

DE LA RECHERCHE À L'INDUSTRIE



***$^{92}, ^{94}\text{Zr}$ irradiation
for 1 keV – 1 MeV neutron flux
determination by means of (n, γ)
reaction***

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*ND2016, 11-16 / 09 2016 Bruges,
Belgium*



- **Dosimetry goal** : to provide a reaction rate / neutron flux in a given place inside a reactor

- **Applications** :
 - Flux calculation on the vessel to anticipate the embrittlement process (*atoms displacements creation, modification of mechanical properties*) ⇒ PWR
 - **Nuclear data re-evaluation (uncertainty reduction on the cross sections)** ⇒ Critical mock-ups
 - Study about changes in materials properties due to the incidence of high neutronic flux ⇒ Materials Testing Reactors

- **Activation process & analysis**

- **Goal of this work** : to detect neutrons into 1 keV – 1 MeV energy range

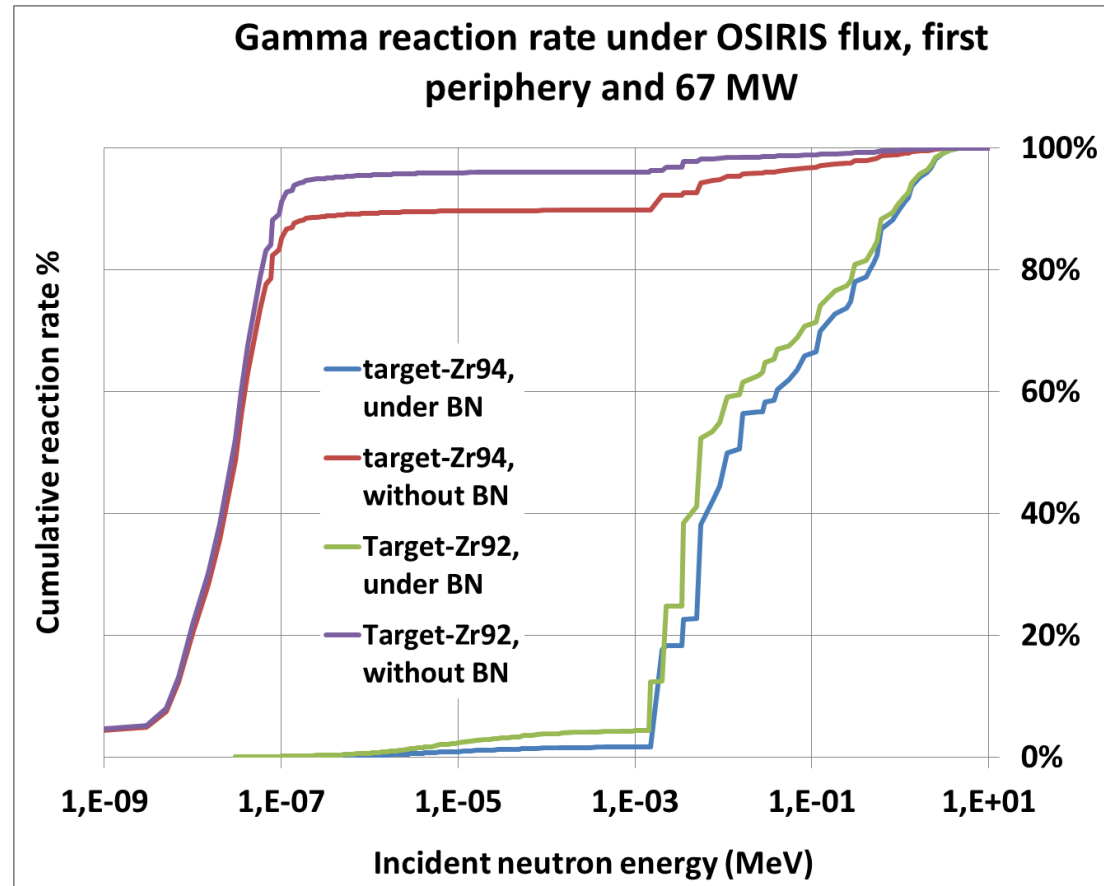
$^{92}\text{Zr} (n, \gamma) ^{93}\text{Zr}$ stable isotope

$^{94}\text{Zr} (n, \gamma) ^{95}\text{Zr}$ radioactive isotope

Response in
1 keV - 1 MeV energy
region with a 3 mm boron
nitride filter

$T_{1/2} (^{95}\text{Zr}) \approx 2$ months

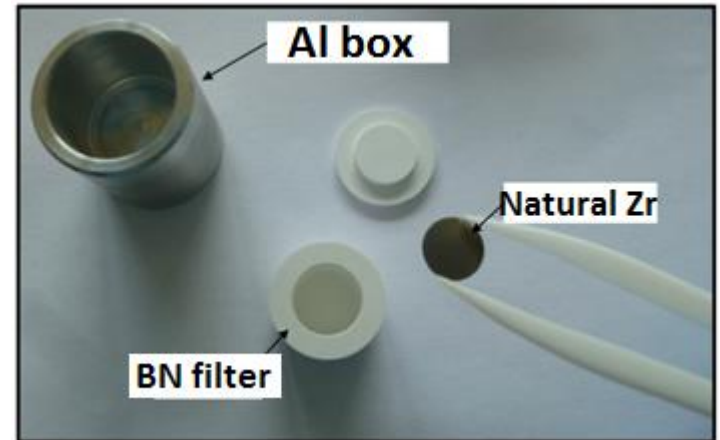
Post-irradiation analysis:
 **γ spectrometry &
accelerator mass
spectrometry**



EXPERIMENTAL RESULTS

 γ Spectrometry [^{94}Zr (n, γ) ^{95}Zr]

Irradiation duration	Average activity ^{95}Zr (Bq/sample)	Measurement error (%) k=2
1 h $\frac{1}{2}$	$4,5 \cdot 10^4$	2,8
30 h	$8,8 \cdot 10^5$	2,7
4 d	$3,1 \cdot 10^6$	2,7



Accelerator Mass Spectrometry

[^{92}Zr (n, γ) ^{93}Zr]

Irradiation duration	Isotopes ratio [^{93}Zr] / [^{92}Zr]	Measurement error (%) k=1
1 h $\frac{1}{2}$	$1,2 \cdot 10^{-8}$	20,8
30 h	$2,6 \cdot 10^{-7}$	14,6



CALCULATION VS EXPERIENCE: NUCLEAR DATA

Calculations are performed with CEA neutron transport code: TRIPOLI, based on MC method. **Nuclear data from JEFF3.1.1.**

Irradiation duration	Average C/E ratio for ^{95}Zr activity	$\pm \Delta(\text{C/E})_{\text{abs}}$ k=2
1 h ½	1,16	0,23
30 h	1,15	0,23
4 d	1,12	0,23

Final uncertainty value for C/E $\approx \pm 20\%$

Main contribution: [$^{94}\text{Zr}(n, \gamma)^{95}\text{Zr}$] cross section uncertainty

$\Delta\sigma_{\text{XS}} \approx 19\%$, $\Delta\sigma_{\text{YSpectrum}} = 2,8\%$, + $\Delta\sigma_{\text{other}} < 1\%$

k=2

Irradiation duration	C/E ratio for $^{93}\text{Zr}/^{92}\text{Zr}$	$\pm \Delta(\text{C/E})_{\text{abs}}$ k=2
1 h ½	0,9	0,40
30 h	0,8	0,27

Final uncertainty value for C/E $\approx \pm 33,7\%$

Main contribution: Accelerator Mass Spectrometry uncertainty

$\Delta\sigma_{\text{AMS}} = 29,2\%$, $\Delta\sigma_{\text{XS}} \approx 18\%$ + $\Delta\sigma_{\text{other}} < 1\%$

k=2

NUCLEAR DATA : $^{92,94}\text{Zr}$ (n, γ) CROSS SECTIONS IMPACT

Irradiation duration	Average C/E ratio for ^{95}Zr activity, JEFF3.1.1	Average C/E ratio for ^{95}Zr activity, JEFF3.3.T1
1 h $\frac{1}{2}$	1,16	1,04
30 h	1,15	1,04
4 d	1,12	1,0

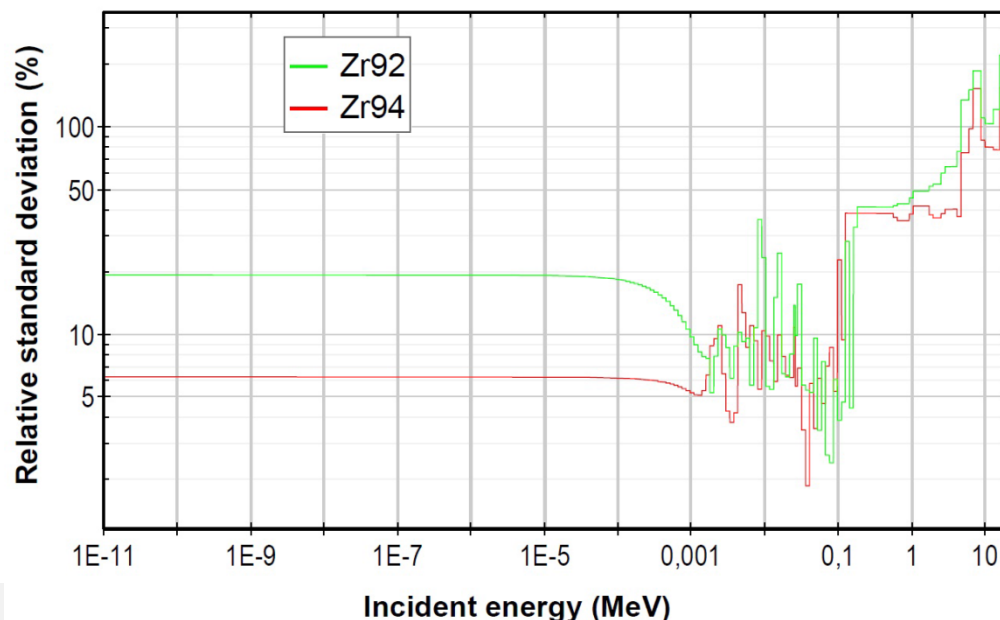
Irradiation duration	C/E ratio for $^{93}\text{Zr}/^{92}\text{Zr}$ JEFF3.1.1	C/E ratio for $^{93}\text{Zr}/^{92}\text{Zr}$ JEFF3.3.T1
1 h $\frac{1}{2}$	0,9	0,8
30 h	0,8	0,9

*For $^{92,94}\text{Zr}$ (n, γ) reaction, JEFF3.1.1 library takes values from JENDL3.3.
JENDL library uses CCONE code to evaluate cross sections.*

JEFF3.3.T1 library uses TALYS code.

We may imagine that improving fit of C/E values with JEFF3.3.T1 is due to different nuclear models parameters used by 2 different codes CCONE and TALYS.

Incident neutron data / TENDL-2015 // MT=102 : (z, γ) /
Covariances data (BOXER) Relative standard deviation



Best C/E adjustment :

^{94}Zr (n, γ) reaction \rightarrow JEFF 3.3.T1, JENDL 4.0

^{92}Zr (n, γ) \rightarrow JEFF 3.1.1, ENDF/B VII.1

But! Uncertainty on $^{94, 92}\text{Zr}$ (n, γ) XS values \rightarrow $\approx 20\%$ in 1 keV – 1 MeV

Very few experimental data is available for $^{94, 92}\text{Zr}$ (n, γ) XS.

$^{94, 92}\text{Zr}$ irradiation experience shows that **1 keV – 1 MeV neutron detection is possible**, but **we need to reduce uncertainties on $^{94, 92}\text{Zr}$ (n, γ) XS values.**

The purpose of this work is to show the possible $^{92, 94}\text{Zr}$ application. We demonstrated Zr neutron detection feasibility. We hope to motivate more studies in Zirconium nuclear data evaluation.

NUCLEAR DATA : $^{92,94}\text{Zr}$ (n, γ) CROSS SECTIONS IMPACT

Irradiation duration	$\Phi_{\text{calc}} / \Phi_{\text{exp}}$ (by ^{94}Zr (n, γ) reaction)				
	JEFF 3.1.1	JEFF 3.2	ENDF/B VII.1	TENDL 2014	JENDL 4.0
1 h ½	1,2	1,1	1,2	1,1	1,0
30 h	1,2	1,1	1,2	1,1	1,0
4 d	1,2	1,1	1,2	1,0	1,0

Irradiation duration	$\Phi_{\text{calc}} / \Phi_{\text{exp}}$ (by ^{92}Zr (n, γ) reaction)				
	JEFF 3.1.1	JEFF 3.2	ENDF/B VII.1	TENDL 2014	JENDL 4.0
1 h ½	1,0	0,85	1,0	0,8	0,8
30 h	0,9	0,8	0,9	0,8	0,75

$$A(^{95}\text{Zr})(t) = N(^{94}\text{Zr}) * \sigma_{(n,\gamma)}(^{94}\text{Zr}) * \Phi * (1 - e^{-\lambda(^{95}\text{Zr}) * T_{\text{irrad}}}) * e^{-\lambda(^{95}\text{Zr}) * T_{\text{cooling}}}$$

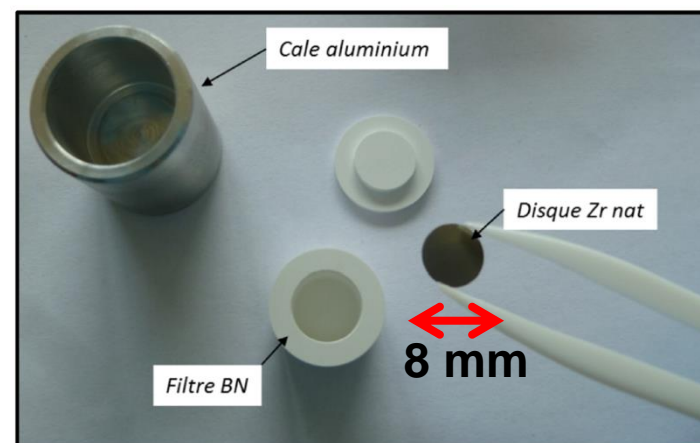
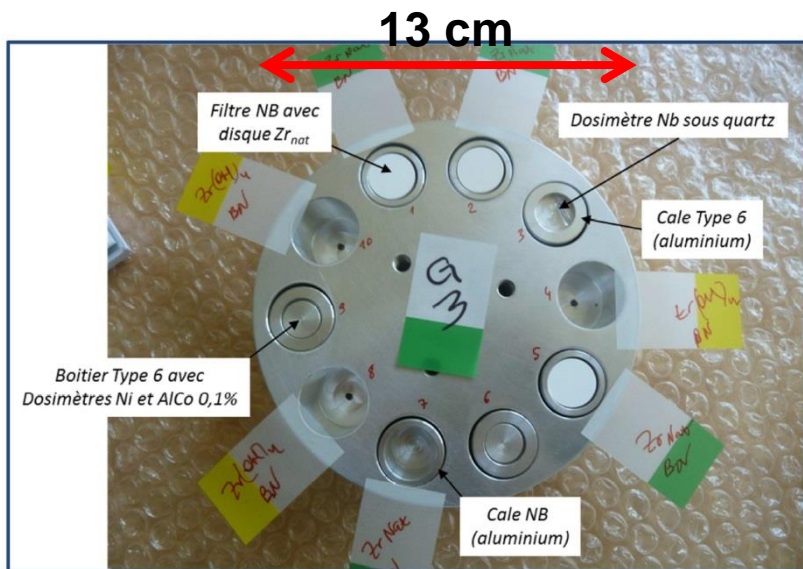
$$\Phi = LN\left(\frac{r}{\alpha} + 1\right) * 1 / (T_{\text{irrad}} * \sigma_{(n,\text{tot})}(^{92}\text{Zr})) \quad r = \frac{[^{93}\text{Zr}]}{[^{92}\text{Zr}]} \quad \alpha = \frac{\sigma_{(n,\gamma)}(^{92}\text{Zr})}{\sigma_{(n,\text{tot})}(^{92}\text{Zr})}$$

EXPERIMENTAL RESULTS

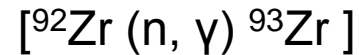
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