An intrinsically safe facility for forefront research and training on nuclear technologies —A zero-power experiment

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1 Goals

For the design of a new nuclear plant (either critical or sub-critical), the availability of infrastructures for research, where the theoretical evaluations on the behaviour of these innovative systems can be experimentally tested, is of paramount importance. In particular, the possibility to perform measurements of nuclear parameters such as the multiplicative coefficient (k_{eff}), the neutron flux distributions and others related to neutron kinetics, is extremely important in order to validate the computational codes used for the plant design. Due to their historical utilization and validation, the benchmark of these codes is even more important if they are used for the design of a sub-critical fast-neutron spectrum plant, such as an ADS [1–5].

The University of Pavia operates, among other facilities, a Sub-critical Multiplication installation (named SM1). This plant could be converted from the actual thermal-neutron configuration to a fast-neutron one, replacing the actual water moderator with a new solid lead diffuser. In this new configuration, the plant could be utilized to perform some benchmark experiments, at zero power level, whose results would be valuable for the design of an ADS. Aim of this activity, developed within the framework of the INFN-E “NUCSMILE” project, was to perform a preliminary study on the new fast-neutron spectrum solid lead-diffuser configuration of the SM1 plant.

The first part of the study was focused on the validation of the model of the SM1 plant in its actual thermal neutron configuration. The plant was simulated by means of the Monte Carlo code MCNP (version 4C) and the multiplicative coefficient and the neutron flux distributions were evaluated inside the complex. For three specific positions, measurements of the neutron fluxes were performed by means of the foils activation and spectrum deconvolution technique based on the code SAND II. The measurements were used to benchmark the Monte Carlo model of the plant and a good agreement between the results of the simulations and the measurements was obtained.

Once the model has been validated, the second part of the study focused on the analysis of the neutron flux distribution and of the multiplicative coefficient in the SM1 plant converted from thermal- to fast-neutron spectrum.

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Fig. 1. SM1 plant view.

2 SM1 plant description

SM1 is a thermal sub-critical complex moderated with light water (see fig. 1). The complex has the geometry of a hexagonal prism with a radial dimension of 114 cm and a height of 135 cm. The fuel is natural uranium in metallic form. The plant configuration considered for this study is made of 206 aluminium-clad fuel elements with an inner diameter of 2.8 cm and a length of 132 cm. Each rod is filled with 5 metallic uranium ingots with cylindrical shape (inner diameter 2.74 cm and length 21.5 cm). In fig. 2 the equatorial section of the SM1 plant is shown, in which the neutron source position and the three irradiation channels (A, B, C) positions are indicated. If we consider in this plane an $x - y$ coordinate system with the origin located at the neutron source, the three irradiation channels have the following coordinates: A ($x = 6.2$ cm, $y = -4.4$ cm), B ($x = -15.2$ cm, $y = 8.8$ cm), C ($x = 0.0$ cm, $y = 26.4$ cm). The numbers of elements in each lattice ring are presented in table 1.

The neutron source is a Pu-Be with an emission yield of 8.9×10^6 n/s over the solid angle. The source energy spectrum is displayed in fig. 3.

3 Neutron flux evaluations for SM1 thermal-neutron configuration

The calculations of the neutron flux distributions were performed by means of the Monte Carlo code MCNP (version 4C). Since the k_{eff} of the system is far from criticality, the SDEF input card mode (*i.e.* fixed source) was used to model the source and the neutron transport inside the lattice. The value of the k_{eff} of the plant was computed using the following equation:

$$k_{\text{eff}} \approx k_{\text{eff}}^{FS} = \frac{N-1}{N-\frac{1}{\bar{v}}} ,$$

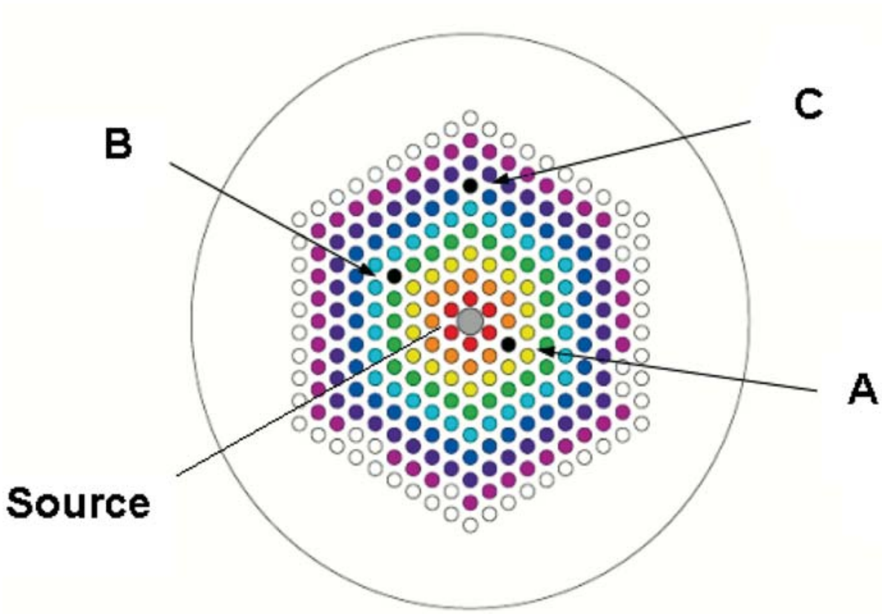

Fig. 2. SM1 plant equatorial section: the grey circle at the centre represents the neutron source. Black circles (labelled A, B and C) are the irradiation channel positions.

Table 1. Number of uranium fuel elements in each lattice ring.

Lattice ring	Number of fuel elements
1	6
2	11
3	18
4	23
5	30
6	35
7	42
8	41
9	0

Table 2. Simulation results for the integral neutron flux (normalized to source emission yield) in each irradiation channel (thermal-neutron plant configuration).

Irradiation channel	Integral neutron flux ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
A	$(5.716 \pm 0.004)10^4$
B	$(2.573 \pm 0.003)10^4$
C	$(1.067 \pm 0.003)10^4$

where N is the net multiplication factor and $\bar{v}$ is the average number of neutrons emitted per fission. Both parameters were evaluated by means of MCNP and a $k_{\mathrm{eff}} = 0.88$ was computed, in good agreement with the historical data of the plant which reports a $k_{\mathrm{eff}} = 0.86$.

The total average neutron flux (per neutron source) inside each ingot positioned at the equatorial level of the lattice is shown in fig. 4 while the values of the integral neutron flux (normalized to source emission yield) in each irradiation channel are displayed in table 2.

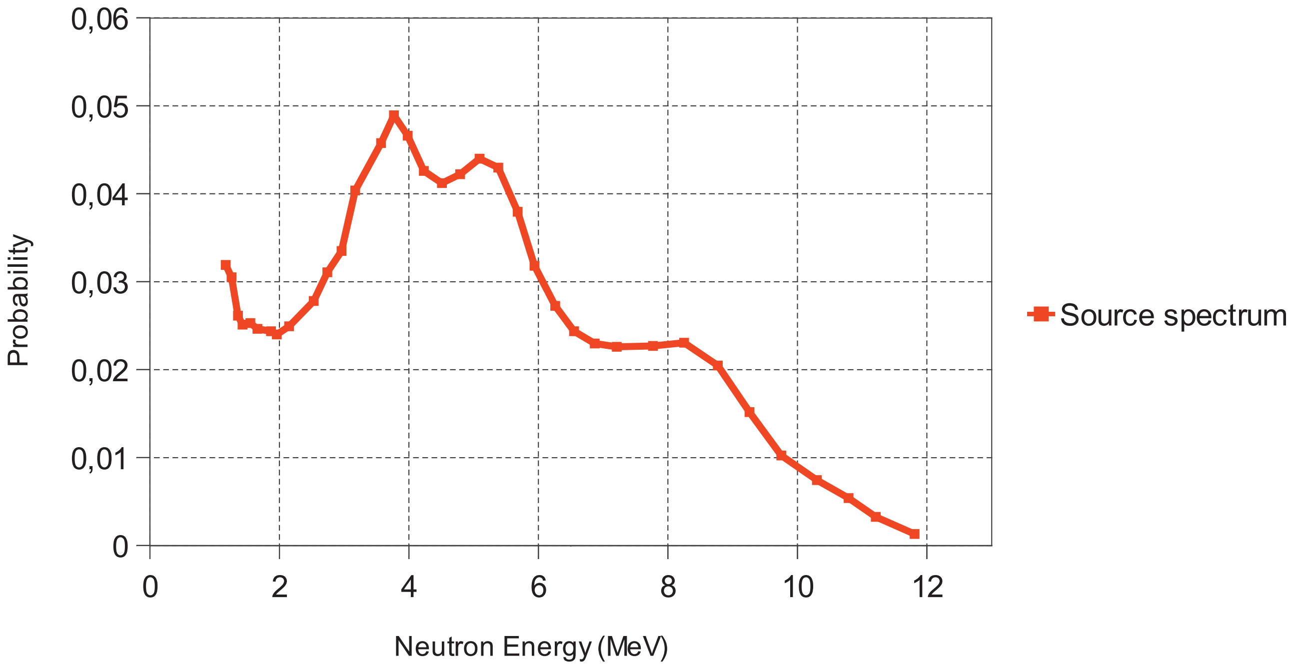

Fig. 3. Normalized Pu-Be neutron source energy spectrum.

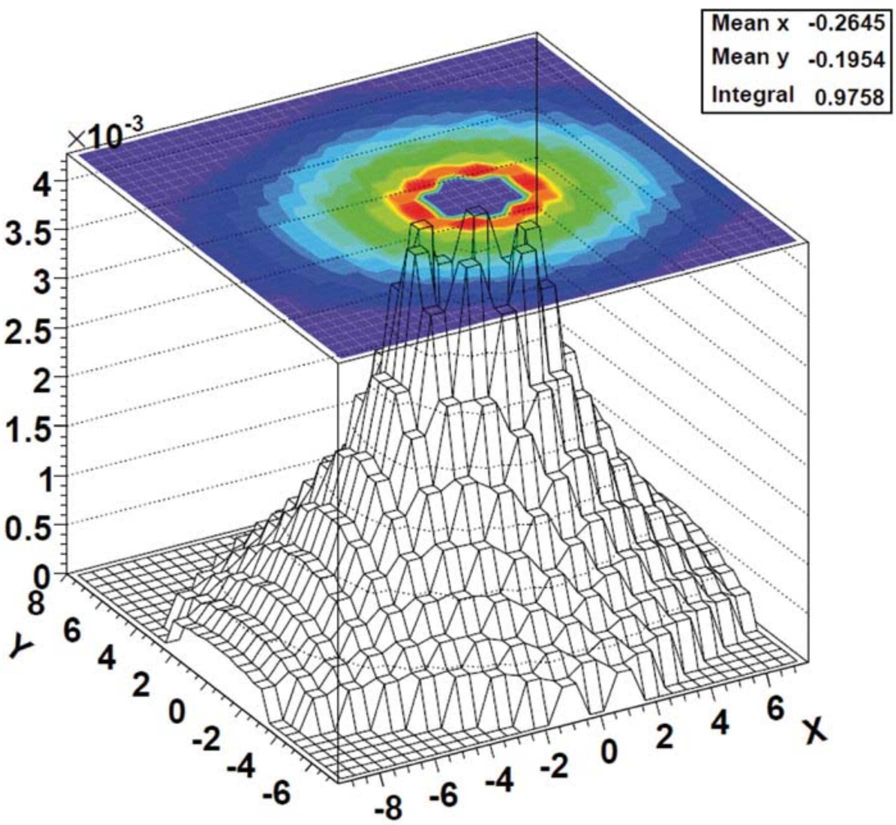

Fig. 4. Simulation results for the total average neutron flux (per neutron source) inside each ingot positioned at the equatorial level of the lattice.

Table 3. Measured integral neutron fluxes in each irradiation channel (thermal-neutron plant configuration)

Irradiation channel	Integral neutron flux ($cm^{-2}s^{-1}$)
A	$(5.90 \pm 0.20)10^4$
B	$(2.59 \pm 0.08)10^4$
C	$(0.99 \pm 0.07)10^4$

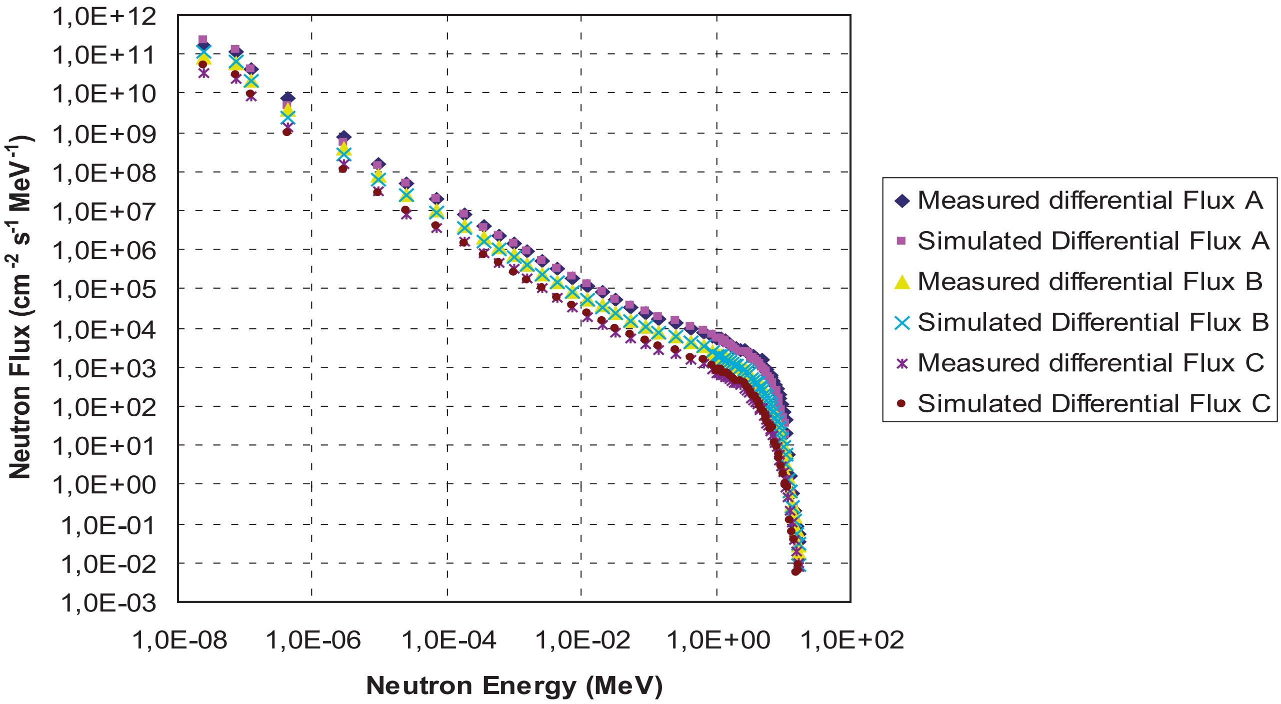

Fig. 5. Comparison between measured and simulated differential neutron fluxes for the three irradiation channels (thermal-neutron plant configuration).

4 Neutron flux measurements

For the thermal-neutron plant configuration, measurements were performed by means of the foils activation and with the SAND II code data processing, based on spectrum deconvolution technique. Based on irradiation and measurement time optimization and on radiation protection constraints, the following activation reactions were selected:

$$
\begin{aligned}
&{}^{197}\mathrm{Au} + \mathrm{n} \to {}^{198}\mathrm{Au}^* \to {}^{198}\mathrm{Hg}^* \to {}^{198}\mathrm{Hg} + \gamma,\\
&T_{1/2} = 2.7\,\mathrm{d}\\
&{}^{63}\mathrm{Cu} + \mathrm{n} \to {}^{64}\mathrm{Cu}^* \to {}^{64}\mathrm{Ni}^* \to {}^{64}\mathrm{Ni} + \gamma,\\
&T_{1/2} = 12.7\,\mathrm{h}\\
&{}^{115}\mathrm{In} + \mathrm{n} \to {}^{116\mathrm{m}}\mathrm{In}^* \to {}^{116}\mathrm{In} + \gamma,\\
&T_{1/2} = 54.3\,\mathrm{m}\\
&{}^{115}\mathrm{In} + \mathrm{n} \to {}^{115\mathrm{m}}\mathrm{In}^* + \mathrm{n}' \to {}^{115}\mathrm{In} + \gamma.\\
&T_{1/2} = 4.5\,\mathrm{h}
\end{aligned}
$$

Measurements of the activated foils were performed by means of a high-resolution γ-ray spectrometry using an HPGe detector (1.9 keV FWHM @ 1332.5 keV – r.e. 26–30% – peak/Compton ratio 55/1). The integral neutron fluxes in each irradiation channel position, evaluated with the SAND II deconvolution code, are presented in table 3.

In fig. 5 a comparison between measured and simulated differential neutron fluxes for the three irradiation channels is presented.

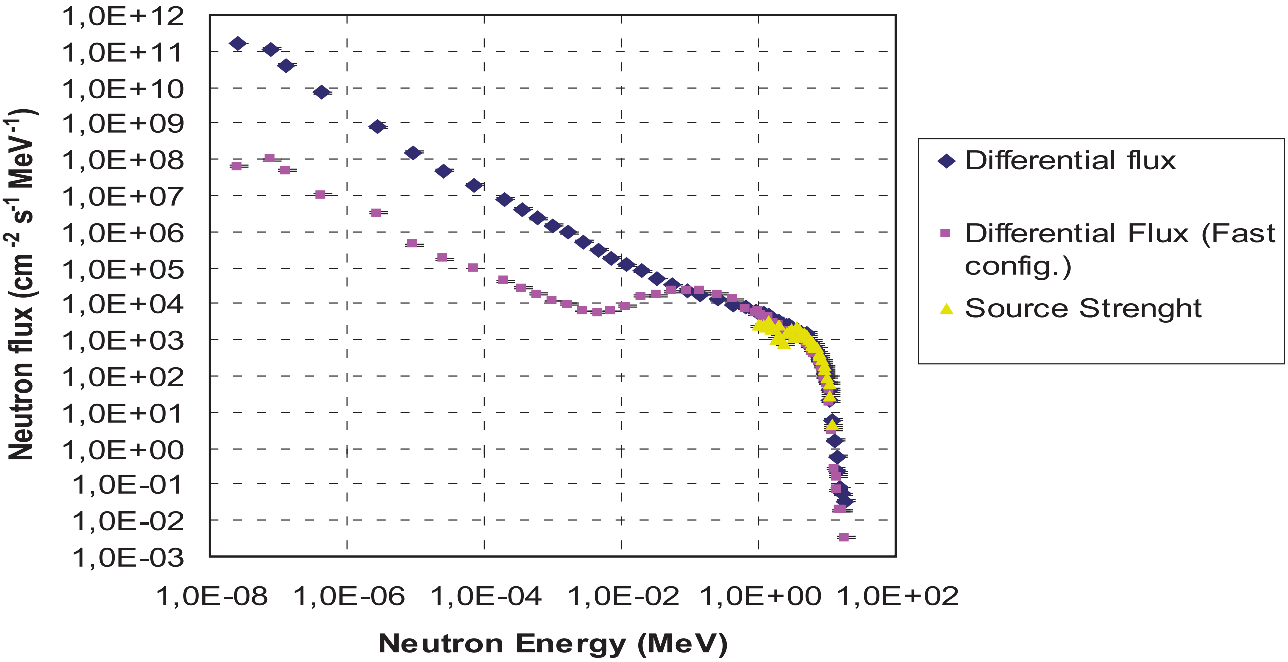

Fig. 6. Irradiation channel A: comparisons between differential neutron fluxes computed by means of MCNP code for thermal-neutron and fast-neutron plant configuration.

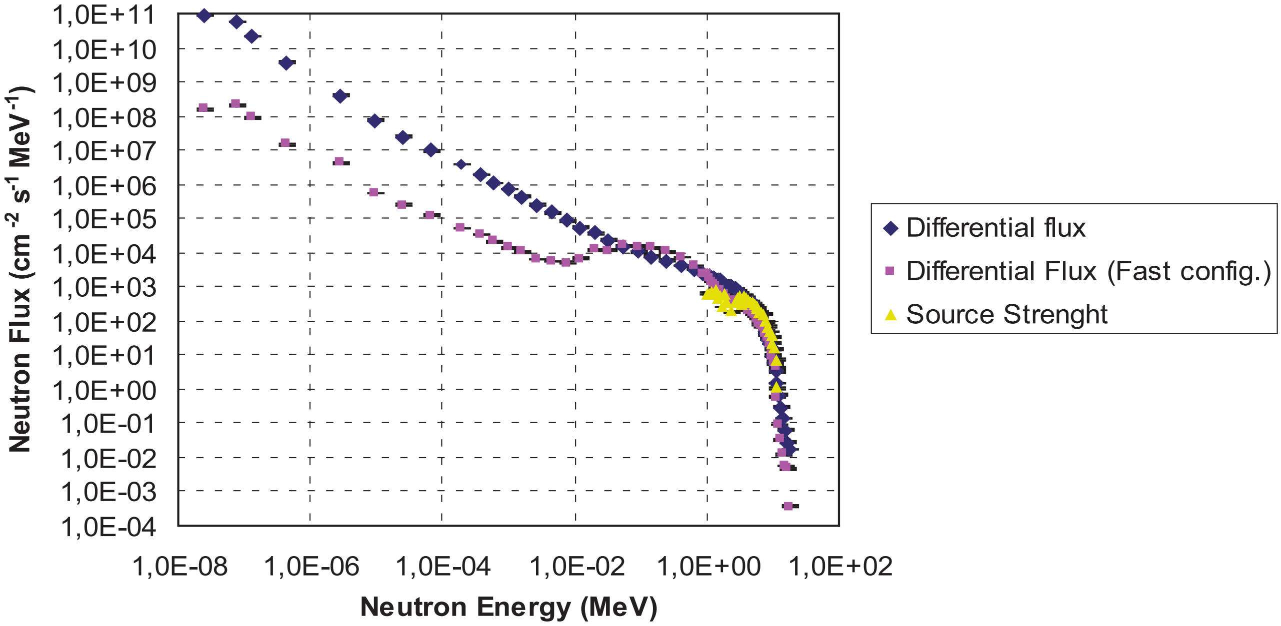

Fig. 7. Irradiation channel B: comparisons between differential neutron fluxes computed by means of MCNP code for thermal-neutron and fast-neutron plant configuration.

5 Neutron flux evaluations for SM1 fast-neutron configuration

In this preliminary study of conversion of the SM1 plant from *thermal-* to *fast-neutron* configuration the water moderator was replaced, in the MCNP model, with a solid lead diffuser. The simulations were performed in the same manner described in the previous paragraphs, *i.e.* the same geometry of the fuel lattice and the same neutron injection source.

In figs. 6, 7 and 8 the comparisons between the simulated neutron fluxes for thermal-neutron and fast-neutron plant configuration and for the three irradiation channels (A, B and C) are shown. The neutron source spectrum is also shown in the figures.

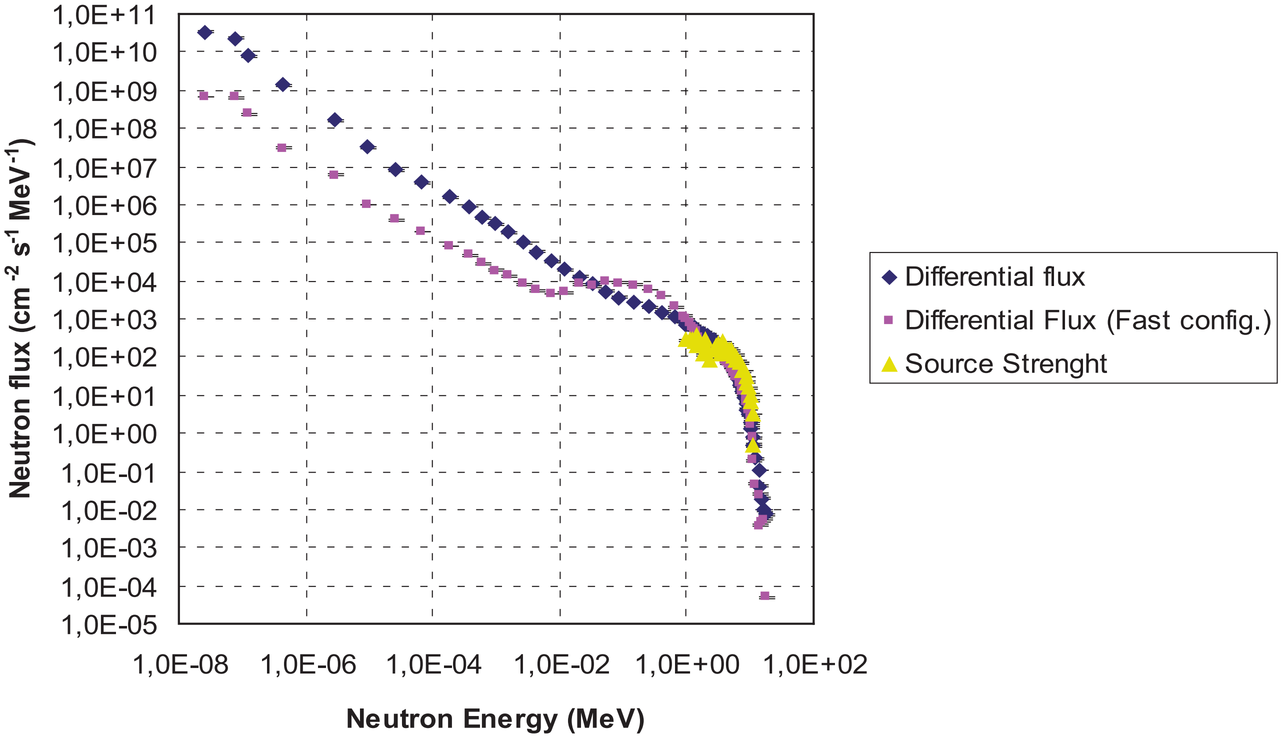

Fig. 8. Irradiation channel C: comparisons between differential neutron fluxes computed by means of MCNP code for thermal-neutron and fast-neutron plant configuration.

Table 4. Values of the integral neutron flux (normalized to source emission yield) in each irradiation channel computed by means of MCNP (fast-neutron plant configuration).

Irradiation channel	Integral neutron flux ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
A	$(2.12 \pm 0.006)10^4$
B	$(0.92 \pm 0.008)10^4$
C	$(0.49 \pm 0.001)10^4$

The integral neutron flux in each irradiation channel, evaluated by means of MCNP code for the fast-neutron plant configuration, is reported in table 4. In this configuration, the effective multiplication factor was estimated and the result was $k_{\mathrm{eff}} = 0.53$ (to be compared to $k_{\mathrm{eff}} = 0.88$ for the thermal-neutron configuration).

6 Conclusions

This research activity, performed within the framework of the INFN “NUCSMILE” project, aims to study the conversion of the SM1 subcritical plant of the University of Pavia from thermal-neutron to fast-neutron spectrum. In this new configuration, the plant would be a “zero power – solid lead diffuser —fast neutrons— subcritical assembly” that could be useful to perform preliminary measurements and experiments for the validation of computational codes to be used for the analysis of sub-critical fast-neutron installations. As a first step, the conversion would be performed by substituting the actual water moderator with a solid lead diffuser. In order to perform the preliminary study, a model of the plant in the actual thermal-neutron configuration was simulated by means of the Monte Carlo code MCNP (version 4C). The simulations were validated by comparison with the measurements performed at the plant and the results showed very good agreement. Then, the fast-neutron spectrum configuration was modelled and, again, the effective multiplication factor and the neutron flux distributions were evaluated by MCNP. From these results it is possible to conclude that, as expected, the k_{eff} of the plant in the new configuration drops to a very low value ($k_{\mathrm{eff}} = 0.53$) giving a total multiplication factor of about 2 and bringing the plant to a safer operational condition. On the other hand, the values of the integral neutron fluxes in the irradiation channels decrease, in average, of a factor about 2.5. This loss, though, is partially compensated by the fact that the distribution of the neutron spectrum is shifted towards higher energies, allowing using the SM1 plant in the new configuration for research and benchmark activities on fast-neutron nuclear complexes.

References

1. RSICC Computer Code Collection – *MCNP4C Monte Carlo N-Particle Transport Code System*, Los Alamos National Laboratory and Oak Ridge National Laboratory.
2. A. Borio di Tigliole, A. Cammi, M. Clemenza, V. Memoli, L. Pattavina, E. Previtali, Progr. Nucl. Energy **52**, 494 (2010).
3. A. Borio di Tigliole, A. Cammi, D. Chiesa, M. Clemenza, L. Pattavina, E. Previtali, G. Scian, *Neutronic Analysis of the Pavia University TRIGA Mark II Reactor Core*, in *Proceedings of the 15th International Topical Meeting of Research Reactor Fuel Management (RRFM 2011) – Rome (Italy) 21/24 March 2011*, pp. 66–71 ISBN 978-92-95064-11-9.
4. A. Cazzola, *Caratterizzazione del flusso neutronico nel complesso moltiplicante sottocritico SM1 dell'Università di Pavia*, Tesi di Laurea Magistrale in Scienze Fisiche (Università degli Studi di Pavia – A.A. 2009/2010).
5. J.R. Lamarsh, *Introduction to Nuclear Reactor Theory* (Addison-Wesley Publishing Company, 1972).