TAPIRO fast spectrum research reactor characteristics for neutron radiation damage analyses.

M. CARTA[1], K. W. BURN[2], P. CONSOLE CAMPRINI[2], S. DULLA[3], V. FABRIZIO[1], L. FALCONI[1],

P. RAVETTO[3], A. SANTAGATA[1]

[1]ENEA CR Casaccia - via Anguillarese 301 00123 Santa Maria di Galeria, Italy

[2]ENEA C.R. BOLOGNA - Via Martiri Monte Sole 4 - 40129 Bologna – Italy

[3] Politecnico di Torino, Dipartimento Energia, Corso Duca degli Abruzzi, 24 - 10129 Torino - Italy

ABSTRACT

Although Material Testing Reactors, 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 and mention is made of what is expected from the first phase of the international experimental campaign AOSTA, foreseen the next year 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.

1. Introduction

Research reactors have always been considered as a powerful tool to investigate the effects of neutron radiation damage on a wide class of structural components of interest for both research and industrial applications. In particular, depending on the damage level demanded after irradiation, high power MTRs (Material Testing Reactors) or Low Power Research Reactors (LPRRs) are usually selected as radiation fields. Currently important high neutron flux facilities, such as JHR (France) [1], MYRRHA (Belgium) [2], MBIR (Russia) [3] are under construction or in advanced planning stage. Nevertheless, there is an increasing attention also towards LPRRs for neutron radiation damage analyses, essentially because they can provide very qualified, in terms of both intensity and energy spectrum, neutron radiation fields, such characteristics being very useful for irradiation of electronic components and/or innovative neutron detectors. The ENEA low power fast spectrum TAPIRO research reactor [4], located at the ENEA 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, and some mention is made of what is expected from the first phase of the international experimental campaign AOSTA [5], planned in 2018, conceived in the framework of the NEA Expert Group on Integral Experiments for Minor Actinide Management [6] and focused on a MAs (Minor Actinides) irradiation campaign in TAPIRO. Finally characteristics of some ASTM damage parameters [7], such as 1 MeV equivalent neutron flux and hardness parameter, are provided for different positions along the main irradiation channels.

2. ASTM standard damage functions

In [7] are provided the definitions of the 1 MeV equivalent neutron flux and hardness parameter damage functions. Such functions are connected with quantities such as the displacement KERMA (Kinetic Energy Released in MAterials) functions (units [barn·eV]) for neutron collisions, which are provided in [7] for ^{28}Si and GaAs in the 640 energy group SAND-II structure [8]. For each energy group g the damage KERMA functions are defined, for a given material m, as:

$$F^{(m)}_{D,g} = \sum_{\alpha} \sigma^{(m)}_{g,\alpha} < T^{(m)}_{g,\alpha} \cdot L(T^{(m)}_{g,\alpha}) > \quad [\text{barn} \cdot \text{eV}]$$

where the summation is over the α reaction channels (elastic scattering, inelastic scattering,...), <> indicate suitable average over the energy group g, σ are the microscopic cross sections, T are the energies of the PKAs (Primary Knock-on Atoms) and L(T) are the Lindhard partition functions, providing the fraction of energy deposited in the lattice by the recoil atom cascade generated by a PKA of energy T (see [9] for a review on the subject). As an example, in Fig. 1 a comparison between the damage KERMA functions for ^{28}Si provided in [7] and provided by JANIS [10] viewer for JEFF 3.1 nuclear data library is shown.

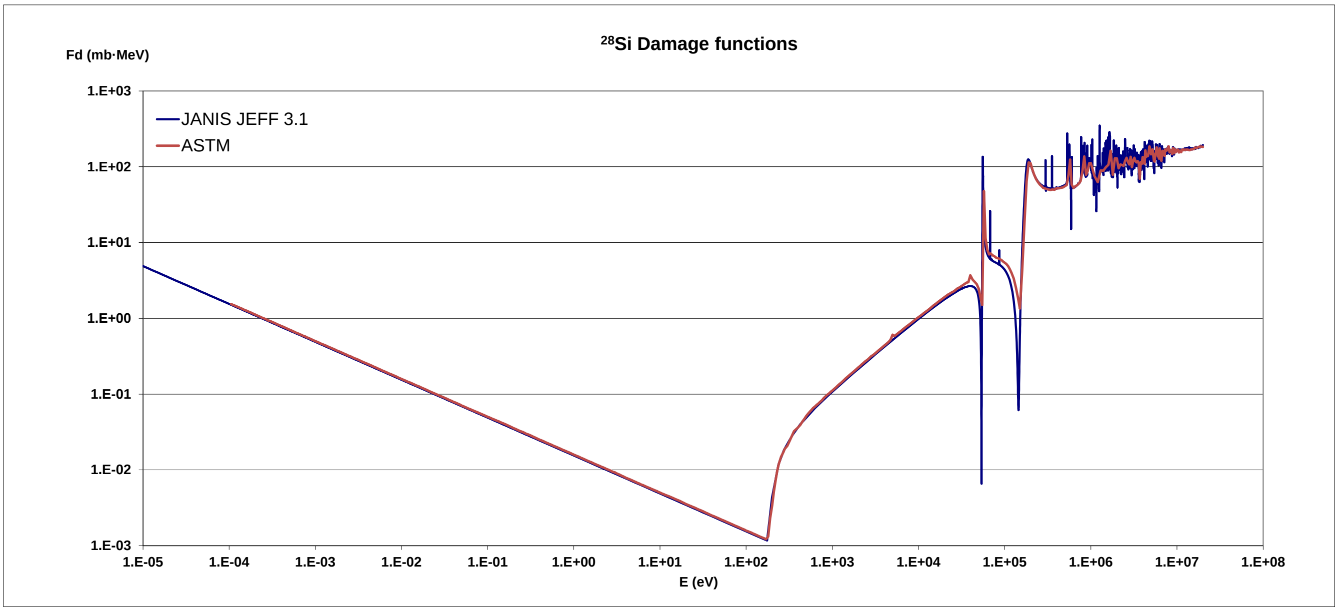

Figure 1. Comparison between damage KERMA functions for ^{28}Si provided in [5] and JEFF 3.1.

For a given position **r** in the facility the (monochromatic) 1 MeV equivalent neutron flux satisfies (by definition) the relation:

$$F^{(m)}_{D,1\ \text{MeV}} \cdot \phi_{eq}(\mathbf{r}, 1\,\text{MeV}) = \sum_{g} F^{(m)}_{D,g} \cdot \phi_g(\mathbf{r}) \qquad [\text{eV} \cdot \text{s}^{-1}] \tag{1}$$

i.e. this equivalent neutron flux has the property to produce the same damage power produced by the facility neutron flux at the same position **r** of the system. From (1) it results:

$$\phi_{eq}(\mathbf{r}, 1\,\text{MeV}) = \frac{\sum_{g} F^{(m)}_{D,g} \cdot \phi_g(\mathbf{r})}{F^{(m)}_{D,1\ \text{MeV}}} \tag{2}$$

meaning that the denominator in (2) acts as a sort of normalization factor (for example, for ^{28}Si it is equal to 95 mbarn·MeV [7]).

The hardness parameter H is defined as:

$$H(\mathbf{r}) = \frac{\phi_{eq}(\mathbf{r}, 1\,\mathrm{MeV})}{\sum_g \phi_g(\mathbf{r})} = \frac{\sum_g F_{D,g}^{(m)} \cdot \phi_g(\mathbf{r})}{F_{D,1\,\mathrm{MeV}}^{(m)} \sum_g \phi_g(\mathbf{r})} \qquad (3)$$

It can be noticed that the case H<1 indicates that a lower 1 MeV neutron flux is needed to produce the same damage as produced by the system neutron spectrum. The system neutron spectrum tends to be “softer” with respect to the 1 MeV equivalent neutron flux. The case H=1 indicates that the same 1 MeV or system neutron spectrum neutron fluxes are needed to produce the same damage: the system neutron spectrum tends to be “damage analogous” with respect to the 1 MeV equivalent neutron flux. Finally, the case H>1 indicates that a greater 1 MeV neutron flux is needed to produce the same damage as produced by the system neutron spectrum, thus it tends to be “harder” with respect to the 1 MeV equivalent neutron flux.

It can be seen from Eqs. (2) and (3) that to accurately evaluate these damage parameters we have to accurately know the reactor neutron flux intensity and spectrum at different positions, which in turn depends on reactor materials and reactor geometrical complexity, plus of course nuclear data. The challenge for LPRRs, generally providing less damage with respect to MTRs, is trying to compensate this lack in damage level by a higher accuracy in experimental data.

3. The TAPIRO reactor

TAPIRO (“TAratura Pila Rapida a Potenza 0”, meaning in English “fast pile calibration at zero power”) is a fast neutron source reactor licensed in 1971 for a maximum thermal power of 5 kW [4]. The project, entirely developed by ENEA's staff, was based on the general concept of AFSR (Argonne Fast Source Reactor - Idaho Falls). Since 1971, it has been used for fast reactor shielding experiments, biological effects of fast neutrons, electronic component neutron damage, etc.

The reactor has a homogeneous HEU uranium-molybdenum alloy (98.5 % U, 1.5 % Mo in weight) cylindrical core of about 6 cm of radius and 11 cm height. The core is divided into two parts: the upper one is fixed to the reactor structure whereas the lower one is movable and can be dropped in order to rapidly shut down the system.

For a thermal power greater than 50 W the core is cooled by means of forced circulation of helium.
The core is totally reflected by copper (cylindrical-shaped) of about 30 cm of thickness. The reflector is divided into two concentric blocks: a 10 cm thick inner block contained inside the primary cooling system and an outer block about 20 cm thick.
Finally, the reactor is surrounded by borate concrete shielding about 170 cm thick.
The reactor is controlled by 5 control rods, made of copper, positioned in 5 cavities inside the inner reflector where the control rods can be moved controlling the amount of reflector present in the system, i.e. acting on the neutron leakage. Furthermore, a rapid shut-down may be realized by dropping the mobile part of the core. A horizontal section of the reactor is shown in Fig. 2.

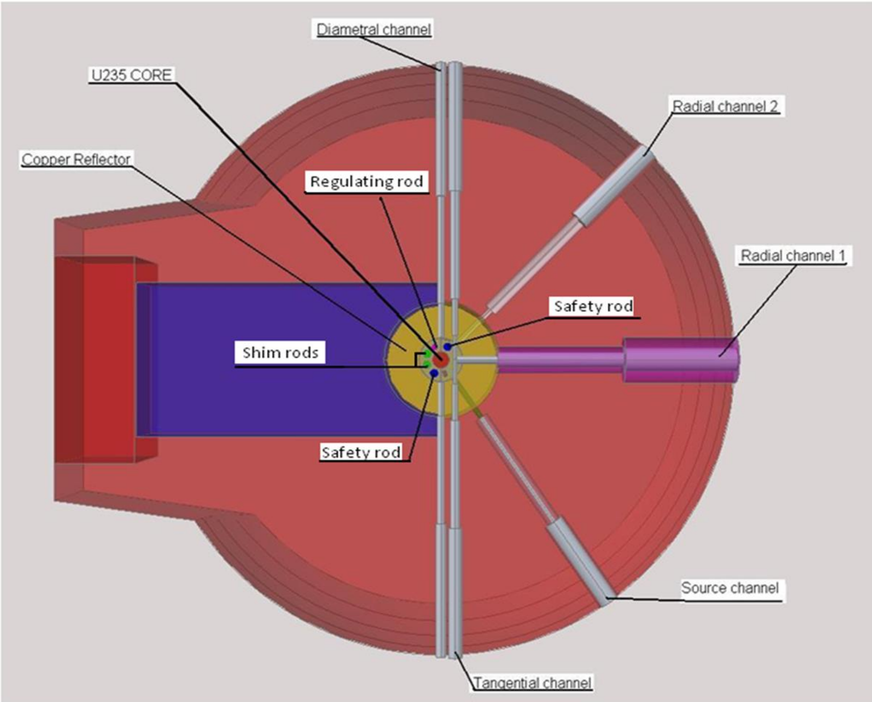

Figure 2. TAPIRO horizontal section.

With regard to the irradiation facilities the reactor has 6 main experimental channels (4 horizontal and 2 vertical channels) and a large cavity, named the thermal column (a parallelepiped 110×110×160 cm^3), see Fig. 2. One mid-plane channel traverses the core allowing irradiation of small samples (~ 1 cm) in an almost pure ^{235}U fission spectrum.
At maximum thermal power, the total core integrated neutron source strength is ≈ 3×10^{14} n s^{-1}, equivalent to a neutron flux ≈ 4×10^{12} $n\cdot cm^{-2}\cdot s^{-1}$ at the core center and a neutron flux ≈ 1.5×10^{10} $n\cdot cm^{-2}\cdot s^{-1}$ at the entrance of the thermal column.

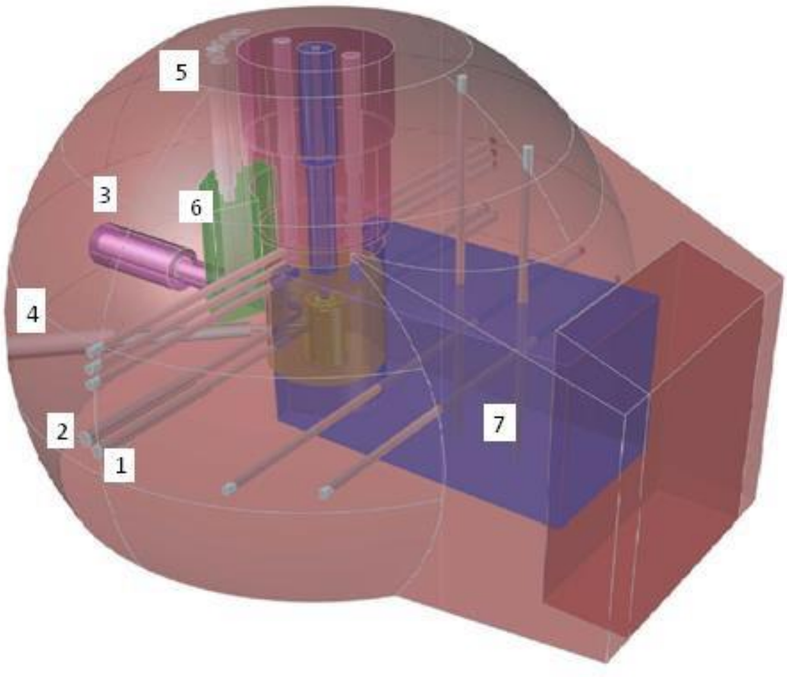

Figure 3. TAPIRO Irradiation facilities: 1) diametral channel; 2) tangential channel; 3) radial channel 1; 4) radial channel 2; 5) detector channels; 6) paraffin; 7) thermal column.

The irradiation channels (Fig. 3) allow to insert devices also in high flux regions. They are enclosed in metallic sleeves and have a reduced section going toward the core to limit the gamma streaming effect. Each channel plug is made of a casing filled with shielding material with a copper extension placed in the reflector zone. This extension can be modified to host samples [4].

4. TAPIRO Neutronic characterization

In the framework of an agreement between ENEA and SCK•CEN Mol (Belgium), an extensive neutronic characterization of the TAPIRO source reactor was carried-out (1980÷1986). The program was led by A. Fabry (SCK•CEN Mol) [11]. As a result it was found that TAPIRO is able to provide a family of neutron spectra of variable hardness (nearly a pure fission spectrum near the core center). This feature makes TAPIRO suitable for many metrology applications, also taking into account that a good spherical symmetry of the neutron flux shape was highlighted by the joint ENEA- SCK•CEN Mol experimental campaign.
The neutronic characterization was performed following the so-called "Benchmark-Field Referencing" (inter-laboratories experimental campaign) approach. The theoretical basis of this technique can be briefly described as follows.

For a given position *k* in the reactor and for a detector *i* 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 detector *i* and $I_{i,k}$ is the integral response. Two broad classes of integral data need to be distinguished, using specific determination for the response function $r_i(E)$, namely:

a) Integral reaction rates:

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

b) Equivalent fission fluxes (in the 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:

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

If the observed counting rates from a detector (having efficiency ε_i and density N_i atoms·cm^{-3}) are given in two different neutron fields 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:

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

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

$$R_{i,k} = \overline{\sigma}_{i,\chi_{235}} \phi_{i,k}^{EQ} = c_{i,k} \left(\frac{\overline{\sigma}_{i,\chi_{235}}}{c_{i,\chi_{235}}} < \phi_{\chi_{235}} > \right) \quad (4)$$

where $c_{i,k}$ are the measured counting rates in TAPIRO.
The activity “Flux Maintenance” (at SCK•CEN Mol – Belgium) allowed the certification of the value $<\phi_{\chi_{235}}>$ in cooperation with the US NBS (National Bureau of Standards) by means of a certified Californium source:

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

The ratio $\overline{\sigma}_{i,\chi_{235}}/c_{i,\chi_{235}}$ in Eq. (4) was measured at the SCK•CEN Mol Cavity ^{235}U Fission Spectrum Standard Neutron Field. A recent article concerning detector calibration for spectrum index measurements in the MOL cavity can be found in [12]. Fig. 4 shows a synopsis of the “Benchmark-Field Referencing” method.

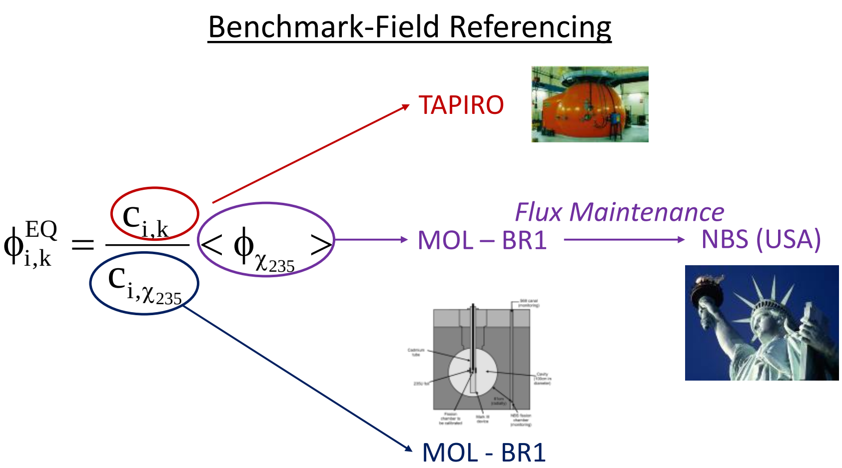

Figure 4. Benchmark-Field Referencing at TAPIRO.

In the near future, in the framework of the NEA Expert Group on Integral Experiments for Minor Actinide Management [6], a joint collaboration between ENEA and CEA has been established with the aim to study the feasibility of selected MAs irradiation campaign in the TAPIRO fast neutron source reactor. The campaign is named AOSTA (Activation of OSMOSE Samples in TApiro) [5]. Preliminary to this campaign there will be a characterization campaign focusing on assessing the neutron spectra in the TAPIRO radial, tangential and diametral channels.
Several measurement techniques are foreseen and will be cross-compared:

- Spectral indices with calibrated miniature fission chambers (typically ^{238}U fission rate over ^{235}U fission rate). Detectors from CEA, JAEA and INL will be used to produce complementary results.
- Axial flux distribution measured with miniature fission chambers (^{235}U, ^{238}U, ^{237}Np).
- Dosimetry measurements using metallic activation foils analyzed by gamma spectroscopy.

5. TAPIRO damage parameters

Some calculations of the damage parameters for ^{28}Si, together with some experimental evaluations, have been performed for irradiation campaigns recently carried out at TAPIRO. As an example, in Figs. 5 and 6 the equivalent 1 MeV neutron flux radial behavior in correspondence of the diametral and radial 1 TAPIRO experimental channels for a 1 kW reactor power is shown. Plotted values have been obtained by Monte Carlo simulations [13] using ENDF/B-VII.1 as nuclear database.

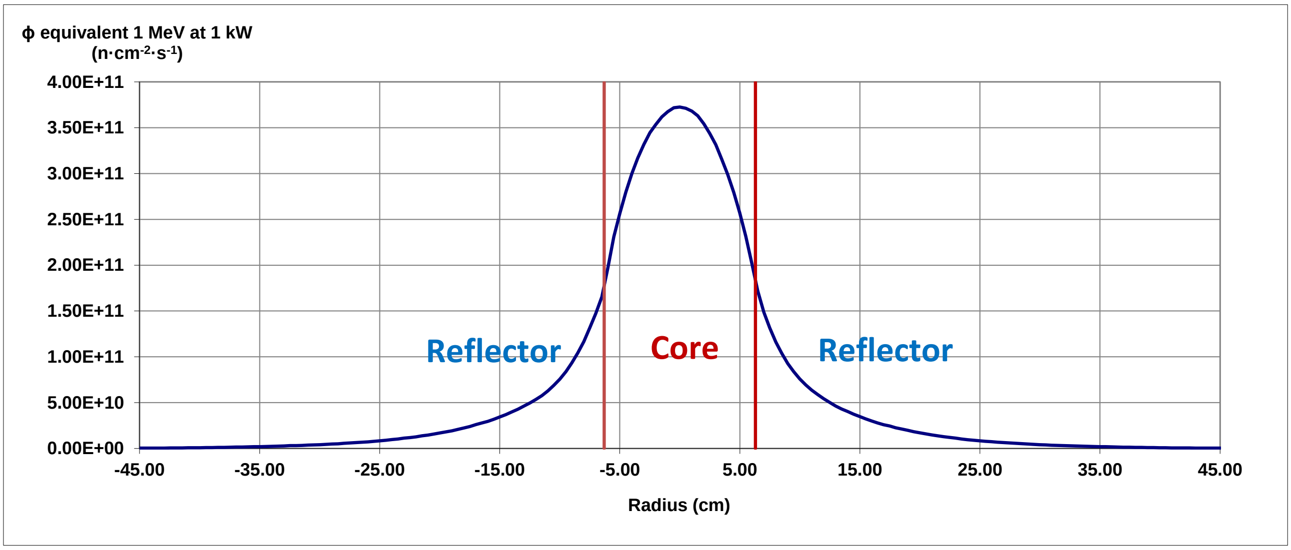

Figure 5. Equivalent 1 MeV flux radial behavior for TAPIRO diametral channel at 1 kW power.

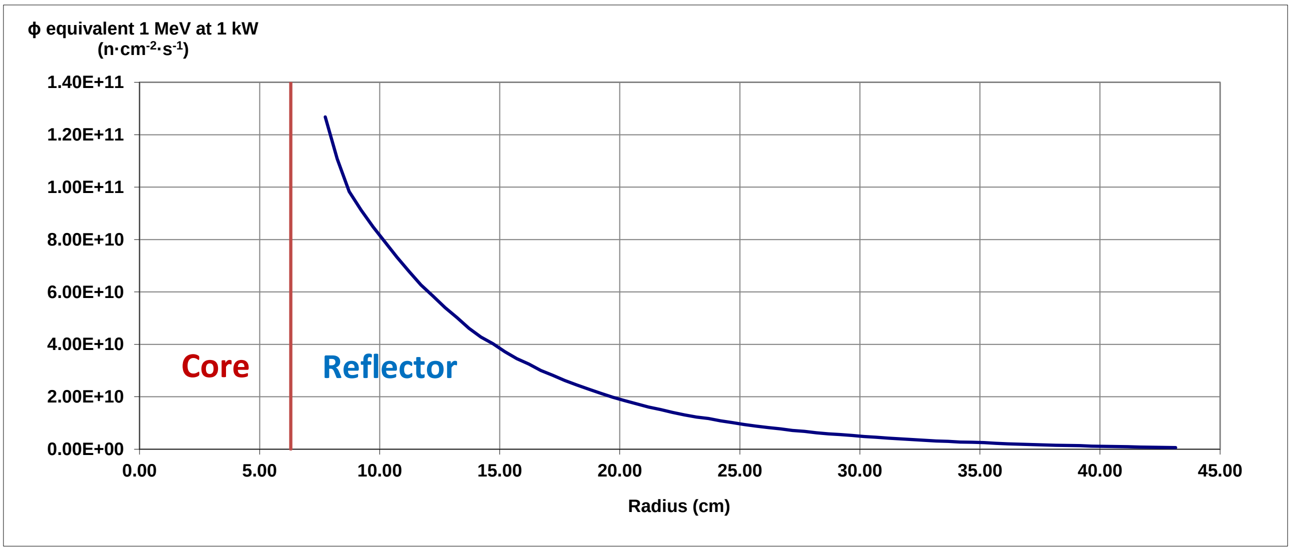

Figure 6. Equivalent 1 MeV flux radial behavior for TAPIRO radial 1 channel at 1 kW power.

In Figs. 7 and 8 the hardness parameter radial behavior in correspondence of the diametral and radial 1 TAPIRO experimental channels is shown. As above, plotted values have been obtained by Monte Carlo simulations using ENDF/B-VII.1 as nuclear database.

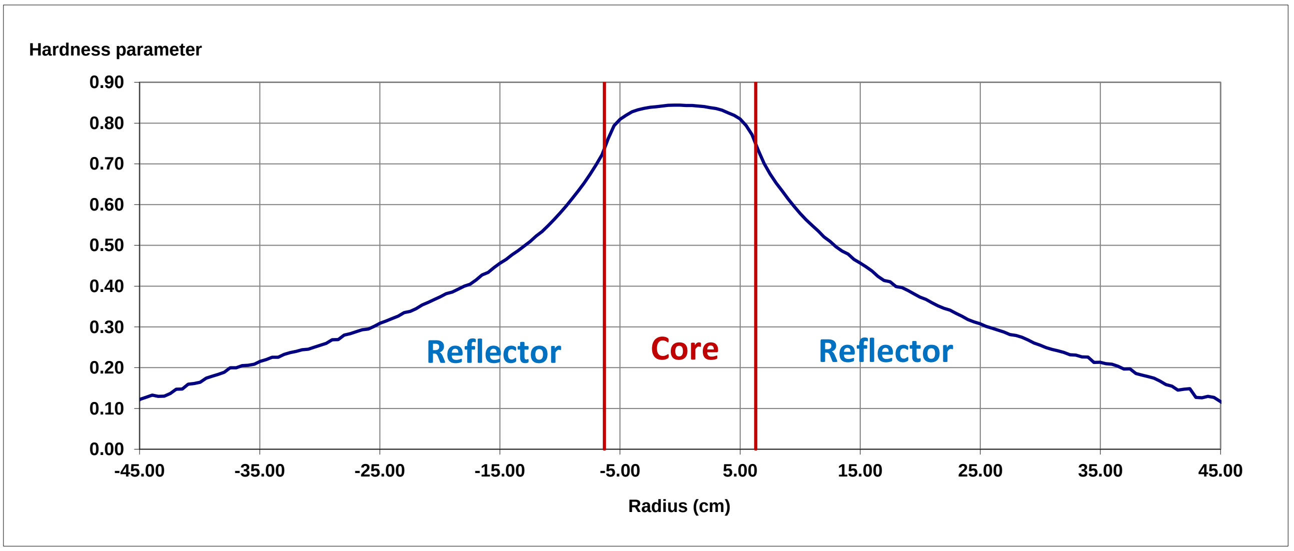

Figure 7. Hardness parameter radial behavior for TAPIRO diametral channel.

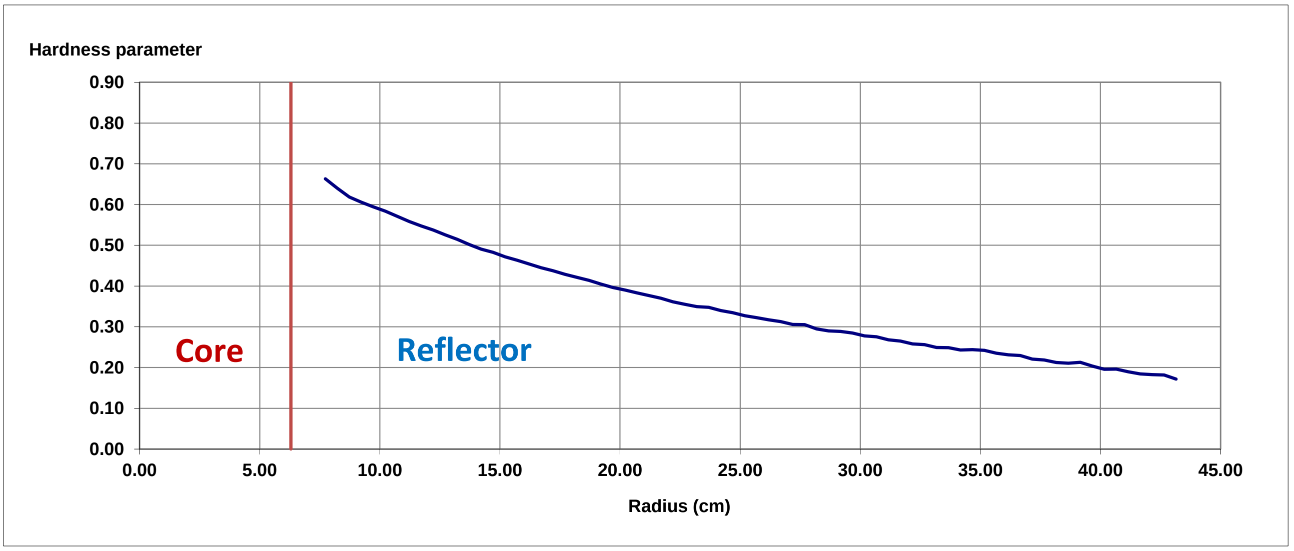

Figure 8. Hardness parameter radial behavior for TAPIRO radial 1 channel.

It is interesting to notice for the case of the diametral channel that although the equivalent 1 MeV flux, providing information on the intensity of the neutron flux, peaks in the core center (Fig. 5), the hardness parameter, which provides information on the neutron flux spectrum, tends to be flat (Fig. 7).

6. Conclusions

Usually MTRs, having significant powers up to hundreds of MeV, 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. This high quality level is often required for irradiation of electronic components (also for space applications) and/or innovative neutron detectors.
As described in this paper, the ENEA fast LPRR TAPIRO has particular features which match with the above quality requirements, thanks to the neutronic characterization performed in the 80's following the so-called "Benchmark-Field Referencing" approach. In addition an important

contribution to the TAPIRO experimental neutron characterization will be provided by the first phase of the international experimental campaign AOSTA, foreseen next year at TAPIRO.
The radial behavior, in the diametral and radial 1 TAPIRO experimental channels, of some main ASTM standard damage parameters has been provided. These damage parameters, in particular 1 MeV equivalent neutron flux at 1 kW power and hardness parameter, show that TAPIRO is well suited for neutronic irradiation damage analyses (at low power), reaching Hardness parameter values in positions close to the core of around 0.7÷0.8.

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