THE TAPIRO AS A FAST RESEARCH REACTOR FOR GENERATION IV TECHNOLOGIES

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Abstract. TAPIRO is a 5kW fast neutron source operating at the ENEA CASACCIA Research Center since 1971 in Italy. The reactor, included in the Mediterranean Research Reactor Network (MRRN) promoted by IAEA for maximize the utilization and the collaborations of RRs in the Mediterranean region, is composed by a high-enriched core made of Uranium-Molybdenum alloy cooled by He and surrounded by a copper reflector and a large concrete biological shield. A large experimental cavity, labeled thermal column, is suitable for the installation of experimental assemblies for any research purpose. Aim of this paper is to describe the main feature of TAPIRO fast neutron research reactor and analyze, by deterministic (ERANOS) and probabilistic (MCNP) simulation codes, the feasibility of an experimental campaign of neutron propagation in lead, using the thermal column of the TAPIRO reactor. Measurements of neutron spectra or reaction rates evaluations, well correlated to integral parameters of the reference reactor, can be considered as a valuable basis for the design of next generation of LFR. In this concern, a key factor is the correlation coefficient between integral parameters (for example vacuum effect and reaction rates), evaluated in different cores, is a measure of the impact of the physical characteristics of the systems on the assessment of such integral quantities. The results obtained in this preliminary study are encouraging since they indicate a significant degree of correlation between the quantities considered in TAPIRO and in the reference system taken into account.

1. INTRODUCTION

In the seventies at ENEA/Casaccia there was an important commitment in relation to methods for exploiting the experimental data relevant to integral quantities measured in critical facilities, the so called ‘a posteriori’ information along with Bayes’ terminology, with the objective of ‘adjusting’ neutron group cross section data, the ‘a priori’ information, adopting statistical inference methods. Such commitment stemmed on the possibility of rapidly calculating the sensitivity coefficients required making use of the Generalized Perturbation Theory (GPT) methodology, on development in the same period [1] [2]. Such differential data adjustment approach was also proposed in some cases for exploiting experimental data measured in shielding benchmarks [3]. As mentioned above, the adjustment methodology is based on statistical inference methods and have been first proposed by Linnik [4]. This methodology, adapted to the nuclear domain, is illustrated in [5] and [6]. In [5] the nuclear data do be adjusted were assumed to be in a multi-group form, which was considered an unavoidable (at that time) limitation. Its application for the definition of optimal multi-group cross section set libraries, as well as appropriately assessed covariance matrices based on integral experiments on experimental facilities, has been however pursued by different laboratories (see comments on this and equivalent methodologies in Ref. [7]). In particular, in the 70s and 80s at CEA it was decided to use integral experiments to assess multi-group cross-section uncertainties by using adjustment procedures. The library ERALIB1 [8] used with the ERANOS code system [9] is the result of this methodology. The interest in high-quality integral benchmark data is increasing as efforts to quantify and reduce calculational uncertainties accelerate to meet the demands of next generation reactor and advanced fuel cycle concepts. The International Reactor Physics Experiment Evaluation Project (IRPhEP) and the International Criticality Safety Benchmark Evaluation Project (ICSBEP) continue to expand their efforts and broaden their scope to identify, evaluate, and provide integral benchmark data for method and data validation. Benchmark model specifications provided by these two projects are used heavily by the international reactor physics, nuclear data, and criticality safety communities [10]. To note that in the IRPhEP integral data base are included also experiments relevant to the TAPIRO reactor as described in Ref. [11]. The most meaningful activities performed at TAPIRO reactor and connected to the present work were performed in the early 70's for studying the propagation of neutrons along the axis of a large sodium tank inserted in place of the graphite column. It was a measurement campaign made in collaboration with CEA Cadarache within the fast reactor program and had a similar purpose, i.e., that of testing the ability of neutronic codes to reproduce the measured quantities [12]. This paper is focused on a preliminary analysis of a propagation expertiment correlation in a lead block placed in the thermal column of the TAPIRO reactor. In particular the above mentioned GPT methodology have been applied to study a potential correlation among integral quantities relevant to the TAPIRO and to a reference system. ELSY reactor has been selected as reference system. MCNPX [13] and ERANOS codes have been used for the analysis.

2. INTEGRAL DATA CORRELATION ANALYSIS

Consider that the experimental information available is contained in the measurements of integral quantities $Q_{A,\ell}$ (ℓ =1, 2, …, L) obtained from an experimental facility (system A). This information has to be transposed to a set of quantities $Q_{B,m}$ (m=1, 2, …, M) relevant to a reference system (system B). Let's define the (LxJ) and (MxJ) sensitivity matrices $\mathbf{S}_A$ and $\mathbf{S}_B$, with elements, respectively,

$$s_{A,\ell j} = \frac{p_{o,j}}{Q^{cal}_{A,\ell}} \frac{\partial Q_{A,\ell}}{\partial p_j} \tag{2.1}$$

$$s_{B,mj} = \frac{p_{o,j}}{Q^{cal}_{B,\ell}} \frac{\partial Q_{B,m}}{\partial p_j} \tag{2.2}$$

which can be calculated via GPT methods [1][2]. The transposition of the experimental information to the set of quantities $Q_{B,m}$ can be made using different statistical inference method, for instance the Lagrange's multipliers [14]. As a result we can obtain adjusted estimates of the quantities $Q_{B,m}$ or, in a more convenient form, estimates of the relative quantities

$$y_{B,m} = \frac{Q_{B,m} - Q^{cal}_{B,m}}{Q^{cal}_{B,m}} \tag{2.3}$$

where $Q^{cal}_{B,m}$ represents the same quantities calculated with the 'a priori' differential information. Vector $\tilde{\mathbf{y}}_B$ of the new estimates $\tilde{y}_{B,m}$, defined as

$$\tilde{y}_{B,m} = \frac{\tilde{Q}_{B,m} - Q^{cal}_{B,m}}{Q^{cal}_{B,m}}, \tag{2.4}$$

results [14]

$$\tilde{\mathbf{y}}_B = \mathbf{S}_B \mathbf{C}_p \mathbf{S}_A^T (\mathbf{C}_A + \mathbf{S} \mathbf{C}_p \mathbf{S}_A^T)^{-1} \mathbf{y}_A^{ex} \tag{2.5}$$

where $\mathbf{C}_A$ is the dispersion matrix of the integral experimental data, $\mathbf{C}_P$ is the cross-section dispersion matrix and where $\mathbf{y}_A^{ex}$ is a vector of elements

$$y_{A,\ell}^{ex} = \frac{Q_{A,\ell}^{ex} - Q_{A,\ell}^{cal}}{Q_{A,\ell}^{cal}} \qquad (2.6)$$

Let us now consider the extreme case in which we wish to evaluate a single quantity Q_B relative to the reference system, on the basis of the information contained in a single measurement, $Q_{A,1}^{ex}$, more or less correlated with Q_B. By following the above procedure we obtain its relative correction estimate,

$$\frac{\tilde{y}_B}{\varepsilon_B} = r_{B,1} \frac{y_{A,1}^{ex}}{\varepsilon_{A,1}} \ , \qquad (2.7)$$

where $r_{B,1}$ is the correlation coefficient

$$r_{B,1} = \frac{S_{A,1}^T D S_B}{\sqrt{(S_{A,1}^T D S_{A,1})(S_B^T D S_B)}} \qquad (2.8)$$

while $\varepsilon_{A,1}$ and ε_B are the *a priori* errors associated with $Q_{A,1}^{cal}$.and Q_B^{cal}, respectively. From this equation we can clearly see how, as expected, the relative correction $\tilde{y}_B$ increases proportionally with the correlation coefficient $r_{B,1}$, with the *a priori* error ε_B and with the ratio $y_{A,1}^{ex} / \varepsilon_{A,1}$. To note that the value $r_{B,1}$ lies between 0 and 1. The closer it is to unity, the more the information inherent with the experiment in A is significant with respect to the integral quantity considered in the reference system. The correlation coefficient expressed by the Eq.(2.8) can be defined as 'relative' as there is assigned more weight to energy groups in which the cross sections are affected by larger relative errors. An ‘absolute’ correlation coefficient, that is, independent from nuclear data errors, could also be defined by the same expression (2.8) in which the dispersion matrix D is replaced by a unitary one. The correlation coefficients represent indeces of representativity of quantities measured in an experimental facility with respect to quantities of interest of a reference reactor. They may be used to reduce their uncertainties, along with equation (2.7) which gives the correction estimates based on the experimental ('a posteriori') data. This use implies adopting a full variance/covariance matrix, so to take into proper account the 'a priori' information relevant to the differential data errors. If a unitary dispersion matrix is used, which implies disregarding this information, the correlation coefficients represent only indeces of representativity. They may be considered 'pure' representativety indeces in the sense that only the sensitivity profiles enter in their definition.

3. TAPIRO EXPERIMENTAL FACILITY

TAPIRO (TAratura PIla Rapida a Potenza 0) is a fast neutron source reactor licensed in 1971 for a maximum thermal power of 5 kW. 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 with about 6 cm of radius and 11 cm of height. The core is divided in 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 of 50 W the core is cooled by mean of forced circulating 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 is contained inside the primary cooling system and a 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 realized inside the inner reflector where the control rods can be moved controlling the amount of reflector, and therefore the number of nuclear fissions inside the core. Furthermore, a rapidly shut down may be realized dropping the mobile core part. With regard to the irradiation facilities the reactor has 6 main experimental channels (4 horizontal and 2 vertical channels) and a large cavity, labeled thermal column (parallelepiped 110×110×160 cm^3). One mid-plane channel crosses the core allowing irradiations of small samples (≈ 1 cm) in an almost pure U-235 fission spectrum. In the thermal column a more energetic neutron spectrum is realized removing a 60° sector from the outer reflector. At the maximum thermal power, the total core integrated neutron source strength is of $\approx 3\times10^{14}$ n/s that is equivalent to a total neutron flux of $\approx 4\times10^{12}$ $n/cm^2/s$ at the core centre and a total neutron flux of $\approx 1.5\times10^{10}$ $n/cm^2/s$ at the entrance of the thermal column. A vertical and horizontal section of the reactor are shown in figure 1.

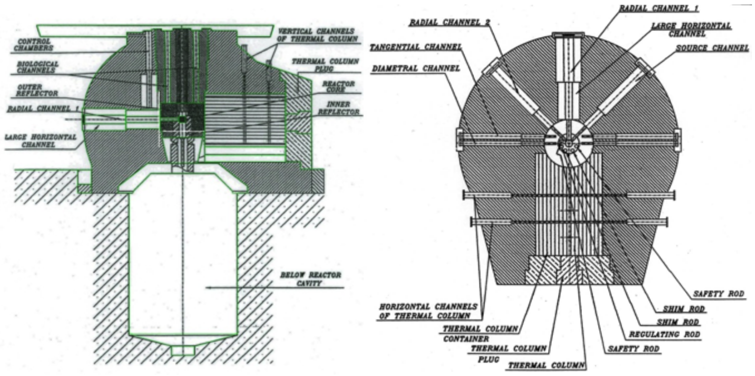

Figure 1. TAPIRO vertical section (left) and horizontal section (right)

4. ELSY “REFERENCE” REACTOR

The ELSY project (European Lead Fast Reactor) [15] has been developed from September 2006 to February 2010, in the frame of the Sixth Framework Programme of EURATOM. The ELSY reference design is a 600 MWe pool-type reactor cooled by pure lead. The ELSY project demonstrates the possibility of designing a competitive and safe fast critical reactor using simple engineered technical features fully compliant with the Generation IV goal of sustainability and minor actinide (MA) burning capability. Currently the project ELSY provides two possible geometric configurations: the first is with rectangular elements, and the second with hexagonal elements. Table 2 shows reference data on rectangular elements configuration on which is based the ERANOS model described in the next paragraph.

Table 1. ELSY main characteristics.

ELSY REFERENCE CONFIGURATION		UNIT
THERMAL POWER	1530	MW
NUMBER OF FUEL ASSEMBLIES	272	
CORE DIAMETER (D)	5,24	m
TOTAL HEIGHT (H)	3,63	m
ACTIVE HEIGHT	1,11	m
PINS PER FUEL ASSEMBLY (FA)	17x17- 5 pins (284)	
INNER/INTERMEDIATE/OUTER FAs NUMBER	132/72/68	
INNER/INTERMEDIATE/OUTER PU ENRICHMENT (VF)	13,4/15/18,5	%
AVERAGE LINEAR POWER	220	W/cm
COOLANT INLET TEMPERATURE	400	°C
COOLANT AVERAGE OUTLET TEMPERATURE	480	°C
CLAD MAXIMUM TEMPERATURE	540	°C

5. CALCULATIONS SPECIFICATIONS

The simulated experiment in TAPIRO, and the calculated integral data (reaction rate ratios) obtained, are relevant for measurements at different axial positions in an exponential column made of lead. The TAPIRO serves here as a neutron source reactor. The neutron source (only its energy distribution is of interest) at the side of the column facing the core has been calculated by the Monte Carlo code MCNP. The TAPIRO reactor is assumed of course at critical conditions. The integral quantities in the lead column, with a fixed neutron source at one side, calculated using the ERANOS code, may be then assumed as quantities to be measured in a typical exponential experiment. The value calculated in ELSY correspond to integral quantities at conditions assumed critical. The correlation coefficients are indeces of representativity of integral data measured in an experimental set-up (in TAPIRO) with respect to integral data relevant to a reference reactor (ELSY). Since the integral data considered here are strongly dependent on the neutron spectrum, comments on the calculated spectra profiles are introduced first in "RESULTS".

5.1. MCNPX TAPIRO model and source calculation

The investigation of the neutron propagation in a lead block inserted into the TAPIRO thermal column, concerning the correlation analysis with LFR ELSY “reference reactor”, requires GPT methods calculations [section 2]. ERANOS, differently from MCNPX, allows to perform these calculations. However it is quite difficult to realize an accurate ERANOS model of the TAPIRO experimental facility due to the presence of particular heterogeneities in the facility. To face this problem, in the present work it has been established to characterize the neutron source spectrum at the column entrance using a MCNPX TAPIRO model. Subsequently the estimated MCNPX neutron source has been coupled to a “semplified” TAPIRO lead column ERANOS model, as described in the next section. The MCNPX TAPIRO input model has been suitably modified (see Fig.2). Lead has been take into account inside the “thermal column”. Three different total flux detectors (F-4 track length tallies type) have been considered in correspondence of the middle-plane of the lead column. Radially, the detector positions have been considered at the entrance of the lead column in correspondence. The 60° copper outer reflector sector has been considered removed from the core and replaced by void (in order to try to reproduce a harder neutron spectrum closer to the ELSY one). To well estimate the “effective” neutron source entering the lead column, filtered by the lead back-scattering contributions, in the KCODE simulation has been set to 0 the neutron transport importance of the lead medium on the left side (green area of fig.2).

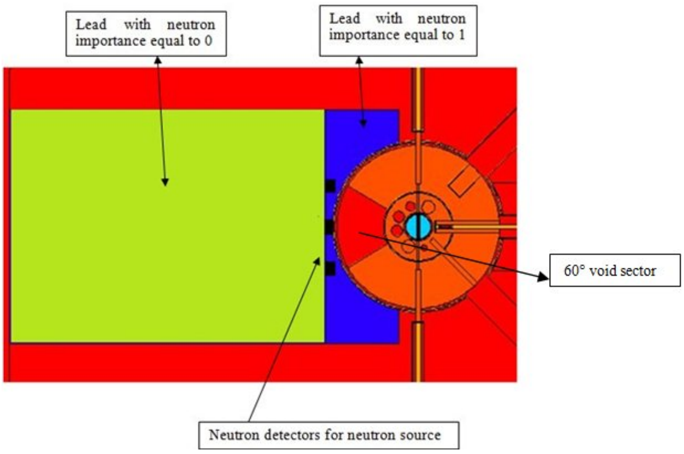

Figure 2. MCNPX TAPIRO model.

5.2. ERANOS TAPIRO lead column model with MCNPX source

Since ERANOS nuclear code is able to perform perturbation and sensitivity analysis only in 2D dimension, the TAPIRO lead column facility (TLF) has been modeled as an XY slab. The model, shown in Fig.3, consists in the lead thermal column surrounded by concrete biological shield. Inside the first calculation mesh of the lead column has been inserted the neutron external source estimated by MCNPX. The neutron propagation has been performed in transport approximation by 2D ERANOS BISTRO module. The neutron flux spectrum has been analyzed in correspondence of 3 neutron detectors placed at three different positions (DET1 40 cm, DET2 80 cm, DET3 140 cm) along the central axis of the lead column, as shown in Fig. 3.

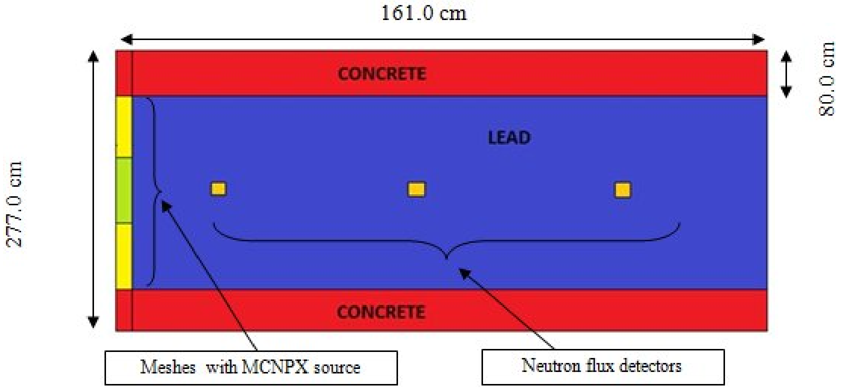

Figure 3. TAPIRO lead column X-Y model in ERANOS calulations.

5.3. ERANOS RZ model of "reference" ELSY reactor

The ELSY ERANOS calculation has been performed in R-Z cylindrical geometry, with a heterogeneous cell treatement of the rectangular fuel elements. The core layout model used for perturbation calculations is shown in Fig. 4. The core model take into account the presence of three different enrichment active zones (indicated such as Fuel_INN, Fuel_INT and Fuel_OUT), radially sorrounded by a control rod zone ('active zone' with B_4C enriched at 90% in B^{10}) and an external lead reflector (Pb_EXT in the figure).

The whole fuel zone is sorrounded axially by two upper and lower fertile UO_2 insulation zones and by two (even upper and lower) plenum zones with steel, lead and void volumes homogenized in one region.

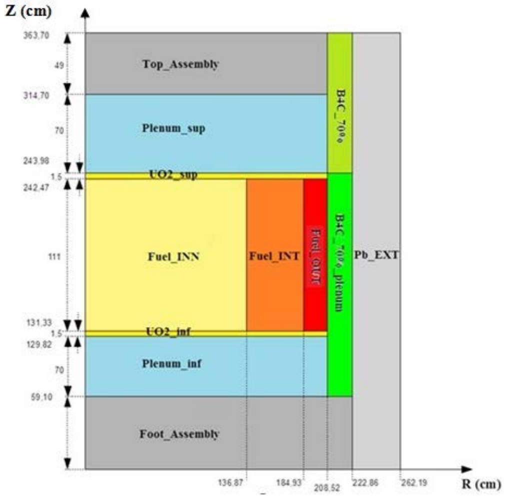

Figure 4. (R-Z) ERANOS ELSY model – axial section.

5.4. ERANOS GPT calculations

The analysis performed by ERANOS aimed to calculate the Correlation Coefficient (Eq. 2.8) between ELSY and TAPIRO systems for the following spectral indexes: F8/F5 and F7/F5. The F8/F5 and F7/F5 behaviour following a lead density variation of -10%, has been analyzed by GPT procedures of

BISTRO ERANOS modules [9]. All the calculations have been performed at 33 energy groups, P_0 transport approximation, using JEFF 3.1 as nuclear data library. GPT calculations have been carried out as follows:

(1) calculation of the importance function [1] relative to F8/F5 and F7/F5 spectral indexes for both TAPIRO and ELSY systems;
(2) calculation of the sensitivity coefficients for both systems and spectral indexes;
(3) calculation of the correlation coefficient using both the variance-covariance dispersion BOLNA matrix at 15 energy groups [16] and a unitary matrix at 33 energy groups, as mentioned in section 2.

The adjoint function has been calculated by placing the spectral index functionals in a 2x2 square mesh area around the following points:

- TAPIRO: X = 40.0 cm   Y = 138.5 cm
- ELSY: R = 68.3 cm   Z = 181.85 cm

6. RESULTS

Fig.5 shows the MCNPX neutron source estimation at the lead column entrance. It can be noticed that, in comparison with the quasi fission spectrum in the core, at the column entrance we have a neutron spectrum picked around 300-400 keV.

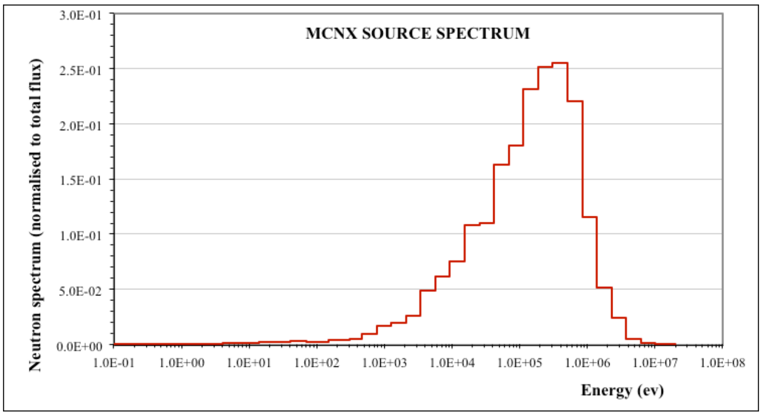

Figure 5. MCNPX source spectrum.

Fig.6 shows the ERANOS and MCNPX comparison relative to the neutron flux estimation of the first detector. It can be seen that there are some remarkable differences in the energy region below about 300 keV. Such differences can affect the results of the F7/F5 spectral index taking into account the threshold.

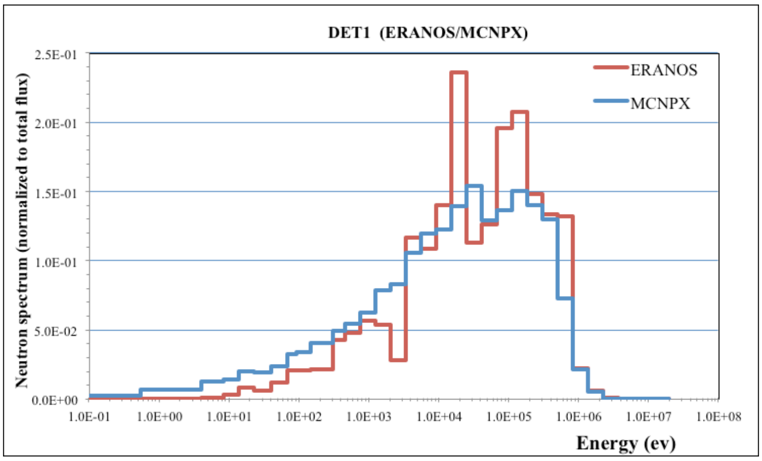

Figure 6. ERANOS/MCNPX spectra at detector 1 position (40 cm in lead).

Fig.7 shows the attenuation of the neutron flux through the central axis of the lead column.

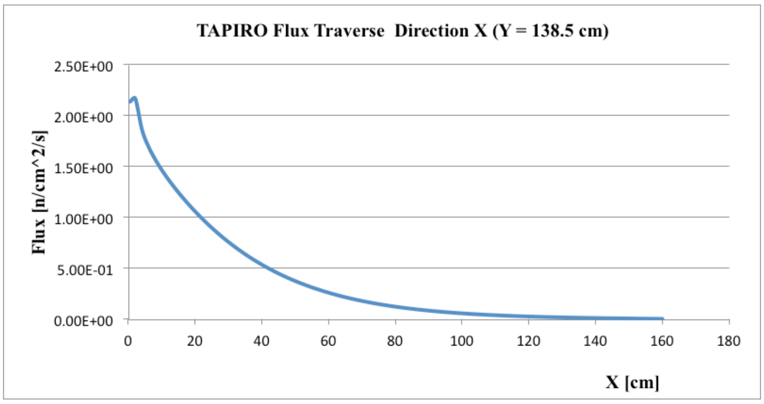

Figure 7. TAPIRO flux profile in X direction through the lead medium.

Fig. 8 shows the comparison between TAPIRO and ELSY in correspondence of the two systems locations where the spectral indexes correlation has been studied. It can been noticed that there are some remarkable differences between the two profiles, even if for energies above 1 MeV some analogies can be evinced concerning the relative behaviour of the two spectra.

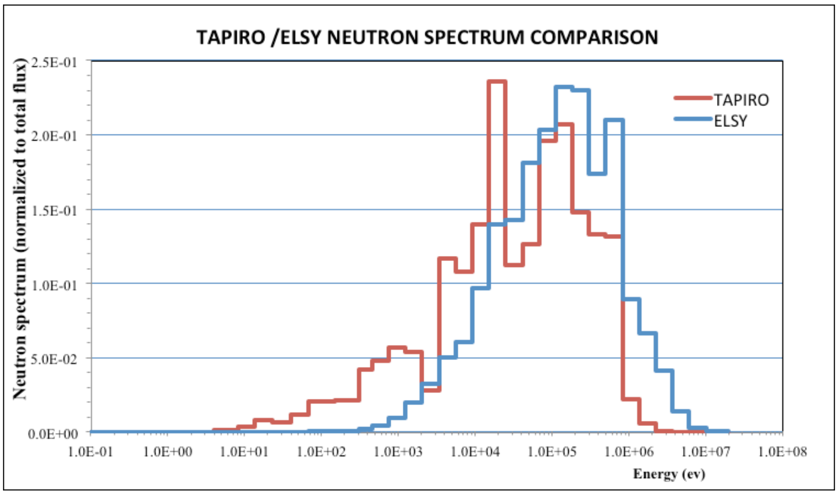

Figure 8. ERANOS/MCNPX spectra comparison.

The results show a good correlation between the integral quantities considered in the reactor facility TAPIRO and the reference system considered (ELSY), as shown in Table 2.
In Table 2 are shown the results concerning the correlation coefficients for the spectral indexes F8/F5 and F7/F5. The results partially reflect the spectral differences noticed between TAPIRO and ELSY in the preselected locations. Being such differences mainly detectable in the energy below 1 MeV, these can partially explaines the relative good correlation obtained for the F8/F5 spectral index respect to the F7/F5 one. Of course further investigations are needed in particular for different locations in TAPIRO lead column. (The meaning of the values in the column 'Unitary dispersion matrix' of Table 2 is given in Section 2)

Table 2. Correlation coefficients

Reaction rates in TAPIRO to be correlated with the 10% void effect in ELSY	**Variance-Covariance BOLNA dispersion matrix**	**Unitary dispersion matrix**
fiss_U238 / fiss_U235	0.775	0.623
fiss_Np237 / fiss_U235	0.509	0.564

7. CONCLUSIONS

This report has been focused on the sensitivity and correlation analysis performed by the ERANOS GPT procedure in relation to the “reference” LFR ELSY reactor and the TAPIRO lead column facility (TLF). The results obtained in this preliminary study indicate that a certain degree of correlation for the spectral index F8/F5, which has an high energy threshold, can be observed. To note that the correlation coefficients of the integral quantities (fission reaction ratios) relevant to the TAPIRO lead column facility with respect to the lead void effect in ELSY result larger than the value (0.38) obtained in a similar study [17] relevant to a 10% lead density reduction effect in both the GUINEVERE reactor facility [18] and ELSY. In a more recent study [19], the correlation coefficients were fission reaction ratios (F9/F5, F8/F5 and F7/F5) for both systems at unperturbed and perturbed (by lead density reduction) conditions. In this case the correlation coefficients exceed the 0.9 value.
Further different TLF configurations are envisaged in a next step of simulation analysis. The possibily of interposing a neutron spectrum filter material (e.g., iron, grafite, etc.) will be in particular investigated in view of obtaining an even better correlation between the integral quantities considered the two systems. In conclusion, these first results of the simulation study, appear to confirm the role of the TAPIRO reactor facility as a useful tool for the design of next generation of LFRs.

ACKNOWLEDGEMENTS

We wish to thank Dr.Giuseppe Palmiotti, of INL for his precious suggestions in the use of ERANOS, and Dr. Nunzio Burgio, of ENEA, for his advise in the use of MCNPX.

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