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# Validation of the $^{10}$B Capture Reaction in Nuclear Fuel Casks Using Sensitivity Analysis

**Sedat Goluoglu, K. R. Elam, B. T. Rearden, B. L. Broadhead, C. M. Hopper, and C.V. Parks**

Oak Ridge National Laboratory,*
P.O. Box 2008, MS-6370
Oak Ridge, TN 37831-6370 USA
Telephone: (865) 574-5255
FAX: (865) 576-3513
Email: goluoglus@ornl.gov

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*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6370, USA goluoglus@ornl.gov*

## INTRODUCTION

Many currently licensed or proposed storage and transportation casks for nuclear fuel employ sheets of borated material between fuel assemblies to ensure or enhance nuclear criticality safety. Before the calculations to determine the nuclear safety margin for various fuel loadings are deemed acceptable, as part of the safety basis, the computer code and cross sections must be validated against experimental benchmarks that cover the area of applicability of the proposed cask design. There has been some question as to whether the boron cross sections used in these calculations have been properly validated, given the limited set of experimental benchmarks available that utilize borated material between sets of fuel, and the difference between the experiments and the new cask designs. In an effort to address this issue, the recently developed sensitivity and uncertainty (S/U) methodology in SCALE [1,2] was used to compare some nuclear fuel casks with experimental benchmarks. These methods provide a measure of the similarity between the cask systems and the benchmark systems. In particular, the $^{10}$B capture reaction was studied to determine if any of the selected benchmarks are applicable for criticality code validation for selected fuel shipping casks containing both fresh and spent fuel with boron poison plates.

## METHOD

The sensitivity of the system $k_{eff}$ to each nuclide (for all reactions and all energy groups) is calculated with the TSUNAMI-3D (formerly SEN3) sensitivity analysis tool [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. A triplet is defined as a reaction *x* for a neutron energy group *i* of a nuclide *j*. Consequently, the associated computational bias and uncertainty can be determined using an appropriate trending analysis, which is beyond the scope of this paper. 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 used here is described in detail in Ref 3. It 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. The assessment is accomplished by computing the *g*-values between the application and the benchmarks for each nuclide and all reactions of interest:

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

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 and $S^{j,x}_{b',i}$ is the benchmark's sensitivity for the groups where the application's sensitivity is greater than the benchmark's sensitivity, i.e., $\left|S^{j,x}_{a,i}\right| > \left|S^{j,x}_{b,i}\right|$. Note that in the above equation, $g'$ is defined as, for a specific nuclide-reaction pair, the summed difference between the application and the benchmark for all energy groups where the application's sensitivity is greater than the benchmark's sensitivity, normalized with respect to the application's total sensitivity (sum over all groups). A $g$ value of 1 indicates complete coverage, whereas a $g$ value of 0 indicates a complete non-coverage.

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 greater sensitivities than

the application is tallied for each group. If some of the groups have no benchmarks that provide coverage, then the minimum of the sensitivity differences ($S_{nc}$) between the benchmarks and the application for those groups are calculated. The cross-section uncertainties and $S_{nc}$ are used to calculate the adjusted $k_{eff}$. The adjusted $k_{eff}$ ($k'_{eff}$) is the $k_{eff}$ value after including the penalty (additional artificial bias) due to non-coverage (i.e., $k'_{eff} = k_{eff} + \left| k_{eff} S_{nc} \omega \right|$, where $\omega$ is the fractional calculated bias in $k_{eff}$ due to uncertainty in the cross section for the nuclide-reaction pair of interest and is calculated for all nuclide-reaction pairs in the problem that have covariance data in the cross-section library).

## APPLICATION TO $^{10}$B CAPTURE

The characteristic values for the applications along with the maximum *g* values for each of the cask models against the 50 selected benchmarks are given in Table I. As the *g* values indicate, none of the benchmarks exhibit $^{10}$B capture sensitivities greater than the individual applications' $^{10}$B capture sensitivity across the entire energy range. The differences in the sensitivities make up more than 20% (more than 70% for GA-4 cask) of the application's sensitivity to the $^{10}$B capture cross section for the energy groups for which the application exhibits greater sensitivity to the $^{10}$B capture cross section than the benchmark.

The greatest sensitivity differences are observed for the MPC-68 and GA-4 casks. However, the highest of these differences is on the order of $10^{-2}$, which corresponds to a difference on the order of $10^{-4}$ in the value of calculated $k_{eff}$ (0.01% of the calculated $k_{eff}$) for a 1% change in the $^{10}$B capture cross section.

Since the uncertainties in the calculated $k_{eff}$ values due to $^{10}$B capture cross section uncertainties are less than $10^{-6}$ ($10^{-4}$ %), the adjusted $k_{eff}$, which is the calculated $k_{eff}$ adjusted with the sum of minimum differences in $^{10}$B cross sections weighted by the $^{10}$B capture cross-section uncertainties, is identical to the calculated $k_{eff}$ with 4 digit precision. Therefore, the penalty due to non-coverage of $^{10}$B capture cross sections is determined to be zero for all practical purposes.

## CONCLUSIONS

Although the example nuclear fuel cask applications' sensitivities that have been analyzed are not completely covered by the set of benchmarks that were used in this study with regard to the $^{10}$B capture cross section, analysis of the coverage using *g*-values method indicates that the effect of lack of coverage on the $k_{eff}$ is minimal. Thus, no additional bias due to high boron loading should be imposed, and the experimental biases are appropriate for the cask applications.

## REFERENCES


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2. S. GOLUOGLU, C. M. HOPPER, B. T. REARDEN, "Extended Interpretation of Sensitivity Data for Benchmark Areas of Applicability," *Trans. Am. Nucl. Soc*., **88**, 77 (2003).
3. S. GOLUOGLU, C. M. HOPPER, *Assessment of Areas of Applicability of Benchmarks for Gadolinium Using KENO V.a and the 238-Group SCALE Cross-Section Library*, ORNL/TM-2003/106, in preparation.


TABLE I. Nuclear Fuel Cask Model Characteristics and Results

| Cask | $^{10}$B Surface Density (at/cm$^2$) | Calculated $k_{eff} \pm \sigma$ | EALCF (eV) | $^{10}$B Capture Sensitivity | *g* | $S_{nc}$ for $^{10}$B Capture | Adjusted $k_{eff}$ |
|---|---|---|---|---|---|---|---|
| MPC-24 | 1.216E21 | 0.9458 | 2.257E−01 | −2.62E−02 | 0.79 | −4.76E−04 | 0.9458 |
| MPC-68 | 1.658E21 | 0.9349 | 2.775E−01 | −5.05E−02 | 0.46 | −1.91E−02 | 0.9349 |
| GA-4 | 4.750E22 | 0.9221 | 4.572E−01 | −2.38E−02 | 0.29 | −1.69E−02 | 0.9221 |
| GBC-32 | 1.688E21 | 0.8941 | 2.474E−01 | −2.76E−02 | 0.73 | −1.65E−03 | 0.8941 |
| OECD | 3.918E20 | 1.1302 | 6.311E−02 | −4.45E−02 | 0.75 | −5.73E−03 | 1.1302 |
| MPC-68m* | 3.588E20 | 1.0012 | 2.502E−01 | −4.13E−02 | 0.83 | −3.16E−03 | 1.0012 |
| GA-4m* | 1.396E21 | 0.9959 | 3.881E−01 | −2.20E−02 | 0.86 | −1.81E−04 | 0.9959 |

* Modified by reducing boron concentration