Impacts of U-238 Thermal Movement on Safety Parameters of CANDU-6

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1. Introduction

It is well known that the coolant void reactivity of CANDU-6 is positive for operational conditions and the coolant temperature coefficient (CTC) is also positive. The positive coolant void reactivity is a long-standing safety concern of CANDU-6. In addition, due to the unique arrangement of the fuel and moderator and the resulting very soft neutron spectrum, the fuel temperature coefficient (FTC) is known to be quite small for CANDU-6. As a result, the power coefficient of reactivity (PCR) is traditionally known to be very close to zero for the full power condition [1].

In this study, the safety parameters (FTC and PCR) of CANDU-6 reactor are re-evaluated by using continuous-energy Monte Carlo code MCNPX [2]. In most deterministic and stochastic codes, the scattering kernel is based on an unphysical assumption that the target is at rest. In MCNPX, the problem was solved by implementing the so-called Doppler-broadened rejection correction (DBRC) [3] scheme. It was reported that the fuel Doppler effect is noticeably enhanced by accounting for the target motion [4,5]. A modified MCNPX, called MCNPX-DBRC, is used in this work to analyze the FTC and PCR of a standard CANDU-6 fuel lattice for several burnup conditions including near-equilibrium burnups. In order to maximize reliability of the results, the Monte Carlo calculations are performed such that standard deviation of k-inf should be only 0.6~1 pcm.

2. Doppler Broadened Rejection Correction[3,4]

The DBRC method has been developed to account for the thermal motion of target nuclei in the neutron scattering reaction. It is a statistical approach which is based on the use of a complementary rejection technique in the MCNPX code. In this method, a modification of the probability density function to sample the target velocity and scattering angle is necessary. With the corrected probability density function, MCNPX is able to include the effect of the energy dependence of the cross sections on the scattering kernel.

The corrected probability function can be written as:

$$P(V,\mu_t) \to a) \left\{\frac{\sigma_s(E_r,0)}{\sigma_s^{max}(E_\xi,0)}\right\} \; b) \left\{\frac{v_r}{v+V}\right\}$$

$$c) \left\{\frac{2\beta^4 V^3 e^{-\beta^2 V^3} + (\beta v\sqrt{\pi}/2)(4\beta^3/\sqrt{\pi})V^2 e^{-\beta^2 V^3}}{1+\beta v\sqrt{\pi}/2}\right\} \quad (1)$$

where v is the neutron speed, V is the speed of the target and neutron speed v_r is relative velocity to the target at rest.

The brackets a) and b) represent the two constraints in the chosen value of V and μ_t. The ratio of $\frac{v_r}{v+V}$ cannot exceed unity and a rejection technique is applied in MCNPX. If a random number between 0 and 1 is less than $\frac{v_r}{v+V}$, the choice of the target velocity V and μ_t (which defines v_r) is accepted. The choice of the target velocity V is performed by sampling a specific velocity for the target nucleus out of a Maxwell-Boltzmann distribution. The term in a) expressed by the ratio of two cross sections is always below unity and it is the missing term added. This term introduces correctly the Doppler broadening of the scattering kernel.

3. CANDU Model Problem

A standard CANDU fuel lattice is modeled and analyzed in this work in order to characterize the generic safety parameters of CANDU-6. As shown in Fig. 1, the standard fuel bundle consists of 37 fuel rods. The fuel bundle is loaded into a pressure tube and a Calandria tube surrounds the pressure tube that physically separates the moderator from the coolant. Heavy water is used for both coolant and moderator. The fuel lattice pitch is 28.575 cm and average linear power is about 12.94 kW/cm.

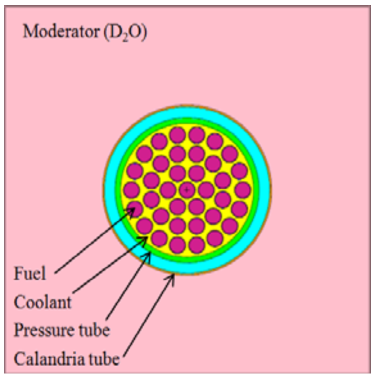

Fig. 1. The standard CANDU fuel lattice

4. Results and Discussion

The CANDU-6 fuel lattice was depleted up to 230 days corresponding to 7.5 GWd/tU. To determine continuous FTC, the calculated k-inf values are fitted into a continuous function and FTC is calculated as the derivative of the resulting fitting function. First, the infinite multiplication factor is fitted into the following equation:

$$k_\infty = a + bT_f^{1/2} + cT_f \,, \quad (1)$$

where T_f is the fuel temperature. The constants *a*, *b*, and *c* are determined by using the least-square method. Then, continuous FTC can be obtained by taking derivative of Eq. (1).

Figure 2 shows the results for ENDF/B-VI.8 and ENDF/B-VII.0. One can see that the new FTC from MCNPX-DBRC is clearly more negative than those obtained with the original MCNPX code. Figure 3 shows the burnup-dependent FTC of CANDU-6. FTC is strongly negative for fresh fuel and it increases with burnup and finally becomes positive at discharge burnup at the full power condition (T_{fuel}=960 K)

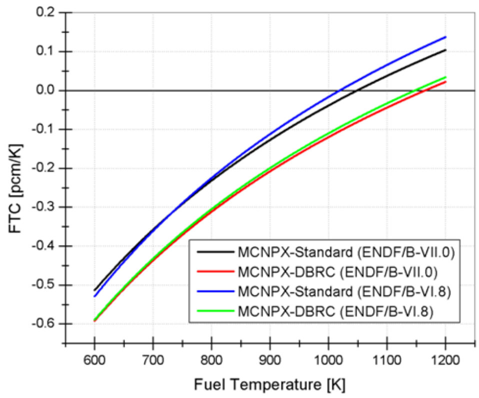

Fig. 2. FTC calculated using ENDF/B-VI.8 and ENDF/B-VII.0 libraries.

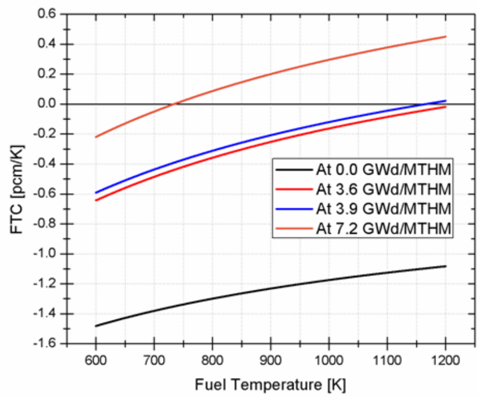

Fig. 3. FTC at several burnups (ENDF/B-VII).

The PCR of CANDU-6 reactor can be well estimated by using a lattice model if the coolant and fuel properties are appropriately determined [1]. For the PCR evaluation, seven power levels are considered: 65%, 75%, 85%, 95%, 100%, 105%, and 110%. The results are provided for 3.6 GWD/tU and 3.9 GWD/tU in Fig. 4. It is clearly observed that the PCR value becomes less positive or more negative when the DBRC module is applied. This is mainly because of the enhanced Doppler effect of U-238. It is worthwhile to note that PCR increases with power level and it quickly increases when the power is above about 105%. The sudden increase of PCR is due to local coolant boiling in the exit of the coolant channel of CANDU-6. At 3.6 GWD/tU, the PCR is very close to zero at the full power condition with the DBRC scheme while it is likely to be positive in the standard calculation.

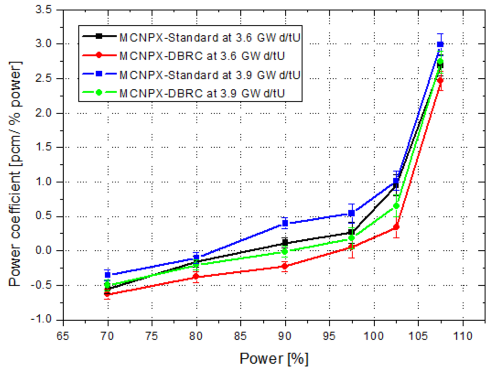

Fig. 4. PCR at 3.6 GWD/tU and 3.9 GWD/t.

5. Conclusions

At the fresh condition, the FTC of CANDU-6 reactor is clearly negative and it becomes less negative with burnup and is clearly positive at the discharge burnup of ~7,200 MWD/tU. The FTC can be noticeably enhanced by accounting for the thermal motion of U-238 in the elastic scattering reactions. At the mid-burnup condition (~3.6 GWD/tU), the FTC turns out to be clearly negative. Consequently, the resulting power coefficient is also improved if the scattering resonance Doppler broadening is correctly considered. The relatively simple lattice model analysis predicts that PCR at 100% power condition is close to zero. For a more concrete conclusion, a full 3-dimensional core thermo-hydraulic -coupled neutronic analysis should be performed.

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