NENE 2014
September 8-11
PORTOROŽ
SLOVENIA
23rd International Conference Nuclear Energy for New Europe

Computational study of neutron screens performance considering different absorbing materials

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ABSTRACT

The upcoming development of the IV generation fast reactor systems requires the examination of the behaviour exhibited by the structural and fuel materials under the irradiation conditions prevailing in these reactors. The lack of operating fast reactors and, hence, the lack of capability to perform experiments in such irradiation environments can be compensated by creating the desired irradiation conditions in existing reactors that are in operation, such as the Material Test Reactors (MTRs). This can be achieved via neutron shielding materials, the so-called neutron screens, which can be installed in specific irradiation locations of the above mentioned reactors. The effectiveness of various neutron screens in tailoring the neutron spectrum inside their performance area is hereby investigated, by examining different screen materials and thicknesses. Performance characteristics of these materials were estimated by performing simulations based on a model of Jules Horowitz Reactor (JHR) Cadarache. All calculations have been performed with the TRIPOLI-4.8 code and the JEFF-3.1.1 cross-section library. The materials have been selected based on their capability to absorb neutrons of low (thermal, E<1eV) energies and neutrons of intermediate energies (epithermal, 1eV<E<1MeV), thus providing irradiation conditions similar to those of a fast reactor with respect to the ratio of the fast (E>1Mev) component to the thermal and epithermal neutron component. Such materials include Boron, Europium, Cadmium, Gadolinium, etc. The present study intends to highlight the materials that could be effectively used as neutron spectrum tailoring media, aiming also at specifying the most appropriate neutron screen, i.e. the one combining a material of the highest absorbing capability in conjunction with the smallest screen thickness.

1 INTRODUCTION

The presence of fast neutron spectra in new reactor concepts (such as Gas Cooled Fast Reactors, new generation sodium cooled fast reactors, lead fast reactors, accelerator driven systems and nuclear fusion reactors) is expected to induce a strong impact on the contained materials, including structural materials, nuclear fuels, neutron reflecting materials and tritium breeding materials [1]. Therefore, the introduction of these reactors into operation will require extensive testing of their components, which must be performed under neutronic conditions representative of those expected to prevail inside the reactor cores when in operation.

Neutron screens [1-2] offer an option for irradiation under fast neutrons in current thermal reactors [1-8]. This is achieved by adapting materials with adequate absorbing capability in an irradiation channel; a hardened neutron spectrum is created through the filtering capability of the materials.

Absorbers of thermal and epithermal neutrons are successfully utilized in several reactor concepts (i.e. control rods, neutron flux flattening, etc) [2].

In order to fulfil the requirement of a neutron energy spectrum with the lowest possible thermal and epithermal component, thus attempting to imitate the shape of the neutron spectrum prevailing in a fast reactor, several materials characterized by their adequate neutron capture capability at low (E<1eV) and intermediate (1eV<E<1MeV) energies were studied in this work. In this framework simulations were performed using the Monte Carlo code TRIPOLI-4.8 with the JEFF-3.1.1 neutron cross-section library [9] for a model of the thermal Jules Horowitz Reactor (JHR) in CEA/Cadarache [10-12]. Selected materials with capability to absorb neutrons of low and intermediate energies were used as neutron screens, aiming to create a fast reactor material irradiation environment.

2 MATERIALS

Since, the shape of a thermal reactor's spectrum is high at low energies (E<1eV) whereas it is reduced at intermediate (1eV<E<1MeV) energies, materials or isotopes which present high neutron capture capability at low energies and adequate at intermediate ones were studied. Materials or isotopes with physical properties inappropriate for in-core utilization (i.e.: low melting point) or unavailable in the material/isotope market were excluded from the study. The latter was limited to the following absorbers: ^{113}Cd, ^{157}Gd, ^{10}B, ^{151}Eu, Dy and ^{167}Er. In table 1, information on the physical properties of the studied absorbers is given, together with information on their commercial distribution form (enrichment level and name of the distributing company); melting and boiling points are referred to natural elements. It should be noted that although it is widely used in reactors as thermal neutron absorber, tests made for Hf, indicated that it does not achieve an adequate reduction of the thermal spectrum; therefore Hf results are not presented in this work.

3 COMPUTATIONAL METHOD

Calculations presented here were performed using the TRIPOLI-4.8 code with the JEFF-3.1.1 neutron cross-section library. Instead of testing the filters in a modelled JHR version, their outcome was examined by performing independent computational experiments with the filters exposed in a virtual neutron source environment with energy distribution similar to that existing in an irradiation position of the JHR Beryllium reflector area. This was done because the large amount of calculations needed and the high complexity of the reactor's geometry would necessitate large computation time.

Table 1: Properties and availability of studied absorbers

Material	**Melting Point (°C)**	**Boiling Point (°C)**	**Natural Abundance (%)**	**Commercial distribution of enriched isotopes**	
				Available Enrichment levels (%)[1]	Example of Distributor
^{10}B	2075	4000	19.9	90-99+	Trace Sciences[2]
^{151}Eu	822	1527	47.81	99.2	JSC Isotope
Dy	1412	2567			
^{167}Er	1497	2868	22.93	94.7 - 96.3	JSC Isotope
^{157}Gd	1313	3250	15.65	87.1 - 88.4	JSC Isotope
^{113}Cd	321.07	767	12.22	94.5 - 96.1	JSC Isotope

Figure 1 is a visual representation of (a) the configuration that would be utilized in case that the numerical experiment was performed in JHR (Fig. 1a) and (b) the experiment as it was approached in this study (Fig. 1b). It should be noted that the similarity between the two experiments was previously confirmed through the identification of the results obtained by using the two configurations in a single case. It is also noteworthy that corresponding calculations were also performed with the MCNP code [13] and provided almost identical results to those obtained with TRIPOLI-4.8. A maximum filter thickness of 1cm was tested in all cases.

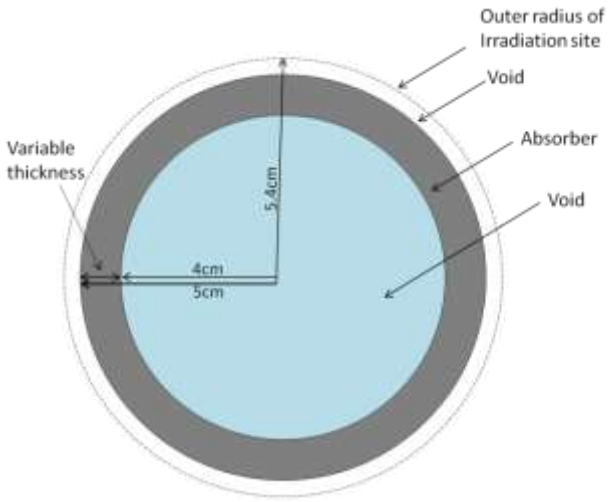

Figure 1a: Axial Cross Section of the irradiation site with filter (grey) installed

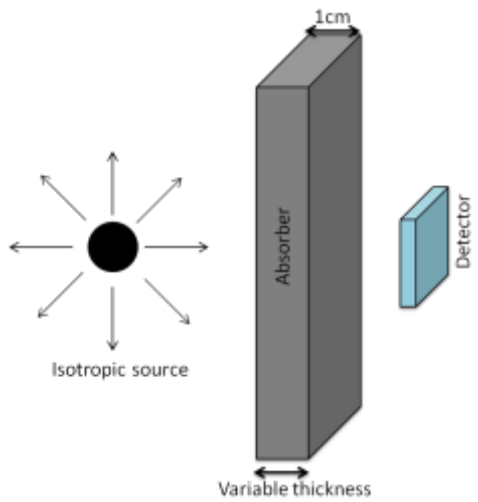

Figure 1b: A view of the experiment as it was approached

[1] For all filters pure isotopes are considered (100% enrichment) except Dy which is used in natural form
[2] Trace Sciences International Corporation

4 ANALYSIS AND RESULTS

The computational study was divided into two stages; at first the filter thickness of all the materials was set at 1cm, in order to have a first indication of the filter impact on the spectrum. This study aims to the determination of the most appropriate spectrum shape, regarding the required spectrum tailoring. Therefore for each isotope the neutron flux normalized to the sum of the flux components in the various energy groups is plotted vs energy (Figs 2-8). In Figure 2 the neutron spectra are presented. A reference case corresponding to the omission of the absorber is also included for comparisons.

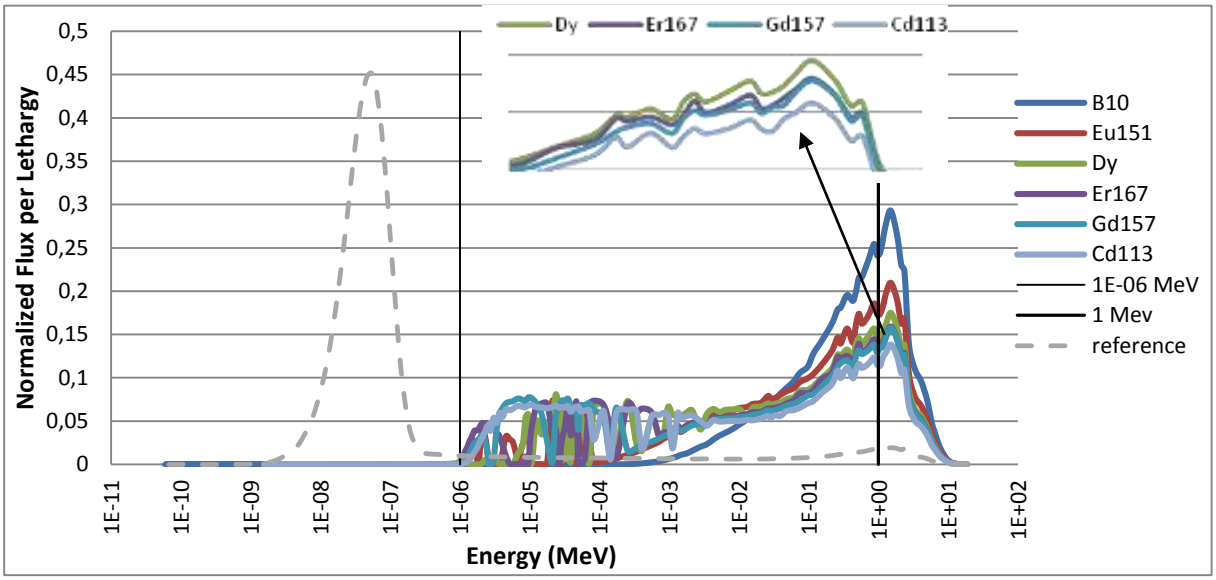

Figure 2: Neutron Spectra after filtering by 1cm-thick materials. Curves in the upper graph part correspond to the area indicated by the arrow origin, after magnification.

From the graph it is obvious that the most effective filter is provided by ^{10}B, immediately followed by ^{151}Eu. ^{10}B is also distinguished among the other materials by achieving a more gradual flux increase with energy, whereas the other materials display fluctuations in the intermediate area due to the resonances of their absorption cross section. The filter effectiveness is reduced going in order for the materials Dy, ^{167}Er, ^{157}Gd and ^{113}Cd. The close-up figure shows that ^{157}Gd and ^{167}Er coincide in the energy area between 1E-02 and 20MeV.

^{113}Cd has also an interesting effect since it minimizes the fast component of the spectrum more efficiently than the other materials. The term “efficiency” denotes the capability of each absorber to eliminate the thermal, limit the low epithermal and relatively increase the higher epithermal-fast component. However, although not very clear in the graph, it must be noted that ^{113}Cd as well as ^{157}Gd are the less efficient materials in the intermediate neutron energy area. At very low energies (E<1e-07MeV) no evident differences between investigated materials were found.

In order to investigate the efficiency of each material with respect to its thickness, the following sequential calculations were carried out: the thickness of the absorbers was gradually reduced by 1mm and the neutron flux for each case was calculated. The obtained results are shown in Figs.3-8, where the neutron spectrum for varying thickness is presented separately for each material. In these graphs, the black line corresponds to the maximum thickness of 1cm and the red line to the minimum of 1mm. The reference case (no screen) is illustrated with a red dashed line. The results are briefly outlined in the following paragraph.

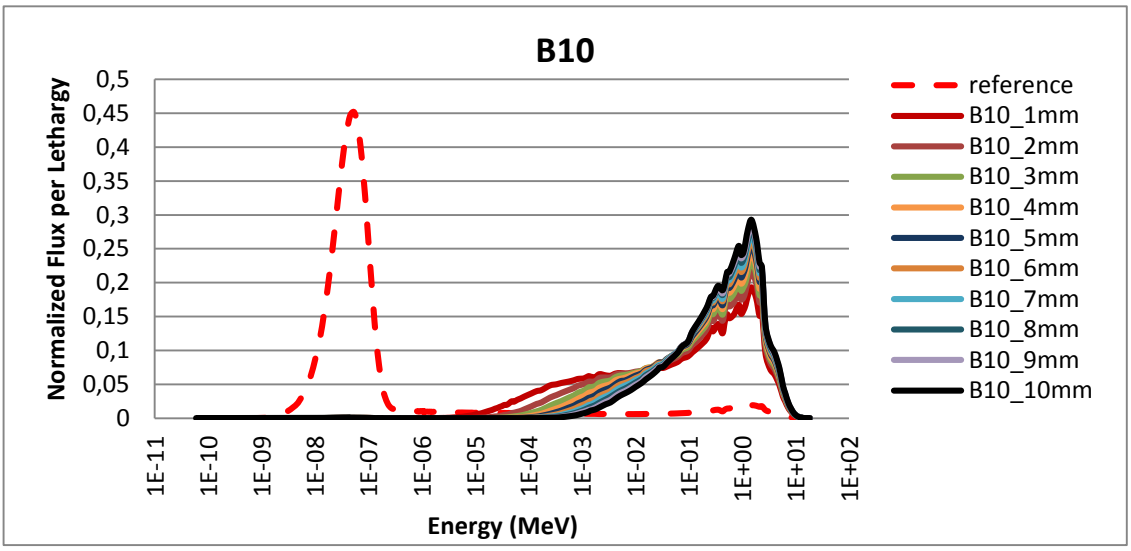

Figure 3: Neutron Spectra after filtering with ^{10}B screen of varying thickness

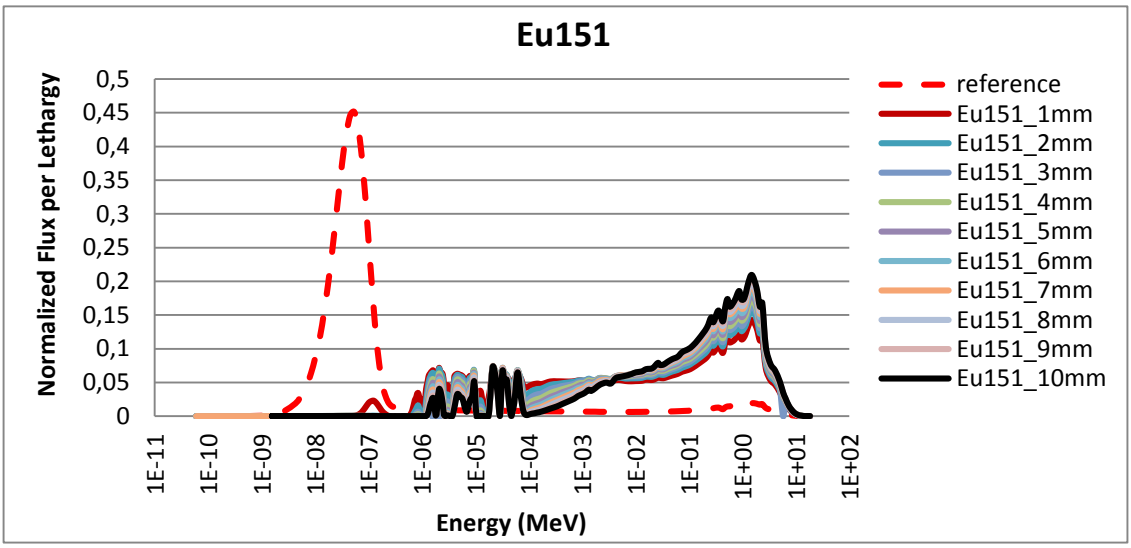

Figure 4: Neutron Spectra after filtering with ^{151}Eu screen of varying thickness

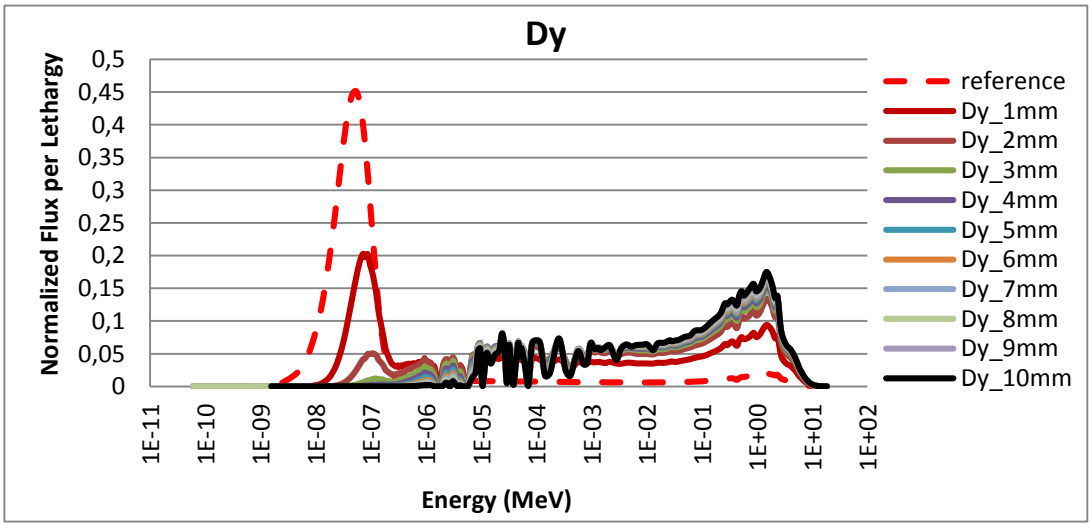

Figure 5: Neutron Spectra after filtering with Dy screen of varying thickness

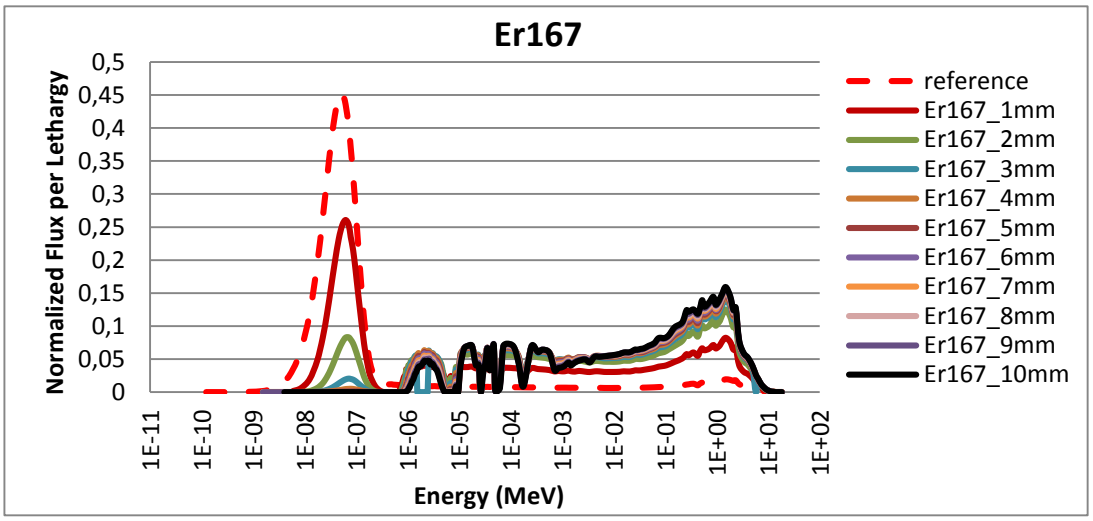

Figure 6: Neutron Spectra after filtering with ^{167}Er screen of varying thickness

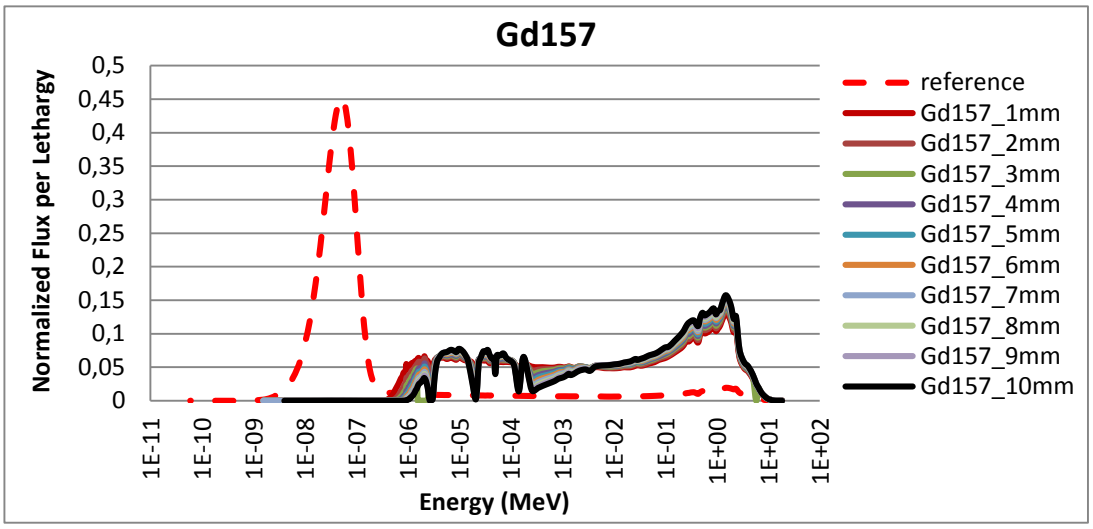

Figure 7: Neutron Spectra after filtering with ^{157}Gd screen of varying thickness

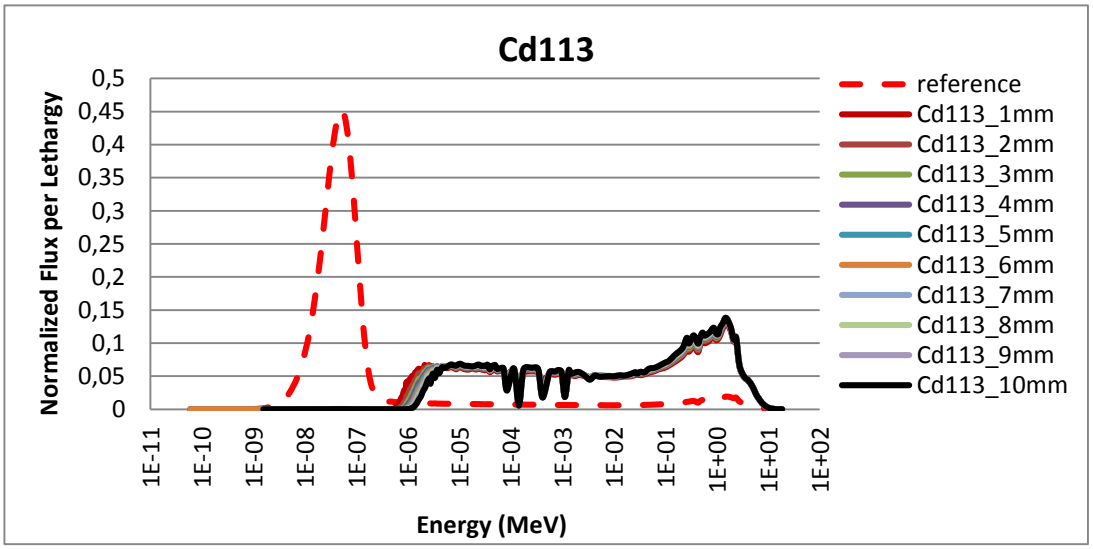

Figure 8: Neutron Spectra after filtering with ^{113}Cd screen of varying thickness

- ^{10}B: In the case of ^{10}B the increase of thickness influences rather significantly the efficiency of the filter, especially between 1mm and 7mm. Above this thickness the obtained spectra almost coincide (Fig. 3).
- ^{151}Eu: For $E>10^{-4}$MeV the spectrum is free from resonances and its behaviour is similar to ^{10}B although with lower maxima; 2mm of ^{10}B is almost equivalent in efficiency to 1cm of ^{151}Eu (Fig. 4). Only the case of 1mm can be distinguished in the thermal energy region –where all other cases being negligible- indicating thus a threshold of 1mm.
- Dy: the increase of thickness influences rather significantly the efficiency of the filter between 2mm and 3mm (Fig. 5). Beyond the 3mm thickness the differences concerning the efficiency are rather minimal.
- ^{167}Er: The same as Dy with a slightly less noticeable efficiency at 2mm. The 3mm of thickness can be assumed as a threshold. (Fig. 6)
- ^{157}Gd: Thickness does not seem to influence here, since 1mm and 1 cm of ^{157}Gd have almost the same efficiency (Fig. 6).
- ^{113}Cd: As in the case of ^{157}Gd, 1mm of ^{113}Cd is sufficient to perform as the 1cm (Fig. 7).

For all material cases, the depreciation of the neutron spectrum in the thermal and epithermal energies results in a relative enhancement in the fast energy range.

5 CONCLUSIONS

In this study the ability of ^{113}Cd, ^{157}Gd, ^{10}B, ^{151}Eu, Dy and ^{167}Er to create in an irradiation site in the reflector area of the JHR the conditions that simulate the neutron spectrum of a fast reactor, was investigated. The neutron energy spectrum of JHR and the influence of the various neutron screens have been computed with the TRIPOLI-4.8 code and cross-checked with corresponding MCNP calculations.

The thickness of the materials was altered in order to examine their efficiency as a function of their thickness. From the results obtained it can be concluded that among the studied materials, ^{10}B is the most appropriate since it provides the hardest neutron spectrum.

Moreover, a thickness threshold for each material (above which the screen efficiency does not vary appreciably) has been roughly estimated, as follows: 3mm for the ^{167}Er and for the Dy and 1mm for the ^{151}Eu. For ^{113}Cd and ^{157}Gd even 1mm has a minimal difference from bigger thicknesses. There is no threshold in the case of ^{10}B since even 1mm is quite effective.

The results obtained may also prove useful in the conception/design phases of several experimental/irradiation devices.

ACKNOWLEDGMENTS

This research paper has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Thales. Investing in knowledge society through the European Social Fund.

Authors would also like to thank Dr G. Bignan, Dr C. Colin, Dr C. Gonnier and Dr C. Huot-Marchand from CEA/Cadarache, as well as Professors E. Gazis and Th. Alexopoulos

from Technical University of Athens and Emeritus Professor M. Antonopoulos-Domis for their contribution to the realization of this research.

REFERENCES

[1] "MTR+I3", available online. URL http://www.mtri3.eu/WP21.html (2013)

[2] N. Chrysanthopoulou, P. Savva, M. Varvayanni, N. Catsatos. "Compilation of existing neutron screen technology". Sci. Technol. Nucl. Install., 2014.

[3] T.S. Ellis, B. Forget, M.S. Kazimi, T. Newton, E. Pilat *Design of a Low Enrichment, Enhanced Fast Flux Core for the MIT Research Reactor*, MIT, Department of Nuclear Science and Engineering, United States (2009)

[4] R.J. Ellis "Comparison of Calculated and Measured Neutron Fluence in Fuel/Cladding Irradiation Experiments in HFIR", *Trans. Am. Nucl. Soc.*, volume(105), pp. 808-810 (2011)

[5] J.C. Gehin, R.J. Ellis, J. McDuffe, R. Hobbs, L. Snead "Development of a Fast Spectrum Irradiation Facility for Fuels Development in the High Flux Isotope Reactor", Report, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (2008)

[6] A. Horvath, A. Brolly, "Neutron screen technology: Report evaluation of new types of absorbers", *MTR+I3 Technical Report*, Contract Number: FI6O-656-036440 (2009) – restricted

[7] J.L. McDuffee, J. C. Gehin, R. J. Ellis, R. W. Hobbs, and R. T. Primm III, "Proposed Fuel Pin Irradiation Facilities for the High Flux Isotope Reactor", *Proc. of ICAPP 08*, Anaheim, CA USA, Paper 8424 (June 8−12 2008)

[8] J.R. Parry, "Designing a Gas Test Loop for the Advanced Test Reactor", *ANS 2005 Winter Meeting*, Washington, D.C. (November 13-17, 2005)

[9] http://www.oecd-nea.org/tools/abstract/detail/nea-1716

[10] G. Bignan, P. Lemoine, X. Bravo, "The Jules Horowitz Reactor: a new european MTR open to international collaboration, description and status." Knoxville, IGORR 13, September 2010.

[11] T. Dousson, P. Roux, C. Gonnier, L. Ferry, S. Gaillot, D. Parrat, "Experimental devices in JHR dedicated to the fuel studies in support to the actual and future nuclear power plant." Prague: IGORR 14, March 18-22 2012.

[12] C. Colin, J. Pierre, C. Blandin, C. Gonnier, D. Moulin, M. Auclair, F. Rosenblum, " Experimental devices in Jules Horowitz Reactor dedicated to the material studies in support to the current and future nuclear power plants", Prague, IGORR 14, March 18-22 2012, Czech Republic

[13] http://mcnp.lanl.gov/