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DETERMINATION OF CONSISTENT BENCHMARKS USED FOR NUCLEAR CRITICALITY SAFETY ANALYSIS APPLICATIONS

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Determination of Consistent Benchmarks Used for Nuclear Criticality Safety Analysis Applications

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INTRODUCTION

Recently, the Generalized Linear Least Squares (GLLS) methodology has been applied to criticality safety analysis, and a GLLS code has been developed within the SCALE code system [1] to determine biases and uncertainties in neutron multiplication factors by consolidating differential data and benchmark integral experiments. The adjustment code uses the GLLS method to consolidate a prior set of integral responses measured in critical benchmark experiments and a corresponding set of calculated values obtained using the SCALE code system. The code modifies the initial estimates for calculated and measured responses by varying the nuclear data used in the transport calculations as well as the values of the measurements, taking into account their correlated uncertainties, such that the most self-consistent set of data is obtained. This approach forces the modified estimates of the calculated and measured responses to agree, while at the same time constraining the data variations to minimize a generalized chi-square. This ensures maximum overall consistency in the set of calculated and measured responses for a specified set of data and experimental uncertainties; thus, the modified results represent the “best estimates” for the true response values. Consolidation of the original integral experimental data and calculated results reduces the prior uncertainty in the response estimates, compared with either the measured or calculated results alone, because additional information has been incorporated.

TSURFER

TSURFER (***T****ool for* ***S****ensitivity/****U****ncertainty Analysis of* ***R****esponse* ***F****unctionals Using* ***E****xperimental* ***R****esults*) is a functional module in the SCALE sensitivity and uncertainty analysis methodology. The main functions of the code are (1) to compute uncertainties in calculated integral responses, such as k_{eff}, due to uncertainties in the input nuclear data and (2) to analyze measured responses from benchmark integral experiments in order to establish the bias and associated uncertainty in a specific application response that has been calculated. As a result, the observed discrepancies between the measured and calculated responses are reduced, as well as the uncertainties associated with the adjusted quantities.

The value of chi-square, χ^2, is a key to the proper interpretation of the TSURFER results. The χ^2 statistic is a measure of the overall consistency of the set of experimental values of the benchmark responses and the nuclear parameters used for their calculation. TSURFER edits the total χ^2 value, as well as individual values for each experiment. The individual χ^2 values may suggest which experiments contain inconsistencies (i.e., the magnitude of the measured-to-calculated k_{eff} discrepancy is larger than their combined uncertainties). However, the source of inconsistencies may well lie in the nuclear input parameters and, although all responses have small individual χ^2 values, the whole suit may not turn out to be consistent. Values of chi-square per degree of freedom should generally be within about 20% of unity for defensible results. Results in which this test is not met may still be valid, but in general these should be viewed with skepticism unless the reasons for the test failure are understood.

Several established methods can be used to modify the value of chi-square per degree of freedom. One includes a reevaluation of experimental uncertainties and their correlations. A high value of χ^2 indicates that the predicted data variations are well outside the bounds of the standard deviations. If the input experimental uncertainties are underestimated, the data movements can be too extreme and are reflected in high χ^2 values. Values of χ^2 that are too low often suggest that the input experimental uncertainty estimates might be too high, and again a reevaluation should be performed. Thus, it is quite important to utilize *realistic* (not conservative) estimates for the uncertainties in nuclear data and experimental measurements. Yeivin et al. [2] presented a detailed discussion of inconsistencies and demonstrated a technique for rejecting the responses most responsible for the inconsistencies of the whole suit. An alternative rejection technique based on the value of the “diagonal contribution to chi square,” which is the product of the square of the deviation of the measured from the calculated response values and the respective diagonal value of the inverse of the deviation uncertainty matrix, is presented here.

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RESULTS

Twenty-two International Criticality Safety Benchmark Evaluation Project (ICSBEP) [3] highly enriched thermal solution systems were used for this analysis. Throughout the calculations of proposed adjustments, the last three responses (20, 21, and 22, or hst014-01, hst015-01, and hst015-02) were used only as "applications" (i.e., they participated only passively in the adjustment). The chi-square per degree of freedom, χ^2/n, of this setup was 4.2598**,** an unacceptable result. The ICSBEP names, calculated k_{eff}, and the χ^2 properties for each of the remaining 19 systems are presented (Table I). Systems 9, 6, and 14, which had the highest values of the "diagonal contribution to chi-square," were excluded from the adjustment campaign, resulting in a χ^2/n of 0.9976**,** which is quite acceptable. One could have guessed a priori that these three systems are candidates for rejection because of the deviation of their calculated values of k_{eff} from the experimental value of 1. However, their individual chi-square values do not deviate from unity and the criterion we chose takes into account the global effect of the information analyzed. The k_{eff} values of each of the systems are depicted in Fig. 1 for each of the adjustment campaigns. The curve labeled "c" shows the original calculated k_{eff} values; "a-4.3," the adjusted k_{eff} values using all 19 systems; "a-3.5," the adjusted k_{eff} values after system 9 was rejected; "a-1.6," the adjusted k_{eff} values after the rejection of systems 9 and 6; and the curve labeled "best," the adjusted k_{eff} values after the rejection of the three systems 9, 6, and 14, resulting in chi-square per degree of freedom of ~1. Obviously, the predicted k_{eff} values of systems 1, 2, and 3 that do not exclude the inconsistent systems are significantly out of line with the "best" k_{eff} values.

TABLE I. HST Systems Properties.

System no.	Name	C	Indep. chi-sq.	Diag. of chi-sq.
1	hst009-01	1.0033E+00	0.0646	1.1857
2	hst009-02	1.0038E+00	0.0972	2.6007
3	hst009-03	1.0029E+00	0.0681	2.4198
4	hst009-04	9.9681E-01	0.0937	1.7902
5	hst010-01	1.0030E+00	0.0965	17.3072
6	hst010-02	1.0038E+00	0.1527	**27.4728**
7	hst010-03	1.0004E+00	0.0013	0.2446
8	hst010-04	9.9859E-01	0.0205	3.7139
9	hst011-01	1.0067E+00	0.5041	**37.0796**
10	hst011-02	1.0025E+00	0.0699	5.0769
11	hst012-01	1.0019E+00	0.0567	1.6014
12	hst013-01	9.9980E-01	0.0265	0.399
13	hst043-01	9.99752E-01	0.0104	0.3155
14	hst043-02	1.0078E+00	0.8847	**20.6383**
15	hst043-03	1.0028E+00	0.1981	3.3844
16	hst042-05	1.0000E+00	0	0
17	hst042-06	1.0003E+00	0.0011	0.0105
18	hst042-07	1.0011E+00	0.016	0.1778
19	hst042-08	1.0014E+00	0.0265	0.3112

CONCLUSIONS

A numerical illustration of a systematic rejection campaign demonstrates the importance of rejecting inconsistent systems in order to obtain meaningful biases and uncertainties utilizing the GLLS methodology in criticality safety applications.

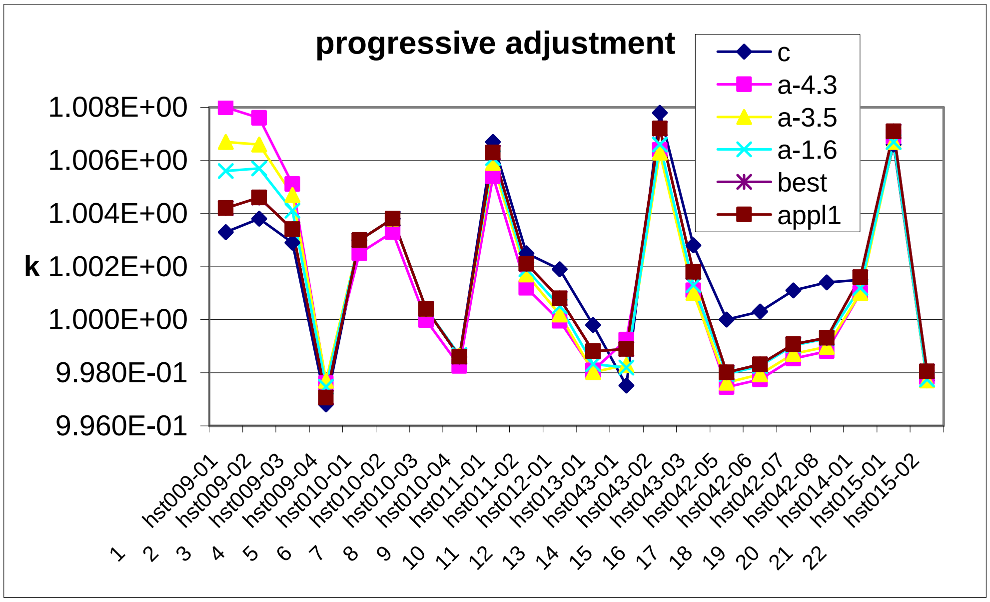

Fig. 1. Inconsistent systems rejection.

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