Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

TAPIRO fast spectrum research reactor for neutron radiation damage analyses

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Layout of the presentation

1. Introduction
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3. The TAPIRO reactor
4. TAPIRO neutronic characterization
5. TAPIRO damage parameters
6. Roundup

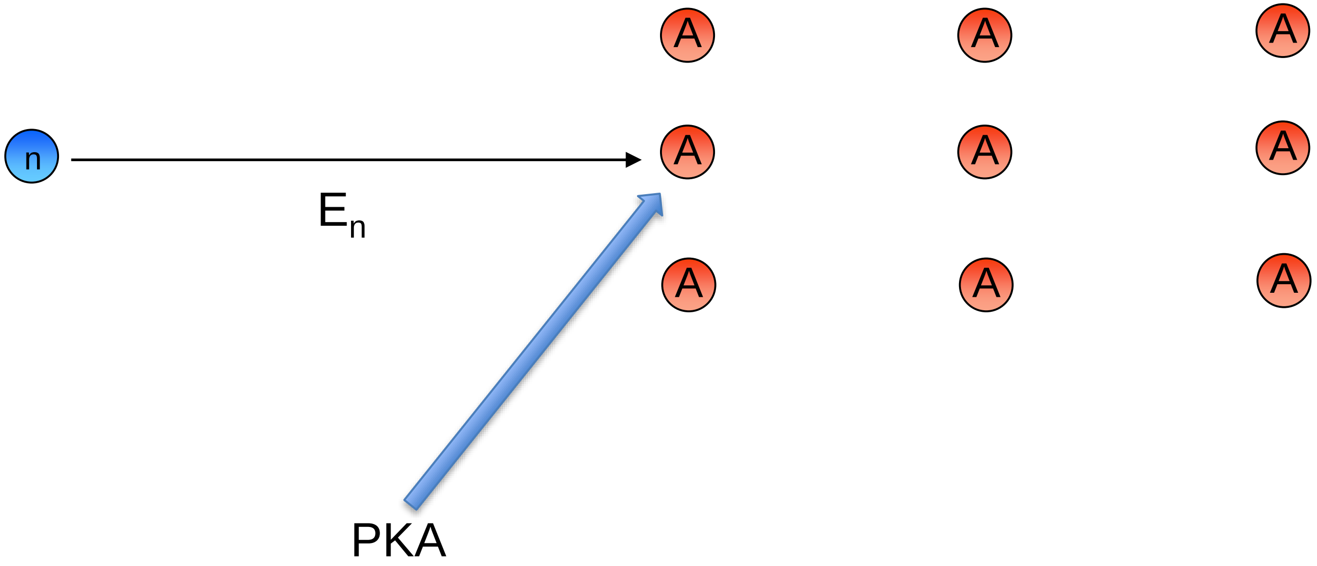
Introduction

- Although Material Testing Reactors (MTRs), having powers greater than 5÷10 MW, are usually selected as radiation fields for neutron radiation damage analysis, nowadays an increasing attention is paid also to low power research reactors because they can provide very qualified, in terms of both intensity and energy spectrum, neutron radiation fields.
- The ENEA low power fast spectrum TAPIRO research reactor, located in the Casaccia Research Center near Rome, Italy, complies with the above quality requirements.
- This paper describes how the neutron flux characterization has been performed in the past at TAPIRO.
- Characteristics of some main ASTM standard damage parameters, such as 1 MeV equivalent neutron flux and hardness parameter, are provided for different positions along the main irradiation channels.

ASTM standard damage functions
The damage mechanism

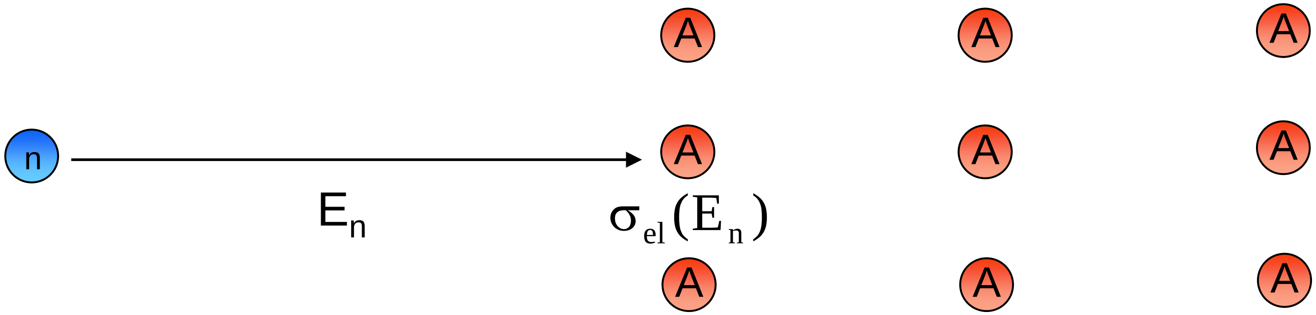
Rate of displacements produced by a Primary Knock-on Atom (PKA)

after elastic (for example) collision with neutrons having energy E_n



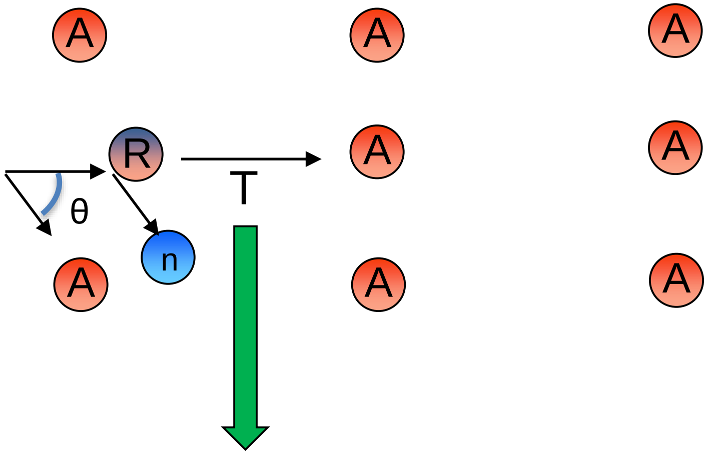
ASTM standard damage functions
The damage mechanism

$$dpa(E_n) \propto \sigma_{el}(E_n) \cdot \phi(E_n)$$



ASTM standard damage functions
The damage mechanism

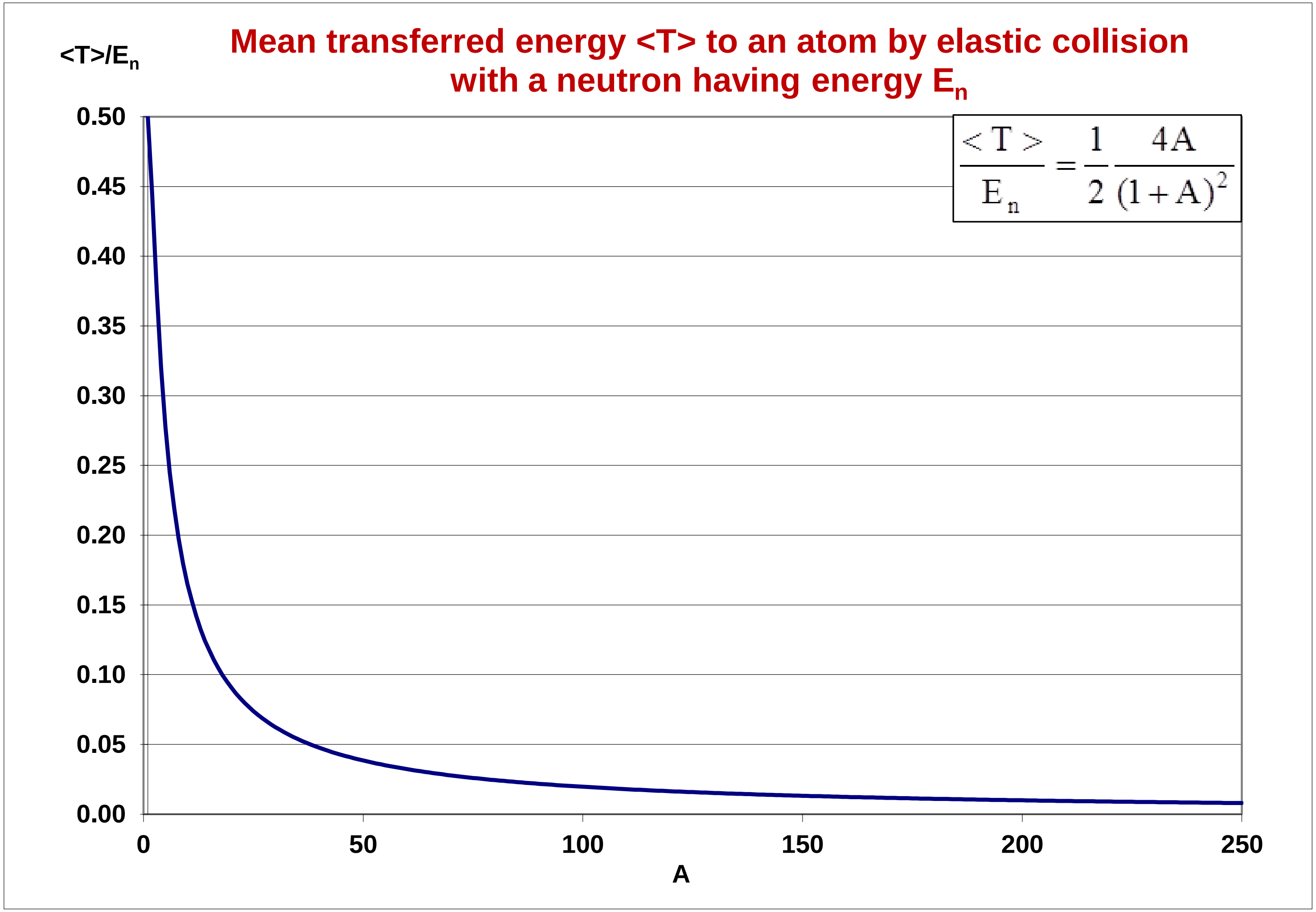
$$\mathrm{dpa}(E_n) \propto \sigma_{el}(E_n) \cdot \phi(E_n)$$



$$T = \frac{1}{2}\Lambda E_n(1-\cos\theta) = \frac{1}{2}\frac{4A}{(1+A)^2}E_n(1-\cos\theta)$$

$$0 \le T \le \Lambda E_n\left(= \frac{4A}{(1+A)^2}E_n\right)$$

ASTM standard damage functions
The damage mechanism

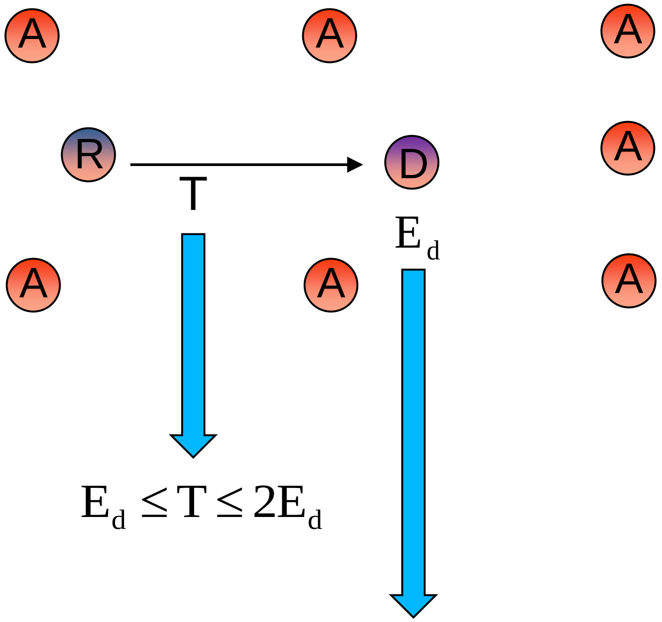


Mean transferred energy <T> to an atom by elastic collision with a neutron having energy E_n

$$\frac{<T>}{E_n} = \frac{1}{2}\frac{4A}{(1+A)^2}$$

ASTM standard damage functions
The damage mechanism

$$\mathrm{dpa}(E_n) \propto \sigma_{el}(E_n) \cdot \phi(E_n)$$

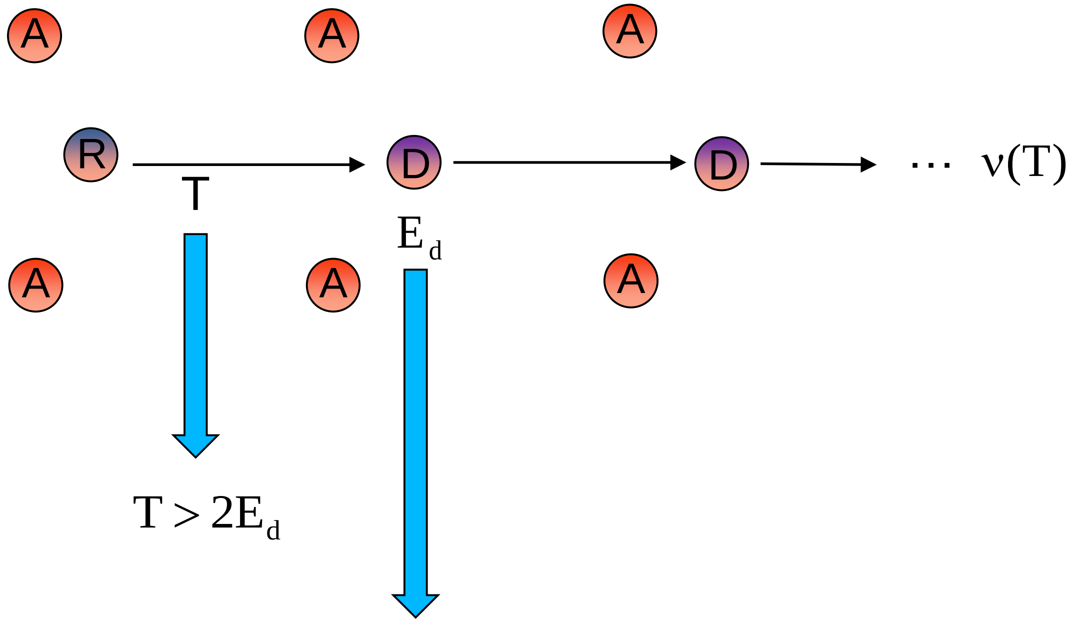


$$E_d \leq T \leq 2E_d$$

average threshold displacement energy for an atom

ASTM standard damage functions
The damage mechanism

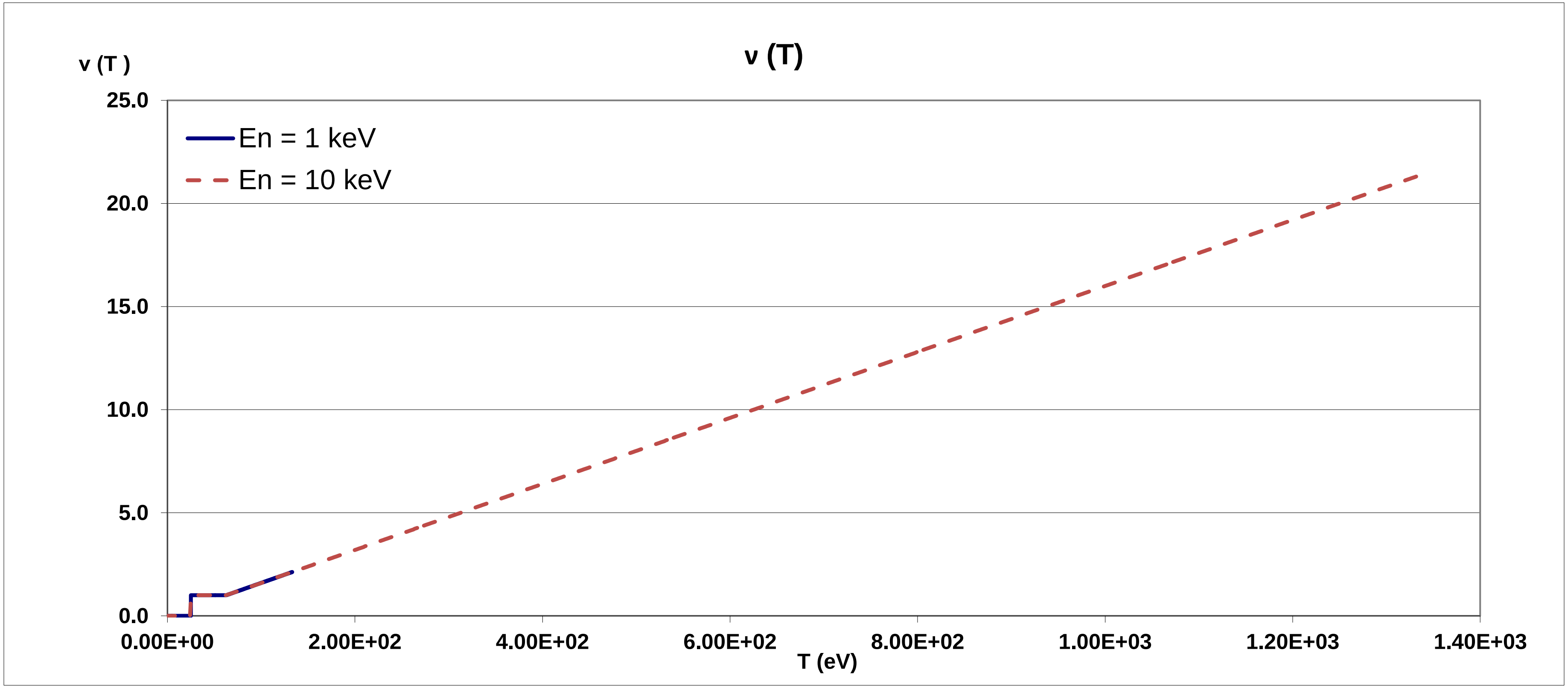
$$dpa(E_n) = \sigma_{el}(E_n) \cdot \phi(E_n) \cdot \int_{E_d}^{\Lambda E_n} P[E_n;T] \cdot \nu(T) \cdot dT$$



$$T > 2E_d$$

average threshold displacement energy for an atom

ASTM standard damage functions
The damage mechanism



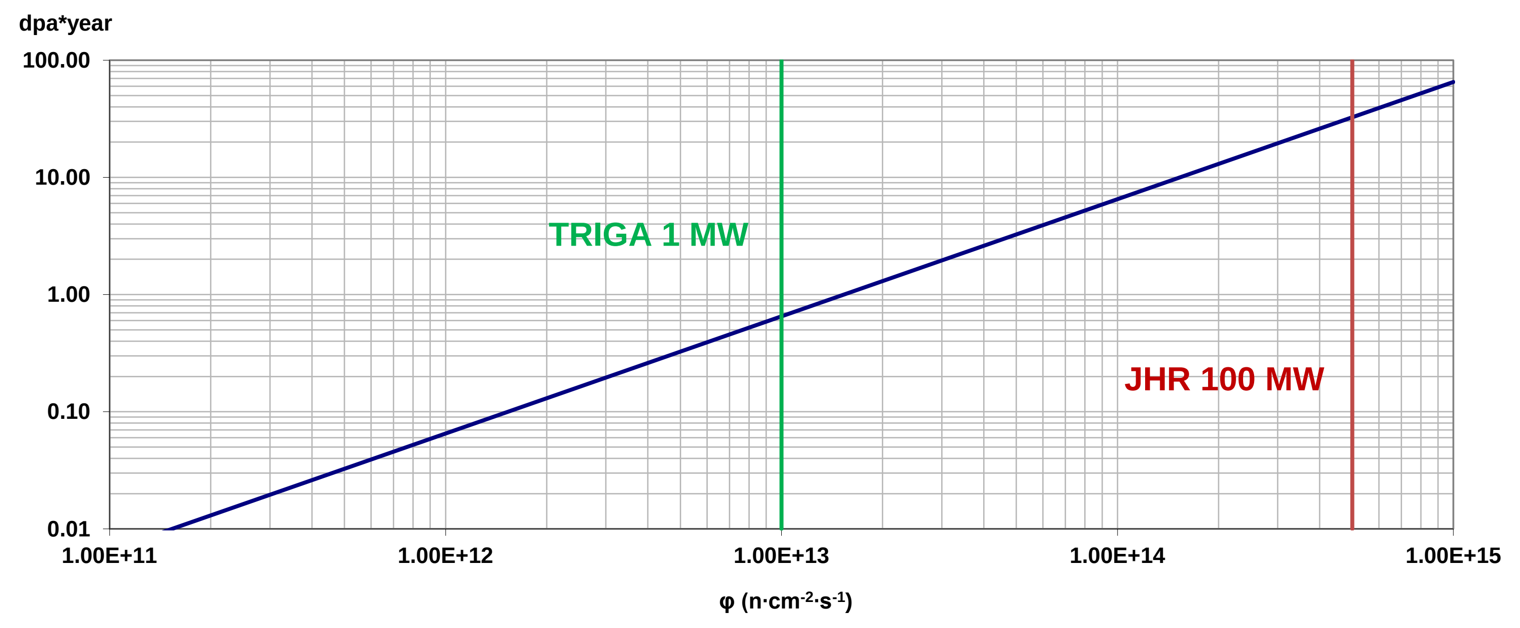
$$\nu(T) = \begin{cases} 0 \quad \text{for} \;\; T < E_d \\ 1 \quad \text{for} \;\; E_d \le T < \dfrac{2}{0.8} E_d \\ 0.8 \dfrac{T}{2E_d} \quad \text{for} \quad \dfrac{2}{0.8} E_d \le T \le \Lambda E_n \end{cases}$$

ASTM standard damage functions
The damage mechanism

An approximate relation is:

$$\mathrm{dpa}(\Delta t) = \frac{\Lambda < E_n >}{4E_d} < \sigma_{el} >< \phi > \Delta t$$

For example, assuming for ^{27}Al $<\sigma_{el}> = 3$ barn, $<E_n> = 0.5$ MeV, $E_d = 25$ eV, $\Delta t = 1$ year we obtain the figure below for different flux intensities.



ASTM standard damage functions
KERMA functions

In general a PKA will generate a cascade of ν displacements. This cascade will deposit in the lattice a damage energy $E_D(T)$, also indicated as partition energy, proportional to the PKA energy T, given by:

$$E_D(T) = T \cdot L(T)$$

where L(T) is the Lindhard partition function. It can be defined a displacement KERMA (Kinetic Energy Released in MAterials) function (units [barn·eV]) for neutron collisions. This function F_D provides the rate, following neutron collisions, of deposit in the lattice of a damage energy $E_D(T)$, for unit atom and unit flux.

$$\boxed{F_D(E_n)} = \sigma_{el}(E_n) \int P(E_n;T) \cdot T \cdot L(T) \cdot dT \quad [\mathrm{barn} \cdot \mathrm{eV}]$$

ASTM Standards

ASTM standard damage functions
KERMA functions

ASTM standard damage functions
KERMA functions

In general we’ll have for a certain neutron flux, being N the atomic density of the material:

$$w_D = N\int F_D(E_n)\cdot\phi(E_n)dE_n \quad [eV\cdot cm^{-3}\cdot s^{-1}]$$

where w_D is the rate, following neutron collisions, of deposit in the lattice of the damage energy density. w_D has units [eV·cm^{-3}·s^{-1}]. It can be noticed that w_D is a “damage” power density. For an interval time Δt we have:

$$D = N\cdot\Delta t\int F_D(E_n)\cdot\phi(E_n)dE_n \quad [eV\cdot cm^{-3}]$$

ASTM standard damage functions
1 MeV equivalent flux

For a certain position of the system we can define a monochromatic flux with energy E_{ref} given by :

$$\phi_{eq}(\mathbf{r}, E_n)\delta(E_n - E_{ref})$$

having the properties to produce the same damage power at the same position of the system:

$$W_{D,eq,ref}(\mathbf{r}) = F_D(E_{ref}) \cdot \phi_{eq}(\mathbf{r}, E_{ref}) = W_D(\mathbf{r}) = \int F_D(E_n) \cdot \phi(\mathbf{r}, E_n) dE_n$$

This flux it's named the E_{ref} equivalent flux. In particular, if E_{ref}=1 MeV, we'll have:

$$F_D(1\,\mathrm{MeV}) \cdot \phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV}) = \int F_D(E_n) \cdot \phi(\mathbf{r}, E_n) dE_n$$

Or:

$$\phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV}) = \frac{\int F_D(E_n) \cdot \phi(\mathbf{r}, E_n) dE_n}{F_D(1\,\mathrm{MeV})}$$

and this flux it's named the 1 MeV equivalent flux.

ASTM standard damage functions
Spectrum hardness parameter

We can define a neutron spectrum hardness parameter as:

$$H(\mathbf{r}) = \frac{\phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV})}{\int \phi(\mathbf{r}, E_n)dE_n}$$

$$H < 1 \quad \Rightarrow \quad \phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV}) < \int \phi(\mathbf{r}, E_n)dE_n$$

We need less 1 MeV neutrons to produce the same damage produced by the system neutron spectrum. The system neutron spectrum tends to be "softer " respect 1 MeV eq.

$$H = 1 \quad \Rightarrow \quad \phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV}) = \int \phi(\mathbf{r}, E_n)dE_n$$

The same 1 MeV or system neutron spectrum neutrons are needed to produce the same damage. The system neutron spectrum tends to be "damage analogous" respect 1 MeV eq.

$$H > 1 \quad \Rightarrow \quad \phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV}) > \int \phi(\mathbf{r}, E_n)dE_n$$

We need more 1 MeV neutrons to produce the same damage produced by the system neutron spectrum. The system neutron spectrum tends to be harder " respect 1 MeV eq.

ASTM standard damage functions
The role of low power research reactors (LPPRs)

To accurately evaluate these damage parameter we have to accurately know:

- Reactor spectrum, which in turns depends on reactor materials and geometrical complexity, plus nuclear data
- Damage mechanisms, including annealing times

$$\mathrm{dpa}(\Delta t) = \Delta t \sum_k < \nu_k > < \sigma_k > < \phi >$$

$$w_D = N \sum_k \int F_{D,k}(E_n) \cdot \phi(E_n)\, dE_n \quad [\mathrm{eV} \cdot \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1}]$$

$$D = N \cdot \Delta t \sum_k \int F_{D,k}(E_n) \cdot \phi(E_n)\, dE_n \quad [\mathrm{eV} \cdot \mathrm{cm}^{-3}]$$

The challenge for LPRRs, providing largely less damage respect to High Power Research Reactors, is to try to compensate this lack in damage level by a higher accuracy in experimental data.

The TAPIRO reactor
What it means TAPIRO?

TAPIRO (Tapir in English)?

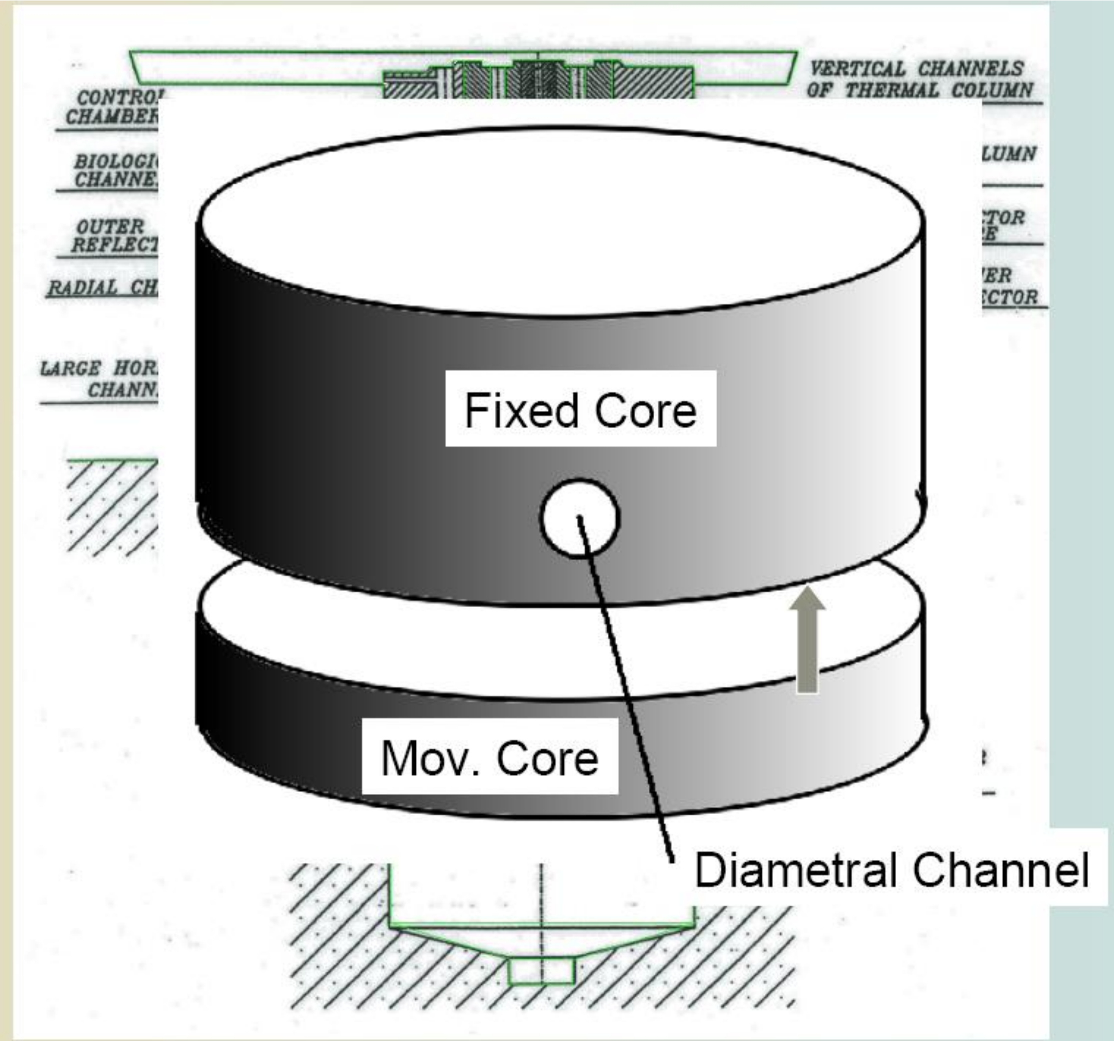
Taratura Pila Rapida a potenza zerO

Fast Pile Calibration at Zero Power

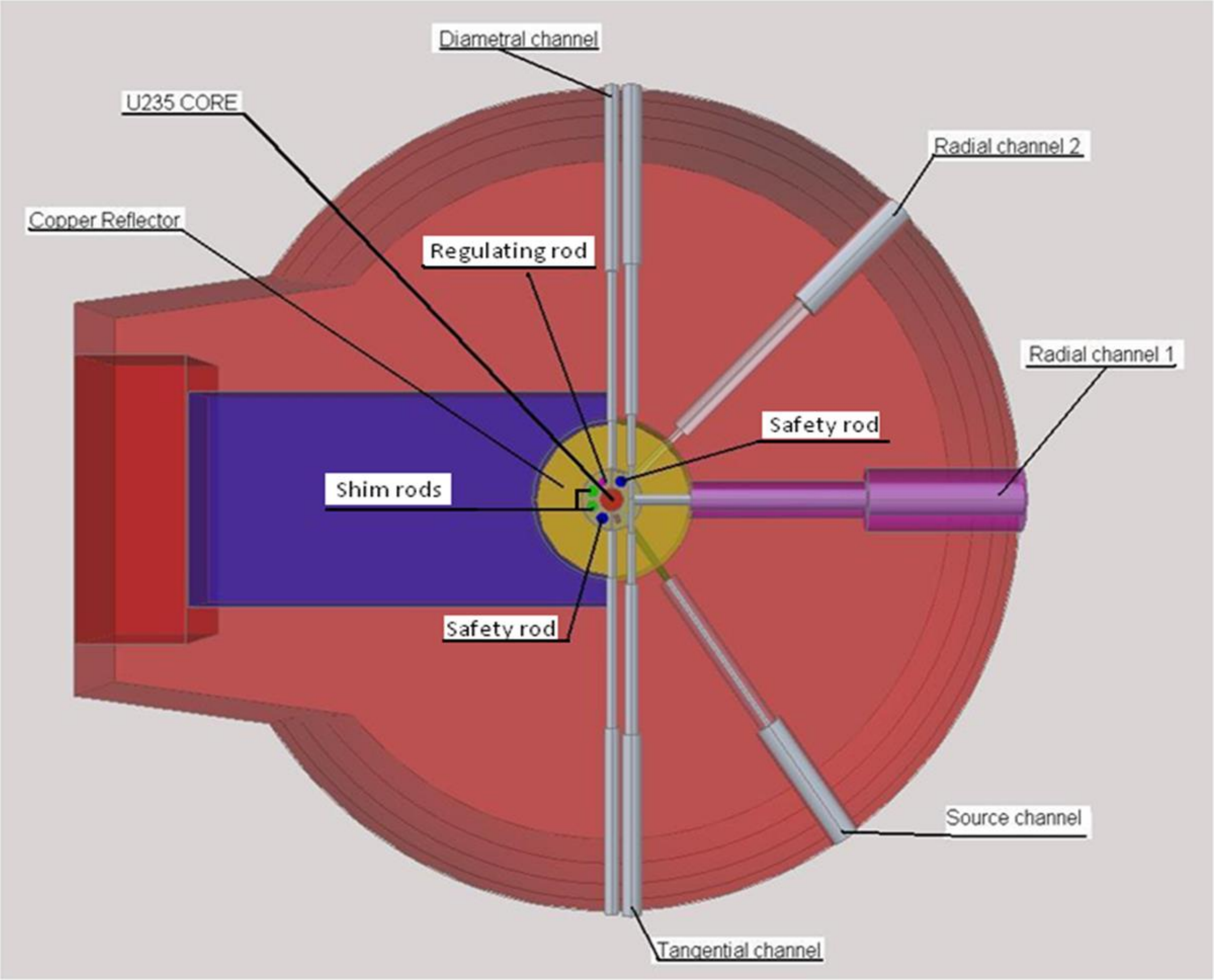
The TAPIRO reactor
Origins

- Fast source reactor
- Based on the concept of AFSR (Argonne Fast Source Reactor - Idaho Falls)
- Designed by ENEA's staff
- Start-up: 1971

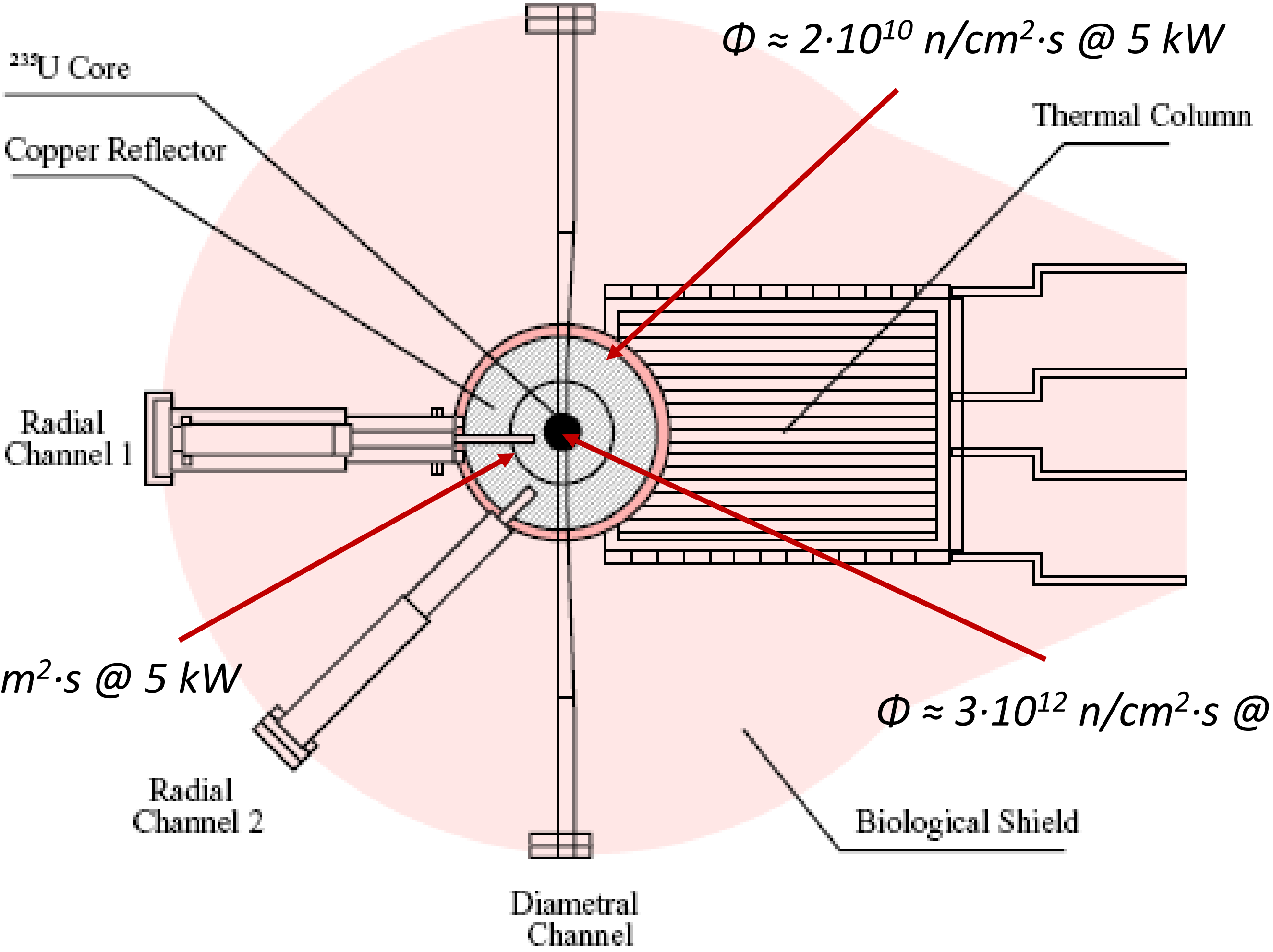
The TAPIRO reactor
Core layout



The TAPIRO reactor
Experimental channels



The TAPIRO reactor
Neutronic features



$\Phi \approx 2 \cdot 10^{10}$ $n/cm^2 \cdot s$ @ 5 kW

$\Phi \approx 5 \cdot 10^{11}$ $n/cm^2 \cdot s$ @ 5 kW

$\Phi \approx 3 \cdot 10^{12}$ $n/cm^2 \cdot s$ @ 5 kW

TAPIRO neutronic characterization
Theoretical basis

For a given position k in the reactor and for the i detector all integral experimental techniques measure quantities of the type:

$$I_{i,k} = \int_E r_i(E)\phi_k(E)dE$$

Where $r_i(E)$ is the differential-energy response of the i detector and $I_{i,k}$ is the integral response.

TAPIRO neutronic characterization
Theoretical basis

$$I_{i,k} = \int_E r_i(E)\, \phi_k(E)dE$$

Two broad classes of integral data need to be distinguished:

1. Integral reaction rates where:

$$r_i(E) = \sigma_i(E)$$

1. Equivalent fission fluxes where (in case of fast reactors):

$$r_i(E) = \frac{\sigma_i(E)}{\int_E \sigma_i(E)\phi_{\chi_{235}}(E)dE \Big/ \int_E \phi_{\chi_{235}}(E)dE} = \frac{\sigma_i(E)}{\overline{\sigma}_{i,\chi_{235}}}$$

In the second relation $\phi_{\chi_{235}}$ denotes a pure ^{235}U fission spectrum.

TAPIRO neutronic characterization
Theoretical basis

In the first case we have:

$$I_{i,k} = R_{i,k} = \int_{E} \sigma_i(E)\phi_k(E)dE$$

In the second case we have:

$$I_{i,k} = \phi^{EQ}_{i,k} = \int_{E} \frac{\sigma_i(E)}{\overline{\sigma}_{i,\chi_{235}}}\phi_k(E)dE = \frac{R_{i,k}}{\overline{\sigma}_{i,\chi_{235}}}$$

TAPIRO neutronic characterization
Theoretical basis

If the observed counting rates from the detectors are given by:

$$c_{i,k} = \varepsilon_{i,k} N_i \int_E \sigma_i(E)\phi_k(E)dE$$

$$c_{i,\chi_{235}} = \varepsilon_{i,\chi_{235}} N_i \int_E \sigma_i(E)\phi_{\chi_{235}}(E)dE$$

And if the efficiencies ε are equal we can write:

$$\frac{c_{i,k}}{c_{i,\chi_{235}}} = \frac{\int_E \sigma_i(E)\phi_k(E)dE}{\int_E \sigma_i(E)\phi_{\chi_{235}}(E)dE}$$

Or:

$$\phi_{i,k}^{EQ} = \frac{c_{i,k}}{c_{i,\chi_{235}}} \int_E \phi_{\chi_{235}}(E)dE \equiv \frac{c_{i,k}}{c_{i,\chi_{235}}} < \phi_{\chi_{235}} >$$

TAPIRO neutronic characterization
Benchmark-Field Referencing

This is the base concept of “Benchmark-Field Referencing” (inter-laboratories experimental campaign). Reaction rates in TAPIRO have been obtained by:

$$\boxed{R_{i,k} = \overline{\sigma}_{i,\chi_{235}} \phi_{i,k}^{EQ} = c_{i,k}\left(\frac{\overline{\sigma}_{i,\chi_{235}}}{c_{i,\chi_{235}}} < \phi_{\chi_{235}} > \right)}$$

TAPIRO neutronic characterization

Flux Maintenance

$$\boxed{R_{i,k} = \overline{\sigma}_{i,\chi_{235}} \phi^{EQ}_{i,k} = c_{i,k}\left(\frac{\overline{\sigma}_{i,\chi_{235}}}{c_{i,\chi_{235}}} < \phi_{\chi_{235}} > \right)}$$

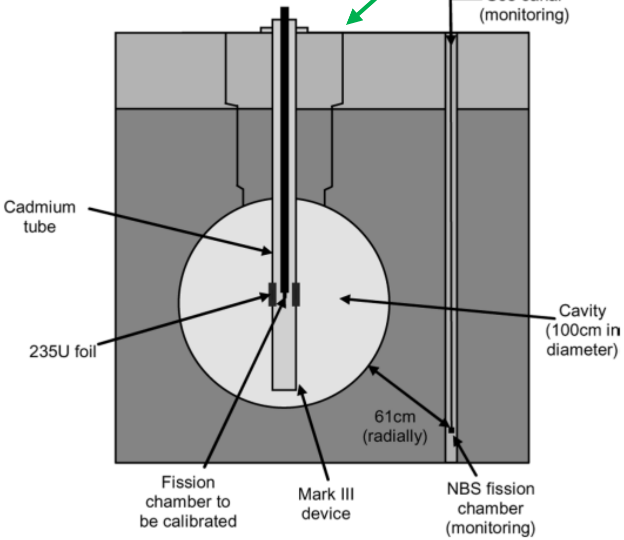
$$< \phi_{\chi_{235}} > = \frac{c_{i,\chi_{235}}}{c_{i,Cf(R)}} \frac{\overline{\sigma}_{i,Cf(R)}}{\overline{\sigma}_{i,\chi_{235}}} \frac{S_{Cf}}{4\pi R^2}$$

NBS (USA)

The activity “Flux Maintenance” (at SCK•CEN Mol – Belgium) allowed the certification of the value $\phi_{\chi_{235}}$ in cooperation with US NBS (National Bureau of Standards).

TAPIRO neutronic characterization
Detectors calibration at SCK•CEN Mol

$$R_{i,k} = \overline{\sigma}_{i,\chi_{235}} \phi^{EQ}_{i,k} = c_{i,k} \left(\frac{\overline{\sigma}_{i,\chi_{235}}}{c_{i,\chi_{235}}} < \phi_{\chi_{235}} > \right)$$



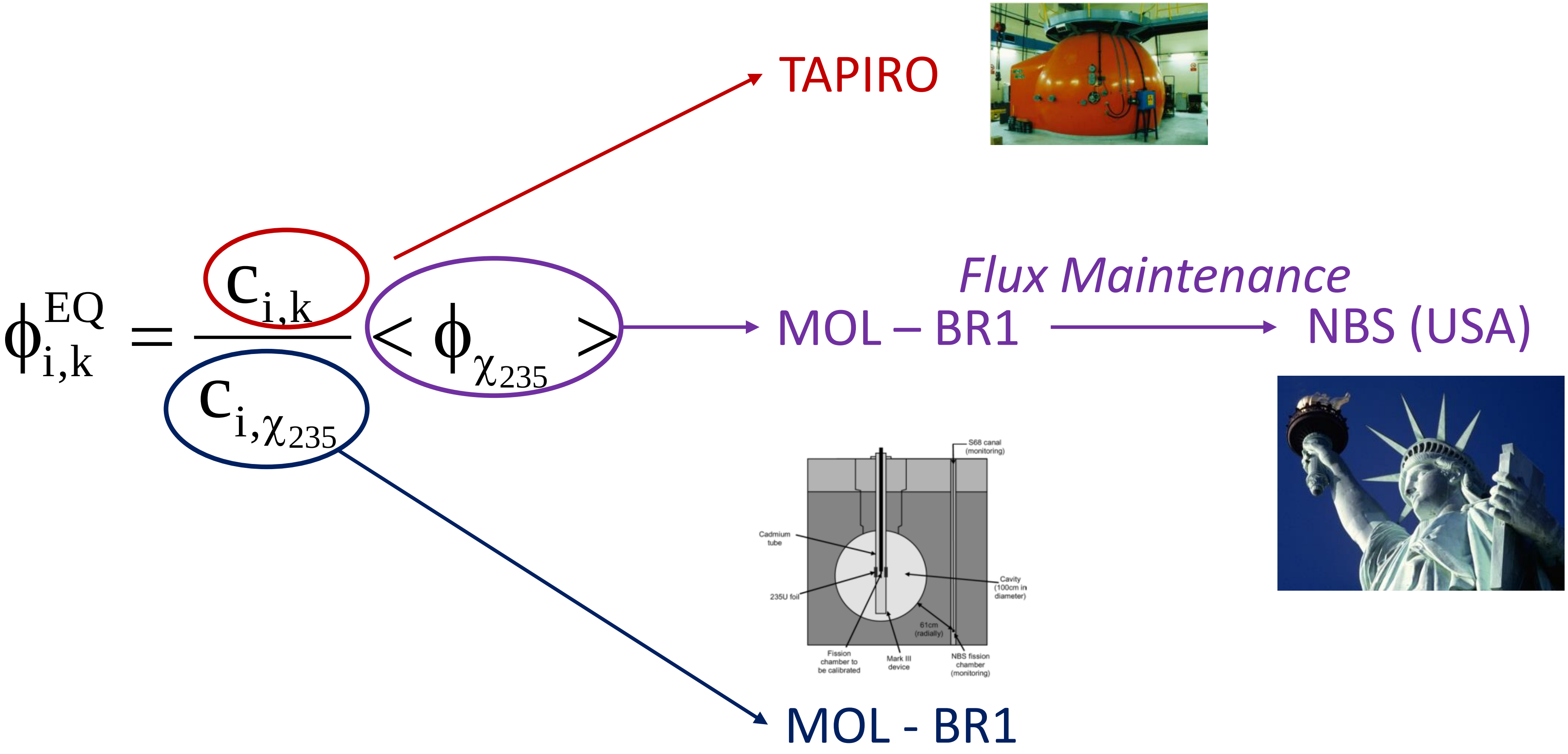
SCK•CEN Mol Cavity ^{235}U Fission Spectrum Standard Neutron Field

TAPIRO neutronic characterization
TAPIRO measurements

$$R_{i,k} = \overline{\sigma}_{i,\chi_{235}} \phi^{EQ}_{i,k} = c_{i,k} \left(\frac{\overline{\sigma}_{i,\chi_{235}}}{c_{i,\chi_{235}}} < \phi_{\chi_{235}} > \right)$$

TAPIRO neutronic characterization
Overall philosophy

Benchmark-Field Referencing



$$\phi_{i,k}^{EQ} = \frac{C_{i,k}}{C_{i,\chi_{235}}} < \phi_{\chi_{235}} >$$

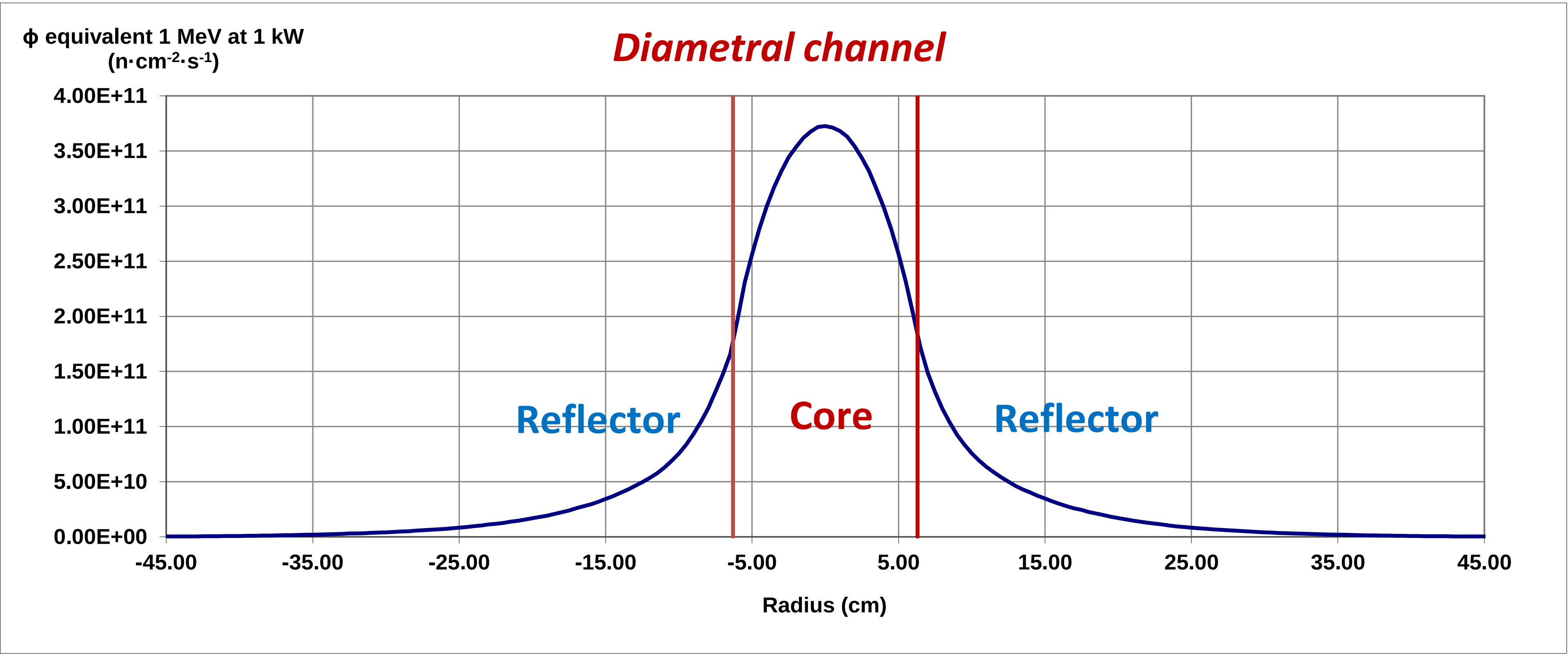
TAPIRO

Flux Maintenance

MOL – BR1 → NBS (USA)

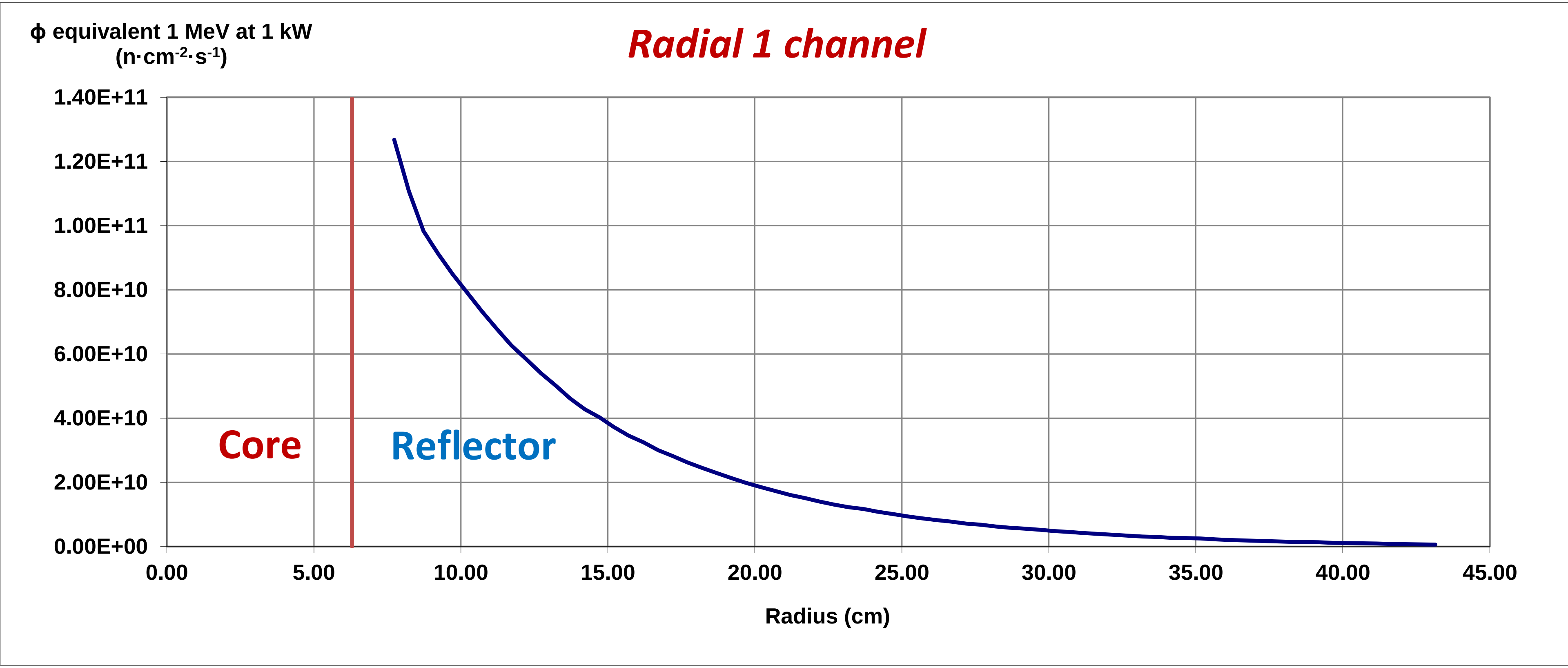
MOL - BR1

TAPIRO damage parameters
Equivalent 1 MeV neutron flux



$$\phi_{eq}(\mathbf{r},1\,\mathrm{MeV}) = \frac{\int F_D(E_n)\cdot\phi(\mathbf{r},E_n)\,dE_n}{F_D(1\,\mathrm{MeV})}$$

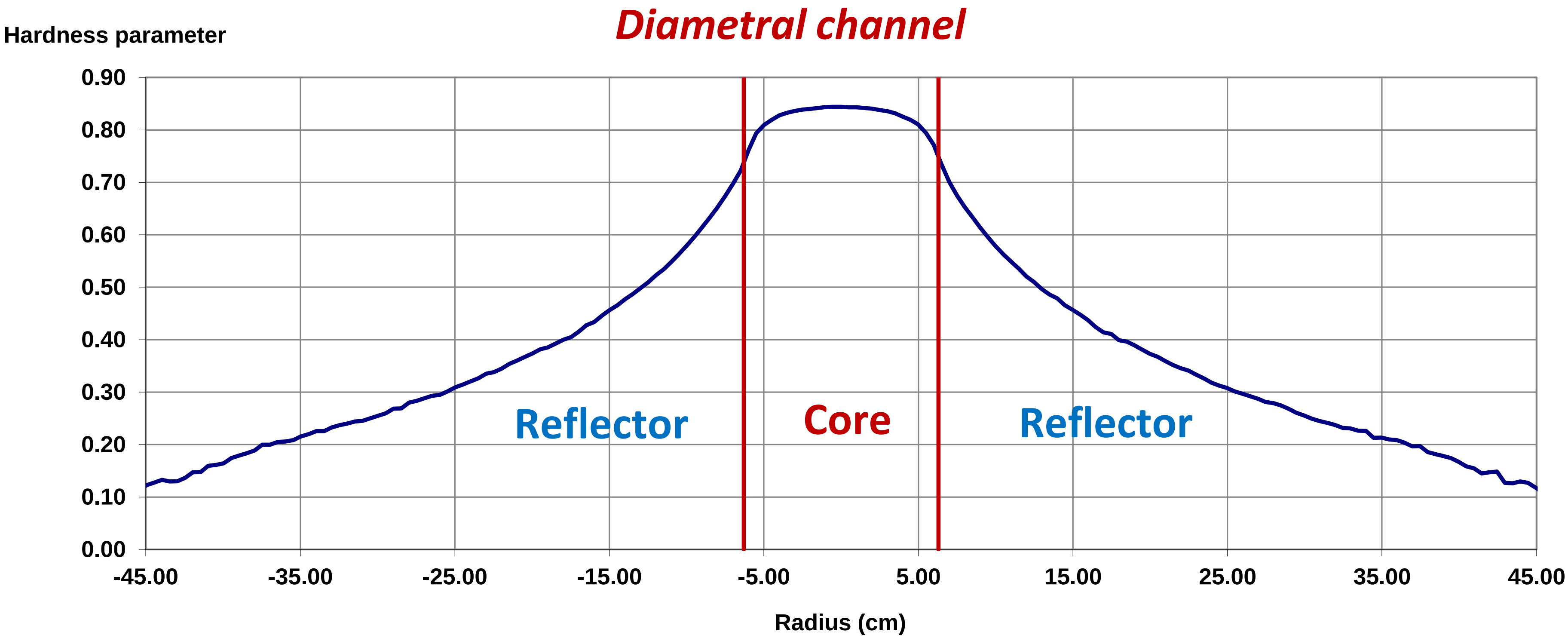
TAPIRO damage parameters
Equivalent 1 MeV neutron flux



$$\phi_{eq}(\mathbf{r},1\,\mathrm{MeV}) = \frac{\int F_D(E_n)\cdot\phi(\mathbf{r},E_n)dE_n}{F_D(1\,\mathrm{MeV})}$$

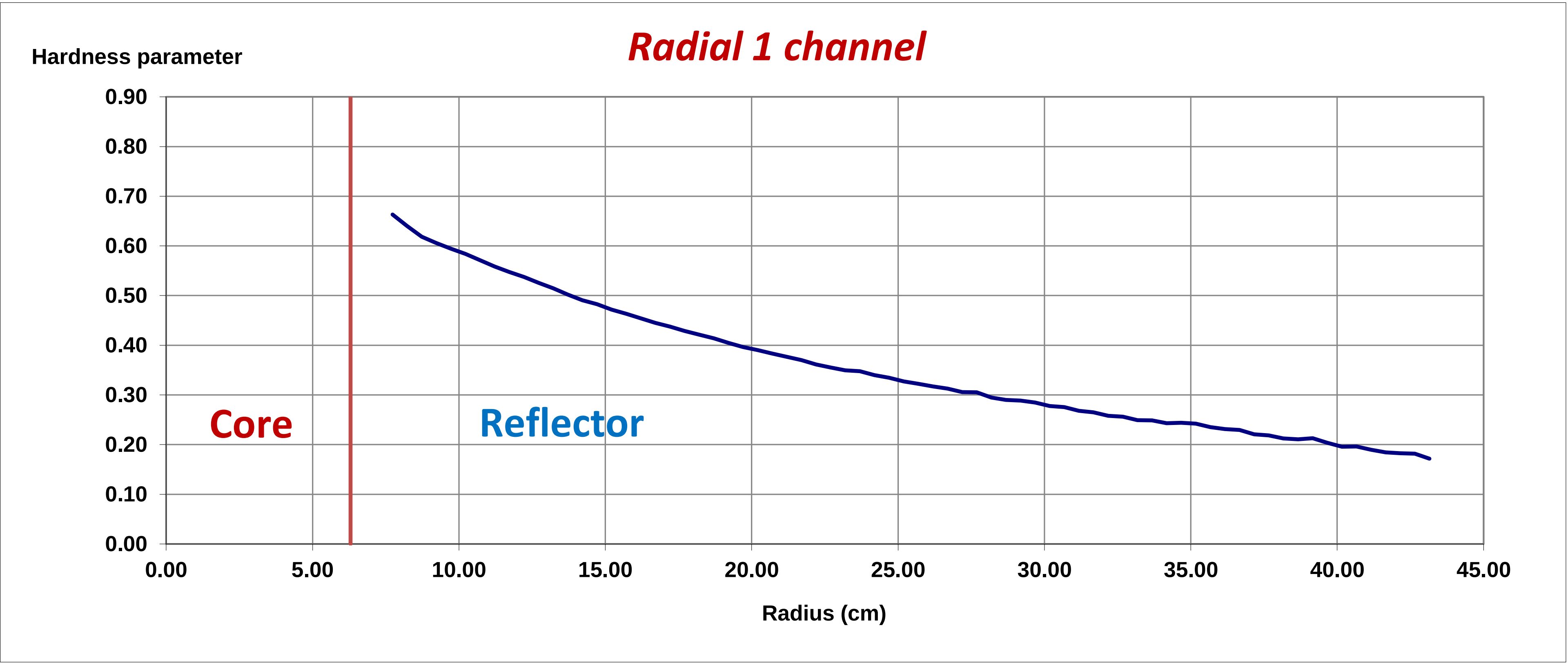
TAPIRO damage parameters

Hardness parameter



$$H(\mathbf{r}) = \frac{\phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV})}{\int \phi(\mathbf{r}, E_n)\,dE_n}$$

TAPIRO damage parameters
Hardness parameter



$$H(\mathbf{r}) = \frac{\phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV})}{\int \phi(\mathbf{r}, E_n)\,dE_n}$$

Roundup

- Usually MTRs, having significant powers up to hundreds of MW, are selected as radiation fields for neutron radiation damage analysis. However when a high quality is needed in terms of knowledge of both intensity and energy spectrum of the neutron field, LPRRs can play their role.
- ENEA TAPIRO fast neutron source reactor has particular features which match with the above quality requirements, thanks to the neutronic characterization performed following the so-called "Benchmark-Field Referencing” approach.
- TAPIRO damage parameters, in particular 1 MeV equivalent neutron flux and hardness parameter, show that TAPIRO is well suited for neutronic irradiation damage analyses (at low power).
- Also 1 MW TRIGA RC-1 reactor at ENEA – Casaccia is candidate to perform neutron irradiations for damage analysis, especially at the core center, and feasibility studies are currently going on.

Thank you for your attention!

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