Annals of Nuclear Energy 120 (2018) 642–655

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Comparisons between RFSP and MCNP for modeling pressure tube heavy water reactor cores with thorium-based fuels

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ARTICLE INFO

Article history:
Received 16 February 2018
Received in revised form 24 April 2018
Accepted 18 June 2018

Keywords:
Reactor core physics
Reactor lattice physics
Heavy water reactors
Code-to-code comparisons
Advanced fuels
Thorium

ABSTRACT

Thorium-based fuels are recognized to hold significant promise as an option for achieving a long-term, sustainable nuclear fuel cycle and energy security. Pressure tube heavy water reactors (PT-HWRs) are well suited to exploit the energy potential of thorium. Deterministic reactor physics codes are often used in exploratory studies to evaluate the performance and operational characteristics of various fuel bundle, lattice and core concepts with thorium based fuels in PT-HWRs. Because of the approximations inherent in deterministic codes, they are often considered less accurate than stochastic codes. In order to enhance confidence in deterministic code-based predictions, these codes are often benchmarked against stochastic codes, when experimental data is not available for code validation. Code-to-code comparisons of core physics calculations were made between the deterministic reactor physics toolset WIMS-AECL/WIMS-Utilities/RFSP and the stochastic neutron transport code MCNP for a series of core configurations with mixed oxide fuels containing thorium in PT-HWRs. The core neutron multiplication factors (k_{eff}) appear to have a difference (RFSP-MCNP) ranging between −2.4 mk and +4.0 mk. The MCNP full-core calculations confirm that that thorium-based fuels have a lower coolant void reactivity (CVR), ranging from +8.3 mk to +11.3 mk (versus 14 mk for NU fuel). The core cases with NU fuel have a small difference (RFSP-MCNP) in peak bundle power (ranging between −0.13% and 0.65%). Cores with LEU at 1.2 wt% ^{235}U/U, Pu/Th, and LEU/Th (LEU at 5 wt% ^{235}U/U) fuel have higher differences in peak bundle power (ranging between −7% and −12%). All these core cases have peak channel power differences between −2.1% and −8.9%. Core with ^{233}U fuel has the smallest peak bundle difference (−0.05%) and smallest peak channel differences (−0.58%) which represent the best agreement between MCNP and RFSP simulations. The performed code-to-code comparisons have demonstrated that the core physics parameters estimated by RFSP calculations are consistent with MCNP simulations, especially for fuel where the main fissile component are ^{235}U-based and ^{233}U-based fuel.

1. Introduction

Thorium, a fertile nuclear fuel which is nearly three times as abundant as uranium, represents a long-term energy source that could complement uranium and eventually replace it, helping to ensure energy sustainability and security (OECD Nuclear Energy Agency and the International Atomic Energy Agency, 2014). With the uncertain in deployment of fast neutron reactors and the delay of realisation of geological repositories in some countries, introducing thorium into the nuclear fuel cycle (e.g. using thorium-based fuel) as a means of plutonium management and recycling the fissile material from used fuels shows potential for improving the medium-term flexibility of nuclear energy and its long-term sustainability (OECD Nuclear Energy Agency, 2015). In recent years, there has been initiative in Canada (Floyd et al., 2016) to examine and close the gaps that exist between current science and engineering capability and the potential implementation of advanced fuels (including thorium-based fuels) in conventional pressure tube heavy water reactors (PT-HWRs), which are a power reactor technology in current use in several nations throughout the world. PT-HWRs are advantageous for implementing thorium-based fuels because of their high neutron economy and fuel cycle flexibility, enabled by the use of heavy water as a moderator and a coolant, and on-line refuelling capability.

Abbreviations: PT-HWR, Pressure Tube Heavy Water Reactor; LC, Lattice Concept; CVR, Coolant Void Reactivity; MCNP®, Monte Carlo N-Particle transport code; NRMSD, Normalized Root Mean Square Deviation; RFSP, Reactor Fueling Simulation Program; WIMS-AECL, 2D multi-group neutron transport code developed by AECL at Chalk River Laboratories.

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https://doi.org/10.1016/j.anucene.2018.06.036
0306-4549/

In previous deterministic reactor physics studies, a number of fuel types were investigated as possible short-term and long-term options for incorporating thorium into the fuel cycle of a PT-HWR (Bromley, 2014; Colton et al., 2016; Colton et al., 2017). The fuel types include natural uranium (as a reference case for comparison), LEU at 1.2 wt% $^{235}U/U$ augmented by small amounts of thorium, and thorium-based fuels mixed with LEU at 5 wt% $^{235}U/U$, reactor grade plutonium (RGPu, 67 wt% Pu-fissile/Pu) or ^{233}U as the initial source of fissile fuel. It is expected that LEU could be obtained from existing enrichment facilities; RGPu (Nakahara et al., 2002) could be obtained from stockpiles of spent light water reactor fuel and the ^{233}U could be obtained from a future stockpile of spent thorium-based fuels. Note that, as a simplifying approximation, the fresh fuel for cores involving the use of $(^{233}U,Th)O_2$ fuel is assumed to be made of pure ^{233}U mixed with thorium. Lattice physics calculations for these various fuel types in different fuel bundles concepts have been performed previously (Colton et al., 2016) using the 2D, multi-group collision-probability neutron transport code WIMS AECL version 3.1 (Altiparmakov, 2008) in conjunction with an 89-group nuclear data library based on ENDF/B VII.0 (Altiparmakov, 2010). At the same time, code-to-code comparisons in lattice physics modeling was performed between WIMS-AECL and the stochastic continuous energy neutron transport code MCNP (X-5 Monte Carlo Team, 2005).

The deterministic reactor physics calculations for PT-HWR cores were performed previously (Colton et al., 2017) using the 3D, two-group neutron diffusion code RFSP (Rouben, 2002), testing the various fuels previously investigated in lattice physics calculations. Using the data-processing program WIMS Utilities (Liang et al., 2008), the detailed 89-group WIMS-AECL lattice physics calculation data for the lattice cell models were spatially homogenized over the lattice cell, and collapsed to two-group structure, to create two-group macroscopic cross-sections as a function of burnup/irradiation which were then used subsequently in the 3D RFSP diffusion model of the PT-HWR reactor cores. The effects of leakage and online refuelling were modelled in RFSP, and the key physics parameters such as the full core-average burnup, refuelling rates, the maximum bundle and channel powers, and the power distributions were evaluated.

The purpose of this work is to perform comparisons of full-core reactor physics calculations between the deterministic toolset WIMS-AECL/WIMS Utilities/RFSP and the stochastic code MCNP to assess the relative accuracy of WIMS-AECL/WIMS Utilities/RFSP physics calculations for the core cases with uranium-based fuels augmented by small amounts of thorium, and thorium based fuels. Such comparisons can help to identify potential discrepancies and opportunities for improvement in both deterministic and stochastic modeling and they can also establish the potential magnitude of systematic or random errors. Thus, in the absence of experimental benchmark data for reactors operating with such fuels, the comparisons can help to establish greater confidence in the deterministic results obtained with WIMS-AECL/WIMS Utilities/RFSP.

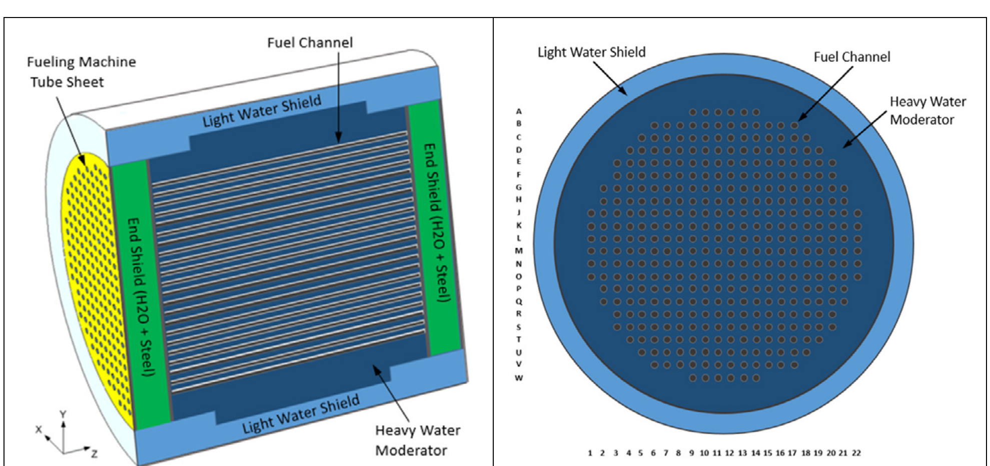
2. Description of fuels and core models

Several types of uranium-based fuels augmented by small amounts of thorium, thorium-based mixed-oxide fuels in PT-HWRs are analyzed. These fuels are considered to be used in a once-through thorium (OTT) fuel cycle in a conventional 380 channel, 700-MWe-class (PT-HWR), with one fuel type in the core (see Fig. 1).

The geometric specifications for the core model (calandria tank, fuel channel and end-shield dimensions) used in MCNP modeling are shown in Table 1. The bundle types are BUNDLE-37 (B37), with 37 fuel elements, and BUNDLE-35 (B35), with 35 fuel elements (and central graphite displacer rod). The two types of fuel bundle lattice are illustrated in Fig. 2. The geometric specification of the two fuel bundles can be found in Table 2. BUNDLE-37 is made up of four rings of fuel elements, while BUNDLE-35 has a large central graphite displacer rod and two rings of fuel. BUNDLE-35 is

Table 1
Calandria Tank (CT), Fuel Channel (FC) and End Shield (ES) Dimensions.

Description	Dimension (cm)	Description	Dimension (cm)
C-Tank – IR	379.7	CT IR/OR	6.47/6.60
C-Tank Small Cylinder IR	337.8	PT IR/OR	5.17/5.60
C-Tank Wall Thickness	2.85	End Shield (ES) Radius	340.7
Large Cylinder Length	409.36	ES Inner tubesheet thickness	8.0
Small Cylinder Length	92.5	ES Fuelling-machine tubesheet thickness	8.0
FC Lattice pitch	28.6	ES 60% steel + 40% H_2O region thickness	75.4



(a) PT-HWR 3D Cut-away View of Calandria Tank (b) Core Layout (the middle section) for PT-HWR

Fig. 1. Illustration of a Pressure Tube Heavy Water Reactor.