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

The Role of Low Power Research Reactors in Material (and Fuel Cycle) R&D

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3. Some examples of LPRRs supporting programs for Innovative Nuclear Energy Systems
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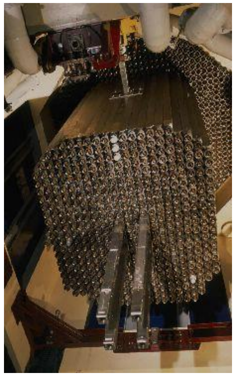
Introduction

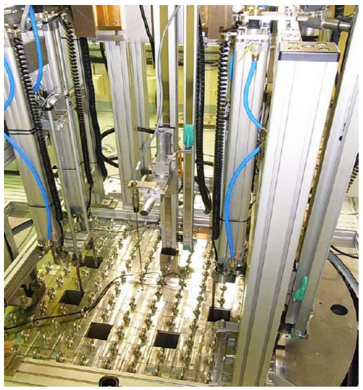
- This introduction is intentionally short, in practice telegraphic. This will be a long speech, and in my view I would like to provide you not merely a cold review about what Low Power Research Reactors (LPRRs) can do for their role in Material (and Fuel Cycle) R&D, but also trying to provide you with some tips about the physics behind some experimental programmes (in this area) carried out in LPRRs.
- As you already know from previous presentations (LPRRs) are those facilities having a power < 5MW. In particular, facilities having power of some kW are named “zero power” facilities.
- Even if in this presentation you’ll see not only phrases and figures but also formulas () ,I hope to hold your attention up to the coffee break time.
- In any case the first formula is at slide number 20, so you can start relaxed.

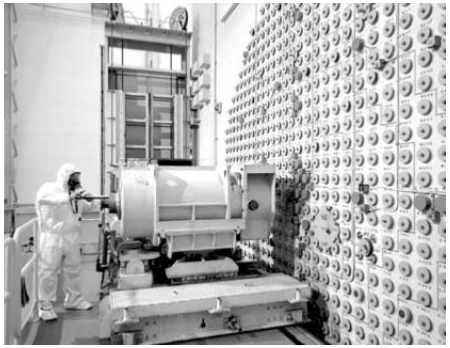
Utilization of LPRRs
Non nuclear oriented applications
Overview

Some fields of application are:

- ✓Education & Training
- ✓Neutron Activation Analysis
- ✓Silicon doping
- ✓Radioisotope production
- ✓Neutron radiography
- ✓Gem coloration
- ✓Geochronology
- ✓Neutron Therapy







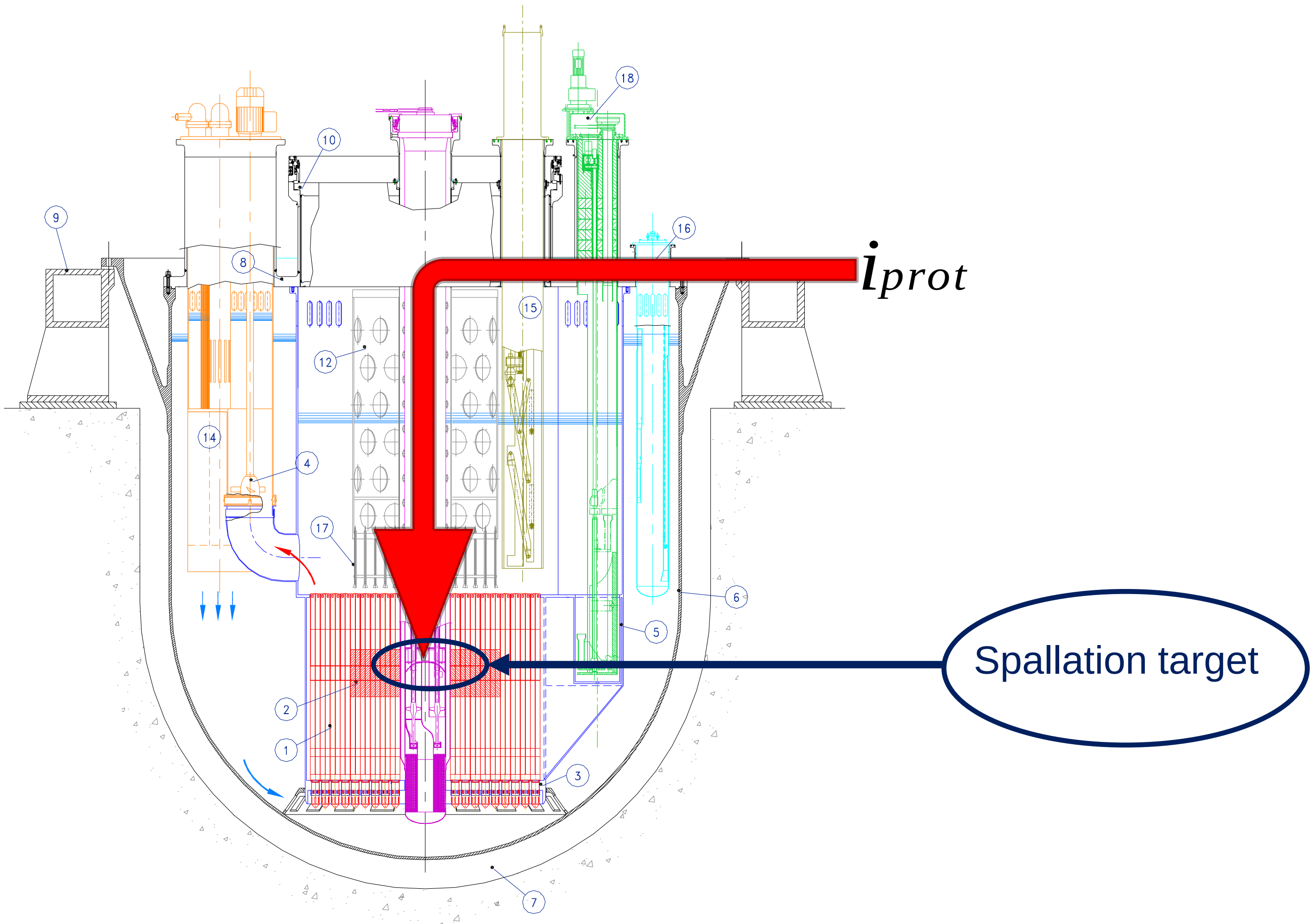
Utilization of LPRRs
Nuclear oriented applications
Overview

Some fields of application are:

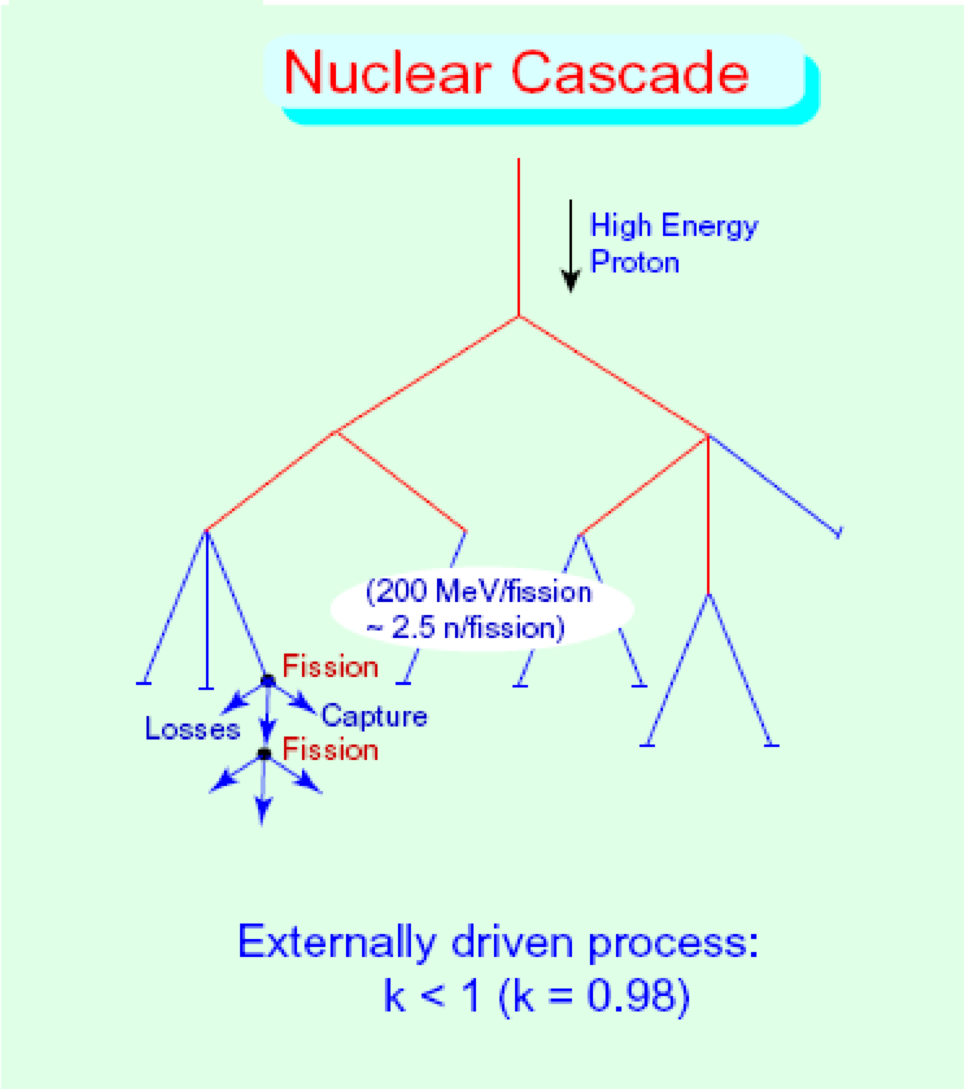
- ✓Materials irradiation (electronics, detectors, instrumentation – also for fusion)
- ✓Nuclear data improvement
- ✓Detectors calibration
- ✓Innovative detectors development
- ✓Neutron scattering – physics (topic not covered in this presentation)
- ✓Research supporting Accelerator Driven System(s) (ADSs)* – next slides

*See IAEA Coordinated Research Project, "Accelerator Driven Systems (ADS) and Use of Low Enriched Uranium (LEU) in ADS", leaded by Frances M. Marshall.

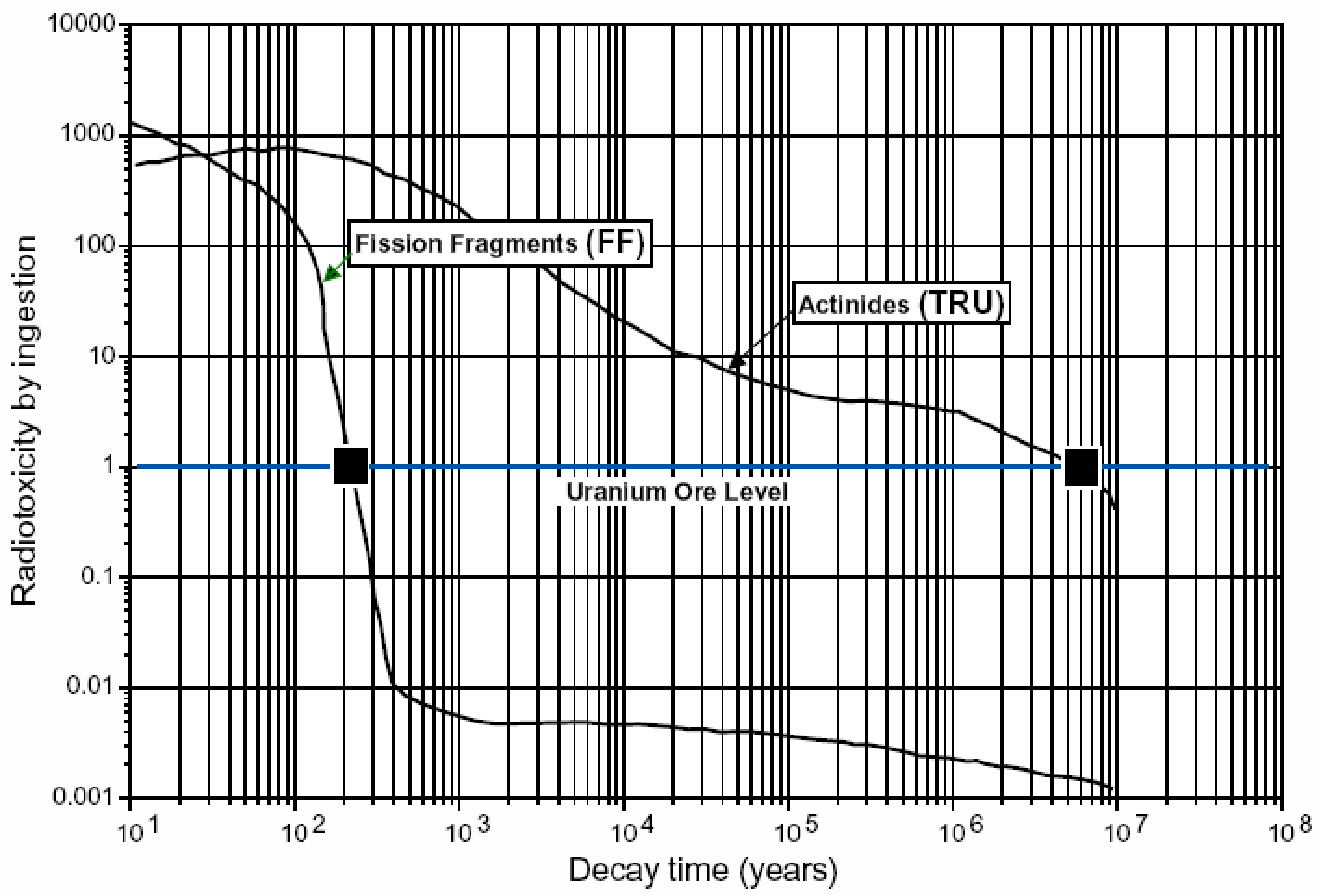
Utilization of LPRRs
Nuclear oriented applications
Accelerator Driven Systems (ADS)



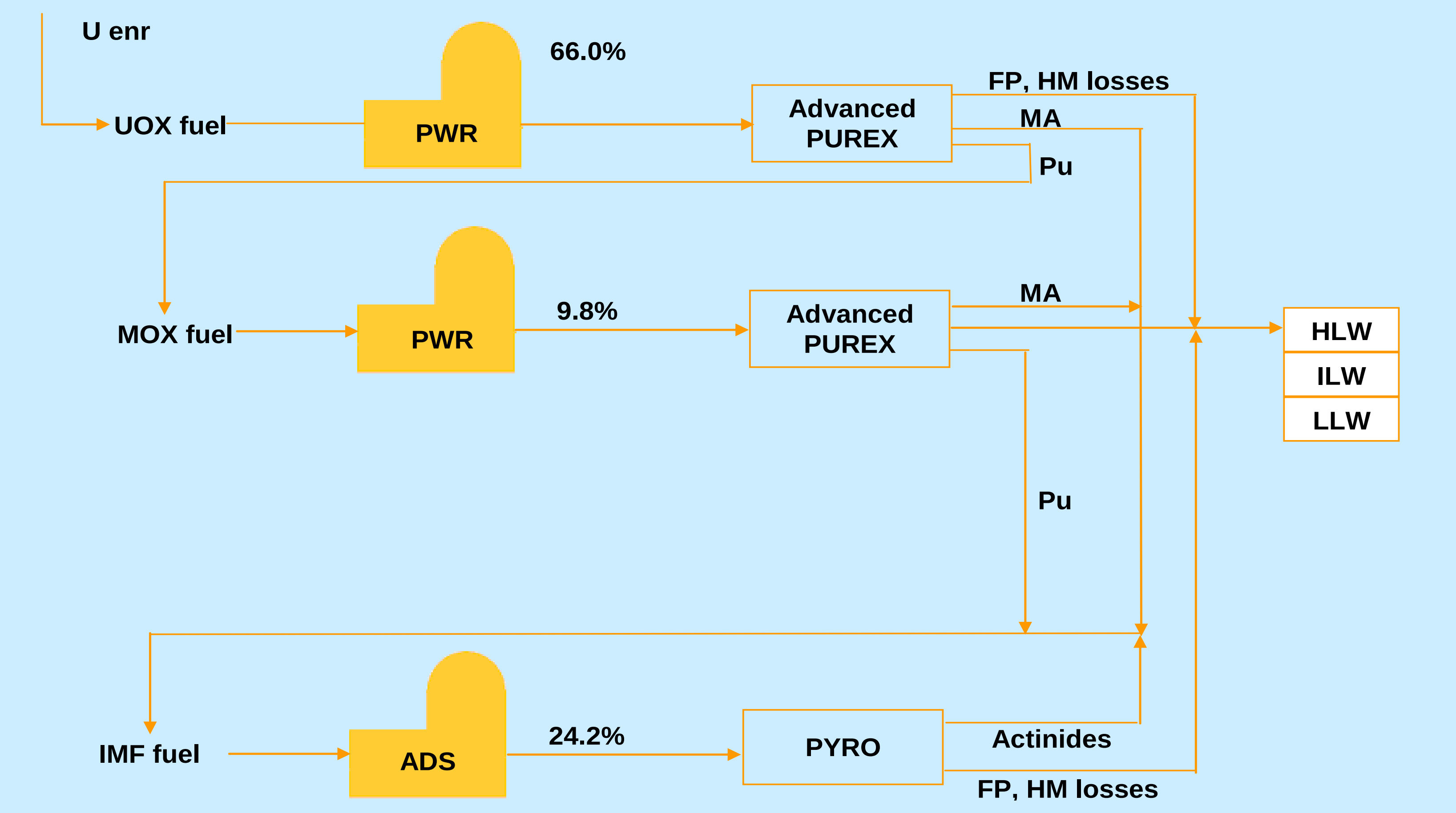
Utilization of LPRRs
Nuclear oriented applications
Accelerator Driven Systems (ADS)



Utilization of LPRRs
Nuclear oriented applications
Accelerator Driven Systems (ADS)

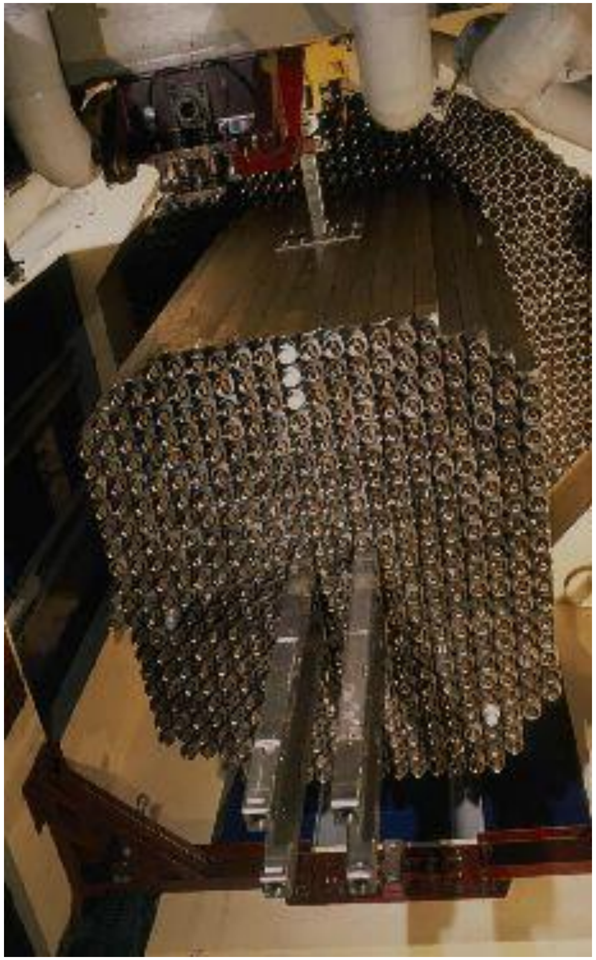


Utilization of LPRRs
Nuclear oriented applications
Accelerator Driven Systems (ADS)



Double strata fuel cycle: Pu is transferred from the PWR-MOX stage directly to the ADS fuel cycle.

MASURCA (France)
The reactor



MASURCA (MAquette SURgénératrice de CAdarache) is one of the critical facilities operated by CEA at the Cadarache Research Centre, France.

This “zero power” nuclear reactor is mainly used for physics studies of fast spectrum lattices. The maximum power, 5 kW, corresponds to a neutron flux of approximately 10^{11} $n \cdot cm^{-2} \cdot s^{-1}$, a level high enough to perform measurements in good conditions, while sufficiently low to consider that the fuel composition does not evolve with time.

The core is cooled by forced air extraction and blowing, and is surrounded by a biological shield in heavy concrete.

The materials used in the MASURCA subassemblies, called “tubes”, are contained in cylindrical or square rodlets.

MASURCA (France)

Main programs

Main research programs of MASURCA have been:

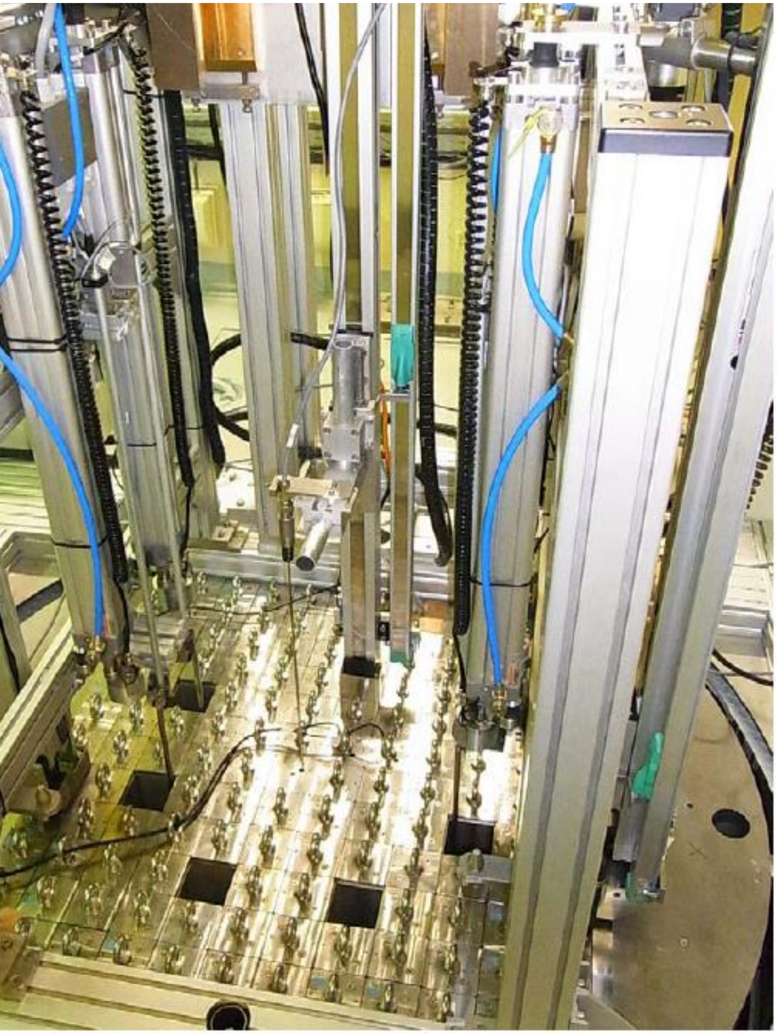
- ✓Homogeneous cores and parametric studies in function of U and Pu content
- ✓ RZ and PLUTO programs supporting the development of calculation tools used for PHENIX and SUPERPHENIX design
- ✓ PRE-RACINE and RACINE programs extending the study area to heterogeneous cores and allowing to validate methods for the loading of the SUPERPHENIX core
- ✓ BALZAC program focused on control rods (anti)reactivity measurements
- ✓ CONRAD program aiming to investigate large axial heterogeneous cores within the frame of the European Fast Reactor project

MASURCA (France)
Main programs

The more recent programs have been carried out under the terms of the French law of 1991 on the management of long lived radioactive wastes (the "Bataille" act). They were essentially conducted within the axis "Partitioning and Transmutation".

- ✓ CIRANO program (1994-1997) contributing to the study of Pu burner reactors within the frame of the CAPRA (plutonium burning in fast reactors) project
- ✓ COSMO program (1998-1999) investigating the principle of transmutation in moderated targets located in a fast reactor
- ✓ MUSE (4) project (2000-2004) focused on the behavior of Accelerator Driven Systems (ADS)

VENUS-F (Belgium)
The reactor



The VENUS (Vulcan Experimental NUclear Study) reactor (SCK•CEN Mol) is an experimental low-power reactor of the "zero-power critical facility" type. It was critical for the first time in 1964 with a water-moderated core. Being a flexible installation, after the first start the VENUS reactor was modified several times in order to better meet the needs in nuclear research.

VENUS has been also used for the validation of reactor physics calculation codes.

In 2008 the reactor has known a major modification. From a water moderated core the reactor was transformed into a fast lead reactor (VENUS-F) to support the R&D of the future GEN-IV reactor and ADS systems.

VENUS-F (Belgium)

Main programs

Main research programs of VENUS-F are or have been:

- ✓ GUINEVERE (Generator of Uninterrupted Intense NEutrons at the lead VEnus REactor) project, started within the EUROTRANS Integrated Project of the 6th EURATOM Framework Programme. These experiments aimed to provide an answer to the questions about online reactivity monitoring, subcriticality determination and operational procedures in ADSs.
- ✓ FREYA (Fast Reactor Experiments for hYbrid Applications) project, started within the 7th Framework Programme of EURATOM. The main objectives of FREYA were the further development and validation of techniques for online reactivity monitoring, as a continuation of the GUINEVERE project, and the validation of computer codes for ADSs studies. See following slide for the meaning of FREYA.
- ✓ MYRTE (MYRRHA Research and Transmutation Endeavour) project, started within the H2020 Programme of EURATOM supporting the development of the MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) research facility, performing additional experiments to validate the reactivity monitoring methods in complement to the ones achieved during the FREYA project.

Some examples of LPRRs supporting programs for Innovative Nuclear Energy Systems

VENUS-F (Belgium)

What it means FREYA?

In Norse mythology,
Freya is a goddess of love and fertility,
and the most beautiful and propitious of the goddesses.

KUCA (Japan)
The reactor

The KUCA (Kyoto University Critical Assembly) is a multi-core type critical assembly established in 1974 as a facility for educational purposes in reactor physics for researchers of all Universities in Japan. It has three independent cores, namely two solid moderated cores (A, B cores) and one light water-moderated core (C core). A pulsed-neutron generator is also installed, which can be used normally in combination with the A-core.

KUCA (Japan)

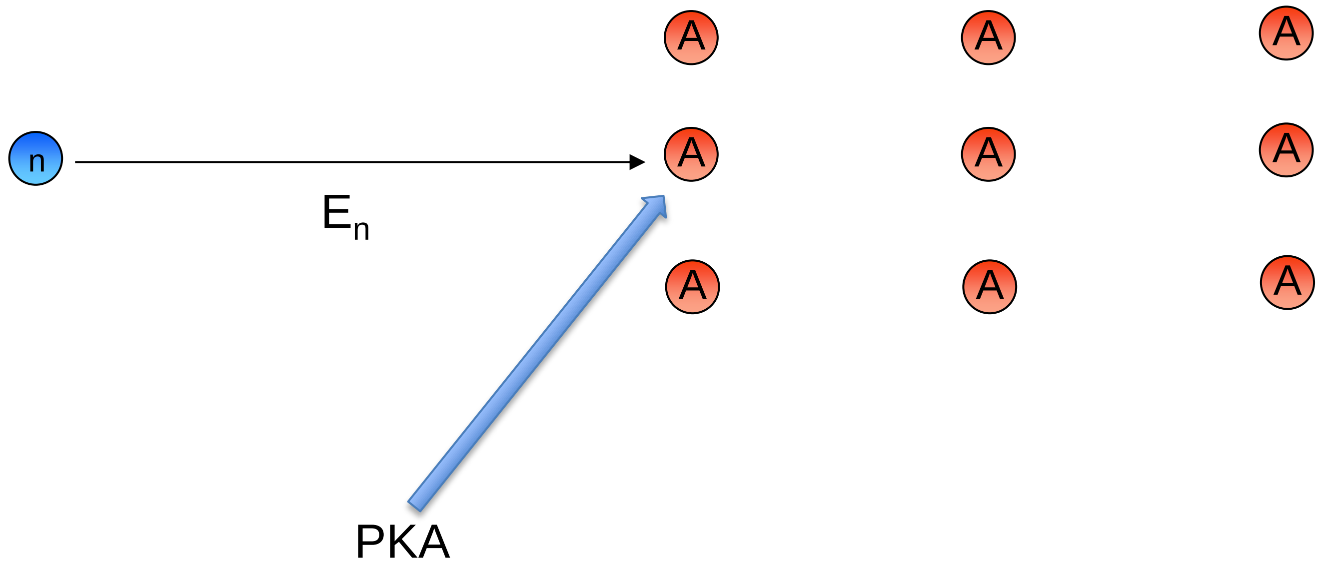
Main programs

Main research programs of KUCA are focused on:

- ✓ Nuclear characteristics of Thorium fueled reactor
- ✓ Nuclear transmutation studies on transuranic elements
- ✓ Critical experiments on highly-enriched Uranium cores with various spectrum indices
- ✓ Subcriticality measurements using various techniques
- ✓ Nuclear characteristics of coupled core systems, with special interest to the eigenvalue separation which is an index of reactor stability
- ✓ Development of innovative techniques for neutron field measurements and their application to reactor physics experiments
- ✓ Simulation experiments of ADSs behavior using coupling of subcritical cores and neutron generator with different spallation targets
- ✓ 14 MeV neutron transport in Thorium media

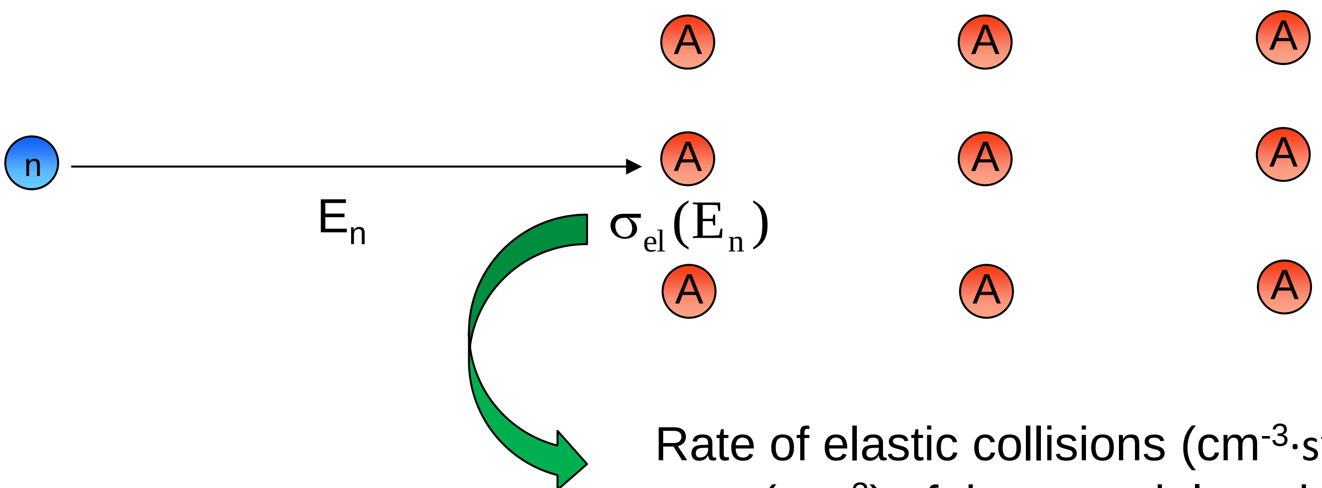
Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

Looking for the rate of displacements ($cm^{-3} \cdot s^{-1}$) produced by a Primary Knock-on Atom (PKA) (cm^{-3}) after an elastic collision with 1 neutron ($cm^{-2} \cdot s^{-1}$) having energy E_n



Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

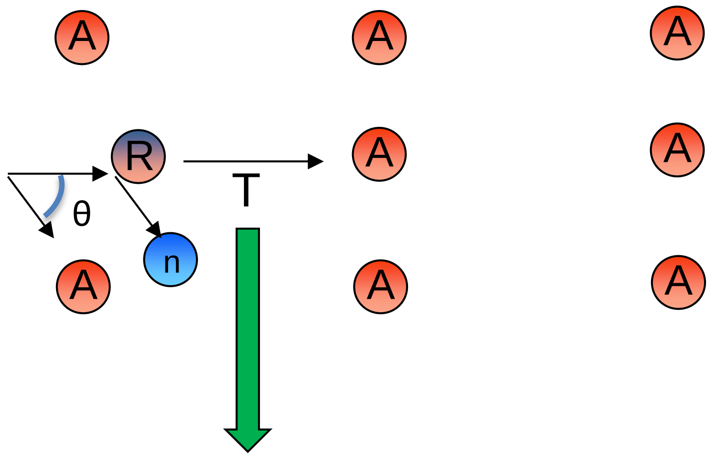
$$\mathrm{dpa}(E_n) \propto \sigma_{el}(E_n) \cdot \left[\phi(E_n) = 1\right]$$



Rate of elastic collisions ($cm^{-3} \cdot s^{-1}$) per atom (cm^{-3}) of the material undergone by 1 neutron ($cm^{-2} \cdot s^{-1}$) with energy E_n

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

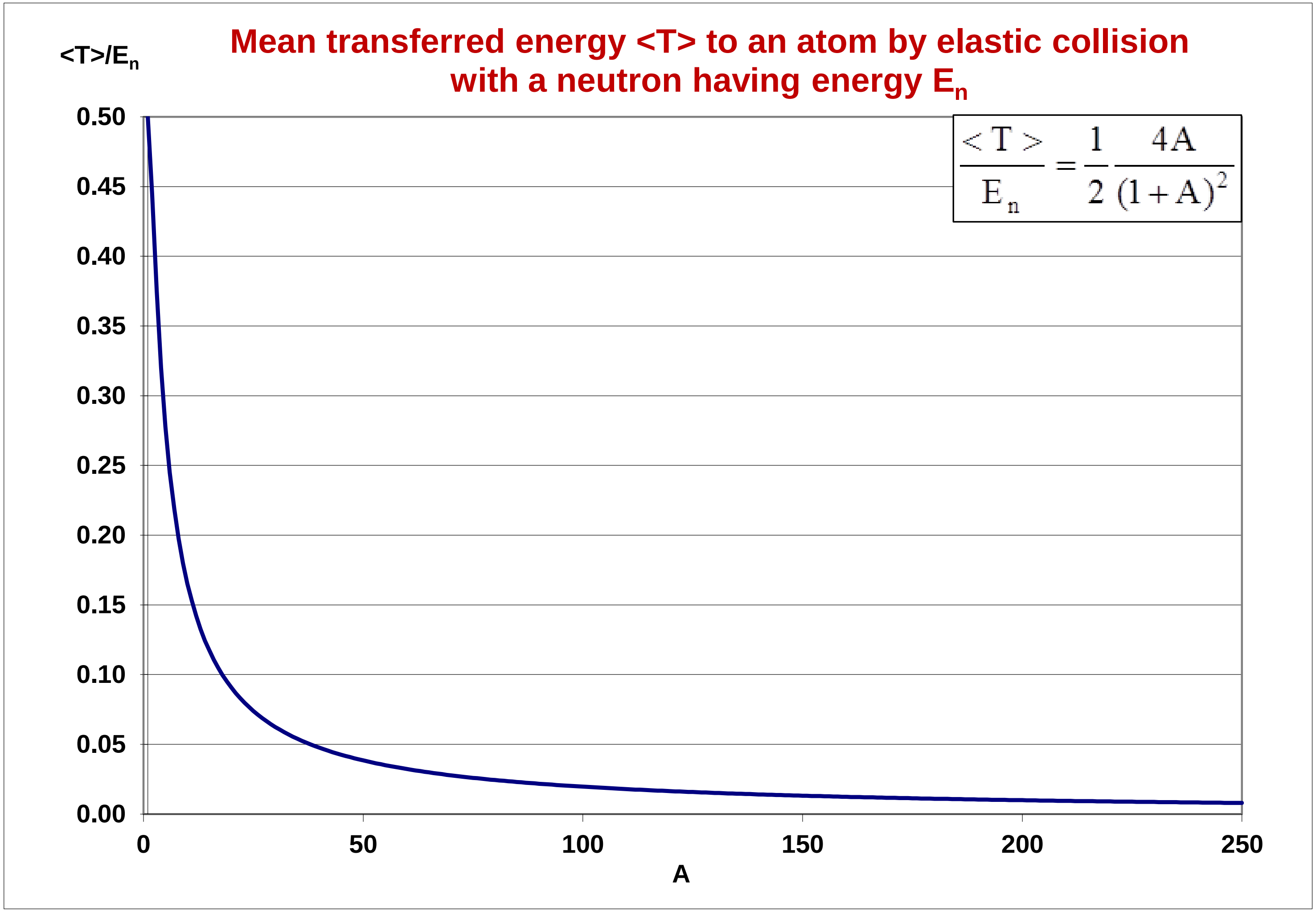
$$\mathrm{dpa}(E_n) \propto \sigma_{el}(E_n) \cdot [\phi(E_n) = 1]$$



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

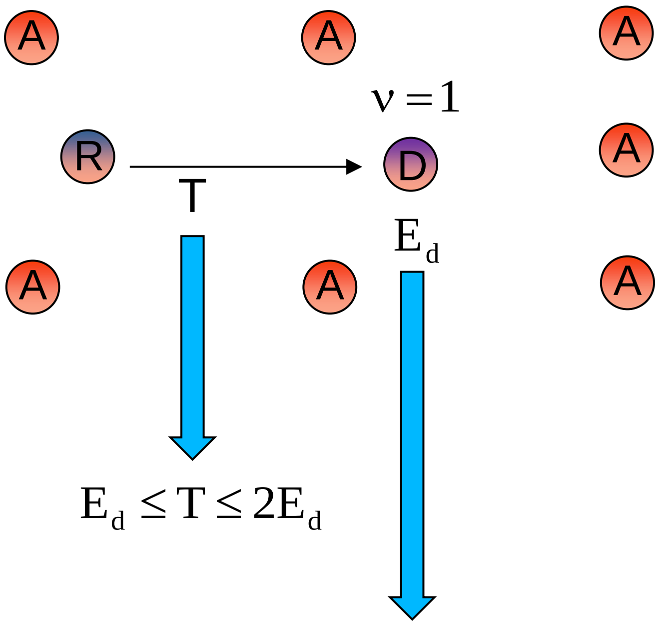
$$0 \le T \le \Lambda E_n\left(= \frac{4A}{(1+A)^2}E_n\right)$$

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa



Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

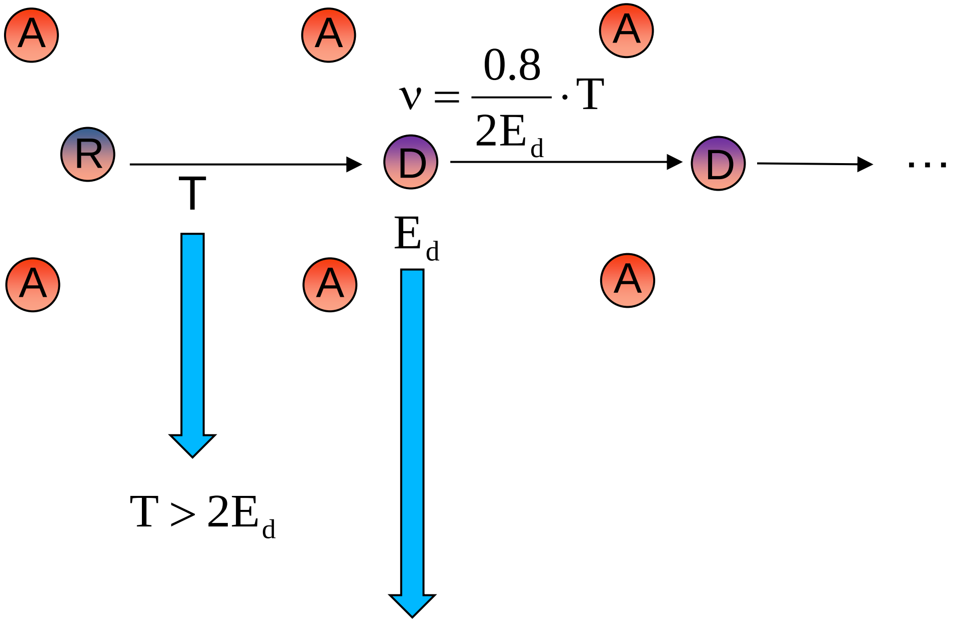
$$\mathrm{dpa}(E_n) \propto \sigma_{el}(E_n) \cdot [\phi(E_n) = 1]$$



average threshold displacement energy for an atom

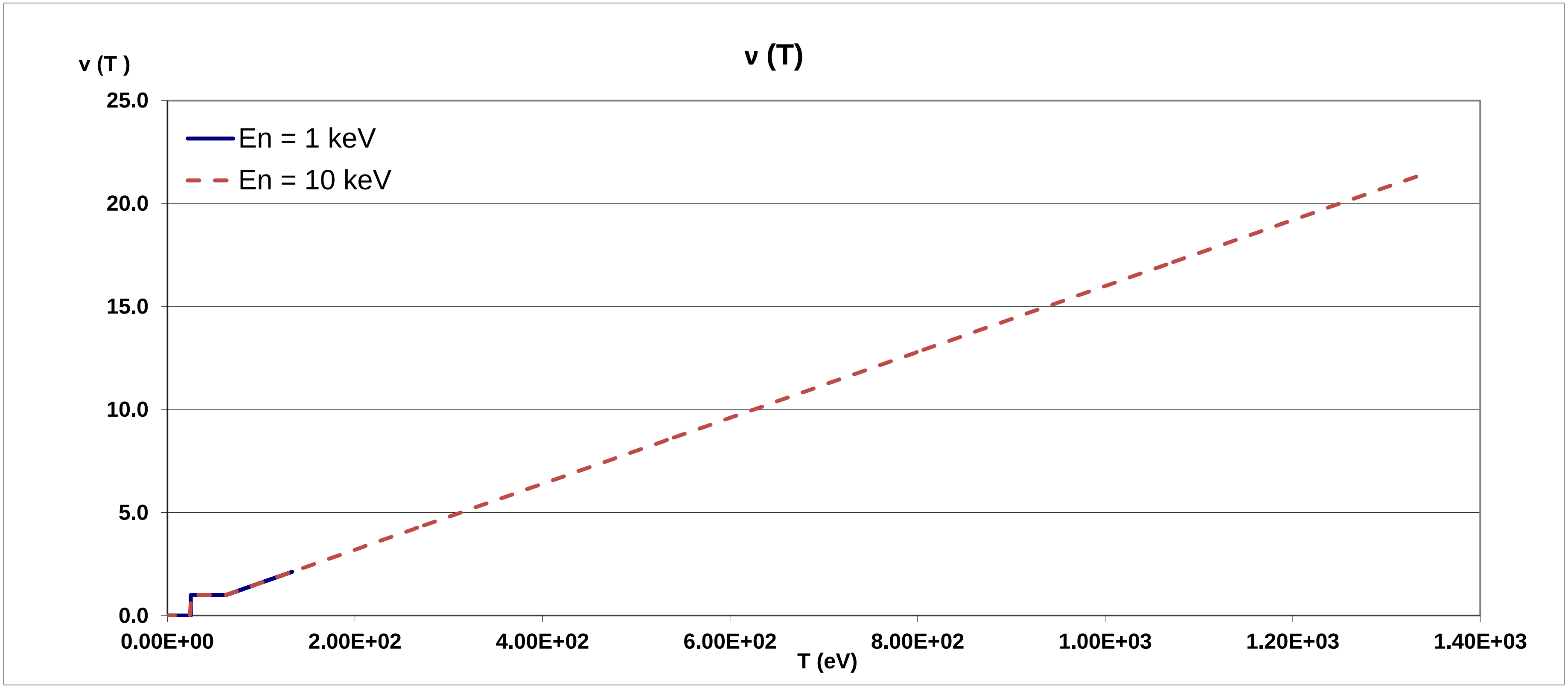
Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

$$\mathrm{dpa}(E_n) = \sigma_{el}(E_n) \cdot [\phi(E_n) = 1] \int_{E_d}^{\Lambda E_n} P[E_n;T] \cdot \nu(T)\,dT$$



average threshold displacement energy for an atom

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa



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

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

$$\mathrm{dpa}(E_n) = \sigma_{el}(E_n)\cdot[\phi(E_n)=1]\int_{E_d}^{\Lambda E_n} P[E_n;T]\cdot\nu(T)\,dT$$

The equation above indicates the rate of atomic displacements production following scattering collisions for unit atom. If, for a generic neutron flux, this rate is integrated over a certain time Δt we'll obtain the number of atomic displacements following scattering collisions for unit atom:

$$\mathrm{dpa}(E_n,\Delta t) = \sigma_{el}(E_n)\cdot <\nu(E_n)> \cdot\phi(E_n)\cdot\Delta t$$

And integrating over all the neutron energies we get:

$$\mathrm{dpa}(\Delta t) = \Delta t <\nu> \int \sigma_{el}(E_n)\phi(E_n)\,dE_n = \Delta t <\nu><\sigma_{el}><\phi>$$

With:

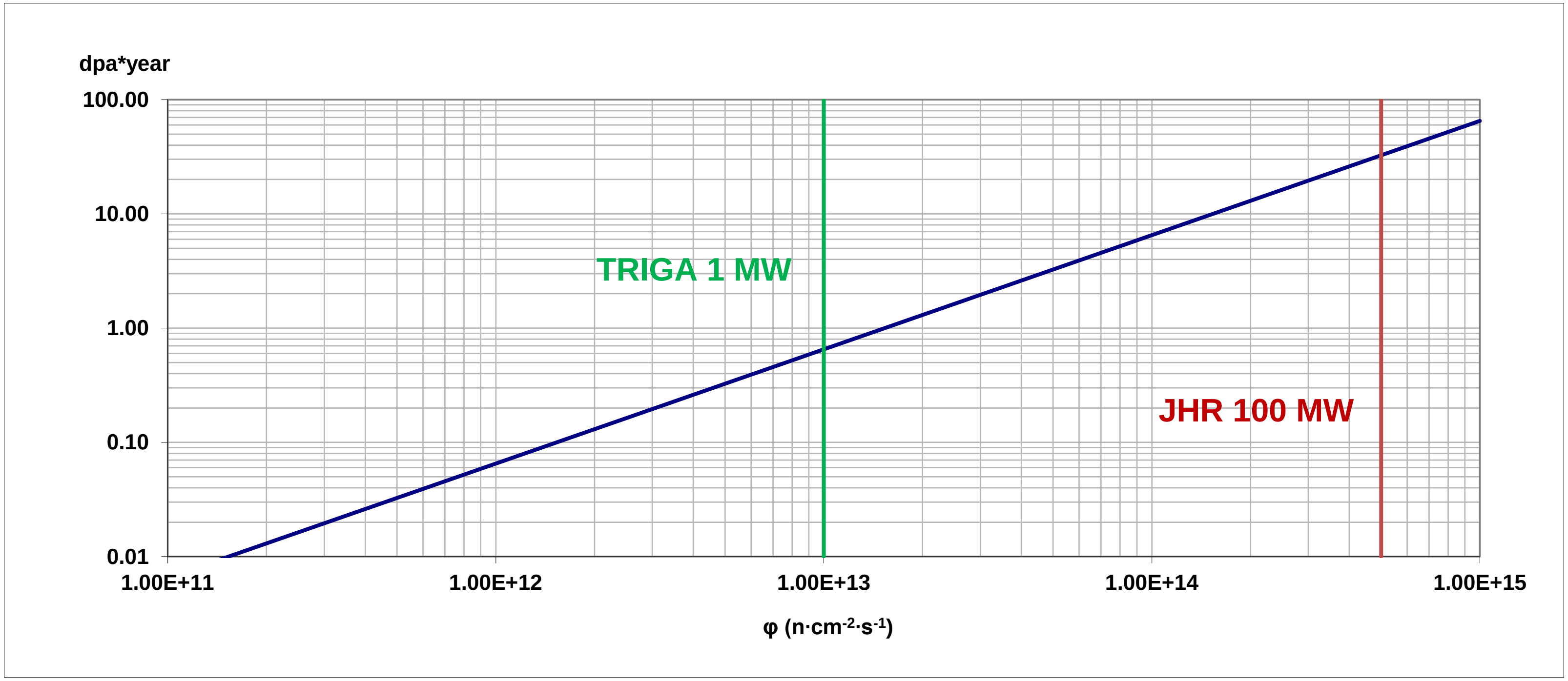
$$<\sigma_{el}> = \frac{\int \sigma_{el}(E_n)\phi(E_n)\,dE_n}{\int \phi(E_n)\,dE_n} \qquad <\phi> = \int \phi(E_n)\,dE_n$$

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
dpa

An approximate relation is:

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

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



Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
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:

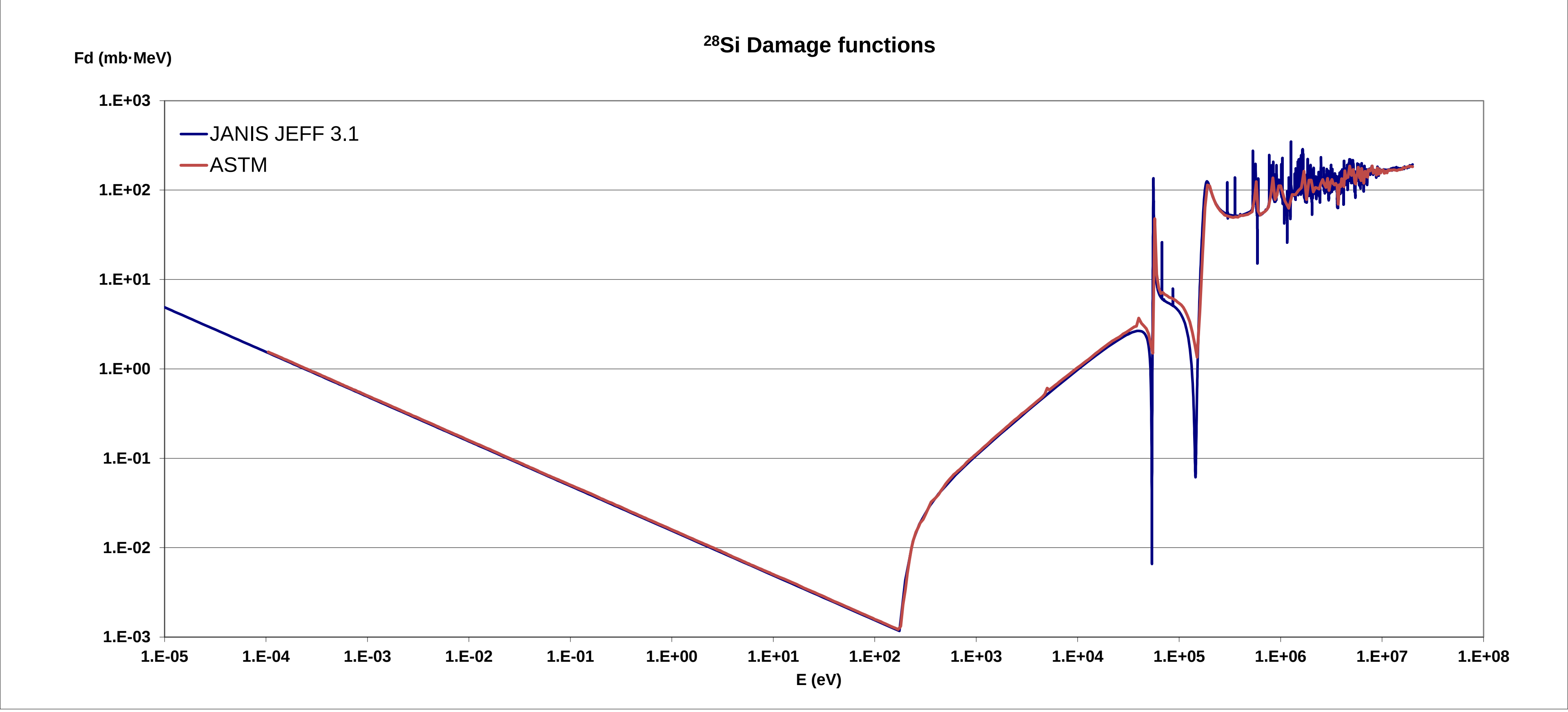
$$E_D(T) = T \cdot L(T)$$

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.

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

ASTM Standards

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
KERMA functions



Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
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:

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

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
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.

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
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.

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
Other reaction channels

By summing over all the k reactions:

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

$$F_D(E_n) \ = \sum_k F_{D,k}(E_n) \quad [\mathrm{barn} \cdot \mathrm{eV}]$$

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

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

Research fields of interest for LPRRs (examples)
Neutron radiation damage analysis (memorandum)
The role of LPRRs

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

$$\mathrm{dpa}(\Delta t) = \Delta t \sum_k \langle \nu_k \rangle \langle \sigma_k \rangle \langle \phi \rangle$$

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

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

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.

Research fields of interest for LPRRs (examples)
Nuclear data improvement by integral experiments
Sensitivity coefficients

An example of integral response is (<> indicates integration over the phase space):

$$R(\alpha) = <\sigma \cdot \phi(\alpha)>$$

Where σ is the cross section of the certain detector and R(α) is the integral response. ϕ is solution of:

$$\mathbf{A}(\alpha)\phi(\alpha) = Q$$

Where A is a linear operator and Q is a fixed source term. If Q=0 we have an eigenvalue problem. The integral response R(α) is implicitly dependent by all the data appearing in the equation defining ϕ, i.e. α, and explicitly dependent by all the data appearing in σ. If we have a small perturbation in α we can write:

$$R^{'} - R_0 \equiv \Delta R \cong \frac{dR}{d\alpha}\Delta\alpha$$

Research fields of interest for LPRRs (examples)
Nuclear data improvement by integral experiments
Sensitivity coefficients

The last relation can be written as:

$$\frac{\Delta R}{R} \cong \left(\frac{\alpha}{R} \frac{dR}{d\alpha} \right) \frac{\Delta\alpha}{\alpha} \equiv S_\alpha \frac{\Delta\alpha}{\alpha}$$

With:

$$S_\alpha \equiv \frac{\alpha}{R} \frac{dR}{d\alpha} \cong \frac{\Delta R / R}{\Delta\alpha / \alpha}$$

The proportionality constant S_α is called sensitivity coefficient of the response R respect to α, usually abbreviated as sensitivity coefficient. It can be noticed that a relative increase in α of 1% will cause a variation in the response equal to S_α %. In general, for M parameters:

$$R^{'} \cong R_0 + \sum_{i=1}^{M} \frac{\partial R}{\partial \alpha_i} \left(\alpha_i^{'} - \alpha_{i,0} \right) \quad \Longrightarrow \quad \frac{\Delta R}{R_0} \cong \sum_{i=1}^{M} S_{\alpha_i} \frac{\Delta \alpha_i}{\alpha_{i,0}}$$

Research fields of interest for LPRRs (examples)
Nuclear data improvement by integral experiments
Sensitivity coefficients

The difficulty with the so-called direct approach to calculate S_α is that usually the response $R(\alpha)$ is an implicit function of α by means of the dependence of ϕ on α. But fortunately exists a particular function, the adjoint function ϕ^*, which is solution of the equation:

$$\mathbf{A}^*\phi^* = Q^* \equiv \frac{\partial R}{\partial \phi} = \sigma$$

With $\mathbf{A}^*$ adjoint operator and Q^* adjoint source.

If the response $R(\alpha)$ and the fixed source Q do not explicitly depend ex on α , the adjoint function ϕ^* allows to write the sensitivity coefficient as:

$$\frac{\Delta R}{R} = -< \frac{\alpha}{R}\left(Y^* \frac{\partial \mathbf{A}}{\partial \alpha} Y \right) \frac{\Delta \alpha}{\alpha} >$$

This relation is extensively used in sensitivity studies of the response to nuclear data. The behavior of the sensitivity coefficients.

Research fields of interest for LPRRs (examples)
Nuclear data improvement by integral experiments
The role of LPRRs

- We have a mathematical tool (from Perturbation Theory) which allows us to build a bridge between measurable quantities, like reaction rates, and nuclear data involved in the responses.

- In parallel, eventual material and geometrical complexities of the system may impact on the quality of our experimental data interpretation, always made with the aid of calculations, influencing in this way the reliability of our neutron flux knowledge (more materials we have in our reactor more nuclear data uncertainties come into play).

- LLPRs, at least in principle, are suitable for an in depth characterization of the neutron flux, and this aspect is of fundamental importance concerning their role in the field of nuclear data improvement by integral experiments.

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
Definitions

Basically a spectral index is nothing more than a ratio of two microscopic cross sections averaged on the same local neutron energy distribution. For a given position k in the reactor and for two detectors i and j spectral indexes are given by:

$$S_{i,j,k} = \frac{\int_E \sigma_i(E)\phi_k(E)dE}{\int_E \sigma_j(E)\phi_k(E)dE} = \frac{\overline{\sigma}_i \int_E \phi_k(E)dE}{\overline{\sigma}_j \int_E \phi_k(E)dE} = \frac{\overline{\sigma}_i < \phi_k >}{\overline{\sigma}_j < \phi_k >} = \frac{\overline{\sigma}_i}{\overline{\sigma}_j} = \frac{R_{i,k}}{R_{j,k}}$$

For this kind of measurements it's of fundamental importance to know the "actual" compositions of the detectors, especially taking into account that the measured quantities are:

$$S^{exp}_{i,j,k} = \frac{c_{i,k}}{c_{j,k}} = \frac{\varepsilon_{i,k} N_i \int_E \sigma_i(E)\phi_k(E)dE}{\varepsilon_{j,k} N_j \int_E \sigma_j(E)\phi_k(E)dE} = \frac{\varepsilon_{i,k} N_i R_{i,k}}{\varepsilon_{j,k} N_j R_{j,k}}$$

Where $c_{(i,j),k}$ are counting rates, $\varepsilon_{(i,j),k}$ are detectors efficiencies (which depend on the neutron spectrum) and $N_{(i,j)}$ are detectors number of atoms.

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
"effective" number of atoms

$$S^{exp}_{i,j,k} = \frac{c_{i,k}}{c_{j,k}} = \frac{\varepsilon_{i,k} N_i \int_E \sigma_i(E)\phi_k(E)dE}{\varepsilon_{j,k} N_j \int_E \sigma_j(E)\phi_k(E)dE} = \frac{\varepsilon_{i,k} N_i}{\varepsilon_{j,k} N_j}\frac{R_{i,k}}{R_{j,k}}$$

This relation may be written as:

$$S^{exp}_{i,j,k} = \frac{c_{i,k}}{c_{j,k}} = \frac{\varepsilon_{i,k} N_i}{\varepsilon_{j,k} N_j}\frac{R_{i,k}}{R_{j,k}} = \frac{N_{i,eff}}{N_{j,eff}}\frac{R_{i,k}}{R_{j,k}}$$

Having included the efficiencies into "effective" number of atoms defined as:

$$N_{i,eff} = \varepsilon_{i,k} N_i = \frac{c_{i,k}}{R_{i,k}} \qquad N_{j,eff} = \varepsilon_{j,k} N_j = \frac{c_{j,k}}{R_{j,k}}$$

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
"effective" masses

Actually it's (at least) difficult to deal with number of atoms, better masses. Because:

$$N = \frac{M \cdot Av}{A}$$

We can write:

$$S_{i,j,k}^{exp} = \frac{c_{i,k}}{c_{j,k}} = \frac{\varepsilon_{i,k} N_i R_{i,k}}{\varepsilon_{j,k} N_j R_{j,k}} = \frac{\varepsilon_{i,k} M_i \left(\frac{Av}{A_i} R_{i,k} \right)}{\varepsilon_{j,k} M_j \left(\frac{Av}{A_j} R_{j,k} \right)} = \frac{M_{i,eff}}{M_{j,eff}} \frac{\tilde{R}_{i,k}}{\tilde{R}_{j,k}}$$

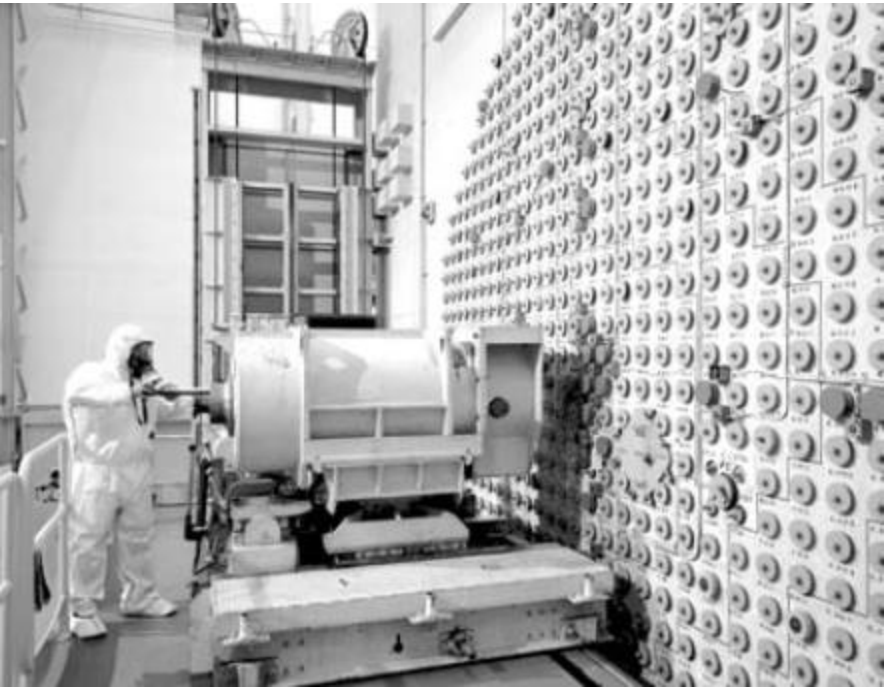
Where now we have "effective" masses and reaction rates defined as:

$$M_{i,eff} = \varepsilon_{i,k} M_i = \frac{c_{i,k}}{\tilde{R}_{i,k}} \qquad M_{j,eff} = \varepsilon_{j,k} M_j = \frac{c_{j,k}}{\tilde{R}_{j,k}}$$

$$\tilde{R}_{i,k} = \frac{Av}{A_i} R_{i,k} = \frac{N_i}{M_i} R_{i,k} \qquad \tilde{R}_{j,k} = \frac{Av}{A_j} R_{j,k} = \frac{N_j}{M_j} R_{j,k}$$

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
Calibration at BR1

An example: calibration at BR (Belgian Reactor) 1 (SCK•CEN – Belgium)

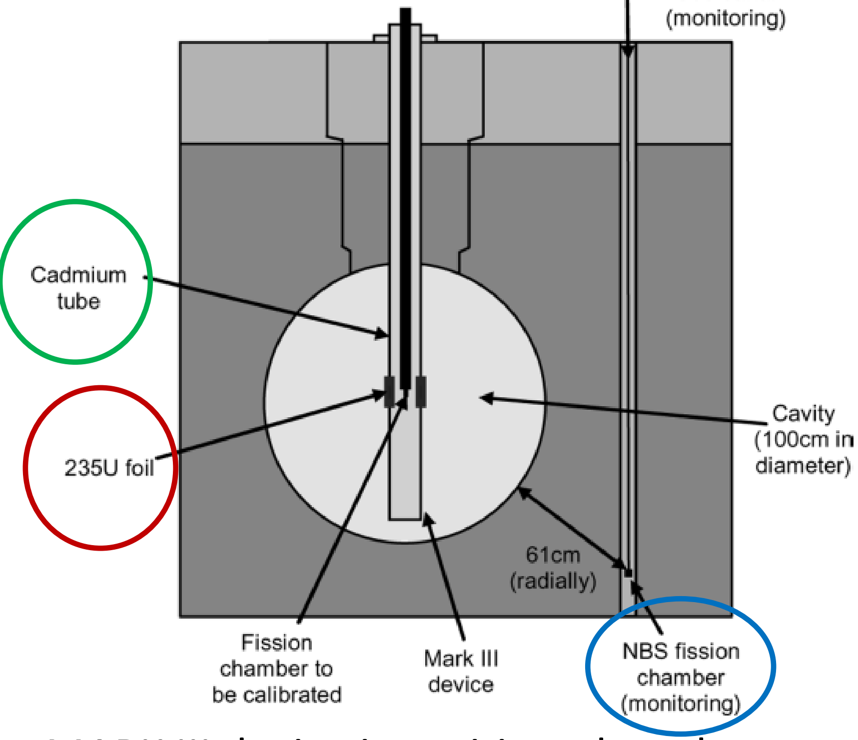


The BR1 is the first Belgian reactor. It was critical for the first time on 11 May 11 1956

The fuel is natural metallic uranium (approximately 25 ton). The uranium is originating from the former Belgian Congo (now Democratic Republic of Congo) where the uranium reserves have played an important role in the development of the nuclear sector in Belgium.

A remarkable fact: the current fuel in BR1 is still the original one. After more than 50 years of working, the burn-up of ^{235}U is only a few% (burn-up: quantity of burnt-out fissile material in comparison with the quantity of fissile material of the fresh nuclear fuel). The moderator of the reactor is graphite (carbon).

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
The MARK III device



MARK III device is positioned on the top of the BR1 reactor, inside a cavity carved in the graphite located above the core. Thus, a large majority of the neutrons in the cavity are thermal.

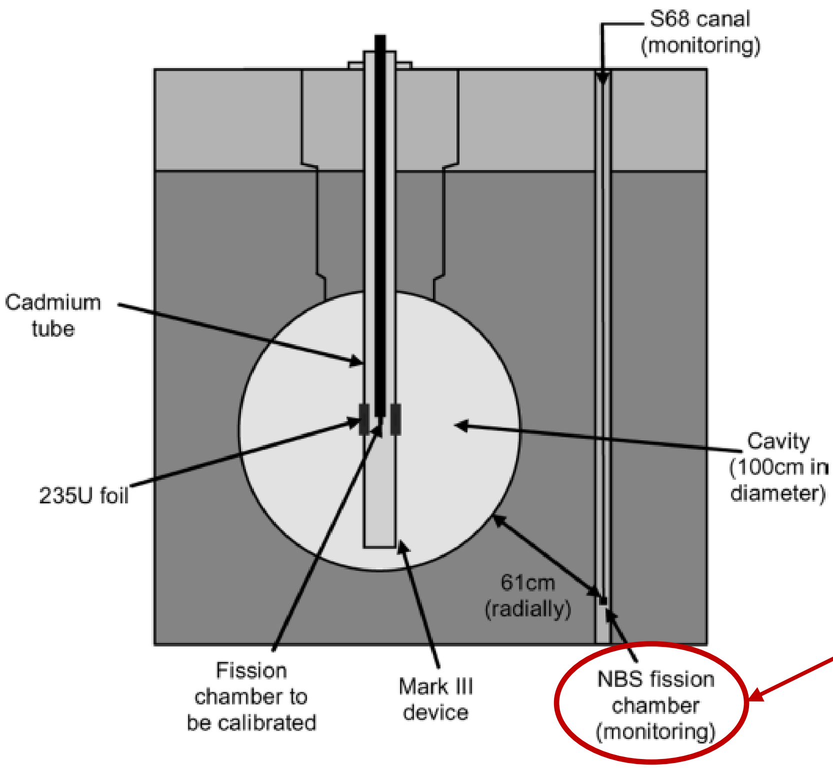
The main part of the MARK III device is a cylinder made of cadmium covered, on its external side, by a thin ^{235}U foil so that the only neutrons inside the MARK III tube are the ones coming from fission reactions in the foil.

Consequently, the neutron field inside the device is perfectly known once some minor physical corrections are applied.

The integral neutron flux it's calculated thanks to the monitoring equipment of the reactor.

The count rate given by the NBS (National Bureau of Standard) fission chamber used for that purpose has been linked by calculation and dosimetry measurements to the absolute total neutron flux in the center of the MARK III device.

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
Obtaining detectors "effective" masses



The so called facility calibration factor K is defined as:

$$< \phi_k >= K \cdot c_{monitor}$$

$$M_{i,eff} = \frac{c_{i,k}}{\tilde{R}_{i,k}} = \frac{c_{i,k}}{\frac{Av}{A_i} \cdot \overline{\sigma}_{i,k} \cdot < \phi_k >} = \frac{c_{i,k}}{\frac{Av}{A_i} \cdot \overline{\sigma}_{i,k} \cdot K \cdot c_{monitor}}$$

Research fields of interest for LPRRs (examples)
Detectors calibration for spectral indexes measurements
Reference

One example of this approach can be found in:

V. Lamirand, B. Geslot, J. Wagemans, L. Borms, E. Malambu, P. Casoli, X. Jacquet, G. Rousseau, G. Grégoire, P. Sauvecane, D. Garnier, S. Bréaud, F. Mellier, J. Di Salvo, C. Destouches and P. Blaise,
"Miniature fission chambers calibration in pulse mode: Interlaboratory comparison at the SCK·CEN BR1 and CEA CALIBAN reactors", 2013 3rd International Conference on Advancements in Nuclear Instrumentation, Measurement Methods and their Applications (ANIMMA).

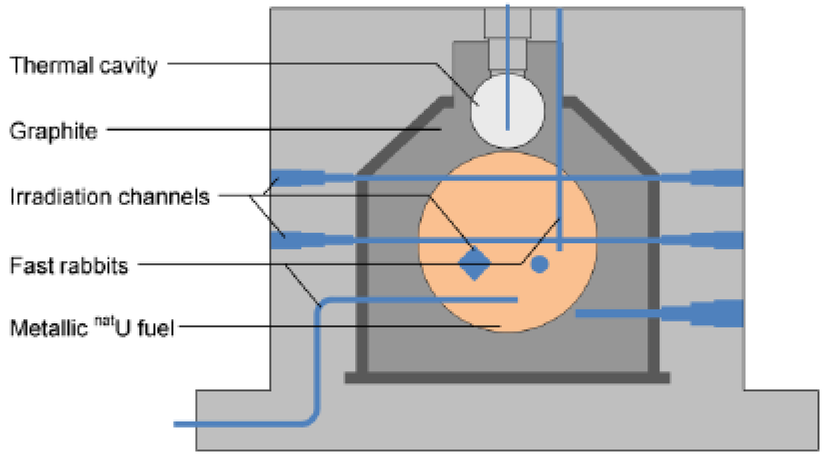


Fig. 1. Schematic view of the irradiation channels at the BR1 reactor.

Fig. 3. Picture of the CALIBAN reactor outside its radioprotection tank.

Research fields of interest for LPRRs (examples)
Innovative detectors development
Example from a PhD Thesis

UNIVERSITE D'AIX-MARSEILLE

ED 352 – Physique et Sciences de la Matière
CEA Cadarache – DER/SPRC/Laboratoire d'Etudes de Physique

Thèse présentée pour obtenir le grade universitaire de docteur

Discipline : Physique et Sciences de la Matière
Spécialité : Energie, Rayonnement et Plasma

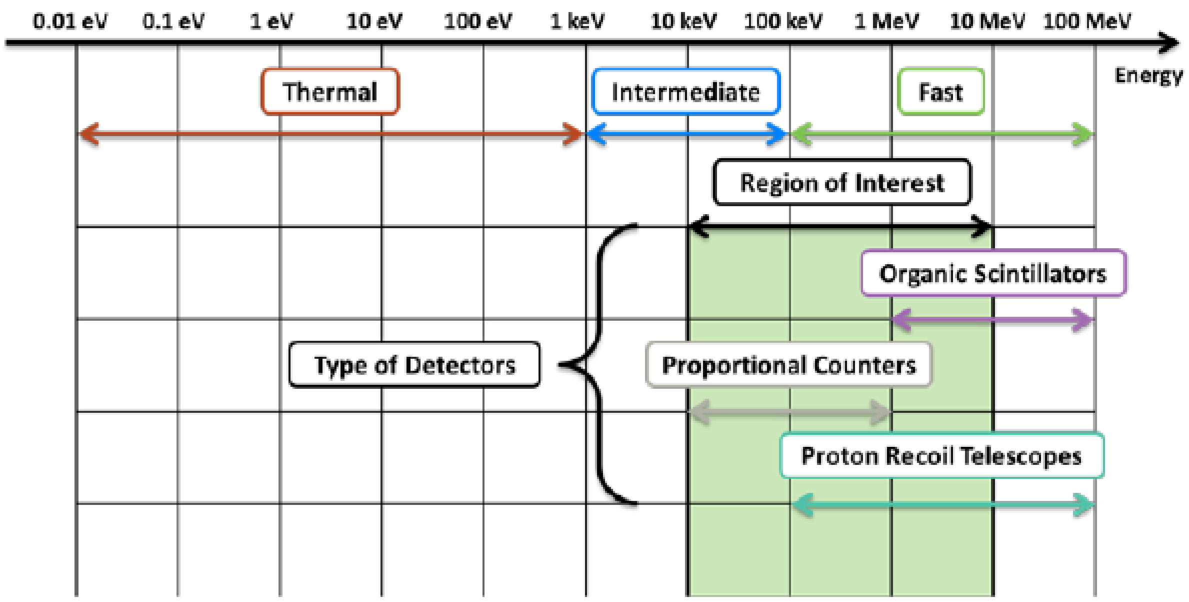
Luca DIONI

Development of a Multi-purpose Fast Neutron Spectrometric Capability in the MASURCA Facility

Soutenue le 21/09/2017 devant le jury :

M. Arjan PLOMPEN	JRC - IRMM	Examinateur
M. Imre PAZSIT	Chalmers University	Examinateur
M. Bertrand PEROT	CEA Cadarache	Examinateur
M. Mossadek TALBY	Aix-Marseille Université	Examinateur
M. Mario CARTA	ENEA	Examinateur
M. Elio TOMARCHIO	Università di Palermo	Examinateur
M. Brian STOUT	Aix-Marseille Université	Directeur de thèse
M. Marco SUMINI	Università di Bologna	Directeur de thèse
M. Robert JACQMIN	CEA Cadarache	Invité
M. Vincent Gressier	IRSN Cadarache	Invité
M. Mourad AICHE	CENBG	Invité

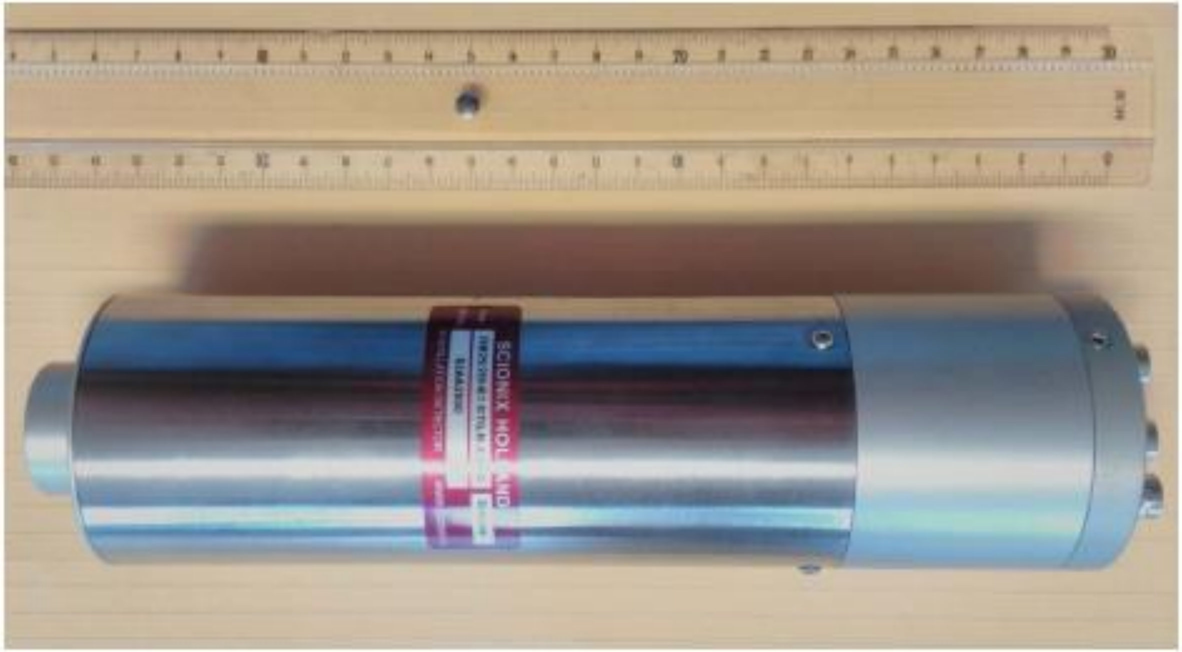
Research fields of interest for LPRRs (examples)
Innovative detectors development
Example from a PhD Thesis



Energy domain covered by different detectors

Source: Luca Dioni PhD thesis (Aix-en-Provence, September 2017)

Research fields of interest for LPRRs (examples)
Innovative detectors development
Example from a PhD Thesis

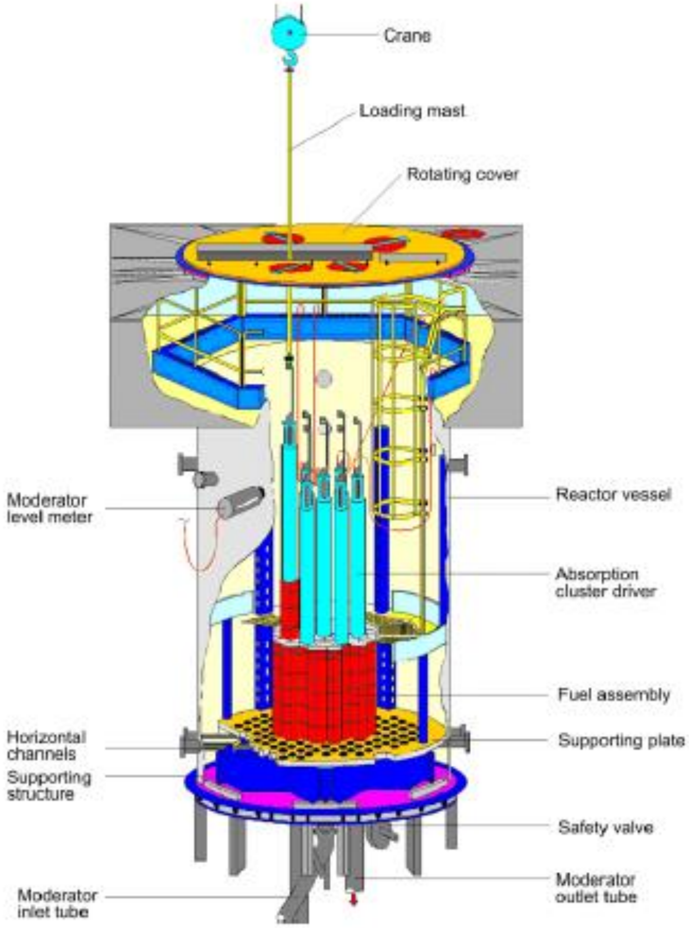


25.4 mm × 25.4 mm ortho-cylindrical solution-grown stilbene detector (plus PMT).

Such a system is capable of providing the means for a fine-enough spectral characterization of neutron fields in the energy domain between 10 keV and 10 MeV (also higher, until 15 - 20 MeV)

Source: Luca Dioni PhD thesis (Aix-en-Provence, September 2017)

Research fields of interest for LPRRs (examples)
Innovative detectors development
Example from a PhD Thesis

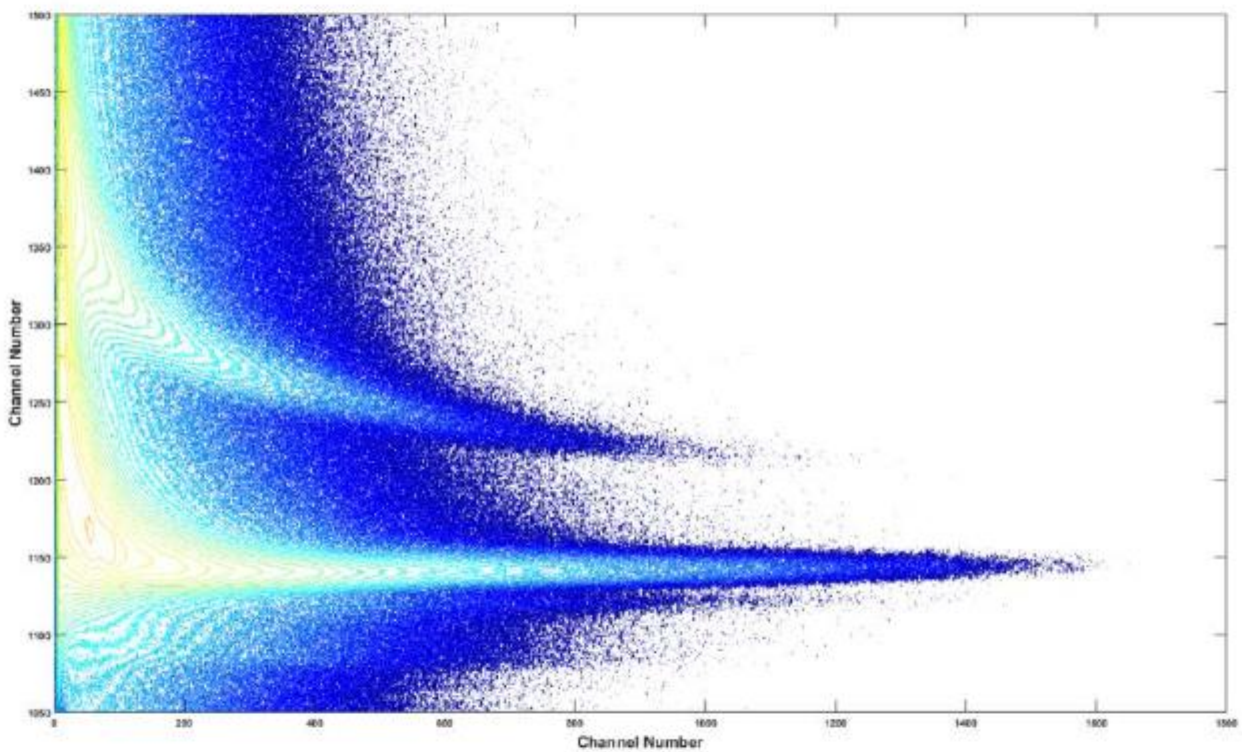


In-core and near-core neutron (and gamma) spectra have been extensively characterized at the LR-0 facility (Rez, Czech Republic).

The LR-0 research reactor is a light-water, zero-power, pool-type reactor. It serves as an experimental reactor for measuring neutron-physical characteristics of VVER (Water-Water Energetic Reactor) type reactors.

Source: Luca Dioni PhD thesis (Aix-en-Provence, September 2017)

Research fields of interest for LPRRs (examples)
Innovative detectors development
Example from a PhD Thesis



Example of separation between neutron and gamma events

Source: Luca Dioni PhD thesis (Aix-en-Provence, September 2017)

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor description
What it means TAPIRO?

TAPIRO (Tapir in English)?

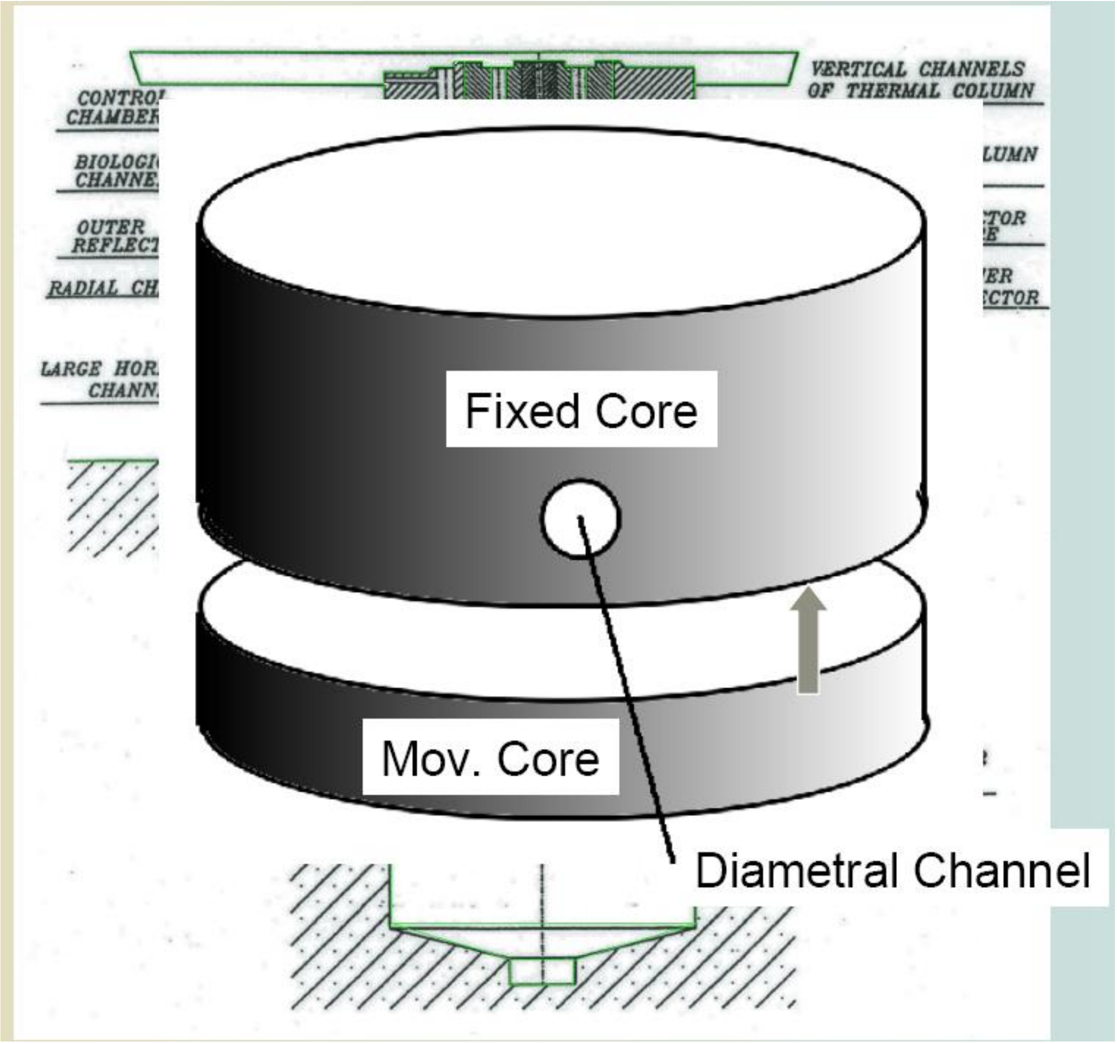
Taratura Pila Rapida a potenza zerO

Fast Pile Calibration at Zero Power

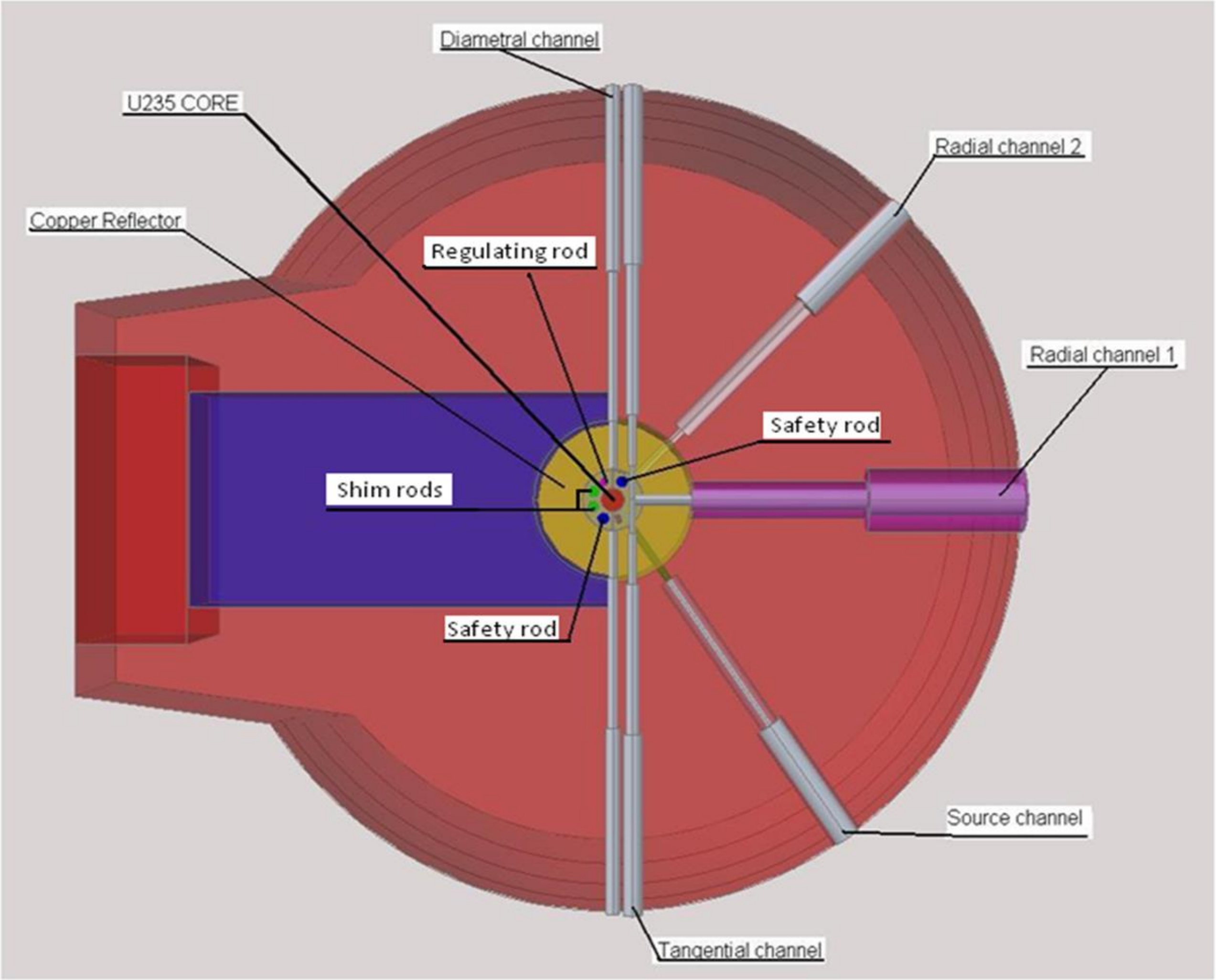
Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor description
Origins

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

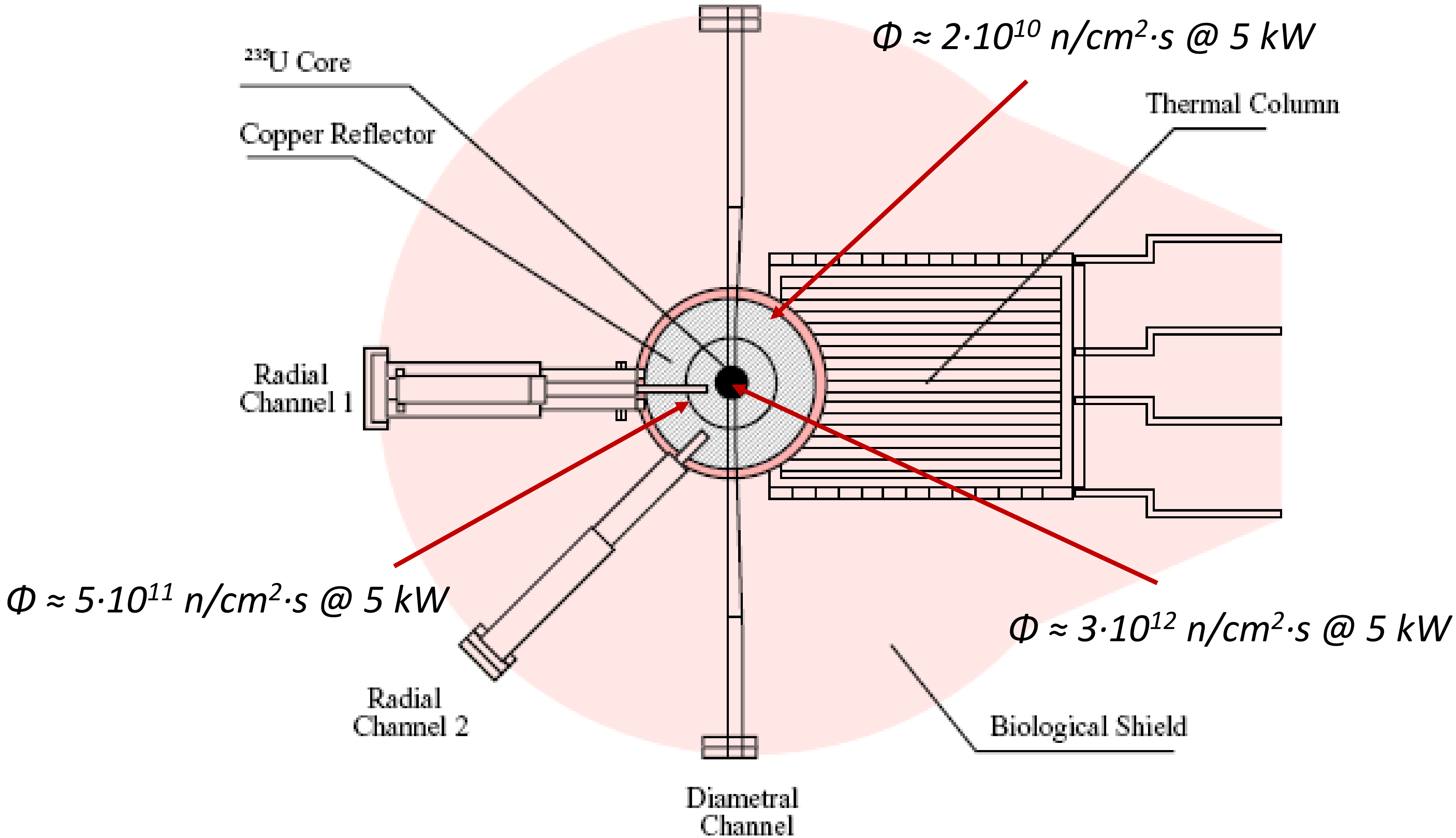
Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor description
Core layout



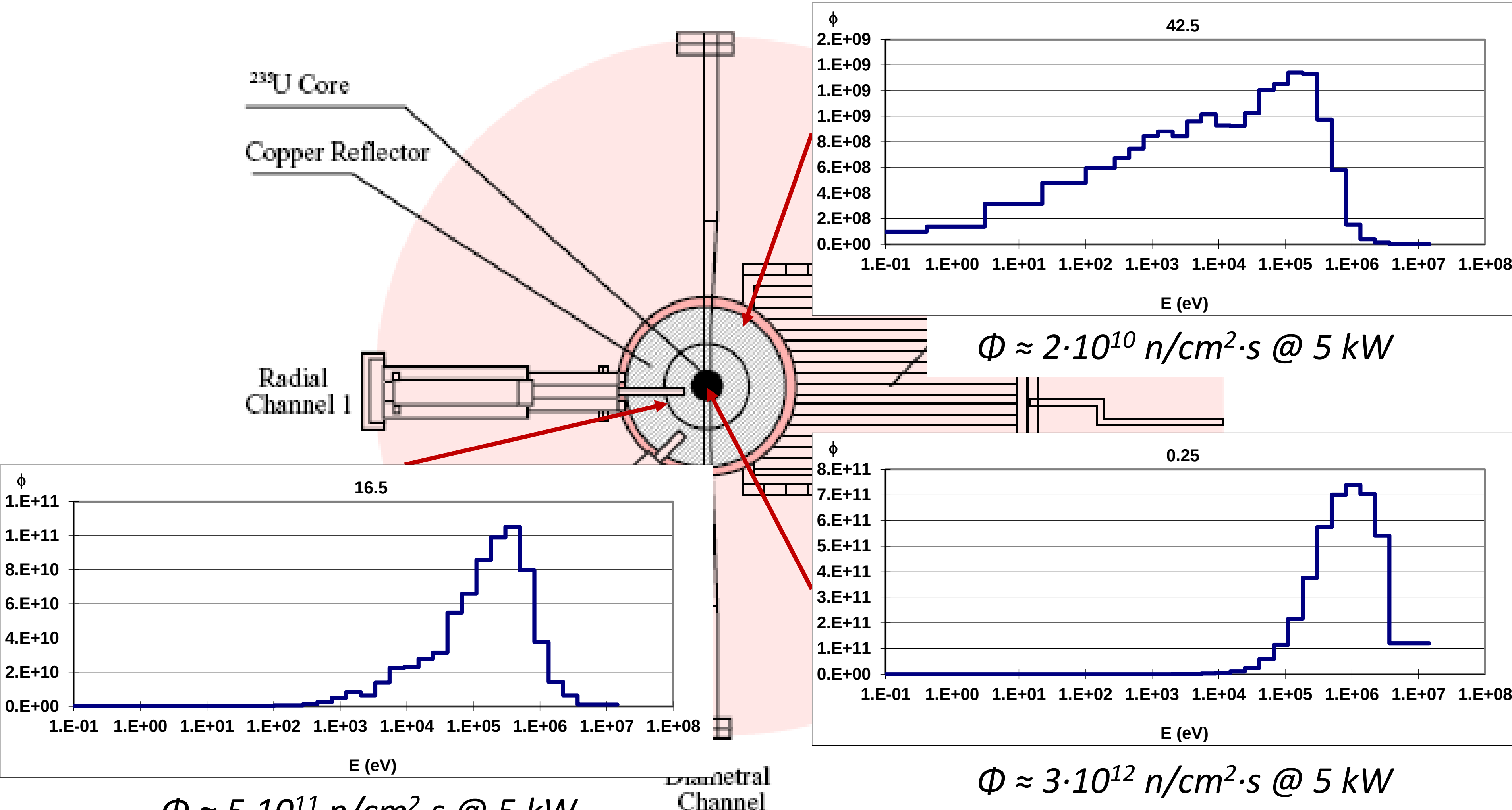
Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor description
Experimental channels



Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor description
Neutronic features



Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor description
Neutronic features



$\Phi \approx 2 \cdot 10^{10}$ n/cm²·s @ 5 kW

$\Phi \approx 3 \cdot 10^{12}$ n/cm²·s @ 5 kW

$\Phi \approx 5 \cdot 10^{11}$ n/cm²·s @ 5 kW

Bilateral agreement ENEA - SCK•CEN Mol (1983-1986)

I must state that I am not aware of any permanent nuclear reactor system that, despite its a-priori complexity, has ever been so comprehensively characterized neutronically, over so large and steep a range of neutron field variation, over so complete an energetic domain and to the accuracy levels defended here.

A. Fabry, *NEUTRONIC CHARACTERIZATION OF THE TAPIRO FAST-NEUTRON SOURCE REACTOR*

Reactor 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.

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor 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.

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:

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

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor 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:

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

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor 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:

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

Flux Maintenance

$$R_{i,k} = \bar{\sigma}_{i,\chi_{235}} \phi^{EQ}_{i,k} = c_{i,k} \left(\frac{\bar{\sigma}_{i,\chi_{235}}}{c_{i,\chi_{235}}} \langle \phi_{\chi_{235}} \rangle \right)$$

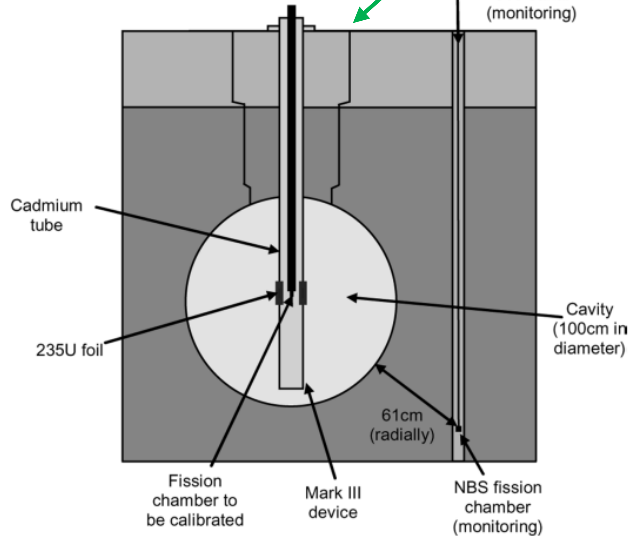
$$\langle \phi_{\chi_{235}} \rangle = \frac{c_{i,\chi_{235}}}{c_{i,Cf(R)}} \frac{\bar{\sigma}_{i,Cf(R)}}{\bar{\sigma}_{i,\chi_{235}}} \frac{S_{Cf}}{4\pi R^2}$$

$c_{i,Cf(R)}$ → 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).

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor 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

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
Reactor neutronic characterization
TAPIRO measurements

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

Overall philosophy

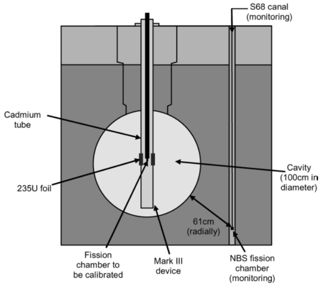
Benchmark-Field Referencing

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

TAPIRO

Flux Maintenance

MOL – BR1 → NBS (USA)

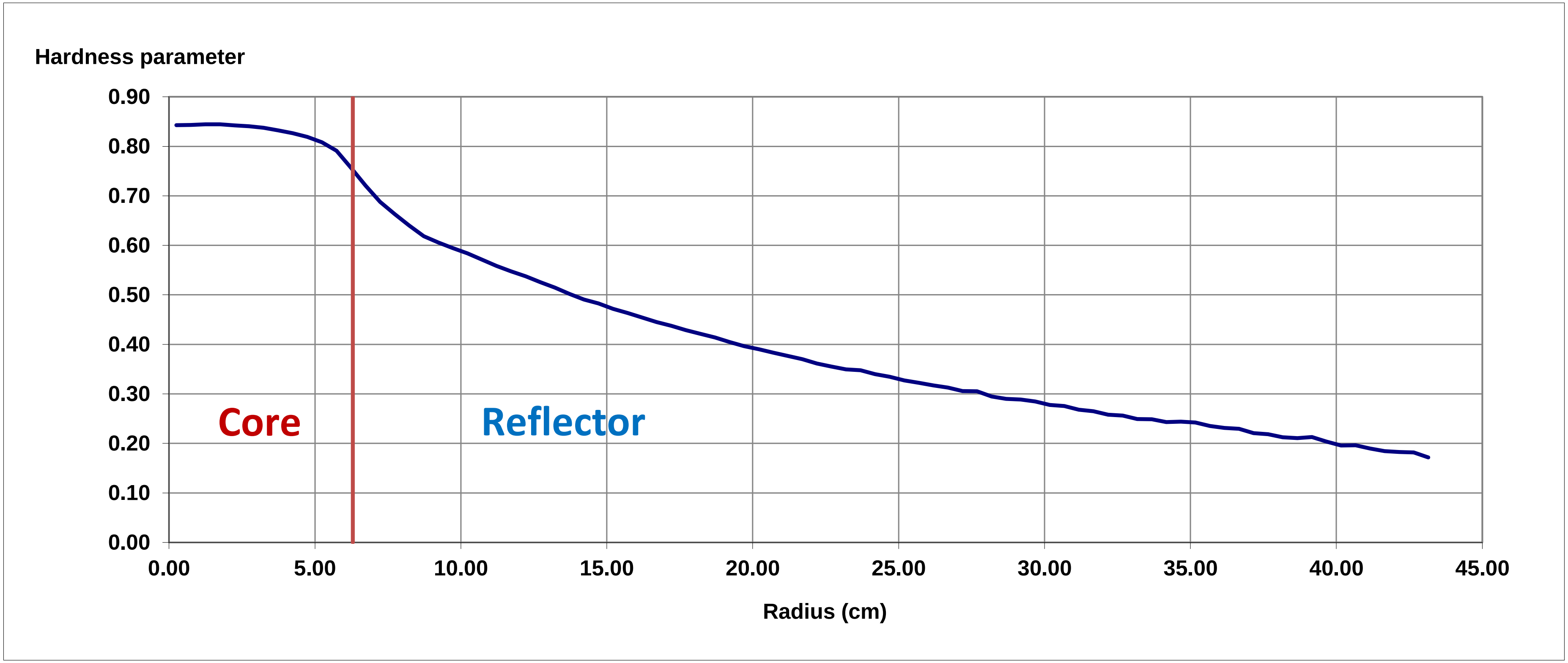


MOL - BR1

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)

Neutron radiation damage parameters

Hardness parameter



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

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
AOSTA experimental campaign on Minor Actinides nuclear data
Background

- The reduction of the nuclear waste is one of the most important nuclear issues.
- The high radiotoxicity of the spent fuel is due to plutonium and some minor actinides (MAs) such as neptunium, americium and curium, above all.
- To allow the MAs destruction an important effort have been done on the nuclear data due to the poor knowledge in this field.
- To improve MAs nuclear data, in the framework of the second *NEA Expert Group on Integral Experiments for Minor Actinide Management* an analysis of the feasibility of MAs irradiation campaign in the TAPIRO fast research reactor is in progress. The work is performed in close collaboration with *CEA*.
- Some preliminary results have been obtained by calculations modelling the irradiation, in different TAPIRO irradiation channels, of some CEA samples coming from the French experimental campaign *OSMOSE*.
- On the basis of neutron transport calculation results, obtained by both deterministic *ERANOS* and Monte Carlo *Serpent* calculation tools, an estimate of the irradiated samples counting levels has been obtained.
- The experimental campaign is named *AOSTA (Activation of OSMOSE Samples in TAPIRO)*.

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy) AOSTA experimental campaign on Minor Actinides nuclear data Background

INL/EXT-10-17622

Principle and Uncertainty Quantification of an Experiment Designed to Infer Actinide Neutron Capture Cross-Sections

G. Youinou
G. Palmiotti
M. Salvatores
G. Imel
R. Pardo
F. Kondev
M. Paul

January 2010

Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy) AOSTA experimental campaign on Minor Actinides nuclear data Background

Time integrated flux

$$\overline{\phi}T \sim \left[\frac{N_{Nd8}(T)}{N_{U5}(T)}\right]_m \frac{1}{\gamma_{Nd8}\,\overline{\sigma}^{f}_{U5}}$$

At TAPIRO core center this value is 1.265 ± 3.5% (barns).

MA capture x-section

$$\left[\frac{N_{A+1}(T)}{N_A(T)}\right]_m \equiv [R_{A+1}(T)]_m$$

$$\overline{\sigma}^{c}_{A} \sim \frac{[R_{A+1}(T)]_m - [R_{A+1}(0)]_m}{[\overline{\phi}\,T]_m}$$

Reasonable irradiation times?

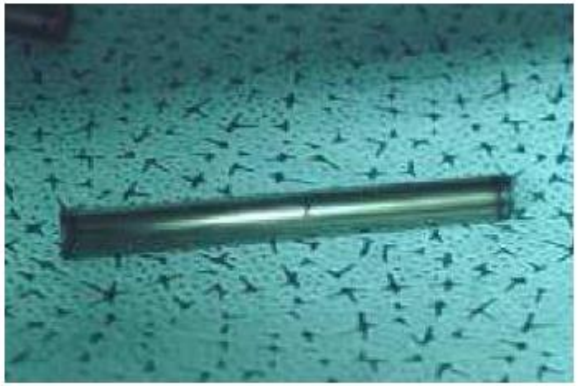
$$\overline{\sigma}^{c}_{A+1} \sim 2\frac{[R_{A+2}(T)]_m}{[R_{A+1}(T)]_m\,[\overline{\phi}\,T]_m}$$

$$\overline{\sigma}^{c}_{A+2} \sim 3\frac{[R_{A+3}(T)]_m}{[R_{A+2}(T)]_m\,[\overline{\phi}\,T]_m}$$

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy) AOSTA experimental campaign on Minor Actinides nuclear data
OSMOSE samples

Dimensions

- Internal sheath (Zy4): 9,56 mm
- External sheath (Zy4): 10,6 mm
- Length : 103.5 mm



Precise Material certificate are available

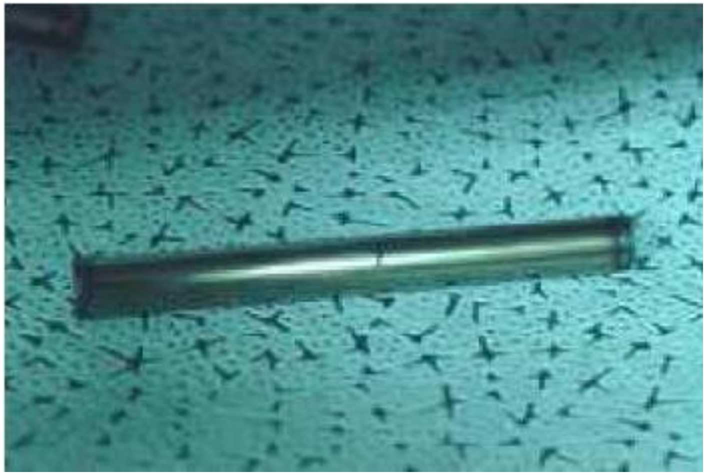
Actinide	Sample n°1 (g)	Sample n°2 (g)	Matrix
Unat	48	/	/
Np237	0.1	0.6	UO2 nat
Pu242	0.5	/	UO2 nat
U236	0.6	2	UO2 nat
Am241	0.06	0.2	UO2 nat
Am243	0.1	0.5	UO2 nat
U234	0.3	/	UO2 nat
Pu238	0.4	/	UO2 nat
Pu240	0.15	/	UO2 nat
Pu239	0.6	/	UO2 nat
U233	0.5	/	UO2 nat
Th232	2	/	UO2 nat
Th232	48	/	/
Pu241	0.1	0.5	UO2 nat

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
AOSTA experimental campaign on Minor Actinides nuclear data
TAPIRO channels and OSMOSE samples compatibility

Name	Position	Penetration	Useful diameter
Diametral channel (D.C.)	Piercing. Horizontal. Diametral in the core.	Inner and outer fixed reflector. Core.	10 mm in core
Tangential channel	Piercing. Horizontal. 50 mm above core mid-plane. Parallel to D.C. 106 mm from core axis.	Inner and outer fixed reflector.	30 mm in reflector
Radial channel 1 (R.C.1)	Radial. Horizontal on core mid-plane, at 90° with respect to D.C.	Inner and outer fixed reflector, up to 93 mm from core axis.	56 mm in reflector
Radial channel 2	Radial. Horizontal on core mid-plane, at 50° with respect to R.C.1.	Outer fixed reflector, up to 228 mm from core axis.	80 mm in reflector
Grand Horizontal Channel (G.H.C.)	Radial. Concentric with R.C.1.	Up to reflector outer surface	400 mm near reflector
Grand Vertical Channel (G.V.C.)	Above core, on the same axis.	Outer fixed reflector, up to 100 mm from upper core base.	800÷900 mm in reflector
Thermal column	Horizontal.	Shield, up to outer reflector	110x116x160 cm^3
Irradiation cavity	On safety plug upper base.	7.4 mm	33 mm

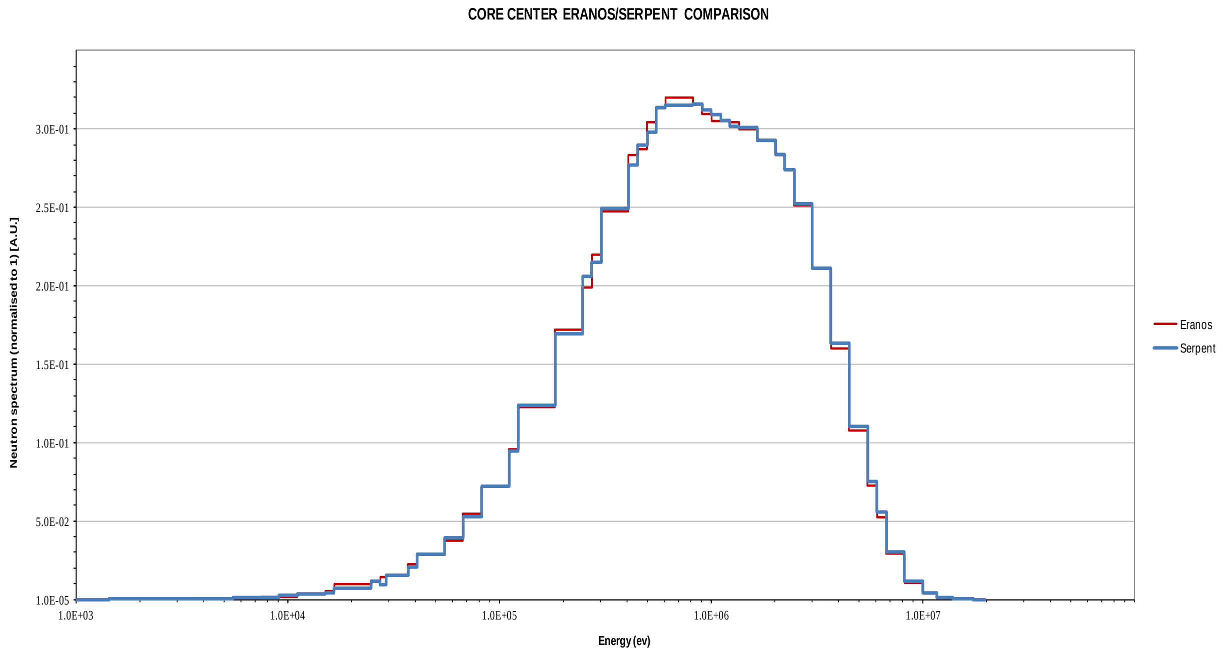
Dimensions

- Internal sheath (Zy4): 9,56 mm
- External sheath (Zy4): 10,6 mm
- Length : 103.5 mm



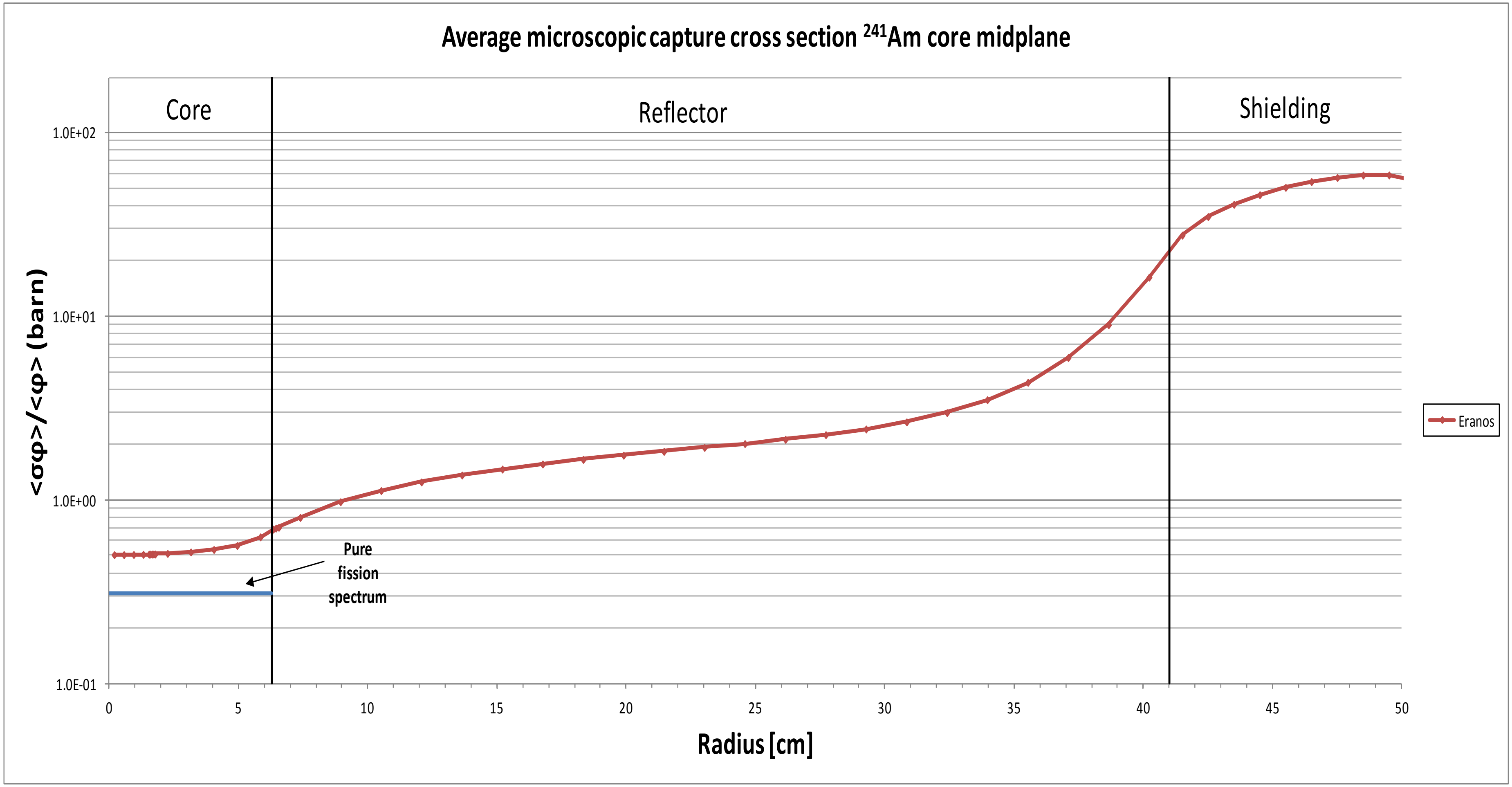
Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
AOSTA experimental campaign on Minor Actinides nuclear data
Average reaction rates in TAPIRO

$$\overline{\sigma_c}(\mathbf{r}) = \frac{< \sigma_c(\mathbf{r},E)\phi(\mathbf{r},E) >_E}{< \phi(\mathbf{r},E) >_E}$$

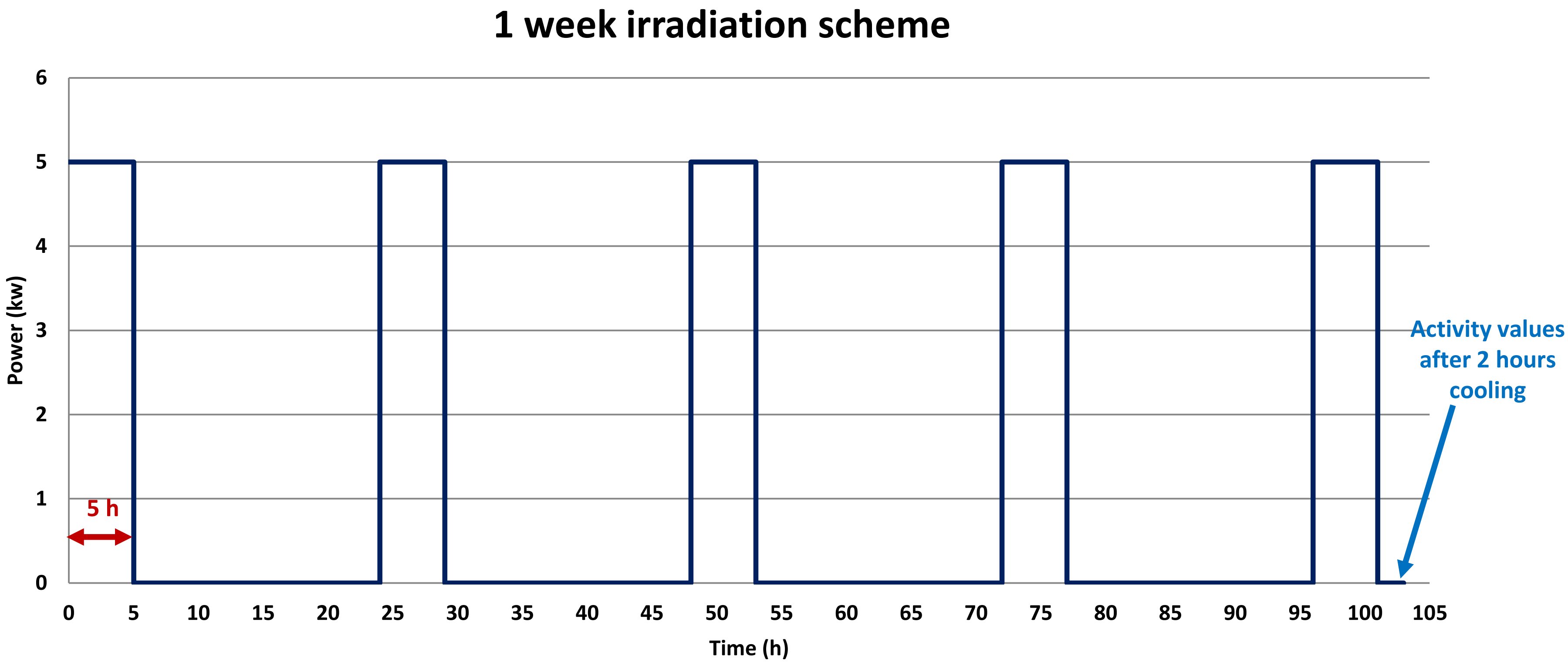


Isotopes considered: Np^{237}, Pu^{242}, Am^{241}, Am^{243}

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
AOSTA experimental campaign on Minor Actinides nuclear data
Average reaction rates in TAPIRO

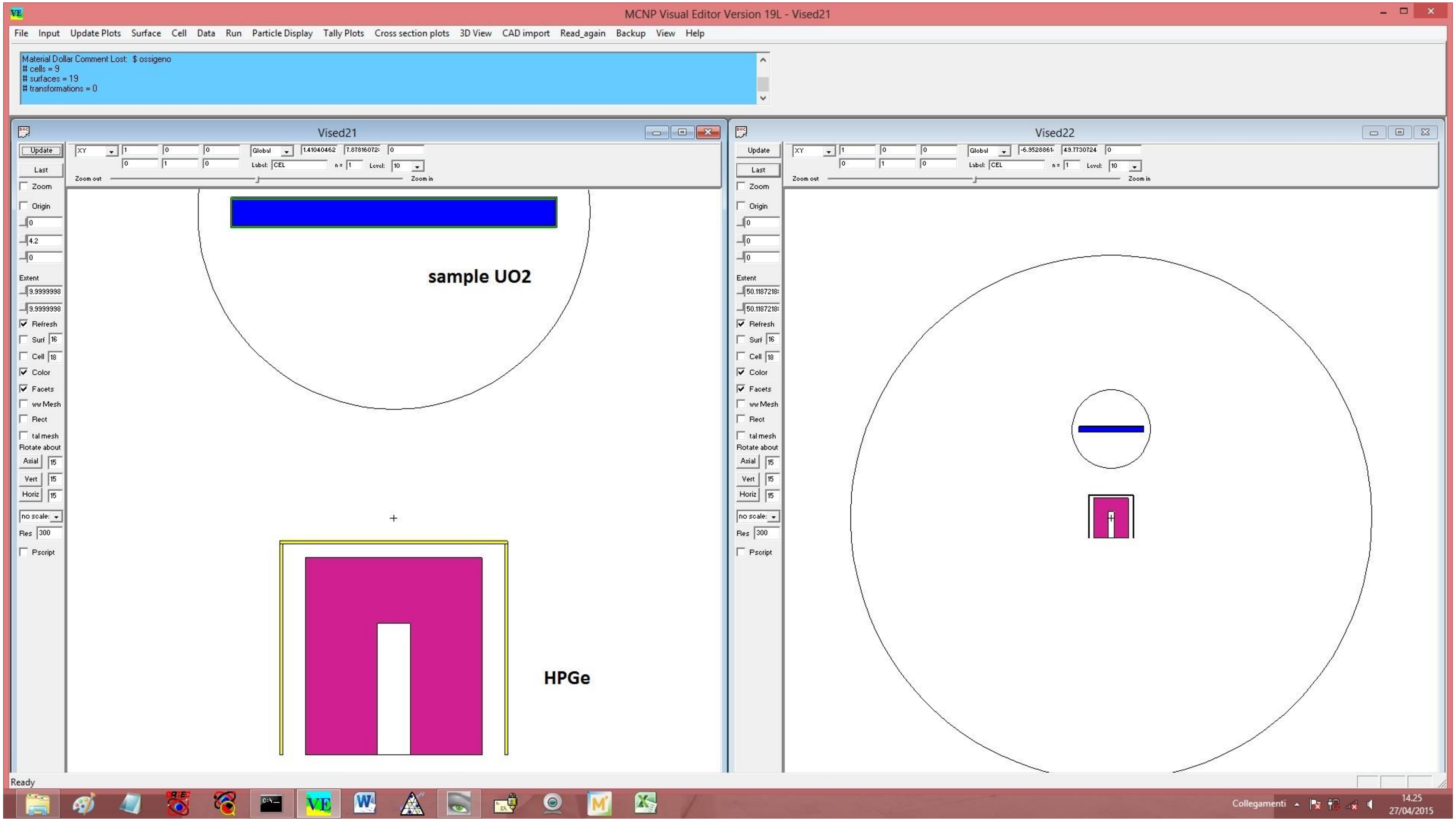


Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
AOSTA experimental campaign on Minor Actinides nuclear data
Hypothesis about irradiation cycles



Example of utilization of a fast spectrum LPRR: TAPIRO (Italy) AOSTA experimental campaign on Minor Actinides nuclear data

Detection efficiency - MCNP evaluation



Example of utilization of a fast spectrum LPRR: TAPIRO (Italy)
AOSTA experimental campaign on Minor Actinides nuclear data
Counting levels estimate

	Position	r = 12.07 cm	r = 24 .58 cm	r = 45.5 cm
OSMOSE Samples	ϕ ($n \cdot cm^{-2} \cdot s^{-1}$)	6.94E+11	1.74E+11	8.79E+09
Np237	Np238 E γ (keV)	984.45	984.45	984.45
	γ Intensity (%)	25.19	25.19	25.19
	ε Detection (%)	0.186	0.186	0.186
	C (cps)	95487	39779	22738
Pu242	Pu243 E γ (keV)	84	84	84
	γ Intensity (%)	23.10	23.10	23.10
	ε Detection (%)	0.021	0.021	0.021
	C (cps)	5559	2572	4698
Am241	Am 242 E $X_{K\alpha 1}$ (keV)	103.374	103.374	103.374
	$X_{K\alpha 1}$ Intensity (%)	5.70	5.70	5.70
	ε Detection (%)	0.107	0.107	0.107
	C (cps)	7014	2745	2204
Am243	Am244 E γ (keV)	743.971	743.971	743.971
	γ Intensity (%)	66.00	66.00	66.00
	ε Detection (%)	0.213	0.213	0.213
	C (cps)	29466	11391	10032

Example of utilization of a fast spectrum LPRR: TAPIRO (Italy) AOSTA experimental campaign on Minor Actinides nuclear data Comments

- **In the framework of the second *NEA Expert Group on Integral Experiments for Minor Actinide Management, in collaboration with CEA* a preliminary analysis of some OSMOSE samples irradiation in TAPIRO has been performed.**
- **Irradiations have been considered for different positions in TAPIRO reactor.**
- **High level counting rates have been obtained, but such levels have to be reduced taking into account the total activity admissible for radiological issues.**
- **More detailed analyses will be performed in the next future.**
- **Preliminary results seem to confirm the feasibility of the *AOSTA (Activation of OSMOSE Samples in TAPIRO)* experimental campaign.**

And finally the roundup!

Roundup

- Low Power Research Reactors cannot be strictly classified as Materials Testing Reactors (MTR) but they have their role in supporting MTR (for example for detectors calibration).
- When talking about "Research Reactors for Development of Materials and Fuels for Innovative Nuclear Energy Systems" probably it's impossible to draw a well defined boundary line between the potential support provided by Low Power Research Reactors and High Power Research Reactors.
- Indeed LPRRs have a very well definite role in the frame of nuclear fuel cycle optimization, see ADSs and nuclear data studies.
- But we have not to forget one of the main mandates of LPRRs: Education and Training, the same mandate of ICTP and IAEA when giving me this opportunity to share with you this morning in Trieste.

Thank you for your attention!

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