SENSITIVITY ANALYSIS FOR NEUTRON PARAMETERS AFFECTED BY TECHNOLOGICAL TOLERANCES IN TYPICAL CANDU CELLS

ANA-MARIA SEGARCEANU and MARIN CONSTANTIN

Institute for Nuclear Research (RATEN ICN) Pitesti, Romania
e-mail: ana.segarceanu@nuclear.ro

Abstract

The numerical simulation of different phenomena plays an important role in nuclear science and engineering. The confidence in the final results is dependent on the accuracy of input data, quality of modelling, and user experience. The present paper is devoted to the sensitivity analysis for some important neutron parameters affected by technological tolerances and/or operational conditions. The input parameters for the CANDU cell calculations were analysed to identify the relevant influence of the technological tolerances and operational conditions. The influence of these deviations from the standard values was investigated at the level of transport cell calculations. The model is based on the direct method (partial derivative and expansion in the power series). The sensitivity coefficients were calculated in order to obtain a rapid estimation of parameters and consequently their range of the confidence.

Keywords: *Sensitivity analysis, CANDU cell, Purity, Isotopic concentrations*

Introduction

In Reactor Physics analyses, the effective cross-sections are crucial parameters for all subsequent calculations from local to the global ones. Usually the cross-sections are generated from multi-group libraries by using transport cell calculations. Some parameters to describe the cell may be affected by technological tolerances such as the dimensions of different structures, the atomic densities, and the presence of some impurities. Other parameters are dependent on the operational conditions such as the temperatures of each material, the burnup, the density of the coolant (influenced by pressures, temperatures, etc.).

As the complexity of the cell increases (for example in 2D calculation of CANDU cell, taking into consideration the evolution of each material properties during the time), the number of parameters becomes important and the associated uncertainties should be investigated to define the confidence range for the final results (k-inf, k-eff, reactivity, flux, cross-sections, burnup, powers, etc.).

One of the critical parameter affected by some technological tolerances is the purity of the heavy water. In CANDU (CANada Deuterium Uranium) reactors, the heavy water is used both as moderator and coolant. The technical specifications for moderator indicate an isotopic purity of at least 99.75% (preferably 99.8% or even 99.9%) in order to accommodate the low reactivity of the core during the life cycle. Even a reduction of 0.1% in the isotopic purity has a significant effect on the neutron economy and on the achievable fuel burnup [1]. As regarding the coolant, the isotopic purity of the heavy water used in the primary heat-transport system must be more than 98.0% [2].

The temperature of the material influences directly the values of the material density and, implicitly, the values of the isotopic concentrations and the cross-sections selected from the library.

The sensitivity analysis is almost always an important part of the model development and plays a key role in understanding the quality of the results. The analysis consists of an analytical examination of input and output parameters and their correlation to support the model validation and provide guidance for future research [3].

Some approaches were developed for different purposes [3]. *Differential Sensitivity Analysis* (PD), also referred as ″the direct method″, is structured on the behaviour of the model for a base-case, e.g., all parameters set equal to their mean value. Differential sensitivity analysis is based on partial differentiation of the aggregated model. When an explicit algebraic equation describes the modelled relationship, the sensitivity coefficient for a particular independent variable is calculated from the partial derivative of the dependent variable with respect to the independent variable [3].

In the present paper, the direct method is used to calculate the sensitivity coefficients for some output parameters characterizing a CANDU cell. The most of the results are focused on the variation of k-inf as a key parameter.

Computer codes used in analyses

Two computer codes based on the solving of the transport equation in first-flight collision probability approximation were used in this paper, namely WIMS [4] and CP_2D [5].

WIMS code is useful to understand the variation of the parameters k-inf, k-eff, and effective cross-sections of a certain cell versus the variations of the input parameters in the range of realistic variations of the input data due to technological tolerances and/or operational conditions.

CP_2D is a two dimensional detailed geometry transport code able to calculate the flux and power distributions at the level of fuel pins and sub-region of them. CP_2D uses effective cross-sections produced by WIMS code, therefore in this case, the study investigates the propagation of the uncertainty influence through a methodology. The main output parameter is the void reactivity coefficient, one of the sensitive issues in CANDU technology.

Two models were developed for the calculation based on WIMS and CP_2D codes. The calculations have been performed for natural Uranium UO_2 fuel. As geometrical configuration, the standard 37 CANDU fuel bundle was used [6, 7].

Method and Methodology

In complex systems, such as the nuclear reactors, a great interdependency of the parameters is encountered. Consequently, in the numerical simulation, an output parameter (f) is dependent on a set (x_1, x_2,…, x_n) of input parameters:

$$f = f\left(x_1, x_2, ..., x_n\right) \tag{1}$$

Majority of them embeds uncertainties resulted from the inherent lack of knowledge or due to the insufficient accuracy of other data and measurements. Therefore, each input parameter has values in a domain $x_i \in \left[x_{i0} - \delta_1, x_{i0} + \delta_2\right]$ rather than a singular one (x_i).

The uncertainties in the values of the set (x_1, x_2,…, x_n) are different for each parameter. In such a case the output parameter f (x_1, x_2,…, x_n) may be calculated as a function of the ″standard″ values of the input parameters (x_{01}, x_{02},…, x_{0n}) by series expansion:

$$f\left(x_1, x_2, ..., x_n\right) = f\left(x_{01}, x_{02}, ..., x_{0n}\right) + \frac{1}{1!}\sum_{i=1}^{n}\frac{\partial f}{\partial x_i}\Delta x_i + \\ + \frac{1}{2!}\sum_{i=1}^{n}\frac{\partial^2 f}{\partial x_i^2}\Delta^2 x_i + ... \tag{2}$$

In case of small variations the first 2-3 terms of the previous expansion are enough for a good approximation.

The key output parameters for cell calculations were, as follows: k-inf, k-eff, and effective cross sections. For core calculations the k-eff, fluxes, and powers are crucial for the proposed analysis.

In the present paper k-inf and k-eff were selected as output parameters of interest. The set of input parameters consists of:

- Atomic composition of the materials (values of the concentrations or densities and mass fractions);
- Temperatures of the materials;
- Burnup of the fuel;
- Size of the geometric volumes defining the materials.

Some of these parameters are affected by technological tolerances such as the composition and geometry parameters, and some of the operational parameters, such as temperatures and fuel burnup.

Based on direct calculation of the k-inf, k-eff, the coefficients of expansion are calculated:

$$C_{1,i} = \frac{\partial f}{\partial x_i} \approx \frac{\delta f}{\delta x_i} \tag{3}$$

supposing small variations of $x_i \in \left[x_{i0} - \delta_1, x_{i0} + \delta_2\right]$, where $\delta_1 = \delta_2 = 1\%.\, x_{i0}$.

These coefficients are used later to define the confidence domain for the value of the output parameter considering a predicted set of deviations (technological and operational) from the design (″standard″) values.

Results and discussions

The influence of the purity (both for the coolant and moderator) on the k-inf value is presented in Figure 1. The values of the coefficients Ci are calculated from the graphs and are slowly dependent on the fuel burnup:

- $\frac{\partial k}{\partial p_c}$ = 0.133, where p_c is the coolant purity and the fuel is at the beginning of the life (BOL);
- $\frac{\partial k}{\partial p_c}$ = 0.095, where p_c is the coolant purity and the fuel is at a burnup of 4000 MWd/tU;
- $\frac{\partial k}{\partial p_m}$ = 4.520, where p_m is the moderator purity and the fuel is at the beginning of the life (BOL);
- $\frac{\partial k}{\partial p_m}$ = 3.473, where p_m is the moderator purity and the fuel is at a burnup of 4000 MWd/tU.

For the end of the life (EOL) the values of the sensitivity coefficients are calculated and their values are presented below:

- $\frac{\partial k}{\partial p_c}$ = 0.084, where p_c is the coolant purity and the fuel is at a burnup of 8000 MWd/tU (considered as EOL);
- $\frac{\partial k}{\partial p_m}$ = 3.197, where p_m is the moderator purity and the fuel is at a burnup of 8000 MWd/tU (EOL).

It can be seen a slowly decreasing of the coefficients versus the increasing of the fuel burnup.

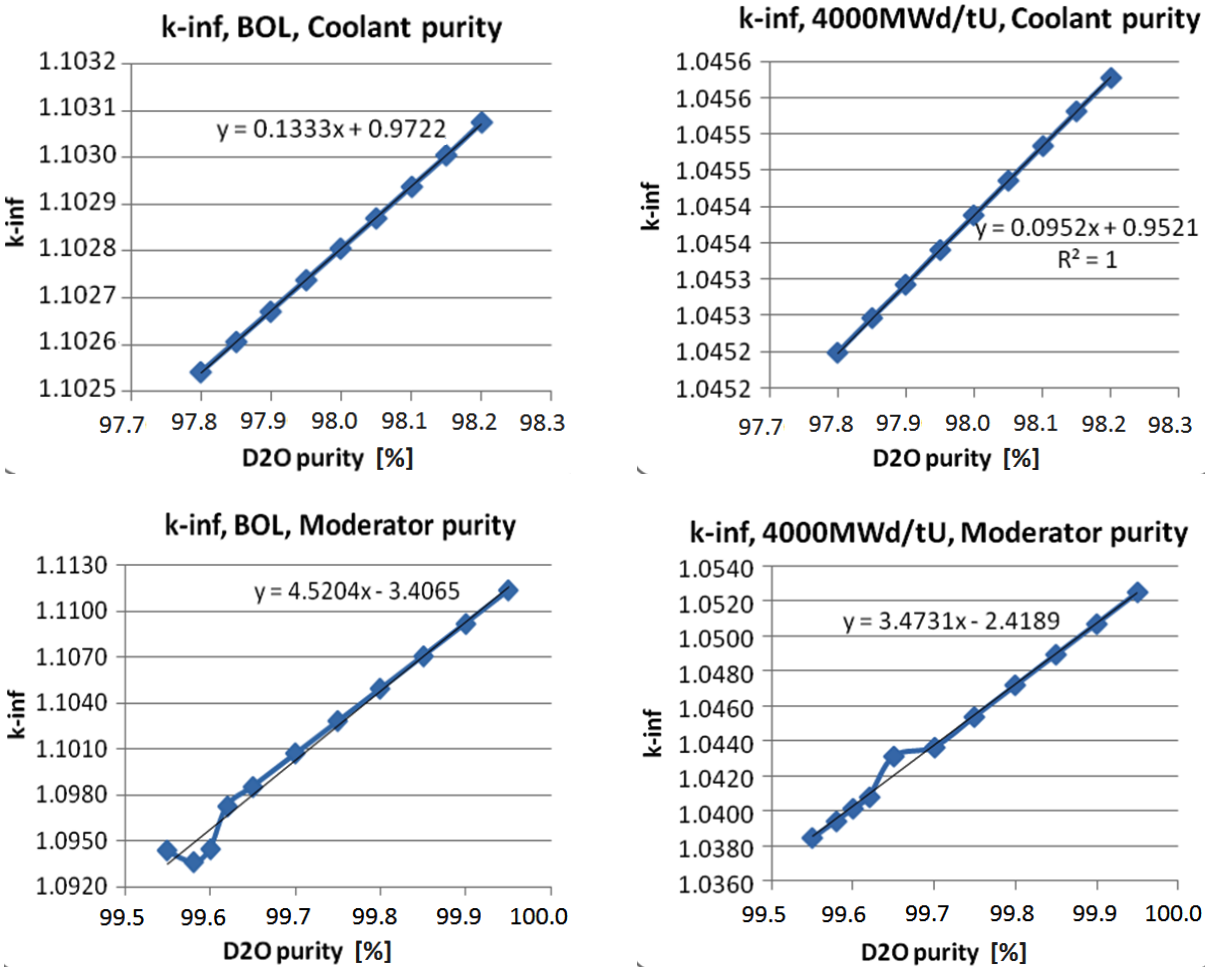


Fig.1. Influence of the D_2O purity on the k-inf of the cell

For the temperature influence on the output parameters it should be noted that, generally, there are two kind of dependence of the output parameter, *p*, on the temperature, *T*. First one is the direct dependence *p(T)*, and the second one is an implicit dependence *p(ρ(T))*, where *ρ* is the material density. To illustrate these influences, k-inf dependence on temperature is presented.

Three coefficients were calculated; one represents the direct dependence of k-inf on the *T*, the second illustrates the implicit dependence of k-inf through the material density *ρ(T)*, and the third one gives the total dependence.

The variation of the moderator and coolant temperatures were calculated by means of the WIMS code. In Table 1 the sensitivity coefficients of k-inf on the variation of the moderator and coolant temperatures are presented.

For the moderator temperature, the variations of k-inf are shown in Figure 2 (for the fresh fuel cell) and in Figure 3 (for a fuel burnup of 4000 MWd/tU), respectively.

It should be noted the opposite variation of k-inf with moderator temperature (for the case of 4000 MWd/tU fuel burnup) for the direct and implicit dependence.

Table 1. Sensitivity coefficients of k-inf on the variation of the moderator and coolant temperatures

Case	**Burnup**	**Coefficients**		
		Temperature of material	**Density**	**Temperature and Density**
Moderator	Fresh fuel	-1.37097E-05	-3.41642E-05	-4.78739E-05
	4000 MWd/tU	1.99413E-05	-1.92815E-05	1.46628E-06
Coolant	Fresh fuel	-1.82196E-05	5.02768E-05	3.21033E-05
	4000 MWd/tU	-5.16605E-06	3.33948E-05	2.90129E-05

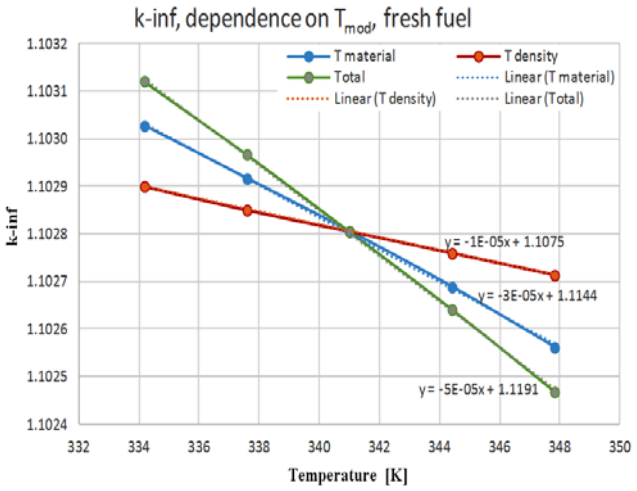


Fig. 2. Dependence of k-inf on the variation of the temperature, for fresh fuel cell

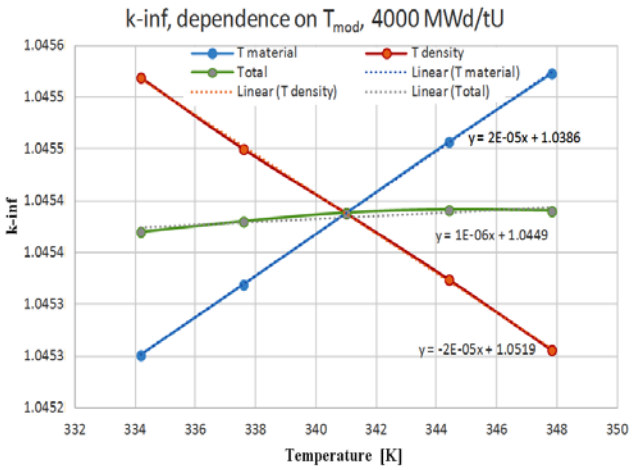


Fig. 3. Dependence of k-inf on the variation of the temperature, for a fuel burnup of 4000 MWd/tU

The reactivity coefficient of voided coolant is positive for CANDU type reactor. The paper investigates the dependence of the void reactivity on the purity of the coolant and moderator. The cross-sections were produced by using the WIMS code. For the reactivity values the CP_2D code was used, taking into consideration the real 2-D geometry of the CANDU 37-fuel elements cell. A 50% void fraction was considered for all calculations.

Figure 4 illustrates the dependence of the void reactivity on the variation of the moderator purity (around the standard value of 99.75%). Consequently, the dependence on the coolant purity (around the standard value of 98.0%) is presented in Figure 5.

The coefficients C_i are calculated from the graphs. It can be seen that a lower purity both for moderator and coolant will produce higher positive void reactivity.

Figure 6 shows the dependence of the void reactivity coefficient, for a cell with a 50% void fraction, on the moderator temperature. Consequently, the dependence on the coolant temperature is presented in Figure 7.

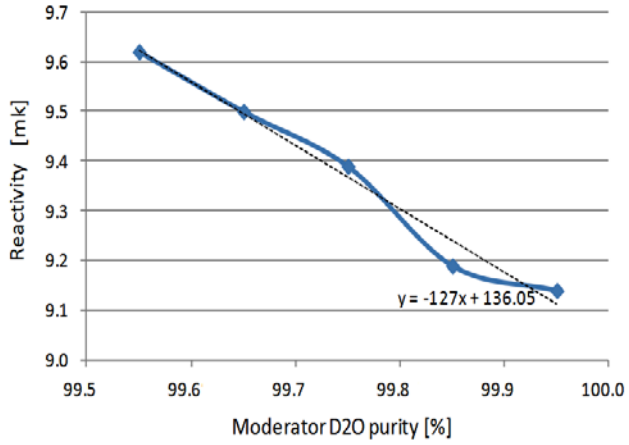


Fig. 4. Dependence of the void reactivity (50% voided cell) on the moderator purity

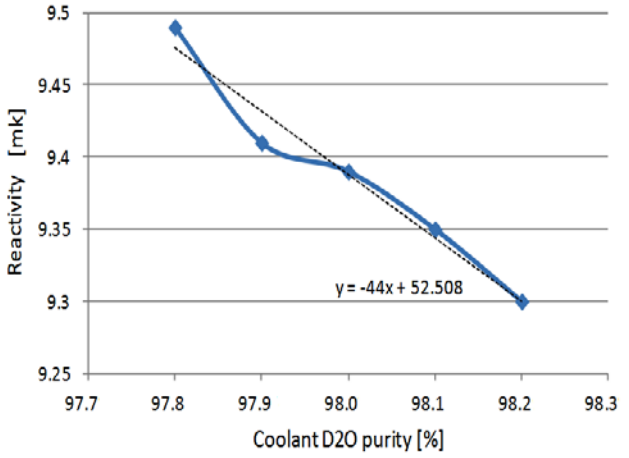


Fig. 5. Dependence of the void reactivity (50% voided cell) on the coolant purity

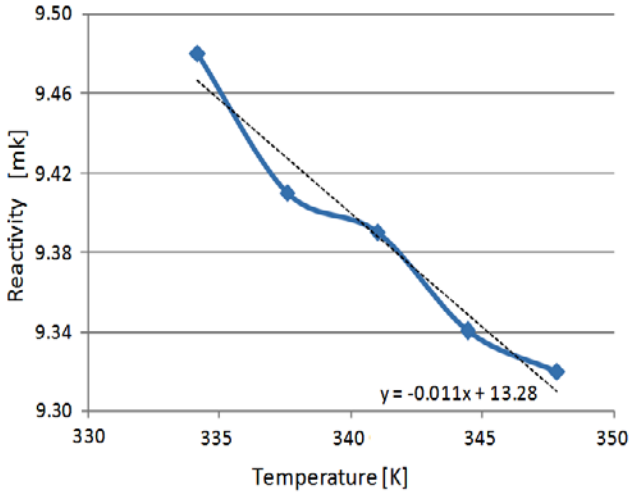


Fig. 6. Dependence of the void reactivity (50% voided cell) on the moderator temperature

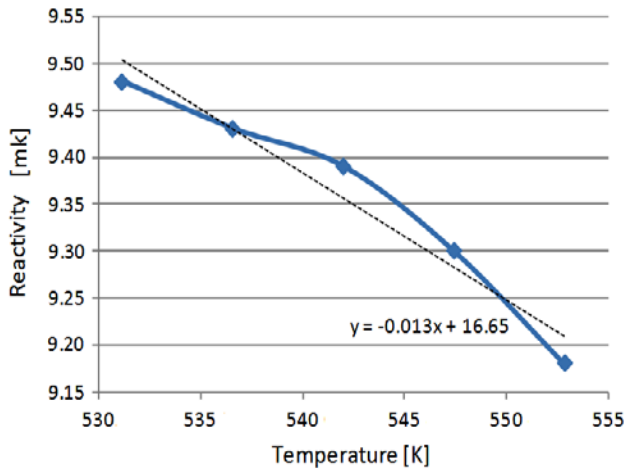


Fig. 7. Dependence of the void reactivity (50% voided cell) on the coolant temperature

The increasing of the temperatures slowly decreases the positive value of the void reactivity coefficient: (1) in case of the variation of the moderator temperature from 9.39 mk (at 341 K) to 9.32 mk (at 347.82 K), (2) in case of the variation of the coolant temperature from 9.39 mk (at 542 K) to 9.18 mk (at 552.84 K).

For other quantities of interest like fluxes, reaction rates, cross-sections, similar treatment may be applied. The coefficients C_i may be easily calculated and, if the linear behaviour is valid, the domain of the output values can be estimated.

Conclusions

The uncertainties play an important role in the simulation of the physical process. Uncertainties are derived from data, models, and user influence. In case of a methodology using a set of computer codes, a study of the uncertainties propagation through the numerical process is necessary.

The paper presents the dependence of the k-inf and void reactivity on some variations of the input parameters: purity of the moderator and coolant, burnup, temperatures.

The variations is quite linear in the domain defined by the technological tolerances, therefore a simple calculation of the coefficient of power expansion is necessary to further estimate the trust domain of the final results. These coefficients are calculated in present study and can be used in future estimations of the influence of the uncertainties in the key parameters.

Besides of the technological tolerances, the operational conditions are affected by small deviations of the parameters related to their nominal values. The effect can be estimated based on the calculated coefficients due to the quasi-linear behaviour.

The study of the uncertainties propagation through a methodology is a complicated mechanism, depending on the quality of data, the involved numerical algorithms, and the user effects (especially at the level of coupling of the codes by input-output results and interface data). A careful treatment is needed for each methodology in order to have a maximum confidence in the final parameters.

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