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A METHODOLOGY FOR DEVELOPING EXPERIMENTAL BENCHMARK SETS FOR NEW REACTOR DESIGNS USING SENSITIVITIY ANALYSIS

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ABSTRACT – A method is examined for generating sets of benchmark experiments that can be used to determine computational biases in new reactor designs. Potential experiments for the ZED-2 test reactor are simulated. The effects on the applicability of a benchmark set resulting from modification of the ZED-2 lattice are studied. The applicability of a potential benchmark set is determined based on a sensitivity analysis using TSUNAMI-3D. Potential experiment sets are developed for a proposed supercritical water reactor design and for thorium fueled CANDU reactor designs. An analogous methodology can be applied to new small modular reactor designs.

1. Introduction

When developing new reactor designs such as the small modular reactor (SMR), or when modifying current reactor designs, reactor physics simulations are relied on to determine important results concerning the neutronics of the system. These simulations have a bias resulting from uncertainties in the nuclear cross section data used in the calculations. For new reactor designs, the results from a set of experiments at test reactor facilities are used to estimate the bias of an application by taking the biases of the experiments and using them as part of a trending or generalized linear least squares (GLLS) analysis.

It is important to ensure the experiments chosen for these procedures adequately represent the application. For a GLLS analysis, it has been suggested that a parameter called the completeness, which analyzes sensitivity values, may be a useful tool in determining whether an experimental benchmark set is appropriate [1]. Based on the completeness parameter, a method of choosing experiments that are sufficiently representative of different applications, such that they can be used in a GLLS analysis has been examined. Here a supercritical water cooled reactor (SCWR) design and (Th, Pu)O_2 fueled CANDU designs have been used as the applications of interest however a similar methodology would be applicable to SMR designs.

2. Sensitivity analysis and the completeness parameter

A GLLS adjustment consists of modifying the nuclear data to ensure the biases of a set of experiments are close to zero. This adjusted data is then used to predict what the k_{eff} of the application would be with no computational bias. When choosing an experiment set for this purpose, a comparison of the sensitivities of the application and the experiments is important. Sensitivities are a representation of the change in the multiplication factor (k_{eff}) of a system due to a small change in nuclear data for a nuclide/reaction/energy. Thus, they are a measure of the importance of the nuclear data to the k_{eff}, implying it is more important to accurately know the value of data with large sensitivities. The explicit sensitivity of the k_{eff} to a cross section Σ is [2]:

$$S_{k,\Sigma} = \frac{\Sigma}{k}\frac{\partial k}{\partial \Sigma} \qquad (1)$$

For a GLLS analysis in which the nuclear data of the application is being modified based on experiments, using experiments with lower sensitivities than the application and thereby underestimating sensitivities means the effect of changes to the cross section data are also underestimated. This could lead to an inaccurate k_{eff} adjustment. To ensure the experiment's sensitivities cover the application, the completeness parameter (R) is used: [2].

$$R = \frac{\sum_n \sum_x \sum_j |dS_{x,j}^{a,n}|}{\sum_n \sum_x \sum_j |S_{x,j}^{a,n}|} \qquad (2)$$

$$d = \begin{cases} 1 \; if \; N_{x,j}^{n} \geq nixlim \\ 0 \; if \; N_{x,j}^{n} < nixlim \end{cases} \qquad N_{x,j}^{n} = number\ of\ experiments\ where\ \left(S_{x,j}^{e,n}\right) > \left(senfac \times S_{x,j}^{a,n}\right)$$

Here S is the sensitivity for nuclide n, reaction x, and energy group j, a is the application, e is the experiment, *senfac* is the specified coverage (between 0 and 1), and *nixlim* is the specified number of systems required for the experiment sensitivities to be included in the R calculation.

Note that the sensitivity for a particular nuclide/reaction/energy is considered covered in the completeness parameter if the absolute value of the experiment's sensitivity is greater than that of the application, which means its importance is not underestimated. Using multiple experiments that cover portions of the sensitivity spectra allows for a high completeness. For a GLLS analysis an experimental benchmark set with a completeness of 0.7 or more is suggested to adequately cover an application, however this cutoff value may change with further analysis [1].

3. Experimental benchmark set for the SCWR and (Th, Pu)O_2 fueled CANDU

To examine the development of an experimental benchmark set for use in a GLLS analysis, simulations were performed for potential experiments at the ZED-2 heavy-water critical facility at the Chalk River Laboratories. An SCWR design [3] at the beginning of cycle (BOC) and end of cycle (EOC) and (Th, Pu)O_2 fueled CANDU reactors were analyzed as potential new reactor designs. Sensitivity information for models of these designs was obtained using the KENO-Va and TSUNAMI-3D modules of the SCALE 6.1 package [4]. The largest sensitivities for each application are:

Table 1 Three largest sensitivities per unit lethargy values for each application.

SCWR (BOC)		SCWR (EOC)		CANDU(37-element)		CANDU (43-element)	
Pu-239 nubar	0.60	Pu-239 nubar	0.51	Pu-239 nubar	0.83	Pu-239 nubar	0.84
Pu-241 nubar	0.31	Pu-241 nubar	0.32	Pu-239 fission	0.48	Pu-239 fission	0.48
Pu-239 fission	0.29	Pu-239 fission	0.27	Pu-239 total	0.31	Pu-239 total	0.32

The plutonium in the fuel has the highest sensitivities and would have the most significant effect on the completeness parameter. For this reason PuO_2 content was modified in different fuel types that were simulated in the ZED-2. In addition, the effect of changing the ZED-2 lattice pitch was observed. It was found that increasing the lattice pitch increases the sensitivity to low energy nuclear data and decreasing it increases in the sensitivity to high energy nuclear data.

To develop a set of possible experiments, the completeness and the sensitivities covered were analyzed iteratively with the addition of each experiment to the set. Nuclides with the largest non-covered sensitivities after each added experiment were the focus of subsequently simulated experiments. ZED-2 simulations with two fuel types, two coolant types, and a lattice pitch between 13 and 45 cm caused the applications to obtain a completeness of ~0.7. As an example, Figure 1 shows the experiment set's coverage of the SCWR Pu-241 fission sensitivity spectrum.

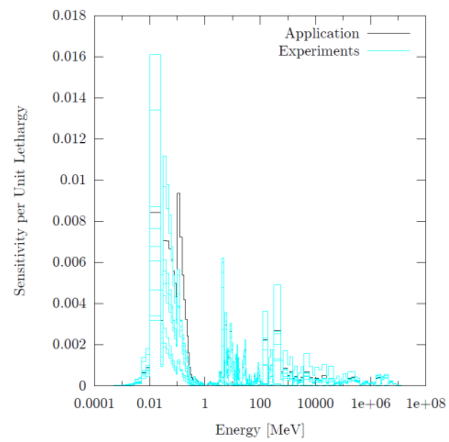

Figure 1 Pu-241 fission sensitivity coverage for the SCWR (BOC).

For SMR designs, a process similar to the one described above could be used to develop an experimental benchmark set that is adequate for a GLLS analysis: (1) examine sensitivities (2) choose fuel type (3) choose lattice arrangement (4) modify lattice pitch (5) modify coolant (6) iterate to accumulate experiment set. Note that there may be iteration between these steps.

7. Conclusions

By examining the completeness parameter, a methodology for designing experiments for use in a GLLS adjustment procedure was developed. A set of experiments at the ZED-2 test reactor applicable to the SCWR and (Th, Pu)O_2 fueled CANDU reactors was designed. A sufficient completeness was obtained by using a set of experiments with different fuel materials, coolants, and lattice pitch values. The addition of each experiment to the set was based on an iterative analysis of the sensitivity coverage. The experiments chosen here are theoretical. A larger experiment set designed to increase simplicity and decrease cost could be developed using a similar analysis for any new reactor design.

8. References

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