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Title: Comparison Study of Upper Subcritical Limits Derived Using Sensitivity/Uncertainty Tools Case Studies of Benchmarks and Applications

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Comparison Study of Upper Subcritical Limits Derived Using Sensitivity/Uncertainty Tools

Case Studies of Benchmarks and Applications

Jennifer Alwin, Forrest Brown, Benjamin Murphy, Matthew Lazaric, Kristina Spencer

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Introduction

Neutron transport methods used to establish subcriticality require validation by comparison to critical experiments considered to be benchmarks. Whisper is a sensitivity/uncertainty analysis tool developed to assist with the task of validation in nuclear criticality safety. Details on the Whisper methodology can be found in References 1-3 on the MCNP® reference collection website at https://mcnp.lanl.gov. Whisper-1.0 was originally developed in 2014 and used to assist with nuclear criticality safety validation at Los Alamos National Laboratory. Whisper was upgraded in 2016 to Whisper-1.1 and prepared for release with MCNP6.2 [References 3-5]. Whisper contains a library of over 1100 critical experiment benchmarks and quantifies neutronic similarity of an application to benchmarks in the library. Using highest similarity benchmarks, Whisper computes a calculational margin (CM) encompassing of the worst-case bias and bias uncertainty at a 99% confidence level for each application. In addition, portions of the margin of subcriticality (MOS) for nuclear data uncertainty and potential code errors are computed. The baseline upper subcritical limit (USL) computed by Whisper is comprised of the CM, $MOS_{\text{nuclear data}}$, and $MOS_{\text{code errors}}$. The Whisper baseline USL is absent a portion of the MOS due to the area of application, which is applied based upon judgment by the criticality safety analyst.

An objective of this paper is to present the baseline USL, CM and portions of the MOS as computed by Whisper for comparison with similar sensitivity/uncertainty tools, such as those used by IRSN and ORNL. The initial comparison involves four critical experiment benchmarks: HEU-MET-FAST-013-001, HEU-SOL-THERM-001-008, PU-MET-FAST-022-001, AND PU-SOL-THERM-001-001, which have been:

1. modeled independently by LANL, IRSN, and ORNL based upon information provided in the ICSBEP Handbook,
2. are common in S/U libraries for LANL, IRSN, and ORNL,
3. span a range of energy spectrum and fissile material, and
4. taken as applications for the purposes of this study and therefore excluded from use as a benchmark for calculating the upper subcritical limit.

Results presented in this paper have been computed using covariance data for all isotopes in ENDF/B-VII.0 using a 44-group energy structure [Reference 6]. Benchmarks in the Whisper library were run in MCNP6.2 using 100,000 neutrons per cycle, skipping 100 cycles for 500 active cycles. Reference 10 also compares the results for baseline USL with an order of magnitude greater neutrons, using the same total number of cycles with 1,000,000 neutrons per cycle. Subsequent to the results presented in Reference 10 changes were made to the benchmark library, as discussed in Reference 11. Newer results using the revised benchmark library are presented herein.

During the process of validation there can be cases where a benchmark experiment may be found to be a statistical outlier, in which the calculated k-effective value and the experiment k-effective value differ by an amount atypical for similar experiments. A methodology optionally employed by Whisper is the exclusion of statistical outliers based upon the iterative diagonal chi-squared statistical rejection technique. Alternatively, there is an option to include all benchmarks in the Whisper library collection, even those benchmarks found to be statistical outliers, when computing the bias, bias uncertainty and margin of subcriticality (MOS) leading to establishment of the baseline upper subcritical limit (USL). Reference 10 includes a comparison study to compute USLs with and without statistical outliers in the Whisper benchmark collection to determine what effect rejection of statistical outliers has on the

recommended USL. The results show little overall difference in the recommended baseline USLs developed by Whisper when excluding statistical outliers. There does not appear to be a clear trend in predicting whether the baseline USL will be higher or lower when rejecting statistical outliers from the benchmark critical experiment collection used for validation. Results presented herein include all benchmarks in the library, including those identified to be statistical outliers. The 2017 revision to ANSI/ANS-8.24 requires that any exclusion of statistical outliers must be based upon physical justification; identification of outliers may be based upon statistical techniques, however the standard does not allow exclusion of identified outliers based upon statistical analysis.

Study

Application models used for this study are HEU-MET-FAST-013-001, HEU-SOL-THERM-001-008, PU-MET-FAST-022-001, AND PU-SOL-THERM-001-001 taken from the Whisper-1.1 benchmark library, and therefore excluded as benchmarks when computing the USL for this study. A short description of each is provided below.

HEU-MET-FAST-013-001: The critical assembly is a sphere of highly enriched uranium reflected by steel.

HEU-SOL-THERM-001-008: The assembly consists of highly enriched uranium foils reflected by polyethylene and interleaved with plates of SiO_2glass and polyethylene.

PU-MET-FAST-022-001: The critical assembly is a bare spherical assembly of δ–phase plutonium (98% ^{239}Pu) metal having a central cavity of 1.4 cm radius.

PU-SOL-THERM-001-001: The critical assembly consists of water-reflected 11.5-inch diameter sphere of plutonium (~95% ^{239}Pu) nitrate solution with a concentration of 73 g/L Pu and acid molarity of 0.2 M nitrate.

Results were computed on the Los Alamos National Laboratory High Performance Computing (HPC) platform Snow. This platform is based on Linux OS with Intel Xeon Broadwell processors and 36 CPU nodes per core. The MCNP6.2 calculations were done using 18 tasks. Each MCNP6.2 case was modeled with 100,000 neutrons per cycle, skipping the initial 100 cycles and running a total of 600 cycles for a total of 50 million neutrons overall.

Once the MCNP6.2 results were obtained, Whisper using all available benchmarks in the library, including those determined to be statistical outliers was used to compute USL. In all cases HEU-MET-FAST-013-001, HEU-SOL-THERM-001-008, PU-MET-FAST-022-001, and PU-SOL-THERM-001-001 were excluded from the benchmark collection since they are used as application cases for the purposes of this study. Results for the calculational margin, the computed statistical bias and bias uncertainty, are compared in several studies, some of which have been previously documented. Two new studies are included in this document. The first study compares the Whisper method using its benchmark library compared with benchmark libraries from SNL and SRNS for use with MCNP6. The second study compares the Whisper method using its benchmark library compared with the ORNL and IRSN methods each with their own benchmark libraries.

Results

HEU-MET-FAST-013-001

Statistical results for the case are shown in Table 1. A subset of the benchmarks in each of the collections, enough found to be neutronically similar for valid statistical analysis in each case, are used to compute the baseline USL. Whisper selected 75 benchmarks as similar when using the LANL library, 62 when using the SNL library, and 59 when using the SRNS library; selections displayed in Table 2. There are 23 benchmarks selected by Whisper from the LANL library that are selected by Whisper from the SNL library and 7 selected in common between the LANL and SRNS libraries. Comparing those selected in common from the SNL library and the SRNS library there are in 24 common. Those benchmarks selected as similar to the application from multiple libraries are highlighted in green.

For the HEU-MET-FAST-013-001 case the series of relevant benchmark experiments are from HEU-MET-FAST. There were also two benchmarks from INT-MET-FAST selected from the SNL library. Benchmarks were found to be highly correlated, or to have high neutronic similarity, to the application case, with ck ranging from 1 to 0.9494.

The baseline USL for a benchmark collection with Whisper library is 0.9841, with SNL library is 0.9721 and with SRNS library is 0.9725.

TABLE 1. COMPARISON OF WHISPER OUTPUT USING HEU-MET-FAST-013-001 AS AN APPLICATION CASE.

$K_{experiment}$	$\sigma_{experiment}$	$K_{MCNP6.2}$	$\sigma_{MCNP6.2}$
0.9990	**0.0015**	**0.99752**	**0.00009**
Whisper-1.1 Results			
	LANL Library	**SNL Library**	**SRNS Library**
Bias	-0.00571	-0.01135	-0.01252
Bias Uncertainty*	0.00391	0.01090	0.00868
Nuclear Data Uncertainty**	0.00050	0.00050	0.00050
MOS code errors	0.00500	0.00500	0.00500
Baseline USL	**0.9841**	**0.9721**	**0.9725**
Benchmark Population	75	62	59

*Statistical bias uncertainty reported at 99% confidence level

**Nuclear data uncertainty reported at 1-sigma level, ×2.6 for USL calculation at 99%.

TABLE 2. BENCHMARKS SELECTED BY WHISPER AS SIMILAR TO APPLICATION HMF-13-001, THOSE SELECTED BY MULTIPLE LIBRARIES HIGHLIGHTED IN GREEN.

Whisper Selected Benchmarks					
LANL Library	**Wt**	**SNL Library**	**Wt**	**SRNS Benchmark**	**Wt**
HMF-001-001	0.236	HMF-001-001	0.565	HMF-001-001	0.542
				HMF-001-002	0.526
		HMF-004-001	0.040		
HMF-007-001	0.334	HMF-007-001	0.615	HMF-007-001	0.597
		HMF-007-002	0.358	HMF-007-002	0.296
		HMF-007-003	0.263	HMF-007-003	0.173

		HMF-007-004	0.125	HMF-007-004	0.026
HMF-007-019	0.300	HMF-007-019	0.593	HMF-007-019	0.573
		HMF-007-020	0.060		
		HMF-007-021	0.039		
		HMF-007-022	0.001		
		HMF-007-027	0.315	HMF-007-027	0.231
		HMF-007-028	0.024		
HMF-007-032	0.073	HMF-007-032	0.461	HMF-007-032	0.421
		HMF-007-033	0.224	HMF-007-033	0.132
HMF-008-001	0.379	HMF-008-001	0.636		
HMF-009-001	0.071	HMF-009-001	0.463		
HMF-009-002	0.093	HMF-009-002	0.482		
HMF-010-001	0.256	HMF-010-001	0.573		
HMF-010-002	0.265	HMF-010-002	0.553		
		HMF-011-001	0.339		
HMF-012-001	0.382	HMF-012-001	0.642	HMF-012-001	0.632
		HMF-013-001	1.000		
HMF-015-001	0.328	HMF-015-001	0.622		
		HMF-016-001	0.274		
		HMF-016-002	0.315		
		HMF-017-001	0.027		
HMF-018-002	0.303	HMF-018-001	0.595		
HMF-019-001	0.309	HMF-019-001	0.599		
HMF-020-002	0.303	HMF-020-001	0.593		
HMF-021-002	0.957	HMF-021-001	0.953	HMF-021-001	1.000
HMF-022-002	0.347	HMF-022-001	0.617	HMF-022-001	0.611
		HMF-023-002	0.596	HMF-023-002	0.566
		HMF-023-003	0.203	HMF-023-003	0.070
		HMF-023-005	0.010		
		HMF-023-006	0.600	HMF-023-006	0.590
		HMF-023-007	0.568	HMF-023-007	0.555
		HMF-023-008	0.142	HMF-023-008	0.075
		HMF-023-012	0.615	HMF-023-012	0.601
		HMF-023-013	0.293	HMF-023-013	0.124
		HMF-023-015	0.015		
		HMF-023-016	0.595	HMF-023-016	0.574
		HMF-023-017	0.585	HMF-023-017	0.567
		HMF-023-018	0.250	HMF-023-018	0.131
		HMF-023-020	0.006		
		HMF-023-021	0.512	HMF-023-021	0.496
				HMF-023-028	0.609
				HMF-023-029	0.529
		HMF-024-001	0.602	HMF-024-001	0.572
HMF-025-001	0.121				
				HMF-026-001	0.623
				HMF-026-002	0.595

				HMF-026-003	0.243
				HMF-026-004	0.112
				HMF-026-005	0.071
				HMF-026-006	0.561
				HMF-026-007	0.570
				HMF-026-008	0.232
				HMF-026-009	0.064
				HMF-026-010	0.110
				HMF-026-011	0.618
				HMF-026-012	0.615
				HMF-026-013	0.601
				HMF-026-014	0.484
				HMF-026-015	0.370
				HMF-026-016	0.267
				HMF-026-017	0.272
				HMF-026-018	0.534
				HMF-026-019	0.583
				HMF-026-020	0.372
				HMF-026-021	0.293
				HMF-026-022	0.295
				HMF-026-023	0.611
				HMF-026-024	0.615
				HMF-026-025	0.439
				HMF-026-026	0.405
				HMF-026-027	0.399
				HMF-026-028	0.547
				HMF-026-029	0.604
				HMF-026-030	0.481
				HMF-026-031	0.408
				HMF-026-032	0.433
HMF-027-001	0.224	HMF-027-001	0.549		
HMF-041-003	0.209	HMF-041-003	0.542		
		HMF-041-004	0.381		
		HMF-041-005	0.258		
		HMF-041-006	0.191		
HMF-043-001	0.634				
HMF-043-002	0.788				
HMF-043-003	0.892				
HMF-043-004	0.948				
HMF-043-005	0.947				
HMF-044-001	0.326				
HMF-044-002	0.318				
HMF-044-003	0.324				
HMF-044-004	0.308				
HMF-044-005	0.321				
		HMF-048-001	0.128		

HMF-051-001	0.364				
HMF-051-002	0.363				
HMF-051-003	0.367				
HMF-051-004	0.362				
HMF-051-009	0.358				
HMF-051-014	0.288				
HMF-051-015	0.345				
HMF-051-016	0.366				
HMF-051-017	0.355				
		HMF-058-004	0.187		
		HMF-058-005	0.374		
HMF-063-001	0.212	HMF-063-001	0.546		
HMF-063-002	0.197	HMF-063-002	0.536		
HMF-065-002	0.278				
HMF-078-003	0.195				
HMF-078-023	0.332				
HMF-078-025	0.293				
HMF-078-027	0.141				
HMF-078-031	0.126				
HMF-078-035	0.115				
HMF-078-037	0.120				
HMF-078-039	0.107				
HMF-078-041	0.348				
HMF-078-043	0.213				
HMF-079-001	0.320				
HMF-079-002	0.287				
HMF-079-003	0.210				
HMF-079-004	0.129				
HMF-079-005	0.118				
HMF-084-001	0.320				
HMF-084-002	0.114				
		HMF-084-003	0.297		
HMF-084-004	0.327				
HMF-084-005	0.267				
HMF-084-007	1.000				
HMF-084-011	0.031				
HMF-084-012	0.027				
HMF-084-015	0.274				
HMF-084-016	0.177	HMF-084-016	0.525		
HMF-084-017	0.343				
HMF-084-019	0.880				
HMF-084-022	0.203				
HMF-084-023	0.296				
HMF-084-026	0.490	HMF-084-026	0.693		
HMF-084-027	0.428	HMF-084-027	0.665		
HMF-087-001	0.891				

HMF-089-001	0.312				
HMF-100-001	0.247				
HMF-100-002	0.270				
		IMF-001-001	0.323		
		IMF-001-002	0.262		

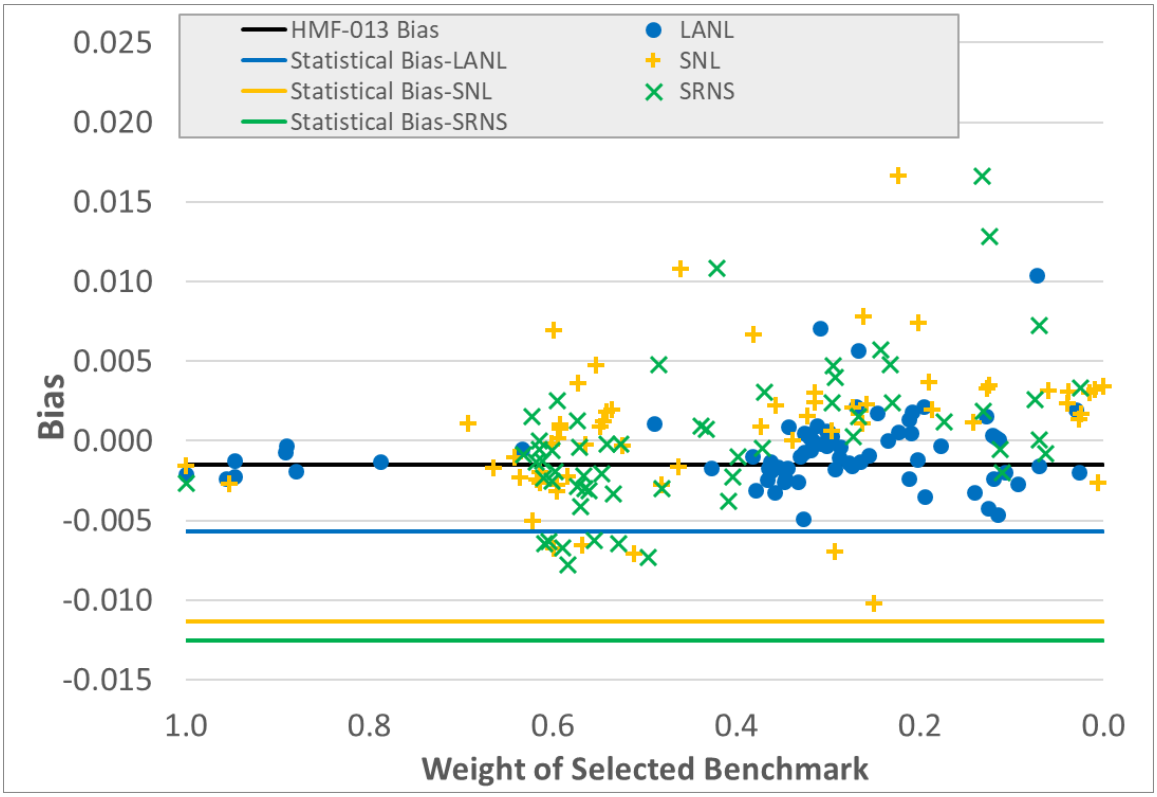

FIGURE 1. INDIVIDUAL BENCHMARK BIAS & STATISTICAL BIAS CALCULATED USING WHISPER WITH LANL/SNL/SRNS BENCHMARK LIBRARIES

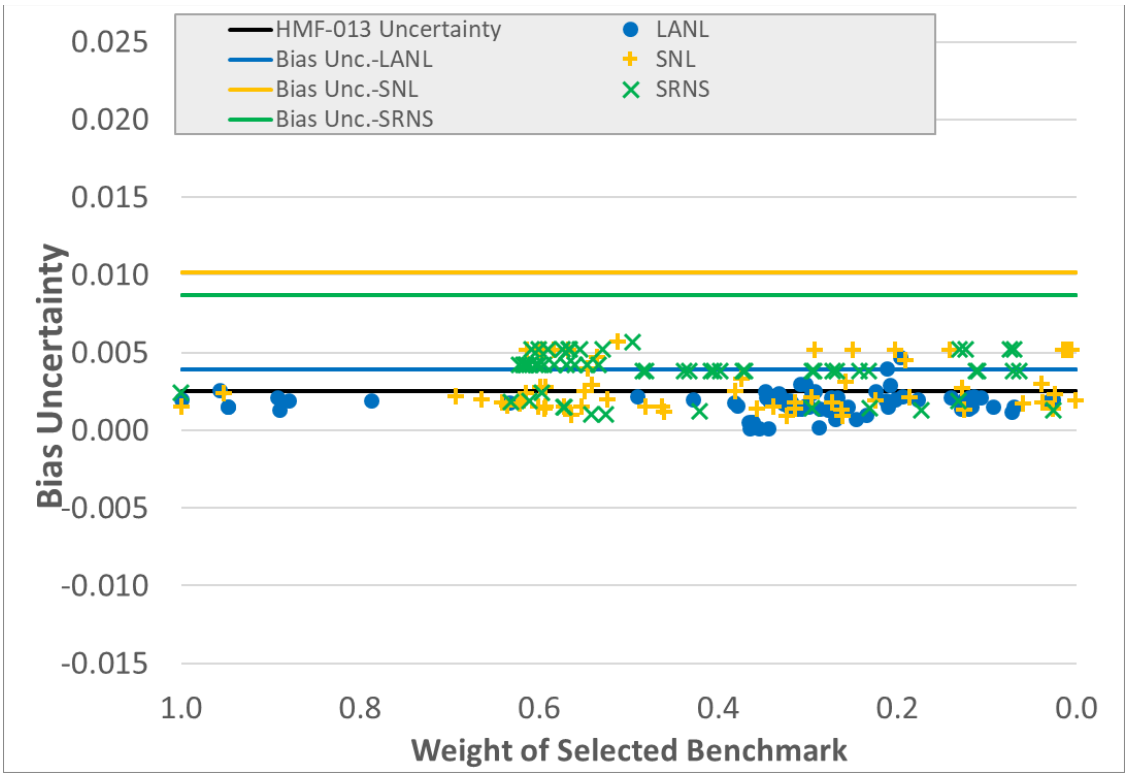

FIGURE 2. INDIVIDUAL BENCHMARK UNCERTAINTY & STATISTICAL UNCERTAINTY CALCULATED USING WHISPER WITH LANL/SNL/SRNS LIBRARIES

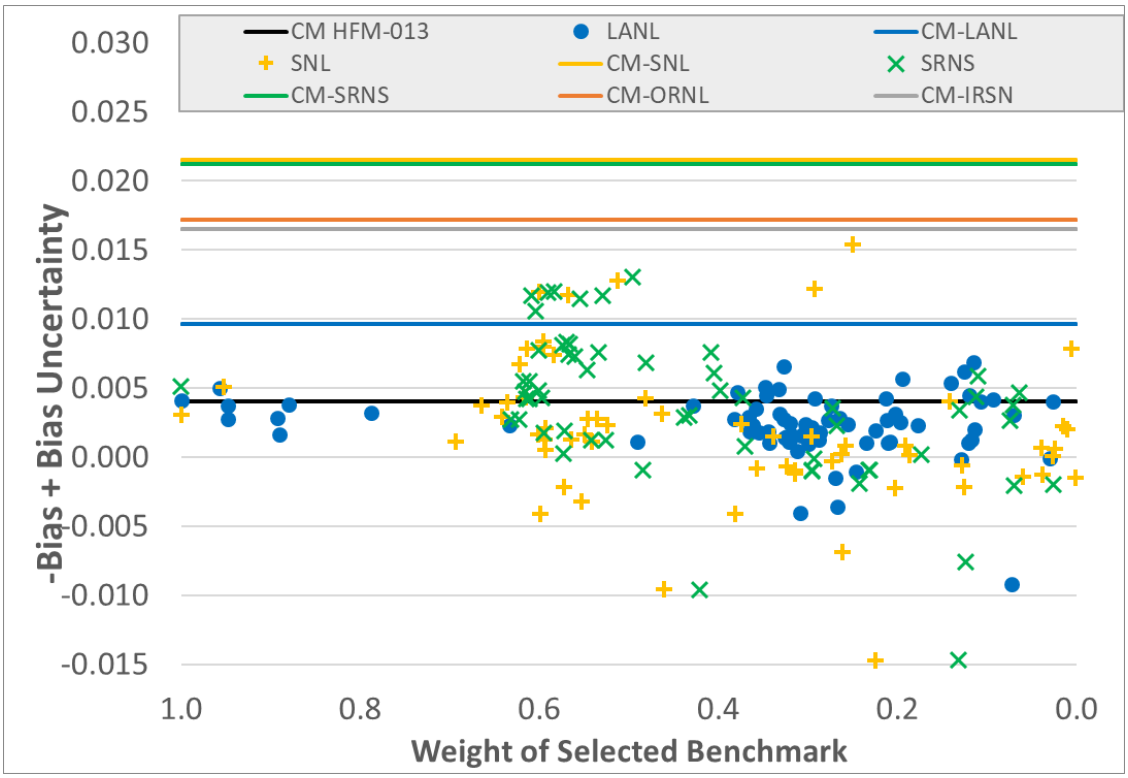

FIGURE 3. CALCULATIONAL MARGIN USING WHISPER WITH LANL/SNL/SRNS LIBRARIES, ORNL METHOD & IRSN METHOD

Results for the bias are in Figure 1, MCNP6.2 calculated k-effective is 0.99752 with a standard deviation of 0.00009, in this case the code calculates very slightly lower than the experimental k-effective of 0.9990, labeled HMF-013 bias in Figure 1 and Table3. The individual data points are bias of selected benchmarks from the LANL, SNL, and SRNS libraries. As can be seen in the figure by comparing the individual biases and the statistical bias calculated by Whisper using the various benchmark selections, the statistical bias encompasses the individual biases.

Results for bias uncertainty are in Figure 2 with individual benchmark uncertainty plotted from the benchmarks selected from the LANL, SNL, and SRNS libraries. As can be seen in the figure by comparing the individual statistical bias uncertainties and those calculated by Whisper, the statistical bias uncertainty encompasses the individual bias uncertainties for each respective set of selected benchmarks. The bias uncertainty reported in Table 3 is at the 95% confidence level, which is slightly lower than the value at the 99% confidence level reported in Table 1.

Figure 3 presents a comparison of all results for the calculational margin. In all cases, the statistically computed calculational margin is conservative. The CM as calculated by ORNL and IRSN methods at the 95% level are also in the figure. The highest CM are for the Whisper method using the SNL and SRNS libraries, the lowest is for the Whisper method using the LANL library. This lower CM, while still conservative, is a result of the lower degree of spread in the data for the LANL distribution than the other data sets. Table 3 shows the CM and baseline USL calculated using Whisper, the ORNL and IRSN methods. Whisper selected 75 benchmarks as similar to HMF-013, ORNL selected 40, and IRSN selected 303. Comparing those selected by LANL and ORNL, there are 11 in common. Between LANL and IRSN, there are 9 in common, and 2 in common between ORNL and IRSN. Baseline USLs are quite similar ranging from 0.9828 to 0.9858.

TABLE 3. STATISTICAL DIFFERENCES BETWEEN LANL, ORNL, IRSN METHODS ALONG WITH BENCHMARKS CHOSEN AS SIMILAR TO APPLICATION

k-effective$_{experiment}$		**$\sigma_{experiment}$**	
0.9990		**0.0015**	
Calculated k-effective & USL Results (95% Confidence)			
	LANL	**ORNL**	**IRSN**
k-effective	0.99752 ± 0.00009	0.99730 ± 0.00010	0.99655 ± 0.00010
HMF-013 Bias	-0.00148	-0.00170	-0.00245
Bias	-0.00571	-0.00780	-0.00358
Bias Uncertainty*	0.00253	0.00940	0.01294
Nuclear Data Unc.**	0.00050	-	-
MOS code errors	0.00500	-	-
Baseline USL	**0.9858**	**0.9828**	**0.9835**
Benchmark Population	75	40	303
Selected Benchmarks			
	LANL Library	**ORNL Library**	**IRSN Library**
	HMF-001-001		HMF001-001
			HMF003-008
			HMF003-009
			HMF003-010

			HMF003-012
	HMF-007-001		
	HMF-007-019		
	HMF-007-032		
	HMF-008-001	HMF-008-001	
	HMF-009-001	HMF-009-001	
	HMF-009-002	HMF-009-002	
	HMF-010-001	HMF-010-001	
	HMF-010-002	HMF-010-002	
		HMF-011-001	
	HMF-012-001		
	HMF-015-001	HMF-015-001	
		HMF-016-001	
		HMF-016-002	
		HMF-017-001	
		HMF-018-001	
	HMF-018-002	HMF-018-001S	
	HMF-019-001	HMF-019-001	
		HMF-019-001S	
		HMF-020-001	
	HMF-020-002	HMF-020-001S	
	HMF-021-002	HMF-021-001S	
		HMF-021-001	
	HMF-022-002		
		HMF-024-001	
	HMF-025-001	HMF-025-001	
		HMF-025-002	
		HMF-025-003	
		HMF-025-004	
		HMF-025-005	
			HMF026-001 to -032
	HMF-027-001		
			HMF-033-001 to -002
			HMF-034-001 to -003
			HMF-036-001 to -002
		HMF-040-001	
	HMF-041-003		HMF-041-003 to 06
	HMF-043-001		HMF-043-001
	HMF-043-002		HMF-043-002
	HMF-043-003		
	HMF-043-004		
	HMF-043-005		
	HMF-044-001		
	HMF-044-002		
	HMF-044-003		
	HMF-044-004		

	HMF-044-005		
	HMF-051-001		
	HMF-051-002		
	HMF-051-003		
	HMF-051-004		
	HMF-051-009		
	HMF-051-014		
	HMF-051-015		
	HMF-051-016		
	HMF-051-017		
			HMF-058-001
			HMF-058-002
			HMF-058-003
			HMF-058-004
			HMF-058-005
	HMF-063-001		
	HMF-063-002		
		HMF-065-001	
	HMF-065-002		
	HMF-078-003		
	HMF-078-023		
	HMF-078-025		
	HMF-078-027		
	HMF-078-031		
	HMF-078-035		
	HMF-078-037		
	HMF-078-039		
	HMF-078-041		
	HMF-078-043		
	HMF-079-001		HMF-079-001
	HMF-079-002		HMF-079-002
	HMF-079-003		HMF-079-003
	HMF-079-004		HMF-079-004
	HMF-079-005		HMF-079-005
		HMF-080-001	
	HMF-084-001		
	HMF-084-002		
	HMF-084-004		
	HMF-084-005		
	HMF-084-007		
	HMF-084-011		
	HMF-084-012		
	HMF-084-015		
	HMF-084-016		
	HMF-084-017		

	HMF-084-019		
	HMF-084-022		
	HMF-084-023		
	HMF-084-026		
	HMF-084-027		
		HMF-086-001	
		HMF-086-002	
		HMF-086-003	
		HMF-086-004	
		HMF-086-005	
	HMF-087-001		
	HMF-089-001		HMF-089-001
			HMF-090 001
		HMF-092-001	HMF-092-001
		HMF-092-002	HMF-092-002
		HMF-092-003	
		HMF-092-004	
		HMF-093-001	HMF-093-001
			HMF-094-001
			HMF-094-002
	HMF-100-001		
	HMF-100-002		
		IMF-005-001	
		IMF-005-001S	
		IMF-019-001	
			HST-001 to -007, -009 to -010
			HST004-003 , -005 and -006
			HST-006-001 to -011, -022 to -026
			HST-007-001 to -017
			HST-016-001 to -03
			HST-017-004 to -06
			HST-020-001 to -005
			HST-025-001 to -018
			HST-028-006
			HST-039-001 to -006
			HST-042 -001 to-0 08
			HST-050 -001 to -011
			PMF-001-001
			PMF-002-001
			PMF-005-001
			PMF-006-001
			PMF-0100-01

			PMF-0110-01
			PMF-016-001, -002
			PMF-019-001
			PMF-023-001
			PMF-024-001
			PMF-025-001
			PMF-027-001
			PMF-028-001
			PMF-029-001
			PMF-030-001
			PMF-031-001
			PMF-032-001
			PMF-035-001
			PMF-038-001
			PMF-039-001
			PMF-040-001
			PMF-045-001 to -007
			PST-001-002 to -006
			PST-004-002 , -003, -005, -006, -008, -011
			PST-010 case 1 to 4
			PST018 case 1 to 9
			PST28 case 1 to 15
			PST30 case 1 to 16
			PST31 case 6 and 7
			PST-032-001 to -017
			PST-033-015 to -017, -027, -030 to -032, -034, -038, -049, -054, -059 to -063
			PST-034-001 to -015

*Statistical bias uncertainty reported at 95% confidence level

**Nuclear data uncertainty reported at 1-sigma level, ×2 for USL calculation at 95%.

HEU-SOL-THERM-001-008

Statistical results for the case are shown in Table 4. A subset of the benchmarks in each of the collections, enough found to be neutronically similar for valid statistical analysis in each case, are used to compute the baseline USL. Whisper selected 51 benchmarks as similar when using the LANL library, 53 when using the SNL library, and 50 when using the SRNS library; selections are displayed in Table 5. There are 11 benchmarks selected by Whisper from the LANL library that are selected by Whisper from the SNL and SRNS libraries. Comparing those selected in common from the SNL library and the SRNS library there are in 44 common. Those benchmarks selected as similar to the application from multiple libraries are highlighted in green.

For the HEU-SOL-THERM-001-008 case the series of relevant benchmark experiments are from HEU-SOL-THERM, HEU-COMP-THERM, AND HEU-MET-THERM. Two cases from INT-MET-THERM are found to be similar from the SRNS collection. Benchmarks were found to be highly correlated, or to have high neutronic similarity, to the application case with ck ranging from 1 to 0.9719. The LANL baseline USL is 0.9616 and the SNL and SRNS are identical 0.9656 as almost all benchmarks are in common.

TABLE 4. COMPARISON OF WHISPER OUTPUT USING HEU-SOL-THERM-001-081 AS AN APPLICATION CASE.

$K_{experiment}$	$\sigma_{experiment}$	$K_{MCNP6.2}$	$\sigma_{MCNP6.2}$
0.9998	**0.0038**	**0.99823**	**0.00015**
Whisper-1.1 Results			
	LANL Library	**SNL Library**	**SRNS Library**
Bias	-0.01462	-0.01720	-0.01623
Bias Uncertainty*	0.01731	0.01075	0.01165
Nuclear Data Uncertainty**	0.00056	0.00056	0.00056
MOS code errors	0.00500	0.00500	0.00500
Baseline USL	**0.9616**	**0.9656**	**0.9656**
Benchmark Population	51	53	50

*Statistical bias uncertainty reported at 99% confidence level

**Nuclear data uncertainty reported at 1-sigma level, ×2.6 for USL calculation at 99%.

TABLE 5. BENCHMARKS SELECTED BY WHISPER AS SIMILAR TO APPLICATION HST-001-008, THOSE SELECTED BY MULTIPLE LIBRARIES HIGHLIGHTED IN GREEN.

Whisper Selected Benchmarks					
LANL Library	**Wt**	**SNL Library**	**Wt**	**SRNS Benchmark**	**Wt**
HST-001-001	0.9908	HST-001-001	0.9642	HST-001-001	0.963
HST-001-002	0.7762	HST-001-002	0.1878	HST-001-002	0.2556
HST-001-003	1	HST-001-003	1	HST-001-003	1
HST-001-004	0.7675	HST-001-004	0.1645	HST-001-004	0.1707
HST-001-005	0.7409	HST-001-005	0.0903	HST-001-005	0.1384
HST-001-006	0.8015	HST-001-006	0.2801	HST-001-006	0.2785
HST-001-007	0.9998	HST-001-007	0.9994	HST-001-007	0.9984
HST-001-009	0.7642	HST-001-009	0.1622	HST-001-009	0.218
HST-001-010	0.81	HST-001-010	0.3288	HST-001-010	0.3427
		HST-002-001	0.958	HST-002-001	0.952
		HST-002-002	0.7779	HST-002-002	0.7703
		HST-002-003	0.2926	HST-002-003	0.3167
		HST-002-004	0.039	HST-002-004	0.0486
		HST-002-005	0.9848	HST-002-005	0.9805
		HST-002-006	0.8148	HST-002-006	0.7639
		HST-002-007	0.3033	HST-002-007	0.342
		HST-002-008	0.0908	HST-002-008	0.1161
		HST-002-009	0.1693	HST-002-009	0.2146
		HST-002-011	0.9847	HST-002-011	0.9796

		HST-002-012	0.6531	HST-002-012	0.6521
		HST-002-013	0.3222	HST-002-013	0.3528
		HST-003-002	0.0302	HST-003-002	0.0582
		HST-003-003	0.9493	HST-003-003	0.9596
		HST-003-004	0.832	HST-003-004	0.8348
		HST-003-005	0.2431	HST-003-005	0.2946
		HST-003-006	0.1871	HST-003-006	0.2317
		HST-003-008	0.9993	HST-003-008	0.9962
		HST-003-009	0.9297	HST-003-009	0.9377
		HST-003-010	0.2675	HST-003-010	0.3115
		HST-003-011	0.3722	HST-003-011	0.3879
		HST-003-012	0.2479	HST-003-012	0.2863
		HST-003-014	0.2005	HST-003-014	0.1618
		HST-003-015	0.1861	HST-003-015	0.2065
		HST-003-016	0.9971	HST-003-016	0.9938
		HST-003-017	0.8724	HST-003-017	0.8809
		HST-003-018	0.2916	HST-003-018	0.3369
		HST-003-019	0.3548	HST-003-019	0.3732
				HST-006-001	0.3654
				HST-006-008	0.3357
				HST-006-012	0.2636
				HST-006-027	0.2115
		HST-008-008	0.1067	HST-008-008	0.1348
HST-009-001	0.2435				
HST-009-002	0.618				
HST-009-003	0.8989	HST-009-003	0.6192	HST-009-003	0.6494
		HST-009-004	0.8826	HST-009-004	0.899
HST-010-001	0.888	HST-010-001	0.6114	HST-010-001	0.6436
		HST-010-002	0.6382	HST-010-002	0.6308
		HST-010-003	0.6764	HST-010-003	0.6902
		HST-010-004	0.7264	HST-010-004	0.708
HST-011-001	0.5288				
HST-011-002	0.5351				
		HST-015-001	0.5335		
		HST-016-001	0.1556		
		HST-017-001	0.3375		
		HST-017-002	0.6015		
		HST-017-003	0.1064		
		HST-017-004	0.0158		
		HST-018-001	0.1521		
		HST-018-002	0.3185		
		HST-018-005	0.0026		
HST-019-001	0.5335				
HST-019-002	0.5255				
HST-019-003	0.331				
HST-025-001	0.3653				

HST-025-002	0.3588				
HST-025-004	0.3927				
HST-025-005	0.6169				
HST-038-001	0.0625				
HST-038-004	0.0165				
HST-038-005	0.0038				
HST-038-011	0.0825				
HST-038-012	0.0859				
HST-043-001	0.9886				
HST-050-001	0.2299				
HST-050-002	0.2346				
HST-050-004	0.2513				
HST-050-005	0.7998				
HST-050-006	0.2472				
HST-050-008	0.2401				
HST-050-010	0.2202				
HST-050-011	0.7867				
HCT-002-001	0.3244				
HCT-002-002	0.4982				
HCT-002-003	0.4549				
HCT-002-004	0.3692				
HCT-002-005	0.1581				
HCT-002-011	0.4801				
HCT-002-012	0.3953				
HCT-002-013	0.1824				
HCT-002-018	0.6615				
HCT-002-019	0.6604				
HCT-002-020	0.345				
HCT-002-023	0.7374				
HCT-002-024	0.5017				
HCT-002-025	0.1572				
HMT-014-001	0.3447				
				IST-002-005	0.2837
				IST-003-016	0.1056

Results for the bias are in Figure 5, MCNP6.2 calculated k-effective is 0.99823 with a standard deviation of 0.00015, in this case the code calculates very slightly lower than the experimental k-effective of 0.9998, labeled HST1 bias in Figure 5 and Table 6. The individual data points are the bias of selected benchmarks from the LANL, SNL, and SRNS libraries. As can be seen in the figure by comparing the individual biases and the statistical bias calculated by Whisper using the various benchmark selections, the statistical bias encompasses nearly all the individual biases. There are two benchmarks from the SNL library, HST-017-002 and -003 with outlying bias in the range of -0.019, which are not in the LANL or SRNS selection. HCT-002-005 in the LANL selection also has an extreme bias of -0.016. The wide distribution of the data accounts for the particularly low USLs using the LANL, SNL, and SRNS libraries.

Results for bias uncertainty are in Figure 6 with individual benchmark uncertainty plotted from the benchmarks selected from the LANL, SNL, and SRNS libraries. As can be seen in the figure by comparing the individual statistical bias uncertainties and those calculated by Whisper, the statistical bias uncertainty encompasses the individual bias uncertainties for each respective set of selected benchmarks. The bias uncertainty reported in Table 6 is at the 95% confidence level, which is slightly lower than the value at the 99% confidence level reported in Table 4.

Figure 7 presents a comparison of all results for the calculational margin. In all cases, the statistically computed calculational margin is conservative. The CM calculated by ORNL and IRSN methods at the 95% level are also in the figure. The highest CM are for the Whisper method using the LANL library, the lowest is for the IRSN method. Table 6 shows the CM and baseline USL calculated using Whisper, the ORNL and IRSN methods. Whisper selected 51 benchmarks as similar to HST-001-008, ORNL selected 46, and IRSN selected 100. Comparing those selected by LANL and ORNL, there are 9 in common. Between LANL and IRSN, there are 21 in common, and 17 in common between ORNL and IRSN. Baseline USLs are variable ranging from 0.9688 to 0.9866, the lower USL due to the HCT-002 series in the LANL library.

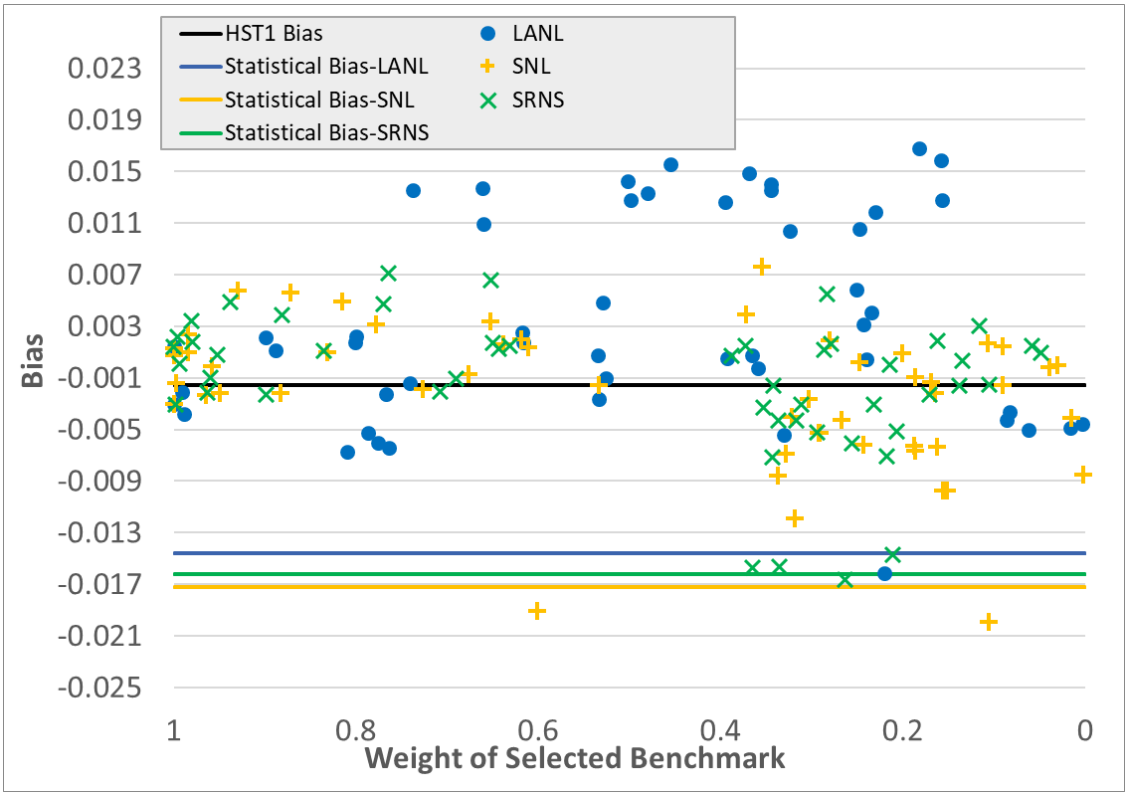

FIGURE 4. INDIVIDUAL BENCHMARK BIAS & STATISTICAL BIAS CALCULATED USING WHISPER WITH LANL/SNL/SRNS BENCHMARK LIBRARIES

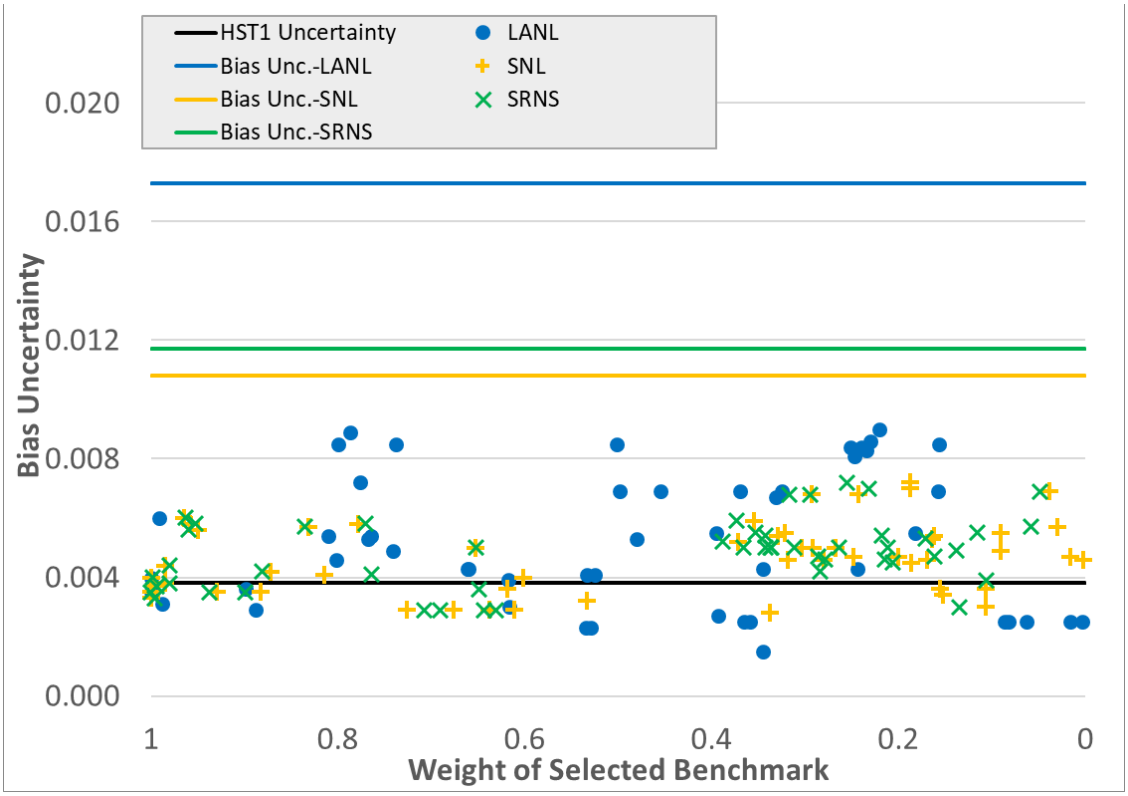

FIGURE 5. INDIVIDUAL BENCHMARK UNCERTAINTY & STATISTICAL UNCERTAINTY CALCULATED USING WHISPER WITH LANL/SNL/SRNS LIBRARIES

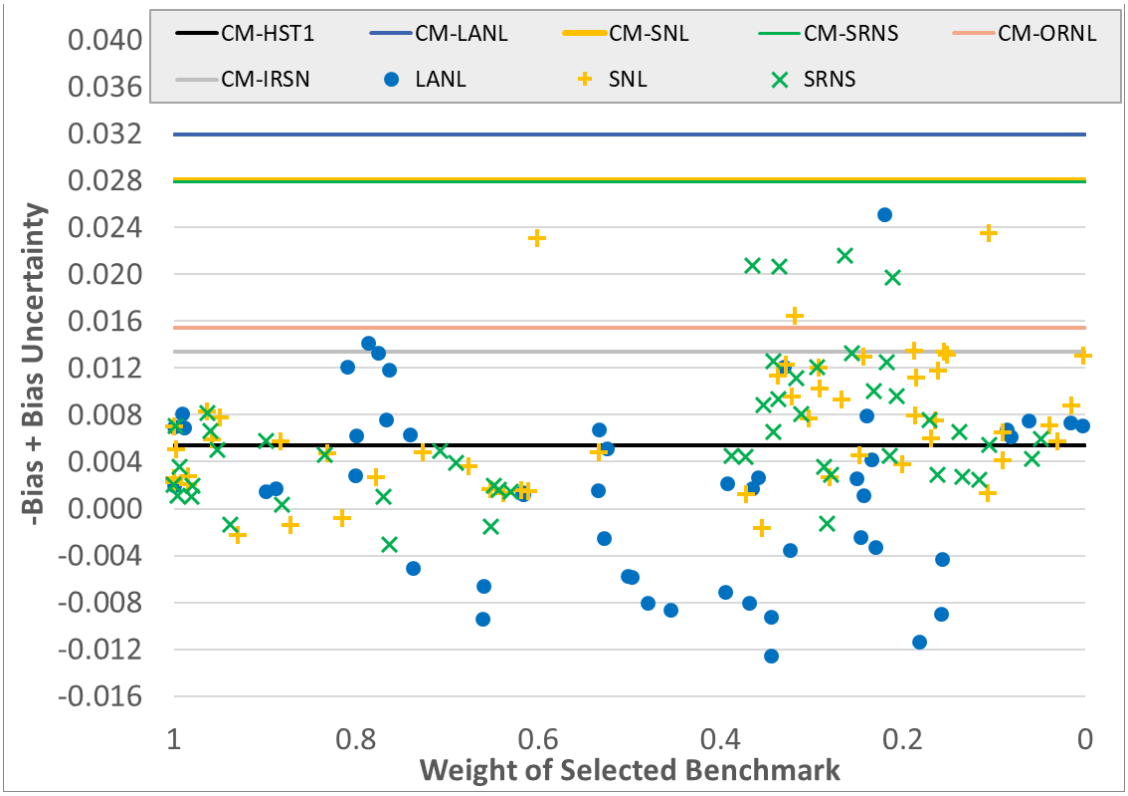

FIGURE 6. CALCULATIONAL MARGIN USING WHISPER WITH LANL/SNL/SRNS LIBRARIES, ORNL METHOD & IRSN METHOD

TABLE 6. STATISTICAL DIFFERENCES BETWEEN LANL, ORNL, IRSN METHODS ALONG WITH BENCHMARKS CHOSEN AS SIMILAR TO APPLICATION. BENCHMARKS THAT WERE CHOSEN FROM MULTIPLE COLLECTIONS HIGHLIGHTED IN GREEN.

k-effective$_{experiment}$		**$\sigma_{experiment}$**	
0.9998		**0.0038**	
Calculated k-effective & USL Results (95% Confidence)			
	LANL	**ORNL**	**IRSN**
k-effective	0.99823 ± 0.00015	0.99590 ± 0.00010	0.99779 ± 0.00010
HST1 Bias	-0.00148	-0.00631	-0.00245
Bias	-0.01462	-0.00500	-0.00358
Bias Uncertainty*	0.01048	0.01040	0.00708
Nuclear Data Unc.**	0.00050	-	-
MOS code errors	0.00500	-	-
Baseline USL	**0.9688**	**0.9846**	**0.9866**
Benchmark Population	51	46	100
Selected Benchmarks			
	LANL Library	**ORNL Library**	**IRSN Library**
	HST-001-001	HST-001-001	HST-001-001
	HST-001-002	HST-001-002	HST-001-002
	HST-001-003	HST-001-003	HST-001-003
	HST-001-004	HST-001-004	HST-001-004

	HST-001-005	HST-001-005	HST-001-005
	HST-001-006	HST-001-006	HST-001-006
	HST-001-007	HST-001-007	HST-001-007
	HST-001-009	HST-001-009	HST-001-009
	HST-001-010	HST-001-010	HST-001-010
			HST-004-003
			HST-004-005
			HST-004-006
			HST-006-001
			HST-006-002
			HST-006-003
			HST-006-004
			HST-006-005
			HST-006-006
			HST-006-007
			HST-006-008
			HST-006-009
			HST-006-010
			HST-006-011
			HST-006-022
			HST-006-022
			HST-006-024
			HST-006-026
			HST-007-001
			HST-007-002
			HST-007-003
			HST-007-004
			HST-007-005
			HST-007-006
			HST-007-007
			HST-007-008
			HST-007-009
			HST-007-010
			HST-007-011
			HST-007-012
			HST-007-013
			HST-007-014
			HST-007-015
			HST-007-016
			HST-007-017
	HST-009-001		
	HST-009-002		
	HST-009-003		
	HST-010-001		
	HST-011-001		
	HST-011-002		

		HST-014-001	
		HST-014-002	
		HST-016-001	HST-016-001
		HST-016-002	HST-016-002
			HST-016-003
			HST-017-004
			HST-017-005
			HST-017-006
	HST-019-001		
	HST-019-002		
	HST-019-003		
			HST-020-001
			HST-020-002
			HST-020-003
			HST-020-004
			HST-020-005
	HST-025-001		HST-025-001
	HST-025-002		HST-025-002
			HST-025-003
	HST-025-004		HST-025-004
	HST-025-005		HST-025-005
			HST-025-006
			HST-025-007
			HST-025-008
			HST-025-009
			HST-025-010
			HST-025-011
			HST-025-012
			HST-025-013
			HST-025-014
			HST-025-015
			HST-025-016
			HST-025-017
			HST-025-018
		HST-028-001	HST-028-001
		HST-028-002	HST-028-002
		HST-028-003	HST-028-003
		HST-028-004	HST-028-004
		HST-028-005	HST-028-005
		HST-028-006	HST-028-006
		HST-028-007	
		HST-028-008	
		HST-028-009	
		HST-028-010	
		HST-028-011	
		HST-028-012	

		HST-028-013	
		HST-028-014	
		HST-028-015	
		HST-028-016	
		HST-028-017	
		HST-028-018	
		HST-029-001	
		HST-029-002	
		HST-029-003	
		HST-029-004	
		HST-029-005	
		HST-029-006	
		HST-029-007	
		HST-030-001	
		HST-030-002	
		HST-030-003	
		HST-030-004	
		HST-030-005	
		HST-030-006	
		HST-030-007	
	HST-038-001		
	HST-038-004		
	HST-038-005		
	HST-038-011		
	HST-038-012		
			HST-039-001
			HST-039-002
			HST-039-003
			HST-039-004
			HST-039-005
			HST-039-006
			HST-042-001
			HST-042-002
			HST-042-003
			HST-042-004
			HST-042-005
			HST-042-006
			HST-042-007
			HST-042-008
	HST-043-001		
	HST-050-001		HST-050-001
	HST-050-002		HST-050-002
			HST-050-003
	HST-050-004		HST-050-004

	HST-050-005		HST-050-005
	HST-050-006		HST-050-006
			HST-050-007
	HST-050-008		HST-050-008
			HST-050-009
	HST-050-010		HST-050-010
	HST-050-011		HST-050-011
	HCT-002-001		
	HCT-002-002		
	HCT-002-003		
	HCT-002-004		
	HCT-002-005		
	HCT-002-011		
	HCT-002-012		
	HCT-002-013		
	HCT-002-018		
	HCT-002-019		
	HCT-002-020		
	HCT-002-023		
	HCT-002-024		
	HCT-002-025		
		LST-003-001	

*Statistical bias uncertainty reported at 95% confidence level

**Nuclear data uncertainty reported at 1-sigma level, ×2 for USL calculation at 95%.

PU-MET-FAST-022-001

Statistical results for the case are shown in Table 7. A subset of the benchmarks in each of the collections, enough found to be neutronically similar for valid statistical analysis in each case, are used to compute the baseline USL. Whisper selected 51 benchmarks as similar when using the LANL library, 43 when using the SNL library, and 44 when using the SRNS library; selections displayed in Table 8. There are 17 benchmarks selected by Whisper from the LANL library that are selected by Whisper from the SNL library. There are 7 benchmarks selected by Whisper from the LANL library that are selected by Whisper from the SRNS library. Comparing those selected in common from the SNL library and the SRNS library there are in 19 common. Those benchmarks selected as similar to the application from multiple libraries are highlighted in green.

For the PU-MET-FAST-022-001 case the series of relevant benchmark experiments are from PU-MET-FAST and MIX-MET-FAST. Many benchmarks in each of the libraries were found to be similar to the application PU-MET-FAST-022-001. A $c_k = 1$ implies perfect correlation, therefore these benchmarks were found to be highly correlated, or to have high neutronic similarity, to the application case with ck ranging from 0.9993 to 0.9120. There is little difference between the USLs computed by Whisper using the three different benchmark libraries. The LANL baseline USL is 0.9791, the SNL is 0.9809, and SRNS is 0.9799.

TABLE 7. COMPARISON OF WHISPER OUTPUT USING PU-MET-FAST-022-001 AS AN APPLICATION CASE.

$K_{experiment}$	$\sigma_{experiment}$	$K_{MCNP6.2}$	$\sigma_{MCNP6.2}$
1.0000	**0.0023**	**0.99830**	**0.00008**
Whisper-1.1 Results			
	LANL Library	**SNL Library**	**SRNS Library**
Bias	-0.00857	-0.00686	-0.00822
Bias Uncertainty*	0.00568	0.00555	0.00521
Nuclear Data Uncertainty**	0.00063	0.00063	0.00063
MOS code errors	0.00500	0.00500	0.00500
Baseline USL	**0.9791**	**0.9809**	**0.9799**
Benchmark Population	51	43	44

*Statistical bias uncertainty reported at 99% confidence level

**Nuclear data uncertainty reported at 1-sigma level, ×2.6 for USL calculation at 99%.

TABLE 8. BENCHMARKS SELECTED BY WHISPER AS SIMILAR TO APPLICATION PMF-022-001, THOSE SELECTED BY MULTIPLE LIBRARIES HIGHLIGHTED IN GREEN.

Whisper Selected Benchmarks					
LANL Library	**Wt**	**SNL Library**	**Wt**	**SRNS Benchmark**	**Wt**
MMF-001-001	0.340	MMF-001-001	0.710		
MMF-003-001	0.052	MMF-003-001	0.621		
MMF-005-001	0.147				
		MMF-007-007	0.232		
		MMF-007-008	0.114		
		MMF-007-014	0.412		

		MMF-007-015	0.370		
		MMF-007-016	0.271		
		MMF-007-017	0.230		
		MMF-007-018	0.139		
MMF-007-019	0.000	MMF-007-019	0.597		
		MMF-007-020	0.555		
		MMF-007-021	0.468		
MMF-007-022	0.448	MMF-007-022	0.770		
MMF-007-023	0.400	MMF-007-023	0.757		
MMF-009-001	0.907				
				PCM-001-001	0.363
PMF-001-001	1.000	PMF-001-001	1.000	PMF-001-001	1.000
PMF-002-001	0.040	PMF-002-001	0.615	PMF-002-001	0.538
		PMF-003-001	0.924	PMF-003-001	0.901
		PMF-003-002	0.894	PMF-003-002	0.865
PMF-003-003	0.465	PMF-003-003	0.756	PMF-003-003	0.684
		PMF-003-004	0.761	PMF-003-004	0.689
		PMF-003-005	0.893	PMF-003-005	0.886
				PMF-004-207	0.580
				PMF-004-208	0.578
				PMF-004-209	0.623
				PMF-004-210	0.654
				PMF-004-211	0.586
				PMF-004-212	0.600
				PMF-004-213	0.744
				PMF-004-214	0.646
				PMF-004-215	0.737
		PMF-006-001	0.059		
PMF-008-001	0.201	PMF-008-001	0.679	PMF-008-001	0.610
		PMF-008-002	0.688		
PMF-009-001	0.835	PMF-009-001	0.939	PMF-009-001	0.922
PMF-011-001	0.378	PMF-011-001	0.750	PMF-011-001	0.696
		PMF-012-001	0.305		
		PMF-016-001	0.163	PMF-016-001	0.012
		PMF-016-006	0.102	PMF-017-201	0.745
				PMF-017-202	0.783
				PMF-017-203	0.757
				PMF-017-204	0.710
				PMF-017-205	0.526
PMF-018-001	0.436	PMF-018-001	0.773	PMF-018-001	0.722
PMF-019-001	0.133	PMF-019-001	0.668		
PMF-021-001	0.623				
PMF-021-002	0.613				
PMF-023-001	0.907			PMF-023-001	0.950
PMF-024-001	0.911	PMF-024-001	0.965		
PMF-025-001	0.830	PMF-025-001	0.930		

PMF-026-001	0.126	PMF-026-001	0.647		
PMF-027-001	0.255				
		PMF-028-001	0.482		
PMF-029-001	0.860				
PMF-030-001	0.756				
PMF-031-001	0.580	PMF-031-001	0.835		
PMF-032-001	0.258				
PMF-035-001	0.879	PMF-035-001	0.957		
PMF-036-001	0.896				
		PMF-037-001	0.707	PMF-037-001	0.653
				PMF-037-002	0.539
				PMF-037-003	0.545
				PMF-037-004	0.548
		PMF-037-005	0.569	PMF-037-005	0.456
				PMF-037-006	0.367
		PMF-037-007	0.508	PMF-037-007	0.389
				PMF-037-008	0.228
				PMF-037-009	0.236
				PMF-037-010	0.312
				PMF-037-011	0.542
		PMF-037-012	0.446	PMF-037-012	0.318
				PMF-037-013	0.099
				PMF-037-014	0.155
		PMF-037-015	0.361	PMF-037-015	0.224
		PMF-037-016	0.471	PMF-037-016	0.359
PMF-039-001	0.895				
PMF-040-001	0.157				
PMF-042-001	0.206				
PMF-042-002	0.361				
PMF-042-003	0.417				
PMF-042-004	0.459				
PMF-042-005	0.421				
PMF-042-006	0.464				
PMF-042-007	0.457				
PMF-042-008	0.440				
PMF-042-009	0.451				
PMF-042-010	0.433				
PMF-042-011	0.426				
PMF-042-012	0.443				
PMF-042-013	0.420				
PMF-042-014	0.414				
PMF-042-015	0.426				
PMF-044-001	0.403				
PMF-044-002	0.690				
PMF-044-003	0.756				
PMF-044-004	0.676				

PMF-044-005	0.751				
PMF-045-005	0.241				

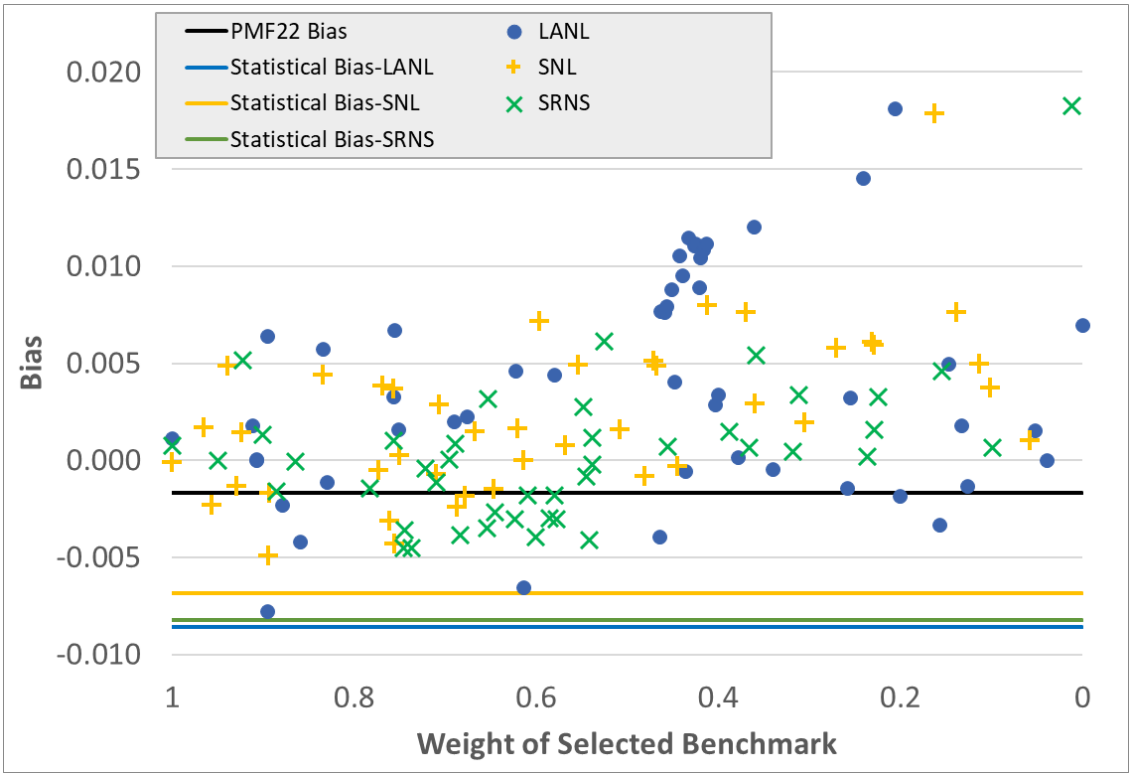

FIGURE 7. INDIVIDUAL BENCHMARK BIAS & STATISTICAL BIAS CALCULATED USING WHISPER WITH LANL/SNL/SRNS BENCHMARK LIBRARIES

Results for the bias are in Figure 8, MCNP6.2 calculated k-effective is 0.99830 with a standard deviation of 0.00008, in this case the code calculates very slightly lower than the experimental k-effective of 1.0000, labeled PMF22 bias in Figure 8 and Table 9. The individual data points are the bias of selected benchmarks from the LANL, SNL, and SRNS libraries. As can be seen in the figure by comparing the individual biases and the statistical bias calculated by Whisper using the various benchmark selections, the statistical bias encompasses nearly the individual biases.

Results for bias uncertainty are in Figure 9 with individual benchmark uncertainty plotted from the benchmarks selected from the LANL, SNL, and SRNS libraries. The bias uncertainty reported in Table 9 is at the 95% confidence level, which is slightly lower than the value at the 99% confidence level reported in Table 7. As can be seen in the figure by comparing the individual statistical bias uncertainties and those calculated by Whisper, the statistical bias uncertainty encompasses nearly all the individual bias uncertainties for each respective set of selected benchmarks. The high bias uncertainty outliers are for PMF-042 series, for which the experiment uncertainties are reported between 0.007-0.008 in Reference 9

Figure 10 presents a comparison of all results for the calculational margin. In all cases, the statistically computed calculational margin is conservative. The CM calculated by ORNL and IRSN methods at the 95% level are also in the figure. The highest CM are for the Whisper method using the LANL library, the lowest is for the IRSN method. Table 9 shows the CM and baseline USL calculated using Whisper, the

ORNL and IRSN methods. Whisper selected 51 benchmarks as similar to PMF-022-001, ORNL selected 4, and IRSN selected 100. Comparing those selected by LANL and ORNL, there are 3 in common. Between LANL and IRSN, there are 7 in common, and 2 in common between ORNL and IRSN. Baseline USLs are vary by about a percent ranging from 0.9816 to 0.9925, the lower USL due to PMF-039-001 and PMF-021-002 in the LANL library.

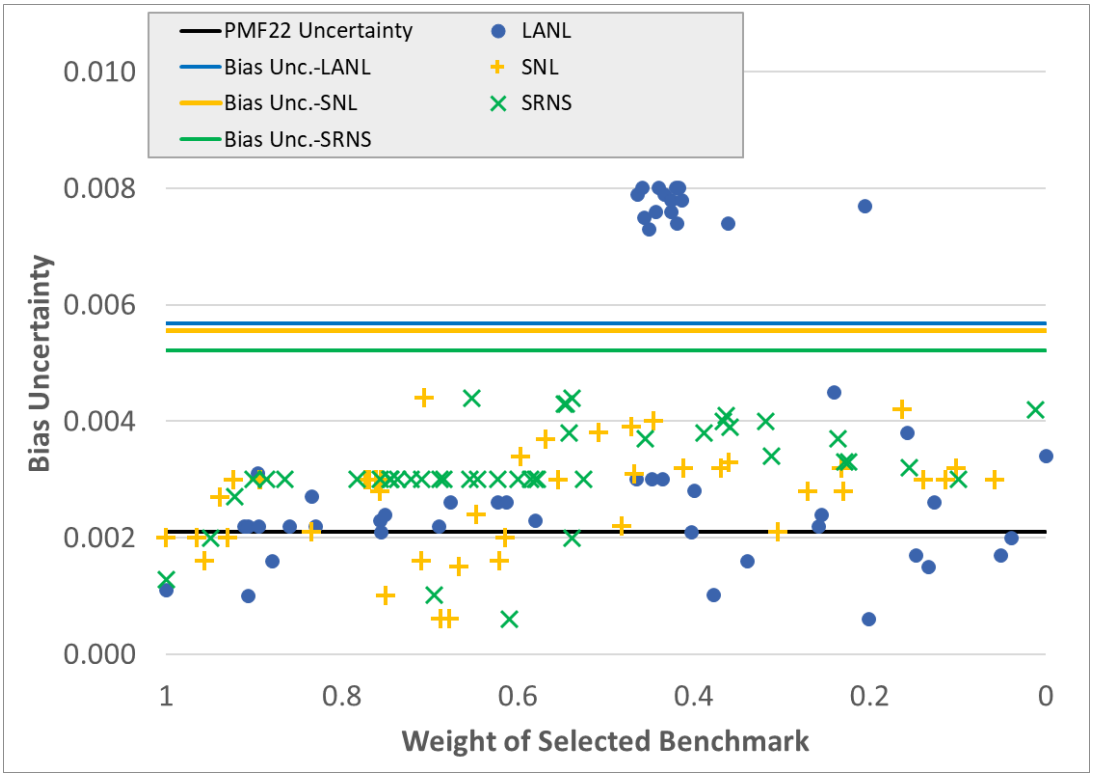

FIGURE 8. INDIVIDUAL BENCHMARK UNCERTAINTY & STATISTICAL UNCERTAINTY CALCULATED USING WHISPER WITH LANL/SNL/SRNS LIBRARIES

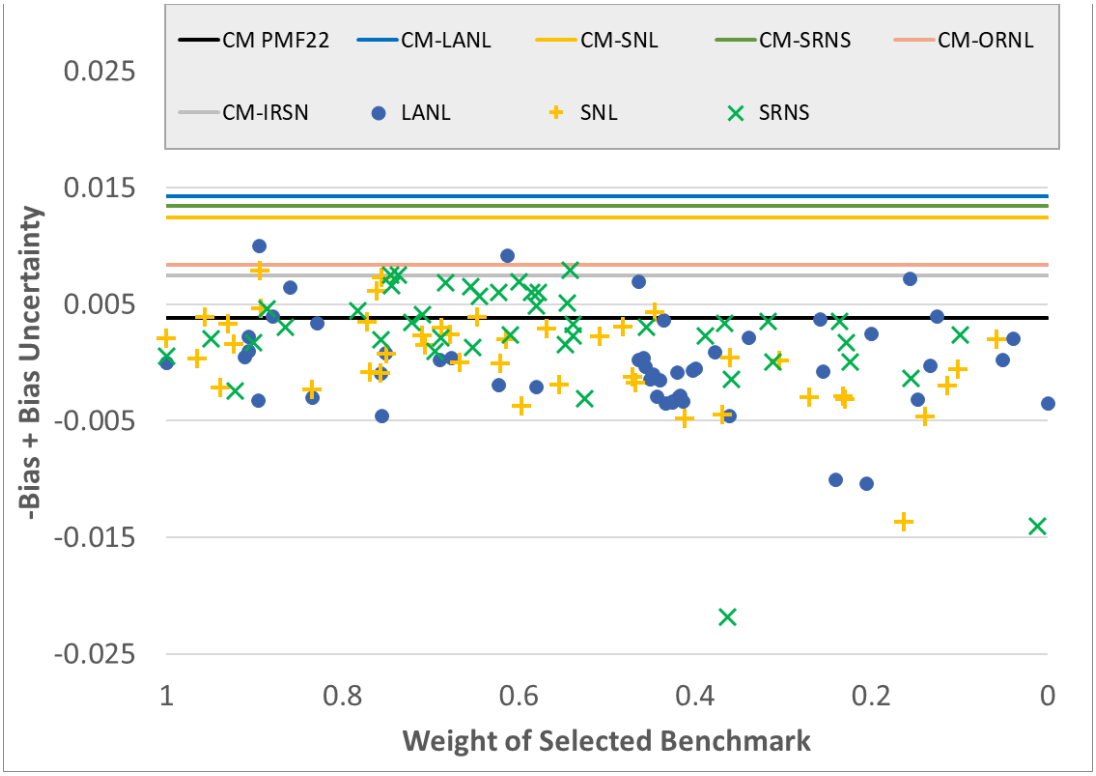

FIGURE 9. CALCULATIONAL MARGIN USING WHISPER WITH LANL/SNL/SRNS LIBRARIES, ORNL METHOD & IRSN METHOD

TABLE 9. STATISTICAL DIFFERENCES BETWEEN LANL, ORNL, IRSN METHODS ALONG WITH BENCHMARKS CHOSEN AS SIMILAR TO APPLICATION FOR CASE PMF-022-001

k-effective$_{experiment}$		**$\sigma_{experiment}$**	
1.0000		**0.0023**	
Calculated k-effective & USL Results (95% Confidence)			
	LANL	**ORNL**	**IRSN**
k-effective	0.99830 ± 0.00008	0.99860 ± 0.00010	0.99794 ± 0.00010
PMF22-001 Calc. Bias	-0.00170	-0.00140	-0.00206
Bias	-0.00857	+0.00070 → 0	-0.00013
Bias Uncertainty*	0.00253	0.00840	0.00740
Nuclear Data Unc.**	0.00050	-	-
MOS code errors	0.00500	-	-
Baseline USL	**0.9816**	**0.9916**	**0.9925**
Benchmark Population	51	4	7
Selected Benchmarks			
	LANL Library	**ORNL Library**	**IRSN Library**
	PMF-001-001	PMF-001-001	PMF-001-001
	PMF-002-001		PMF-002-001
	PMF-003-103		
		PMF-005-001	

	PMF-008-001		
	PMF-009-001		
	PMF-011-001		PMF-011-001
	PMF-018-001		
	PMF-019-001		
	PMF-021-001		
	PMF-021-002		
	PMF-023-001	PMF-023-001	
	PMF-024-001	PMF-024-001	PMF-024-001
	PMF-025-001		
	PMF-026-001		
	PMF-027-001		PMF-027-001
	PMF-029-001		PMF-029-001
	PMF-030-001		
	PMF-031-001		PMF-031-001
	PMF-032-001		
	PMF-035-001		
	PMF-036-001		
	PMF-039-001		
	PMF-040-001		
	PMF-042-001		
	PMF-042-002		
	PMF-042-003		
	PMF-042-004		
	PMF-042-005		
	PMF-042-006		
	PMF-042-007		
	PMF-042-008		
	PMF-042-009		
	PMF-042-010		
	PMF-042-011		
	PMF-042-012		
	PMF-042-013		
	PMF-042-014		
	PMF-042-015		
	PMF-044-001		
	PMF-044-002		
	PMF-044-003		
	PMF-044-004		
	PMF-044-005		
	PMF-045-005		
	MMF-001-001		
	MMF-003-001		
	MMF-005-001		
	MMF-007-019		
	MMF-007-022		

	MMF-007-023		
	MMF-009-001		

*Statistical bias uncertainty reported at 95% confidence level
**Nuclear data uncertainty reported at 1-sigma level, ×2 for USL calculation at 95%.

PU-SOL-THERM-001-001

Statistical results for the case are shown in Table 10. A subset of the benchmarks in each of the collections, enough found to be neutronically similar for valid statistical analysis in each case, are used to compute the baseline USL. Whisper selected 38 benchmarks as similar when using the LANL library, 57 when using the SNL library, and 38 when using the SRNS library; selections displayed in Table 10. There are 17 benchmarks selected by Whisper from the LANL library that are selected by Whisper from the SNL library. There are 33 benchmarks selected by Whisper from the LANL library that are selected by Whisper from the SRNS library, the only differences being 5 different cases from the PST-011 series not selected in common. This very close selection explains the nearly identical baseline USLs between use of the LANL library and the SRNS library. Comparing those selected in common from the SNL library and the SRNS library there are 16 common. Those benchmarks selected as similar to the application from multiple libraries are highlighted in green

For the PU-SOL-THERM-001-001 case the series of relevant benchmark experiments are from PU-SOL-THERM. Many benchmarks in the Whisper library were found to be similar to the application PU-SOL-THERM-001-001, or to have high neutronic similarity, to the application case with ck ranging from 0.9998 to 0.9947. There were also two benchmarks from MST-004 selected using the SNL library.

There is little difference between the USLs computed by Whisper using the three different benchmark libraries. The LANL baseline USL is 0.9797, the SNL is 0.9812, and SRNS is 0.9796.

TABLE 10. COMPARISON OF WHISPER OUTPUT USING PU-SOL-THERM-001-001 AS AN APPLICATION CASE.

$K_{experiment}$	$\sigma_{experiment}$	$K_{MCNP6.2}$	$\sigma_{MCNP6.2}$
1.0000	**0.0050**	**1.00578**	**0.00013**
Whisper-1.1 Results			
	LANL Library	**SNL Library**	**SRNS Library**
Bias	-0.00597	-0.00517	-0.00601
Bias Uncertainty*	0.00829	0.00760	0.00834
Nuclear Data Uncertainty**	0.00039	0.00039	0.00039
MOS code errors	0.00500	0.00500	0.00500
Baseline USL	**0.9797**	**0.9812**	**0.9796**
Benchmark Population	38	57	38

*Statistical bias uncertainty reported at 99% confidence level
**Nuclear data uncertainty reported at 1-sigma level, ×2.6 for USL calculation at 99%.

TABLE 11. BENCHMARKS SELECTED BY WHISPER AS SIMILAR TO APPLICATION PST-001-001, THOSE SELECTED BY MULTIPLE LIBRARIES HIGHLIGHTED IN GREEN.

Whisper Selected Benchmarks

LANL Library	Wt	SNL Library	Wt	SRNS Benchmark	Wt
		MST-004-001	0.334		
		MST-004-002	0.036		
PST-001-002	0.926	PST-001-002	0.974	PST001-002	0.922
PST-001-003	0.681	PST-001-003	0.802	PST001-003	0.682
PST-001-004	0.516	PST-001-004	0.668	PST001-004	0.507
PST-001-005	0.413	PST-001-005	0.608	PST001-005	0.425
PST-002-001	0.797	PST-002-001	0.886	PST002-001	0.797
PST-002-002	0.837	PST-002-002	0.922	PST002-002	0.830
PST-002-003	0.921	PST-002-003	0.968	PST002-003	0.922
PST-002-004	0.949	PST-002-004	1.000	PST002-004	0.951
PST-002-005	0.975	PST-002-005	1.000	PST002-005	0.948
PST-002-006	0.958	PST-002-006	0.997	PST002-006	0.980
PST-002-007	0.917	PST-002-007	0.966	PST002-007	0.913
		PST-003-001	0.170		
		PST-003-002	0.287		
PST-003-003	0.127	PST-003-003	0.381	PST003-003	0.105
PST-003-004	0.179	PST-003-004	0.410	PST003-004	0.177
PST-003-005	0.316	PST-003-005	0.539	PST003-005	0.301
PST-003-006	0.488	PST-003-006	0.656	PST003-006	0.506
		PST-003-007	0.200		
PST-003-008	0.021	PST-003-008	0.235		
		PST-004-010	0.028		
		PST-004-011	0.251		
		PST-005-005	0.040		
		PST-005-006	0.189		
		PST-005-007	0.271	PST005-007	0.030
PST-007-005	0.915			PST007-005	0.910
PST-007-006	0.902			PST007-006	0.909
PST-007-007	0.905			PST007-007	0.906
PST-007-008	0.893			PST007-008	0.901
PST-007-009	0.892			PST007-009	0.883
PST-007-010	0.949			PST007-010	0.964
		PST-008-021	0.582		
		PST-008-025	0.838		
		PST-008-027	0.568		
		PST-008-029	0.835		
PST-010-001	0.879			PST010-001	0.879
PST-010-002	1.000			PST010-002	1.000
PST-010-003	0.795			PST010-003	0.801
PST-010-004	0.794			PST010-004	0.787
PST-010-005	0.584			PST010-005	0.569
PST-010-006	0.638			PST010-006	0.628
PST-010-007	0.345			PST010-007	0.328
PST-010-009	0.957			PST010-009	0.957
PST-010-010	0.722			PST010-010	0.725

PST-010-011	0.674			PST010-011	0.682
PST-010-012	0.412			PST010-012	0.422
				PST011-001	0.170
				PST011-002	0.276
				PST011-003	0.361
				PST011-004	0.388
				PST011-005	0.585
PST-011-161	0.197				
PST-011-162	0.265				
PST-011-163	0.334				
PST-011-164	0.376				
PST-011-165	0.583				
		PST-013-001	0.368		
		PST-013-002	0.313		
		PST-013-004	0.351		
		PST-013-005	0.351		
		PST-013-006	0.332		
		PST-013-007	0.360		
		PST-013-008	0.329		
		PST-013-009	0.329		
		PST-013-010	0.328		
		PST-013-011	0.303		
		PST-013-012	0.326		
		PST-013-013	0.324		
		PST-013-014	0.322		
		PST-013-015	0.250		
		PST-013-016	0.282		
		PST-013-017	0.302		
		PST-013-018	0.235		
		PST-013-019	0.266		
		PST-013-020	0.278		
		PST-013-021	0.217		
		PST-013-022	0.247		
		PST-014-001	0.349		
		PST-014-007	0.341		
		PST-014-013	0.338		
		PST-014-018	0.335		
		PST-014-024	0.320		
		PST-014-030	0.355		

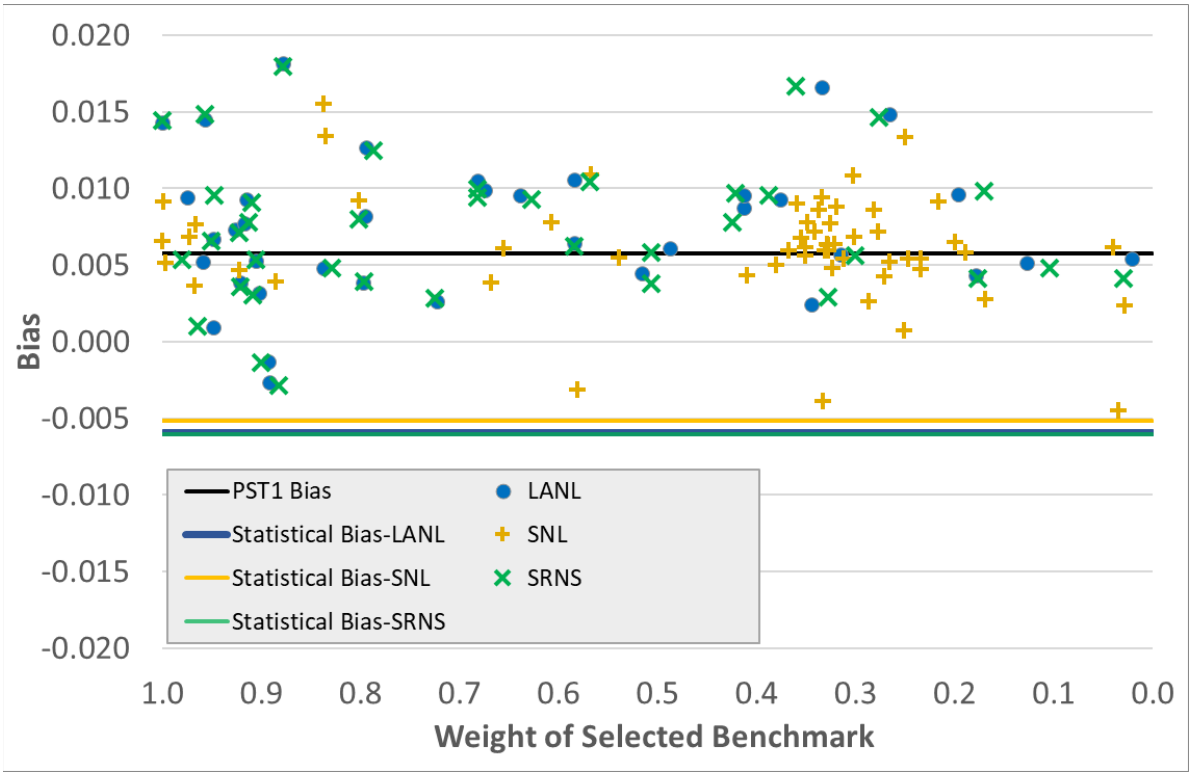

FIGURE 10. INDIVIDUAL BENCHMARK BIAS & STATISTICAL BIAS CALCULATED USING WHISPER WITH LANL/SNL/SRNS BENCHMARK LIBRARIES

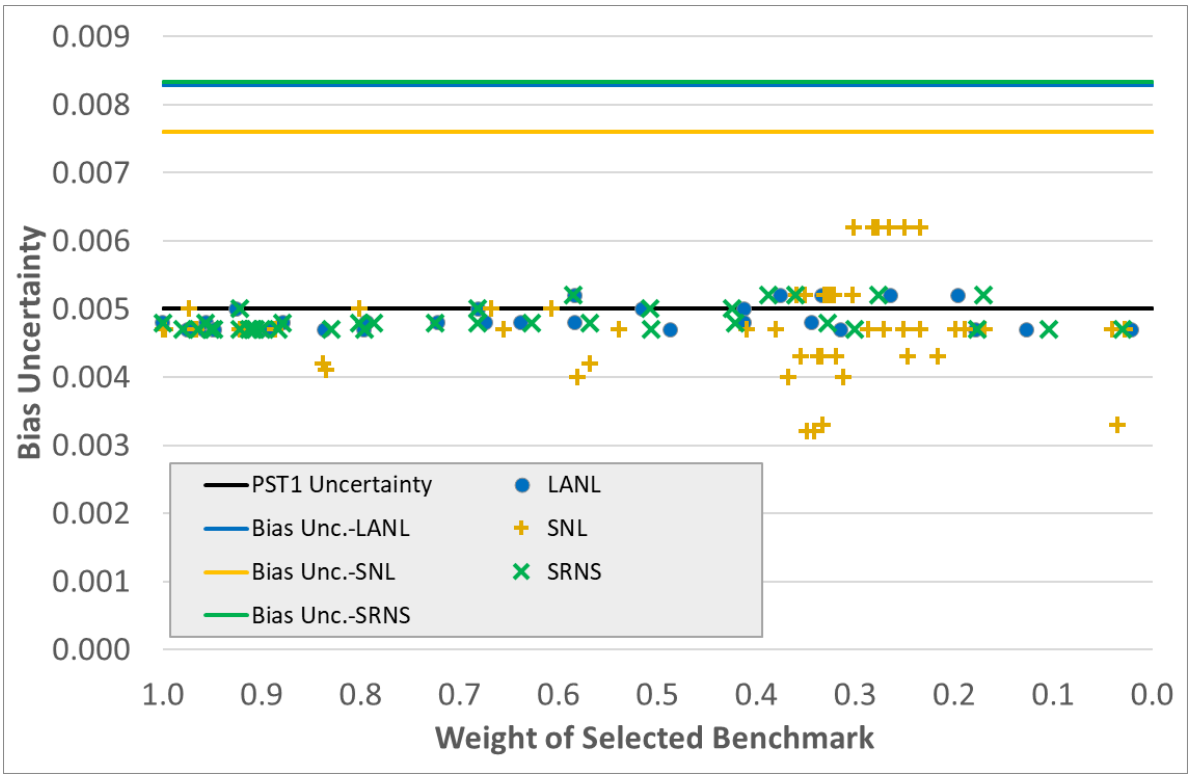

FIGURE 11. INDIVIDUAL BENCHMARK UNCERTAINTY & STATISTICAL UNCERTAINTY CALCULATED USING WHISPER WITH LANL/SNL/SRNS LIBRARIES

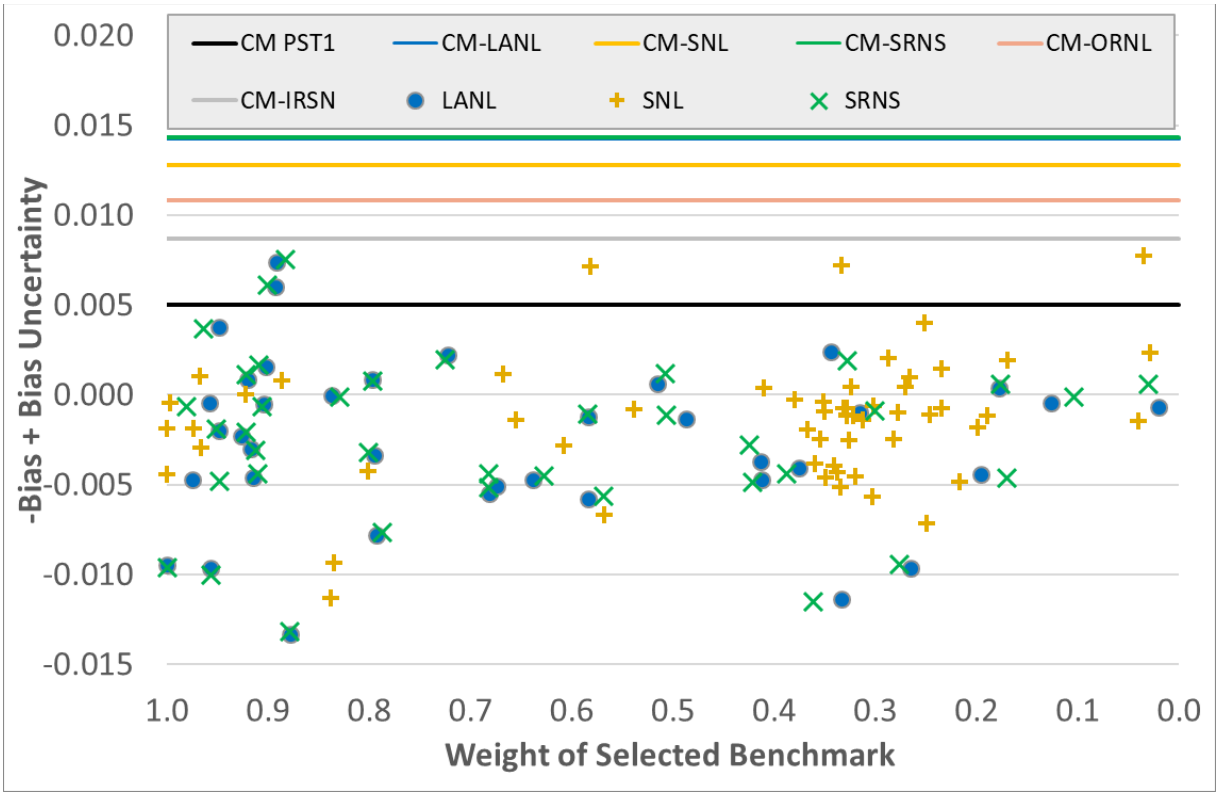

FIGURE 12. CALCULATIONAL MARGIN USING WHISPER WITH LANL/SNL/SRNS LIBRARIES, ORNL METHOD & IRSN METHOD

Results for the bias are in Figure 11, MCNP6.2 calculated k-effective is 1.00578 with a standard deviation of 0.00013, in this case the code calculates slightly higher than the experimental k-effective of 1.0000, labeled PST1 bias in Figure 11 and Table 12. The individual data points are the bias of selected benchmarks from the LANL, SNL, and SRNS libraries. As can be seen in the figure by comparing the individual biases and the statistical bias calculated by Whisper using the various benchmark selections, the statistical bias encompasses all the individual biases.

Results for bias uncertainty are in Figure 12 with individual benchmark uncertainty plotted from the benchmarks selected from the LANL, SNL, and SRNS libraries. The bias uncertainty reported in Table 12 is at the 95% confidence level, which is slightly lower than the value at the 99% confidence level reported in Table 10. As can be seen in the figure by comparing the individual statistical bias uncertainties and those calculated by Whisper, the statistical bias uncertainty encompasses all the individual bias uncertainties for each respective set of selected benchmarks. The high bias uncertainty outliers are for PST-013 and PST-014 series using the SNL library, otherwise the bias uncertainty has very little spread in the data.

Figure 13 presents a comparison of all results for the calculational margin. In all cases, the statistically computed calculational margin is conservative. The CM calculated by ORNL and IRSN methods at the 95% level are also in the figure. The highest CM are for the Whisper method using the LANL and SRNS libraries, the lowest is for the IRSN method. Table 12 shows the CM and baseline USL calculated using Whisper, the ORNL and IRSN methods. Whisper selected 38 benchmarks as similar to PST-001-001, ORNL selected 85, and IRSN selected 100. Comparing those selected by LANL and ORNL, there are 20 in

common. Between LANL and IRSN, there are 4 in common, and 6 in common between ORNL and IRSN. Baseline USLs are vary by about a percent ranging from 0.9800 to 0.9913.

TABLE 12. STATISTICAL DIFFERENCES BETWEEN LANL, ORNL, IRSN METHODS ALONG WITH BENCHMARKS CHOSEN AS SIMILAR TO APPLICATION FOR CASE PST-001-001. BENCHMARKS THAT WERE CHOSEN FROM MULTIPLE COLLECTIONS HIGHLIGHTED IN GREEN.

k-effective$_{experiment}$		**$\sigma_{experiment}$**	
1.0000		**0.0050**	
Calculated k-effective & USL Results (95% Confidence)			
	LANL	**ORNL**	**IRSN**
k-effective	1.00578 ± 0.00013	1.00390 ± 0.00010	1.00492 ± 0.00010
PST1 Bias	0.00578	0.00390	0.00492
Bias	-0.00597	+0.00430 → 0	+0.00878 → 0
Bias Uncertainty*	0.00550	0.01080	0.00868
Nuclear Data Unc.**	0.00050	-	-
MOS code errors	0.00500	-	-
Baseline USL	**0.9828**	**0.9892**	**0.9913**
Benchmark Population	38	85	100
Selected Benchmarks			
LANL Library		**ORNL Library**	**IRSN Library**
	PST-001-002	PST-001-002	
	PST-001-003	PST-001-003	
	PST-001-004	PST-001-004	
	PST-001-005	PST-001-005	
		PST-001-006	
	PST-002-001	PST-002-001	
	PST-002-002	PST-002-002	
	PST-002-003	PST-002-003	
	PST-002-004	PST-002-004	
	PST-002-005	PST-002-005	
	PST-002-006	PST-002-006	
	PST-002-007	PST-002-007	
		PST-003-001	
		PST-003-002	
	PST-003-003	PST-003-003	
	PST-003-004	PST-003-004	
	PST-003-005	PST-003-005	
	PST-003-006	PST-003-006	
		PST-003-007	
	PST-003-008	PST-003-008	
		PST-004-001	
		PST-004-002	PST-004-002
		PST-004-003	PST-004-003
		PST-004-004	
		PST-004-005	PST-004-005

		PST-004-006	PST-004-006
		PST-004-007	
		PST-004-008	PST-004-008
		PST-004-009	
		PST-004-010	
		PST-004-011	PST-004-011
		PST-004-012	
		PST-004-013	
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		PST-005-003	
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		PST-005-006	
		PST-005-007	
		PST-005-008	
		PST-005-009	
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		PST-006-002	
		PST-006-003	
		PST-007-001	
		PST-007-002	
		PST-007-003	
		PST-007-004	
	PST-007-005	PST-007-005	
	PST-007-006	PST-007-006	
	PST-007-007	PST-007-007	
	PST-007-008	PST-007-008	
	PST-007-009		
	PST-007-010		
	PST-010-001		PST-010-001
	PST-010-002		PST-010-002
	PST-010-003		PST-010-003
	PST-010-004		PST-010-004
	PST-010-005		
	PST-010-006		
	PST-010-007		
	PST-010-009		
	PST-010-010		
	PST-010-011		
	PST-010-012		
		PST-011-001	
		PST-011-002	
		PST-011-003	
		PST-011-004	
		PST-011-005	

		PST-011-006	
		PST-011-007	
		PST-011-008	
		PST-011-009	
		PST-011-010	
		PST-011-011	
		PST-011-012	
	PST-011-161		
	PST-011-162		
	PST-011-163		
	PST-011-164		
	PST-011-165		
			PST-018-001
			PST-018-002
			PST-018-003
			PST-018-004
			PST-018-005
			PST-018-006
			PST-018-007
			PST-018-008
			PST-018-009
		PST-020-001	
		PST-020-002	
		PST-020-003	
		PST-020-004	
		PST-020-005	
		PST-020-006	
		PST-020-007	
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		PST-020-013	
		PST-020-014	
		PST-020-015	
			PST-028-001
			PST-028-002
			PST-028-003
			PST-028-004
			PST-028-005
			PST-028-006
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			PST-028-014
			PST-028-015
			PST-030-001
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			PST-033-017
			PST-033-027
			PST-033-030
			PST-033-031

			PST-033-032
			PST-033-034
			PST-033-038
			PST-033-049
			PST-033-054
			PST-033-059
			PST-033-060
			PST-033-061
			PST-033-062
			PST-033-063
			PST-034-001
			PST-034-002
			PST-034-003
			PST-034-004
			PST-034-005
			PST-034-006
			PST-034-007
			PST-034-008
			PST-034-009
			PST-034-010
			PST-034-011
			PST-034-012
			PST-034-013
			PST-034-014
			PST-034-015
			PST-034-016
			PST-034-017
			PST-034-015
		MCT-001-003	
		MCT-001-004	
		MST-007-001	
		MST-007-002	

*Statistical bias uncertainty reported at 95% confidence level

**Nuclear data uncertainty reported at 1-sigma level, ×2 for USL calculation at 95%.

Summary of Benchmark Cases Run as Applications

This paper presents results for the USL, CM and portions of the MOS for HEU and Pu metal and solution systems using Whisper-1.1. The initial part of the study focuses on four cases, in which critical experiment benchmarks (HMF-013-001, HEU-SOL-THERM-001-008, PU-MET-FAST-022-001, AND PU-SOL-THERM-001-001) are chosen to run as applications. This is done to compare statistical bias and bias uncertainty with the actual code bias and experimental uncertainty. In all cases the computed statistical bias and bias uncertainty are conservative with respect to the actual.

Benchmark libraries from LANL, SNL and SRNS are used with Whisper-1.1 to compare the statistical bias and bias uncertainty (CM), USL and nuclear data portion of the MOS. In addition, methods developed by ORNL and IRSN are used with their own benchmark libraries for the same case study comparison. All results are presented in Table 13. The benchmarks taken as cases:

1. are modeled independently by sites based upon information provided in the ICSBEP Handbook,
2. are common in S/U libraries for LANL, IRSN, and ORNL,
3. span a range of energy spectrum and fissile material, and
4. have been taken as applications and therefore excluded from respective benchmark libraries

Results presented in this paper have been computed using covariance data for all isotopes in ENDF/B-VII.0 using a 44-group energy structure [Reference 6]. Benchmarks in the Whisper library were run with MCNP6.2 using 100,000 neutrons per cycle, skipping 100 cycles for 500 active cycles. Reference 10 also compares the results for baseline USL with an order of magnitude greater neutrons, using the same total number of cycles with 1,000,000 neutrons per cycle. There was insignificant difference, ≤ 0.00005, in the USL when running an order of magnitude more neutrons.

A comparison has been done to compute USLs with and without statistical outliers in the Whisper-1.1 benchmark collection to determine what effect rejection of statistical outliers has on the recommended USL in Reference 11. The effect of exclusion of benchmarks which are found to be statistical outliers from the collection of benchmarks used by Whisper-1.1 on nuclear criticality safety validation is found to be small. The results show little overall difference in the recommended baseline USLs developed by Whisper when excluding statistical outliers. Additionally, there does not appear to be a clear trend in predicting whether the baseline USL will be higher or lower when rejecting statistical outliers from the benchmark critical experiment collection used for validation.

This study examines the results from Whisper using various benchmark libraries, including the LANL Whisper library, the SNL library and the SRNS library. The comparison with the same method and different libraries is a good way to see differences in USL stemming from different benchmarks versus different statistical methods. A second part of this study looks at the results using different S/U methods and different libraries. This part of the comparison shows differences when using Whisper with the LANL Whisper library, the ORNL method with its library, and the IRSN method with its library. All results are shown below in Table 13.

TABLE 13. SUMMARY OF USL RESULTS FOR REPRESENTATIVE HEU AND PU SYSTEMS WITH DIFFERENT BENCHMARK LIBRARIES AND S/U METHODS.

HMF-013-001		**K_{exp}**	**0.9990**	**Unc_{exp}**	**0.0015**
	Whisper-LANL	**Whisper-SNL**	**Whipser-SRNS**	**TSUNAMI-ORNL**	**MACSENS-IRSN**
Case Calc. Bias	-0.00148	-0.00148	-0.00148	-0.00170	-0.00245
Bias	-0.00571	-0.01135	-0.01252	-0.00780	-0.00358
Bias Uncertainty*	0.00391	0.01019	0.00868	0.00940	0.01294
Nuclear Data Unc.*	0.00050	0.00050	0.00050	-	-
MOS code errors	0.00500	0.00500	0.00500	-	-
Baseline USL @99%	**0.9841**	**0.9721**	**0.9725**	**0.9799**	**0.9796**
Baseline USL @95%	**0.9858**	**0.9757**	**0.9758**	**0.9828**	**0.9835**

Benchmark Population	75	62	59	40	303
HST-001-008		**K_{exp}**	**0.9998**	**Unc_{exp}**	**0.0038**
	Whisper-LANL	**Whisper-SNL**	**Whipser-SRNS**	**TSUNAMI-ORNL**	**MACSENS-IRSN**
Case Calc. Bias	-0.00157	-0.00157	-0.00157	-0.00390	-0.00201
Bias	-0.01462	-0.01720	-0.01623	-0.00500	-0.00631
Bias Uncertainty*	0.01731	0.01075	0.01165	0.01040	0.00708
Nuclear Data Unc.*	0.00056	0.00056	0.00056	-	-
MOS code errors	0.00500	0.00500	0.00500	-	-
Baseline USL @99%	**0.9616**	**0.9656**	**0.9656**	**0.9814**	**0.9844**
Baseline USL @95%	**0.9688**	**0.9687**	**0.9693**	**0.9846**	**0.9866**
Benchmark Population	51	53	50	46	100
PMF-022-001		**K_{exp}**	**1.0000**	**Unc_{exp}**	**0.0023**
	Whisper-LANL	**Whisper-SNL**	**Whipser-SRNS**	**TSUNAMI-ORNL**	**MACSENS-IRSN**
Case Calc. Bias	-0.00170	-0.00170	-0.00170	-0.00140	-0.00206
Bias	-0.00857	-0.00686	-0.00822	+0.00070 → 0	-0.00013
Bias Uncertainty*	0.00568	0.00555	0.00521	0.00840	0.00740
Nuclear Data Unc.*	0.00063	0.00063	0.00063	-	-
MOS code errors	0.00500	0.00500	0.00500	-	-
Baseline USL @99%	**0.9791**	**0.9809**	**0.9799**	**0.9890**	**0.9902**
Baseline USL @95%	**0.9816**	**0.9831**	**0.9821**	**0.9916**	**0.9925**
Benchmark Population	51	43	44	4	7
PST-001-001		**K_{exp}**	**1.0000**	**Unc_{exp}**	**0.0050**
	Whisper-LANL	**Whisper-SNL**	**Whipser-SRNS**	**TSUNAMI-ORNL**	**MACSENS-IRSN**
Case Calc. Bias	0.00578	0.00578	0.00578	0.00390	0.00492
Bias	-0.00597	-0.00517	-0.00601	+0.00430→0	+0.00878→0
Bias Uncertainty*	0.00829	0.00760	0.00834	0.01080	0.00868
Nuclear Data Unc.*	0.00039	0.00039	0.00039	-	-
MOS code errors	0.00500	0.00500	0.00500	-	-
Baseline USL @99%	**0.9797**	**0.9812**	**0.9796**	**0.9859**	**0.9887**
Baseline USL @95%	**0.9828**	**0.9839**	**0.9826**	**0.9892**	**0.9913**
Benchmark Population	38	57	38	85	100

*Bias uncertainty reported at 99% confidence for Whisper results, 95% for ORNL and IRSN. Nuclear data uncertainty reported at 1-sigma level, multiplied times 2.6 for USL calculation at 99%.

Additional Comparison utilizing Application Cases

Several studies have been done with applications for Pu and HEU systems with metal, oxide and solutions. The studies were all done with MCNP6.2 and Whisper-1.1, the only difference is the benchmark libraries from LANL, SNL and SRNS were used for comparison. The applications involving HEU are with 93% ^{235}U and with Pu are for 100% ^{239}Pu. Specification of metal and oxide cases are:

- Metal and Oxide: 3 right circular cylinders in close proximity, with reflection from water around the perimeter of one of the cylinders and steel on the bottom of all cylinders. The height-to-diameter ratio of all cylinders was 1.
    - HEU metal: 20 kg/cylinder, 18.75 g/cm^3
    - HEU Oxide: 10 kg/cylinder, 10.8g/cm^3
    - Pu metal: 2.3 kg/cylinder, 19.85 g/cm^3
    - Pu Oxide: 3.5 kg/cylinder, 11.5 g/cm^3

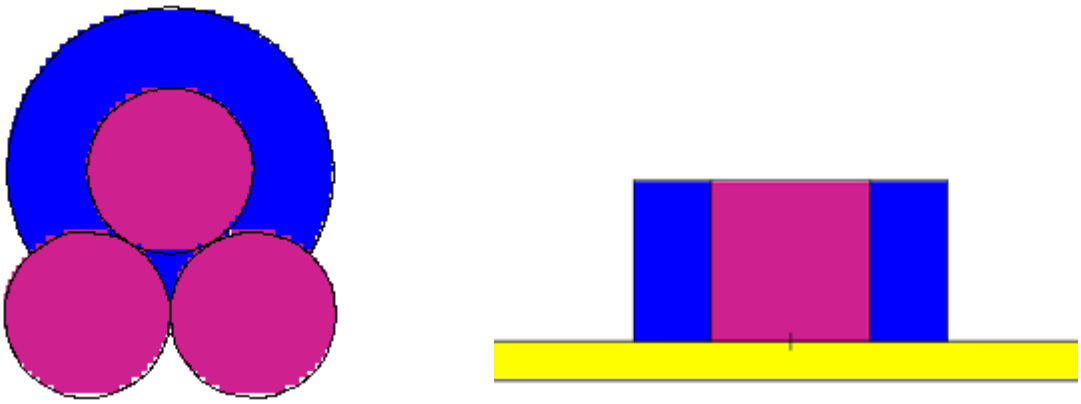

FIGURE 13. MCNP6 ILLUSTRATION OF TOP VIEW (LEFT) AND SIDE VIEW (RIGHT) GEOMETRY FOR METAL AND OXIDE MODELS

- Solution (Metal-Water Mixture): 2 right circular cylinders in close proximity, with reflection from water around the perimeter of one of the cylinders and steel on the bottom of all cylinders. The height-to-diameter ratio of all cylinders was 1.
    - HEU Solution: 1000 g HEU/cylinder @ 40 g/L
    - Pu Solution: 250 g Pu/cylinder @ 30 g/L

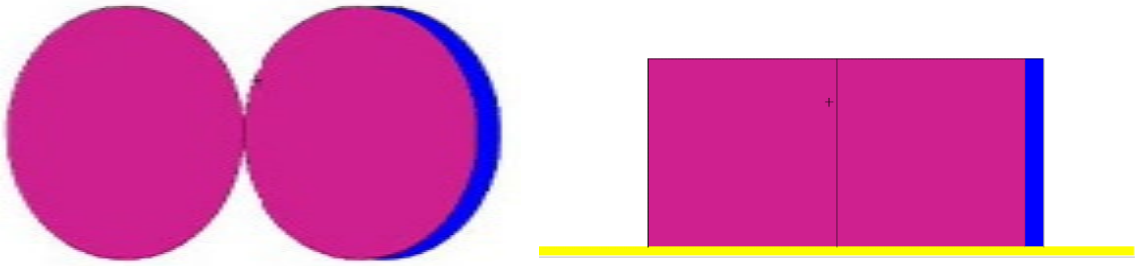

FIGURE 14. MCNP6 ILLUSTRATION OF TOP VIEW (LEFT) AND SIDE VIEW (RIGHT) GEOMETRY FOR "SOLUTION" MODELS

TABLE 14. WHISPER USL RESULTS FOR APPLICATION CASE COMPARISON

Application Case	Whisper USL with LANL Collection	LANL vs. SNL	Whisper USL with SNL Collection	LANL vs. SRNS	Whisper USL with SRNS Collection

HEU Metal	0.9821	1.1%	0.9713	1.0%	0.9726
HEU Oxide*	0.9790	1.2%	0.9676	2.7%	0.9521
HEU Solution	0.9732	0.0%	0.9733	-0.1%	0.9741
Pu Metal	0.9788	-0.2%	0.9807	-0.1%	0.9797
Pu Oxide	0.9779	-0.2%	0.9802	-0.1%	0.9790
Pu Solution	0.9809	0.2%	0.9792	0.0%	0.9809

As can be seen by examining the results in Table 14, most results are within about 1%, however the results for the HEU Oxide case are up to 2.7% different. Since the same application cases are considered with the same MCNP6.2 and the Whisper method, the differences in the benchmark libraries account for the differences in USL. The SRNS library contains HCM series that the LANL and SNL libraries don't. These cases account for the lower USL of 2.7% difference. In order to compute conservative USLs for these types of cases, sites may consider adding HCM into their benchmark collections to make sure this conservative USL is covered. It can be seen by examining the bias results in Figure 16 and bias uncertainty results in Figure 17 that HCM-001 and HCM-002 cases account for the largest differences between selected benchmarks similar to the application from the LANL and SRNS libraries.

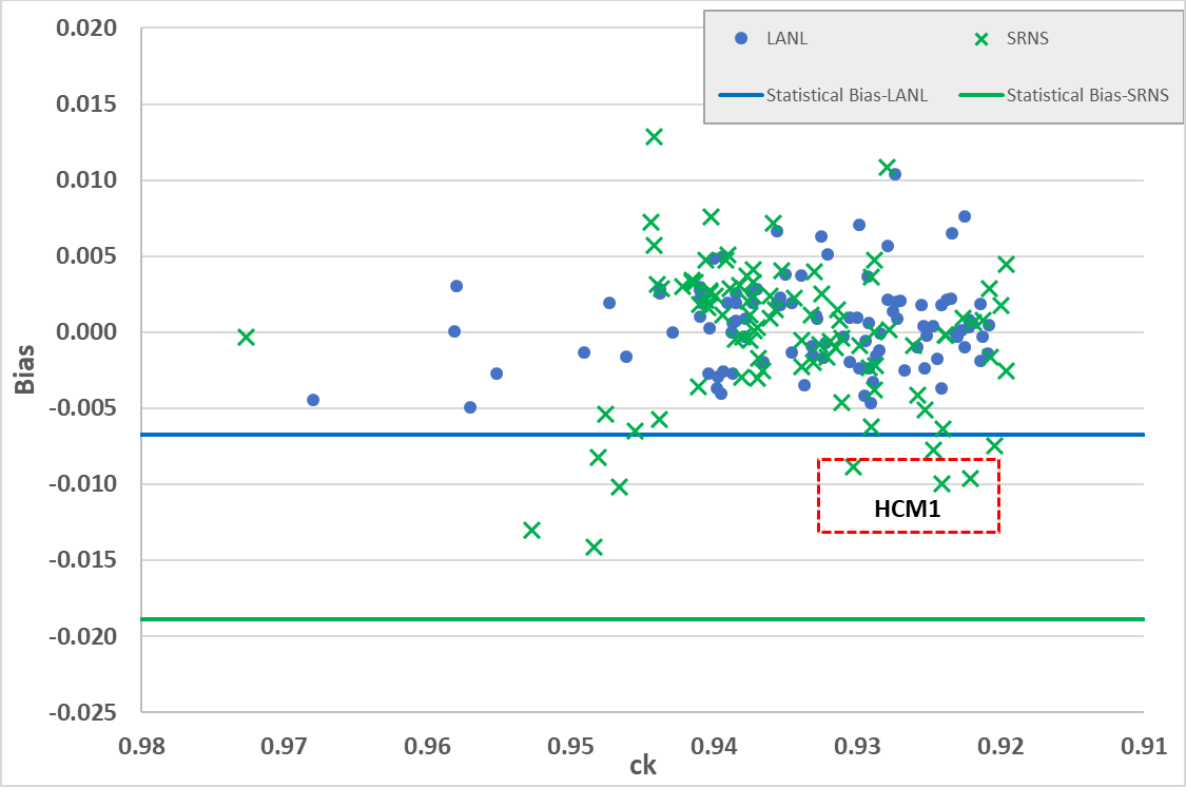

FIGURE 15. BIAS FOR HEU OXIDE CASE WITH LANL AND SRNS BENCHMARK COLLECTIONS

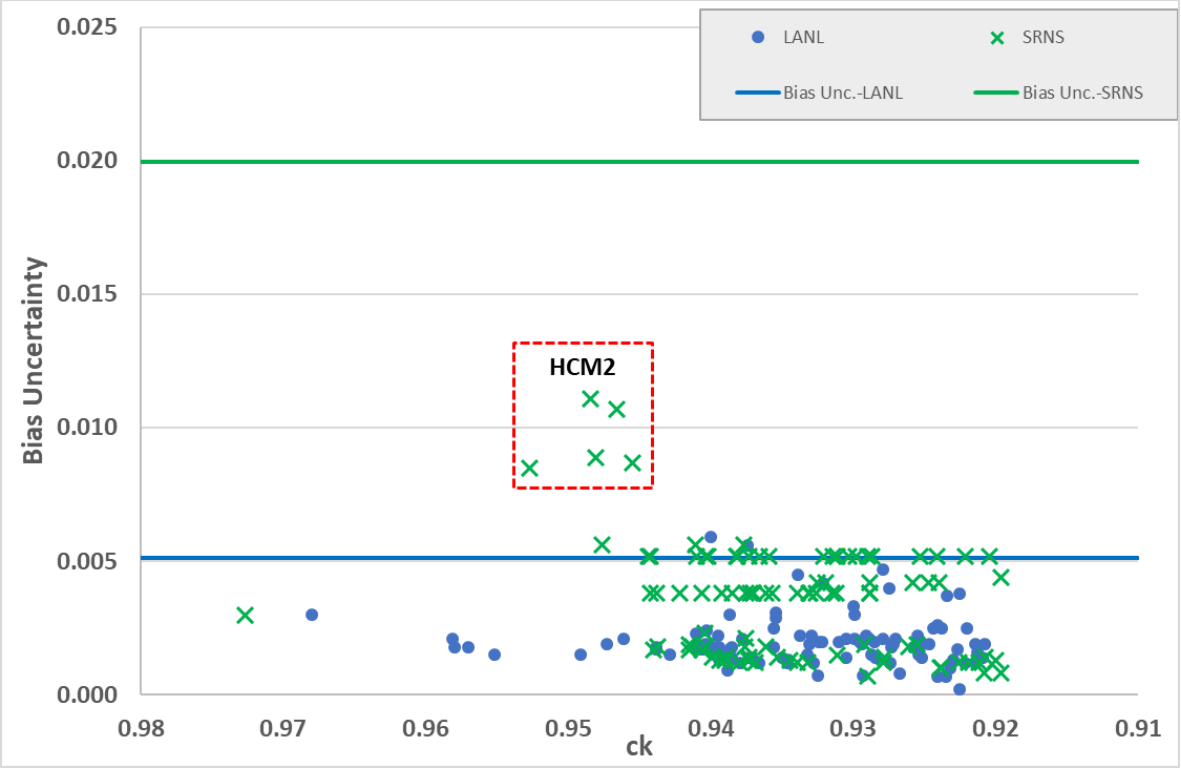

FIGURE 16. BIAS UNCERTAINTY FOR HEU OXIDE CASE WITH LANL AND SRNS BENCHMARK COLLECTIONS

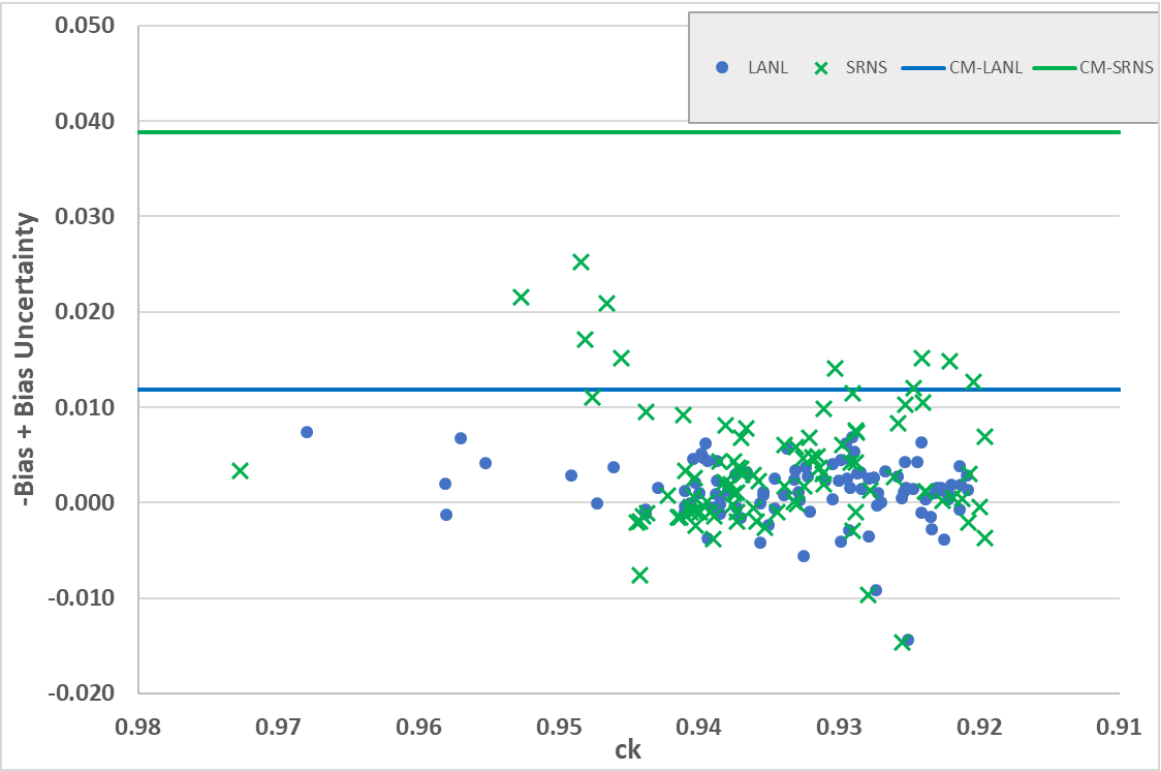

FIGURE 17. CALCULATIONAL MARGIN FOR HEU OXIDE CASE WITH LANL AND SRNS BENCHMARK COLLECTIONS

Summary of USL Study on Benchmark Cases and Application Cases

This paper examines different sensitivity and uncertainty tools and various benchmark libraries to compares the calculational margins and upper subcritical limits. The first study uses four benchmark cases run as application to compare the derived bias and bias uncertainty with the known experiment bias and uncertainty in each case. The maximum difference found for the aforementioned comparison is a difference of 2.7% in USL for the case of HST-001-008. Three other cases USLs were within approximately 1%. The benchmarks which are selected influence the USL more than the particular method of statistical analysis. In the second study, six cases of applications are run using Whisper with three different benchmark libraries; LANL, SNL, and SRNS. The maximum difference in USL is found in the case of HEU oxide, in which there is a 2.7% difference between the Whisper USL computed using the LANL library and the Whisper USL using the SRNS library. This difference is due to the presence of the two experiment series, HCM-001 and HCM-002 which are present in the SRNS libraries but neither the LANL nor SNL library. Again, this demonstrates the difference in USL due to selection of benchmarks rather as the method used is consistent.

Nomenclature

C_k=correlation coefficient or similarity coefficient
CM=Calculational Margin
GLLSM=Generalized Linear Least Squares Method
MOS=margin of subcriticality
MOS_{code}=MOS considered for unknown code errors
MOS_{ND}=MOS considered for nuclear data uncertainty
NCSP=Nuclear Criticality Safety Program
S/U=Sensitivity/Uncertainty

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This work is a portion of the larger comparison study under a DOE Nuclear Criticality Safety Program (NCSP) task involving Analytical Methods; three Laboratories collaborated in a comparison of results obtained from Sensitivity/Uncertainty (S/U) packages relevant to validation of transport codes. The task involves Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL) comparing results of MORET 5/MACSENS V3.0, MCNP6.2/Whisper-1.1, and SCALE 6.2.3/TSUNAMI/USLSTATS respectively. All Monte Carlo transport code results utilize ENDF/B-VII.1. Authors are grateful for collaboration and especially thank Isabelle Duhamel, Frederic Fernex, Luis Leal from IRSN; Mike Rising and Bob Little from LANL; and Doug Bowen, Justin Clarity, B. J. Marshall, Ellen Saylor from ORNL for fruitful exchange of information and discussion of data and methods.

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