimental programme in MINERVE

JEF/DOC-1849

DEN/DER/SPRC/LEPh | **Pierre Leconte**

April 26, 2017.

OUTLINE

- **Context**
- Description of the Experiments
- Calculations methods and models
- Analysis of spectral characteristization experiments
- Analysis of neutron activation experiments
- Analysis of pile-oscillation experiments
- Conclusions and further works

CONTEXT
Validation of ND for structural and moderating materials

- **Several experimental programmes have been designed to validate ND for LWR applications:**
  - Burn-Up Credit programme (1992-2000) on 13 of the most absorbing FP: $^{147,149,152}Sm$, $^{143,145}Nd$, ^{155}Gd, ^{153}Eu, ^{99}Tc, ^{133}Cs, ^{109}Ag, ^{101}Ru, ^{95}Mo, ^{103}Rh
  - OSMOSE programme (2005-2010) on 13 of the most absorbing actinides: ^{232}Th, $^{233,234,236,238}U$, $^{238,239,240,241,242}Pu$, $^{241,243}Am$, $^{244,245}Cm$
  - OCEAN programme (2005-2010) on 16 separated isotopes of absorbers: $^{155,157}Gd$, $^{177,178,179,180}Hf$, $^{160,161,162,164}Dy$, $^{166,167,168,170}Er$, $^{151,153}Eu$
  - HTC programme (2004-2011) on higly irradiated MOX fuels (60GWd/t) and UOx fuels (80GWd/t)

- **A lack of validation remaining for:**
  - Structural materials: *zircaloy, Inconel, stainless steel…*
  - Moderator materials: *light and heavy water, carbon, berylium…*
  - Detection materials (GEN-III+): *cobalt, vanadium, rhodium…*
  - Absorbing materials: *Ag, In, Cd, natural Dy, Er, Eu, Gd, Hf*

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DESCRIPTION OF THE EXPERIMENTS
General purpose

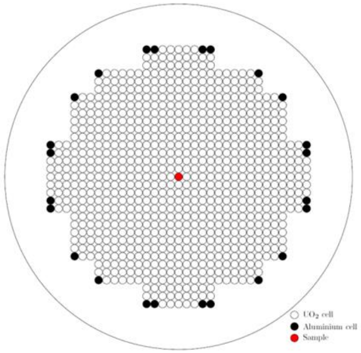
- **Main goals:**
  - Validation of the capture cross sections for structural, dectection and absorbing materials for GEN-III+ applications
  - Validation of the scattering reactivity worth of moderators

- **Materials to be considered:**
  - Moderator elements: H_2O, ^{nat}Be, ^{nat}C, CH_2
  - Structural elements: ^{nat}Mg, ^{nat}Al, ^{nat}Cl, ^{nat}Ca, ^{nat}Ti, ^{nat}Cr, ^{nat}Fe, ^{nat}Ni, ^{nat}Cu, ^{nat}Zn, ^{nat}Zr, ^{nat}Mo, ^{nat}Sn
  - Detection elements: ^{nat}V, ^{nat}Mn, ^{nat}Co, ^{nat}Nb, ^{nat}Rh
  - Absorber elements: ^{nat}Ag, ^{nat}In, ^{nat}Cd ^{nat}Eu, ^{nat}Gd, ^{nat}Dy, ^{nat}Er, ^{nat}Hf ^{153}Eu, ^{107}Ag, ^{nat}Cs
  - Industrial alloys: Zy4, M5, SS304, SS316, Inconel-800

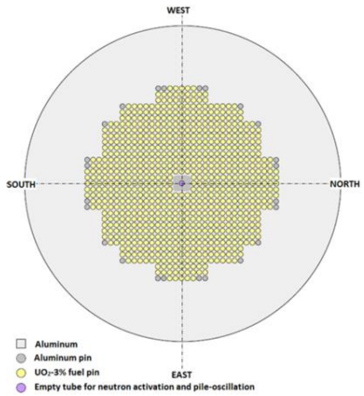
- **Measurements to be performed:**
  - Pile-oscillation experiments on the 48 samples
  - Activation experiments on a set of 10 samples

DESCRIPTION OF THE EXPERIMENTS
MINERVE core configurations

- **MAESTRO PHASE I (2011)**
  - R1UO2 core configuration
  - Pile-oscillation of Rh, Co, Mn, V, Au rods + B, Li, Gd solutions
  - Neutron activation of Co and Mn
  - ➪ *See JEF/DOC-1486*

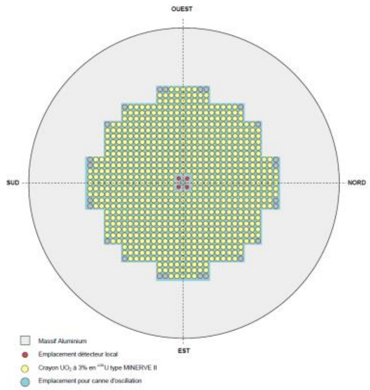


- **MAESTRO Phase II (2012-2013)**
  - MAESTRO core configuration
  - Neutron activation of ^{109}Ag, ^{133}Cs, ^{51}V, ^{115}In, ^{151,153}Eu, ^{64,68}Zn, ^{94,96} Zr, ^{98,100}Mo, ^{112,117,122}Sn, ^{197}Au
  - ➪ *See WONDER2015 proceedings (EPJ-Web of Conference)*



- **MAESTRO Phase III (2013-2014)**
  - MAESTRO core configuration
  - Spectral indices, dosimetry, cadmium ratio, CU8/Ftot
  - Pile-oscillation of Au, B, Li, Ag, Cd, Cl, Ca, V, Co, Cr, Cs, Dy, Er, Eu, Gd, In, Mn, D_2O, H_2O, Be, CH_2, Cu, Fe, Mo, Nb, Ni, Ti , Zn, V, Al_2O_3, Al, C, Mg, Si, Sn, Inconel-718, SS304, SS316, Al-5754, M5^{TM}, Zy4

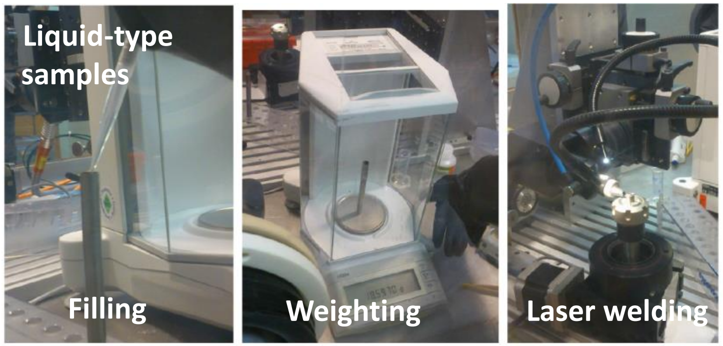
- **MAESTRO Phase IV (2016)**
  - MAESTRO-SL core configuration
  - Pile-oscillation of Hf, ^{107}Ag, Rh and ^{153}Eu



DESCRIPTION OF THE EXPERIMENTS
Samples

- **MAESTRO samples are of three physical forms**
  - Pure rods: Fe, Cr, Ni, Sn, Zn…
  - Liquid solutions: Eu, Cs, In, Gd…
  - Powder mix with Al_2O_3 diluant: Hf, Rh, ^{153}Eu, ^{107}Ag
  - ⇨ Typical external dimensions: diameter 1.2cm / length 10cm

- **Calibration samples**
  - Pure rods of gold (99.995%) of various diameters : 1.0, 1.6 and 2.0mm
  - Al-0.1%Au alloy wire
  - 8 calibrated solutions
    - 350 ppm to 1400 ppm ^{10}B
    - 820 to 3280 ppm of ^{6}Li



- **Reference (dummy) samples to cancel the reactivity worth due to cladding and/or matrix:**
  - Void sample for rod-type samples
  - Al2O3-only samples for powder-type samples
  - Pure water samples for liquid-type

- **Physical characteristics carefully checked:**
  - Mass certificate of the dopant at <0.5% (1s)
  - Accurate metrology of the dimensions (±10µm) and mass (±0.1mg)
  - Reactive impurities

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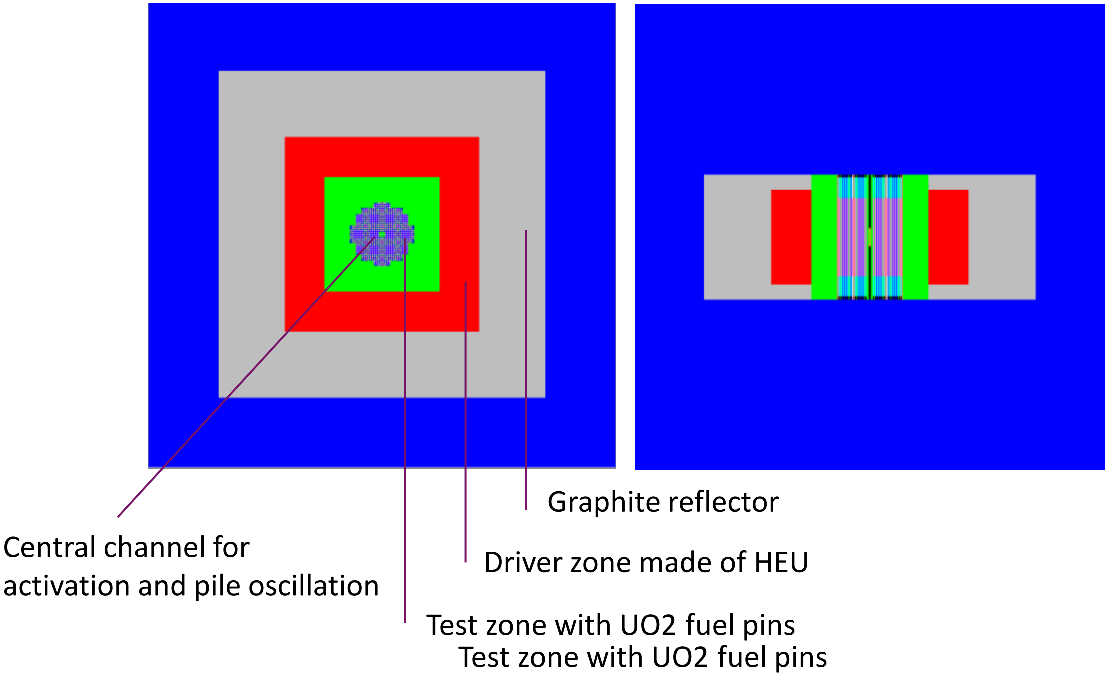
CALCULATION METHODS AND MODELS
TRIPOLI model of the MINERVE core

- **3D detailed full core model**



Model simplifications to improve calculation time:

- Homogeneized driver zone
- Simplified description of the graphite reflector

⇨ Validation studies were done to assess the relevance of these simplifications

- **Neutron activation experiements are analysed by reaction rate computations**

$$\boldsymbol{\Sigma}_i \phi / \boldsymbol{\Sigma}_{Au} \phi$$

- **Pile oscillation experiments are analysed with the new IFP exact perturbation capability in TRIPOLI4-DEV:**

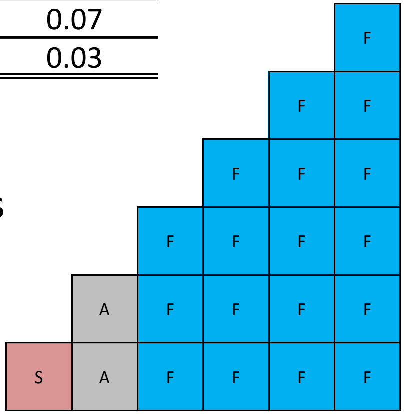
$$\delta\rho_i / \delta\rho_{Au}$$

CALCULATION METHODS AND MODELS
Uncertainty management

- **Uncertainties of three types**
  - Measurement uncertainty (from experimental report)
  - Technological uncertainties (from IRPhE evaluation of CERES program + sample characteristics)
  - Monte-Carlo convergence

Element	Parameter	V	±σ
Fuel pin	UO_2 density (g/cm^3)	**10.21**	0.12
	UO_2 enrichment in ^{235}U (% w/o)	**3.000**	0.005
	Fuel pellet diameter (mm)	**8.046**	0.0008
	Fuel clad outer diameter (mm)	**9.40**	0.07
	Overclad inner diameter (mm)	**9.70**	0.07
	Overclad outer diameter (mm)	**11.0**	0.07
	Lattice pitch (cm)	**1.260**	0.002
Moderator	H_2O density (g/cm^3)	**0.998**	0.001
Oscillation rod	Outer diameter (mm)	**13.00**	0.07
Oscillation basket	Central channel outer diameter	**13.20**	0.07
	Side length (mm)	**36.00**	0.03

- **APOLLO2/P_{ij} model for uncertainty analysis**
  - Fast and enough accurate to evaluate derivates of calculated values to model parameters
  - Use to evaluate Δ between ND libraries



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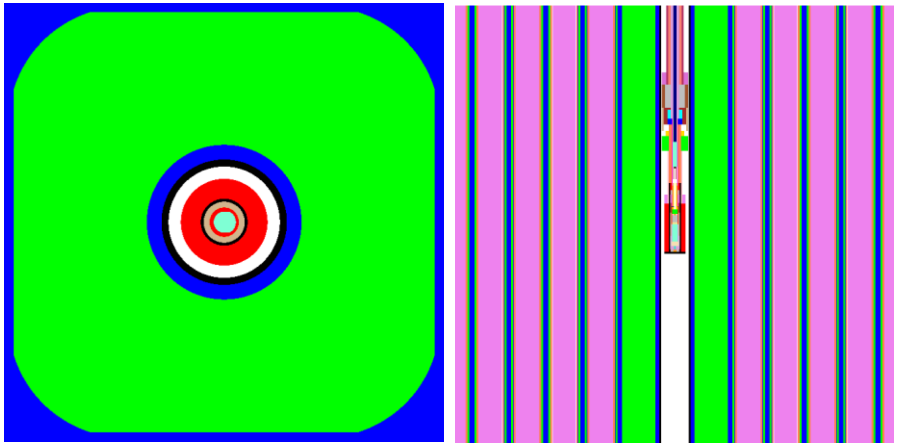
ANALYSIS OF SPECTRAL CHARACTERIZATION EXPERIMENTS
Spectral indice measurements

- **Micro fission chambers of thermal (^{235}U, ^{239}Pu) and threshold reaction (^{240}Pu, ^{242}Pu)**
  ⇨ Measurement of the microscopic fission ratio

- **Monte-Carlo model: accurate FC description to account for flux perturbation**



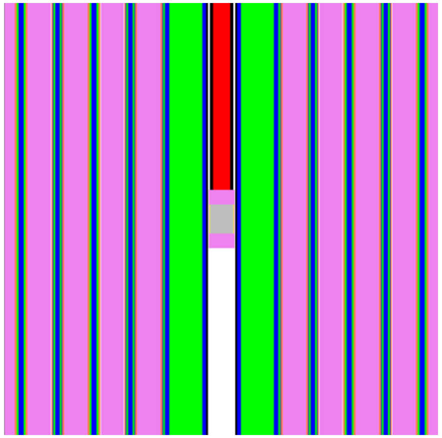
- **C/E results**

Spectral index	Uncertainty budget				C/E-1		
	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$	**T4/3D J32**	T4/3D J311	AP2/MoC J32
^{238}U / ^{235}U	1.3%	1.4%	0.7%	2.0%	**-1.3%**	-4.1%	0.3%
^{237}Np / ^{235}U	1.8%	1.7%	0.7%	2.6%	**-3.4%**	-3.5%	-4.2%
^{239}Pu / ^{235}U	1.0%	0.4%	0.8%	1.4%	**2.9%**	3.2%	0.4%
^{240}Pu / ^{239}Pu	1.5%	1.3%	0.8%	2.1%	**0.1%**	-1.5%	1.9%
^{242}Pu / ^{239}Pu	1.4%	1.3%	0.7%	2.0%	**-3.4%**	-3.6%	-3.8%

ANALYSIS OF SPECTRAL CHARACTERIZATION EXPERIMENTS
Activation dosimetry measurements

- **Thin foils of gold (thermal) and Nickel (> 2MeV)**
  ⇨ Measurement of the activation rate ratio

- **Monte-Carlo model: actual description of the foils to account for their flux perturbation**



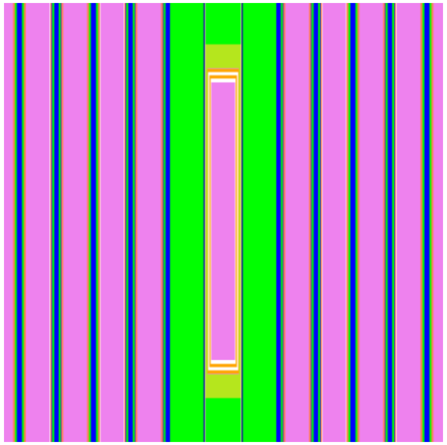
- **C/E results**

Reaction rate ratio	Uncertainty budget				C/E-1
	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$	**T4/3D J32**
$^{58}Ni(n,p)$ / $^{197}Au(n,\gamma)$	1.9%	1.5%	2.0%	3.1%	**-2.6%**

Modified conversion rate measurements

- **UO_2 samples of various enrichments (0.5% and 3%)**
  ⇨ Measurement of the capture rate on ^{238}U and total fission rate of $^{235}U+^{238}U$

- **Monte-Carlo model: actual sample description**



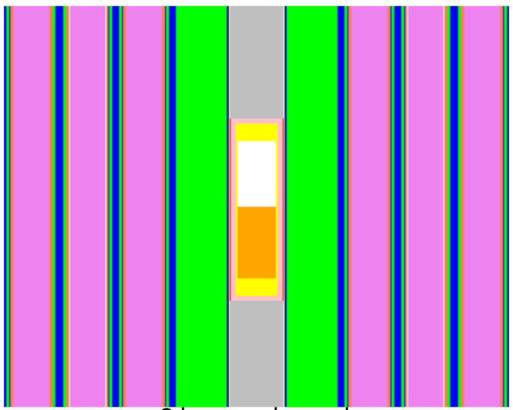
- **C/E results**

Samples	Uncertainty budget				C/E-1	
	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$	**T4/J32**	T4/J311
UO_2-0.5%	1.5%	1.2%	0.4%	2.0%	**-0.9%**	-0.2%
UO_2-3.0%	1.6%	1.4%	0.4%	2.2%	**3.3%**	3.5%

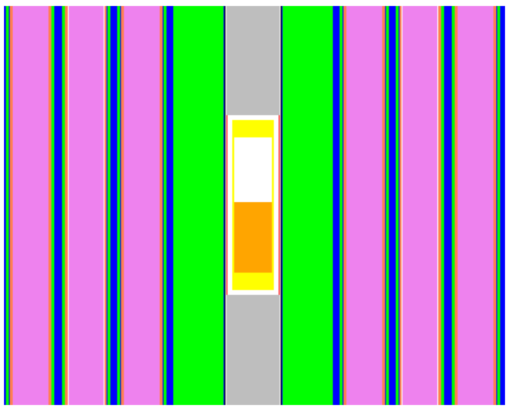
ANALYSIS OF SPECTRAL CHARACTERIZATION EXPERIMENTS
Cadmium ratio measurements

- **Thin foils of gold, indium, silver and small solution sample of CsF**
  ⇨ Measurement of the capture rate with and without a 0.8mm Cd cover

- **Monte-Carlo model: actual description of the foils to account for their flux perturbation**



Cd covered samples



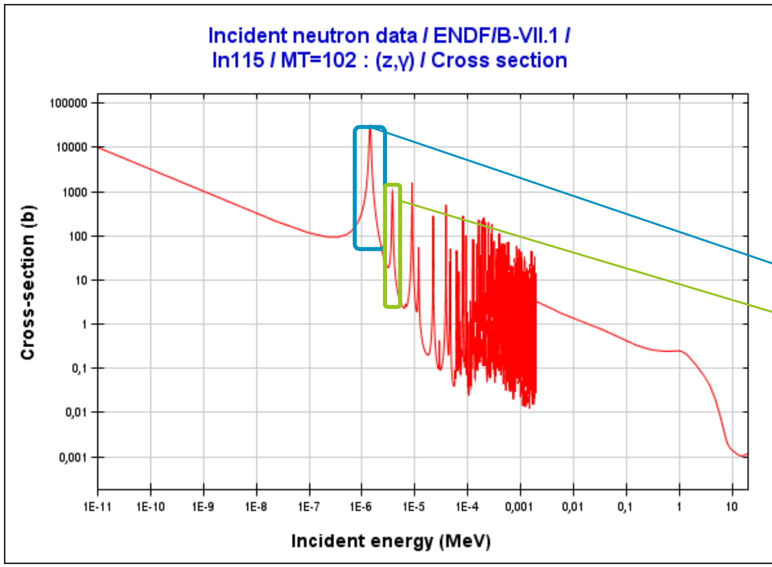
Bare samples

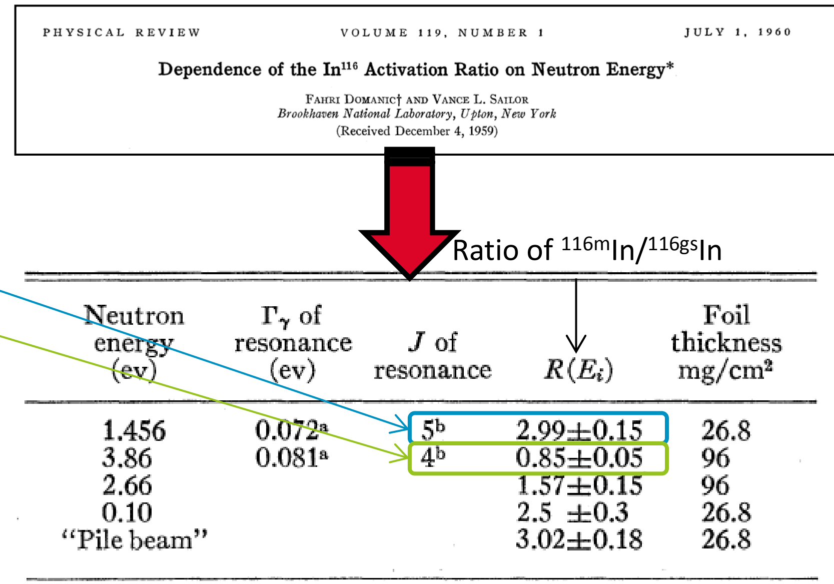
- **C/E results (with isomeric ratio from EAF-2010 at thermal energy)**

	Reaction rate ratio	Uncertainty budget				**C/E-1**	
		$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$	**T4/3D J32**	T4/3D J311
^{198}Au ⟵	$^{197}Au(n,\gamma)_{Cd}$ / $^{197}Au(n,\gamma)$	0.7%	0.5%	0.6%	1.1%	**0.8%**	2.0%
^{116m}In ⟵	$^{115}In(n,\gamma)_{Cd}$ / $^{115}In(n,\gamma)$	1.1%	0.5%	0.4%	1.3%	**6.0%**	6.2%
^{110m}Ag ⟵	$^{109}Ag(n,\gamma)_{Cd}$ / $^{109}Ag(n,\gamma)$	1.1%	0.5%	0.4%	1.3%	**-1.2%**	-2.2%
^{134m}Cs ⟵	$^{133}Cs(n,\gamma)_{Cd}$ / $^{133}Cs(n,\gamma)$	0.7%	1.0%	0.1%	1.2%	**7.0%**	6.9%

ANALYSIS OF SPECTRAL CHARACTERIZATION EXPERIMENTS
Cadmium ratio measurements

- **Possible effect due to the dependance of isomeric ratio with incident neutron energy?**





PHYSICAL REVIEW VOLUME 119, NUMBER 1 JULY 1, 1960

Dependence of the In[116] Activation Ratio on Neutron Energy*

FAHRI DOMANIC† AND VANCE L. SAILOR
Brookhaven National Laboratory, Upton, New York
(Received December 4, 1959)

Neutron energy (ev)	Γ_γ of resonance (ev)	J of resonance	$R(E_i)$	Foil thickness mg/cm²
1.456	0.072[a]	5[b]	2.99±0.15	26.8
3.86	0.081[a]	4[b]	0.85±0.05	96
2.66			1.57±0.15	96
0.10			2.5 ±0.3	26.8
"Pile beam"			3.02±0.18	26.8

- **The isomeric ratio ^{116m}In/^{116gs}In in nuclear data libraries :**
  - Missing from JEFF-3x
  - Energy independant in ENDFBVII (3.77)
  - Linearly decreasing from thermal (3.65) to 2 keV (0.07) in EAF-2010

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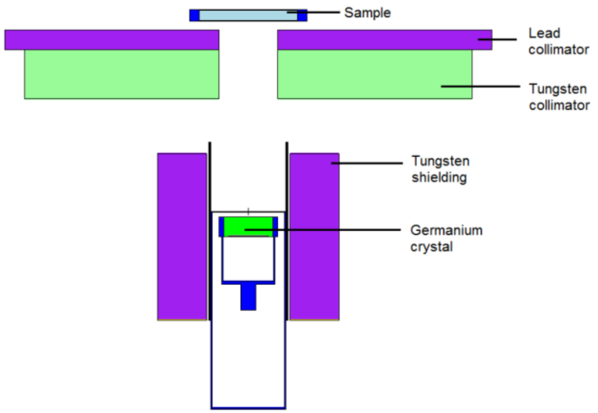
Experimental technique

- **Neutron activation experiments**
  - Irradiation time of 1 to 3h at 80W
  - Cooling time of a few hours
  - γ-spectrum measurements during acquisition time of ~minutes to ~hours

- **Calculated correction factor to account for**
  - Self-absorption inside the sample
  - Volumic distribution of the γ-source



- **Radioactive decay data**
  - Half life
  - γ-emission probability
  - isomeric rate for metastable state nuclides

- **Normalisation of relative activity measurements against gold capture rate**
  ⇨ Use of 3 pure rods and 1 Al alloy of gold

ANALYSIS OF NEUTRON ACTIVATION EXPERIMENTS
C/E comparison

Samples	Composition	Reaction of interest	C/E-1		Uncertainty budget			
			T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\boldsymbol{\sigma_{tot}}$
M-Ag-2	4% HNO_3 + 302 g/L $AgNO_3$	$^{109}Ag(n,\gamma)^{110m}Ag$	**0.4%**	-0.2%	0.5%	0.8%	0.4%	**1.5%**
M-Eu	5% HNO_3 + 8.75g/L Eu	$^{151}Eu(n,\gamma)^{152m}Eu$	**-10.4%**	-11.0%	2.0%	0.9%	0.4%	**1.4%**
		$^{151}Eu(n,\gamma)^{152gs}Eu$	**-10.1%**	-10.5%	0.5%	1.4%	0.4%	**2.1%**
		$^{153}Eu(n,\gamma)^{154}Eu$	**-6.5%**	-7.0%	1.1%	0.8%	0.4%	**1.5%**
M-In-2	4% HNO_3 + 50.1 g/L $In(NO_3)_3$	$^{113}In(n,\gamma)^{114m}In$	**-12.0%**	-12.6%	1.8%	1.3%	0.4%	**2.4%**
		$^{115}In(n,\gamma)^{116m}In$	**-2.5%**	-3.2%	1.4%	0.9%	0.4%	**2.0%**
M-Cs-2	4% HNO_3 + 167 g/L $CsNO_3$	$^{133}Cs(n,\gamma)^{134m}Cs$	**1.0%**	0.4%	3.5%	1.1%	0.4%	**3.8%**
		$^{133}Cs(n,\gamma)^{134(gs+m)}Cs$	**-1.0%**	-1.7%	0.6%	1.1%	0.4%	**1.6%**
M-Zy4	Zy+1%Sn rod (∅=9.8 mm)	$^{94}Zr(n,\gamma)^{95}Zr$	**8.8%**	17.6%	1.0%	2.1%	0.4%	**2.5%**
		$^{96}Zr(n,\gamma)^{97}Zr$	**-3.8%**	-4.4%	0.8%	3.7%	1.8%	**4.4%**
M-Sn	Sn rod (∅=10.0 mm)	$^{112}Sn(n,\gamma)^{113}Sn$	**25.8%**	25.0%	1.3%	1.9%	1.0%	**2.8%**
		$^{122}Sn(n,\gamma)^{123m}Sn$	**-2.7%**	20.1%	1.5%	1.1%	0.5%	**2.1%**
M-Zn	Zn rod (∅=9.7 mm)	$^{64}Zn(n,\gamma)^{65}Zn$	**2.3%**	-	1.3%	2.0%	0.2%	**2.6%**
		$^{68}Zn(n,\gamma)^{69m}Zn$	**7.0%**	-	0.9%	3.9%	0.1%	**4.2%**
M-Mo	Mo rod (∅=6.0 mm)	$^{98}Mo(n,\gamma)^{99}Mo$	**0.0%**	-0.9%	1.0%	2.1%	0.6%	**2.0%**
		$^{100}Mo(n,\gamma)^{101}Mo$	**-2.9%**	-2.7%	1.4%	3.5%	0.6%	**3.5%**

- **Confirmation of JEFF-3.2 capture cross section evaluations for ^{98}Mo, ^{100}Mo, ^{115}In, ^{109}Ag, ^{133}Cs, ^{96}Zr, ^{64}Zn, ^{68}Zn**
- **JEFF-3.1.1 ⇨ JEFF-3.2 impovements for ^{94}Zr, ^{122}Sn**
- **Improvement required for ^{151}Eu, ^{153}Eu, ^{113}In, ^{94}Zr, ^{112}Sn**
- **Underestimation of ^{153}Eu capture consistent with BUC program results**

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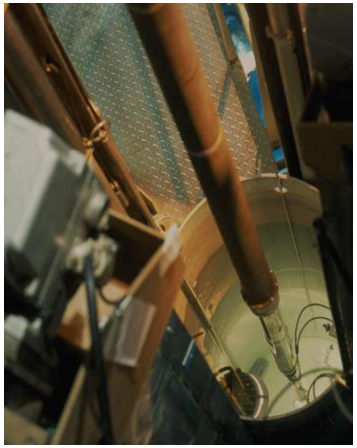
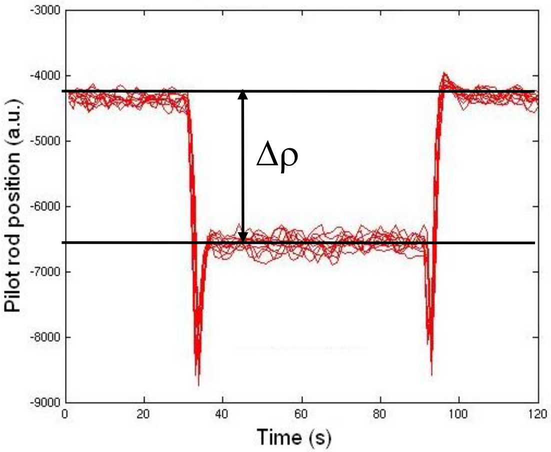
ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
Experimental technique

- **Pile-oscillation experiments**
  - Servo-driven calibrated pilot rod
  - At least 5 measures of 10 cycle oscillations per sample





- **Normalisation of relative reactivity worth measurements against reactivity worth calculations**
  - Pure rods of gold (99.995%) of various diameters : 1.0, 1.6 and 2.0mm
  - 8 calibrated solutions
    - 350 ppm to 1400 ppm ^{10}B
    - 820 to 3280 ppm of ^{6}Li

- **Improvement of measurement uncertainty (±0.01 pcm) with respect to older programmes (±0.02 pcm)**
  - Watertight guide tube
  - Higher reactor power (50W vs 30W)
  - Minimization centering errors in the core (free space reduction)
  - Optimisation between number of cycles and measurements

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – 10cm long rod-type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-Cr	Cr rod (∅=7.1 mm)	-0.5%	-1.8%	0.2%	1.0%	0.1%	1.1%
M-SS316	Stainless-Steel 316L rod (∅=6.0 mm)	-0.7%	-1.1%	0.3%	1.0%	0.2%	1.1%
M-Be	Be rod (∅=7.0 mm)	2.5%	2.2%	1.4%	1.3%	0.1%	1.9%
M-CH2	CH2 rod (∅=6.7 mm)	3.6%	4.2%	0.5%	4.9%	0.1%	4.5%
M-Cu	Cu rod (∅=6.3 mm)	0.4%	-0.6%	0.2%	1%	0.4%	1.9%
M-Fe	Fe rod (∅=7.9 mm)	0.3%	0.5%	0.3%	0.9%	0.4%	1.2%
M-Inco	Inconel-718 rod (∅=6.0 mm)	-8.0%	-8.1%	0.2%	1.0%	0.4%	1.1%
M-Mo	Mo rod (∅=6.0 mm)	0.9%	0.6%	0.3%	1.5%	0.3%	1.3%
M-Nb	Nb rod (∅=9.9 mm)	11.7%	12.0%	0.3%	2.6%	0.3%	2.4%
M-Ni	Ni rod (∅=4.9 mm)	2.6%	2.7%	0.3%	1.0%	0.6%	1.3%
M-SS304	Stainless-Steel 304L rod (∅=6.0 mm)	0.3%	0.0%	0.3%	0.9%	0.3%	1.1%
M-Ti	Ti rod (∅=6.4 mm)	-8.0%	-7.9%	0.5%	1.0%	0.4%	1.3%
M-Zn	Zn rod (∅=9.7 mm)	6.4%	17.3%	0.4%	1.4%	0.3%	1.2%
M-Al2O3-1	Alumina powder	-2.9%	-1.5%	9.8%	1.5%	0.4%	9.9%

- **Confirmation of JEFF-3.2 capture cross section evaluations for Fe, Cr, Ni, Mo, Cu + good consistency with stainless steel results**
- **Confirmation of JEFF-3.2 scattering cross section evaluations for CH2 and Be**
- **Improvement required for Zn, Ti, Nb**
- **Odd result for Inconel-718 alloy (mostly Ni)**

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – 30cm long rod-type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-Al	Al rod (∅=10.2 mm)	**27.1%**	28.7%	1.1%	1.4%	2.5%	2.9%
M-Al5754	Al-5754 rod (∅=10.0 mm)	**-5.2%**	-4.9%	0.8%	1.3%	0.4%	1.4%
M-C	C rod (∅=10.0 mm)	**-30.9%**	-30.5%	0.7%	1.5%	0.6%	1.7%
M-M5	Zy+1%Nb rod (∅=10.0 mm)	**94.7%**	95.3%	1.6%	3.3%	0.4%	3.3%
M-Mg	Mg rod (∅=10.0 mm)	**-76.7%**	-82.0%	4.1%	6.9%	1.3%	8.7%
M-Si	Si rod (∅=10.1 mm)	**34.0%**	34.2%	2.0%	1.3%	0.3%	2.3%
M-Sn	Sn rod (∅=10.0 mm)	**19.7%**	20.0%	0.2%	2.4%	0.4%	2.1%
M-Zy4	Zy+1%Sn rod (∅=9.8 mm)	**112.6%**	113.1%	1.8%	3.1%	0.3%	3.2%

- **Pure Al and Al5754 alloy (3% Mg) should be consistent**

Reactivity worth breakdown for Al

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{27}Al	100	137.4	-19.7	-17.7

Reactivity worth breakdown for Al5754

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{27}Al	87.3	121	-15.6	-18.1
	^{24}Mg	-0.4	0.8	-0.8	-0.4
	^{25}Mg	0.2	0.4	<0.1	<0.1
Matrix and/or impurities	^{28}Si	0.1	0.2	<0.1	<0.1
	^{54}Fe	0.1	0.1	<0.1	<0.1
	^{56}Fe	2.1	2.1	<0.1	<0.1
	^{63}Cu	0.2	0.3	<0.1	<0.1
	^{55}Mn	9.2	9.3	-0.1	<0.1
	^{53}Cr	0.1	0.1	<0.1	<0.1
	^{48}Ti	0.2	0.2	<0.1	<0.1
	^{199}Hg	0.5	0.5	<0.1	<0.1

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – 30cm long rod-type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	±σ_{meas}	±σ_{tech}	±σ_{MC}	±σ_{tot}
M-Al	Al rod (∅=10.2 mm)	**27.1%**	28.7%	1.1%	1.4%	2.5%	2.9%
M-Al5754	Al-5754 rod (∅=10.0 mm)	**-5.2%**	-4.9%	0.8%	1.3%	0.4%	1.4%
M-C	C rod (∅=10.0 mm)	**-30.9%**	-30.5%	0.7%	1.5%	0.6%	1.7%
M-M5	Zy+1%Nb rod (∅=10.0 mm)	**94.7%**	95.3%	1.6%	3.3%	0.4%	3.3%
M-Mg	Mg rod (∅=10.0 mm)	**-76.7%**	-82.0%	4.1%	6.9%	1.3%	8.7%
M-Si	Si rod (∅=10.1 mm)	**34.0%**	34.2%	2.0%	1.3%	0.3%	2.3%
M-Sn	Sn rod (∅=10.0 mm)	**19.7%**	20.0%	0.2%	2.4%	0.4%	2.1%
M-Zy4	Zy+1%Sn rod (∅=9.8 mm)	**112.6%**	113.1%	1.8%	3.1%	0.3%	3.2%

- **Zy4 and M5 rods are more or less consistent**
  ⇨ ^{91}Zr capture??

Reactivity worth breakdown for M5^{TM}

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{90}Zr	-6.7	11.8	-4.5	-14
	^{91}Zr	73.1	79.5	-1.5	-4.8
	^{92}Zr	13.2	24	-1	-9.7
	^{94}Zr	-5.3	7.3	-1.8	-10.6
	^{96}Zr	6.6	8.1	-0.3	-1.1
Matrix and/or impurities	^{93}Nb	11.9	12.7	<0.1	-0.7
	^{16}O	-0.2	<0.1	-0.2	<0.1
	^{10}B	0.5	0.5	<0.1	<0.1
	^{113}Cd	0.3	0.3	<0.1	<0.1
	^{56}Fe	0.6	0.6	<0.1	<0.1
	^{177}Hf	3.9	3.9	<0.1	<0.1
	^{178}Hf	1.2	1.2	<0.1	<0.1
	^{179}Hf	0.2	0.2	<0.1	<0.1
	^{14}N	-0.5	-0.5	<0.1	<0.1
	^{181}Ta	0.8	0.8	<0.1	<0.1

Reactivity worth breakdown for Zy4

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{90}Zr	-6.7	11.3	-4.4	-13.5
	^{91}Zr	69.7	76.2	-1.8	-4.6
	^{92}Zr	11.7	23.1	-2	-9.3
	^{94}Zr	-4.2	7.1	-0.8	-10.2
	^{96}Zr	6.2	7.6	-0.2	-1.1
	^{112}Sn	0.3	0.3	<0.1	<0.1
	^{115}Sn	0.4	0.4	<0.1	<0.1
	^{116}Sn	1.6	1.6	<0.1	<0.1
	^{117}Sn	1.7	1.8	<0.1	<0.1
	^{118}Sn	1.2	1.3	<0.1	<0.1
	^{119}Sn	1	1.1	<0.1	<0.1
	^{120}Sn	0.4	0.6	<0.1	-0.1
	^{124}Sn	0.4	0.4	<0.1	<0.1
Matrix and/or impurities	^{50}Cr	1.1	1.1	<0.1	<0.1
	^{52}Cr	1.1	1.3	<0.1	<0.1
	^{53}Cr	2.9	2.9	<0.1	<0.1
	^{54}Fe	0.3	0.3	<0.1	<0.1
	^{56}Fe	5	5.1	<0.1	-0.1
	^{57}Fe	0.1	0.1	<0.1	<0.1
	^{16}O	-0.2	<0.1	-0.2	<0.1
	^{10}B	0.5	0.5	<0.1	<0.1
	^{113}Cd	0.2	0.2	<0.1	<0.1
	^{1}H	-0.2	<0.1	-0.2	
	^{177}Hf	3.2	3.2	<0.1	<0.1
	^{178}Hf	1.1	1.1	<0.1	<0.1
	^{179}Hf	0.2	0.2	<0.1	<0.1
	^{14}N	-0.4	-0.4	<0.1	<0.1
	^{181}Ta	0.8	0.8	<0.1	<0.1

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – 30cm long rod-type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-Al	Al rod (∅=10.2 mm)	**27.1%**	28.7%	1.1%	1.4%	2.5%	2.9%
M-Al5754	Al-5754 rod (∅=10.0 mm)	**-5.2%**	-4.9%	0.8%	1.3%	0.4%	1.4%
M-C	C rod (∅=10.0 mm)	**-30.9%**	-30.5%	0.7%	1.5%	0.6%	1.7%
M-M5	Zy+1%Nb rod (∅=10.0 mm)	**94.7%**	95.3%	1.6%	3.3%	0.4%	3.3%
M-Mg	Mg rod (∅=10.0 mm)	**-76.7%**	-82.0%	4.1%	6.9%	1.3%	8.7%
M-Si	Si rod (∅=10.1 mm)	**34.0%**	34.2%	2.0%	1.3%	0.3%	2.3%
M-Sn	Sn rod (∅=10.0 mm)	**19.7%**	20.0%	0.2%	2.4%	0.4%	2.1%
M-Zy4	Zy+1%Sn rod (∅=9.8 mm)	**112.6%**	113.1%	1.8%	3.1%	0.3%	3.2%

- **Unexpected result for graphite: C/E-1 = -31% !!!**
  - ⇨ ^{nat}C scattering is a standard cross section
- **Several possible causes of errors were investigated**
  - Bias in the IFP calculation method
    - ⇨ Consistency with APOLLO2.8/MoC (<2%)
  - Missing impurities from the material certificate?
    - ⇨ Capturing isotopes would increase the C/E
  - Photonuclear reaction
    - ⇨ $^{13}C(\gamma,n)$ effect : <0.01%

Neutron Cross-section Standards

Reaction	Neutron Energy Range			
	1987	2002-2005/06		
			ENDF-6 Format	Free text Format
H(n,n)	1 keV to 20 MeV	1 keV to 20 MeV	std-001_H_001.endf	not available
$^{3}He(n,p)$	0.0253 eV to 50 keV	0.0253 eV to 50 keV (1987 adopted)	std-002_He_003.endf	not available
$^{6}Li(n,t)$	0.0253 eV to 1 MeV	0.0253 eV to 1 MeV	std-003_Li_006.endf	standards-6Li_xs-data.txt
$^{10}B(n,\alpha)$	0.0253 eV to 250 keV	0.0253 eV to 1 MeV	std-005_B_010.endf	standards-10B_na-xs-data.txt
$^{10}B(n,\alpha_1\gamma)$	0.0253 eV to 250 keV	0.0253 eV to 1 MeV	std-005_B_010.endf	standards-10B_na1-xs-data.txt
C(n,n)	up to 1.8 MeV	up to 1.8 MeV (1987 adopted)	std-006_C_000.endf	not available
Au(n,γ)	0.0253 eV, and 0.2 to 2.5 MeV	0.0253 eV, and 0.2 to 2.5 MeV	std-079_Au_197.endf	standards-197Au_xs-data.txt
$^{235}U(n,f)$	0.0253 eV, and 0.15 to 20 MeV	0.0253 eV, and 0.15 to 200 MeV	std-092_U_235.endf	standards-235U_xs-data.txt
$^{238}U(n,f)$	threshold to 20 MeV	2 to 200 MeV	std-092_U_238.endf	standards-238U_xs-data.txt

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – 30cm long rod-type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-Al	Al rod (∅=10.2 mm)	**27.1%**	28.7%	1.1%	1.4%	2.5%	2.9%
M-Al5754	Al-5754 rod (∅=10.0 mm)	**-5.2%**	-4.9%	0.8%	1.3%	0.4%	1.4%
M-C	C rod (∅=10.0 mm)	**-30.9%**	-30.5%	0.7%	1.5%	0.6%	1.7%
M-M5	Zy+1%Nb rod (∅=10.0 mm)	**94.7%**	95.3%	1.6%	3.3%	0.4%	3.3%
M-Mg	Mg rod (∅=10.0 mm)	**-76.7%**	-82.0%	4.1%	6.9%	1.3%	8.7%
M-Si	Si rod (∅=10.1 mm)	**34.0%**	34.2%	2.0%	1.3%	0.3%	2.3%
M-Sn	Sn rod (∅=10.0 mm)	**19.7%**	20.0%	0.2%	2.4%	0.4%	2.1%
M-Zy4	Zy+1%Sn rod (∅=9.8 mm)	**112.6%**	113.1%	1.8%	3.1%	0.3%	3.2%

- **Mg, Sn and Si: non usual materials in reactors (or in small amounts)**
  ⇨ Realistic ? Unrealistic?

Reactivity worth breakdown for Mg

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{24}Mg	194.5	-413.3	392.6	215.2
	^{25}Mg	-114.6	-185.3	38.1	31.5
	^{26}Mg	28.1	-33.8	38.4	23.4
Matrix and/or impurities	^{27}Al	-0.1	-0.2	<0.1	<0.1
	^{63}Cu	-0.6	-0.6	<0.1	<0.1
	^{65}Cu	-0.1	-0.1	<0.1	<0.1
	^{56}Fe	-0.4	-0.4	<0.1	<0.1
	^{55}Mn	-5.6	-5.7	<0.1	<0.1
	^{58}Ni	-0.6	-0.6	<0.1	<0.1
	^{60}Ni	-0.1	-0.1	<0.1	<0.1

Reactivity worth breakdown for Si

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{28}Si	93.7	140.1	-30.6	-15.7
	^{29}Si	2.4	5.4	-1.3	-1.7
	^{30}Si	3.9	5.5	-1	-0.7

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – Liquid type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-H2O-1	H_2O (5.35g)	2.1%	2.6%	0.3%	4.9%	0.1%	4.5%
M-H2O-3	H_2O (4.50g)	5.6%	6.1%	0.7%	4.9%	0.1%	4.6%
M-D2O	D_2O	-32.3%	-34.0%	0.6%	1.6%	0.1%	1.6%
M-Cd	5% HNO_3 + 6.74g/L Cd	1.5%	3.9%	0.2%	1.2%	0.5%	1.2%
M-Cl	H_2O + 298g/L NaCl	1.1%(*)	1.2%	0.2%	1.2%	0.3%	1.1%
M-Eu	5% HNO_3 + 8.75g/L Eu	-3.2%	-3.1%	0.2%	1.2%	0.3%	1.1%
M-Gd	5% HNO_3 + 1.25g/L Gd	-2.4%	-2.5%	0.2%	1.0%	0.3%	1.2%
M-Ag-2	4% HNO_3 + 302 g/L $AgNO_3$	3.2%	3.0%	0.4%	1.9%	0.5%	1.7%
M-Co-2	4% HNO_3 + 197 g/L $Co(NO_3)_2$	9.5%	-	1.6%	1.7%	0.4%	2.2%
M-Cs-2	4% HNO_3 + 167 g/L $CsNO_3$	2.6%	2.5%	1.2%	2.4%	0.5%	2.4%
M-Dy-2	4% HNO_3 + 52.6 g/L $DyNO_3$	-1.0%	-0.7%	0.5%	1.2%	0.3%	1.2%
M-Er-2	4% HNO_3 + 49.8 g/L $ErNO_3$	5.8%	5.6%	1.5%	2.0%	0.3%	2.3%
M-In-2	4% HNO_3 + 50.1 g/L $In(NO_3)_3$	6.2%	-	0.9%	2.2%	0.5%	2.1%
M-Mn-2	4% HNO_3 + 299 g/L $Mn(NO_3)_2$	4.8%	3.8%	2.3%	1.9%	0.3%	2.8%

- **Confirmation of JEFF-3.2 reactivity effect of light water**
- **Very odd result for D_2O: same value than ^{nat}C of C/E-1=-32% (both pure scattering materials)**
  - Bias in the IFP calculation method
    - ⇨ Consistency with APOLLO2.8/MoC (0.5%)
  - Missing impurities from the material certificate?
    - ⇨ The C/E would be even worse with the addition of capturing isotopes
  - Photonuclear reaction ⇨ D(γ,n) effet : ~0.1%
  - S(α,β) of D_D2O were replaced by the one of D (free gas): no more than 2% difference

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – Liquid type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-H2O-1	H_2O (5.35g)	2.1%	2.6%	0.3%	4.9%	0.1%	4.5%
M-H2O-3	H_2O (4.50g)	5.6%	6.1%	0.7%	4.9%	0.1%	4.6%
M-D2O	D_2O	-32.3%	-34.0%	0.6%	1.6%	0.1%	1.6%
M-Cd	5% HNO_3 + 6.74g/L Cd	1.5%	3.9%	0.2%	1.2%	0.5%	1.2%
M-Cl	H_2O + 298g/L NaCl	1.1%(*)	1.2%	0.2%	1.2%	0.3%	1.1%
M-Eu	5% HNO_3 + 8.75g/L Eu	-3.2%	-3.1%	0.2%	1.2%	0.3%	1.1%
M-Gd	5% HNO_3 + 1.25g/L Gd	-2.4%	-2.5%	0.2%	1.0%	0.3%	1.2%
M-Ag-2	4% HNO_3 + 302 g/L $AgNO_3$	3.2%	3.0%	0.4%	1.9%	0.5%	1.7%
M-Co-2	4% HNO_3 + 197 g/L $Co(NO_3)_2$	9.5%	-	1.6%	1.7%	0.4%	2.2%
M-Cs-2	4% HNO_3 + 167 g/L $CsNO_3$	2.6%	2.5%	1.2%	2.4%	0.5%	2.4%
M-Dy-2	4% HNO_3 + 52.6 g/L $DyNO_3$	-1.0%	-0.7%	0.5%	1.2%	0.3%	1.2%
M-Er-2	4% HNO_3 + 49.8 g/L $ErNO_3$	5.8%	5.6%	1.5%	2.0%	0.3%	2.3%
M-In-2	4% HNO_3 + 50.1 g/L $In(NO_3)_3$	6.2%	-	0.9%	2.2%	0.5%	2.1%
M-Mn-2	4% HNO_3 + 299 g/L $Mn(NO_3)_2$	4.8%	3.8%	2.3%	1.9%	0.3%	2.8%

- **Confirmation of JEFF-3.2 reactivity worth for Cd, Cl, Gd, Ag, Cs, Dy, Mn**
  - ⇨Cd clearly improved from JEFF-3.1.1 to JEFF-3.2
  - ⇨Consistent trend with neutron activation experiments for Cs and Ag
  - ⇨Mn result not consistent with MAESTRO Phase I experiments using a Mn rods

Reactivity worth breakdown for Cs

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{133}Cs	86.6	86.7	<0.1	-0.2
Matrix and/or impurities	^{1}H	9.9	-2.8	12.6	
	^{14}N	3.6	3.8	-0.2	<0.1

Reactivity worth breakdown for Mn

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{55}Mn	56.4	56.1	0.6	-0.3
Matrix and/or impurities	^{1}H	26.9	-7.3	34.2	
	^{16}O	-0.9	0.1	-1	<0.1
	^{14}N	17.6	18.5	-0.9	<0.1

Reactivity worth breakdown for Ag

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{107}Ag	19.9	20	<0.1	<0.1
	^{109}Ag	74.3	74.3	<0.1	<0.1
Matrix and/or impurities	^{1}H	4	-1.1	5.1	
	^{14}N	1.9	2	<0.1	<0.1

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – Liquid type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-H2O-1	H_2O (5.35g)	2.1%	2.6%	0.3%	4.9%	0.1%	4.5%
M-H2O-3	H_2O (4.50g)	5.6%	6.1%	0.7%	4.9%	0.1%	4.6%
M-D2O	D_2O	-32.3%	-34.0%	0.6%	1.6%	0.1%	1.6%
M-Cd	5% HNO_3 + 6.74g/L Cd	1.5%	3.9%	0.2%	1.2%	0.5%	1.2%
M-Cl	H_2O + 298g/L NaCl	1.1%(*)	1.2%	0.2%	1.2%	0.3%	1.1%
M-Eu	5% HNO_3 + 8.75g/L Eu	-3.2%	-3.1%	0.2%	1.2%	0.3%	1.1%
M-Gd	5% HNO_3 + 1.25g/L Gd	-2.4%	-2.5%	0.2%	1.0%	0.3%	1.2%
M-Ag-2	4% HNO_3 + 302 g/L $AgNO_3$	3.2%	3.0%	0.4%	1.9%	0.5%	1.7%
M-Co-2	4% HNO_3 + 197 g/L $Co(NO_3)_2$	9.5%	-	1.6%	1.7%	0.4%	2.2%
M-Cs-2	4% HNO_3 + 167 g/L $CsNO_3$	2.6%	2.5%	1.2%	2.4%	0.5%	2.4%
M-Dy-2	4% HNO_3 + 52.6 g/L $DyNO_3$	-1.0%	-0.7%	0.5%	1.2%	0.3%	1.2%
M-Er-2	4% HNO_3 + 49.8 g/L $ErNO_3$	5.8%	5.6%	1.5%	2.0%	0.3%	2.3%
M-In-2	4% HNO_3 + 50.1 g/L $In(NO_3)_3$	6.2%	-	0.9%	2.2%	0.5%	2.1%
M-Mn-2	4% HNO_3 + 299 g/L $Mn(NO_3)_2$	4.8%	3.8%	2.3%	1.9%	0.3%	2.8%

- **Improvements and/or new measurements required for Er and In**

  ⇨Indium result not consistent with neutron activation experiments (C/E-1=-2.5±2.0%): impact of isomeric yield?

Reactivity worth breakdown for Er

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{164}Er	0.2	0.2	<0.1	<0.1
	^{166}Er	2.5	2.6	<0.1	<0.1
	^{167}Er	88.7	88.7	<0.1	<0.1
	^{168}Er	0.6	0.6	<0.1	<0.1
	^{170}Er	0.5	0.5	<0.1	<0.1
Matrix and/or impurities	^{1}H	4.4	-1.2	5.6	
	^{16}O	-0.2	<0.1	-0.2	<0.1
	^{14}N	3.2	3.4	-0.2	<0.1

Reactivity worth breakdown for In

	Isotopes	% total	% capture	% elastic	% inelastic
Dopant	^{113}In	0.5	0.5	<0.1	<0.1
	^{115}In	94.4	94.4	<0.1	<0.1
Matrix and/or impurities	^{1}H	3.2	-0.9	4.1	
	^{14}N	2	2.1	-0.1	<0.1

ANALYSIS OF PILE-OSCILLATION EXPERIMENTS
C/E comparison – Powder type samples

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
M-Ag7	Al_2O_3 + 1.34g ^{107}Ag	-3.0%	-2.9%%	0.2%	1.1%	0.3%	1.2%
M-Eu3	Al_2O_3 + 0.425g $^{153}Eu_2O_3$	-3.5%	-3.7%	0.8%	1.2%	0.3%	1.5%
M-Rh	Al_2O_3 + 0.198g ^{103}Rh	1.4%	1.6%	1.2%	0.8%	0.3%	1.4%
M-Hf	Al_2O_3 + 0.777g $^{nat}HfO_2$	1.7%	1.9%	0.4%	1.1%	0.3%	1.2%

- **Slight underestimation of ^{107}Ag but acceptable regarding the low impact in fuel cycle studies**
- **Confirmation of ^{153}Eu underestimation, consistent with neutron activation experiments (C/E-1=-6.5±1.5%)**
- **Confirmation of ^{103}Rh capture with previous experiments on rod-type samples in the MAESTRO Phase-I experiment (C/E-1 = 0.2 ± 1.7%)**
- **Confirmation of ^{nat}Hf capture (mostly ^{177}Hf and ^{178}Hf capture)**

OUTLINE

- Context
- Description of the Experiments
- Calculations methods and models
- Analysis of spectral characteristization experiments
- Analysis of neutron activation experiments
- Analysis of pile-oscillation experiments
- **Conclusions and further works**

CONCLUSIONS

- **Spectral characterization experiments**

  ⇨Very good C/E agreements for all the different measurements

  ⇨Possible identification of energy dependant behaviour in the isomeric ratio of ^{115}In and ^{133}Cs capture that could be of interest to improve nuclear structure data

- **Validation below 2σ uncertainty for**

  ⇨Scattering materials: H2O, CH2, Be

  ⇨Capturing materials: Rh, Hf, Cd, Cl, Gd, Ag, Cs, Dy, Mn, Fe, Cr, Ni, Mo, Cu + consistency with stainless steel 304L and 316L

- **Evaluation improvements and/or additional measurements required for**

  ⇨Scattering materials: D2O, C, Al, Mg

  ⇨Capturing materials: Nb, Ti, Zn, Zr, Si, Sn, Er, In, ^{107}Ag, ^{151}Eu, ^{153}Eu

- **Some clear inconsistencies probably due to sample characterization issues**

  ⇨Inconel-718 not consistent with Ni

  ⇨Al5754 not consistent with Al

- **Clear improvements between JEFF-3.1.1 and JEFF-3.2 for**

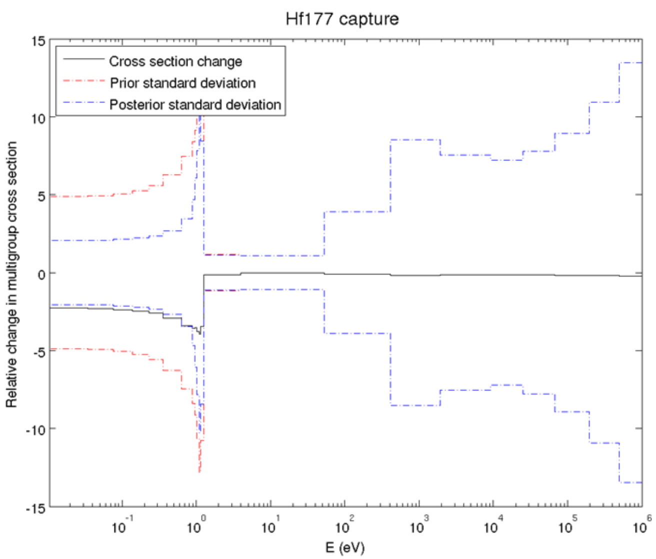
  ⇨Capturing materials: ^{122}Sn, Zn (no isotopic evaluations in JEFF-3.1.1.), ^{113}Cd

FURTHER WORKS
Application of integral data assimilation

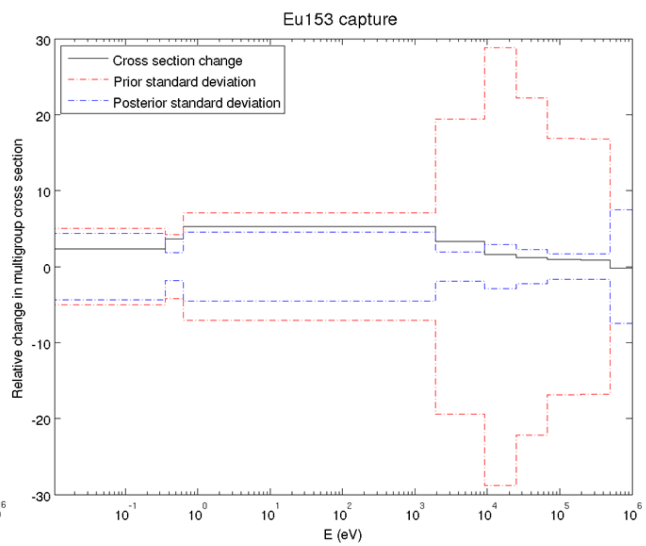
- **Sensitivity coefficients provided by the EGPT method in APOLLO2**

Isotope	*Sensitivity coefficients*				
	Capture	Scattering	Fission	Nu	Spectrum
^{103}Rh	**0.918**	**-7.45E-04**			
^{1}H	3.89E-02	-0.329			
^{235}U	1.88E-04	4.08E-06	0.136	2.22E-03	1.88E-03
^{238}U	4.43E-03	-4.27E-05	-4.73E-04	-1.63E-04	-1.22E-04

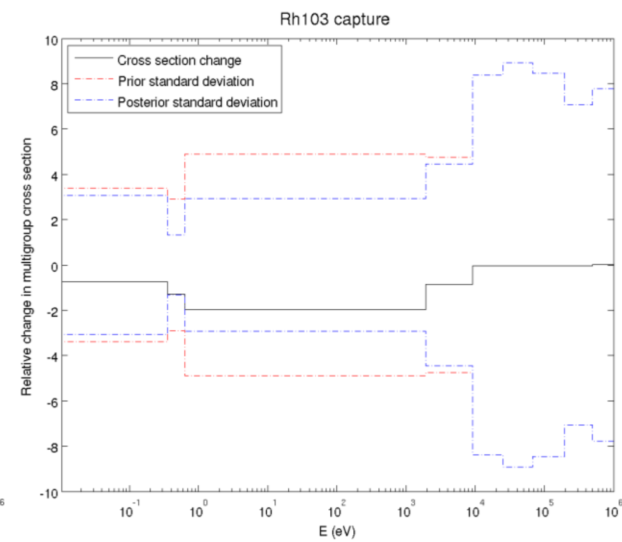
- **Use of CONRAD to derive trend and associated covariances on nuclear data**



^{177}Hf thermal capture :
uncertainty reduction 5 ⇨ 2.5%



^{153}Eu capture :
resonance integral increase of ~5%



^{103}Rh resonance integral:
uncertainty reduction 5⇨3%

THANK YOU
FOR YOUR ATTENTION

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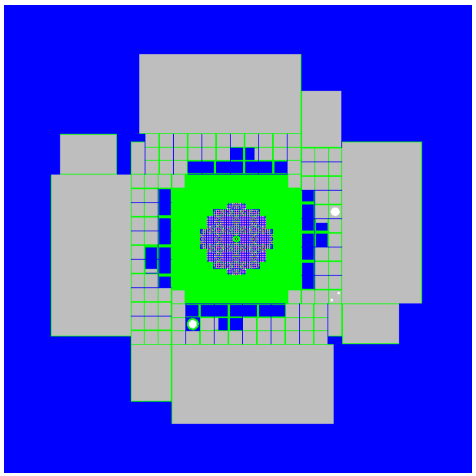
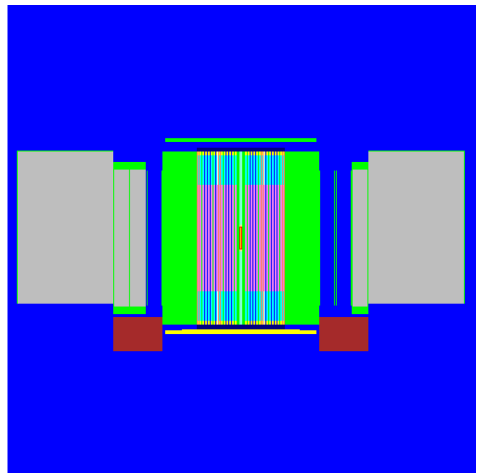
CALCULATION METHODS AND MODELS
TRIPOLI models of the MINERVE core

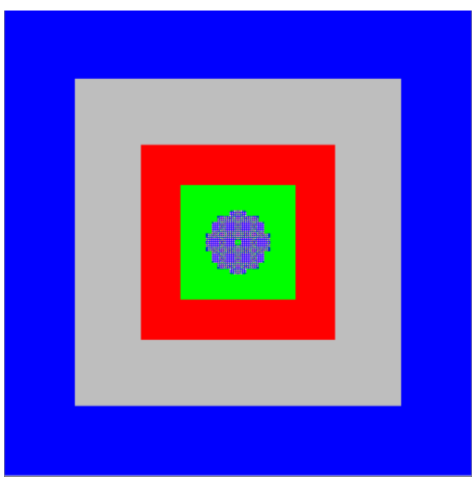
- **Reference 3D detailed model**

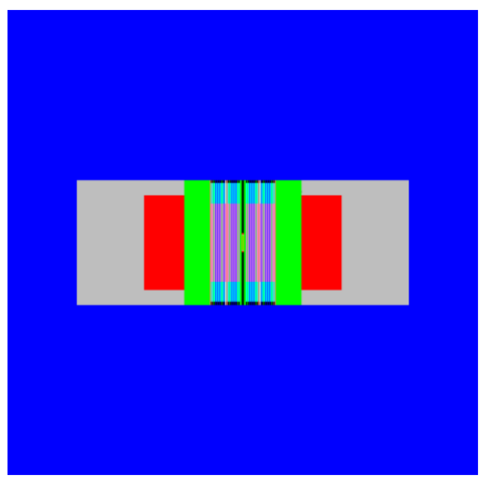




~3000 lines, 400 volumes, 20 materials
+ « Exact model »
- Time consuming

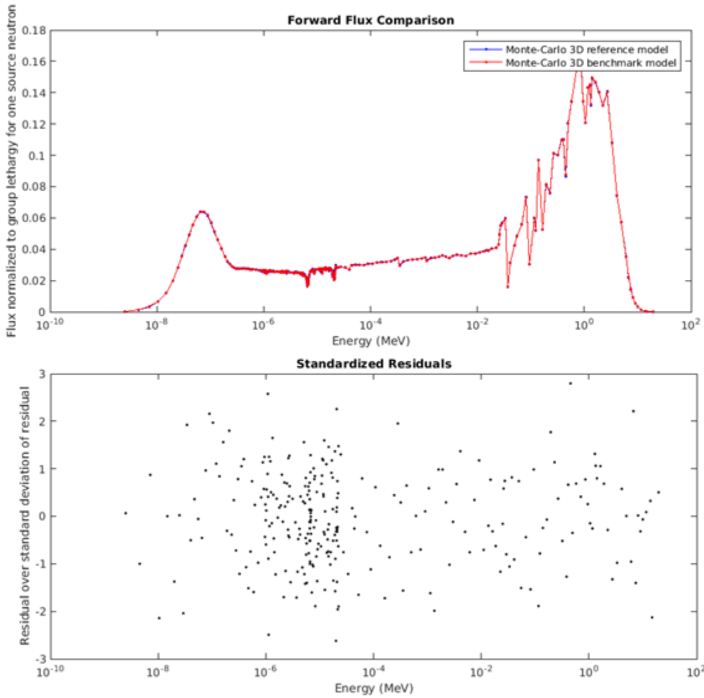
- **« Benchmark » full core model**

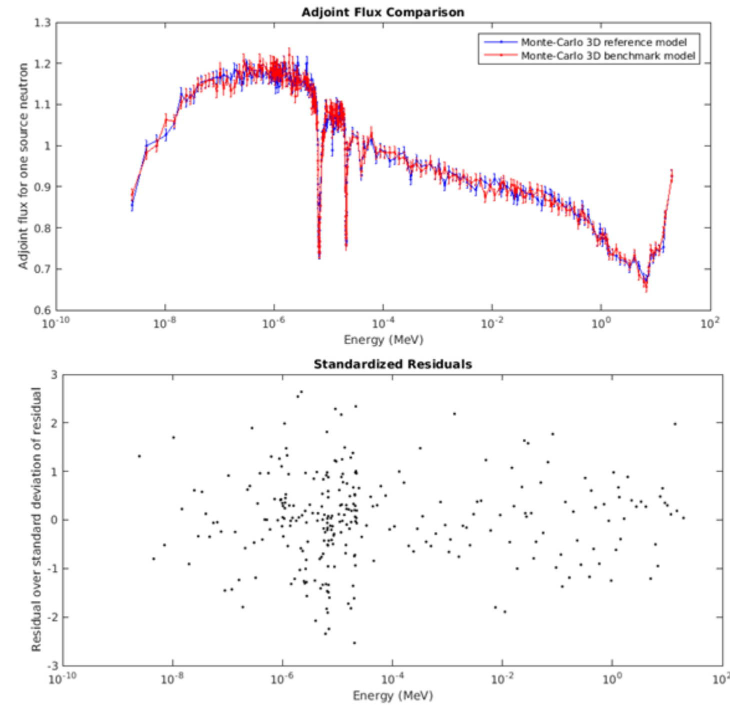




~500 lines, 25 volumes, 12 materials
+ FoM improved by ~3
- Possible spectral error due to modeling simplifications

Forward and adjoint flux





Reaction rates

Isotope	Model simplification bias on capture rates	
	ε	±σ
^{55}Mn	**-0.09%**	0.15%
^{56}Fe	**-0.05%**	0.16%
^{58}Ni	**-0.03%**	0.14%
^{59}Co	**0.00%**	0.25%
^{63}Cu	**0.28%**	0.33%
^{93}Nb	**0.23%**	0.49%

Isotope	Model simplification bias on cadmium ratio	
	ε	±σ
^{197}Au	**1.2%**	1.7%
^{115}In	**1.0%**	1.3%
^{109}Ag	**-1.9%**	1.6%
^{133}Cs	**0.5%**	1.6%

Calibration of neutron activation experiments

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
C-AlAu	Rod of Al+0.1% ^{197}Au	**-1.1%**	-1.1%	0.5%	1.0%	1.4%	1.6%
C-Au-10	Rod of ^{197}Au (∅=1.0 mm)	**-0.9%**	-0.8%	0.5%	0.7%	0.4%	0.9%
C-Au-16	Rod of ^{197}Au (∅=1.6 mm)	**0.3%**	0.3%	0.5%	0.7%	0.4%	0.9%
C-Au-20	Rod of ^{197}Au (∅=2.0 mm)	**0.6%**	0.6%	0.5%	0.7%	0.4%	0.9%

- **Good consistency between the different samples**
  - ⇨ Self-shielding + self-absorption corrections are correctly accounted for pure rods

ADDITIONAL SLIDES
Calibration of pile oscillation experiments

Samples	Composition	C/E-1		Uncertainty budget			
		T4/J32	T4/J311	$\pm\sigma_{meas}$	$\pm\sigma_{tech}$	$\pm\sigma_{MC}$	$\pm\sigma_{tot}$
C-B10-1	H_2O + 0.35g/L ^{10}B	**-1.5%**	-1.5%	0.3%	0.8%	0.3%	0.9%
C-B10-2	H_2O + 0.69g/L ^{10}B	**-2.1%**	-2.1%	0.2%	0.8%	0.3%	0.9%
C-B10-3	H_2O + 1.04g/L ^{10}B	**0.3%**	0.3%	0.1%	0.8%	0.3%	0.9%
C-B10-4	H_2O + 1.39g/L ^{10}B	**-0.7%**	-0.7%	0.1%	0.8%	0.3%	0.9%
C-Li6-1	5% HNO_3 + 0.82g/L ^{6}Li	**-0.1%**	0.2%	0.3%	0.9%	0.2%	1.0%
C-Li6-2	5% HNO_3 + 1.64 g/L ^{6}Li	**0.8%**	1.1%	0.2%	0.9%	0.3%	1.0%
C-Li6-3	5% HNO_3 + 2.46g/L ^{6}Li	**0.5%**	0.8%	0.1%	0.9%	0.3%	1.0%
C-Li6-4	5% HNO_3 + 3.28g/L ^{6}Li	**1.0%**	1.3%	0.1%	0.9%	0.3%	1.0%
C-Au-10	Rod of ^{197}Au (∅=1.0 mm)	**-0.2%**	0.1%	0.4%	1.0%	0.4%	1.2%
C-Au-16	Rod of ^{197}Au (∅=1.6 mm)	**0.8%**	1.1%	0.2%	1.0%	0.3%	1.1%

- **Good consistency between the different samples**
  ⇨ A 1% uncertainty appears to be acceptable (reduced by a factor of 2 compared with previous programmes)