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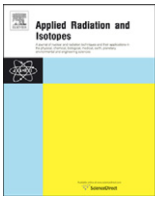

Characterization of the fast neutron irradiation facility of the Portuguese Research Reactor after core conversion

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ABSTRACT

The fast neutron irradiation facility of the Portuguese Research Reactor was characterized after the reduction in uranium enrichment and rearrangement of the core configuration. In this work we report on the determination of the hardness parameter and the 1 MeV equivalent neutron flux along the facility, in the new irradiation conditions, following ASTM E722 standard.

1. Introduction

The behavior of electronic devices and circuits under radiation is a concern shared by the nuclear industry, the space community and the high-energy physics community. In many situations standard commercial components are used instead of radiation hard components to reduce costs. However, standard commercial components need to be tested, to determine their radiation tolerance (Faccio, 2000).

The Portuguese Research Reactor (RPI) is a 1 MW pool-type reactor, operating since 1961. A fast neutron irradiation facility was built at the RPI to test commercial electronic components for CERN (Franco et al., 2005; Zong et al., 2006) within a program started in 1999. Ten years of operation at CERN were simulated during 60 h-long irradiations achieving a fast neutron fluence of 5×10^{13} n/cm^2 with 1–2 kGy simultaneous gamma dose. The irradiation conditions were meanwhile changed, with the reduction of uranium enrichment of the fuel, from ‘Highly Enriched Uranium’ (HEU, 93.2% ^{235}U) to ‘Low Enriched Uranium’ (LEU, 19.8% ^{235}U), and a new core configuration, where an Al block at the entrance of the irradiation facility was removed (Dung et al., 2010). In this work we report on the determination of the hardness parameter and the 1 MeV equivalent neutron flux along the beam tube, in the new irradiation conditions, following ASTM E722 standard (ASTM, 2004).

2. Determination of the 1 MeV equivalent flux

ASTM E722 covers procedures for characterizing the neutron fluence from a source in terms of an equivalent monoenergetic neutron fluence of 1 MeV required to produce the same displacement damage in a specified irradiated material. The standard covers displacement damage in both Si- and GaAs-based devices, but only Si-based devices are considered here. The equivalent fluence is defined as (ASTM, 2004)

$$\phi_{\mathrm{eq,1\,MeV,Si}} = \frac{\int_0^\infty \phi(E)F_{\mathrm{Si}}(E)dE}{F_{\mathrm{Si,1\,MeV}}} \tag{1}$$

In Eq. (1), $\phi(E)$ is the incident neutron fluence spectrum and $F_{\mathrm{Si}}(E)$ is the neutron displacement damage function for Si (displacement damage per unit fluence) as a function of energy. This approach allows a direct comparison with irradiations in different installations, for which the neutron spectra are not identical. The numerical value of the hardness parameter (H_{Si}) is equal to the fluence of 1 MeV monoenergetic neutrons required to produce the same displacement damage in the specified material per unit fluence of neutrons of the neutron spectrum in the irradiation conditions

$$H_{\mathrm{Si}} = \frac{\phi_{\mathrm{eq,1\,MeV,Si}}}{\phi} = \frac{\int_0^\infty \phi(E)F_{\mathrm{Si}}(E)dE}{F_{\mathrm{Si,1\,MeV}}\int_0^\infty \phi(E)dE} \tag{2}$$

Fig. 1 shows the new LEU core of the RPI, mounted on a 6×9 grid. It has seven standard fuel assemblies, numbered N1–N7 and five control assemblies, numbered C1–C5. The core is reflected by two large Beryllium reflectors (Be–N, Be–S), two small Beryllium reflectors (Be) and the outer face of the graphite stacking of the thermal column. Fig. 1 also shows a fission chamber (FC) for reactor start-up, four “dummy” assemblies (DA) without fuel, to improve cooling of the fuel assemblies at the periphery of the core, and the

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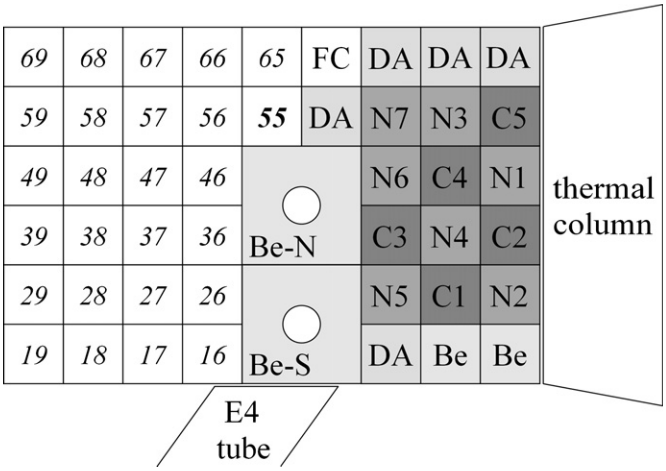

Fig. 1. Core configuration of the RPI with low enriched fuel, where N1–N7 are standard fuel assemblies, C1–C5 are control assemblies and the DA are dummy assemblies. The core is reflected by Be blocks and by the graphite stacking of the thermal column. The beginning of beam tube E4, where the irradiation facility is installed is close to the reflector Be–S.

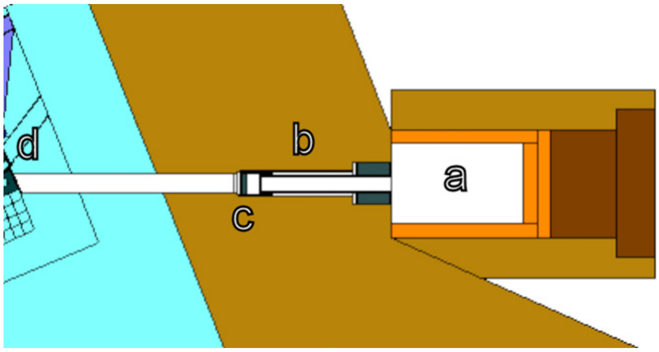

Fig. 2. Plot of the Monte Carlo model of the facility, showing (a) irradiation chamber at the end of neutron beam tube; (b) prolongation inside the tube; (c) neutron and gamma filter; (d) periphery of the core.

beginning of neutron beam tube E4, where the irradiation facility is installed. Free grid positions are shown with their identification numbers.

The fast neutron irradiation facility was simulated using a Monte Carlo (MC) model of the core (Fernandes et al., 2010), extended to include the neutron beam tubes. Fig. 2 shows a view of the model of the facility. It comprises an irradiation chamber (marked “a” in Fig. 2) at the end of neutron beam tube E4, as well as a prolongation inside the tube (marked “b”), made through the introduction of a 1.0 m long cylinder with 0.15 m inner diameter, which is attached to the face of the beam tube housing. The irradiation chamber allows the positioning of equipment, which needs to be very close to the components under test but whose irradiation should be minimized. A filter composed of 0.7 cm Boral (Al–B$_4$C) plus 4.0 cm Pb (marked “c” in Fig. 2) was introduced in the beam tube, in order to decrease the thermal neutron component and the gamma dose. High density concrete and polyethylene lined with Cd are used in the biological shielding.

As the inner face of the prolongation inside the beam tube is far from the core periphery (approximately 1.60 m away), the MC calculations were done in two steps. As a first step, the MCNPX 2.6 code (Pelowitz, 2008) was run in criticality mode, keeping information of all neutrons crossing a surface inside the beam tube, 0.5 m away from the core, before the Boral–Pb filter. Later, the result of the previous calculation (about 320,000 tracks from 128

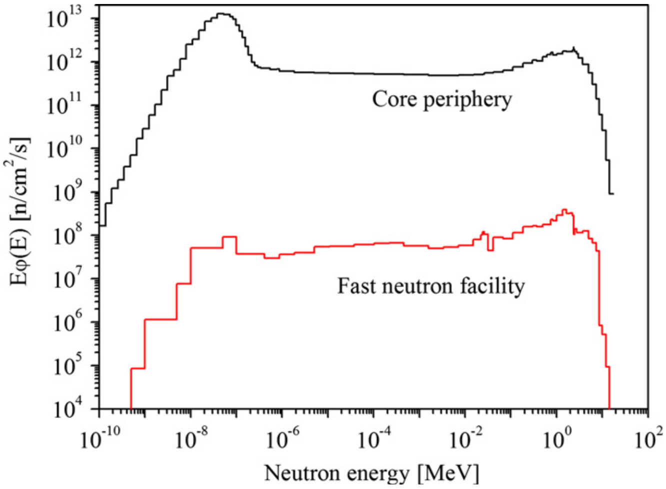

Fig. 3. Neutron spectra (neutron flux per unit lethargy) at a position in the periphery of the core and inside the prolongation of the irradiation chamber, at the point closest to the core.

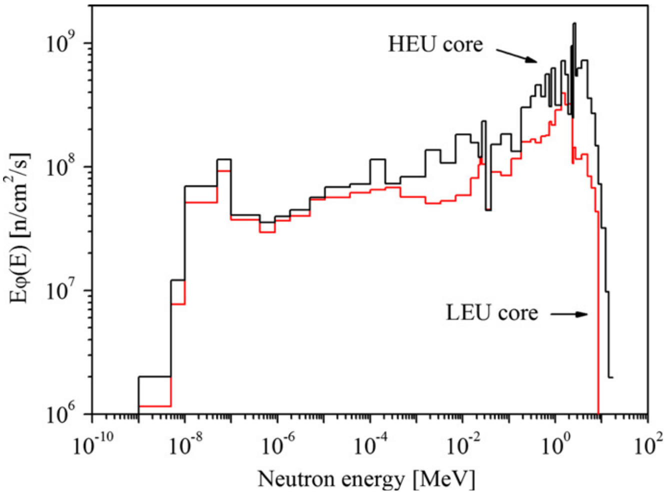

Fig. 4. Neutron spectra (neutron flux per unit lethargy) at the point closest to the core inside the prolongation of the irradiation chamber, for the new core (LEU) and the core previously used (HEU).

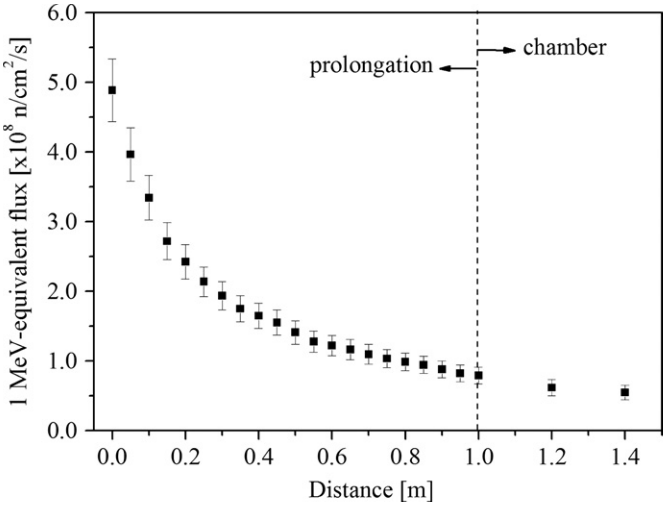

Fig. 5. Calculated 1 MeV equivalent neutron flux along the irradiation facility.

Table 1
Measured values of fast neutron flux ($E>1$ MeV) and fast neutron flux from Ni foils, plus calculated values of the hardness parameter and of the 1 MeV equivalent neutron flux. The uncertainty (one-sigma) in the last digit is indicated inside parenthesis.

Parameter	Distance inside extension of irradiation chamber (m)								
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
Fast neutron flux ($E>1$ MeV) ($\times 10^8$ n/cm^2/s)	4.1(4)	3.0(3)	2.4(2)	1.8(2)	1.6(2)	1.3(1)	1.2(1)	1.1(1)	1.0(1)
Fast neutron flux with Ni foils ($\times 10^8$ n/cm^2/s)	5.5(4)	4.1(4)	3.3(3)	2.7(3)	2.3(2)	2.0(2)	1.7(2)	1.5(2)	1.4(1)
1 MeV equivalent neutron flux ($\times 10^8$ n/cm^2/s)	4.9(4)	3.4(3)	2.4(2)	1.9(2)	1.7(2)	1.4(2)	1.2(1)	1.1(1)	1.0(1)
Hardness parameter	0.85(1)	0.86(1)	0.89(1)	0.90(1)	0.92(1)	0.94(1)	0.97(2)	0.98(2)	0.99(2)

million histories) was propagated throughout the remaining part of the beam tube using variance reduction techniques.

The fast neutron flux ($E>1$ MeV) in the irradiation facility was determined from the irradiation of Al, Ni and In foils using standard procedures (Fernandes et al., 2010; Baard et al., 1989). These measurements were then used to normalize the MC calculations.

Fig. 3 compares the obtained neutron spectrum (neutron flux per unit lethargy) in the dummy assembly in core grid position 54 (to the right of position 55, shown in bold in Fig. 1) at the periphery of the core, with the spectrum inside the prolongation of the irradiation chamber, at the point closest to the core. As could be expected, thermal neutrons are prevalent at the core periphery, while epithermal and fast neutrons are prevalent in the spectrum at the irradiation facility, after the significant reduction of the thermal component imposed by the Boral. Thermal neutrons are mostly a nuisance for the irradiation of electronic components, as they lead to the production of undesired radioisotopes from the activation of the metallic pins and other materials.

Fig. 4 shows the obtained neutron spectra (neutron flux per unit lethargy) inside the prolongation of the irradiation chamber, at the point closest to the core, for the new LEU core and for the previous HEU core. In the point closest to the core the fast neutron flux ($E>1$ MeV) was reduced from 1.0×10^9 n/cm^2/s (Zong et al., 2006) to 4.1×10^8 n/cm^2/s. This reduction is not a direct result of the conversion from HEU to LEU, as the neutron fluxes (thermal and fast) in the core grid are approximately the same after conversion (Marques et al., 2008). It is rather due to the replacement of an Al block by a Be reflector at the entrance of the beam tube. Compared with the Be reflector, the Al block increased the leakage from the core and reduced neutron moderation, thus favoring an increase in the fast neutron component in the neutron beam tube. The new fast neutron flux is still enough for the irradiation of electronic components, as test fluences are usually well below 10^{14} n/cm^2.

Fig. 5 shows the variation of the calculated 1 MeV equivalent neutron flux along the irradiation facility; distances from 0 to 1.0 m correspond to the prolongation inside the beam tube, with zero being the position closest to the core.

Table 1 shows the measured fast neutron flux ($E>1$ MeV), the fast flux determined with Ni foils only, as well as the calculated values of the hardness parameter and of the 1 MeV equivalent neutron flux. The uncertainty (one-sigma) in the last digit of each value is indicated inside parenthesis. The variation of the values is not a simple effect of the distance, due to neutron scattering with the beam tube and the surrounding materials. Neutron dosimetry during the irradiations is normally done using only Ni foils, as the ^{58}Co isotope produced by the ^{58}Ni(n,p)^{58}Co nuclear reaction has a long half-life of 70.8 d. The fast neutron flux is then determined using an averaged cross section for this reaction in a fission spectrum, $\langle\sigma\rangle=0.11$ b (Baard et al., 1989). With the previous HEU core the hardness parameter had only been determined at the point closest to the core, with a value of 0.85(5) (Franco et al., 2005).

The gamma dose rate at the facility was determined using aluminum oxide (Al_2O_3:Mg,Y) thermoluminescent dosimeters (Santos et al., 2006). The maximum gamma dose rate in the irradiation facility (at the point closest to the core) is 63 Gy/h, while for the previous HEU core it was 105 Gy/h. This difference is not significant with reference to the aim of the facility, i.e., irradiation with fast neutrons. In cases where a higher gamma dose is required, or the behavior of the circuits under neutron irradiation is not relevant, irradiations can be done at the ^{60}Co irradiation facility (Belchior et al., 2008) located in the same campus, at dose rates up to 10 kGy/h.

3. Conclusions

The fast neutron irradiation facility of the RPI was completely characterized after the conversion to LEU and rearrangement of the core. ASTM E722 standard was adopted in order to have a widely accepted way to express the fast neutron fluence. The values of the 1 MeV equivalent neutron flux and of the hardness parameter were determined combining measurements with activated foils and Monte Carlo calculations.

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