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A new model with Serpent for the first criticality benchmarks of the TRIGA Mark II reactor

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ABSTRACT

We present a new model, developed with the Serpent Monte Carlo code, for neutronics simulation of the TRIGA Mark II reactor of Pavia (Italy). The complete 3D geometry of the reactor core is implemented with high accuracy and detail, exploiting all the available information about geometry and materials. The Serpent model of the reactor is validated in the fresh fuel configuration, through a benchmark analysis of the first criticality experiments and control rods calibrations. The accuracy of simulations in reproducing the reactivity difference between the low power (10 W) and full power (250 kW) reactor condition is also tested. Finally, a direct comparison between Serpent and MCNP simulations of the same reactor configurations is presented.

1. Introduction

The TRIGA Mark II reactor installed at the Laboratorio Energia Nucleare Applicata (LENA) of the University of Pavia, in Italy, is a research reactor that can be operated up to 250 kW in stationary state. It is a pool-type reactor cooled and partly moderated by light water. The fuel is composed by a mixture of uranium (8% wt., enriched at 20% in ^{235}U) and zirconium hydride, that provides a moderation effectiveness strongly dependent on fuel temperature.

The TRIGA Mark II reactor of Pavia reached its first criticality in 1965 and thereafter was used for several scientific and technical applications.

In the last years, the neutronics, the thermal–hydraulics and the fuel cycle of the TRIGA Mark II reactor of Pavia were analyzed and characterized in detail. Particularly, an MCNP (X-5 Monte Carlo Team, 2008) model of this reactor was developed to simulate the first criticality configuration at low power (Borio di Tigliole et al., 2010; Alloni et al., 2014). The MCNP neutronics calculations were then coupled to a thermal–hydraulic model to simulate the full power steady state (Cammi et al., 2016). Finally, fuel burnup calculations were carried out for the period between 1965 and 2013, exploiting the MCNP simulations and the historical documentation about reactor operation (Chiesa et al., 2016) . Moreover, benchmark measurements were performed with the neutron activation technique to evaluate the intensity, the energy spectrum and the spatial distribution of the neutron flux in the reactor core and in the main irradiation facilities (Borio di Tigliole et al., 2014; Chiesa et al., 2014; Chiesa et al., 2015).

In this paper, we present a new simulation model for the TRIGA reactor of Pavia, implemented with the Monte Carlo code Serpent (version 1.1.19) (Leppänen et al., 2015). We chose this tool because of its powerful capabilities such as built-in burnup calculation, methods for directly coupling neutronics and thermal–hydraulics, fast running time and reactor geometry pre-implementation. Serpent is an increasingly widespread tool in the research field of nuclear reactors and is also used to simulate other TRIGA reactors (D. Ćalić et al., 2016; Validating and Leppänen, 2016). By developing a Serpent model for the TRIGA reactor in Pavia, we can test this simulation tool in a well known reactor configuration for which both experimental and MCNP simulation benchmarks are available. In this paper, we present the first step of this analysis. In the future, we plan to exploit Serpent capabilities to perform burnup calculations and to create a very detailed model for the full

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power reactor through a direct coupling between neutronics and thermal–hydraulics.

In the following sections, after describing the development of the Serpent model for the TRIGA Mark II reactor (Section 2), we present the results of the analysis performed to prove the reliability of this new model. We use as a benchmark the experimental data of the first criticality tests performed in 1965 (Cambieri et al., 1965), thus simulating the initial fuel composition without the contamination of fission products. In Section 3, we present the results of the simulations for the low power reactor condition, in which the fuel is in thermal equilibrium with the water pool. Different configurations of the control rods, recorded when the reactor was critical, are simulated to test the model reliability in predicting the absolute reactivity of the system. In addition, we show the reconstruction of the first calibration curves of the control rods. In Section 4, we simulate the reactor at full power condition (250 kW). The 3D distribution of fuel temperatures evaluated in Cammi et al. (2016) is included in the Serpent model to test its capability to simulate the reactivity loss due to thermal effects in TRIGA reactors. Finally, in Section 5, we compare the results of Serpent simulations with those obtained with the previous MCNP model for the same reactor configurations.

2. The Serpent model of the TRIGA reactor

In order to describe accurately the reactor geometry and materials in the Serpent model, we exploit all the information that was collected in the previous years during the development of the TRIGA Mark II MCNP model (Borio di Tigliole et al., 2010; Alloni et al., 2014). These data are taken from the historical records stored at LENA and from the technical drawings of fuel elements and control rods that were provided by General Atomics. The Serpent model includes the core, the reflector and the water pool. The core is a cylinder 44.6 cm in diameter, delimited at the top and bottom by two aluminium grids spaced 64.8 cm.

We define a *circular cluster array* – a pre-implemented geometry structure available in Serpent – to describe the 91 core locations distributed in concentric rings. These locations are filled by fuel elements, graphite elements (dummy), three control rods (named SHIM, REGULATING and TRANSIENT), two irradiation facilities (Central Thimble and Rabbit Channel) and the neutron source. In Fig. 1 we show the horizontal and vertical sections of the reactor geometry implemented in the Serpent model. The geometry of the 30 cm thick graphite reflector surrounding the core is described in detail, including the Lazy Susan irradiation facility and the holes corresponding to the radial and tangential irradiation channels.

The fuel elements are described with high detail. Particularly, we model the fuel active region, the disks with Sm_2O_3 burnable poison, the graphite axial reflectors and the aluminum cladding. For a better accuracy, we define a different material for each fuel element, setting the precise amount of uranium contained at the beginning of reactor operation in 1965.

Finally, for a direct comparison with the MCNP model, we decide to use the same cross sections also in Serpent. Particularly, the neutron cross sections for all materials are taken from JEFF-3.1 library (The JEFF-3.1.1 Nuclear Data Library, 2009), with the only exception of the $S(\alpha,\beta)$ ones (needed to correctly simulate the moderating properties of zirconium hydride and water) that are taken from the more recent ENDF/B-VII.1 library (Chadwick, 2011).

3. Benchmark analysis of low power reactor

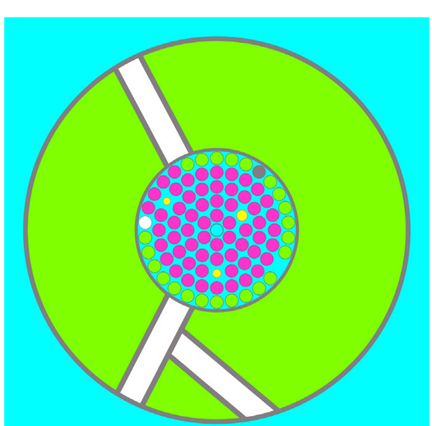
In the first part of this work, we simulate the reactor in the fresh fuel and low power (10 W) condition. No neutron poisons are inside the fuel and the temperature can be set around 300 K for every material, because the fuel can be considered in thermal equilibrium with the reactor pool.

First of all, we check the model accuracy in evaluating the multiplication factor k_{eff}. We use as experimental benchmark the data included in the First Criticality Final Report (Cambieri et al., 1965). Particularly, 26 critical configurations of the reactor are reported. Each configuration corresponds to a different position of the control rods in which the reactor is critical ($k_{eff} = 1$).

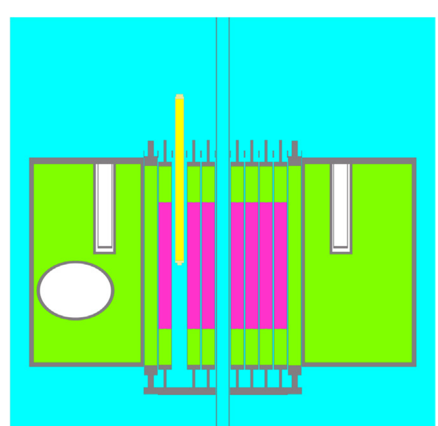
We set the control rod positions in the Serpent model according to the information about control rods motion system and historical documentation. Then, we run the Monte Carlo simulations with 500 active cycles of 4×10^5 neutrons each, for a total of 2×10^8 neutron histories. This choice ensures a high statistical relative precision of k_{eff} evaluation ($\sim 10^{-4}$).

Using the k_{eff} results from Serpent simulations, we calculate the reactivity: $\rho = (k_{eff} - 1)/k_{eff}$. The reactivity is usually expressed in relation to the fraction of delayed neutrons, using the \$ units. For the TRIGA Mark II reactor in Pavia, 1 \$ = 0.0073 (Cambieri et al., 1965).

The simulation results are presented in Fig. 2 and Table 1 (the statistical uncertainties are 1σ). The expected value for each



(a)



(b)

Fig. 1. The geometry of the TRIGA Mark II reactor simulated in Serpent. Cyan is used for water, green for graphite, gray for aluminum, purple for fuel and yellow for control rods. (a) Horizontal section at core equator, showing the concentric rings of fuel/dummy elements and the graphite reflector with the holes corresponding to the radial and tangential irradiation channels. (b) Vertical section of the core in the plane hosting the TRANSIENT control rod. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)