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Validation of the Serpent 2 code on TRIGA Mark II benchmark experiments

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HIGHLIGHTS

- Monte Carlo calculation using Serpent code is demonstrated.
- We model two experiments using 3-D TRIGA research reactor model.
- Results were compared to to Monte Carlo code MCNP and experimental results.
- Good agreement with the experimental and excellent agreement with MCNP results.

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ABSTRACT

The main aim of this paper is the development and validation of a 3D computational model of TRIGA research reactor using Serpent 2 code. The calculated parameters were compared to the experimental results and to calculations performed with the MCNP code. The results show that the calculated normalized reaction rates and flux distribution within the core are in good agreement with MCNP and experiment, while in the reflector the flux distribution differ up to 3% from the measurements.

1. Introduction

Long-term changes in the composition of nuclear fuel and other materials under irradiation are usually performed using deterministic codes. In contrast to deterministic methods where the neutron interactions are treated using approximations and numerical methods that are valid only under certain conditions, in Monte Carlo methods the treatment of the particle interaction physics and problem geometry are very accurate and also problem independent, but in general slower. Nevertheless with the increased multi-core CPU's capabilities and the use of parallelization, full 3-D burnup calculations of research reactors are possible in realistic time. Today the Monte Carlo method is used routinely in neutron transport calculations even for relatively complex systems such as research reactors. At Jožef Stefan Institute the Monte Carlo code MCNP (X-5 Monte Carlo Team, 2004) has been used for almost two decades for the calculations of neutron flux and spectra calculations, dose rate and reaction rate calculations in the JSI TRIGA Mark II reactor (Snoj et al., 2011, 2012; Radulović et al., 2014). Recently TRIPOLI code (Brun et al., 2015) was used for TRIGA reactor modeling (Henry et al., 2015). It is foreseen that in future the TRIPOLI neutronics model will be coupled with thermal hydraulic calculations. A geometrically detailed 3-D MCNP model of the reactor core with its closest surrounding structures was developed that was benchmarked against experimental measurements. It is important to note that although the existing core has been operating since 1991, the fuel in the MCNP model was considered fresh, i.e. with zero burnup. This has been justified by relatively low maximum burnup (<5 MWd per fuel element)

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(Jazbec et al., 2013). Some attempts were made to estimate the bias due to neglecting burnup by using the home developed neutron diffusion core management code TRIGLAV (Peršič et al., 1998) to calculate the burnup and isotopic composition of the fuel and then implement this into MCNP (Peršič et al., 2000; Žerovnik, 2007; Štancar et al., 2015). Recently a new code was developed at VTT Technical Research Centre of Finland, which enables Monte Carlo burnup calculations, called Serpent (Leppänen et al., 2013). It was then decided to use the Serpent tool to support core management, safety evaluations and experiment design of the TRIGA. Firstly we developed the geometrical model of the reactor and validated it against existing benchmark experiments.

The purpose of this paper is to validate the Serpent code and the Serpent TRIGA model with experiments. In the future the model will be validated for kinetic parameters (Snoj et al., 2010; Filliatre et al., 2015), photon production (Žerovnik et al., 2015) as well as for routine applications.

All the calculations presented in this paper were done using the Serpent 2 code version 2.1.24. In regard to Serpent 1, Serpent 2 has many more features and contains a complete redesign of memory management, which is important in burnup calculations using computer clusters with many cores. Before burnup calculations can be undertaken it is necessary to validate the TRIGA model. Validation was performed using steady state core configuration to determine flux and reaction rate distribution calculations. In Section 2 a brief description of the JSI TRIGA reactor model is given. In Section 3 the main results are reported and discussed. In Section 4 conclusions and future plans are presented.

2. Experiment description of TRIGA research reactor

The JSI TRIGA reactor is a typical 250 kW TRIGA Mark II. It is light water reactor cooled by natural convection. There are 91 locations in the core, which can be occupied by fuel rods, neutron source, irradiation channels, etc. Elements in the core are arranged in six concentric rings: A, B, C, D, E and F with 1, 6, 12, 18, 24 and 30 available locations. The core is surrounded by graphite reflector enclosed in aluminum casing. An annular groove in the upper part of the reflector body is provided to contain the so-called carrousel irradiation facility.

In order to validate the computational models of the core a series of experiments was conducted (Snoj et al., 2011). Two experiments are briefly presented in this paper. First, the criticality benchmark experiment that was performed in 1991 (Jeraj and Ravnik, 1999) and is described in the ICSBEP Handbook (ICSBEP, 2006) was analysed. In this experiment two critical core configurations (core no. 132 and 133) were considered. Both configurations had the same number of fuel elements but different loading pattern. Core 132 had 7 fuel elements in the E ring placed at the side of the transient rod (T), while core 133 had 7 elements placed at the opposite side. During the experiment the transient rod and all three other control rods were completely withdrawn from the core. The core configurations are shown in Fig. 1. In the second experiment the Al–Au foils were irradiated in several channels in the reactor core as well as in the rotary groove surrounding the core (Fig. 2). The activity of the samples was measured by using high-purity germanium detector. Two activation reactions were considered:

$$^{27}\mathrm{Al}(n,\alpha)^{24}\mathrm{Na}^{*}\overset{\gamma}{\Longrightarrow}{}^{24}\mathrm{Na}\overset{t_{1/2}=15h}{\Longrightarrow}{}^{24}\mathrm{Mg}+e^{-}+\bar{\nu}+\gamma\quad(\mathrm{E}=1368.6\ \mathrm{keV})$$

$$^{197}\mathrm{Au}(n,\gamma)^{198}\mathrm{Au}^{*}\overset{\gamma}{\Longrightarrow}{}^{198}\mathrm{Au}\overset{t_{1/2}=2.7d}{\Longrightarrow}{}^{198}\mathrm{Hg}+e^{-}+\bar{\nu}+\gamma\quad(\mathrm{E}=411.8\ \mathrm{keV}).$$

First reaction has incident neutron energy threshold at 5 MeV and is thus convenient for investigation of fast neutron flux, while the cross section for the second reaction is the highest for energies below 10 keV and thus useful for investigation of thermal and epithermal neutrons. One of the important aspects are the experimental uncertainties. The main experimental uncertainty is due to the thermal calibration method of the nuclear detectors and can be up to 15% (Žagar et al., 2000), therefore the measured specific activities are normalized in order to avoid additional uncertainty originating from the thermal calibration.

3. Calculations

3.1. Computational model

In order to successfully model both experiments a detailed TRIGA Serpent model was constructed where the core configuration is changed and adjusted to the experimental configuration. The critical benchmark with core configurations 132 and 133 and the reaction rate distribution experiment with the core configuration 189 were evaluated. Serpent TRIGA model with radial and tangential beam ports is presented in Figs. 3 and 4 and it is based on the criticality benchmark model (Jeraj and Ravnik, 1999). Since then new model was developed (Snoj et al., 2011; Radulović et al.,

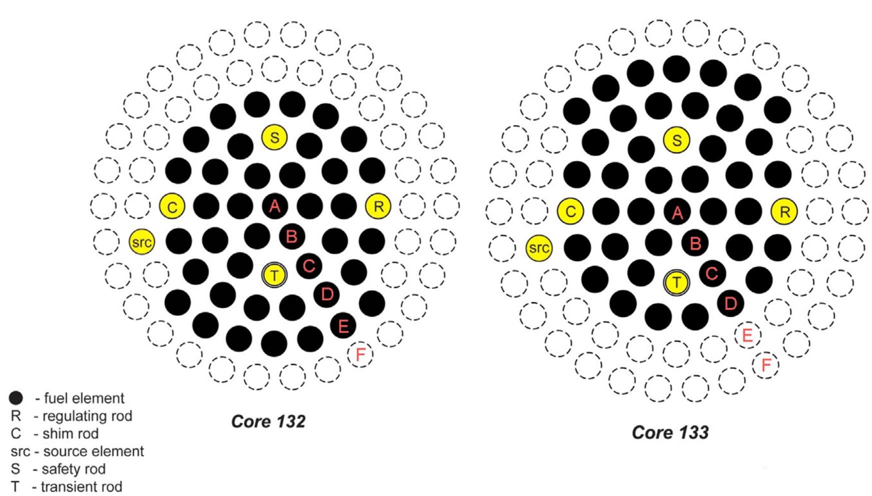

Fig. 1. Criticality core configurations (132 and 133), schematic top view with six concentric rings: A, B, C, D, E and F.