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Extended Interpretation of Sensitivity Data for Benchmark Areas of Applicability

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INTRODUCTION

Almost all nuclear systems that are encountered in nuclear criticality safety analytical practice are multi-isotope, complex geometry systems. Therefore, the codes and the associated data that are used in the analyses of these systems must be validated with experimental benchmarks, in lieu of exact analytical solutions, to assess the computational bias and uncertainty. Sensitivity and uncertainty (S/U) analysis tools[1] allow an analyst to determine if the available experimental benchmarks can be used to validate the computer codes KENO V.a and XSDRNPM, and the associated cross-section libraries for analysis of safety applications.[2] These S/U tools are based on the first-order perturbation theory in which the relative changes in the effective multiplication factor (k_{eff}) due to relative changes in the cross sections for each nuclide, reaction and neutron energy group are calculated. This relative change, or sensitivity, quantifies the importance of a nuclide-reaction-energy group triplet to the computed k_{eff} and as such is indicative of how important it is to know the cross sections accurately. Hence, a triplet is defined to be a specific nuclide, reaction and energy group.

The main issue that is addressed in this paper is how to assess the computational bias and uncertainty for an application with a significant number of triplets that are not covered by any combination of the benchmarks. Coverage is defined as having one or more benchmarks with sensitivities greater than the application's sensitivity for a specific nuclide-reaction-energy group triplet.

METHOD

The sensitivity of the system k_{eff} to each nuclide (for all reactions and all energy groups) is calculated with the SEN1 or SEN3 sensitivity analysis tools[1] for the application and all benchmarks for which similarity to the application is to be assessed. If some benchmarks exhibit higher sensitivities to the nuclide-reaction-energy group triplets than the application, then the application is considered to be within the area of applicability of the selected benchmarks. Consequently, the associated computational bias and uncertainty can be determined using an appropriate trending analysis. In many cases, due to the limited number of benchmarks and diverse variety of application systems, many benchmarks would have to be combined to achieve complete coverage of all triplets. Some benchmarks may provide coverage for high-energy groups, while others may provide coverage for low-energy groups.

The new validation assessment methodology presented here is based on the assumption that a benchmark with a higher sensitivity for the nuclide, reaction and energy group triplet of interest sufficiently covers the triplet in the application. If coverage for a sufficient number of triplets in the application can be demonstrated for a sufficient number of benchmarks, then the validation can be performed using appropriate trending methods, and the computational bias and uncertainty may be determined for the application. The approach that is used in this method is to determine the differences between the application and benchmark sensitivities for all the triplets that are not covered, and to quantify the importance of this non-coverage in terms of its final effect on the k_{eff} value of the application. This is accomplished by analyzing the differences in sensitivities between the application and benchmarks and determining the fractional difference between the application and each benchmark for each nuclide and all reactions of interest. This difference is defined as:

$$g = 1 - \frac{\sum_i (S^{j,x}_{a',i} - S^{j,x}_{b',i})}{\sum_i S^{j,x}_{a,i}},$$

where $S^{j,x}_{a,i}$ is the application's sensitivity for the neutron energy group *i*, nuclide *j*, and reaction *x*, $S^{j,x}_{b,i}$ is the benchmark's sensitivity, $S^{j,x}_{a',i}$ is the application's sensitivity for the groups for which $\left|S^{j,x}_{a,i}\right| > \left|S^{j,x}_{b,i}\right|$, and $S^{j,x}_{b',i}$ is the benchmark's sensitivity for the groups for which

$\left|S_{a,i}^{j,x}\right| > \left|S_{b,i}^{j,x}\right|$. Note that (1–*g*) is defined as, for a specific nuclide-reaction pair, the fractional difference between the application and the benchmark, with respect to the application's total sensitivity, for which the application's sensitivity is greater than the benchmark's sensitivity. The difference can also be calculated for all nuclides for a particular reaction by:

$$G_x = 1 - \frac{\sum_j \sum_i (S_{a',i}^{j,x} - S_{b',i}^{j,x})}{\sum_j \sum_i S_{a,i}^{j,x}},$$

where G_x is the difference for the system corresponding to reaction *x* (e.g., fission, capture, scattering, etc.). The global parameter *G* is calculated similarly by summing over all reactions, nuclides and energy groups:

$$G = 1 - \frac{\sum_x \sum_j \sum_i (S_{a',i}^{j,x} - S_{b',i}^{j,x})}{\sum_x \sum_j \sum_i S_{a,i}^{j,x}}.$$

A high *g* value indicates that the covered part of the application's sensitivity for a specific nuclide-reaction pair makes up the majority of the application's sensitivity for that nuclide-reaction pair. If the value of the total sensitivity for a nuclide-reaction pair is "low", the application can be considered adequately covered by the benchmark over all energy groups even with a low *g* value. Here "low sensitivity" is defined as resulting in less than 0.001 change in k_{eff} for a 100% change in the cross sections. G_x and *G* are interpreted similarly.

The differences between the application and benchmark sensitivities are indicative of how well the benchmark covers the application. If these differences are low, then the application is within the area of applicability of the benchmarks, and the effect of the uncertainties in the cross-section data would be quantified by the trending analysis.

In summary, the application's sensitivity for a nuclide-reaction pair is compared against all available benchmarks (selected to be similar to the application) on a group-wise basis. The number of benchmarks that have higher sensitivities than the application is tallied for each group. If some of the groups have no benchmarks that provide coverage, then the differences between the benchmarks and the application for those groups are calculated. If one or more benchmarks exist such that the sum of the minimum of these differences between the benchmarks and the application is less than 0.001, then the application is considered to be covered by that benchmark set.

APPLICATION TO GADOLINIUM CAPTURE

The use of the *g* value was demonstrated with two hypothetical applications containing ^{239}Pu and Gd in a glass-like matrix that were modeled with KENO V.a and the 238-group ENDF/B-V SCALE cross-section library. System characteristics along with the maximum *g* values for the applications against 47 selected experiments are given in Table I. The results indicate that the experiments that were used in the analyses sufficiently validate the applications for gadolinium cross sections using KENO V.a.

TABLE I. Case Characteristics and Results

Parameter		Case 1	Case 2
Volume (*l*)		218	218
^{239}Pu (g)		4326	4326
Gd (g)		28	42
H/^{239}Pu		400	534
^{155}Gd capture sensitivity		–0.0235 ± 7.57E–5	–0.0336 ± 1.156E–4
^{157}Gd capture sensitivity		–0.105 ± 3.37E–4	–0.150 ± 5.14E–4
$G_{fission}$		0.93	0.85
$G_{scattering}$		0.67	0.69
$G_{capture}$		0.83	0.77
g	^{155}Gd capture	1.0000	0.96
	^{157}Gd capture	0.9998	0.96
Number of groups not covered for ^{157}Gd		8	23
Sum of ^{157}Gd capture sensitivities for groups that are not covered		4.12E–7	–5.22E–3

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