Annals of Nuclear Energy 63 (2014) 731–741

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Comparing neutronics codes performance in analyzing a fresh-fuelled research reactor core

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ARTICLE INFO

Article history:
Received 30 January 2013
Received in revised form 10 July 2013
Accepted 23 August 2013
Available online 11 October 2013

Keywords:
Neutronic codes
Monte Carlo codes
Deterministic codes
MCNP
TRIPOLI
XSDRN

ABSTRACT

In this paper the relative performance of different simulation approaches is examined, focusing on the neutron fluence rate distribution in a nuclear reactor core. The main scope of the work is to benchmark and validate the neutronics code systems utilized in the Greek Research Reactor (GRR-1) for a high-density Low Enriched Uranium (LEU) core of compact size. For this purpose the recently converted core of the Portuguese Research Reactor (RPI), fueled with fresh, low enrichment in U-235 fuel, was simulated with the stochastic code TRIPOLI and the deterministic code system XSDRN/CITATION. RPI was selected on the basis that it is a similar to GRR-1 pool-type reactor, using same fuel and control rods type, as well as same types of coolant, moderator and reflector. The neutron fluence rate in RPI was computed using each numerical approach with changed approximations. In this frame the stochastic code TRIPOLI was tested using two different nuclear data libraries, i.e., ENDF/B-VI versus JEFF3.1, and two different ways of source definition, i.e., "point sources", placed in the center of each fuel cell, versus a "distributed source", where each fuel volume was considered as a neutron source. The deterministic code system XSDRN/CITATION was tested with respect to the definition of the transverse leakages associated to each one-dimensional, user-defined core zone, as analyzed by the XSDRN code in order to provide the zone equivalent cross sections. Thermal, epithermal and fast neutron fluence rates were computed and local values found in a 15 cm segment immediately below the fuel mid-height were compared to activation foil measurements, as well as to corresponding MCNP results obtained at the RPI. The comparisons were performed in representative core positions, including standard fuel assemblies, dummy (non-fuelled) assemblies, beryllium reflectors and free grid positions close to the core. Application options and future improvements of the tested codes are discussed. Finally it is worth noting that this paper, including measurements and calculations by three different codes and tests of different cross section libraries for a new commissioned core, can provide useful material for benchmarking neutronics codes that are under development in various reactor laboratories, as well for optimizing codes already in use.

1. Introduction

The Reduced Enrichment for Research and Test Reactors (RERTR) Program of the US Department of Energy has been a major driving force for the conversion of many research reactors to Low Enriched Uranium (LEU) fuel (National Research Council, 2012). Newly commissioned nuclear reactor cores offer a valuable data base for testing, evaluation and intercomparison of neutronic codes. Fresh cores offer the advantage that commonly provide the set of data which favor such studies since the fuel composition – and therefore the core inventory – is almost perfectly known. For example Bretscher and Snelgrove (1982) compared analytical calculations, based mainly on the three-dimensional diffusion theory, with some of the experimental data obtained after the Ford Nuclear Reactor had become critical with LEU fuel elements. Code evaluation studies have also been performed independently of RERTR Programme, such as the one by Pesić and Ninković (1999), which compare measurements with neutron and gamma-ray spectra computed by MCNP, in the frame of the Third International Intercomparison Experiment on Nuclear Accident Dosimetry. Also, Lucas et al. (2005) used the three-dimensional multi-group deterministic neutron transport code ATTILA to calculate criticality, fluence rate and depletion for the Advanced Test Reactor (ATR) and compare results to ATR data and to MCNP and MCNPX outputs.

The Portuguese Research Reactor (RPI) is a 1 MW pool-type reactor built by American Machinery and Foundry (AMF) Atomics, US and commissioned in 1961. Its design is similar to the one of the

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http://dx.doi.org/10.1016/j.anucene.2013.08.036

Greek Research Reactor (GRR-1), in Athens, the "Hoger Onderwijsreactor" in Delft, The Netherlands, and the McMaster Reactor, in Canada. The activities underway in the RPI cover a broad range, from irradiation of electronic circuits (Franco et al., 2005) to calibration of detectors for dark matter search (Felizardo et al., 2008) through more classical subjects such as neutron activation (Dung et al., 2010).

Core conversion to LEU fuel was concluded in 2007 after feasibility and safety studies, made with the assistance of the RERTR program within project POR4012 of the International Atomic Energy Agency (IAEA). The new LEU fuel (19.75% nominal U-235 enrichment) was supplied by the US, following Y-12 specifications (Nelson and Eddy, 2010), which are more stringent than the ASTM C1462-00 standard (ASTM, 2008), namely in the allowed amounts of U-234 and U-236. Detailed neutronic core analyses using the Monte Carlo code MCNP-4C (Briesmeister, 2000) were performed for the RPI (Matos et al., 2006).

In a previous work (Fernandes et al., 2010), the results of the MCNP model developed for the new LEU core of the RPI were compared with neutron fluence rate measurements performed shortly after the reactor commissioning, when fresh fuel conditions could reasonably be assumed. That study allowed an evaluation of the RPI core model for the determination of absolute neutron fluence rates and vertical neutron fluence rate profiles in favorable conditions, to be considered as reference for subsequent analysis of effects such as fuel burnup and cross section libraries on the model's accuracy. The same model has been used for the evaluation of the conversion impact in the neutron fluence rate available in some irradiation facilities (Dung et al., 2010; Marques et al., 2011).

In the present work, the fresh fuelled RPI core is simulated applying two different neutronics codes, i.e. the Monte Carlo code TRIPOLI and the deterministic code system XSDRN/CITATION, which are commonly utilized in the Greek Research Reactor Laboratory for the GRR-1 core analysis. The analysis aims at benchmarking and validating the above numerical approaches for a LEU core similar to that of the GRR-1, focusing on the neutron fluence rate prediction in representative core positions. The optimum utilization of the above code systems was pursued by testing different applications of each code, based on different approximations. Regarding the stochastic computations, the latter involve the cross section library selection and the source definition, while in the deterministic simulation, cell calculation aspects were tested with respect to the transverse leakages associated to each one-dimensional, user-defined core zone. Comparisons of the results derived with the different approximations adopted for each computational method were made with corresponding measurements as well as with previous MCNP results obtained at the RPI for average thermal, epithermal and fast neutron fluence rates, in segments of 15 cm length immediately below the fuel mid-height, where the maximum value of the vertical fluence rate distribution is known to occur. The comparisons were made for eleven representative positions, i.e. four in-core positions including standard fuel assemblies, four peripheral core cells including dummy (non-fuel) assemblies, one irradiation position in the beryllium reflector and two positions located in the core grid, in water. Relative (i.e., normalized to the maximum) vertical profiles of thermal, epithermal and fast neutron fluence rates were also obtained by CITATION and TRIPOLI in four representative channels (i.e., a standard fuel assembly, a dummy assembly, a beryllium block and a free grid position inside the pool). The profiles obtained by the above two codes for thermal and fast neutrons were compared with the corresponding, earlier obtained MCNP results.

Based on the codes intercomparison as well as on the comparisons with measurements, the study attempts to designate the optimum approximations combination adopted in each tested computational method, for the calculation of neutron fluence rates in high-density, compact size pool type LEU cores, using MTR fuel elements of slab geometry. The study provided useful conclusions regarding application options and future improvements of the tested codes.

2. Core configuration

The analyzed core configuration (Fig. 1) consists of seven standard and five control LEU fuel assemblies of the Materials Test Reactor (MTR) type (Rosenthal, 2010), manufactured by CERCA (AREVA group, France). Control and standard fuel assemblies (Fig. 2) contain 10 and 18 fuel flat plates, with approximately 20.9 g of U-235 per plate, respectively. Each fuel plate contains a meat of U_3Si_2 (silicide) powder dispersed in pure Al, clad in AG3NE Al alloy (similar to 6061 Alcoa alloy). Silicide dispersion fuel was fully qualified by the US Nuclear Regulatory Commission in 1988 (Nuclear Regulatory Commission, 1988) and is widely used in research reactors.

For control purposes, four shim-safety rods and one regulation rod are used, located in the central channels of the control assemblies. The shim-safety rods consist of a 1 mm-thick cadmium layer supported and covered by 1.5 mm-thick stainless steel, while the regulating rod is a hollow 2.2 mm-thick stainless steel tube. Rods have oval cross-sectional shapes and 61 cm length. When fully inserted, the centre line of the rods is displaced 14 mm above that of the fuel meat. Further details about the fuel description and assemblies design are given in Table 1 and reported elsewhere (Matos et al., 2006).

The core is reflected by graphite (in the thermal column), by beryllium and by light water. The beryllium reflectors were supplied by the former USSR through the Technical Cooperation program of the IAEA in the 1980s. A set of impurities was considered based on previous experience with Be of the same origin (Matos, 2005).

Four dummy assemblies were introduced in the core periphery in order to improve the thermal hydraulic safety margin. The fuel, dummies and beryllium reflectors are mounted on a grid plate with a (9×6) pattern. Samples are routinely irradiated in the free grid positions, in the dummies and in cavities at some beryllium reflectors. The dummies consist of the same external structure as fuel assemblies but, instead of fuel plates, they contain only an aluminum tube in the central region allowing sample irradiation.

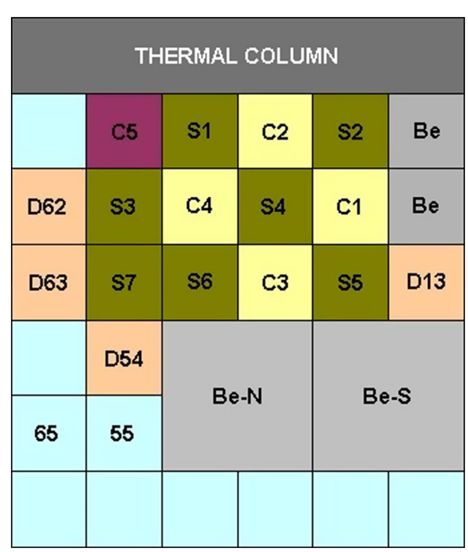

Fig. 1. The investigated RPI core configuration.