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Comparative Evaluation of Fuel Temperature Coefficient of Standard and CANFLEX Fuels in CANDU 6

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1. Introduction

The fuel temperature reactivity coefficient (FTC) of CANDU-6 has become a concerning issue. The FTC was found to be slightly positive for the operating condition of CANDU-6. Since CANDU-6 has unique fuel arrangement and very soft neutron spectrum, its Doppler reactivity feedback of U-238 is rather weak. The upscattering by oxygen in fuel and Pu-239 buildup with fuel depletion are responsible for the positive FTC value at high temperature.[1]

In this study, FTC of both standard CANDU and CANFLEX fuel lattice are re-evaluated. A Monte Carlo code Serpent2 [2] was chosen as the analysis tool because of its high calculational speed and it can account for the thermal motion of heavy nuclides in fuel by using the Doppler Broadening Rejection Correction (DBRC) method. It was reported that the fuel Doppler effect is noticeably enhanced by accounting the target thermal motion [3]. Recently, it was found that the FTC of the CANDU-6 standard fuel is noticeably enhanced by the DBRC.[4]

2. Doppler Broadening Rejection Correction

When dealing with neutron scattering in most of the well-known codes, the temperature of the interacting heavy nuclide is set arbitrarily to zero. This leads to inconsistency between the loss and production terms of the very basic transport equation [5]. The DBRC method is proposed to deal with this problem. It is a statistical approach which is based on the use of a complementary rejection technique [5]. In this method, a modification of the probability density function is necessary. The probability function is used by Serpent2 to simulate the target velocity $V$and the angle between neutron and target μ_t .With the corrected probability density function, Serpent2 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:

$$P(V,\mu_t) \rightarrow a)\ \left\{\frac{\sigma_s(E_r,0)}{\sigma_s^{max}(E_{\xi},0)}\right\}\ b)\ \left\{\frac{v_r}{v+V}\right\}$$
$$c)\ \left\{\frac{2\beta^4V^3e^{-\beta^2V^3}+(\beta v\sqrt{\pi}/2)(4\beta^3/\sqrt{\pi})V^2e^{-\beta^2V^3}}{1+\beta v\sqrt{\pi}/2}\right\} \quad (1)$$

where $\beta = \left(\frac{A_m}{2k_BT}\right)^{1/2}$, 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 in the bracket c). The ratio of $\frac{v_r}{v+V}$ cannot exceed unity and a rejection technique is applied in Serpent2. 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].

3. CANDU Model Problems

The standard CANDU fuel lattice and CANFLEX fuel lattice are modeled and analyzed in this work. As shown in Fig. 1, the standard CANDU fuel bundle consists of 37 uniform fuel pins (left), while CANFLEX fuel bundle has 43 fuel pins with two different radii (right). Both fuel bundles are 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 in CANDU-6.

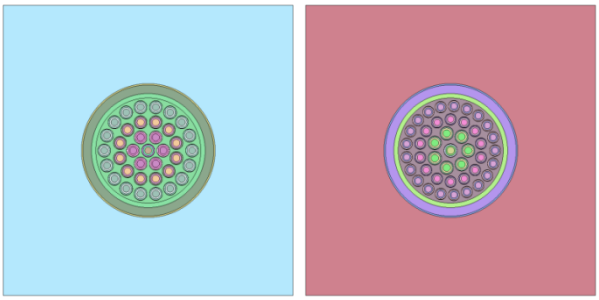

Figure 1. The standard CANDU 37 pin fuel lattice (left) and CANFLEX 43 pin fuel lattice (right)

The coolant temperature and density for equilibrium core of both fuel lattice models were obtained from NUCIRC code calculation result. The fuel temperatures are calculated with fuel bundle power by using correlation equation:

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

where T_{fuel} is fuel temperature, $T_{coolant}$ is coolant temperature, P_{bundle} is bundle power, and (A, B) are burnup dependent constants.

And the ring-wise fuel temperatures are simply obtained by normalization [6]. The temperatures used in this analysis are shown in Table II.

Table I. Fuel and coolant temperature of standard fuel and CANFLEX fuel lattice

	Standard fuel (K)	CANFLEX (K)
1st ring fuel	830.51	871.45
2nd ring fuel	844.18	889.21
3rd ring fuel	884.66	834.17
4th ring fuel	975.20	898.80
fuel average	920.68	875.57
coolant	562.98	561.83

4. Results and Discussion

The CANDU fuel lattice depletion was performed up to 3.6 GWd/tU for both standard fuel and CANFLEX fuel by using the Serpent2 code based on the ENDF/B-VII library. The fuel isotope composition at mid-burnup (3.6 GWd/tU) was used to describe the equilibrium core.

To determine continuous FTC, the k-inf value calculated at five fuel temperatures were fitted into a continuous function:

$$k_\infty = a + bT_f^{1/2} + dT_f , \quad (3)$$

and FTC is calculated as the derivative of the resulting fitting function:

$$\frac{\partial \rho_\infty}{\partial T_f} = \frac{1}{k_\infty^2}\frac{\partial k_\infty}{\partial T_f} \quad (4)$$

Figure 2 shows that the calculated data can be well fitted into the function. The standard deviation of the k-inf values is about 2 pcm in this work. It is noted that CANFLEX and standard CANDU fuels show similar trend of the k-inf values, while CANFLEX always has a smaller multiplication factor than the standard fuel. Also, the DBRC implementation results in a slightly smaller multiplication factor and the effect becomes stronger as the fuel temperature increases.

Figure 3 compares the FTC values of the two types of CANDU fuel bundles. By implementing DBRC scheme, the FTC value decreases more effectively at higher temperature, resulting in a decrease of about 0.15 pcm/K at 1200 K. Meanwhile, one can also note that the effect of CANFLEX is not significant for the same temperature. The average fuel temperature of CANFLEX is about 876 K, while it is about 921 K for the standard fuel. However, the effective fuel temperature for the standard one was calculated to be 960 K. Taking into account the average fuel temperature of the two fuel designs, it is clear that CANFLEX provides a slightly more negative FTC.

5. Conclusions

The fuel temperature coefficient of two types of CANDU fuel lattices has been evaluated by using a Monte Carlo code, Serpent2. Regardless of the DBRC implementation, CANFLEX fuel lattice shows a more negative fuel temperature coefficient than standard fuel lattice. To assess the full advantages of CANFLEX, other safety parameters such as PCR (power coefficient of reactivity) need to be evaluated.

Table II. FTC value at average fuel temperature.

	with DBRC	without DBRC
Standard 37 (T_{avg}=960K)	-0.303 pcm/K	-0.202 pcm/K
CANFLEX 43 (T_{avg}=878K)	-0.384 pcm/K	-0.310 pcm/K

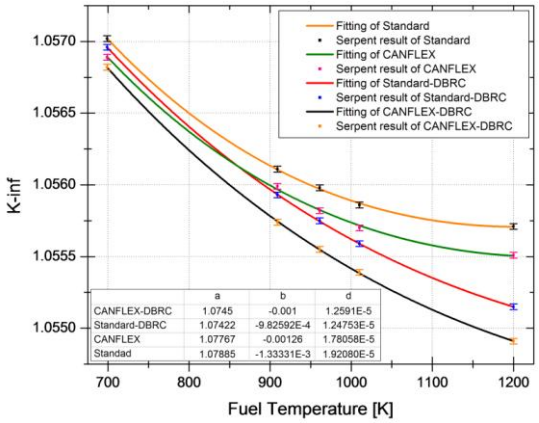

Figure 2. The multiplication factor vs. fuel temperature

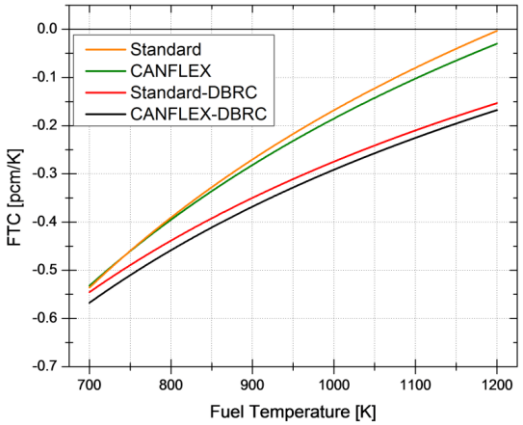

Figure 3. FTC of CANFLEX fuel lattice by Serpent2

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