Neutron dosimetry in Nuclear Reactors

C. Destouches

CEA/DES-IRESNE-DER

EDUCAM Rabat School (REISS)

02/07/24

Table of Contents

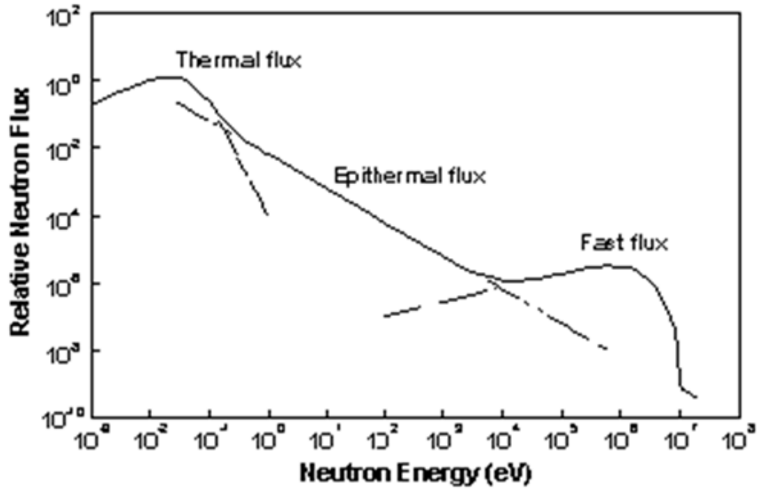
Definition of the Reactor Dosimetry

→ Quantitative (Fluence) and Qualitative (Spectrum) characterization of the neutron population that has passed through a given point over a defined period of time.

Neutron fluence (1 to 10^{15} n/cm²): quotient of the number of neutrons penetrating a given time interval in a suitably small sphere centered at that point, divided by the area of the great circle of that sphere.

Neutron spectrum (in energy: eV or in lethargy unit (ln(E0)/ln(E)) : Neutron population distribution as a function of energy (kinetic) or lethargy unit.

Neutrons Energy Distribution



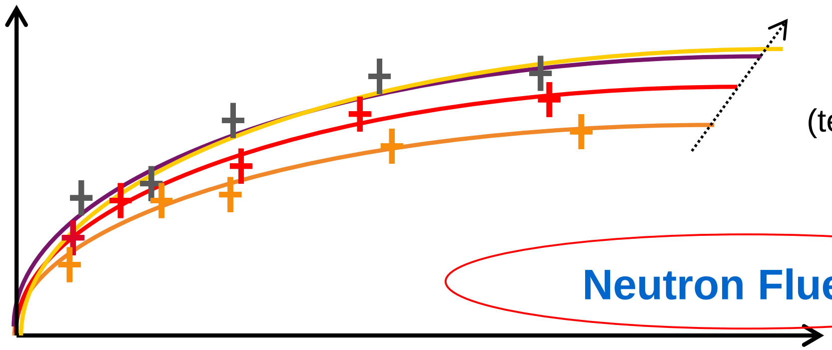
1 - Principle and Objectives of Reactor Dosimetry

Goals

→ Helping to establish/validate/improve the laws of behaviour of materials and systems under irradiation

Properties

(ex : embrittlement, damage, Burn up, corrosion, conductivity, etc.)



Influnece parameters

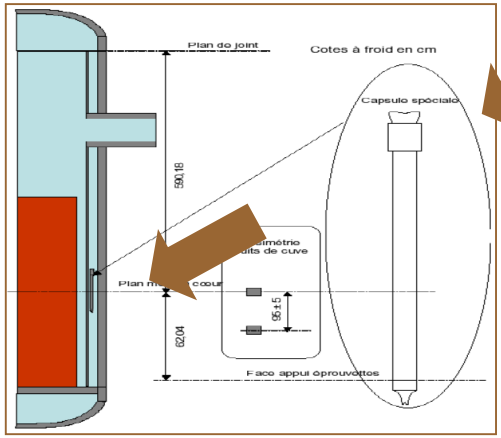
(temperature, Physico-chemical constants, pressure, etc.)

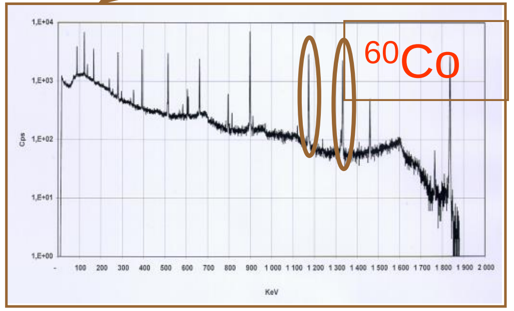
Neutron Fluence

≠ Personal Dosimetry
Radioprotection

Principle and Objectives of Reactor Dosimetry

- Spectrum shape qualification
- Neutron response quantification
- Neutron dose quantification





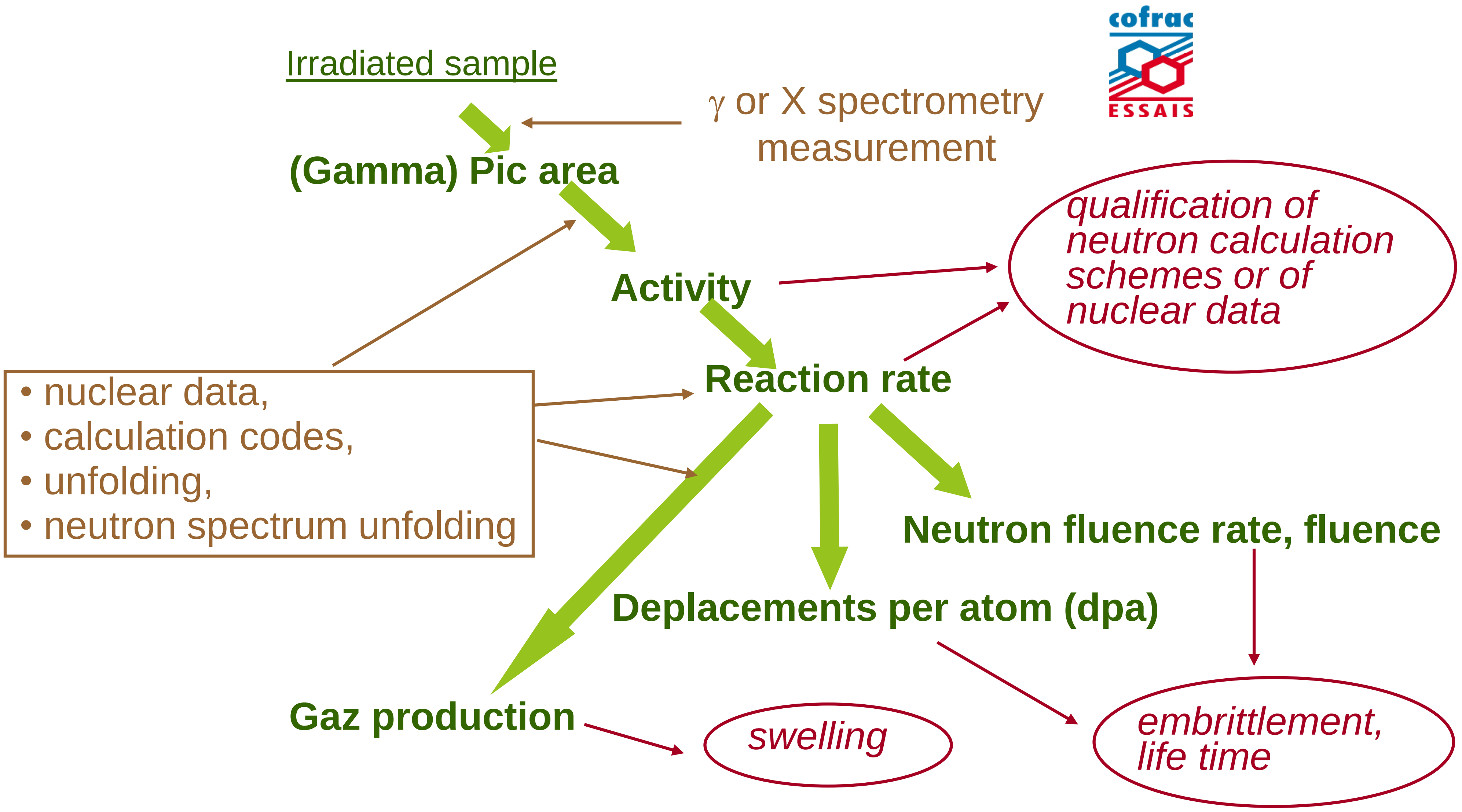
- irradiation history, space modeling

Cross section

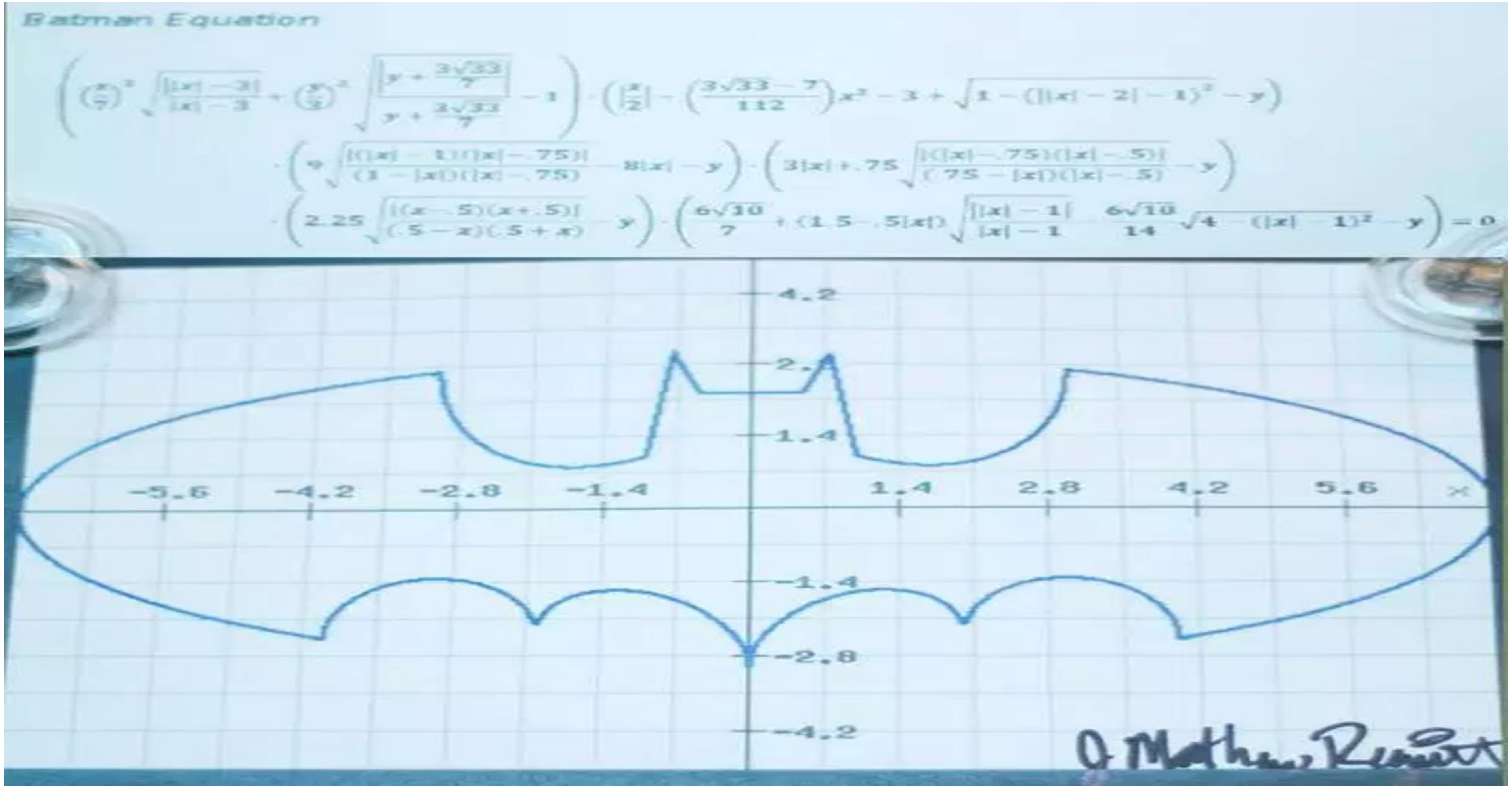
Activity

Reaction rate,
Neutron fluence rate,
Gaz production rate ….

1 - Principle and Objectives of Reactor Dosimetry



Bateman’s Equation



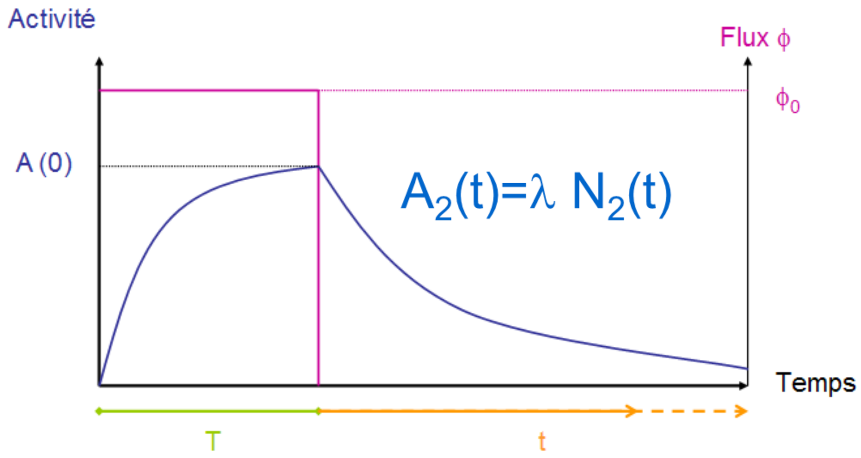
1 - Principle and Objectives of Reactor Dosimetry

Bateman's Equation

Flux — Cross Section — Decay constant — Irradiation Duration — Decay Time

$$A_2(t) = \Phi_0 \times N_1 \times \sigma_1 \times (1 - e^{-\lambda_2 \times T}) \times e^{-\lambda_2 \times t}$$

Activity (Bq) — Number of Nuclei



→ Diminution of the father isotope concentration (BU)

- → Reducing dimensions: High-purity metals (wires, discs, strips)
  - → Limits/ handling (fil 1/10 mm x 3mm)
- → Alliages : Al-Co (0,01%), Al-Au
  - → Composition knowledge

PAGE 8

Table of Contents

$$A_2(t) = \Phi_0 \times N_1 \times \sigma_1 \times (1 - e^{-\lambda_2 \times T}) \times e^{-\lambda_2 \times t}$$

Activity (Bq)

Flux

Number of Nuclei

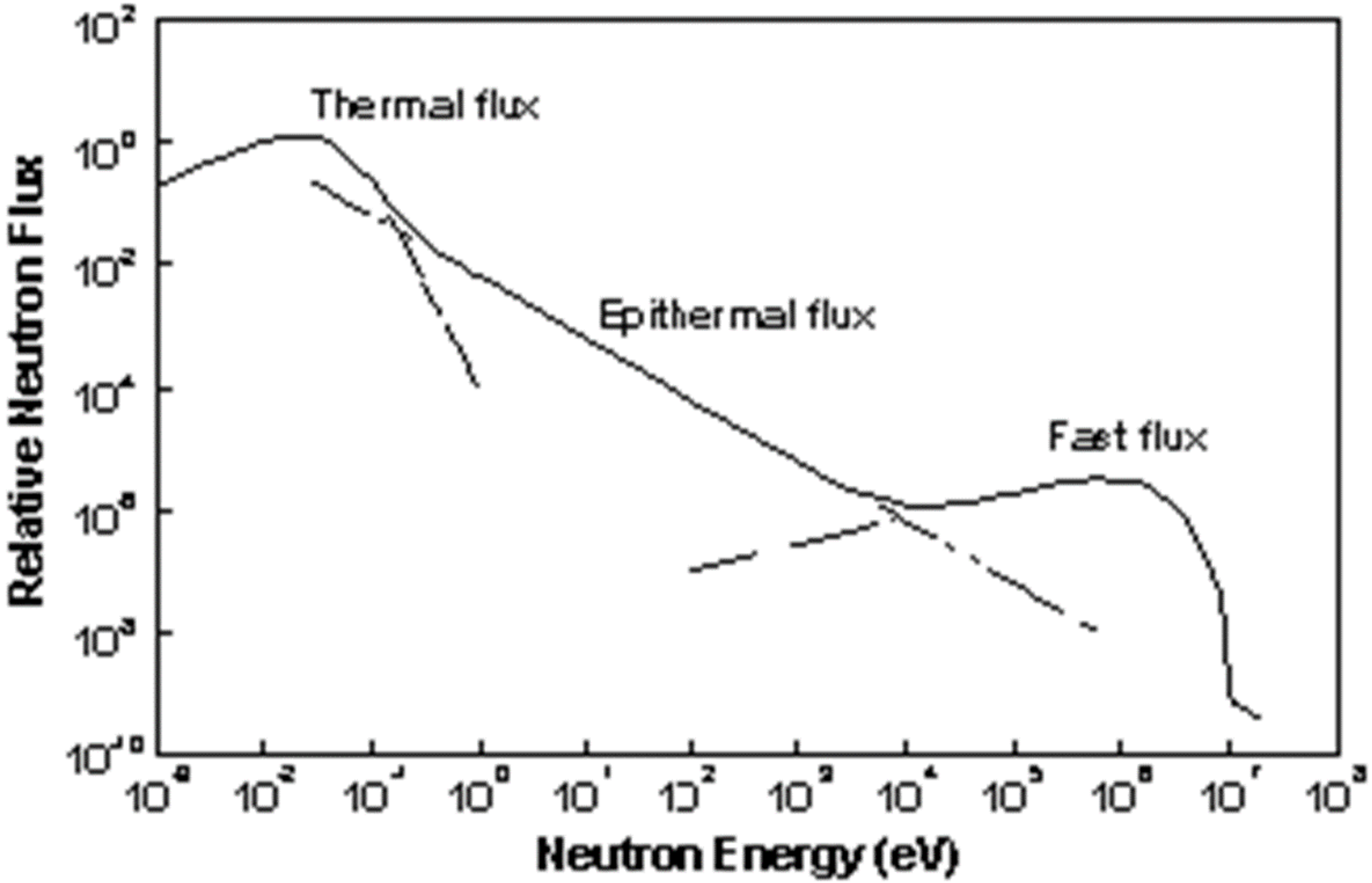
Cross Section

Decay constant

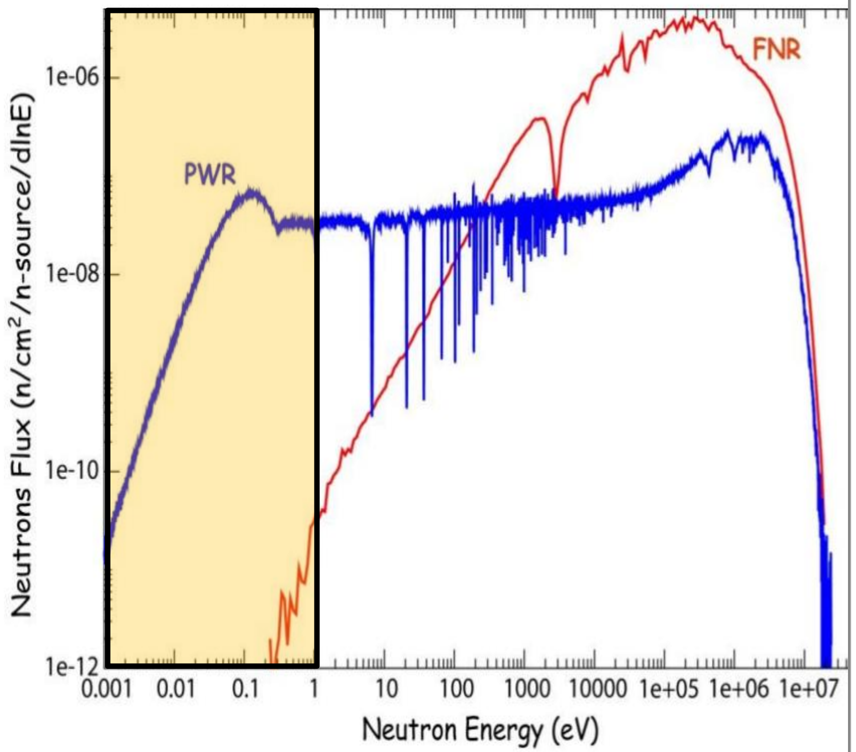
Irradiation Duration

Decay Time

2 - Neutron Spectra and Flux

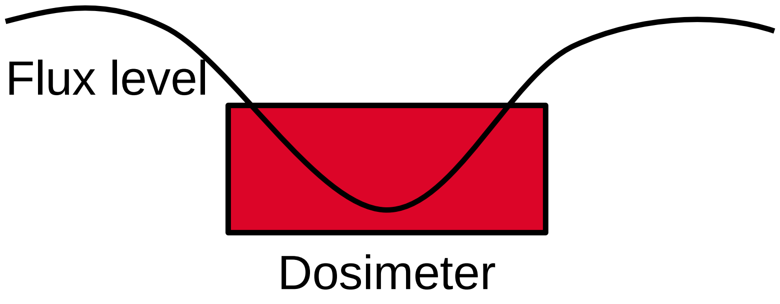


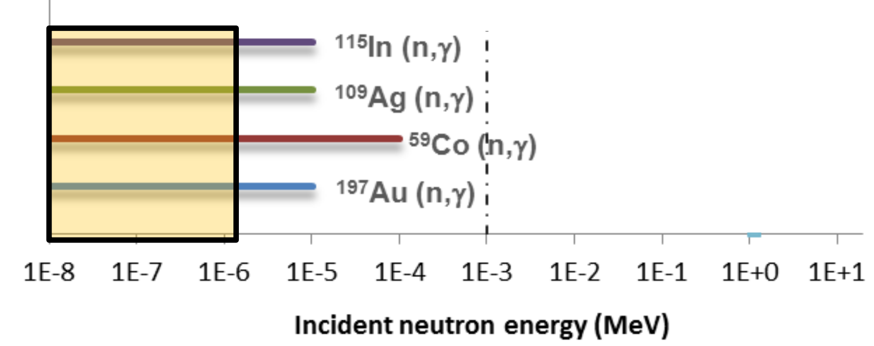
2 - Neutron Spectra and Flux



Spécificities:

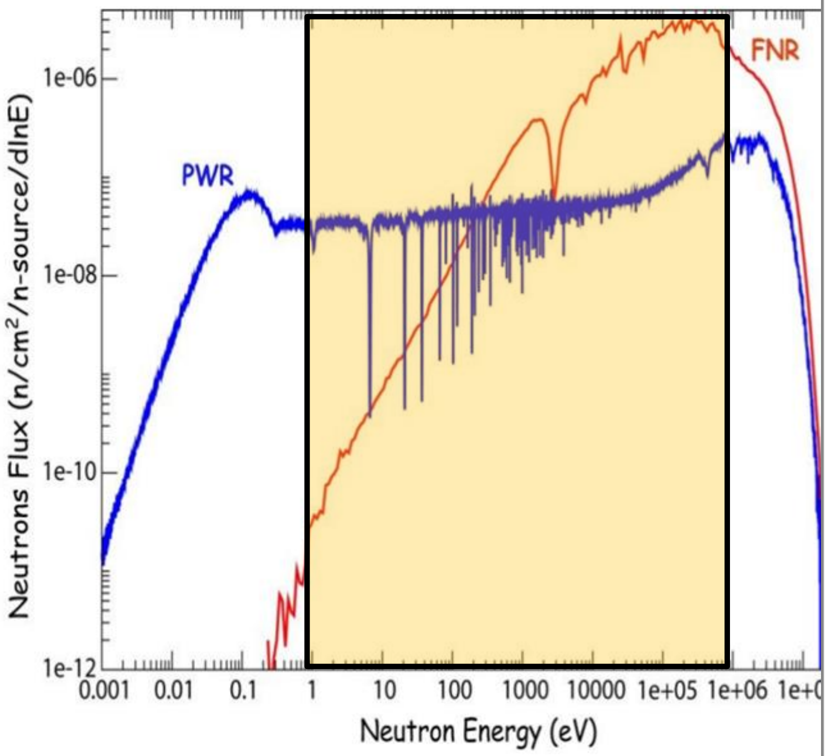
- Resonance Self-shielding effect
- Flux depletion





Neutrons:
Activation, Power Calibration

2 - Neutron Spectra and Flux



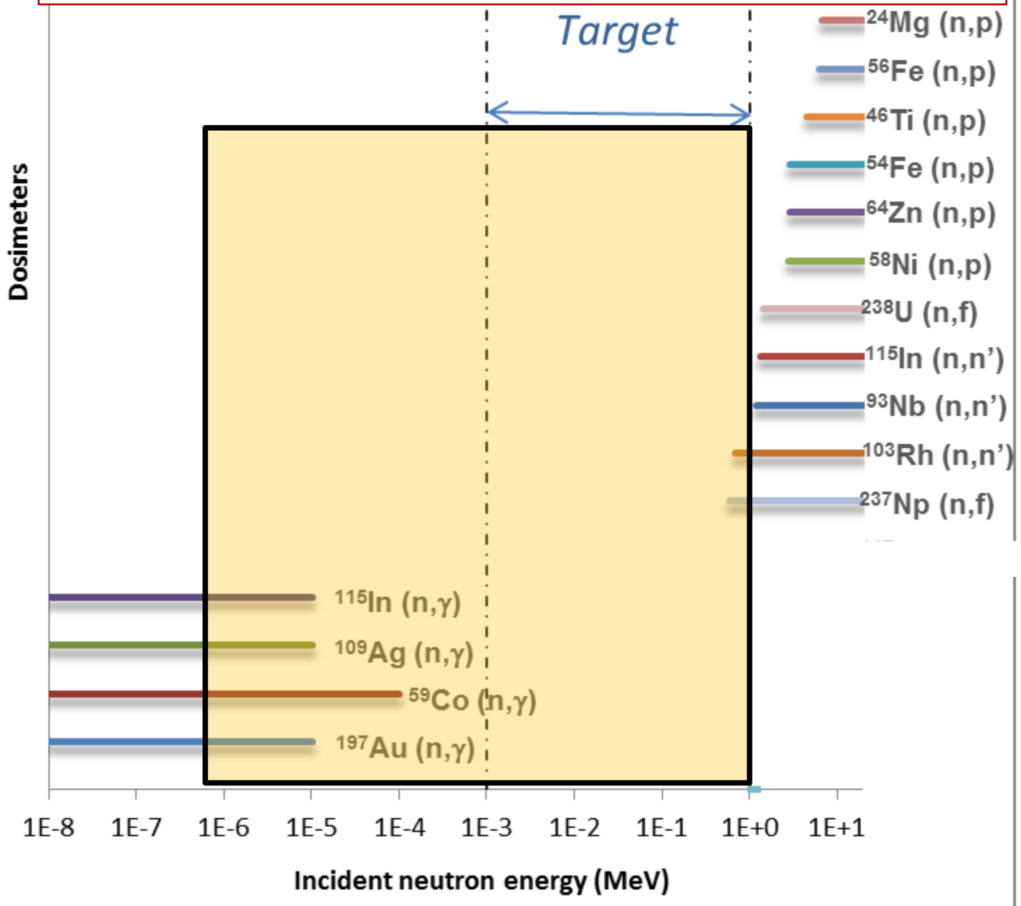
Thermal Neutrons:
Activation, Power Calibration

Epithermal neutrons :
Damage (DPA), GEN-IV concepts

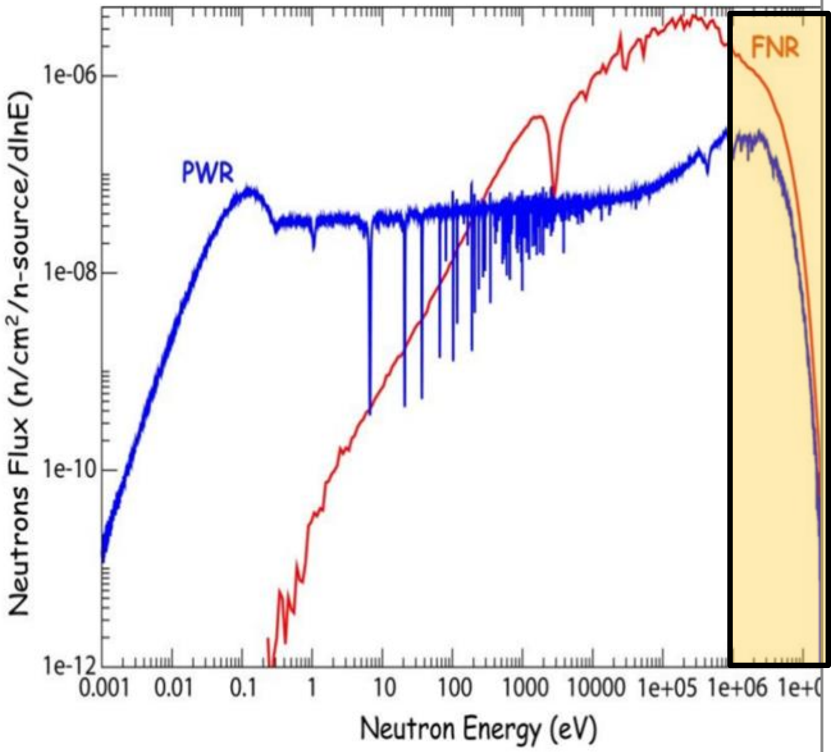
Fast neutrons:
Damage (DPA), Accelerator devices

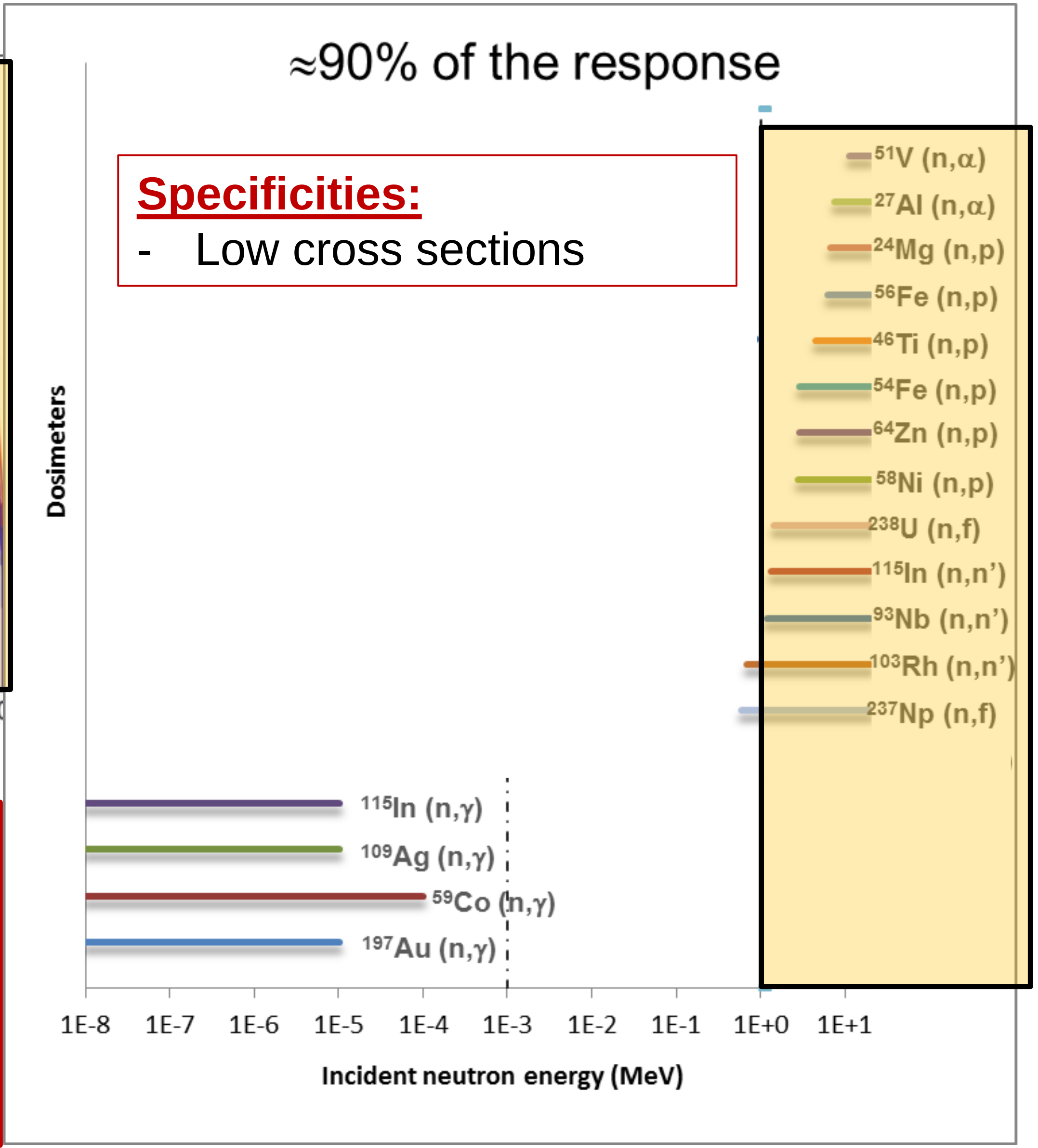
Specificities:

- No response from 1keV to 1MeV
- Thermal Reaction parasitic contributions



2 - Neutron Spectra and Flux

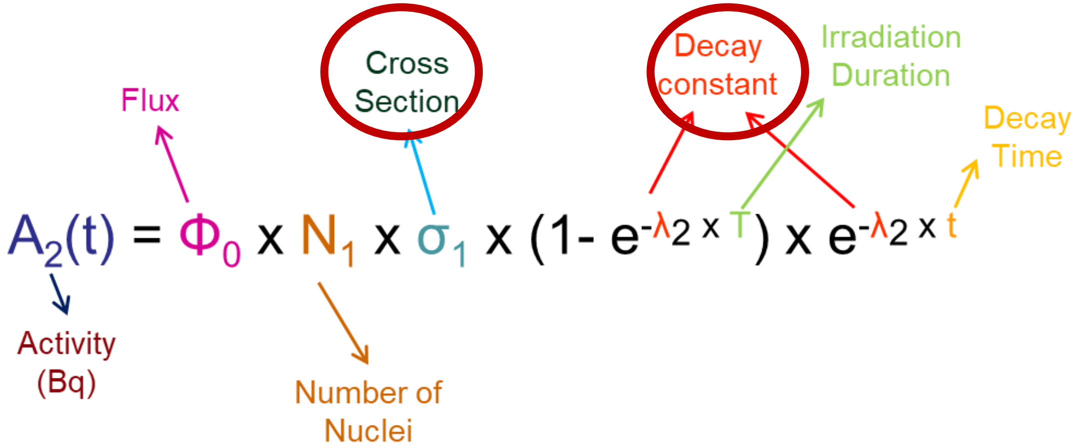




Specificities:
- Low cross sections

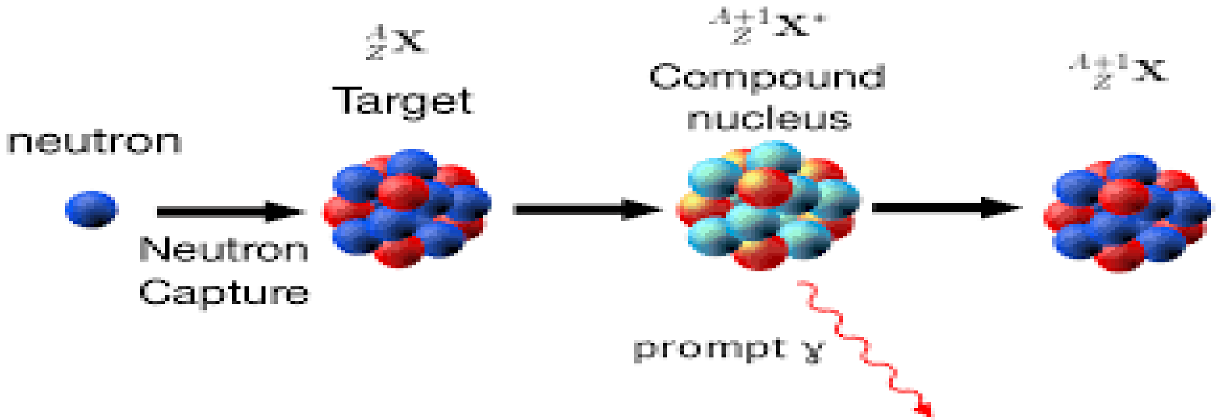
Fast neutrons:
Damage (DPA), Accelerator devices

Table of Contents



3 – Nuclear data

Interactions neutron-matière



Reactions (n, γ) : interaction with neutrons of varying energy (strong response in the thermal domain and epithermal resonances)

Reactions (n, p) & (n, α) : energy threshold usually > 1 MeV – excpetion : ^{10}B

Reactions (n, f) : fass or thermal responses (resonances in the epithermal domain)

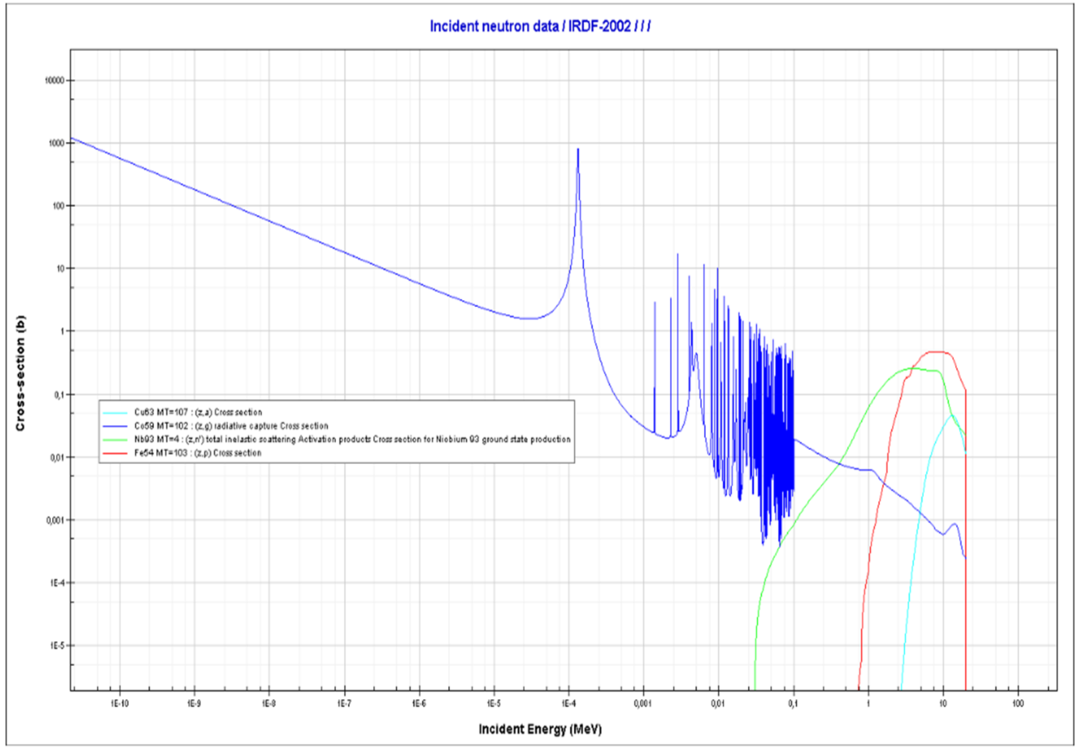
Reactions (n, n') : energy threshold usually 0,4 MeV

3 – Nuclear data

Material	Reaction	Energy range	T½
Gold	$^{197}Au(n,\gamma)^{198}Au$	Thermal + Epithermal	2,7 d
Cobalt	$^{59}Co(n,\gamma)^{60}Co$	Thermal + Epithermal	5,27 y
Indium	$^{115}In(n,\gamma)^{116}In$	Thermal + Epithermal	54 m
Cobalt/Cd	$^{59}Co(n,\gamma)^{60}Co$	> 0,74 eV	5,27 y
Zirconium/BN	$^{94}Zr(n,\gamma)^{95}Zr$	From 1 keV to 1 MeV	64 d
Neptunium	$^{237}Np(n,f)^{137}Cs$	> 0,6 MeV	30 y
Rhodium	$^{103}Rh(n,n')^{103m}Rh$	> 0,7 MeV	56 m
Indium	$^{115}In(n,n')^{115m}In$	> 1,3 MeV	4,5 h
Niobium	$^{93}Nb(n,n')^{93m}Nb$	> 1,2 MeV	16,1 y
Uranium	$^{238}U(n,f)^{137}Cs$	> 1,4 MeV	30 y
Nickel	$^{58}Ni(n,p)^{58}Co$	> 2,7 MeV	71 d
Zinc	$^{64}Zn(n,p)^{64}Cu$	> 2,8 MeV	12,7 h
Iron	$^{54}Fe(n,p)^{54}Mn$	> 2,8 MeV	312 d
Copper	$^{63}Cu(n,\alpha)^{60}Co$	> 5,5 MeV	5,27 y
Magnesium	$^{24}Mg(n,p)^{24}Na$	> 6,7 MeV	15 h
Aluminum	$^{27}Al(n,\alpha)\ ^{24}Na$	> 7,3 MeV	15 h
Vanadium	$^{51}V(n,\alpha)^{48}Sc$	> 11,5 MeV	1,8 d

3 – Nuclear data

Cross Sections Librairies



Multipurpose Libraries:

- JEFF 3 (NEA)
- ENDF/B-VIII
- JENDL 4.0
- CENDL,…

For Reactor Dosimetry applications:

- IRDFF (AIEA) :
- Systematic covariance matrices

JANIS 4.0 : www.oecd-nea.org/janis

3 – Nuclear data

Effective Cross Sections and Reaction Rates

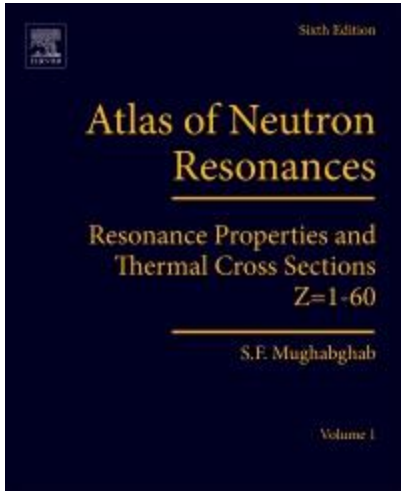
Westcott formalism and Effective Cross Sections

$$Tx = (\sigma_O + \rho\,(I_{res} + I_{1/v}))\ {*}\phi_{2200ms} + \sigma_{(E>1MeV)} * \phi_{(E>1MeV)}$$

→ $\sigma_{O,}$ ρ: tabulated

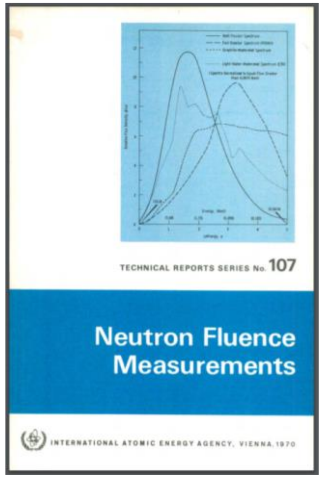
→ Self shielding Correction to use : g_{th}, g_{res} $g_{1/v}$

→ $\sigma_{(E>1MeV)}$: condensed on the effective neutron spectrum



Neutron Calculation codes

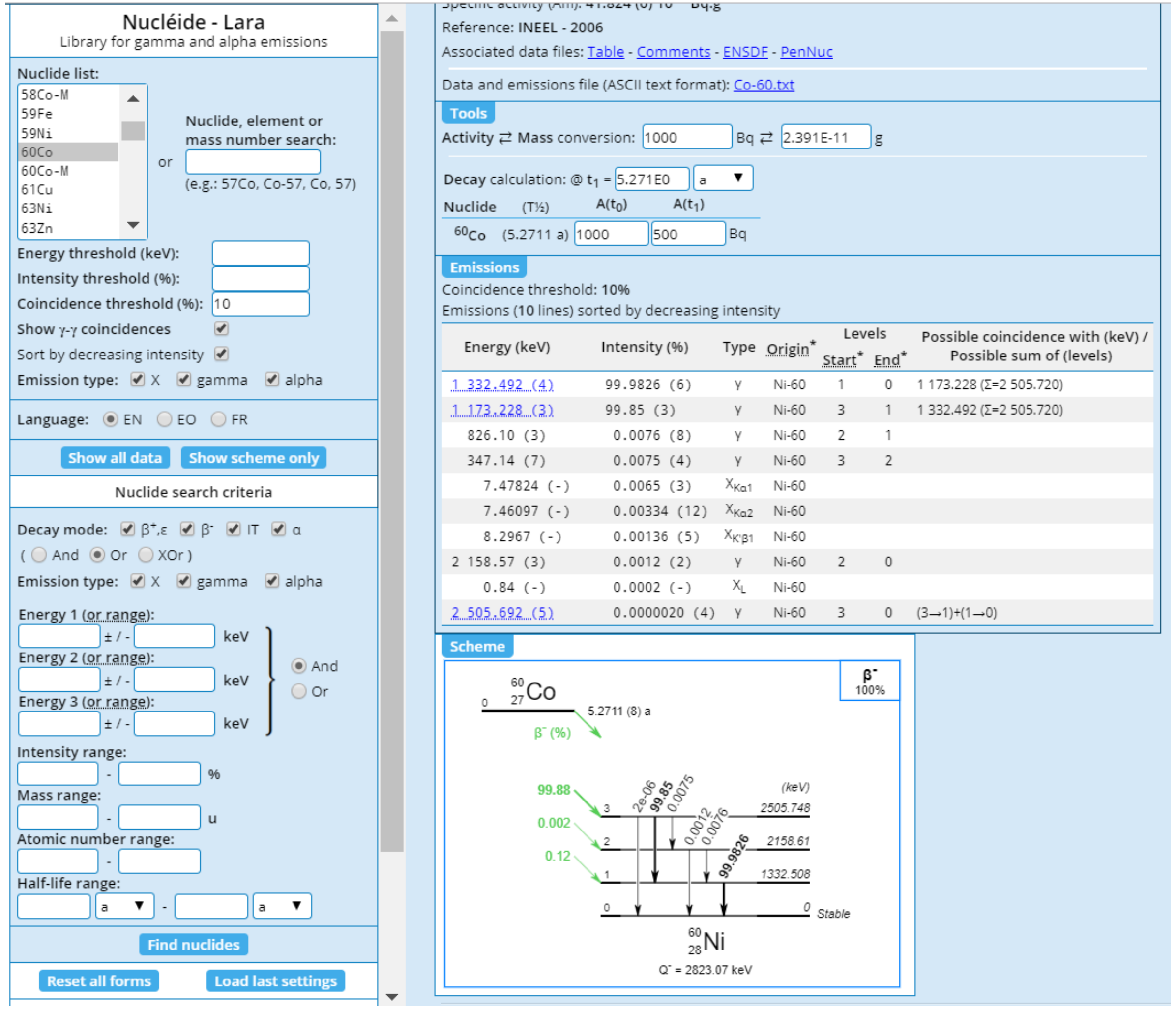
→ Energy pointwise / continuous Reaction Rates & Effective XS



3 – Nuclear data

Decay Data (λ, Emission Intensities)

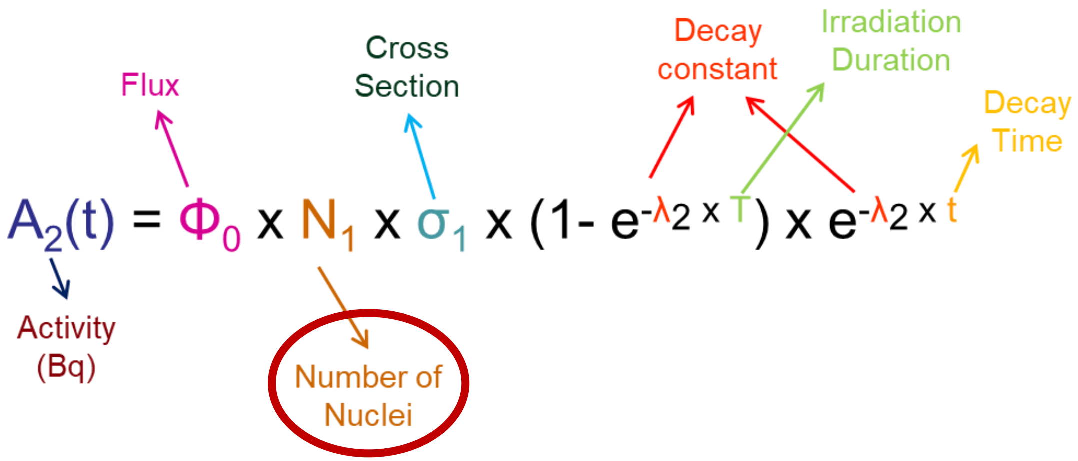
Nuclides : www.nucleide.org/Laraweb



Selection criteria

- Suitable energy response range
- Sufficient effective cross-section level
- Radioactive half-life compatible with operating constraints
- Nature and detectability of particles emitted by the excited nucleus (emission probabilities)

Table of Contents

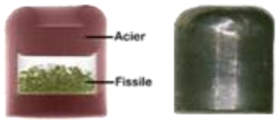


4 – Dosimeters

- Controlled composition: pure material, alloy or oxides
- Controlled impurities: example of copper (Co<0.1 ppm)
- Controlled dimensions (solid or powder) and mass

→ Reduction of uncertainties on "N

Fissiles
(Ø 4,6 mm x H 5,0 mm)



Uranium

Neptunium

Table of Contents

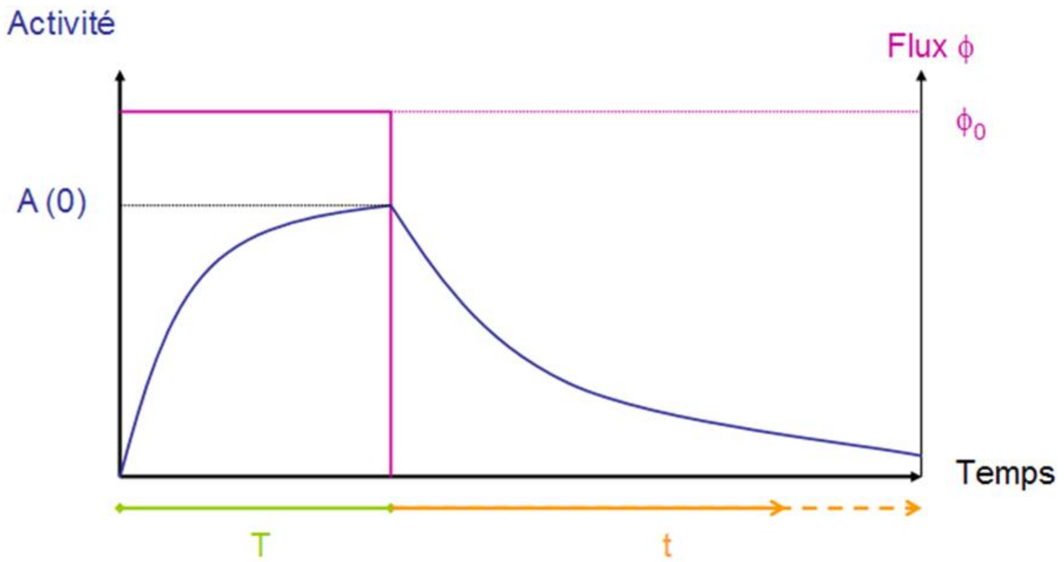
5 – Irradiation

Condition d’irradiation

Control:

- Irradiation conditions (duration and flux level) to obtain measurable and manageable activity (ALARA):
  - Integrator behaviour over short time t<<T
  - Saturation Activity   t >3T
  - Period of oblivion beyond

  → Power history time recording (relative format)



- Time before measurement (recovery, transport, parasitic contributions, deletion if t >10T, etc.)

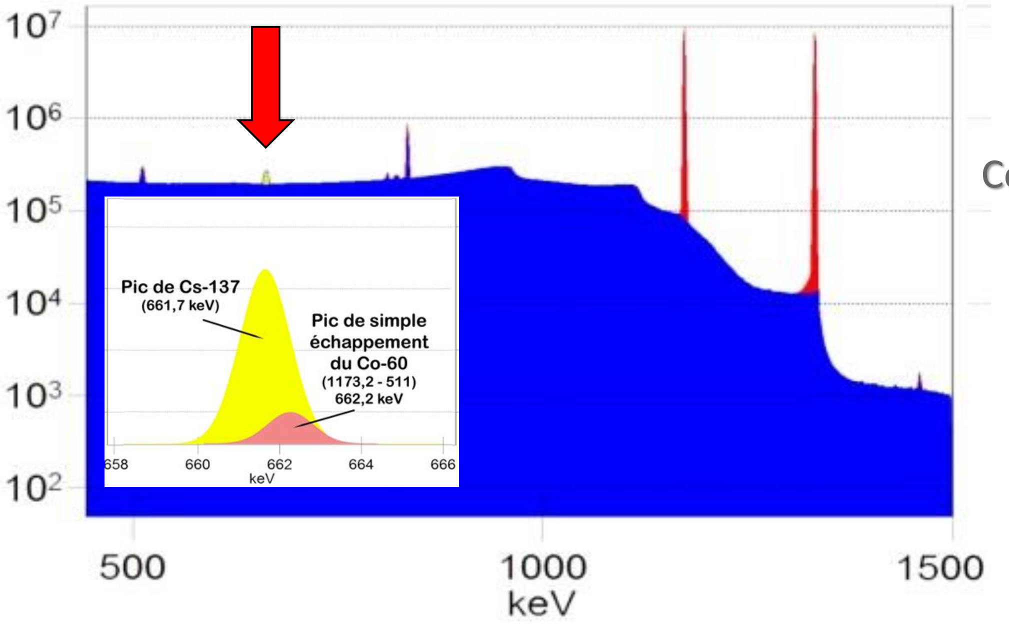
Table of Contents

$$A_2(t) = \Phi_0 \times N_1 \times \sigma_1 \times (1 - e^{-\lambda_2 \times T}) \times e^{-\lambda_2 \times t}$$

- Activity (Bq)
- Flux
- Number of Nuclei
- Cross Section
- Decay constant
- Irradiation Duration
- Decay Time

6 - Activity measurement

Example of measurement of Cs-137 activity from a fissile dosimeter (Np-237 & U-238)

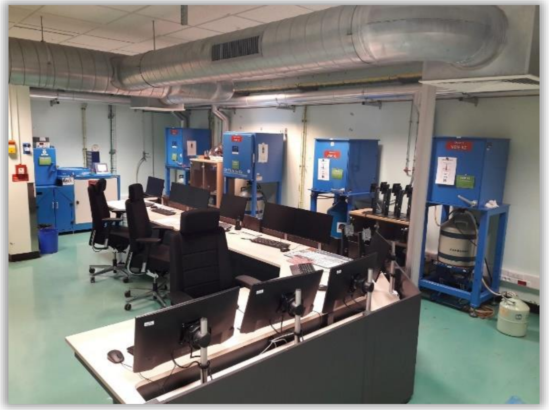


Constraints

- Dosimeter for Np-237 and U-238
- High Co-60 activity
- Remote counting geometry
- Consideration of stainless steel casing thickness

Other methods: chemical dissolution

6 - Activity measurement



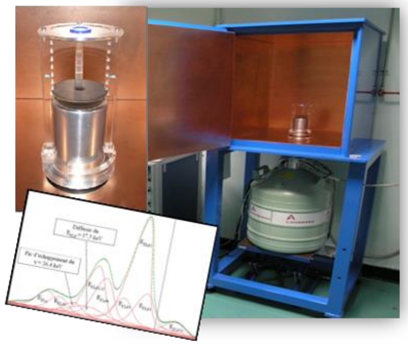
2 standard γ - detectors

cofrac
ESSAIS
ACCREDITATION
N° 1-0736
PORTEE
DISPONIBLE SUR
WWW.COFRAC.FR

6 HPGe + 2 BeGe detectors
0,1 – 10^7 Bq
γ / X emitters

25 years of Cofrac accreditation

Modelisation/simulation of detectors
(TRIPOLI-4, GEANT4, MCNP-6)



2 X - detectors

1 automatic bench (γ)

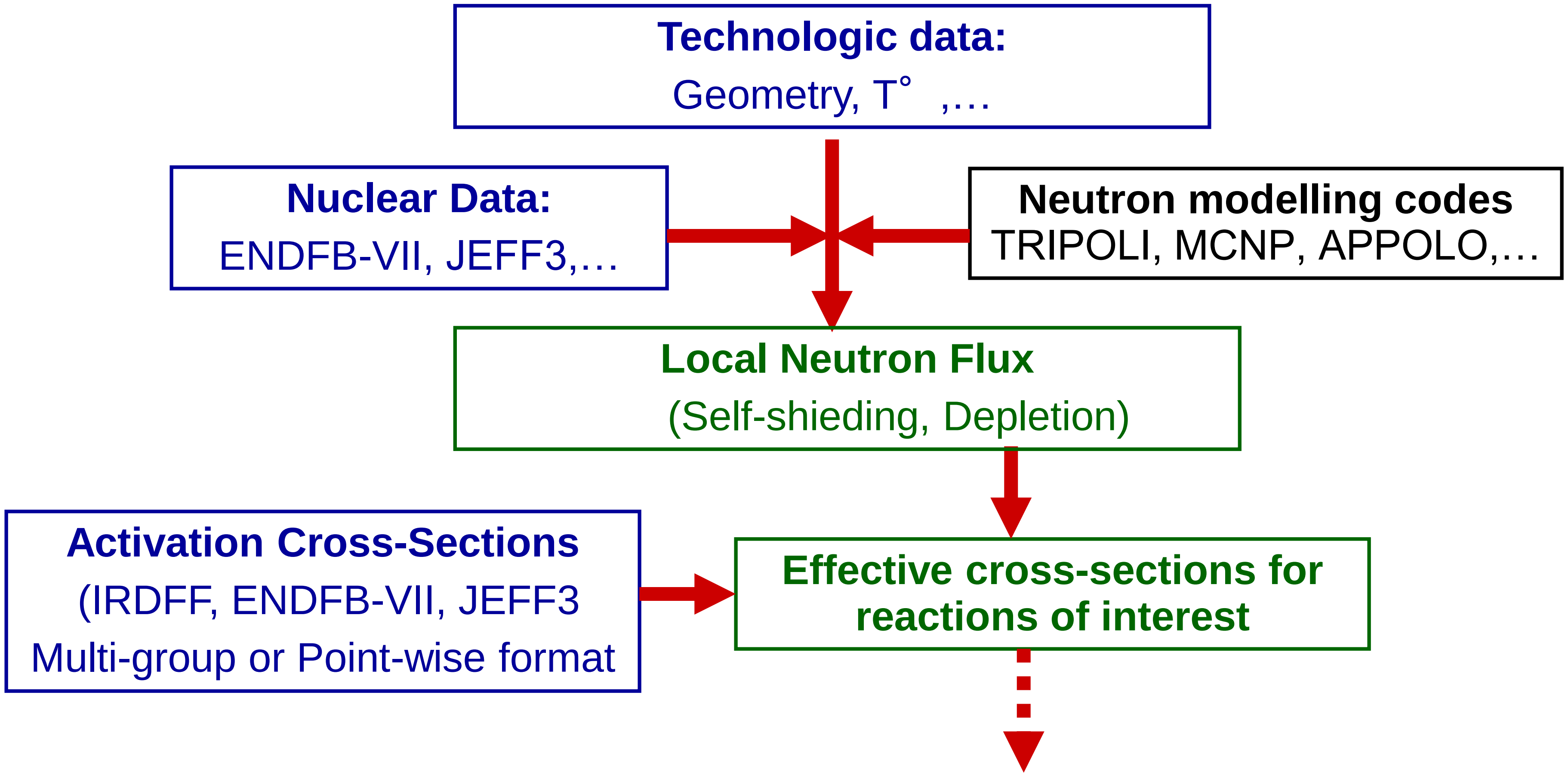
2 HE γ - detectors

1 mobile γ/X - detector

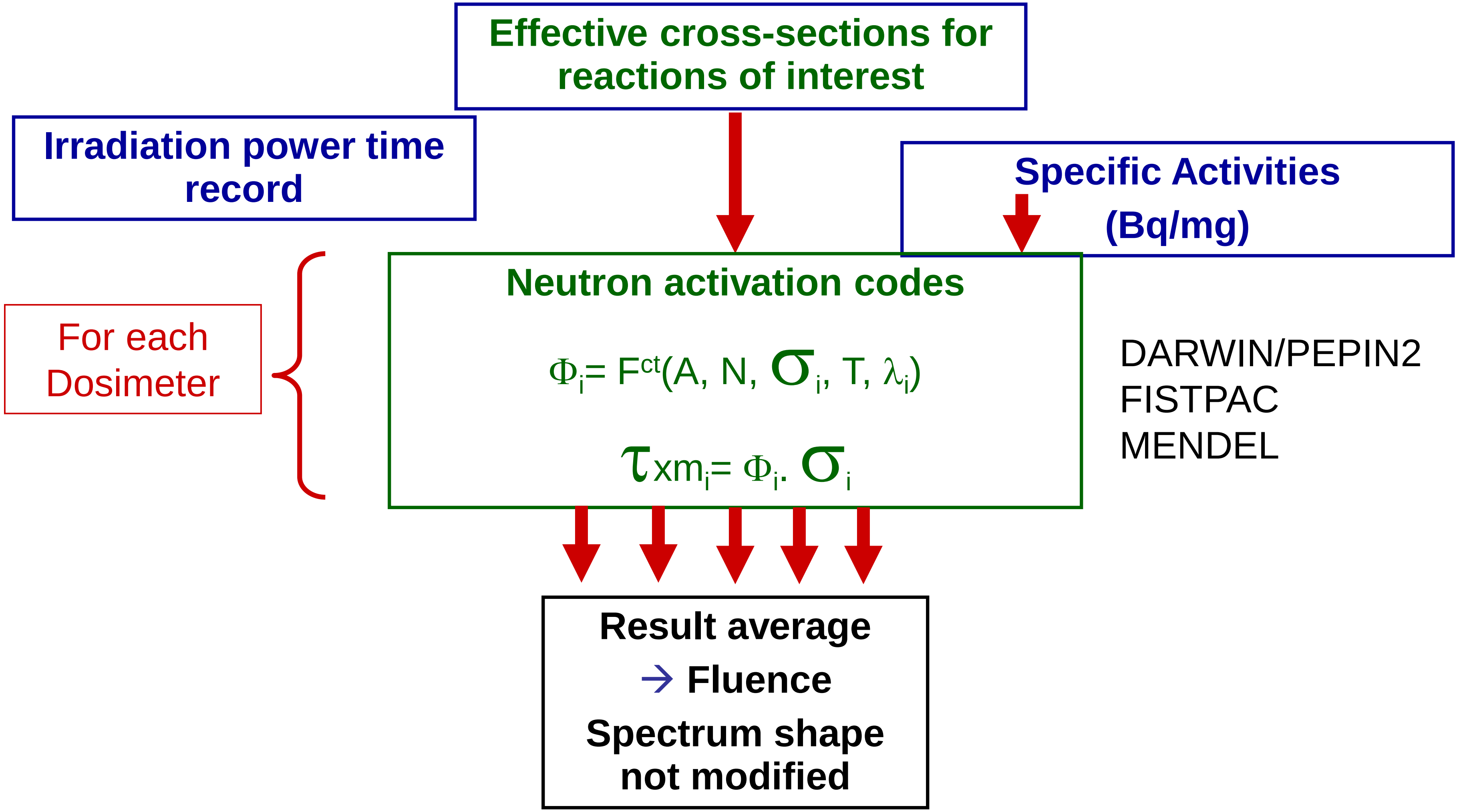
https://www.youtube.com/watch?v=-ajtgl4eejk

Table of Contents

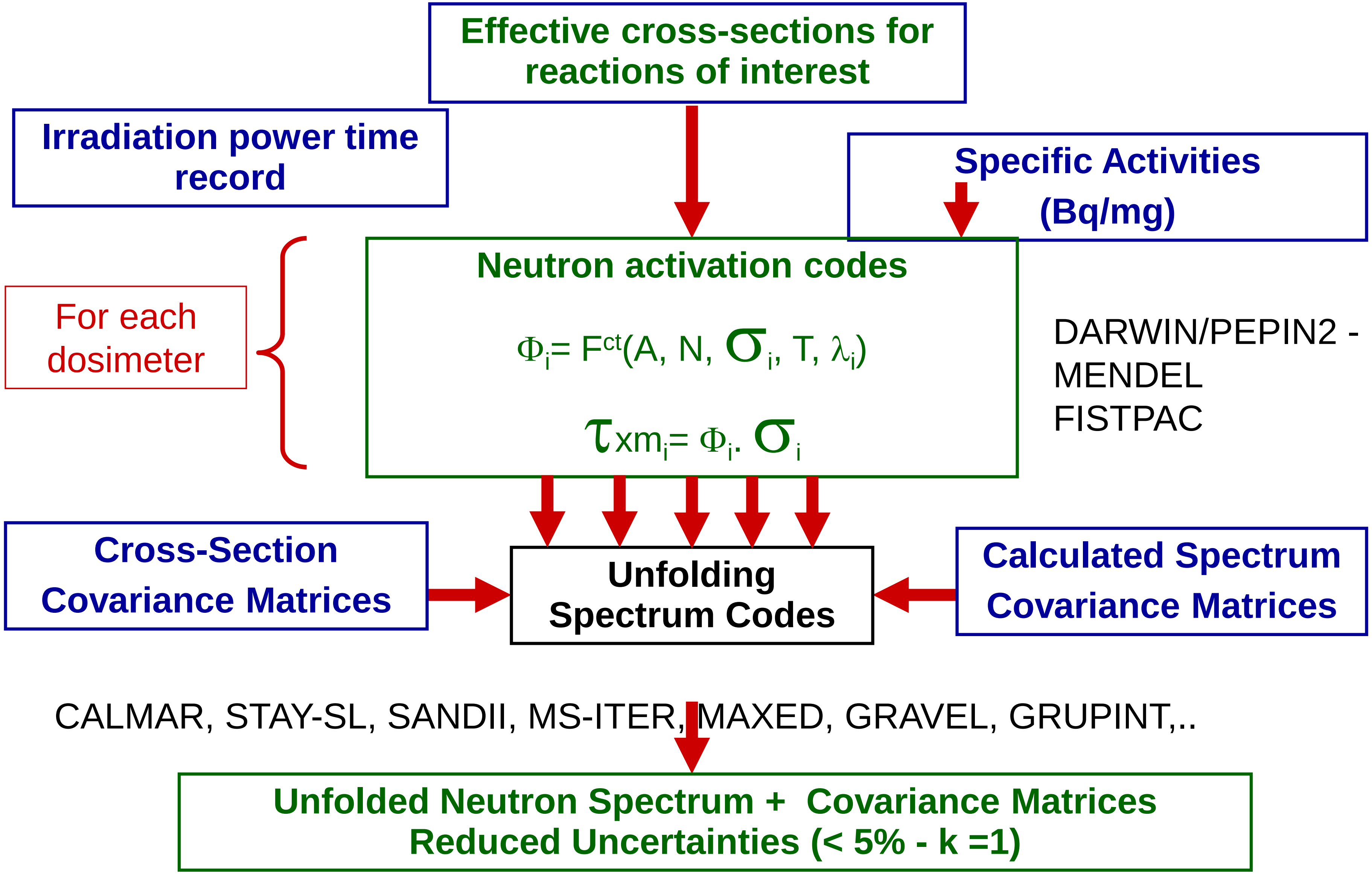
7 - Interpretation of measurements



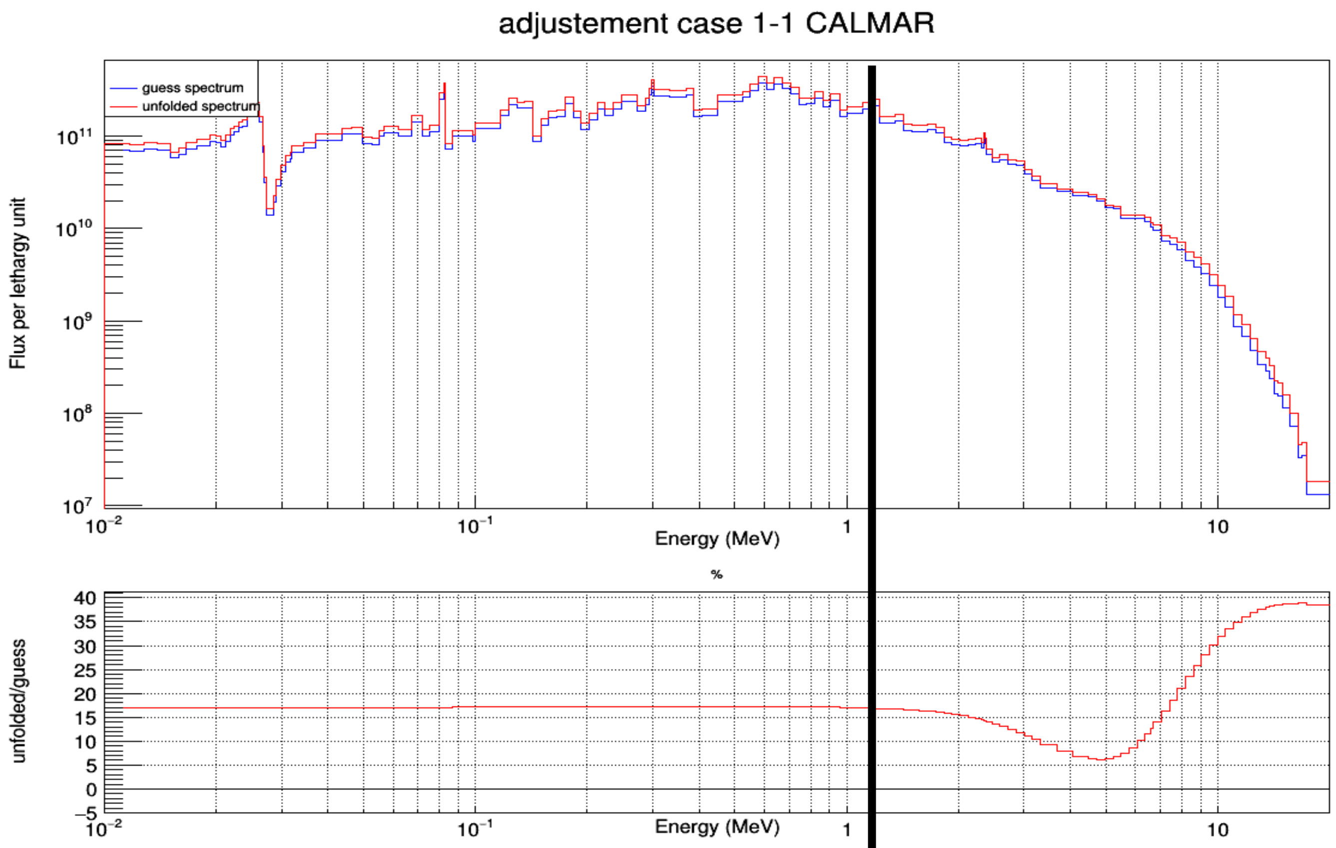
7 - Interpretation of measurements



7 - Interpretation of measurements



7 - Interpretation of measurements



No spectral information from measurements
➔ only normalization

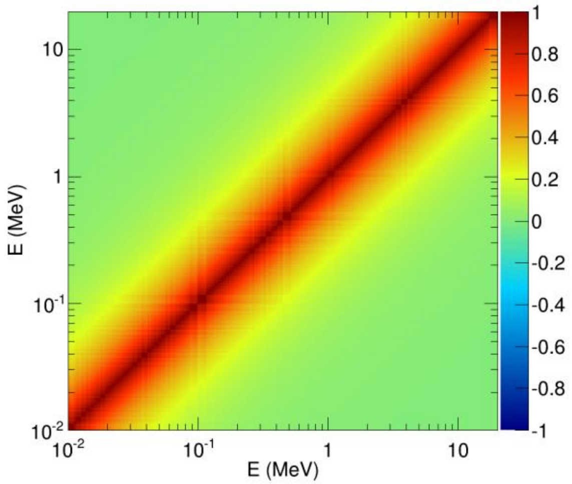
spectral information from measurements
➔ shape fitting

7 - Interpretation of measurements

Effect of the Normalization Process on Correlation Matrices

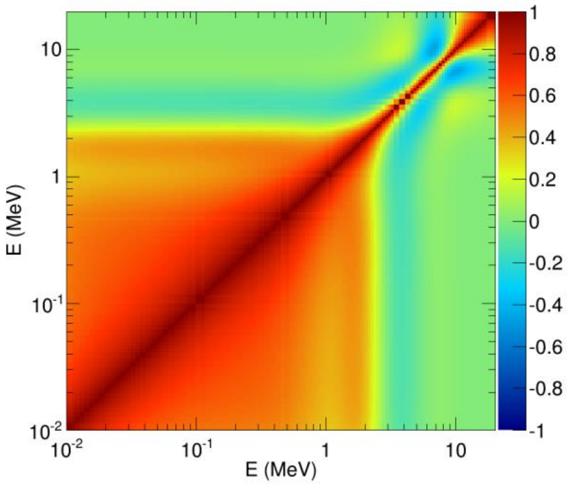
Spectral Information given by the measurements
→ Minimization of the correllations

Test spectrum correlation matrix



CALMAR

Correlation matrix of the adjusted spectrum



No added information
Addition of correlation issued from the normalization process

Table of Contents

8 - Examples of applications

→ Nuclear test and irradiation reactors (RJH, CABRI, RES, etc.)

- →Characterisation of irradiation location spectra and fluences
- →Characterisation of spectra and fluences in irradiated devices
- →Analysis of material behaviour under flux (damage, gas, etc.)
- → Characterisation of cores (spectrum, flux levels and profiles, power)
- → V&V approach to neutron codes
- → Qualification of new core configurations (CABRI)
- → Start-up campaign for new reactors (RJH)
- → Calibration of other instrumentation (on-line measurements)
- → Monitoring of very short events (power pulses)
- → Measurement using Neutron Activation Analysis (NAA) :
  - →Quantification of low impurity levels (<ppm)

PAGE 35

8 - Examples of applications

→ Nuclear Power Reactor (NPP)

- → Monitoring damage to the reactor vessel under irradiation
- → Core characterization (spectrum, flux levels and profiles, power)
- → V&V of neutron protection codes (TRIPOLI 4)
- → Calibration of other instrumentation (on-line measurements) : EPR AMS

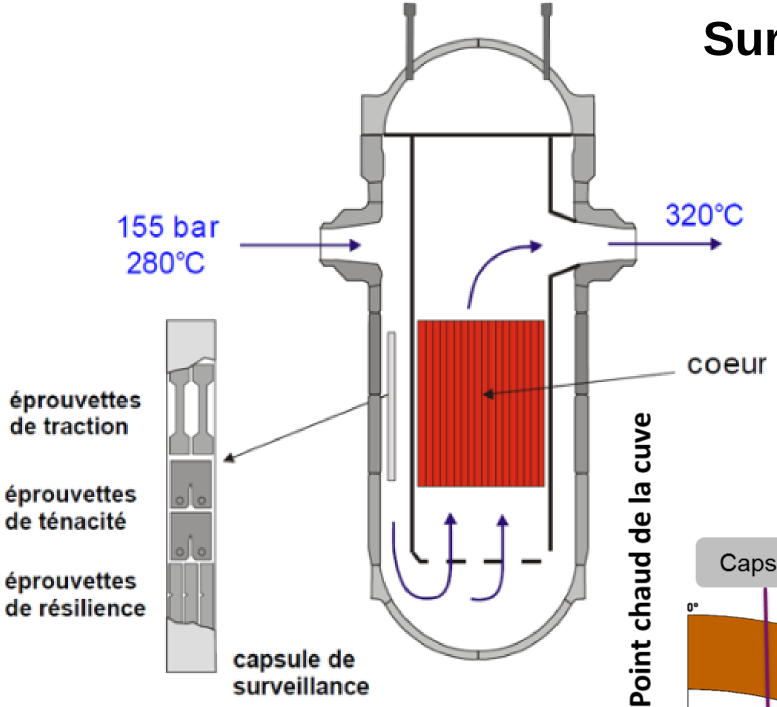
→ Estimation of residual activity in structures / dismantling

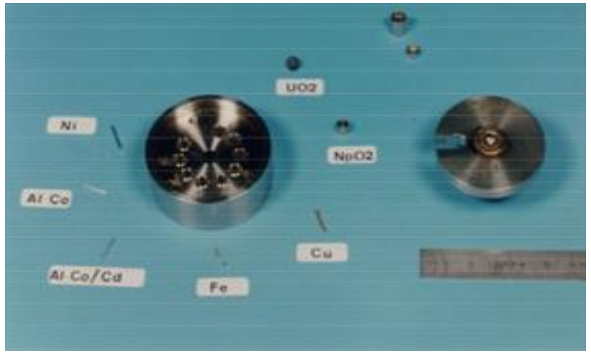
→ Accelerators Beam calibration

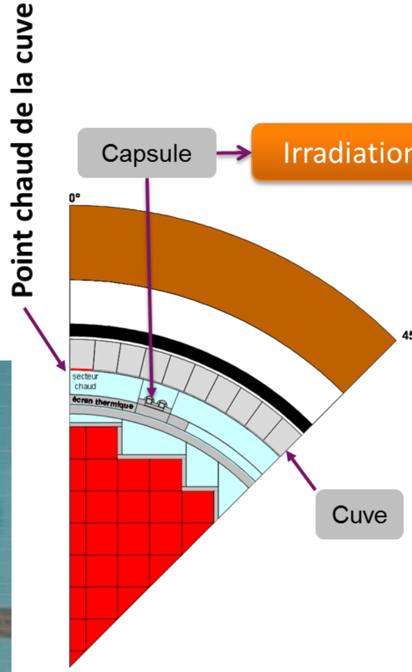
→ Accident situation: SNEAK devices to assess the fluence emitted in a criticality accident

8 - Examples of applications

Survey of the Nuclear Vessel Embrittlement since the 80's

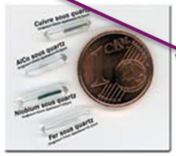






Capsule → Irradiation

Tests sur éprouvettes mécaniques EDF → ΔRT_{ndt}



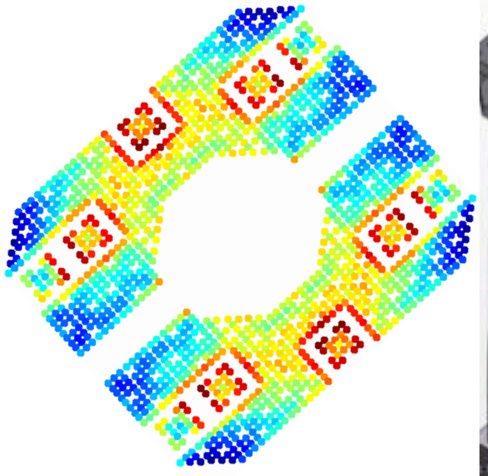
Dosimétrie CEA → $\Phi_{>1\,MeV}$

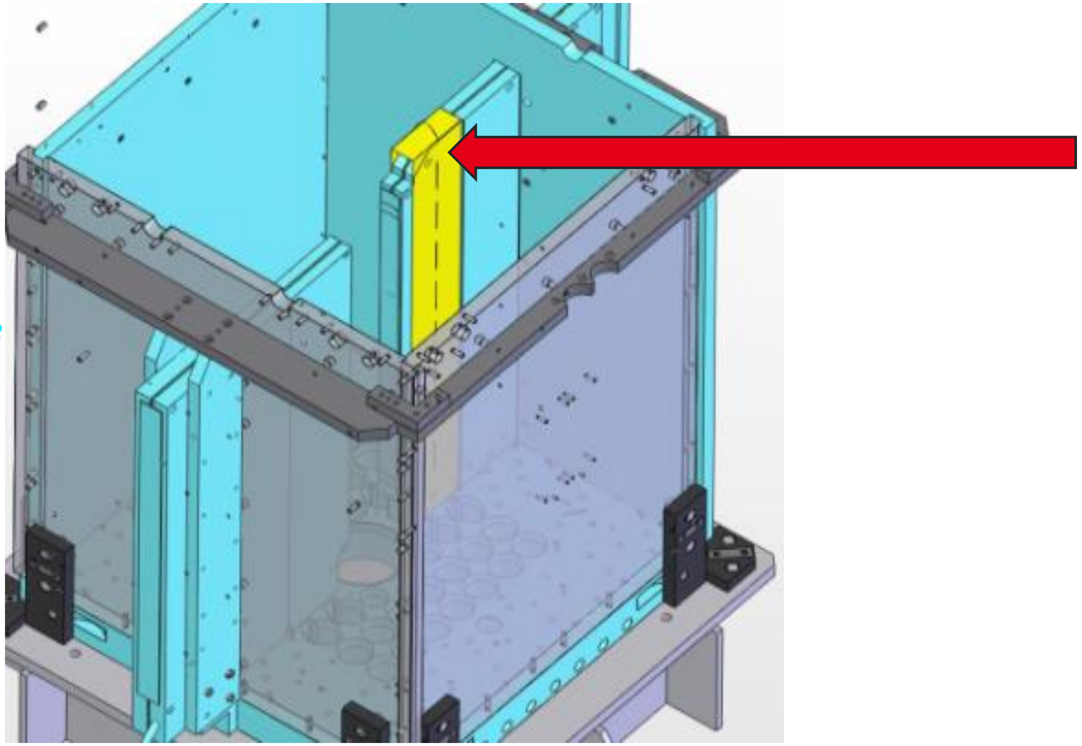
$\Delta RT_{ndt} = f(\Phi_{>1\,MeV}, \text{impuretés})$

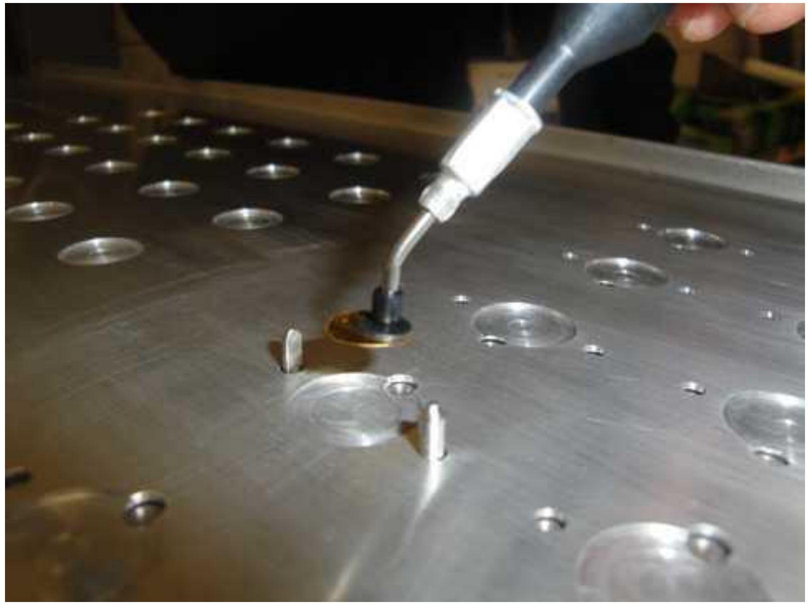
8 - Examples of applications

Mapping of thermal flux for the CABRI start-up

With Au dosimeters



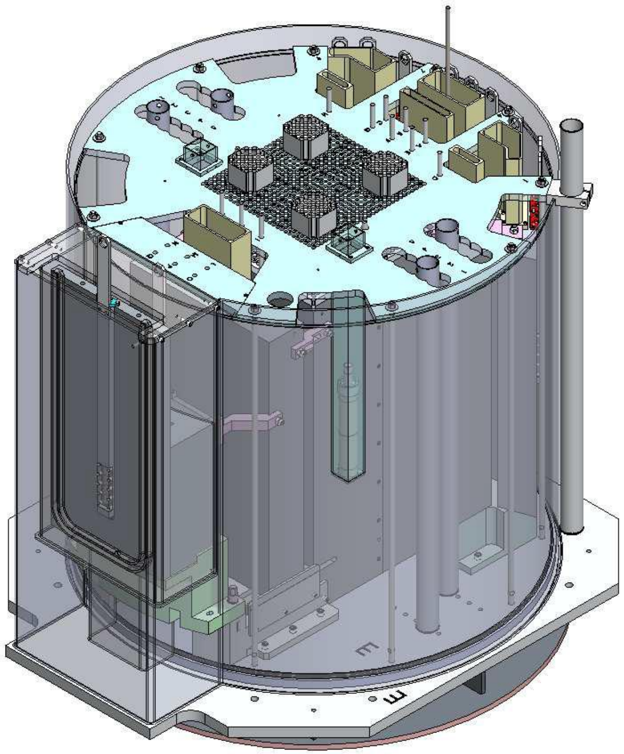




8 - Examples of applications

Characterization of a reactor configuration:
FLUOLE 2 experimental program in EOLE reactor facility (2014 -2015)

More than 800 dosimeters measured for the V&V of a TRIPOLI4® based reactor modelling scheme



EOLE

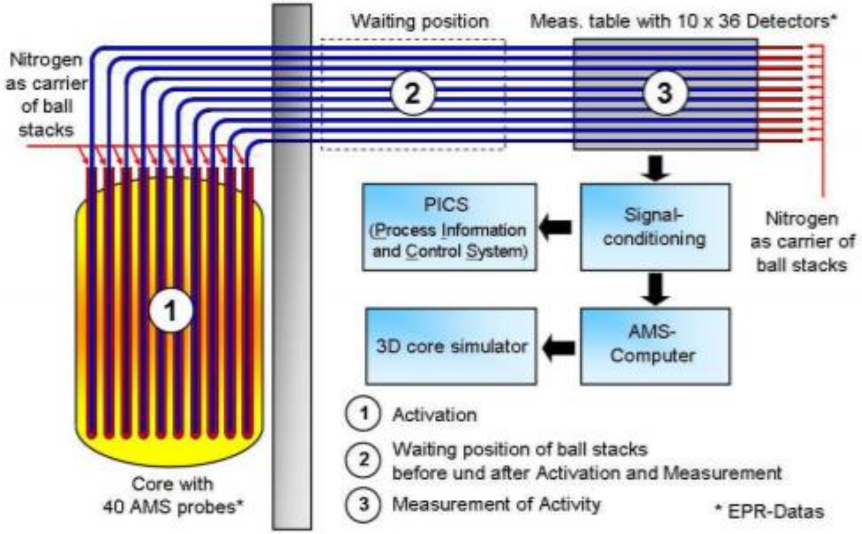
Thermal dosimeter
Co

Epithermal dosimeter
Sn ⇨ 0,3 MeV
Rh ⇨ 0,7 MeV
In ⇨ 1,3 MeV

Fast dosimeter
Ni ⇨ 2,7 MeV
Fe ⇨ 2,8 MeV
Ti ⇨ 4,4 MeV
Al ⇨ 7,3 MeV
V ⇨ 11,0 MeV

8 - Examples of applications

EPR- AMS system



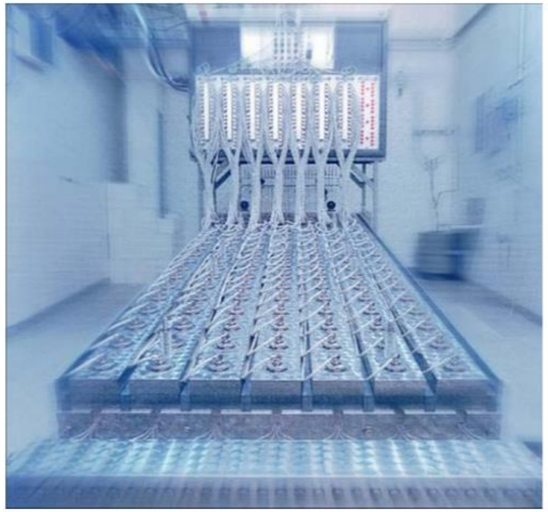
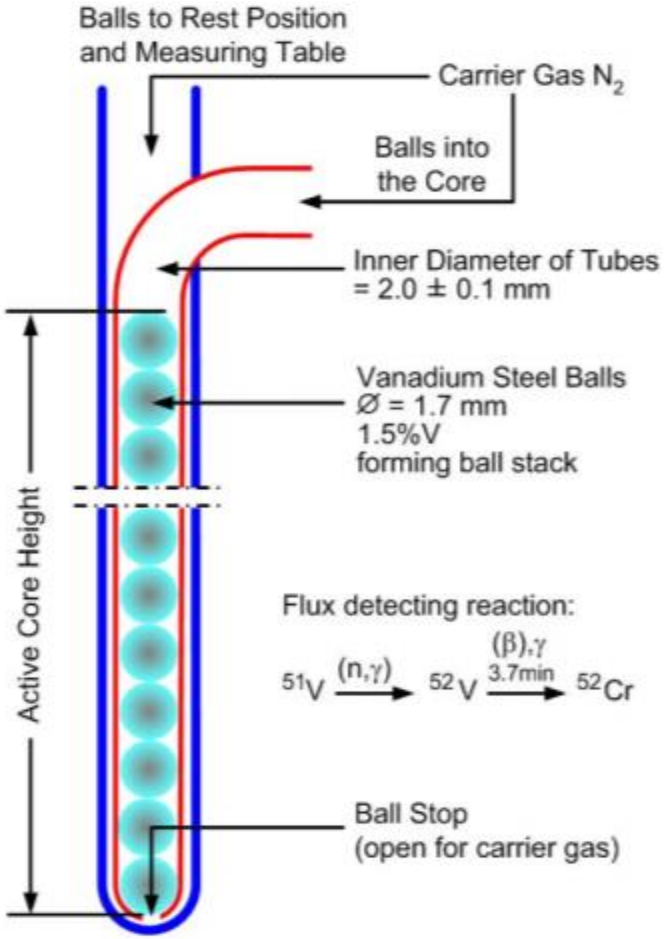


Fig. 4. The Aeroball measuring table with 7 measuring rows. The measurement table of the EPR™ will consist of 10 measuring rows.



→ Periodic calibration of Cobalt SPNDs
→ Periodic Neutron / Power map flux

Table of Contents

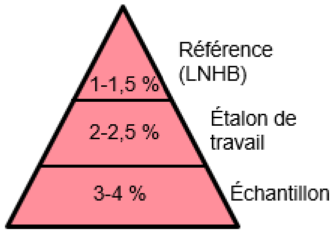
9 - Areas for development

Nuclear Data
IRDFF

Dosimétrie

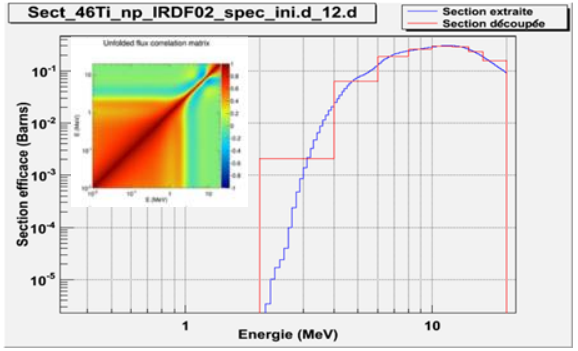
X Spectrometry

→ Nb, Rh Dosimeters
- Fluorescence, ND
- Measurement Techniques



Spectrum Unfolding

→ Covariances Matrices (ϕ et σ)
→ International Benchmark



High Doses and Temperatures

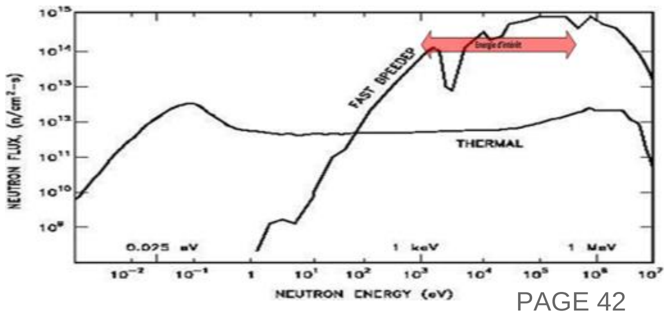
- $\Phi > 10^{20}$ n/cm²
- T° > 500°C

Retrospective Dosimetry

- Measurement Techniques

Epithermal Dosimetry

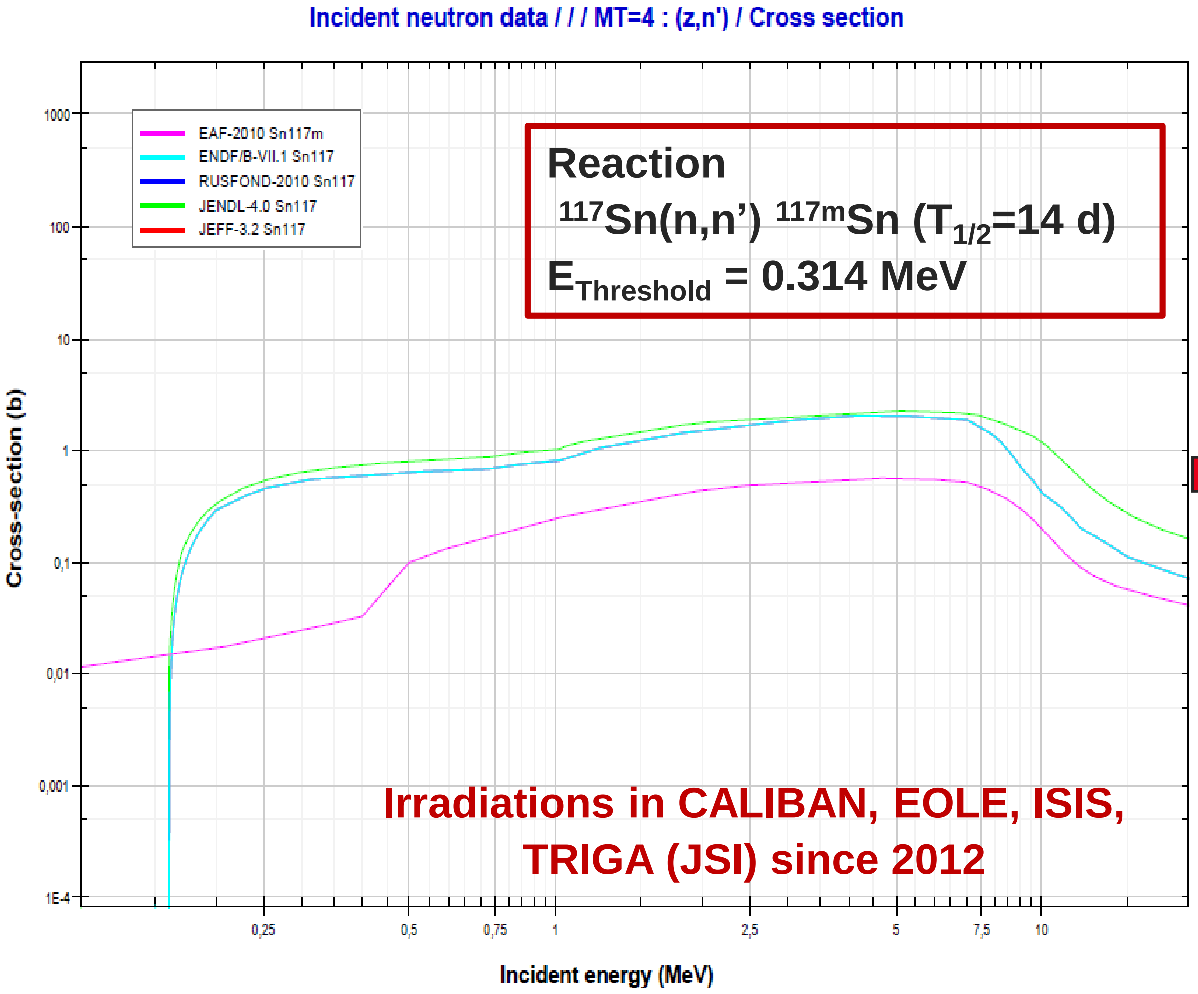
1keV-1MeV Region
→ ^{117}Sn
→ ^{92}Zr



PAGE 42

9 - Areas for development

Enriched 117Sn



Reaction

^{117}Sn(n,n') ^{117m}Sn ($T_{1/2}$=14 d)

$E_{Threshold}$ = 0.314 MeV

Irradiations in CALIBAN, EOLE, ISIS, TRIGA (JSI) since 2012

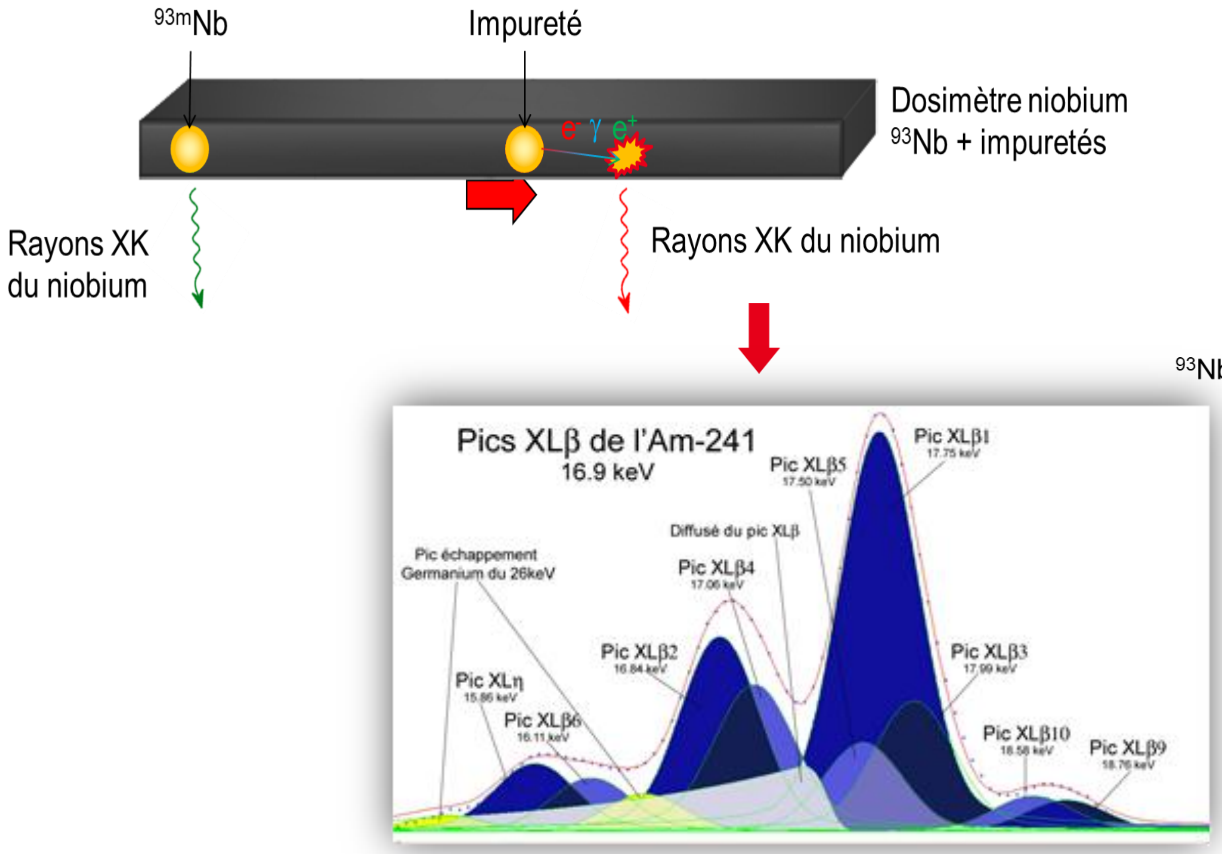
- **Feasability - ok**
- **updated $T_{1/2}$**
- **Improved Measurement Method (ε_A<5%)**
- **C/E < 10%**

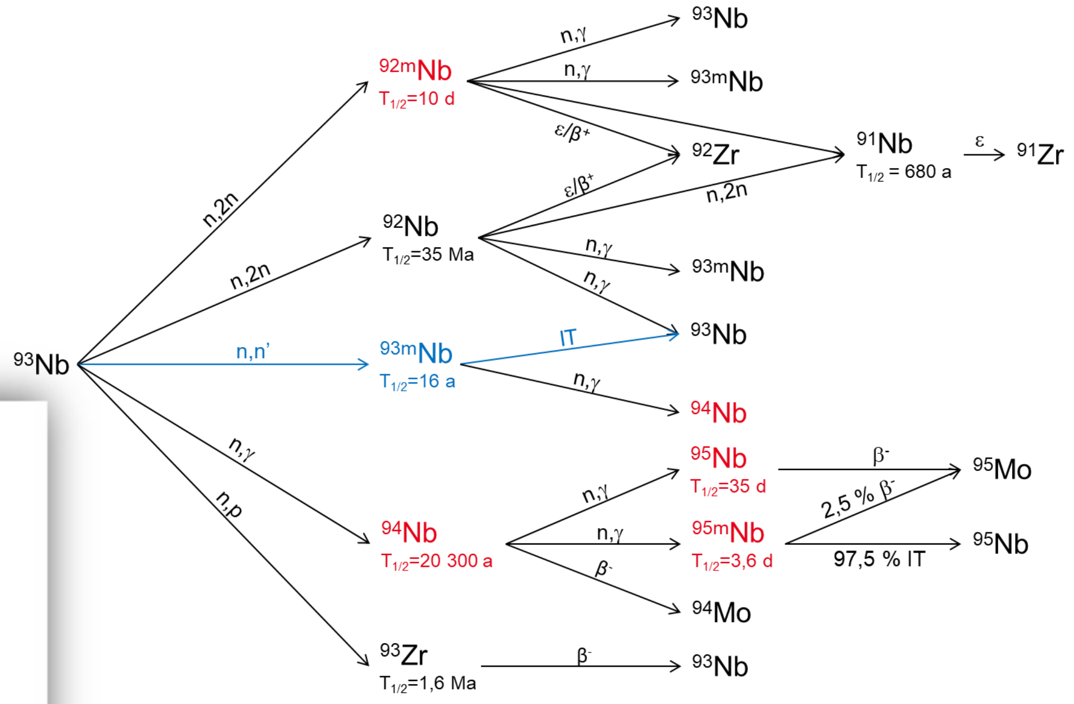
Nuclear data to be Improved (JEFF & IRDFF project)

C. Destouches "Review of nuclear data improvement needs for nuclear radiation measurement techniques used at the CEA experimental reactor facilities" Wonder EPJ Web of Conferences 111 01002 (2016)

9 - Areas for development

Improvement in measurements of X-ray emitter activity (ex Nb)





C. Domergue et al. "Improvement of the activity measurement method for solid dosimeters emitting x-rays" ICRM 2017

J. Riffaud et al. "Measurement of ^{103m}Rh X-ray emission intensities and evaluation of the decay scheme" ICRM 2017

9 - Areas for development

RETROSPECTIVE - DOSIMETRY

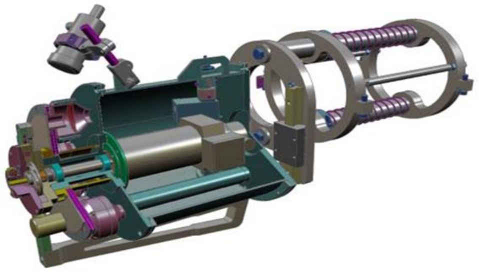
Direct measurement of the activity induced by neutrons on a sample taken from a device of interest (hot spot in the vessel, internals, screw, etc.).

Sample Collection → *Sample Preparation* → *Separation of the daughter radioisotope* → *Activity Measurement* → *Activity Analysis*

Sample Preparation → *Measuring the concentration of parent isotope* → *Activity Analysis*

Irradiation data → *Activity Analysis*

Activity Analysis → *Reaction Rate* → *Neutron Fluence*



- **Accessibility at any location (+)**
- **Prior knowledge of the father isotope concentration(-)**

Table of Contents

10 - Summary and outlook

Reactor Dosimetry

- **Reference post-mortem measurement for determining neutron fluence:**
    - Accurate
    - Absolute
    - Enables the neutron spectrum to be characterised

- **Requires considerable expertise to carry out successfully:**
    - Measurement
    - Modelling
    - Nuclear data

- **Historical method for determining fluxes/fluences, but still relevant today (EPR) and being developed further:**
    - Retro-dosimetry
    - X-measurement
    - Epithermal dosimetry
    - High dose and T° dosimeters
    - Modelling
    - High energies (fusion, accelerators) ... (IRDFF) [3]

We are not measuring a neutron flux but a reaction rate.This gives a flux/fluence value

Thank you !