Nuclear Engineering and Technology 50 (2018) 1024–1036

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

Criticality benchmark of McCARD Monte Carlo code for light-water-reactor fuel in transportation and storage packages

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ARTICLE INFO

Article history:
Received 27 February 2018
Received in revised form
14 May 2018
Accepted 29 May 2018
Available online 31 May 2018

Keywords:
McCARD
LWR benchmark

ABSTRACT

In this paper, McCARD code was verified using various models listed in the NUREG/CR-6361 benchmark guide, which provides specifications for single pin-cells, single assemblies, and the whole core classified depending on the nuclear properties and structural characteristics. McCARD code was verified by comparing its results with those of SCALE code for single pin-cell and single assembly benchmark problems. The difference in the multiplication factor obtained through the two codes did not exceed 90 pcm. The benchmark guide treats a total of 173 whole core experiments. The experiments are categorized as simple lattices, separator plates, reflecting walls, reflecting walls and separator plates, burnable absorber fuel rods, water holes, poison rods, and borated moderator. As a result of numerical simulation using McCARD, the mean value of the multiplication factors is 1.00223 and the standard deviation of the multiplication factors is 285 pcm. The difference between the multiplication factors and the experimental value is in the range of -665 pcm to + 1609 pcm. In addition, statistics of results for experiments categorized by reactor shape, additional structure, burnable poison, etc., are detailed in the main text.

1. Introduction

McCARD is neutron and photon transport simulation code developed at Seoul National University (SNU) for nuclear reactor design. The code simulates the behavior of photons induced by neutrons and neutrons using the MC method. It is therefore useful to estimate reactor design parameters such as effective multiplication factor (k_{eff}), fission power and neutron flux [1].

The Monte Carlo (MC) code was developed to simulate the behavior of neutrons in a reactor using a computerized method. Before performing calculations using Monte Carlo codes, verification and validation (V&V) is very important in terms of reliability of the calculational results. Therefore, V&V of McCARD code have been performed using various types of nuclear reactors such as PWRs, CANDUs, VHTRs, and various research reactors [2–5].

The NUREG/CR-6361 criticality benchmark guide treats the light water reactor (LWR) type transportation and storage packages. The benchmark provides specifications of 173 fuel lattice models with materials, core geometries and key-parameter information. The experiments are categorized as simple lattices, separator plates, reflecting walls, reflecting walls and separator plates, burnable absorber fuel rods, water holes, poison rods, and borated moderator [6]. In addition, the benchmark provides input information and calculational results based on KENO V.a, one of the SCALE packages developed by Oak Ridge National Laboratory (ORNL) [7].

In this work, McCARD code was verified against single pin-cell and single assembly benchmark problems by comparing the results of McCARD code and those of SCALE-6.2.1 code and then McCARD code was validated against the LWR-type criticality benchmark experiments provided in reference 6. All the McCARD and SCALE simulations were performed with ENDF-B VII.0 cross-section library.

2. Verification of McCARD code against single pin-cell and single assembly benchmark problems

The NUREG/CR-6361 document provides a total of 173 LWR-type critical core configurations for criticality experiment benchmark. Before validation of McCARD code against these experiment benchmark, McCARD code was verified against single pin-cell problems and single assembly benchmark problems derived from the criticality experiment benchmark problems.

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https://doi.org/10.1016/j.net.2018.05.010
1738-5733/

2.1. Verification of McCARD code against single pin problems

Fig. 1 illustrates the layout of the six fuel pins used in the NUREG/CR-6361 benchmark guide and Table 1 summarizes the fuel design parameters: pellet and outside diameter, total fuel length, enrichment of ^{235}U, and fuel density. Aluminum, 304-stainless steel and zircaloy-4 were used as the cladding material and the outside diameter including the cladding thickness ranges from a minimum of 0.94 cm to a maximum of 1.4 cm. In addition, the enrichment values are between 2.35wt% and 5.74wt% [6].

Six pin-cell benchmark problems were defined based on the fuel pin cells shown in Fig. 1. Each single pin-cell benchmark problem is defined by assuming that each type of fuel pin is located at the center of square lattice cell filled with light water. A reflective boundary condition was imposed for radial directions and a vacuum boundary condition was imposed at the top and the bottom of the fuel pin. As shown in Fig. 1, there is a free space and 6.9-cm-long spring above the fuel pellet to accommodate the fission gases and fuel pellet expansion. However, this spring was omitted in code modeling and the space was just filled with helium gas. For McCARD criticality calculation, 20 inactive cycles and 300 active cycles were used with 100,000 histories per cycle. For SCALE calculation, 300 generations were used with 100,000 neutrons per generation and 20 generations were skipped.

Table 2 compares the multiplication factors obtained by performing calculations for the six pin-cell benchmark problems using McCARD and SCALE codes. Standard deviations are expressed as σ_M and σ_S for McCARD and SCALE, respectively. The last two columns of Table 2 show the difference of the k values of the two codes and the standard deviation. The difference of the k value is larger than 2σ in four cases out of six and larger than 3σ in three cases out of six, which means the two codes give different results in statistical point of view. However, the maximum difference is less than 90 pcm and the results of the two codes are comparable in practical point of view.

2.2. Verification of McCARD code against single assembly problems

Various fuel assemblies depending on the uranium enrichment, the number of fuel rods, presence of burnable poison, the structure of support grid are described in the NUREG/CR-6361 benchmark guide. The six fuel assemblies listed in Table 3 were chosen as fuel assembly benchmark problems for McCARD verification.

Fig. 2 illustrates simple fuel assembly in the BAW-1484 experiment given in the benchmark. The fuel assembly consists of 192 fuel rods and 4 support rods at the corners in a 14 × 14 lattice structure with a pin pitch of 1.636 cm. The support grid is an aluminum rod with a diameter of 1.27 cm. The space between the fuel rods is filled with light water moderator with soluble boron concentration of 72.0 ppm up to 151.69 cm from the bottom of the fuel assembly. One of the unique features of the fuel assembly is the separate plate that surrounds the outside of the assembly. It is made of 0.1 wt% borated aluminum and the thickness is 0.645 cm. There is a gap of 0.3725 cm between the plate and the fuel assembly. The separator is generally used in transportation packages to prevent nuclear reactions between spent fuel assemblies [6].

Fig. 3 shows the fuel assembly that is one of the components of the BAW-1810 experiment. It has a total of 231 fuel pins, 17 water holes and 8 UO_2-Gd_2O_3 rods in a 16 × 16 lattice structure. In the original LWR fuel assembly, there are guide tubes in the water hole positions. However, they were neglected in BAW-1810 fuel assembly model for this analysis [6].

Just like in the fuel pin benchmark problems, a reflective boundary condition was imposed for radial directions and a vacuum boundary condition was imposed at the top and the bottom of the fuel assembly. For McCARD criticality calculation, 20 inactive cycles and 300 active cycles were used with 100,000 histories per cycle. For SCALE calculation, 300 generations were used with 100,000 neutrons per generation and 20 generations were skipped. Table 4 provides the comparison of multiplication factors for the fuel assemblies obtained using McCARD and SCALE code. The differences in multiplication factor are between -44 pcm and +74 pcm, which is comparable.

3. Validation of McCARD code against whole core experiments

The NUREG/CR-6361 benchmark guide provides information on a total of 173 LWR type whole core benchmark experiments and their main parameters are summarized in Table 5. The experiments are categorized as simple lattices, separator plates, reflecting walls, reflecting walls and separator plates, burnable absorber fuel rods, water holes, poison rods, and borated moderator [6]. The experiments in each category have been selected to demonstrate the ability of predicting the multiplication factor of the experiments in the condition given for each category. For example, Fig. 4 shows BAW-1231 experiments (Case No. 12–13), which is used to test the ability of predicting the multiplication factors of systems with borated water moderator. The experiments consist of large arrays of fuel rods moderated by borated water [8]. Fig. 5 shows BAW-1810 experiments (Case No. 31–40), which is used to test the ability of predicting the multiplication factors of experiments simulating

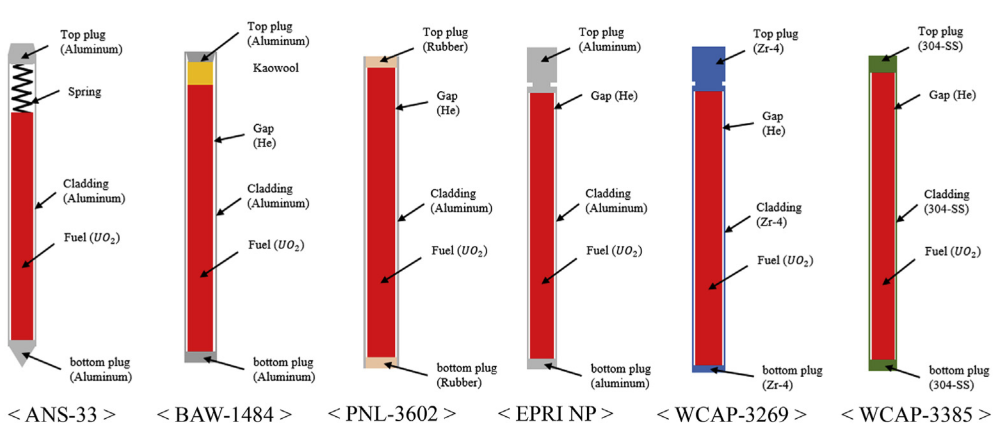

Fig. 1. Configurations of fuel pins.