The Case for and against a Gadolinium Bias in SCALE: Opening Arguments

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INTRODUCTION

The results from a number of validation studies [1, 2] performed with the SCALE code system [3] include poor results for the HEU-SOL-THERM-014 (HST-014) and HEU-SOL-THERM-016 (HST-016) evaluations from the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [4]. These results are interesting because each evaluation contains three cases; the first case contains no soluble gadolinium poison, and the subsequent cases include increasing gadolinium concentrations. The strong positive bias in the calculated k_{eff} results may indicate an error in the gadolinium cross sections. The current SCALE 6.2.2 validation report [5] contains an additional evaluation for a solution system containing soluble gadolinium poison, MIX-SOL-THERM-007 (MST-007). These results do not show a bias, nor do results from the Haut Taux de Combustion (HTC) Phase 2 experiments containing soluble gadolinium [6]. The experiments considered in this paper include naturally occurring gadolinium, no enriched gadolinium is used. This paper consolidates all of these results to present the current evidence for and against a gadolinium bias within SCALE. Additional recent results from other code systems would help address the potential for a broader bias within systems and data sets.

HEU-SOL-THERM-014 AND -016 RESULTS

The HST-014 and -016 evaluations are part of a set of six series of experiments performed at the Institute for Physics and Power Engineering (IPPE) in Obninsk, Russia. The experiments consisted of a single tank containing HEU solution reflected by water radially and below the solution tank. The uranium concentration in the solution is varied among each of the evaluations, and the gadolinium concentration is varied within each solution in each evaluation. The HST-014 experiments contain 70 gU/L and the HST-016 experiments contain 150 gU/L. The other experiments contain uranium concentrations up to 400 g/L. The gadolinium concentration in HST-014 ranges from 0 to 0.2 g/L and in HST-016 from 0 to 0.5 g/L. Sample results from the ICSBEP evaluations are shown in Fig. 1 along with more recent results from SCALE 6.2.2 continuous-energy (CE) KENO. As mentioned previously, the same trend is evident in all four code and cross section combinations for both evaluations; the calculated k_{eff} value increases significantly with increasing gadolinium concentration [4].

These two evaluations were the only two cases in the SCALE 6.1 validation report [1] that contain gadolinium, so there was potential evidence for a bias in the gadolinium cross sections. The majority of the absorptions in natural gadolinium occur in ^{157}Gd, so this would be the prime candidate as the source of the bias. Two arguments are presented in [1] as indications that the discrepant results do not indicate a problem with the gadolinium cross sections. The first is based on the observed results, as shown in Fig. 1, for a range of different cross section sets and transport codes all showing similar results. This can be strengthened at this point because the ENDF/B-VII.0 and ENDF/B-VII.1 results are largely the same despite a new ^{157}Gd evaluation in ENDF/B-VII.1 [7]. The other argument examines the sensitivity of the calculated k_{eff} to the ^{157}Gd cross section and estimates the magnitude of the error that would be required to account for the observed bias in the results. The result of the sensitivity/uncertainty (S/U) analysis is that the ^{157}Gd absorption cross section would have to be in error by a factor of approximately 16 to account for the 2.5% Δk error in the HST-016-003 result [1]. The sensitivity techniques and uncertainty data used are described in [8]. In conclusion, it is difficult to believe that such a large bias exists in the gadolinium absorption cross sections, but it also cannot be excluded based on the results of these two evaluations.

MIX-SOL-THERM-007 RESULTS

The MST-007 evaluation is part of a set of four experiments related to criticality safety of reprocessing and validation of codes and cross sections performed at Pacific Northwest National Laboratory (PNNL). The experiments in MST-007 were specifically used to study the effect of soluble gadolinium as a poison. The solutions had a Pu/U+Pu ratio of 0.3, a plutonium concentration of approximately 76 g/L, and gadolinium concentrations ranging from 0.042 to 1.06 g/L. These experiments covered a wider range of gadolinium concentrations than the HST-014 and HST-016 experiments. Models of the MST-007 evaluation have been added to the VALID library and are now included in the validation of SCALE 6.2.2 [5].

The calculated-to-experiment (C/E) ratios for k_{eff} from the MST-007 evaluation are shown in Fig. 2, along with the C/E values for HST-014 and HST-016. The C/E values for all cases were calculated using SCALE 6.2.2 and the

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CE library based on ENDF/B-VII.1. The results are plotted as a function of gadolinium concentration, and uncertainty bars are shown on both the C/E and the gadolinium concentration. The uncertainty in the gadolinium concentration is provided in the evaluation for each case in each evaluation [4]. Three experiments were excluded from the MST-007 evaluation because of large reported uncertainties in the gadolinium concentrations. The bias in the HST-014 and HST-016 results is clear in the figure, as is the complete lack of any bias as a function of gadolinium concentration in the MST-007 results.

The total ^{157}Gd sensitivities for the highest gadolinium concentration case in each of the three evaluations are provided in Fig. 3. The sensitivities are very similar, indicating that a bias in the ^{157}Gd cross sections should result in a similar bias in all three systems. The lack of a bias in MST-007, coupled with these similar sensitivities, indicates that there is likely not a significant bias in the ^{157}Gd cross sections.

HAUT TAUX DE COMBUSTION RESULTS

Phase 2 of the HTC experiments [6] contains a series of measurements of mixed oxide fuel rods in light water with soluble gadolinium poisons. The fissile material was designed to be representative of typical discharge burnup pressurized-water reactor fuel, and the soluble gadolinium concentrations range from 0.05 to 0.2 g/L. This type of system is clearly different from the solution systems discussed previously, but the soluble gadolinium present in the system provides significant negative reactivity. The C/E results for the HTC Phase 2 experiments with soluble gadolinium are added to the solution experiment results and shown in Fig. 4. As with Fig. 2, all results in Fig. 4 were generated in SCALE 6.2.2 with the CE library based on ENDF/B-VII.1. The HTC models are not in VALID but have been reviewed for use in NUREG/CR-7109 [9].

The HTC results also show no bias as a function of gadolinium concentration. These experiments cover the smallest range in gadolinium concentration but also show the smallest variation in C/E results. The HTC results provide further confidence that there is not a significant bias in the ^{157}Gd cross sections.

CONCLUSIONS

There is evidence in the results of the HST-014 and HST-016 evaluations for a reactivity bias caused by ^{157}Gd in a thermal system. The number of code and cross section sets that show similar results point to a problem with the experiment description and not with the nuclear data. Investigations of the results using S/U tools also indicate that the discrepancies seen in the results are not a result of errors in the cross sections. Some additional benchmark results containing soluble gadolinium have been presented which show no evidence of bias due to gadolinium. Further work is needed to examine the remainder of the evaluations in the ICSBEP Handbook which contain soluble gadolinium. The generation of an extensive suite of benchmark models will also assist new evaluations of the ^{157}Gd cross section [10]. Also, as mentioned before, an examination of current results from other code systems would provide additional information regarding the potential of a bias in the nuclear data prior to its use within SCALE.

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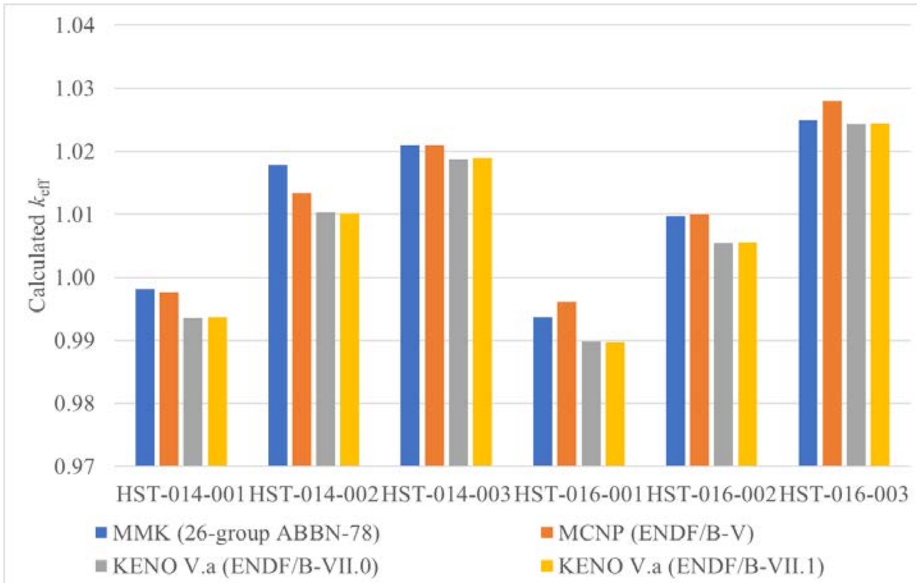

Fig. 1. Calculated k_{eff} values for HST-014 and HST-016 using different codes and cross section sets.

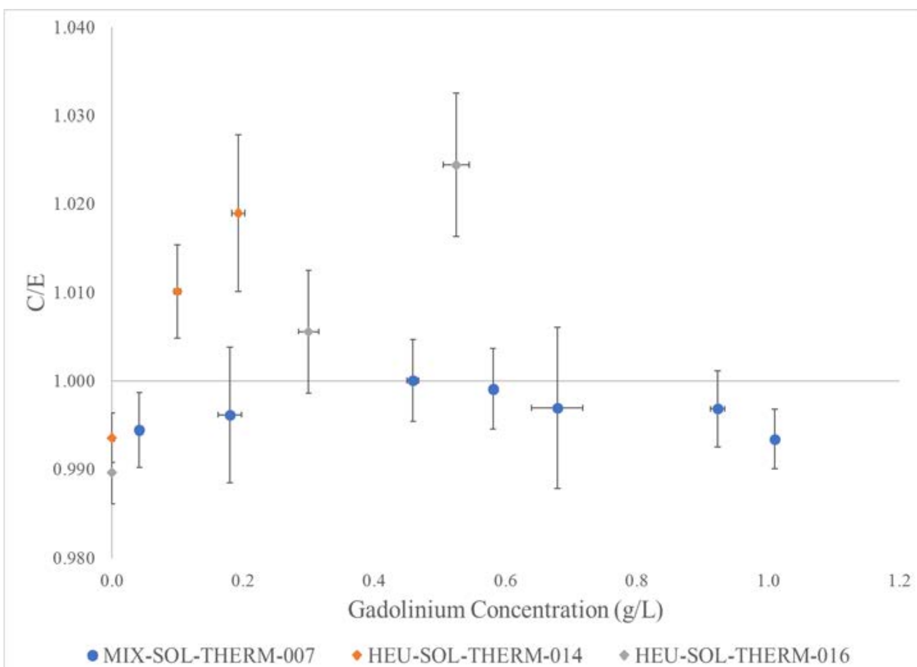

Fig. 2. C/E results for HST-014, HST-016, and MST-007 using the SCALE 6.2.2 CE ENDF/B-VII.1 library.

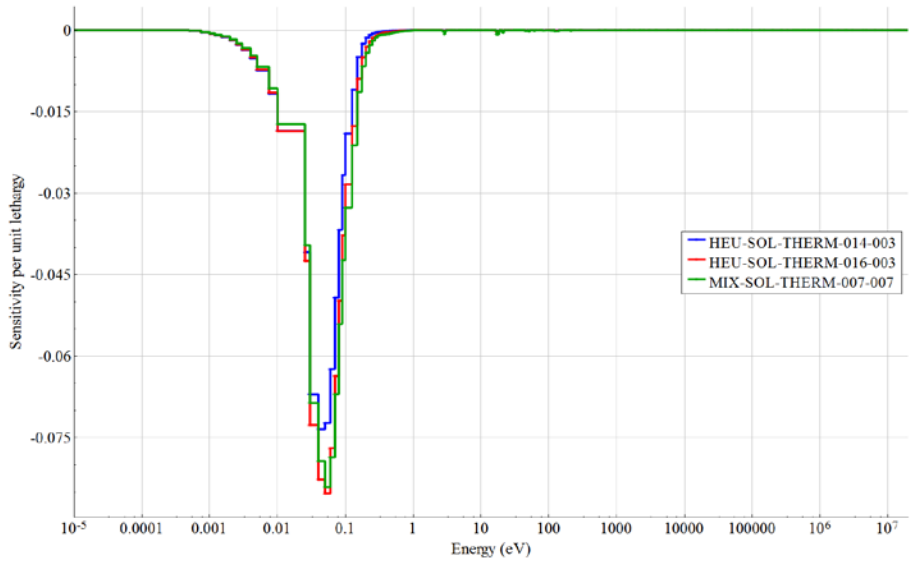

Fig. 3. k_{eff} sensitivities to the total ^{157}Gd cross section for the highest gadolinium concentration case in each evaluation.

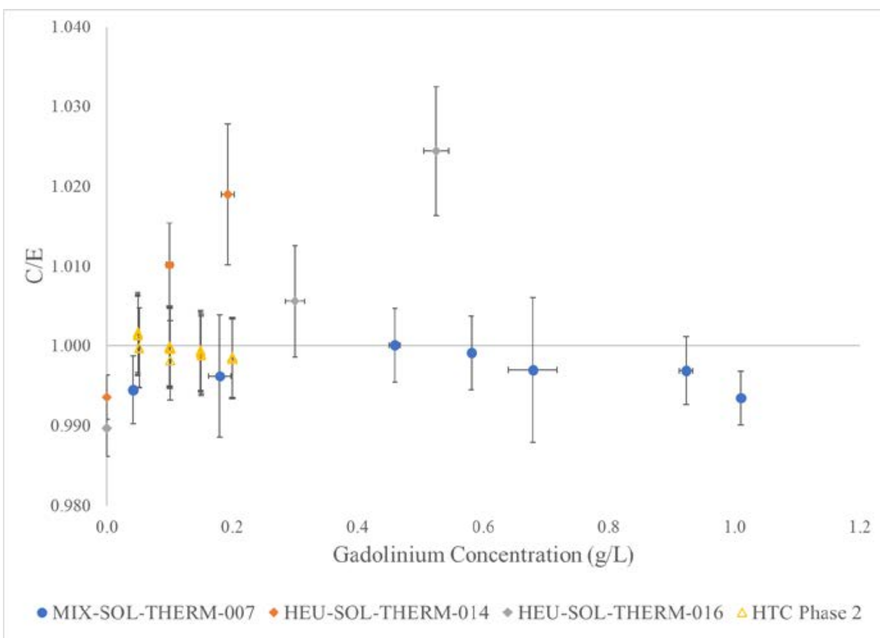

Fig. 4. C/E results for HST-014, HST-016, MST-007, and HTC Phase 2 with soluble gadolinium using the SCALE 6.2.2 CE ENDF/B-VII.1 library.