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Analysis of the proposed ENDF/B-VII.1(β2) Nuclear Data Library

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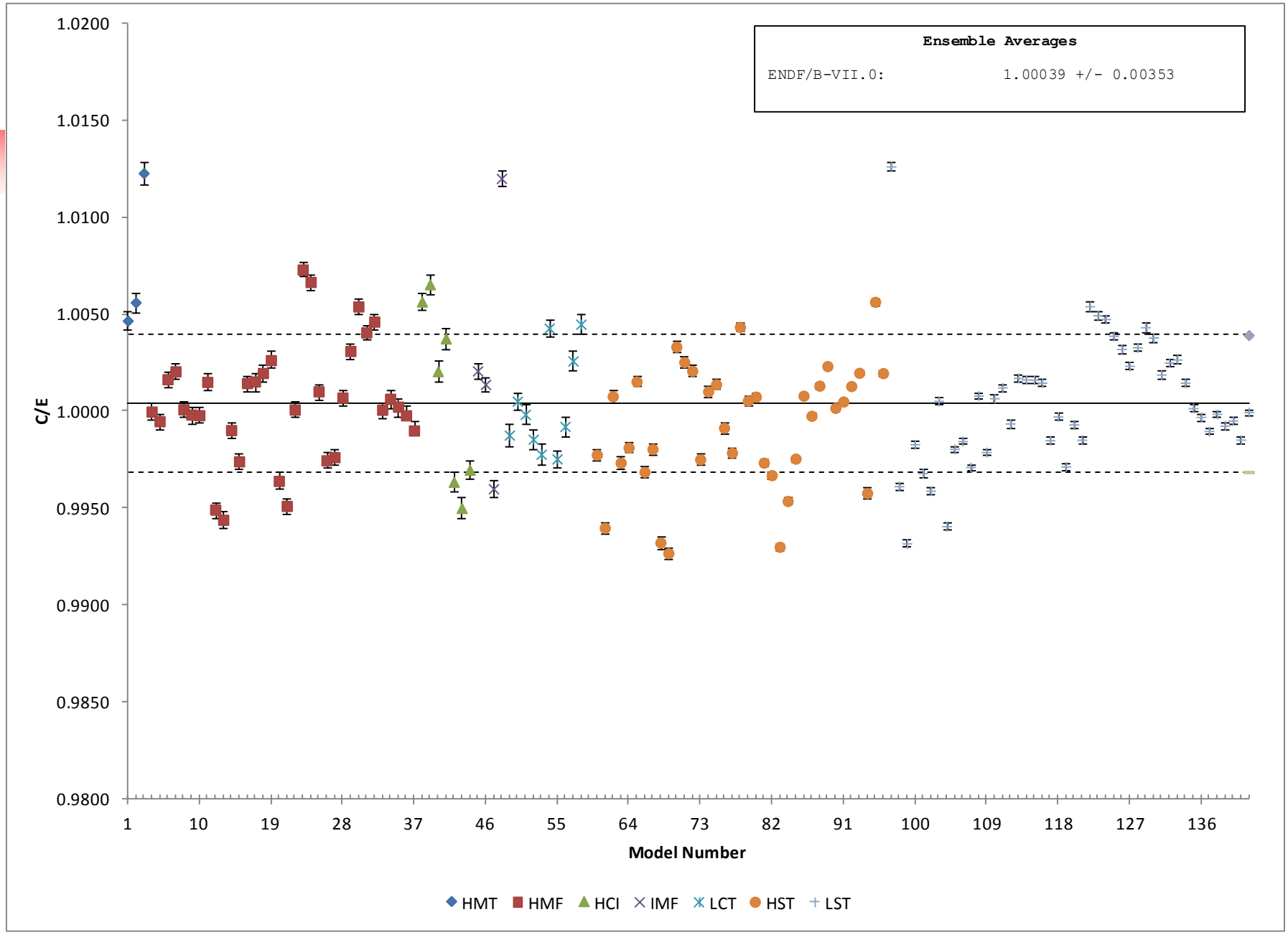
Outline of Analyses

- Suite of 142 ICSBEP Models run using 3 libraries:
  - ENDF/B-VII.0, ENDF/B-VII.1(β2), ENDF/B-VII.1(β2) with ENDF/B-VII.0 ^{16}O.
  - Population-average eigenvalues and standard deviations, Goodness-of-Fit parameters.
  - Trend analysis using ATLF, ATFF, & selected absorption rates.
- ICT-003 "Triga" Model
  - Comparison of ENDF/B-VII.1(β2), ENDF/B-VII.1(BNL), and JENDL-4.0 zirconium to ENDF/B-VII.0 and effects on k-eff.
- Performance in Proprietary NR benchmark suites at KAPL and Bettis.
- All calculations performed with MC21.

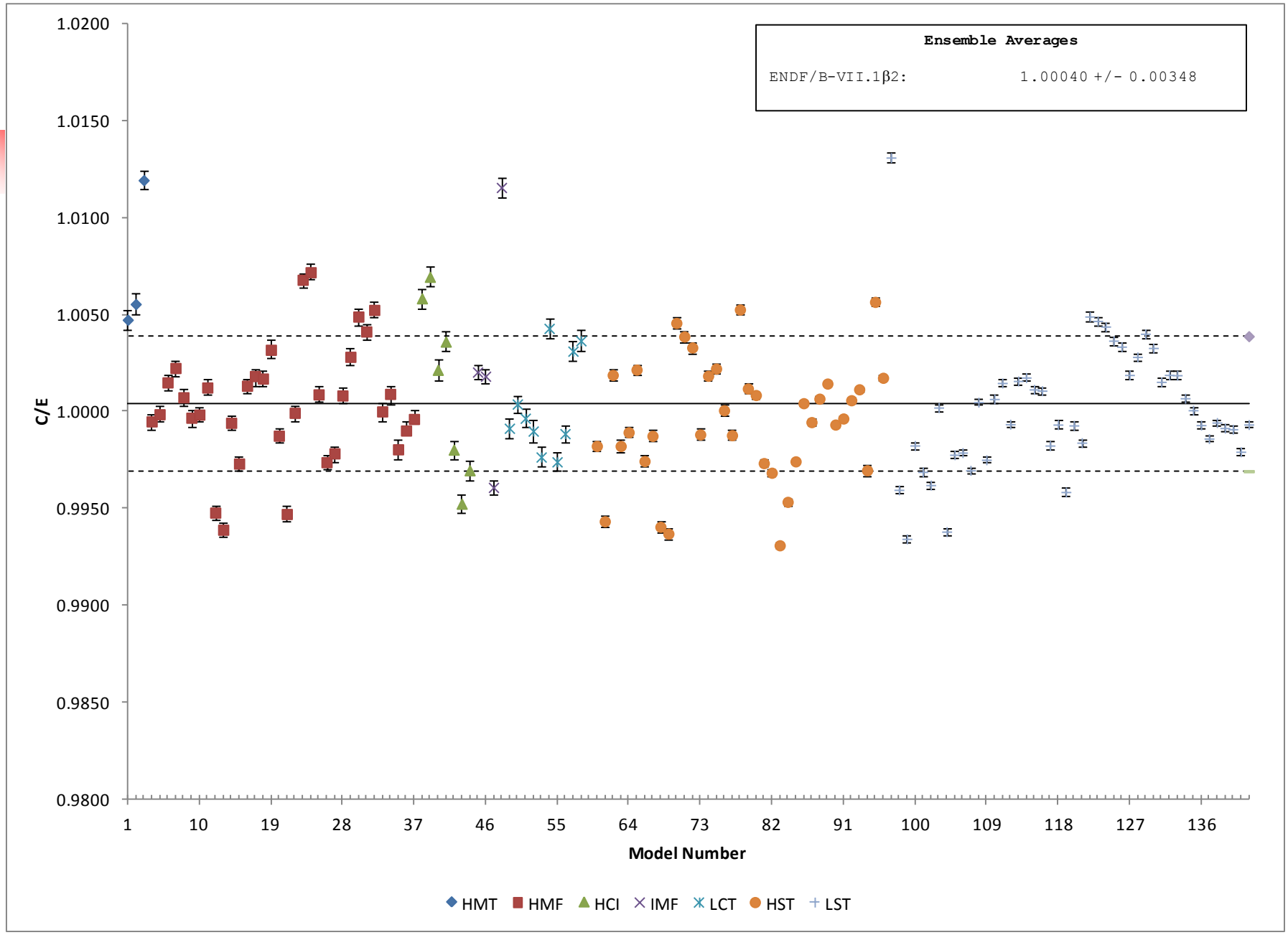
ICSBEP Suite Models

Model	Job ID	Benchmark k-eff	Benchmark Unc.	Model	Job ID	Benchmark k-eff	Benchmark Unc.	Model	Job ID	Benchmark k-eff	Benchmark Unc.
HMT_001_01	1	1.00100	0.00600	LCT_002_03	51	0.99970	0.00200	LST_003_01	101	0.99970	0.00390
HMT_001_01D	2	1.00100	0.00600	LCT_002_04	52	0.99970	0.00200	LST_003_02	102	0.99930	0.00420
HMT_014_01	3	0.99390	0.00150	LCT_002_05	53	0.99970	0.00200	LST_003_03	103	0.99950	0.00420
HMF_001_01A	4	1.00000	0.00100	LCT_010_01	54	1.00000	0.00210	LST_003_04	104	0.99950	0.00420
HMF_001_01B	5	1.00000	0.00100	LCT_010_08	55	1.00000	0.02100	LST_003_05	105	0.99970	0.00480
HMF_002_01	6	1.00000	0.00300	LCT_010_12	56	1.00000	0.00210	LST_003_06	106	0.99990	0.00490
HMF_002_02	7	1.00000	0.00300	LCT_010_17	57	1.00000	0.00280	LST_003_07	107	0.99940	0.00490
HMF_002_03	8	1.00000	0.00300	LCT_010_21	58	1.00000	0.00280	LST_003_08	108	0.99930	0.00520
HMF_002_04	9	1.00000	0.00300	LCT_010_30	59	1.00000	0.00280	LST_003_09	109	0.99960	0.00520
HMF_002_05	10	1.00000	0.00300	HST_001_01	60	1.00040	0.00600	LST_004_01	110	0.99940	0.00080
HMF_002_06	11	1.00000	0.00300	HST_001_02	61	1.00210	0.00720	LST_004_29	111	0.99990	0.00090
HMF_003_01	12	1.00000	0.00500	HST_001_03	62	1.00030	0.00350	LST_004_33	112	0.99990	0.00090
HMF_003_02	13	1.00000	0.00500	HST_001_04	63	1.00080	0.00530	LST_004_34	113	0.99990	0.00100
HMF_003_03	14	1.00000	0.00500	HST_001_05	64	1.00010	0.00490	LST_004_46	114	0.99990	0.00100
HMF_003_04	15	1.00000	0.00300	HST_001_06	65	1.00020	0.00460	LST_004_51	115	0.99940	0.00110
HMF_003_05	16	1.00000	0.00300	HST_001_07	66	1.00080	0.00400	LST_004_54	116	0.99960	0.00110
HMF_003_06	17	1.00000	0.00300	HST_001_08	67	0.99980	0.00380	LST_007_14	117	0.99610	0.00090
HMF_003_07	18	1.00000	0.00300	HST_001_09	68	1.00080	0.00540	LST_007_30	118	0.99730	0.00090
HMF_004_01	19	1.00200	0.00010	HST_001_10	69	0.99930	0.00540	LST_007_32	119	0.99850	0.00100
HMF_009_01	20	0.99920	0.00150	HST_009_01	70	0.99900	0.00430	LST_007_36	120	0.99880	0.00110
HMF_015_01	21	0.99960	0.00170	HST_009_02	71	1.00000	0.00390	LST_007_49	121	0.99830	0.00110
HMF_018_01	22	1.00000	0.00140	HST_009_03	72	1.00000	0.00360	LST_016_105	122	0.99960	0.00130
HMF_019_01	23	1.00000	0.00280	HST_009_04	73	0.99860	0.00350	LST_016_113	123	0.99990	0.00130
HMF_019_02	24	1.00000	0.00280	HST_010_01	74	1.00000	0.00290	LST_016_125	124	0.99940	0.00140
HMF_020_01	25	1.00000	0.00280	HST_010_02	75	1.00000	0.00290	LST_016_129	125	0.99960	0.00140
HMF_021_01	26	1.00000	0.00240	HST_010_03	76	1.00000	0.00290	LST_016_131	126	0.99950	0.00140
HMF_022_01	27	1.00000	0.00190	HST_010_04	77	0.99920	0.00290	LST_016_140	127	0.99920	0.00150
HMF_027_01	28	1.00000	0.00250	HST_011_01	78	1.00000	0.00230	LST_016_196	128	0.99940	0.00150
HMF_028_01	29	1.00000	0.00300	HST_011_02	79	1.00000	0.00230	LST_017_001	129	0.99810	0.00130
HMF_029_01	30	1.00000	0.00200	HST_012_01	80	0.99990	0.00580	LST_017_002	130	0.99860	0.00130
HMF_032_01	31	1.00000	0.00160	HST_013_01	81	1.00120	0.00260	LST_017_003	131	0.99890	0.00140
HMF_032_02	32	1.00000	0.00270	HST_013_02	82	1.00070	0.00360	LST_017_004	132	0.99920	0.00140
HMF_032_03	33	1.00000	0.00170	HST_013_03	83	1.00090	0.00360	LST_017_005	133	0.99870	0.00150
HMF_032_04	34	1.00000	0.00170	HST_013_04	84	1.00030	0.00360	LST_017_006	134	0.99960	0.00150
HMF_034_01	35	0.99900	0.00120	HST_032_01	85	1.00150	0.00260	LST_020_001	135	0.99950	0.00100
HMF_034_02	36	0.99900	0.00120	HST_042_01	86	0.99570	0.00390	LST_020_002	136	0.99960	0.00100
HMF_034_03	37	0.99900	0.00120	HST_042_02	87	0.99650	0.00360	LST_020_003	137	0.99970	0.00120
HCI_003_01	38	1.00000	0.00570	HST_042_03	88	0.99940	0.00280	LST_020_004	138	0.99980	0.00120
HCI_003_02	39	1.00000	0.00610	HST_042_04	89	1.00000	0.00340	LST_021_001	139	0.99830	0.00090
HCI_003_03	40	1.00000	0.00560	HST_042_05	90	1.00000	0.00340	LST_021_002	140	0.99850	0.00100
HCI_003_04	41	1.00000	0.00550	HST_042_06	91	1.00000	0.00370	LST_021_003	141	0.99890	0.00110
HCI_003_05	42	1.00000	0.00470	HST_042_07	92	1.00000	0.00360	LST_021_004	142	0.99930	0.00120
HCI_003_06	43	1.00000	0.00470	HST_042_08	93	1.00000	0.00350				
HCI_003_07	44	1.00000	0.00500	HST_043_01	94	0.99860	0.00310				
IMF_003	45	1.00000	0.00170	HST_043_02	95	0.99950	0.00260				
IMF_005	46	1.00000	0.00210	HST_043_03	96	0.99900	0.00250				
IMF_006	47	1.00000	0.00230	LST_001_01	97	0.99910	0.00290				
IMF_009	48	1.00000	0.00530	LST_002_01	98	1.00380	0.00400				
LCT_002_01	49	0.99970	0.00200	LST_002_02	99	1.00240	0.00370				
LCT_002_02	50	0.99970	0.00200	LST_002_03	100	1.00240	0.00440				

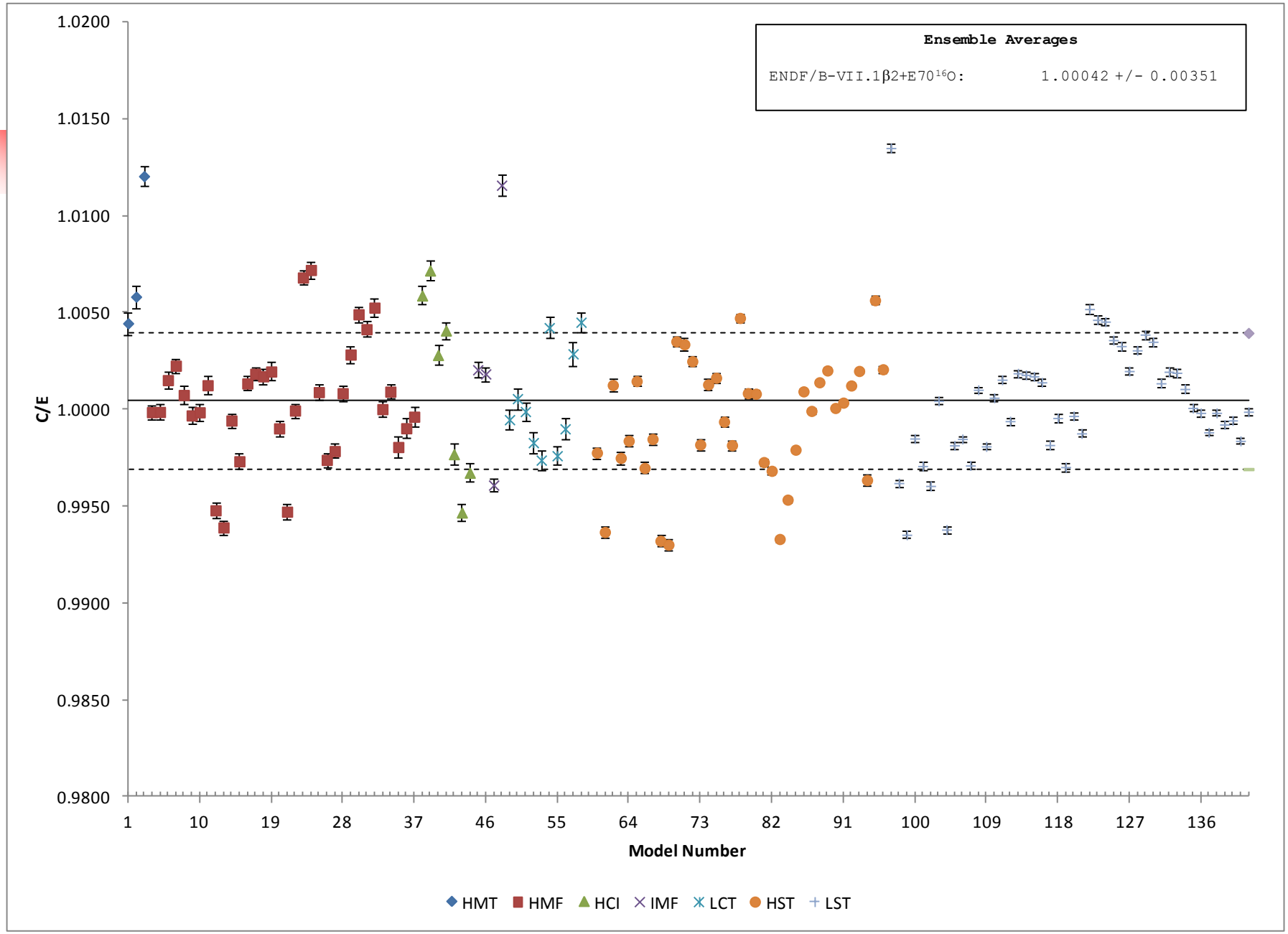
C/E Plots: ENDF/B-VII.0 (the baseline)



C/E Plots: ENDF/B-VII.1(β2)



C/E Plots: ENDF/B-VII.1(β2) + ENDF/B-VII.0 ^{16}O



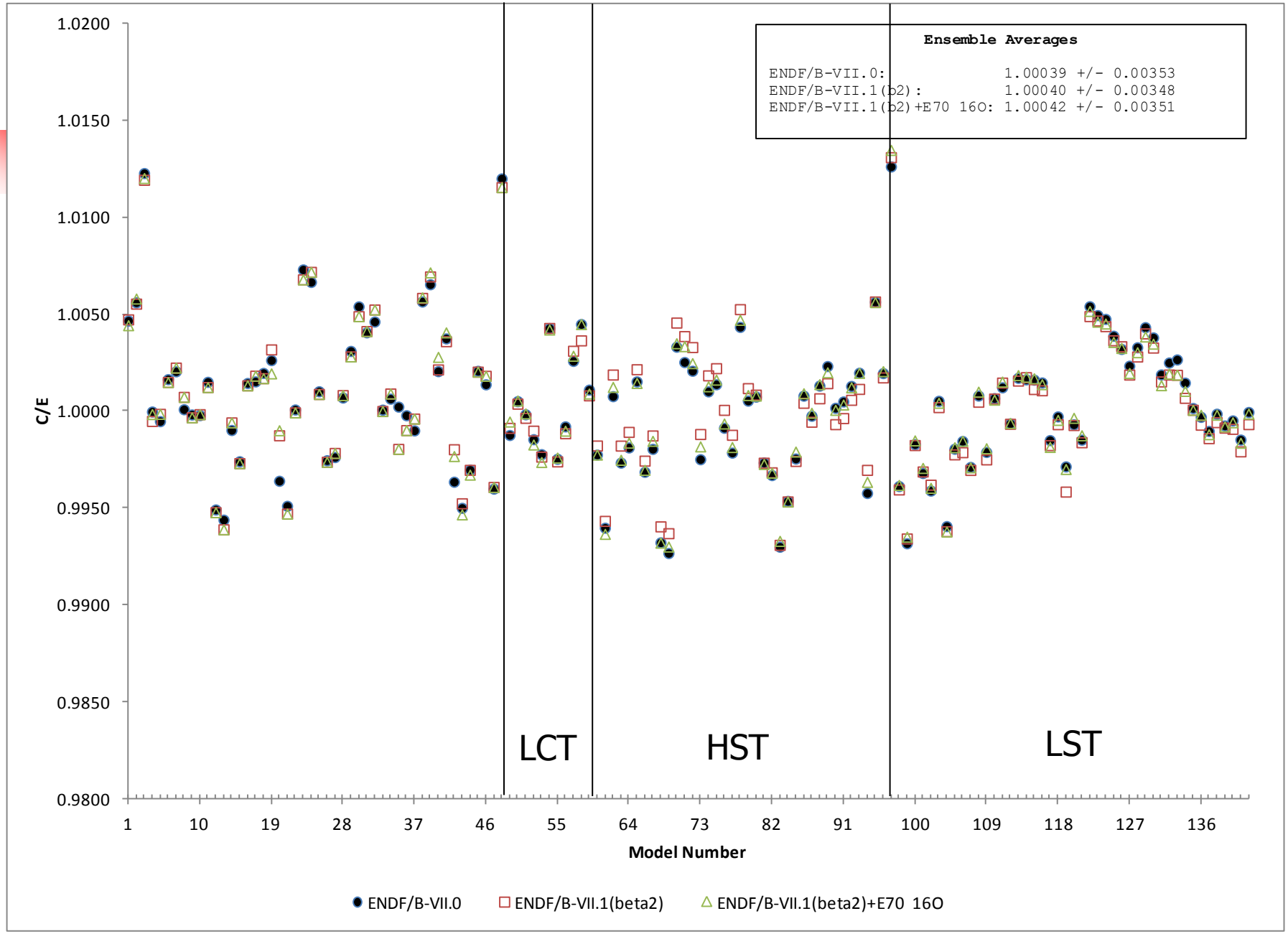
Population Statistics

- Ensemble-average E/C and Std. Dev.
- Goodness-of-Fit for E/C:

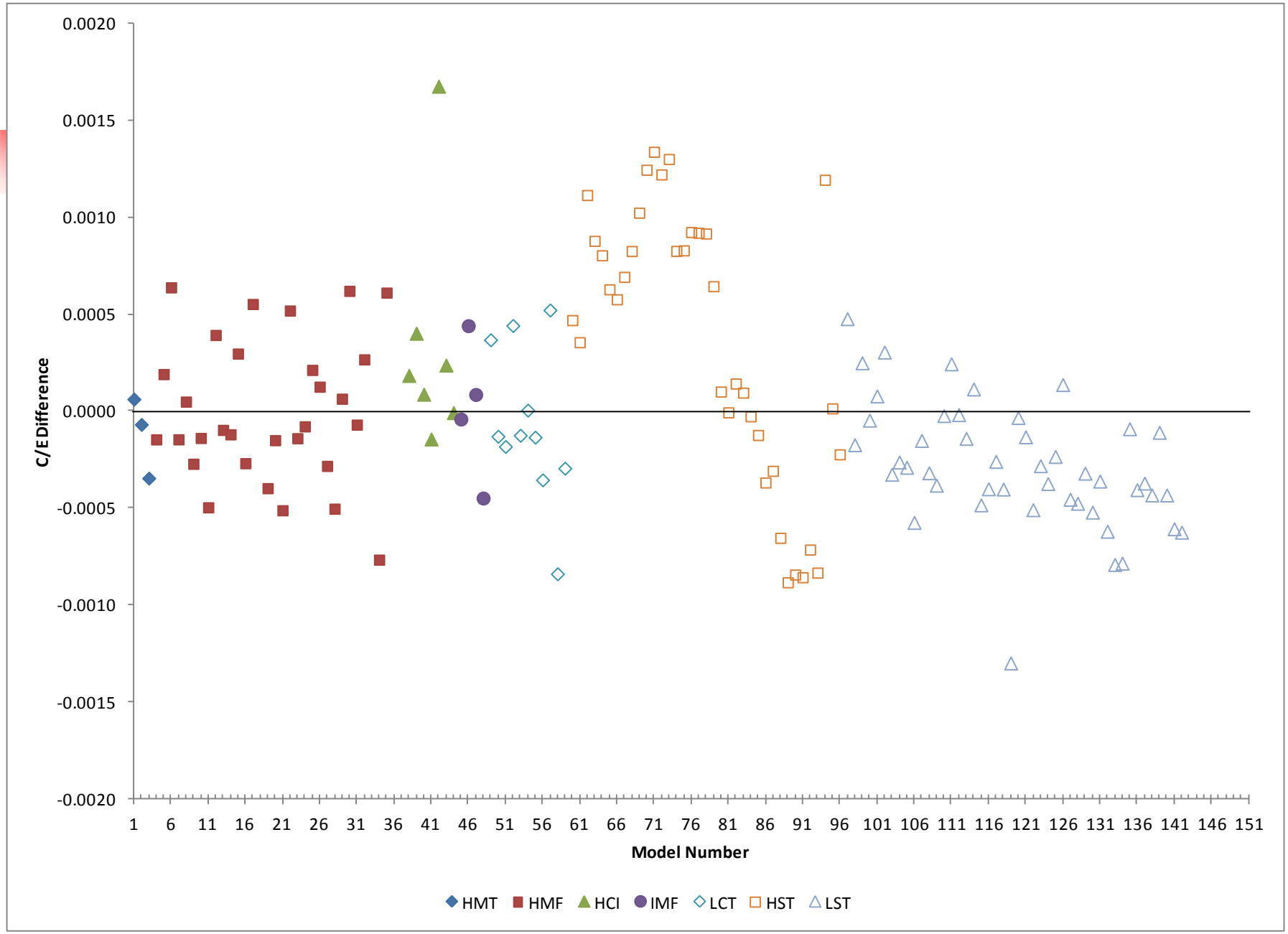
$$\chi^2 = \frac{1}{N-1}\sum_{i=1}^{N}\frac{\left(1-C_i/E_i\right)^2}{\sqrt{\sigma_{C,i}^2+\sigma_{E,i}^2}}$$

Library	Average	Std. Dev.	χ^2
ENDF/B-VII.0	1.00039	0.00353	0.00472
ENDF/B-VII.1(b2)	1.00040	0.00348	0.00464
ENDF/B-VII.1(b2) + E70 ^{16}O	1.00042	0.00351	0.00457

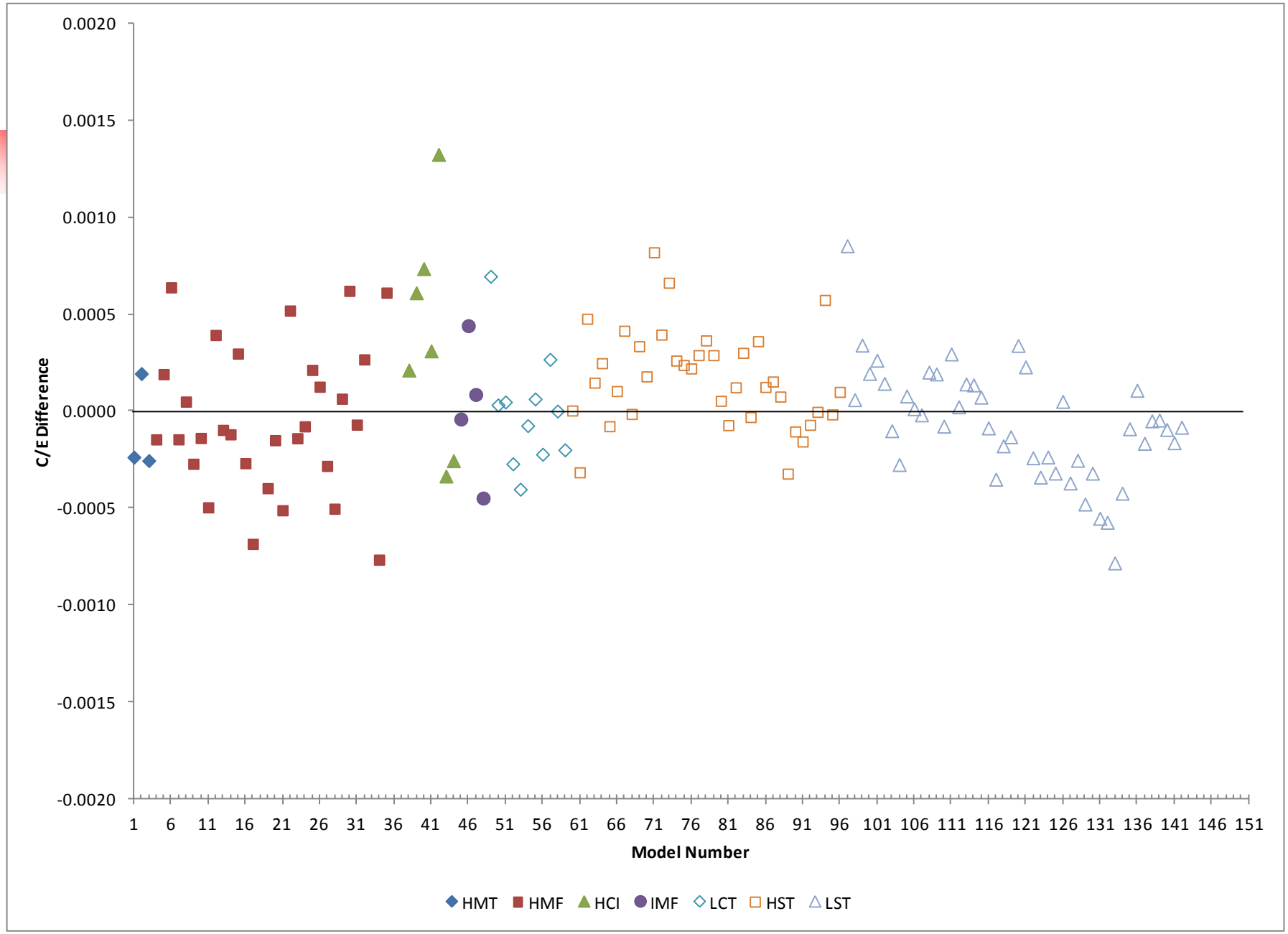
C/E Plots: All together



C/E Difference Plots: ENDF/B-VII.1(β2) – ENDF/B-VII.0



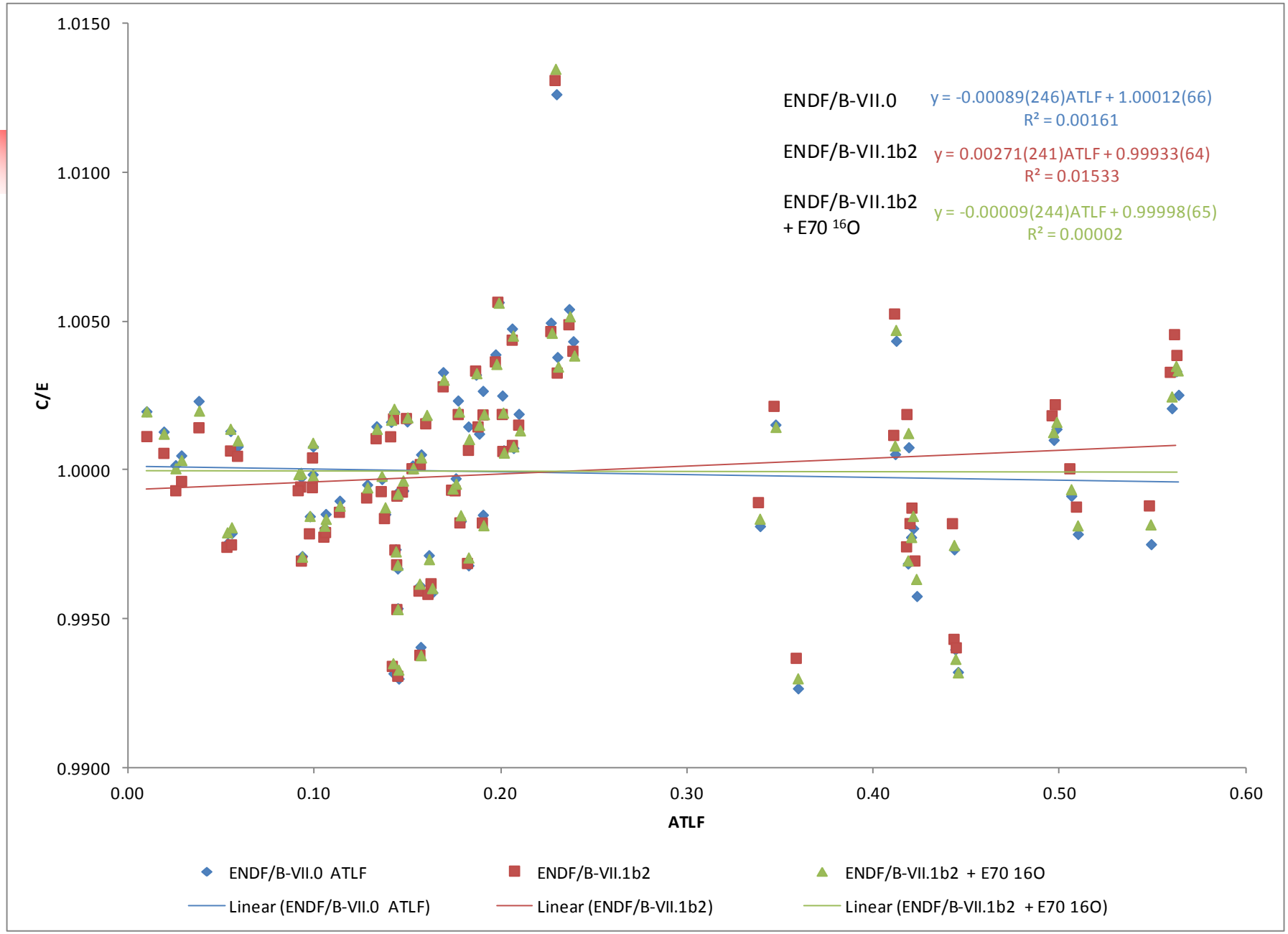
C/E Difference Plots: ENDF/B-VII.1(β2)+E70 ^{16}O – ENDF/B-VII.0



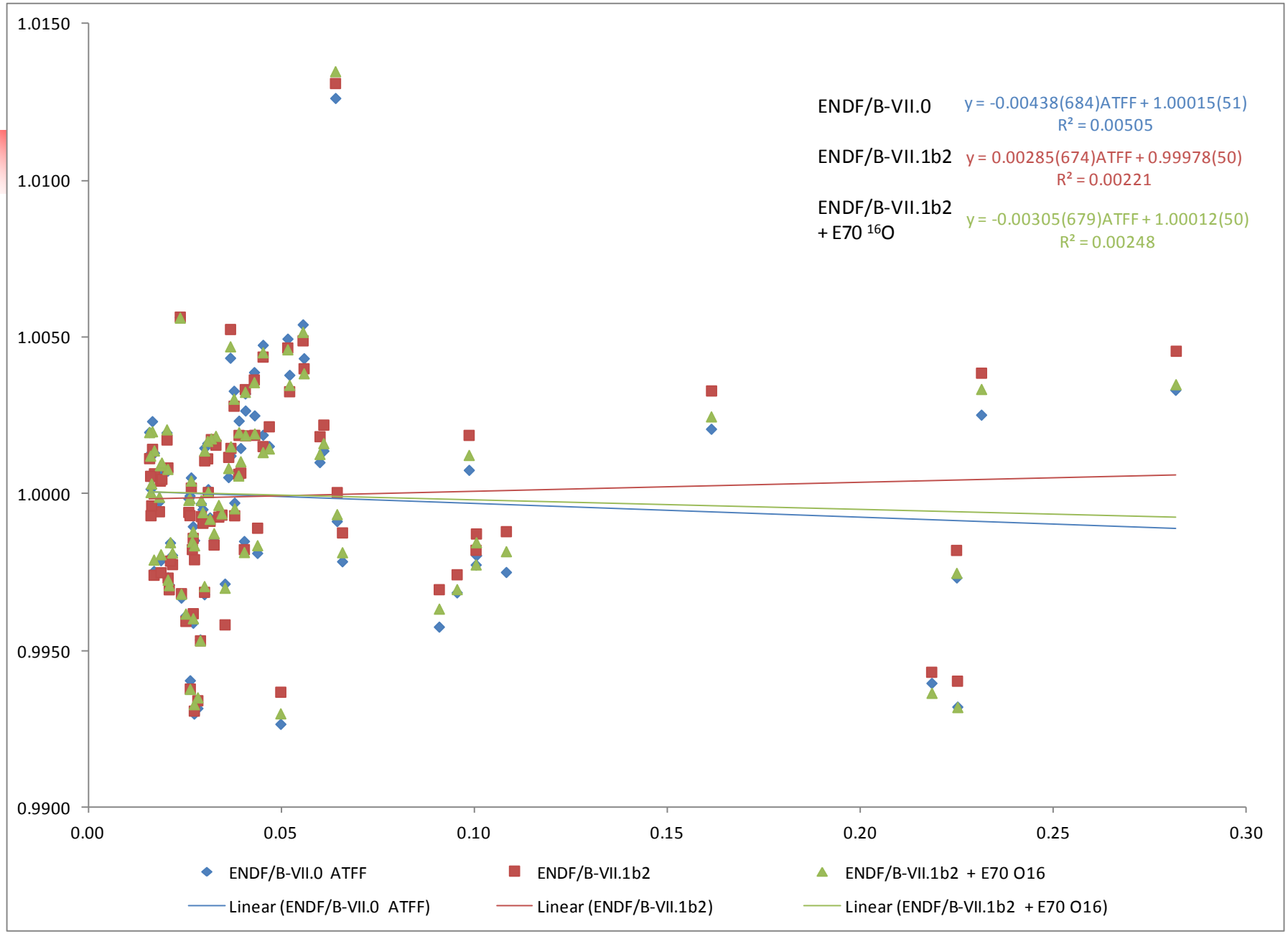
Population Ensemble-average E/C and Std. Dev. For LCT, HST, LST Series Separately:

Library	Average	Std. Dev.
ENDF/B-VII.0	1.00042 (LCT)	0.00245
	0.99925 (HST)	0.00319
	1.00046 (LST)	0.00332
ENDF/B-VII.1(b2)	1.00036 (LCT)	0.00237
	0.99961 (HST)	0.00315
	1.00018 (LST)	0.00334
ENDF/B-VII.1(b2) + E70 ^{16}O	1.00042 (LCT)	0.00250
	0.99942 (HST)	0.00319
	0.99944 (LST)	0.00331

Trend Analysis (HST & LST Series): Above Thermal Leakage Fraction (ATLF)



Trend Analysis (HST & LST Series): Above Thermal Fission Fraction (ATFF)



Summary of ICSBEP Suite Analysis

- All three libraries performed well
  - Average C/E's and standard deviations, goodness-of-fit parameters are all very similar.
- The analysis supports reverting to the ENDF/B-VII.0 ^{16}O
  - ENDF/B-VII.1(β2) ^{16}O introduces slight bias in ATLF trend.

Zirconium Substitution Analysis using ICT-003 "TRIGA"

Description	K-eff (95% CI)
ENDF/B-VI.8 for all	1.00012(79)
ENDF/B-VII.0 for all	1.00352(53)
ENDF/B-VII.0 + JENDL-4.0 Zr isos.	1.00133(52)
ENDF/B-VII.0 + VII.1(b2) Zr isos.	1.00280(54)
ENDF/B-VII.1(b2) for all	1.00385(54)
ENDF/B-VII.1(b2) + VII.1(BNL)	1.00289(55)

- The use of JENDL-4.0 Zr isotopes brings calculated k-eff ~220 pcm lower.
- ENDF/B-VII(β2) Zr also brings calculated k-eff down, but only ~ 70 pcm.
- However, when the entire ENDF/B-VII(β2) library is used, k-eff creeps back up ~30 pcm higher than ENDF/B-VII.0
- Substituting the proposed BNL zirconium into ENDF/B-VII(β2) brings down k-eff ~100 pcm.

Summary of TRIGA Analysis

- The proposed BNL zirconium improves the calculated k-eff for TRIGA, relative to $\beta 2$
- There is still room for improvement
  - JENDL-4.0 Zirconium evaluation performs better than ENDF/B-VII.0, VII.1($\beta 2$), and VII.1(BNL).
    - We speculate that fast elastic scattering angular distributions may be contributing to the higher k-eff.

Conclusions

- Based on the analysis performed on the ICSBEP Benchmark Suite:
  - ENDF/B-VII.1(β2) is statistically equivalent to ENDF/B-VII.0.
  - ATLF Trend analysis of HST/LST models showed better performance using the ENDF/B-VII.0 ^{16}O.
- ENDF/B-VII.1(β2) increases the calculated k-eff in the TRIGA model
  - However, the proposed β3 zirconium isotopes mitigate the effects.
  - JENDL-4.0 Zirconium evaluation performs better than VII.0, VII.1(β2) and VII.1(β3).
- Analysis using KAPL and Bettis suite of proprietary benchmarks:
  - ENDF/B- VII.1(β2) hafnium isotopes introduce a negative reactivity bias.
  - ENDF/B-VII.1(β2) zirconium isotopes introduce reactivity trend with temperature.
  - Prefer the JENDL-4.0 Zirconium isotopes and JEFF-3.1.1 hafnium isotopes, compared to ENDF/B- VII.1(β2)
  - ENDF/B- VII.1(β2) Nickel isotopes are an improvement.

Hf Cross Section Comparison:

Table 1. Thermal capture cross-section data for ENDF/B-VII.1

Isotope	ENDF/B-VII.0 (b)	JENDL 3.3/JEFF-3.1 (b)	ENDF/B-VII.1 (b)	1984 Atlas of Neutron Resonances (b)
^{174}Hf	561.8	549.5	549.1	549 ± 7
^{176}Hf	13.8	21.3	21.4	23.5 ± 3.1
^{177}Hf	373.5	373.5	373.5	375 ± 10
^{178}Hf	84.0	83.9	83.9	84 ± 4
^{179}Hf	43.6	42.8	42.8	41 ± 3
^{180}Hf	13.01	13.10	13.06	13.04 ± 0.07

Table 2. Capture resonance integrals for ENDF/B-VII.1

Isotope	ENDF/B-VII.0 (b)	JENDL 3.3/JEFF-3.1 (b)	ENDF/B-VII.1 (b)	1984 Atlas of Neutron Resonances (b)
^{174}Hf	355.0	442.3	345.0	307 ± 15
^{176}Hf	401.3	694.3	691.3	708 ± 15
^{177}Hf	7175	7197	7197	7200 ± 200
^{178}Hf	1905	1872	1879	1882 ± 20
^{179}Hf	548	522	523	527 ± 30
^{180}Hf	34.5	29.7	33.5	33 ± 1