Annals of Nuclear Energy 92 (2016) 369–377

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Technical note

Full 3-D core calculations with refueling for the OPAL Research Reactor using Monte Carlo Code Serpent 2

Diego Ferraro [a,*], Eduardo Villarino [b]

[a] INVAP Nuclear Engineering Department, Buenos Aires, Argentina
[b] INVAP Nuclear Engineering Department, Bariloche, Argentina

ARTICLE INFO

Article history:
Received 29 January 2016
Accepted 5 February 2016
Available online 23 February 2016

Keywords:
Monte Carlo Code
Serpent Code
OPAL Research Reactor
MTR

ABSTRACT

Monte Carlo (MC) neutron transport codes have been extensively used for more than three decades to perform criticality calculations and to solve shielding problems due to their capability to model complex systems without major approximations. The irruption of affordable low-cost high performance computer resources in the last decade allows to consider some initially unexpected applications, such as full core burnup calculations or cell level modeling for few group parameters calculations. In this work the concern of the potential use of Monte Carlo codes to perform full 3-D calculations including burnup for a state of art Research Reactor is analyzed, regarding aspects related to accuracy, performance and resources requirements. For such purpose *Serpent 2 v.1.24* Code, developed by VTT Technical Research Centre of Finland is used for full core burnup calculations of the 20MWth OPAL Research Reactor. This code is the second version of a brand-new Monte Carlo code designed to perform burn dependent cell-level and full 3-D core calculations using optimized schemes to diminish the computational effort. In past works the first version of *Serpent* Code was tested as a cell-level-code to model the MTR-type fuel assemblies from OPAL Research Reactor, obtaining fairly good results. Further works were developed for full 3-D models, where several parameters such as critical configurations, in-core thermal neutron flux profiles and effective delayed neutron parameters were obtained and compared to experimental data and other codes results, showing a very good performance. In the present work, a full 3-D model is developed using specifications and high quality experimental data from IAEA Technical Report Series. This model is used to perform full-core 3-D calculations including burnup and refueling for the first six operating cycles without the aim of an external calculation code. To perform such task, an ad hoc code to manipulate *Serpent 2* restart files was developed in order to model the overall full core burnup problem without the help of any other calculation code. The results were compared with the experimental data available showing a very good agreement. Finally several aspects of the computational issues related with this modeling such performance, scalability and resources requirements are discussed, showing that the use of full core 3-D MC models including burnup for small cores represents nowadays a feasible alternative for specific calculations.

1. Introduction

The concern on the future use of Monte Carlo neutron transport codes for full-core level calculations including burnup has arised in last decade due to the availability of low-cost computational resources. Accordingly, the traditional use of Monte Carlo neutron transport codes such as criticality calculations and general transport (f.e. shielding problems) is nowadays being extended to other applications such as group constant generation, burnup calculations and full modeling, which have been prohibitive in the past decades.

One of the major aspects to take into account when calculations including burnup are intended to be performed for full Reactor Core models is the amount of materials to evolve and quantity of costly transport calculations to be performed. As far as computational costs both in CPU and memory requirements increase rapidly, performance and scalability must be analyzed when realistic applications are into consideration.

Due to the irruption of affordable low-cost high performance computers and clusters technology during last years, the

* Corresponding author.
E-mail addresses: dferraro@invap.com.ar (D. Ferraro), men@invap.com.ar (E. Villarino).

http://dx.doi.org/10.1016/j.anucene.2016.02.004
0306-4549/

consideration of this approach is becoming more common. Despite large Power Reactor Cores still present limitations due to computer resources in this scheme, the special case of small Reactor cores (such as the Research Reactors) where the amount of different materials to evolve and the size of the core is significantly lower, represents an attractive field.

In spite of the fact that full 3-D Monte Carlo calculations are usually performed in Research Reactors for specific goals (such as detailed flux profile obtention and criticality calculations), it is the intention of this work to analyze the potential use of Monte Carlo Codes to perform full 3-D calculations including burnup for a state of art Research Reactor as an alternative to the traditional calculation scheme, regarding aspects related to accuracy, performance and resources requirements.

For such purpose, the Monte Carlo *Serpent 2 v1.24* code (Leppänen et al., 2015) developed by VTT Technical Research Centre of Finland is used. This code is the second version of a brand-new Monte Carlo Code designed to perform cell-level burnup calculations and full 3-D core calculations, using optimized schemes that enhance the calculation capabilities and reduce the computational effort. *Serpent 2* also allows the user to obtain relevant information for reactor level calculations, reactor design and general analysis such as condensed and homogenized group constants, neutron fluxes, kinetic parameters and burned compositions, among others.

1.1. Available experimental data for an state of art Research Reactor

In order to develop this study high quality experimental data that includes burnup analysis is required for a state of art Research Reactor. Fortunately, data from the IAEA technical Series No. 480 (International Atomic Energy, 2015) for the 20MWth OPAL Research Reactor, designed, constructed and commissioned by INVAP was selected.

This high quality data is the result of a Coordinated Research Project (CRP) developed by the International Atomic Energy Agency from 2008 on Innovative Methods in Research Reactor Physics, which provides experimental data and specifications from diverse reactor intended to be used to perform experimental benchmarking of advanced codes and methods.

As a result, this technical report contains facility specifications, experiment descriptions, and corresponding experimental data for nine different research reactors covering a wide range of Research Reactor types, power levels and experimental configurations. Each data set was prepared in order to serve as a stand-alone resource of well documented experimental data, which can subsequently be used in benchmarking and validation of the neutronic and thermal hydraulic computational methods and tools employed for improved utilization, operation and safety analysis of research reactors.

1.2. Past works and current work objectives

The capabilities of *Serpent* Code to be used as a cell-level code to model MTR-type Fuel Assemblies (FA) to obtain few group constants to be used in core calculations have been already tested in past works (Ferraro and Villarino, 2011) for the OPAL Research Reactor, where comparisons with INVAP's own Calculation line (Villarino et al.) were performed showing fairly good results. Additionally full 3-D core calculations including burnup for small cores were also performed and compared with deterministic calculation codes (Ferraro et al., 2013).

Encouraged by the good performance shown by *Serpent* Code, a full 3-D model for the 20Mth OPAL Research Reactor was developed in Ferraro and Villarino (2014), where several parameters such as critical positions, effective delayed neutron fraction (β_{eff}), in-core thermal neutron flux profiles and some burnup cases were calculated and compared both with experimental data and with INVAP's calculation line results showing a fairly good performance. Using this model, the main neutronic parameters measured during reactor Commissioning were compared with experimental data and reported calculations (Ferraro and Villarino, 2014) showing a very good agreement.

Encouraged by these results, it is now intended to perform the burnup calculations for a full 3-D model in *Serpent 2* OPAL Research Reactor including burnup and Fuel Management for the 6 cycles reported in International Atomic Energy (2015) in order to:

- Asess the capability of *Serpent 2* Code to perform full-core 3-D calculations including burnup for diverse core configurations and fuel burnup levels.
- Compare the obtained results with experimental data in order to estimate the prediction capabilities of the model developed and calculation code in a realistic condition.
- Study the computational performance, regarding scalability and hardware requirements of CPU and RAM memory in order to analyse the feasibility of the use of MC codes to these kind of calculations.

To reach these objectives the following steps are developed:

(a) Adjust a full 3-D model in order to perform the material subdivisions required for burnup calculations.
(b) Calculate the Control Rod Worths and compare with measured ones in order to asess the criticality calculations accuracy.
(c) Develop a refueling management code in order to allow the fuel reshuffling for the cycles to be calculated.
(d) Calculate measured critical configurations during the reported cycles in International Atomic Energy (2015).
(e) Study the performance behavior of the Code to model a full-scope problem.

2. Problem description

2.1. The OPAL Research Reactor

The OPAL Research Reactor (International Atomic Energy, 2015) is a state of art 20MWth multi-purpose open-pool type Research Reactor located at Lucas Heights, Australia. It was designed, built and commissioned by INVAP between 2000 and 2006 and it has been operated by the Australia Nuclear Science and Technology Organization (ANSTO) showing a very good overall performance.

The Reactor consists of a compact core of 16 LEU (<20%wgt ^{235}U) MTR-type dispersed Uranium-silicide fuels. The Reactor is cooled and moderated by light water and reflected by heavy water contained in a Reflector Vessel. This Reactor counts with two independent shutdown system, namely:

- A fast-actuation First Shutdown System, comprised by five Hafnium Control rods; four plate-type (namely CRs 1–4) and a central cross-type rod that is also used as regulating rod (namely CR 5).
- A Second Shutdown System, comprised by the draining of the heavy water present in the Reflector Vessel.

Besides, several irradiation facilities are located in the Reflector Vessel, including a Cold Neutron Source (CNS) with two Cold beams, a thermal neutron source with two beams, a region reserved for a future hot neutron source, a hot neutron beam, 17 vertical irradiation tubes with place for 5 targets each for bulk