Annals of Nuclear Energy 85 (2015) 183–192

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Adjustment method of deterministic control rods worth computation based on measurements and auxiliary Monte Carlo runs

Guan-bo Wang *, Ji-min Ma, Shu Yuan, Run-dong Li, Da-zhi Qian

Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics (INPC), Mianyang 621900, China

ARTICLE INFO

Article history:
Received 24 February 2015
Received in revised form 4 May 2015
Accepted 5 May 2015

Keywords:
Control rods worth
WIMS/SN2
CITATION
JRR-3M
Engineering adjustment

ABSTRACT

The control rods (CRs) worth is key parameter for the research reactors (RRs) operation and utilization. Control rods worth computation is a challenge for the full deterministic calculation methodology, including the few group cross section generation, and the core analysis. The purpose of this work is to interpret our codes system, and their applicability of obtaining reliable CRs worth by some engineering adjustments. Cross sections collapsing in three energy groups is made by WIMS and SN2 codes, while the core analysis is performed by CITATION. We use these codes for the design, construction, and operation of our research reactor CMRR (China Mianyang Research Reactor). However, due to the intrinsic deficiency of the diffusion theory and homogenizing approximation, the directly obtained results, such as CRs worth and neutron flux distributions are not satisfactory. So two points of simple adjustments are made to generate the few group cross-sections with the assistance of measurements and auxiliary Monte Carlo runs. The first step is to adjust the fuel cross sections by changing properly the mass of a non-fissile material, such as the mass of the two 0.4 mm Cd wires existing at both sides of each uranium plate, so that the core model of CITATION can get good eigenvalue when all CRs are completely extracted. The second step is to revise the shim absorber cross section of CRs by adjusting the hafnium mass, so that the CITATION model can get correct critical rods position. In this manuscript, the JRR-3M (Japan Research Reactor No. 3 Modified) reactor is employed as a demonstration. Final revised results are validated with the stochastic simulation and experimental measurement values, including the critical rods position, the differential/integral CR curves, and the thermal neutron flux distributions.

1. Introduction

The control rods (CRs) provide a facile way for starting, shutting down, maintaining power level of the reactor. It is very important to predict the CRs worth numerically as precisely as possible. Although good neutron flux results can be obtained by improving homogeneous treatment (Varvayanni et al., 2009a,b), it is not an easy job to compute the CRs worth accurately with the deterministic method for the research reactor, such as JRR-3M (Japan), HFR (Netherland), GRR-1 (Greece), and CARR (China). This might be caused by the RR intrinsic features of very compact core structure and very uneven in-core neutron flux distribution, which challenge the validity of diffusion theory near CR absorber, and the accuracy of common homogenizing methods. From another aspect, the precision of CR worth can reflect the quality of the whole deterministic scheme.

A possible question might be: why do we study on the deterministic codes which are based on the diffusion theory for core analysis, since the Monte Carlo codes can provide very accurate results even for extremely complex geometries with continuous energy nuclear data. In fact, although modern nuclear reactor consist of absorbers with the dimensions of order of few neutron mean free paths, diffusion codes are still widely used for core neutronic analysis to make accurate prediction (Varvayanni et al., 2009b). Regarding the extremely fast execution, and the licensing purposes, we employ the deterministic way doing the RR analyses on refueling, coupling with heat transfer analyzing, and the measuring equipment revising.

The quality of diffusion core analysis strongly depends on the few-group neutronic parameters, which can be generated by deterministic or stochastic methods. Lattice codes, such as HELIO (Wemple et al., 2008), DRAGON (Marleau et al., 2012), NEWT (Chandler et al., 2011; DeHart, 2009), APOLLO2 (Sanchez et al., 1988), CASMO-5, XSDRN (Greene and Petrie, 2000) and WIMS (Halsall and Tauman, 1997) are the deterministic ones. Recent developments of such codes have made them convenient to model

* Corresponding author.
E-mail address: wgb04dep@hotmail.com (G.-b. Wang).

http://dx.doi.org/10.1016/j.anucene.2015.05.005
0306-4549/

two-dimensional geometry or even 3-D super cell, with discrete-ordinates, collision probability or MOC solver. While for the stochastic collapsing way, lots of researches also have been performed, such as the two doctoral thesis (Redmond, 1997; Zhang, 2012), MC21 improvements (Herman et al., 2013), and the Serpent study (Fridman et al., 2013; Rachamin et al., 2013).

In INPC, lots of efforts have been made for years to establish, validate, revise, and use our neutronics codes system and reactor models. The pin-cell code WIMS-D5b (Halsall and Tauman, 1997) and the home-made 2-D assembly code SN2 are used to perform the homogenizing and collapsing work. Then the 3-D diffusion code CITATION is used for the core analysis with 3-group macro cross sections, with the assistance of an interface code we developed for burn-up calculation, moving rods, refueling, and changing core configuration by transposing fuel assemblies. Besides, the continuous energy MCNP models are important parts for cell level and core level as reference. These codes and models has been used to accomplish the design, construction and operation of our reactor CMRR.

However, the original approximations are not satisfactory when to get CRs worth curve for CMRR, and even unsatisfactory when applied on the JRR-3M rector. From the perspective of generating collapsed cross sections, our tools WIMS/SN2 cannot describe the geometry of fuel elements exactly with the 0.4 mm Cd wires. From the perspective of core analysis, the diffusion theory has limitations or even mistake near the shim absorber in CRs, where serious discontinuities cannot be accurately analyzed by the diffusion theory.

In this work, a procedure is selected to improve to deterministic calculation results by measured control rods worth and auxiliary Monte Carlo, since the CRs worth is easy to measure experimentally. Such adjustment method is easy to handle in practice, reasonable in physics, and valid in results. In Section 2, the JRR-3M and its experimental measuring methods of control rods worth and thermal neutron flux are briefly presented, collected from the JAERI report (Tokai et al., 2000). In Section 3, our calculation codes and models are presented in detail, including the WIMS/SN2 tool for cell calculation, CITATION model for core analysis, and MCNP models for validation. The adjusting methods are described in detail in Section 4. The final results of the rod worth and thermal neutron flux distributions are compared with the stochastic simulation and experimental values.

2. Core description

2.1. JRR-3M core

JRR-3M is a light water moderated and cooled, beryllium and heavy water reflected pool type research reactor, operating at the maximum power of 20 MW, located at Japan Atomic Energy Research Institute (JAERI) for the purpose of beam experiments, irradiation tests and activation analysis. The simplified horizontal cross-section view of core is represented in Fig. 1(left). The core contains 26 standard fuel elements, 6 control rods elements, and 12 pieces of beryllium reflectors. The fuel elements and control rods structure are illustrated in Fig. 2. Each control rod contains a follower fuel part and a hafnium absorber part. The control rods are classified into 3 groups according to their operation mode, the R rods, the S rods and the SA rods (see Figs. 1 and 3). In 1999, JRR-3M has finished the conversion work from using U-Al$_x$ fuel to U_3Si_2-Al fuel to achieve higher uranium loading, about 14 kg U-235, and higher maximum burn-up. Some important parameters used in this manuscript are listed in Table 1.

2.2. Experimental measurements

The control rods (CR) worth of JRR-3M was measured at JAERI by inverse kinetics method (IK method) when it first became critical with silicide fuel in 1999. IK method is a classical method. The reactivity meter assesses the reactivity at time t by the following formula:

$$\rho(t) = \beta_{eff} + \Lambda \frac{dn/dt}{n} - \frac{\beta_{eff}}{n} \sum_{i=1,6} \alpha_i \cdot \left[n_0 \cdot e^{-\lambda_i t} + \lambda_i \cdot \int_0^t n(\tau) \cdot e^{-\lambda_i (t-\tau)} d\tau \right] - \frac{S \cdot \Lambda}{n}$$

where ρ is the reactivity, n is the neutron number at time t, n_0 is the neutron number at time 0 (the initial steady state), β_{eff} is the effective delayed neutron fraction, α_i is the ratio of delayed neutron fraction of group i that is $\alpha_i = \beta_i/\beta_{eff}$, λ_i is the decay constant of the ith group of delayed neutron precursor, Λ is the effective neutron generation time, and S is the external neutron source intensity. Among all these quantities, β_{eff}, α_i, λ_i, Λ are pre-given in the reactivity meter. While the n is expressed as the neutron detector's signal amplitude.

To measure the CR worth of one rod, taking R1 for example, the initial state is that, the tested rod R1 is completely inserted at the bottom of height 0 cm, the compensating rod R2 is completely withdrawn at the top of height 80 cm. The other four rods, S1 S2 SA1 SA2, are all withdrawn to the height of about 20 cm above the bottom to make the reactor critical and maintain the power at a certain level. At the second stage, R1 rod is raised for a short distance to lead into a positive reactivity of about 0.03%$\Delta k/k$, which brings the power up. Wait until the power raise to 6 times of initial value, then insert R2 to bring the power back to initial. All other 4 rods remain at the fixed position during the whole procedure. Fig. 3 illustrates this process of measuring R1 rod worth.

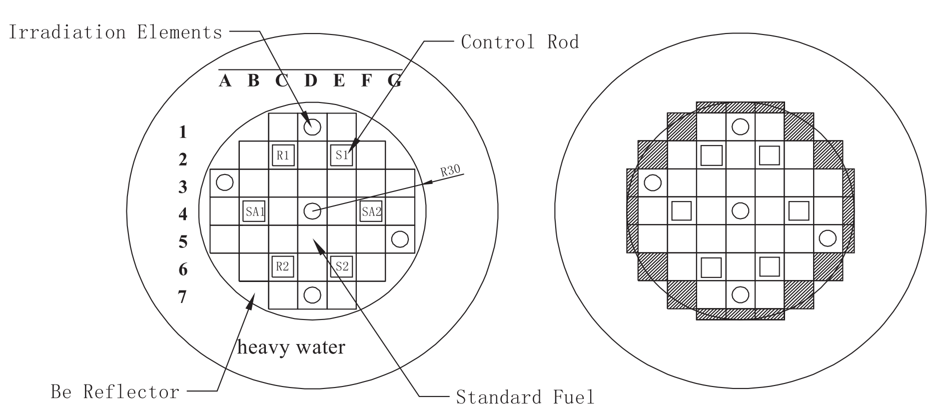

Fig. 1. Horizontal cross-section view of JRR-3M core (left) and the approximate model for CITATION calculation (right).