Final characterization of the first critical configuration for the TRIGA Mark II reactor of the University of Pavia using the Monte Carlo code MCNP

D. Alloni [a], A. Borio di Tigliole [a,1], A. Cammi [b], D. Chiesa [c,d], M. Clemenza [c,d], G. Magrotti [a], L. Pattavina [d,2], S. Pozzi [c,d], M. Prata [a], E. Previtali [c,d,*], A. Salvini [a], A. Sartori [b], M. Sisti [c,d]

[a] Laboratorio Energia Nucleare Applicata (L.E.N.A.) of the University of Pavia, Via Aselli 41, 27100, Italy
[b] Energy Department of Polytechnical University of Milan, Via La Masa 34, 20156, Italy
[c] Physics Department "G. Occhialini" of the University of Milano-Bicocca, P.zza della Scienza 3, 20126 Milano, Italy
[d] INFN Section of Milano-Bicocca, P.zza della Scienza 3, 20126, Italy

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1. Introduction

The TRIGA Mark II Reactor at the Applied Nuclear Energy Laboratory (L.E.N.A.) of the University of Pavia was studied for its characterization in several respects. The reactor was brought to its first criticality in 1965 and since then it has been used for several scientific and technical applications. To fully exploit the reactor performances a detailed model of the TRIGA Mark II reactor based on a MCNP Monte Carlo simulation was implemented. The advantages of the MCNP (X-5 Monte Carlo Team (LANL) code are given by its general geometry modeling capability, correct representation of transport effects and continuous-energy cross-sections treatment. This provides the opportunity to completely implement the structure of the reactor taking into account the geometry, the fuel composition and the various operating conditions.

A preliminary analysis of the TRIGA Mark II reactor of the Pavia University was done in the past (Borio di Tigliole et al., 2010) with a simplified model. To evaluate the complete reactor parameters a new and better refined analysis was done introducing all the information which was possible to collect during the last few years. In the present refined 3-D model of the TRIGA Mark II Reactor great care was dedicated to introduce all the information that were collected from the reactor constructor and from the original data reported on the manual referring to the first working period of the machine, in which the fresh fuel was not heavily contaminated with fission reaction products. All fresh fuel, control rods, and other elements (graphite-loaded elements and structural grids) were described in detail in order to reconstruct all the effects on the neutron distributions. The comparison between the measured and the simulated data gave us the possibility to focalize our attention on some specific aspects that are very peculiar of the TRIGA Mark II reactor operation. The present analysis is based on the criticality tests described in the First Criticality Final Report (Cambieri et al.). The present TRIGA MCNP model provides a very precise description of the neutronic parameters (Borio di Tigliole et al., 2014) and the criticality condition of the machine operating with fresh fuel and at low power and temperature.

2. Reactor description

The TRIGA (Training Research and Isotope production General Atomics) Mark II is a pool type reactor moderated and cooled by

* Corresponding author. Physics Department "G. Occhialini" of the University of Milano-Bicocca, P.zza della Scienza 3, 20126 Milano, Italy. Tel.: +39 02 6448 2311.
E-mail address: ezio.previtali@mib.infn.it (E. Previtali).
1 Present address: IAEA, Wagramer Straβe 5, Vienna 1220, Austria.
2 Present address: LNGS, Strada Statale 17bis, Km 18.910, 67100 L'Aquila, Italy.

light water. It has a nominal power of 250 kW in stationary-state operation. The core is shaped as a right cylinder and contains 90 slots, distributed over 5 concentric rings: in the original reactor configuration, in 1965, these were filled by 61 fuel elements, 23 graphite rods, 3 control rods, one irradiation channel and one compartment for a neutron source, while one slot was left empty (Fig. 1).

2.1. Fuel elements

TRIGA fuel consists of a uniform mixture of zirconium hydride (ZrH) and uranium, enriched 19.75% wt in ^{235}U. Fuel rod structure is described in Fig. 2: the fuel itself [**A**] is placed at the center, while the top and bottom parts of the rod, made of nuclear graphite, play the role of axial neutron reflectors [**B**]. Two burnable poison disks [**C**], containing samarium oxide (Sm_2O_3) are placed between the fuel and the reflectors. Everything is contained by a 0.76 mm-thick aluminum cladding [**E**] and by two aluminum endcaps [**D**] (see Table 1).

2.2. Control rods

The TRIGA Mark II reactivity control is handled by three absorbing rods, named SHIM, Regulating (REG) and Transient (TRANS). The SHIM and REG control rods are made of hot-pressed boron carbide powder (B_4C); the TRANS rod is a solid graphite rod containing 25% wt free boron. The documentation at our disposal describes just the SHIM and REG rods geometrical structure in great detail (Fig. 3); the Transient rod was modeled in the same way, assuming that there are no great differences between the three rods. Anyway, this approximation will have only marginal effects on our simulation results, since the TRANS rod has safety purposes only and is rarely used during the reactor normal operation. The three control rods radii are reported in Table 2.

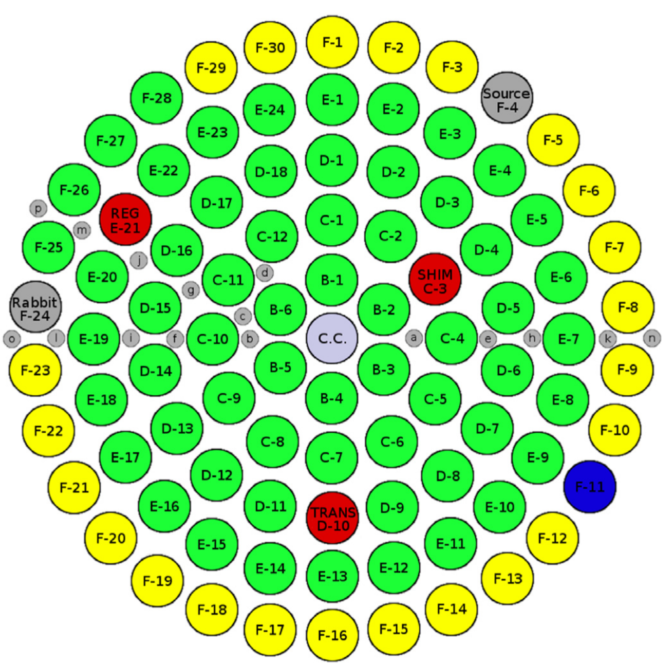

Fig. 1. Original core configuration. Fuel elements are represented in green, graphite rods in yellow, control rods in red and the empty slot in blue. The Central Channel is labeled with C.C. The smaller gray circles represent the holes found on the top core grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

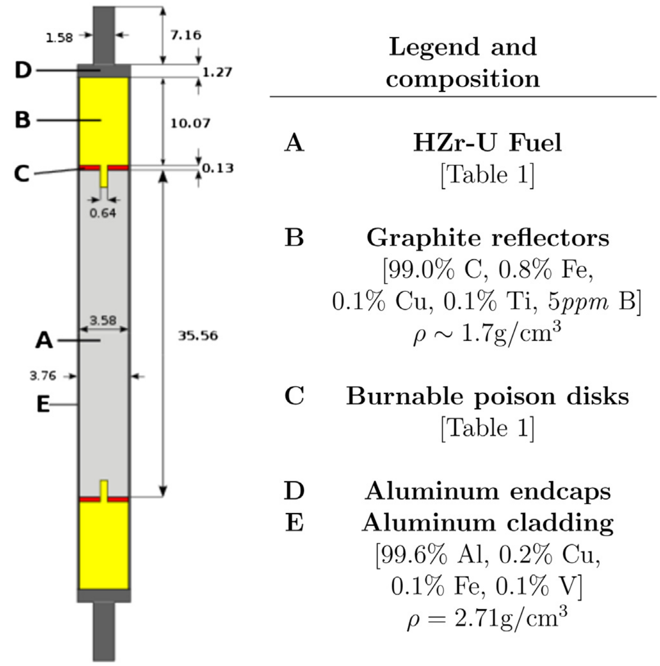

Fig. 2. Fuel rod structure. All values are measured in centimeters [cm].

Table 1
Fuel and burnable poison composition.

Poison disks	
Element	Wt%
Al	5.25E-1
O	4.68E-1
Sm	7.07E-3
Density [g/cm^3]	2.42
HZr−U fuel	
Element	Wt %
H	1.03E-2
Zr	9.09E-1
^{235}U	1.59E-2
^{238}U	6.46E-2
Density [g/cm^3]	6.34

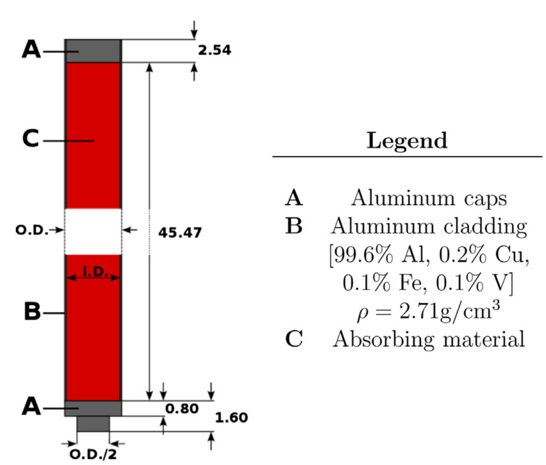

Fig. 3. Control rod structure. All values are measured in centimeters [cm]. I.D. stands for Inner Diameter, O.D. for Outer Diameter (see Table 2).

Table 2
Inner (**I.D.**) and Outer (**O.D.**) control rods diameters.

	I.D. [cm]	O.D. [cm]
SHIM	2.85	3.18
REG	1.93	2.22
TRANS	2.21	2.54

Table 3
Control rods composition and density.

Boron carbide (B_4C)	
Element	Atom%
C	2.00E-1
^{10}B	1.58E-1
^{11}B	6.42E-1
Density [g/cm^3]	2.52
Borated graphite	
Element	Atom%
C	7.23E-1
^{10}B	5.35E-2
^{11}B	2.17E-1
Density [g/cm^3]	2.23

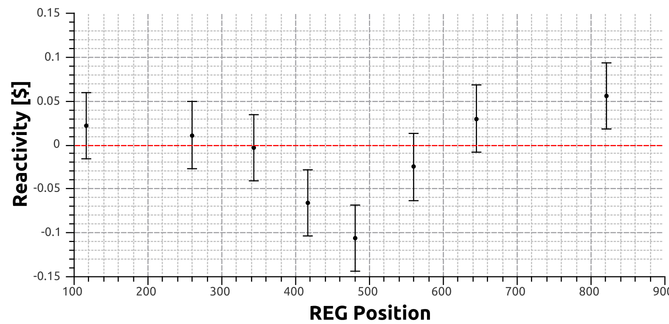

Fig. 5. Critical configurations obtained by inserting the SHIM and REG control rods.

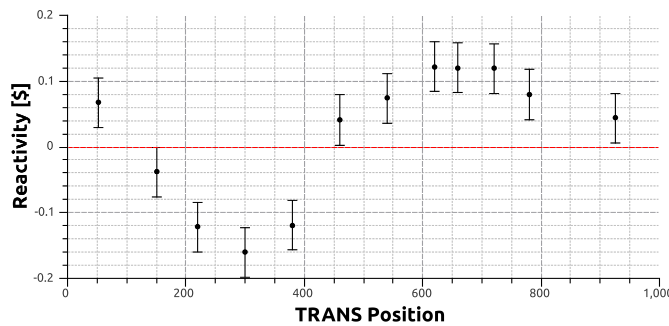

Fig. 6. Critical configurations obtained by inserting the SHIM and TRANS control rods.

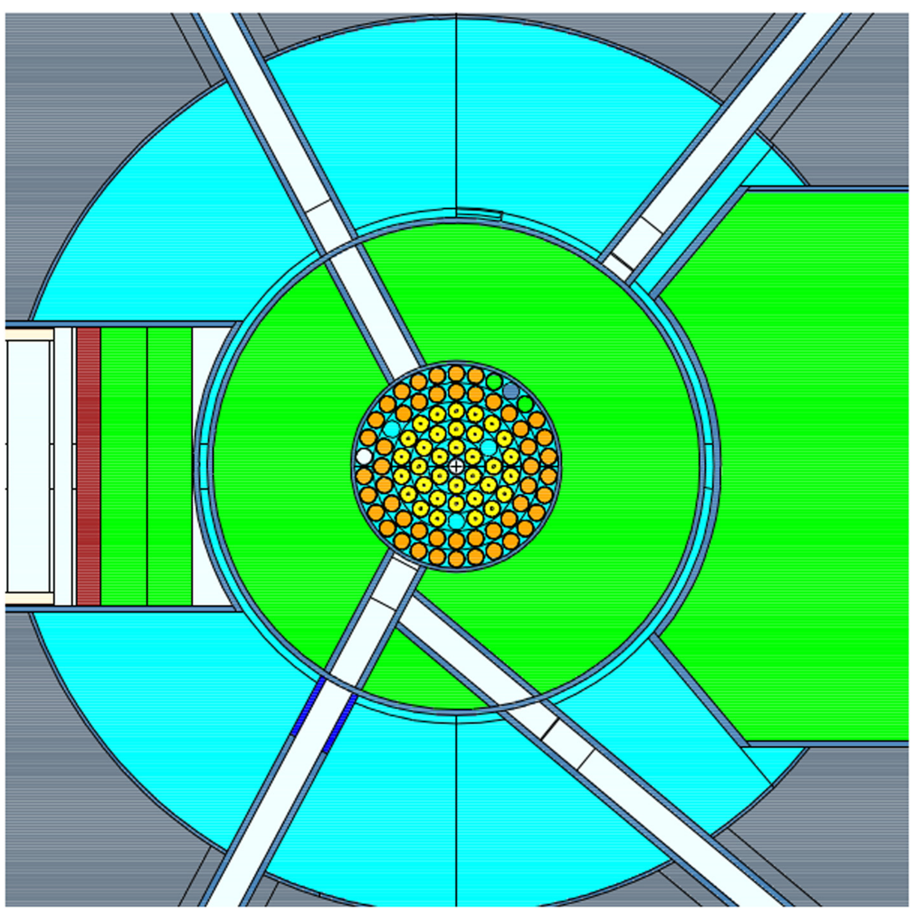

Fig. 4. Horizontal section of the MCNP model. The core is 44.6 cm in diameter and is surrounded by a graphite reflector 30 cm thick (green); the pool (azure) has a diameter of 1.98 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

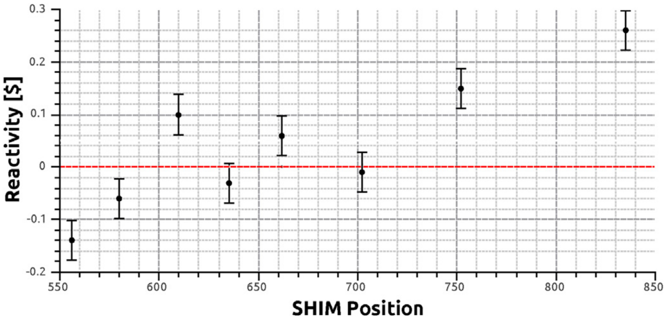

Fig. 7. Critical configurations obtained by inserting the three control rods simultaneously.

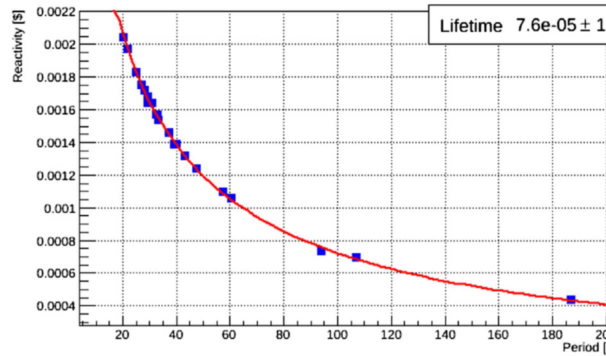

Fig. 8. Fit to experimental data of the *in hour* equation.

Table 4
Critical configurations obtained by inserting the SHIM and REG control rods.

Control rod positions (digit)			Reactivity ($)
REG	SHIM	TRANS	[± 0.038$]
116	556	OUT	0.022
260	534	OUT	0.011
344	511	OUT	−0.003
417	485	OUT	−0.066
480	462	OUT	−0.106
559	436	OUT	−0.025
645	410	OUT	0.030
821	386	OUT	0.056

Data regarding the control rods composition and density are shown in Table 3.

3. TRIGA reactor model

Thanks to the constant interaction with General Atomics, it was possible to obtain very detailed data regarding the core components; system geometry and material composition were modeled with the greatest possible accuracy (Fig. 4). In our model we aimed at reproducing the experimental results obtained in 1965, during the operations that followed the reactor first start-up (Cambieri et al.). In those experiments, the reactor power was kept at a minimum level (10 W), so the temperature of every core material was set to around 300 K. To account for thermal neutron scattering, the appropriate $S(\alpha, \beta)$ treatment was applied to graphite, zirconium hydride and water. In each simulation, the MCNP KCODE card was set to produce 1000 cycles, with 10,000 neutrons per cycle, for a total of 10 million simulated neutrons.

Table 5
Critical configurations obtained by inserting the SHIM and TRANS control rods.

Control rod positions (digit)			Reactivity ($)
TRANS	SHIM	REG	[± 0.038$]
53	607	OUT	0.067
150	583	OUT	−0.038
220	562	OUT	−0.122
300	535	OUT	−0.160
380	503	OUT	−0.119
460	476	OUT	0.041
540	447	OUT	0.074
620	425	OUT	0.122
660	417	OUT	0.120
720	403	OUT	0.120
780	393	OUT	0.079
926	386	OUT	0.044

Table 6
Critical configurations obtained by inserting the three control rods simultaneously.

Control rod positions (digit)			Reactivity ($)
SHIM	REG	TRANS	[± 0.038$]
556	503	433	−0.140
580	440	433	−0.056
610	821	53	0.101
635	664	53	−0.034
662	592	53	0.059
702	527	53	−0.007
752	469	53	0.148
835	428	53	0.264

3.1. Critical reactor configurations

We reproduced a set of critical reactor configurations, corresponding to different positions of the control rods inside the core. In these configurations the expected value for the reactivity is $\rho = 0\$$ ($k_{\text{eff}} = 1$).[3] The documentation reported three sets of experimental measures: 8 critical configurations were obtained by using the three control rods at the same time, 8 involved the SHIM and Regulating control rods only and 11 involved the Transient and SHIM rods. The simulation results for all the configurations are reported in Figs. 5–7 and in Tables 4–6. Control rod positions are reported as they appear on the reactor equipment: each step corresponds to about 0.05 cm displacement from the bottom of the reactor core, while the distance spanned by the rods from the full inserted to the full withdrawn position is equal to 38.1 cm for SHIM and REG and 47.2 cm for TRANS. In 1965, the step digits ranged from 116 to 821 in the case of REG, from 130 to 835 in the case of SHIM and from 53 to 926 in the case of TRANS control rod. The error bars are associated with the standard deviations in reactivity as obtained from MCNP runs, equal to $\sigma_\rho = 0.038\$$.

Most of the criticality values fall in the $\pm 2\sigma$ range from the expected value ($\rho = 0\$$), showing a good agreement between simulated and experimental data. The reported values of σ_ρ include only the statistical uncertainty; if we consider a systematic error σ_{sys} equal to $\sim 0.26\$$ (derived in more detail in Section 3.3), we find an even better agreement with the experimental results. The configurations where the Transient rod was involved show a slightly worse behaviour with respect to the first set of simulations; this is most probably due, as stated before, to the approximations used in the rod description.

[3] The effective delayed neutron fraction for the TRIGA reactor ($\beta_{\text{eff}} = 0.0073$ (Cambieri et al.)) was used for the calculation of the reactivity value in $.

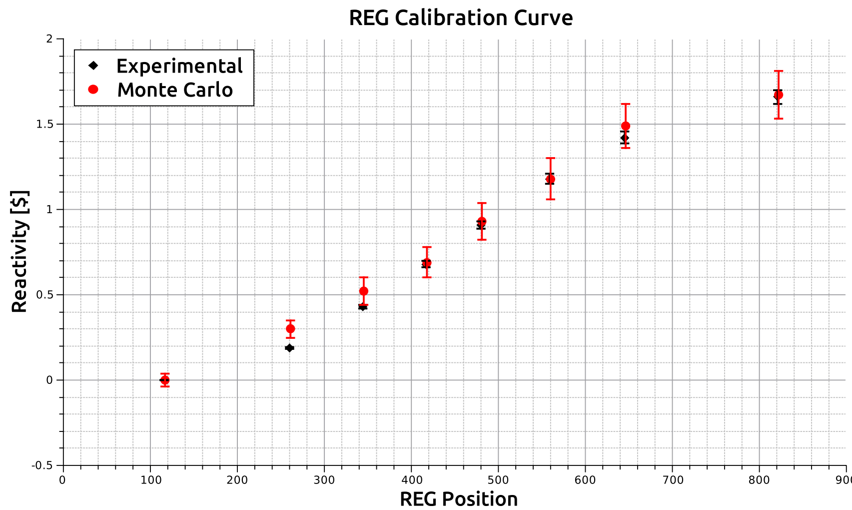

Fig. 9. Comparison between experimental and Monte Carlo calibration curves for the Regulating control rod.

3.2. *Control rod calibration*

Control rod calibration curves represent the relationship between a rod's position inside the reactor core and its effect on system reactivity. The experimental procedure used to obtain the TRIGA calibration curves is the Reactor Stable Period method. The reactor is at first brought to a critical state; one of the control rods is then moved by a small step, causing an increase of the power output. The simple exponential relationship between power rise P and time allows to obtain the reactor stable period T by measuring the time t taken by the system to increase its power output by 50%:

$$P = P_0 e^{t/T} \rightarrow T = \frac{t}{ln\left(\frac{P}{P_0}\right)} = 2.47 \cdot t. \tag{1}$$

The reactor stable period can then be used to calculate the change in system reactivity induced by the small control rod step, $\Delta\rho$, via the *in hour* equation. If we group the delayed neutron precursors into 6 groups (Lamarsh, 1966), each providing a delayed neutron fraction f_i with decay constant λ_i, the *in hour* equation takes the following form:

$$\Delta\rho = \frac{l}{k_{\mathrm{eff}} T} + \beta_{\mathrm{eff}} \sum_{i=1}^{6} \frac{f_i}{1 + \lambda_i T}, \tag{2}$$

where l is the average prompt neutron lifetime. This process is repeated several times, until the entire length of the control rod is analyzed; the calibration curve is then obtained by adding up all the reactivity steps. While the available documentation does not contain any reference to experimental errors regarding the reactor stable period, we could estimate it thanks to a recent set of measurements; the obtained value was $\sigma_T/T \simeq 5\%$. From this value we can estimate the error associated with the reactivity, $\sigma_{\Delta\rho}$:

$$\sigma_{\Delta\rho} = \left|\frac{\partial\Delta\rho}{\partial T}\right| \sigma_T. \tag{3}$$

This calculation requires the knowledge of all the constants that appear in Equation (2). While the values for f_i and λ_i for $S(\alpha, \beta)$ fission are well known and can be easily obtained (Lamarsh, 1966), the same is not true for the prompt neutron lifetime l, since it is heavily system-dependent and it is not reported in the reactor original documentation. Thanks to the experimental historical data referring to the control rod calibration, though, we were able to estimate the value of l. The documentation contains reactor period-

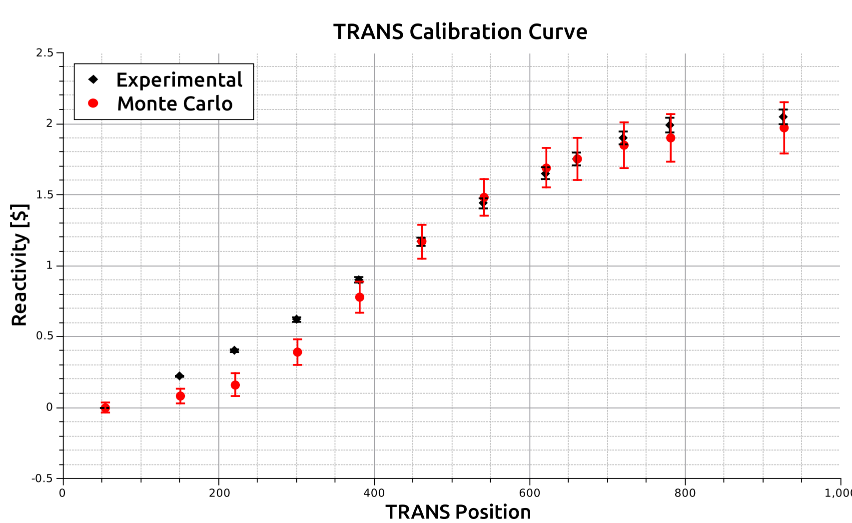

Fig. 10. Comparison between experimental and Monte Carlo calibration curves for the Transient control rod.

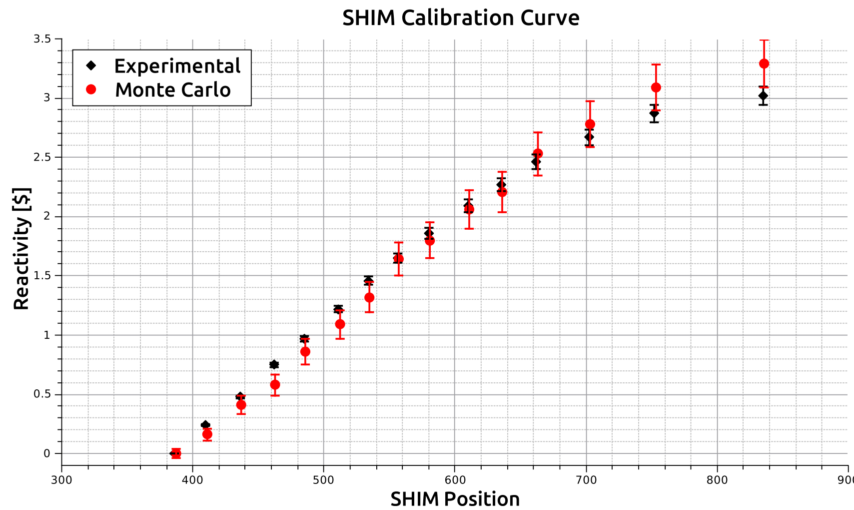

Fig. 11. Comparison between experimental and Monte Carlo calibration curves for the SHIM control rod.

reactivity couples for every control rod calibration step: we fitted those data with Equation (2), setting the prompt neutron lifetime as the only unknown parameter. The results are shown in Fig. 8: the resulting value for the prompt neutron lifetime is equal to 7.61×10^{-5} s.

The experimental uncertainty related to every reactivity step ($\Delta\rho$) in the control rod calibration procedure could finally be estimated and it was found to be $\sigma_{\Delta\rho} \simeq 2.5\%$.

The comparison between experimental data and Monte Carlo simulation results is reported in Figs. 9–11. The error value associated with the Monte Carlo results is once again given by the statistical component alone.

In order to verify the goodness of our simulations, experimental and Monte Carlo results were compared with a chi-squared test (Metzger, 2010). The χ^2 variable was calculated as follows:

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{x_i - \mu_i}{\sigma_i} \right)^2, \tag{4}$$

where x_i is the Monte Carlo result, μ_i the experimental value and σ_i is given by the combination in quadrature of the experimental and Monte Carlo uncertainties. The sum is performed over the N calibration points,[4] which in this case are also equal to the number of *degrees of freedom* (*dof*). The values for χ^2/dof obtained for the three calibration curves are reported in Table 7.

The χ^2/dof values show that the simulations are in good agreement with the experimental data. As expected the Regulating calibration curve was the most accurate, since Transient rod characteristics were assumed (see Section 2.2) and it was the only curve obtained with the Transient rod completely extracted from the reactor core.

3.3. *Systematic errors*

The systematic errors associated to some of the reactor parameters were evaluated to better characterize our model. In particular, the effects of fuel enrichment and nuclear graphite density were analyzed separately, in order to quantify each individual effect.

[4] The first point is excluded because it is conventionally set to zero in both curves.

3.3.1. *Fuel enrichment*

TRIGA fuel enrichment in ^{235}U is equal to $(19.75 \pm 0.05)\%$. If every fuel element had a different enrichment falling in this interval, the global effect on reactor criticality would be completely negligible. Since nearly every fuel element contained in the reactor has sequential serial numbers, however, we can assume that most of them were manufactured from the same batch of ZrH—U fuel: in this situation the enrichment percentage is shared by every fuel element, and not randomly distributed among them. A set of 100 simulations was studied in which the enrichment percentage was randomly picked from the documented interval and assigned to every fuel element in the reactor core. The standard deviation of this distribution is a combination of statistical and systematic uncertainties. After subtracting the statistical uncertainty, which is directly obtained from the simulation results, we derived the systematic error component, which resulted equal to 0.22$.

3.3.2. *Nuclear graphite density*

The density of the nuclear graphite elements is not directly reported on the official reactor documentation. The value we used, equal to 1.7g/cm^3, was found in various reports on AGOT-grade nuclear graphite (Eatherly et al., 1958; University of Arizona, 2009; Tyler and Wilson, 1953). However, other sources report different values, with the density ranging from 1.62 g/cm^3 (Fermi, 1952) to 1.77g/cm^3 (Manning and Simpson, 1949). A set of 100 simulations, each with graphite density in the $1.62 - 1.77$ g/cm^3 interval, was run in order to evaluate the systematic error component with the same procedure as before: in this case, a systematic uncertainty equal to 0.14$ was obtained.

Since this uncertainty is not correlated with that of fuel enrichment, the total systematic error was finally calculated by combining the two errors in quadrature and resulted to be $\sigma_{sys} = 0.26\$$.

Table 7
χ^2/dof values for the three calibration curves.

Control Rod	χ^2	χ^2/dof
Regulating	8.94	1.28
Transient	20.62	1.87
SHIM	24.28	1.74

4. Discussion

A complete model of the TRIGA Mark II reactor at the University of Pavia was produced using the Monte Carlo code MCNP5. Particular care was taken to describe reactor geometry and material composition with great precision. Model validation was performed by simulating critical reactor configurations and control rod calibration curves. Both statistical and systematic errors have been estimated and accounted for in the results. All the obtained simulation results were in good agreement with experimental data, proving the reliability of this model.

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