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Nuclear data sensitivity and uncertainty for the Canadian supercritical water-cooled reactor II: Full core analysis

S.E. Langton [a], A. Buijs [a], J. Pencer [a,b,*]

[a] Department of Engineering Physics, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L7, Canada
[b] Chalk River Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario K0J 1J0, Canada

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ABSTRACT

Uncertainties in nuclear data are a fundamental source of uncertainty in reactor physics calculations. To determine their contribution to uncertainties in calculated reactor physics parameters, a nuclear data sensitivity and uncertainty study is performed on the Canadian supercritical water reactor (SCWR) concept. The nuclear data uncertainty contributions to the neutron multiplication factor k_{eff} are 6.31 mk for the SCWR at the beginning of cycle (BOC) and 6.99 mk at the end of cycle (EOC). Both of these uncertainties have a statistical uncertainty of 0.02 mk. The nuclear data uncertainty contributions to Coolant Void Reactivity (CVR) are 1.0 mk and 0.9 mk for BOC and EOC, respectively, both with statistical uncertainties of 0.1 mk. The nuclear data uncertainty contributions to other reactivity parameters range from as low as 3% of to as high as ten times the values of the reactivity coefficients. The largest contributors to the uncertainties in the reactor physics parameters are Pu-239, Th-232, H-2, and isotopes of zirconium.

1. Introduction

The supercritical water reactor (SCWR) is a fourth-generation reactor concept that uses supercritical water (SCW) as coolant. The use of SCW enables a substantial increase (by a factor of approximately 1.6) of the thermodynamic efficiency of the SCWR relative to current nuclear reactors. Thus, the SCWR is potentially an economical option for future nuclear power production. The Canadian SCWR concept is one of a number of SCWR concepts in various stages of development internationally (Schulenberg et al., 2013). Its development is being led by Atomic Energy of Canada Limited (AECL) (Leung et al., 2011) with support through the Natural Resources Canada (NRCan) GEN-IV National Program (Boyle et al., 2009) and the NSERC/NRCan/AECL Generation IV Energy Technologies Program (Brady et al., 2009).

An essential part of the development of any new or advanced reactor concept is the quantification of the uncertainties in the modelling predictions of its behaviour. The uncertainty due to the nuclear data is the most fundamental source of uncertainty in reactor physics simulations. Unlike the uncertainties due to model descriptions and computational methods, the uncertainty in the nuclear data cannot be reduced through the choice of model complexity or modelling method. Uncertainty due to the nuclear data arises from variances and covariances in the experimentally determined energy-dependent nuclear data used in the simulations. The variances and covariances in the nuclear data propagate to the calculated reactor physics parameters and result in calculation uncertainties that must be determined in order to analyse the results correctly. To calculate the reactor physics parameter uncertainties due to nuclear data uncertainties, a sensitivity and uncertainty analysis can be performed in which the response of the system to a small change in a nuclear data parameter is used to determine the resulting uncertainty.

In this paper, a sensitivity and uncertainty analysis has been performed to establish the uncertainty in reactor physics parameters due to nuclear data. This work expands upon the work of Blomeley et al. (2014) on nuclear data sensitivity and uncertainty analysis of a single Canadian SCWR fuel channel with fresh fuel using a previously developed 54-element fuel assembly concept. The SCWR model was updated based on the 78-element fuel concept and extended to a full core with equilibrium irradiated fuel at the beginning (BOC) and end of cycle (EOC). The SCALE 6.1 code package (Rearden et al., 2011) was used to model the SCWR core and to determine the sensitivities and uncertainties for k_{eff}, Coolant Void Reactivity (CVR), coolant temperature reactivity, moderator temperature reactivity, fuel temperature reactivity, and moderator purity reactivity.

* Corresponding author at: Chalk River Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario K0J 1J0, Canada. Tel.: +1 6135848811x46267; fax: +1 6135848033.
E-mail address: pencerj@aecl.ca (J. Pencer).

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2. Sensitivity and uncertainty theory and calculation methods

A brief description of the sensitivity and uncertainty analysis and computational methods used is provided below. A more detailed discussion of the analysis method and background theory can be found in Rearden et al. (2011).

2.1. Sensitivity

The relative sensitivity $S_{k,\alpha}$ of the multiplication factor of a system is the ratio of the relative change dk, in the multiplication factor k, to the relative change $d\alpha$, in a particular cross section α, expressed as

$$S_{k,\alpha} = \frac{\alpha}{k}\frac{dk}{d\alpha}. \quad (1)$$

The sensitivity to an eigenvalue difference response (i.e. the reactivity worth of a perturbation to the system) $\rho_{1\to 2}$ is then (Williams and Jesse, 2011)

$$S_{\rho,\alpha} = \frac{\alpha}{\rho_{1\to 2}}\frac{d\rho_{1\to 2}}{d\alpha}, \quad (2)$$

where

$$\rho_{1\to 2} = \rho_2 - \rho_1 = \frac{1}{k_1} - \frac{1}{k_2}. \quad (3)$$

This sensitivity term can be calculated directly based on the multiplication factor sensitivities of the two states of the system (e.g. the cooled and voided states)

$$S_{\rho,\alpha} = \frac{\frac{1}{k_2}S_{k_2,\alpha} - \frac{1}{k_1}S_{k_1,\alpha}}{\rho_{1\to 2}}. \quad (4)$$

For convenience, the absolute value of the reactivity change is used in the calculations of sensitivities of reactivity differences. With this convention, a positive sensitivity indicates that a positive change in the cross section results in a positive shift in the reactivity change due to a perturbation. A negative sensitivity indicates that a positive change in the cross section results in a negative shift in the reactivity change due to a perturbation

$$S_{\rho,\alpha} = \frac{\frac{1}{k_2}S_{k_2,\alpha} - \frac{1}{k_1}S_{k_1,\alpha}}{|\rho_{1\to 2}|}. \quad (5)$$

2.2. Uncertainty

The uncertainty in the k_{eff} or in the eigenvalue difference response (reactivity change) that results from the uncertainties in the nuclear data is computed as a combination of the sensitivity S to a particular cross section and the uncertainty for that cross section.

For a matrix α containing nuclear data, where $\alpha = \alpha_m$, $m = 1, 2, \ldots, M$, and M is the product of the number of nuclide/reaction pairs for the number of energy groups, the matrix containing the relative variances and covariances is (Rearden et al., 2011)

$$C_{\alpha\alpha} = \frac{COV(\alpha_m, \alpha_p)}{\alpha_m \alpha_p}, \quad m = 1, 2, \ldots, M, \; p = 1, 2, \ldots, M, \quad (6)$$

where $COV(\alpha_m, \alpha_p)$ represents the covariance of α_m and α_p.

The variance σ^2 in the k_{eff} or eigenvalue difference response resulting from the nuclear data uncertainties is then

$$\sigma^2 = SC_{\alpha\alpha}S^T, \quad (7)$$

where T represents the transpose of the matrix.

The individual energy-integrated contributions to this total variance from each nuclide/reaction to nuclide/reaction pair are

$$\sigma^2_{\substack{i,j \\ x,y}} = S_{\alpha^i_x} C_{\alpha^i_x \alpha^j_y} S^T_{\alpha^j_y}, \quad (8)$$

where i and j are isotopes, and x and y are reactions.

2.3. Calculation methods

The Canadian SCWR core was modelled using modules of the SCALE 6.1 code package (Rearden et al., 2011) available from the Radiation Safety Information Computational Center (Radiation Safety Information Computational Center, 2013). A three-dimensional quarter-core model of the SCWR was made in the KENO V.a module (Petrie and Landers, 2011). This was then used in a k_{eff} sensitivity and uncertainty analysis using the Sensitivity Analysis Module for SCALE (SAMS) (Rearden et al., 2011). The sensitivities and uncertainties for the differences between eigenvalue responses were also determined. This was completed using the Tool for Sensitivity Analysis of Reactivity Responses TSAR (Williams and Jesse, 2011) module. The TSUNAMI-3D driver module was used to determine the multiplication-factor sensitivity coefficients for the core under reference conditions and for the core under the perturbations needed to evaluate various reactivity coefficients. This driver module uses the KENO V.a module to perform forward and adjoint flux Monte Carlo calculations. Here, the 238-group ENDF/B-VII Rel.0 cross section data library distributed with SCALE was used. The sensitivities and uncertainties were then calculated using the SAMS module with a 44-group covariance library (based on a combination of several nuclear data evaluations Rearden et al., 2011) distributed with SCALE. Finally, the TSAR module was used to compute the sensitivities and uncertainties of eigenvalue difference responses.

The total relative sensitivity coefficient calculated with SAMS is computed as the sum of two parts: an explicit portion and an implicit portion. The explicit portion of the sensitivity coefficient is a representation of the change in the multiplication factor with a change in a particular cross section when the effects of self-shielding are not significant. This is computed using perturbation theory methods. The implicit portion of the sensitivity coefficient arises from the effects of a change in a particular cross section on resonance self-shielded cross sections. It is a representation of the resulting change in the multiplication factor due to this change in resonance self-shielded cross sections. The eigenvalue response sensitivity calculated by TSAR uses the total sensitivity coefficient for the multiplication factor of each system.

The k_{eff} sensitivity values calculated using the SAMS module of SCALE 6.1 (and by extension the k_{eff} nuclear data uncertainty contributions) have statistical uncertainties resulting from the Monte Carlo method used to perform the calculations. The statistical uncertainty in the sensitivities results from statistical uncertainty in the forward and adjoint flux solutions as well as the k_{eff} solution and are calculated using standard error propagation techniques (Rearden et al., 2011). The statistical uncertainties in the sensitivity of eigenvalue difference responses calculated using TSAR are based on the statistical uncertainties of the k_{eff} sensitivity values and the k_{eff} solutions for each system state. These are also calculated using standard error propagation techniques.

3. SCWR sensitivity analysis models

The SCWR concept analysed here is described in detail in McDonald et al. (2011). It consists of a heavy-water moderated, vertical pressure-tube geometry with 78-element fuel assemblies. The fuel is $(Th,Pu)O_2$ with 13 wt% PuO_2. The coolant within the channels is pressurised to 25 MPa, with a channel inlet temperature of 350 °C, is heated by the fuel, and reaches a temperature of 625 °C at the channel outlet. The core contains a total of 336