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Investigation of the Power Coefficient of Reactivity of 3D CANDU Reactor through Detailed Monte Carlo Analysis

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1. Introduction

In the CANDU-6 (CANADA Deuterium Uranium) reactor, heavy water (D_2O) is used as coolant and a bulky heavy water is also used as moderator to obtain a highly thermalized neutron spectrum. The heat is removed by the heavy water coolant completely separated from stationary moderator. Due to the good neutron economy of the CANDU reactor, natural uranium fuel is used without enrichment. Because of the unique core configuration characteristic, there is less resonance absorption of neutron in fuel which leads to a relatively small fuel temperature coefficient (FTC). The value of FTC can even be positive due to the ^{239}Pu buildup during the fuel depletion and also the neutron up-scattering by the oxygen atoms in the fuel. Unlike the pressurized light water reactor, it is well known that CANDU-6 has a positive coolant void reactivity (CVR) and coolant temperature coefficient (CTC). As a result the power coefficient of reactivity (PCR) is known to be slightly positive during full power operation [1].

To improve the inherent stability and the generic safety features of the reactor, a negative PCR is essential. Due to the small value of the FTC and PCR of CANDU, high-fidelity physics approaches are necessary for the precise estimation of the safety parameters. In a traditional reactor analysis, the asymptotic scattering kernel has been used and neglects the thermal motion of nuclides such as U-238. However, it is well accepted that in a scattering reaction, the thermal movement of the target can affect the scattering reaction in the vicinity of scattering resonance and enhance neutron capture by the capture resonance. Some recent works have revealed that the thermal motion of U-238 affects the scattering reaction and that the resulting Doppler broadening of the scattering resonance enhances the FTC of the thermal reactor including PWRs by 10- 15% [2].

In order to observe the impacts of the Doppler broadening of the scattering resonances on the criticality and FTC, a recent investigation [3] was done for a clean and fresh CANDU fuel lattice using Monte Carlo code MCNPX [4] for analysis. In ref. 3 the so-called DBRC (Doppler Broadened Rejection Correction) method [5, 6] was adopted to consider the thermal movement of U-238.

In this study, the safety parameter of CANDU-6 is re-evaluated by using the continuous energy Monte Carlo code SERPENT 2 [7] which uses the DBRC method to simulate the thermal motion of U-238. The analysis is performed for a full 3-D CANDU-6 core and the PCR is evaluated near equilibrium burnup. For a high-fidelity Monte Carlo calculation, an extremely large number of neutron histories are used in this investigation.

2. 3D CANDU Model Problem

In order to characterize the generic safety parameters of the CANDU-6 reactor, the 3D full core is modelled. The rated power of the CANDU-6 is 2061.4 MW. There are 380 fuel channels and each channel contains 12 fuel bundles. Currently, a standard fuel bundle consists of 37 fuel rods. The fuel bundles are loaded into a pressure tube and a calandria tube surrounds the pressure tube that separates the coolant from moderator. The design data of the CANDU-6 core and fuel are given in Tables I and II.

Table I. Design data of CANDU-6 core.

Number of fuel channels	380
Lattice pitch	28.575 cm (square)
Inner radius of calandria	379.7 cm
Length of fuel channels	594.4 cm
Reactor core radius	314.3 cm
Reflector thickness	65.6 cm
Number of adjuster rods	21
Number of light water control zone units	6
Number of mechanical control absorbers	4
Number of shutoff rods	28
Number of liquid poison injection nozzles	6
Total fission power	2158.5 MW
Total reactor power	2061.4 MW
Total electric power	378.8 MW(e)

Table II. Design data of CANDU-6 fuel

Fuel pin	
- Number of pin	37
- Fuel pin radius	0.608 cm
- Cladding radius	0.648 cm
Pressure tube	
- Inner radius	5.179 cm
- Outer radius	5.163 cm
Calandria tube	
- Inner radius	6.450 cm
- Outer radius	6.590 cm
Fuel density	10.492 gr/cc
Clad density	6.520 gr/cc
Pressure tube density	6.515 gr/cc
Coolant D_2O purity	99.10 wt%
Moderator D_2O	99.85 wt%

In this calculation the core is divided into 14 zones corresponding to the 14 liquid zone control (LZC), as shown in Fig.1.

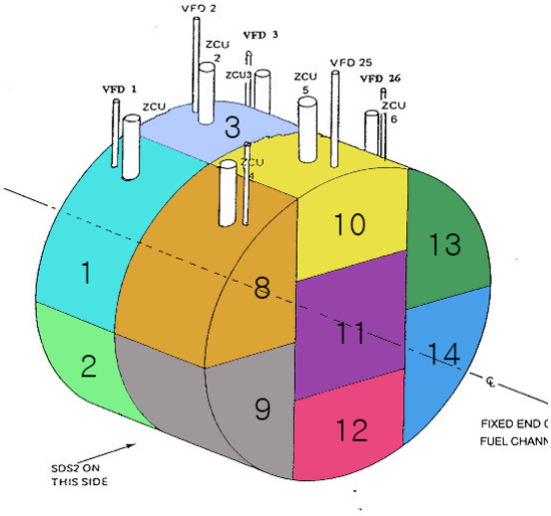

Figure 1. 14 LZC of CANDU-6 core.

The equilibrium CANDU-6 core can be modelled by using the zone average burnup fuel compositions, fuel and coolant properties. A CANDU-6 bundle has been depleted with SERPENT 2 up to the corresponding zone average burnup to obtain the zone average fuel composition. The coolant temperature and density distribution and also the fuel power distribution are determined by the NUCIRC [8] and RFSP [9] code respectively. From the coolant temperature and the fuel bundle power distribution the bundle average fuel temperature can be determined by using the following equation [9].

$$T_{fuel} = T_{coolant} + A \times P_{bundle} + B \times P_{bundle}^2 \qquad (1)$$

where, T_{fuel} is the bundle average temperature, $T_{coolant}$ is the coolant temperature, P_{bundle} is the bundle power, and A, B are the burnup dependent coefficients.

3. Numerical Results and Discussion

The PCR of CANDU-6 reactor can be well estimated by using a lattice model if the coolant and fuel properties are properly determined. Previously, it was clearly shown that the PCR value becomes less positive, or even negative, when the DBRC option is applied [10, 11, 12]. In this paper, the study was extended into 3D CANDU-6 core simulation including the reactivity control devices by using the Monte Carlo method.

The safety parameters of CANDU-6 strongly depend on the burnup since the fuel composition changes significantly with the burnup. Particularly, Pu-239 rapidly builds up with burnup and it affects the safety parameters of the CANDU-6 core. A wide range of power level from 65% to 115% was considered to evaluate the PCR. The ENDF/B-VII.0 library was used in this Monte Carlo calculation. The PCR is directly approximated by using a linear interpolation of the calculated discrete reactivity at the seven power levels. Since magnitude of the PCR is very low, the estimated PCR is quite sensitive to the statistical uncertainty of the Monte Carlo results, the calculated results should be very precise. Though it is very time consuming and requires costly computation facilities, the standard deviation of k-effective values for PCR evaluation should be less than 1 pcm. In this calculation, 5000 cycles with 500 inactive cycles and 3,000,000 particles per cycles have been considered to reduce the standard deviation of k-effective. The estimated standard deviation of k-effective is found ~1.1 pcm in this evaluation. The calculated results are depicted in Fig. 2.

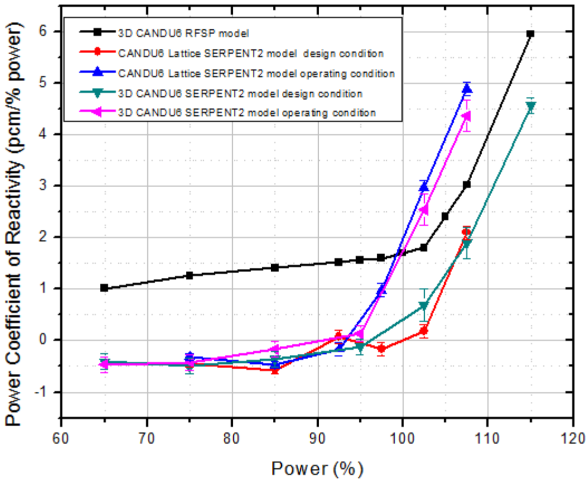

Figure 2. PCR as a function of power level.

The 3D RFSP code result [13] have been presented in the Fig. 2 as a reference. Two-D CANDU-6 lattice results also included in Fig. 2 to compare with the 3D CANDU-6 results. It is observed that both lattice and 3D results are quite similar with the uncertainty limit. It is clearly noted that PCR values of the Monte Carlo analysis are much less positive than the reference. The RFSP results are not very accurate because of rather old cross section library and also the thermal motion of the U-235 is not considered. This less positive or more negative PCR is achieved due to the consideration of DBRC scheme applied in the SERPENT2 code and the latest nuclear data. This is mainly due to the enhanced Doppler effect of U-238, i.e. the enhanced fuel temperature coefficient due to the DBRC method. At low power, PCR for both design and operating condition are very similar within their uncertainty limit. It is worthwhile to note that after 75% power, operating condition PCR go faster than that of design condition. At 95% power condition PCR is slightly positive whereas the design condition PCR is still slightly negative. The impact of the elevated inlet coolant temperature on the PCR is clearly observed after 95% power. The rapid upsurges of PCR is due to the coolant outlet temperature which is quite close to the saturation temperature at full power condition and also due to the sub cooled boiling at the exit region of high power channels. In our 3D model, we consider two zones axially which deviates our model from the actual state. It is necessary to consider more zones axially and determine a more reliable quasi equilibrium CANDU-6 core for better results.

4. Conclusions

A detailed 3D CANDU-6 core has been modelled to re-evaluate the power coefficient of reactivity (PCR). The continuous-energy Monte Carlo code SERPENT2 code has been used to take into account the impact of the Doppler broadened elastic scattering resonance on the fuel temperature coefficient and the PCR. For the PCR evaluation as a function of power level, two inlet temperatures (design and operating conditions) were considered for a wide range of reactor power, 60 ~ 120% power. From the current study, the PCR is found to be slightly negative up to 90% power level for both operating and design condition, the PCR is found to be slightly negative up to ~95% in the design condition. However, the PCR value begins to quickly increase if the power level exceed 90% or 95% due to the enhanced coolant boiling. The current results clearly indicates that the standard core design tools for CANDU should be improved for more accurate evaluation of physics parameters. For a validation of the current study, the analysis results need to be compared with measured PCR values of CANDU-6.

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