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# COG Beta-Effective Benchmarks

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## Benchmarks

Beta-eff ($\beta_{eff}$) values have been established for several critical assemblies as provided in Table 1. Note that these values as taken from the references cited generally agree well with Table XXXIV of Brown (2018) but with some minor discrepancies. As Brown (2018) provides no references for the experimental values cited in this "big paper," the curated data in Table 1 are preferred and used in this work.

*Table 1. Beta-effective benchmark values*

| No. | Name | Reference | Experiment |
|---|---|---|---|
| 1 | NASA ZPR-1 H/X=190 | Alger (1966) | 900 ± 60 |
| 2 | NASA ZPR-1 H/X=473 | Alger (1966) | 860 ± 50 |
| 3 | NASA ZPR-1 H/X=565 | Alger (1966) | 820 ± 40 |
| 4 | TCA 1.50U 19x19 | Suzaki (1999) | 771 ± 18 |
| 5 | TCA 1.83U Cylinder | Nakajima (2001) | 771 ± 17 |
| 6 | TCA 1.83U 17x17 | Suzaki (1999) | 766 ± 18 |
| 7 | TCA 2.48U 16x16 | Suzaki (1999) | 765 ± 18 |
| 8 | SNEAK 9C1 | Fischer (1977) | 758 ± 24 |
| 9 | IPEN/MB-01 | dos Santos (2013) | 750 ± 4 |
| 10 | TCA 3.00U 15x15 | Suzaki (1999) | 749 ± 17 |
| 11 | FCA XIX-1 | Okajima (2002) | 742 ± 24 |
| 12 | BFS-73-1 | Manturov (2006) | 735 ± 13 |
| 13 | U9 | Fort (1999) | 731 ± 15 |
| 14 | Masurca R2 | Okajima (2002) | 721 ± 11 |
| 15 | Big Ten | Kodeli (2017) | 720 ± 7 |
| 16 | U/Fe (ZPR9/34) | Fort (1999) | 671 ± 14 |
| 17 | Topsy (25 Flattop) | Kodeli (2017) | 665 ± 13 |
| 18 | Godiva | Keepin (1965) | 659 ± 28 |
| 19 | OR Sphere Config. 1 | Marshall | 657 ± 9 |
| 20 | OR Sphere Config. 2 | Marshall | 657 ± 9 |
| 21 | SNEAK 7B | Ivanov (2009) | 429 ± 22 |
| 22 | SNEAK 9C2 | Fischer (1977) | 426 ± 19 |
| 23 | SNEAK 7A | Ivanov (2009) | 395 ± 22 |
| 24 | C Ref (ZPPR21B) | Fort (1999) | 384 ± 8 |
| 25 | FCA XIX-2 | Okajima (2002) | 364 ± 9 |
| 26 | 23 Flattop | Kodeli (2017) | 360 ± 9 |
| 27 | Masurca Zona 2 | Okajima (2002) | 349 ± 6 |
| 28 | Skidoo (Jezebel 23) | Kodeli (2017) | 290 ± 10 |
| 29 | Popsy (49 Flattop) | Kodeli (2017) | 276 ± 7 |
| 30 | FCA XIX-3 | Okajima (2002) | 251 ± 4 |
| 31 | P/C/SST (ZPR6-10) | Fort (1999) | 223 ± 5 |
| 32 | Jezebel | Kodeli (2017) | 195 ± 10 |

## Models

Table 2 provides references where each benchmark model is published, and it may be observed that 66% are taken from ICSBEP or IRPhE evaluations. Note that the errors given in Table 1 do not include uncertainties due to materials and geometry.

*Table 2. Beta-effective benchmark models*

| No. | Name | Model | Reference | Filename |
|---|---|---|---|---|
| 1 | NASA ZPR-1 H/X=190 | Alger (1966) | NASA TN D-3709 | nasa-zpr1-1 |
| 2 | NASA ZPR-1 H/X=473 | Alger (1966) | NASA TN D-3709 | nasa-zpr1-2 |
| 3 | NASA ZPR-1 H/X=565 | Alger (1966) | NASA TN D-3709 | nasa-zpr1-3 |
| 4 | TCA 1.50U 19x19 | ICSBEP | LEU-COMP-THERM-006, Rev. 1 | lct006-1 |
| 5 | TCA 1.83U Cylinder | Nakajima (2001) | J. Nucl. Sci. and Tech. **38** (12) 1120 (2001)*[*] | TCA183UCYL |
| 6 | TCA 1.83U 17x17 | ICSBEP | LEU-COMP-THERM-006, Rev. 1 | LCT006-4 |
| 7 | TCA 2.48U 16x16 | ICSBEP | LEU-COMP-THERM-006, Rev. 1 | LCT006-9 |
| 8 | SNEAK 9C1 | Fischer (1977) | NSE **62**, 105-116 (1977) | SNEAK9C1 |
| 9 | IPEN/MB-01 | IRPhE | IPEN(MB01)-LWR-RESR-001 | IPENMB01 |
| 10 | TCA 3.00U 15x15 | ICSBEP | LEU-COMP-THERM-006, Rev. 1 | lct006-14 |
| 11 | FCA XIX-1 | Okajima (2002) | Prog. In Nuclear Energy **41** (1-4) 285 (2002) | FCA-XIX-1 |
| 12 | BFS-73-1 | IRPhE | BFS1-LMFR-EXP-001 | bfs73-1 |
| 13 | U9 | ICSBEP | IEU-MET-FAST-010 | imf010-1 |
| 14 | Masurca R2 | Okajima (2002) | Prog. In Nuclear Energy **41** (1-4) 285 (2002) | MASURCA-R2 |
| 15 | Big Ten | ICSBEP | IEU-MET-FAST-007 | imf007-1d |
| 16 | U/Fe (ZPR9/34) | ICSBEP | HEU-MET-INTER-001 | hmi001 |
| 17 | Topsy (25 Flattop) | ICSBEP | HEU-MET-FAST-028 | hmf028 |
| 18 | Godiva | ICSBEP | HEU-MET-FAST-001 | hmf001 |
| 19 | OR Sphere 1 | ICSBEP | HEU-MET-FAST-100 | hmf100-1 |
| 20 | OR Sphere 2 | ICSBEP | HEU-MET-FAST-100 | hmf100-2 |
| 21 | SNEAK 7B | IRPhE | SNEAK-LMFR-EXP-001 | SNEAK7B |
| 22 | SNEAK 9C2 | Fischer (1977) | NSE **62**, 105-116 (1977) | SNEAK9C2 |
| 23 | SNEAK 7A | IRPhE | SNEAK-LMFR-EXP-001 | SNEAK7A |
| 24 | C Ref (ZPPR21B) | ICSBEP | MIX-MET-FAST-011 | mmf011-b |
| 25 | FCA XIX-2 | Okajima (2002) | Prog. In Nuclear Energy **41** (1-4) 285 (2002) | FCA-XIX-2 |
| 26 | 23 Flattop | ICSBEP | U233-MET-FAST-006 | umf006-1 |
| 27 | Masurca Zona 2 | Okajima (2002) | Prog. In Nuclear Energy **41** (1-4) 285 (2002) | MASURCA-ZONA2 |
| 28 | Skidoo (Jezebel 23) | ICSBEP | U233-MET-FAST-001 | umf001-1 |
| 29 | Popsy (49 Flattop) | ICSBEP | PU-MET-FAST-006 | pmf006 |
| 30 | FCA XIX-3 | Okajima (2002) | Prog. In Nuclear Energy **41** (1-4) 285 (2002) | FCA-XIX-3 |
| 31 | P/C/SST (ZPR6-10) | ICSBEP | PU-MET-INTER-002 | pmi002 |
| 32 | Jezebel | ICSBEP | PU-MET-FAST-001 | pmf001 |

## Methods

Three beta-eff estimators are available in COG 11.3: the "new method" and "prompt method" described by van der Marck (2004) and a "modified new method" described by Pearlstein (1999). In COG, prompt neutrons and delayed neutrons are tracked as separate particles so that both estimates can be calculated in just one (forward) calculation.

> The "new method" defines beta-eff as the number of fissions induced by delayed neutrons divided by the number of all fissions, or $\beta_{eff} = F_d/F_t$.

[*] Reference cited for loading patter and critical height. All else taken from LEU-COMP-THERM-006, Rev. 1.

The "modified new method" defines beta-eff as the number of neutrons from fissions induced by delayed neutrons divided by the number of neutrons from all fissions, or $\beta_{eff} = (\nu F)_d/(\nu F)_t$.

The "prompt method" is estimated as $\beta_{eff} = 1 - (k_p/k_{eff})$, where $k_p$ is the prompt effective neutron multiplication factor.

## Results

The results of COG 11.3 calculations with ENDF/B-VIII.0 and JEFF-3.3 nuclear data libraries are provided in Appendix A, Tables A-1 and A-2, respectively. C/E results shown in **RED** in these tables correspond to calculations where $|C/E - 1| > 3\sigma$, where $\sigma$ is the combined experimental and calculational uncertainty. The corresponding calculated k-eff results are provided in Appendix B.

COG 11.3 calculations with the "new method" using ENDF/B-VIII.0 data are shown to produce results with $|C/E - 1| < 3\sigma$ in all cases, whereas the other methods produce a few minor outliers. Furthermore, the "new method" using ENDF/B-VIII.0 data is observed to produce "over" and "under" results consistent with 50/50 expectations whereas the other methods appear to be slightly over or under predicting. JEFF-3.3 results are slightly larger overall than ENDF/B-VIII.0 results.

*Table 3. C/E – 1 Statistics*

| | ENDF/B-VIII.0 | | | | JEFF-3.3 | | | |
|---|---|---|---|---|---|---|---|---|
| Method | X > 0 | X = 0 | X < 0 | $\lvert X\rvert > 3\sigma$ | X > 0 | X = 0 | X < 0 | $\lvert X\rvert > 3\sigma$ |
| $\beta_{eff} = F_d/F_t$ | 15 | 2 | 15 | 0 | 24 | 0 | 8 | 3 |
| $\beta_{eff} = (\nu F)_d/(\nu F)_t$ | 6 | 0 | 26 | 2 | 12 | 1 | 19 | 2 |
| $\beta_{eff} = 1 - (k_p/k_{eff})$ | 5 | 1 | 26 | 3 | 10 | 0 | 22 | 2 |

In all but a few cases, it is also observed that $F_d/F_t \geq (\nu F)_d/(\nu F)_t \geq 1 - (k_{prompt}/k_{eff})$, and all estimators produce equivalent results for the most thermal systems. In those other cases, this relation holds within the given statiscs.

## References


Donald Alger et al., "Measurement of Effective Delayed Neutron Fraction for NASA Zero Power Reactor I," NASA TN D-3709, November 1966.

Adimir dos Santos, et al., "Reactor Physics Experiments in the IPEN/MB-01 Research Reactor Facility," IPEN(MB01)-LWR-RESR-001, CRIT-BUCK-SPEC-REAC-COEF-KIN-RRATE-POWDIS, March 31, 2013. International Handbook of Evaluated Reactor Physics Measurements, NEA/NSC/DOC(2006)1.

D. A. Brown et al., "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data," Nuclear Data Sheets **148** (2018) 1-142.

S. Okajima et al., "Summary on International Benchmark Experiments for Effective Delayed Neutron Fraction ($\beta_{eff}$)," Progress in Nuclear Energy: **41** (1-4) 285-301 (2002).

E. A. Fischer, "Integral Measurements of the Effective Delayed Neutron Fractions in the Fast Critical Assembly SNEAK," Nuclear Science and Engineering: **62,** 105-116 (1977).

E. Fort et al., "Recommended Values of the Delayed Neutron Yield for: U-235; U-238 and Pu 239," JEFDOC-820, 1999.

Evgeny Ivanov et al., "SNEAK 7A and 7B Pu-Fueled Fast Critical Assemblies in the Karlsruhe Fast Critical Facility," SNEAK-LMFR-EXP-001, CRIT-BUCK-SPEC-COEF-KIN-RRATE-MISC, Rev. 1, March 31, 2011. International Handbook of Evaluated Reactor Physics Measurements, NEA/NSC/DOC(2006)1.

Ivan Kodeli, "Combined Use of k-effective and beta-effective Measurements for Nuclear Data Validation and Improvement," EPJ Web of Conferences, **146**, 06018 (2017).

Gennady Manturov et al., "BFS-73-1 Assembly: Experimental Model of Sodium Cooled Fast Reactor with Core of Metal Uranium Fuel of 18.5% Enrichment and Depleted Uranium Dioxide Blanket," BFS1-LMFR-EXP-001, CRIT-SPEC-COEF-KIN-RRATE, March 31, 2006. International Handbook of Evaluated Reactor Physics Measurements, NEA/NSC/DOC(2006)1.

Margaret A. Marshall, "ORSPHERE: Physics Measurements for Bare, HEU(93.2)-Metal Sphere," ORSPHERE-FUND-EXP-001, CRIT-REAC-COEF-KIN-RRATE, Rev. 1, March 31, 2015. International Handbook of Evaluated Reactor Physics Measurements, NEA/NSC/DOC(2006)1.

Ken Nakajima, "Re-evaluation of the Effective Delayed Neutron Fraction Measured by the Substitution Technique for a Light Water Moderated Low-enriched Uranium Core," Journal of Nuclear Science and Technology: **38** (12) 1120-1125 (2001).

Sol Pearlstein, "The Effective Delayed Neutron Fraction for Bare-Metal Criticals," Nuclear Technology: **128**, 482-408 (1999).

Takenori Suzaki et al., "Precise Determination of $\beta_{eff}$ for Water-Moderated U and U-Pu Cores by a Method Using Buckling Coefficient of Reactivity," pp. 386-394, Sixth International Conference on Nuclear Criticality Safety, ICNC '99, September 20-24, 1999.

Steven C. van der Marck and Robin Klein Meulekamp, "Calculating the effective delayed neutron fraction using Monte Carlo techniques," Proceedings of the International Conference on the Physics of Reactors, PHYSOR 2004, Chicago, IL, April 25-29, 2004.

# Appendix A

*Table A-1. COG 11.3 calculated beta-eff results (in pcm) with ENDF/B-VIII.0*

| | Assembly | Experiment | $\beta_{eff}$ = Fissions by delayed neutrons divided by all fissions | | $\beta_{eff}$ = Neutrons from fissions by delayed neutrons divided by neutrons from all fissions | | $\beta_{eff}$ = 1 – (k-prompt/k-eff) | |
|---|---|---|---|---|---|---|---|---|
| No. | Name | $\beta_{eff}$ | $\beta_{eff}$ | C/E | $\beta_{eff}$ | C/E | $\beta_{eff}$ | C/E |
| 1 | NASA ZPR-1 H/X=190 | 900 ± 60 | 844 | 0.938 ± 6.7% | 844 | 0.938 ± 6.7% | 844 ± 2 | 0.938 ± 6.7% |
| 2 | NASA ZPR-1 H/X=473 | 860 ± 50 | 806 | 0.937 ± 5.8% | 805 | 0.936 ± 5.8% | 805 ± 1 | 0.936 ± 5.8% |
| 3 | NASA ZPR-1 H/X=565 | 820 ± 40 | 794 | 0.968 ± 4.9% | 794 | 0.968 ± 4.9% | 794 ± 1 | 0.968 ± 4.9% |
| 4 | TCA 1.50U 19x19 | 771 ± 18 | 772 | 1.001 ± 2.3% | 765 | 0.992 ± 2.3% | 763 ± 6 | 0.990 ± 2.5% |
| 5 | TCA 1.83U Cylinder | 771 ± 17 | 771 | 1.000 ± 2.2% | 766 | 0.994 ± 2.2% | 763 ± 5 | 0.990 ± 2.3% |
| 6 | TCA 1.83U 17x17 | 766 ± 18 | 770 | 1.005 ± 2.3% | 764 | 0.997 ± 2.3% | 762 ± 5 | 0.995 ± 2.4% |
| 7 | TCA 2.48U 16x16 | 765 ± 18 | 764 | 0.999 ± 2.4% | 759 | 0.992 ± 2.4% | 757 ± 5 | 0.990 ± 2.4% |
| 8 | SNEAK 9C1 | 758 ± 24 | 727 | 0.959 ± 3.2% | 706 | 0.931 ± 3.2% | 700 ± 4 | 0.923 ± 3.2% |
| 9 | IPEN/MB-01 | 750 ± 4 | 748* | 0.997 ± 0.5% | 744* | 0.992 ± 0.5% | 743 ± 38 | 0.991 ± 5.1% |
| 10 | TCA 3.00U 15x15 | 749 ± 17 | 758* | 1.012 ± 2.3% | 754* | 1.007 ± 2.3% | 752 ± 5 | 1.004 ± 2.4% |
| 11 | FCA XIX-1 | 742 ± 24 | 737 | 0.993 ± 3.2% | 725 | 0.977 ± 3.2% | 723 ± 5 | 0.974 ± 3.3% |
| 12 | BFS-73-1 | 735 ± 13 | 735 | 1.000 ± 1.8% | 715 | 0.973 ± 1.8% | 710 ± 8 | 0.966 ± 2.1% |
| 13 | U9 | 731 ± 15 | 734 | 1.004 ± 2.1% | 705 | 0.964 ± 2.1% | 696 ± 4 | 0.952 ± 2.1% |
| 14 | Masurca R2 | 721 ± 11 | 738 | 1.024 ± 1.5% | 719 | 0.997 ± 1.5% | 715 ± 21 | 0.992 ± 3.3% |
| 15 | Big Ten | 720 ± 7 | 729 | 1.013 ± 1.0% | 699 | 0.971 ± 1.0% | 688 ± 4 | **0.956** ± 1.1% |
| 16 | U/Fe (ZPR9/34) | 671 ± 14 | 687 | 1.024 ± 2.1% | 683 | 1.018 ± 2.1% | 683 ± 8 | 1.018 ± 2.4% |
| 17 | Topsy (25 Flattop) | 665 ± 13 | 658 | 0.989 ± 2.0% | 625 | 0.940 ± 2.0% | 617 ± 7 | **0.928** ± 2.3% |
| 18 | Godiva | 659 ± 28 | 679 | 1.030 ± 4.2% | 647 | 0.982 ± 4.2% | 642 ± 4 | 0.974 ± 4.3% |
| 19 | OR Sphere Config. 1 | 657 ± 9 | 680 | 1.035 ± 1.4% | 648 | 0.986 ± 1.4% | 643 ± 4 | 0.979 ± 1.5% |
| 20 | OR Sphere Config. 2 | 657 ± 9 | 679 | 1.033 ± 1.4% | 646 | 0.983 ± 1.4% | 641 ± 4 | 0.976 ± 1.5% |
| 21 | SNEAK 7B | 429 ± 22 | 414 | 0.965 ± 5.1% | 410 | 0.956 ± 5.1% | 406 ± 6 | 0.946 ± 5.3% |
| 22 | SNEAK 9C2 | 426 ± 19 | 381 | 0.894 ± 4.5% | 374 | **0.878** ± 4.5% | 371 ± 6 | **0.871** ± 4.7% |
| 23 | SNEAK 7A | 395 ± 22 | 368 | 0.932 ± 5.6% | 362 | 0.916 ± 5.6% | 359 ± 6 | 0.909 ± 5.8% |
| 24 | C Ref (ZPPR21B) | 384 ± 8 | 366 | 0.953 ± 2.1% | 354 | **0.922** ± 2.1% | 353 ± 28 | 0.919 ± 8.2% |
| 25 | FCA XIX-2 | 364 ± 9 | 372 | 1.022 ± 2.5% | 366 | 1.005 ± 2.5% | 364 ± 8 | 1.000 ± 3.3% |
| 26 | 23 Flattop | 360 ± 9 | 359 | 0.997 ± 2.5% | 340 | 0.944 ± 2.5% | 336 ± 8 | 0.933 ± 3.5% |
| 27 | Masurca Zona 2 | 349 ± 6 | 343 | 0.983 ± 1.7% | 338 | 0.968 ± 1.7% | 336 ± 22 | 0.963 ± 6.8% |
| 28 | Skidoo (Jezebel 23) | 290 ± 10 | 311 | 1.072 ± 3.4% | 294 | 1.014 ± 3.4% | 294 ± 4 | 1.014 ± 3.7% |
| 29 | Popsy (49 Flattop) | 276 ± 7 | 272 | 0.986 ± 2.5% | 259 | 0.938 ± 2.5% | 256 ± 9 | 0.928 ± 4.3% |
| 30 | FCA XIX-3 | 251 ± 4 | 258 | 1.028 ± 1.6% | 254 | 1.012 ± 1.6% | 253 ± 7 | 1.008 ± 3.2% |
| 31 | P/C/SST (ZPR6-10) | 223 ± 5 | 230 | 1.031 ± 2.2% | 228 | 1.022 ± 2.2% | 227 ± 8 | 1.018 ± 4.2% |
| 32 | Jezebel | 195 ± 10 | 197 | 1.010 ± 5.1% | 184 | 0.944 ± 5.1% | 183 ± 5 | 0.938 ± 5.8% |

*The COG calculational uncertainty in $\beta_{eff}$ is ± 1 pcm in these cases. Cases highlighted in **RED** have $|C/E-1| > 3\sigma$.

**Appendix A (continued)**

*Table A-2. COG 11.3 calculated beta-eff results (in pcm) with JEFF-3.3*

| | Assembly | Experiment | $\beta_{eff}$ = Fissions by delayed neutrons divided by all fissions | | $\beta_{eff}$ = Neutrons from fissions by delayed neutrons divided by neutrons from all fissions | | $\beta_{eff}$ = 1 – (k-prompt/k-eff) | |
|---|---|---|---|---|---|---|---|---|
| No. | Name | $\beta_{eff}$ | $\beta_{eff}$ | C/E | $\beta_{eff}$ | C/E | $\beta_{eff}$ | C/E |
| 1 | NASA ZPR-1 H/X=190 | 900 ± 60 | 870* | 0.967 ± 6.7% | 870 | 0.967 ± 6.7% | 869 ± 7 | 0.965 ± 6.7% |
| 2 | NASA ZPR-1 H/X=473 | 860 ± 50 | 828 | 0.963 ± 5.8% | 828 | 0.963 ± 5.8% | 829 ± 7 | 0.964 ± 5.9% |
| 3 | NASA ZPR-1 H/X=565 | 820 ± 40 | 815 | 0.994 ± 4.9% | 815 | 0.994 ± 4.9% | 816 ± 5 | 0.995 ± 4.9% |
| 4 | TCA 1.50U 19x19 | 771 ± 18 | 794 | 1.030 ± 2.3% | 787 | 1.021 ± 2.3% | 785 ± 6 | 1.018 ± 2.5% |
| 5 | TCA 1.83U Cylinder | 771 ± 17 | 794* | 1.030 ± 2.2% | 788 | 1.022 ± 2.2% | 785 ± 8 | 1.018 ± 2.4% |
| 6 | TCA 1.83U 17x17 | 766 ± 18 | 791 | 1.033 ± 2.3% | 785 | 1.025 ± 2.3% | 784 ± 6 | 1.023 ± 2.5% |
| 7 | TCA 2.48U 16x16 | 765 ± 18 | 786 | 1.027 ± 2.4% | 781 | 1.021 ± 2.4% | 779 ± 7 | 1.018 ± 2.5% |
| 8 | SNEAK 9C1 | 758 ± 24 | 735* | 0.970 ± 3.2% | 712 | 0.939 ± 3.2% | 705 ± 8 | 0.930 ± 3.4% |
| 9 | IPEN/MB-01 | 750 ± 4 | 770* | **1.027** ± 0.5% | 765 | **1.020** ± 0.5% | 765 ± 8 | 1.020 ± 1.2% |
| 10 | TCA 3.00U 15x15 | 749 ± 17 | 780 | 1.041 ± 2.3% | 775 | 1.035 ± 2.3% | 774 ± 6 | 1.033 ± 2.4% |
| 11 | FCA XIX-1 | 742 ± 24 | 744* | 1.003 ± 3.2% | 731 | 0.985 ± 3.2% | 734 ± 8 | 0.989 ± 3.4% |
| 12 | BFS-73-1 | 735 ± 13 | 741* | 1.008 ± 1.8% | 720 | 0.980 ± 1.8% | 707 ± 8 | 0.962 ± 2.1% |
| 13 | U9 | 731 ± 15 | 752 | 1.029 ± 2.1% | 724 | 0.990 ± 2.1% | 702 ± 7 | 0.960 ± 2.3% |
| 14 | Masurca R2 | 721 ± 11 | 742* | 1.029 ± 1.5% | 723 | 1.003 ± 1.5% | 709 ± 8 | 0.983 ± 1.9% |
| 15 | Big Ten | 720 ± 7 | 750* | **1.042** ± 1.0% | 719 | 0.999 ± 1.0% | 701 ± 7 | 0.974 ± 1.4% |
| 16 | U/Fe (ZPR9/34) | 671 ± 14 | 686* | 1.022 ± 2.1% | 682 | 1.016 ± 2.1% | 688 ± 8 | 1.025 ± 2.4% |
| 17 | Topsy (25 Flattop) | 665 ± 13 | 663 | 0.997 ± 2.0% | 629 | 0.946 ± 2.0% | 617 ± 7 | **0.928** ± 2.3% |
| 18 | Godiva | 659 ± 28 | 674 | 1.023 ± 4.2% | 641 | 0.973 ± 4.2% | 634 ± 7 | 0.962 ± 4.4% |
| 19 | OR Sphere Config. 1 | 657 ± 9 | 675 | 1.027 ± 1.4% | 642 | 0.977 ± 1.4% | 637 ± 2 | 0.970 ± 1.4% |
| 20 | OR Sphere Config. 2 | 657 ± 9 | 678 | 1.032 ± 1.4% | 646 | 0.983 ± 1.4% | 640 ± 2 | 0.974 ± 1.4% |
| 21 | SNEAK 7B | 429 ± 22 | 433 | 1.009 ± 5.1% | 427 | 0.995 ± 5.1% | 423 ± 7 | 0.986 ± 5.4% |
| 22 | SNEAK 9C2 | 426 ± 19 | 397 | 0.932 ± 4.5% | 389 | 0.913 ± 4.5% | 385 ± 7 | 0.904 ± 4.8% |
| 23 | SNEAK 7A | 395 ± 22 | 385 | 0.975 ± 5.6% | 377 | 0.954 ± 5.6% | 375 ± 7 | 0.949 ± 5.9% |
| 24 | C Ref (ZPPR21B) | 384 ± 8 | 366 | 0.953 ± 2.1% | 354 | **0.922** ± 2.1% | 349 ± 7 | **0.909** ± 2.9% |
| 25 | FCA XIX-2 | 364 ± 9 | 388 | 1.066 ± 2.5% | 381 | 1.047 ± 2.5% | 373 ± 7 | 1.025 ± 3.1% |
| 26 | 23 Flattop | 360 ± 9 | 366 | 1.017 ± 2.5% | 345 | 0.958 ± 2.5% | 339 ± 7 | 0.942 ± 3.2% |
| 27 | Masurca Zona 2 | 349 ± 6 | 357 | 1.023 ± 1.7% | 351 | 1.006 ± 1.7% | 347 ± 7 | 0.994 ± 2.7% |
| 28 | Skidoo (Jezebel 23) | 290 ± 10 | 308 | 1.062 ± 3.4% | 290 | 1.000 ± 3.4% | 289 ± 7 | 0.997 ± 4.2% |
| 29 | Popsy (49 Flattop) | 276 ± 7 | 284 | 1.029 ± 2.5% | 269 | 0.975 ± 2.5% | 264 ± 6 | 0.957 ± 3.4% |
| 30 | FCA XIX-3 | 251 ± 4 | 265 | **1.056** ± 1.6% | 260 | 1.036 ± 1.6% | 257 ± 7 | 1.024 ± 3.2% |
| 31 | P/C/SST (ZPR6-10) | 223 ± 5 | 235 | 1.054 ± 2.2% | 232 | 1.040 ± 2.2% | 232 ± 7 | 1.040 ± 3.8% |
| 32 | Jezebel | 195 ± 10 | 201 | 1.031 ± 5.1% | 187 | 0.959 ± 5.1% | 186 ± 6 | 0.954 ± 6.1% |

*The COG calculational uncertainty in $\beta_{eff}$ is ± 1 pcm in these cases. Cases highlighted in **RED** have |C/E–1| > 3σ.

## Appendix B

*Table B-1. COG 11.3 calculated k-eff results with ENDF/B-VIII.0 and JEFF-3.3*

| | Assembly | ENDF/B-VIII.0 | JEFF-3.3 |
|---|---|---|---|
| No. | Name | k-eff | k-eff |
| 1 | NASA ZPR-1 H/X=190 | 0.99846 ± 0.00001 | 0.99870 ± 0.00005 |
| 2 | NASA ZPR-1 H/X=473 | 1.00157 ± 0.00001 | 1.00161 ± 0.00001 |
| 3 | NASA ZPR-1 H/X=565 | 1.00174 ± 0.00001 | 1.00136 ± 0.00005 |
| 4 | TCA 1.50U 19x19 | 1.00023 ± 0.00001 | 1.00332 ± 0.00005 |
| 5 | TCA 1.83U Cylinder | 1.00027 ± 0.00001 | 1.00204 ± 0.00005 |
| 6 | TCA 1.83U 17x17 | 1.00055 ± 0.00001 | 1.00374 ± 0.00001 |
| 7 | TCA 2.48U 16x16 | 1.00086 ± 0.00001 | 1.00085 ± 0.00005 |
| 8 | SNEAK 9C1 | 1.00296 ± 0.00001 | 1.00612 ± 0.00005 |
| 9 | IPEN/MB-01 | 1.00368 ± 0.00010 | 1.00312 ± 0.00005 |
| 10 | TCA 3.00U 15x15 | 1.00091 ± 0.00003 | 1.00231 ± 0.00005 |
| 11 | FCA XIX-1 | 1.01412 ± 0.00001 | 1.01067 ± 0.00005 |
| 12 | BFS-73-1 | 0.99395 ± 0.00001 | 0.99622 ± 0.00005 |
| 13 | U9 | 0.99118 ± 0.00001 | 0.99401 ± 0.00005 |
| 14 | Masurca R2 | 0.98971 ± 0.00001 | 0.99240 ± 0.00005 |
| 15 | Big Ten | 1.00023 ± 0.00001 | 1.00077 ± 0.00005 |
| 16 | U/Fe (ZPR9/34) | 0.99866 ± 0.00001 | 1.01033 ± 0.00005 |
| 17 | Topsy (25 Flattop) | 1.00112 ± 0.00001 | 1.00448 ± 0.00005 |
| 18 | Godiva | 1.00028 ± 0.00001 | 1.00051 ± 0.00005 |
| 19 | OR Sphere Config. 1 | 1.00407 ± 0.00001 | 1.00429 ± 0.00002 |
| 20 | OR Sphere Config. 2 | 0.99802 ± 0.00001 | 0.99801 ± 0.00002 |
| 21 | SNEAK 7B | 1.00255 ± 0.00001 | 1.00880 ± 0.00005 |
| 22 | SNEAK 9C2 | 1.00087 ± 0.00001 | 1.00842 ± 0.00005 |
| 23 | SNEAK 7A | 1.00616 ± 0.00001 | 1.01256 ± 0.00005 |
| 24 | C Ref (ZPPR21B) | 0.99030 ± 0.00001 | 0.99037 ± 0.00005 |
| 25 | FCA XIX-2 | 0.98632 ± 0.00001 | 0.99143 ± 0.00005 |
| 26 | 23 Flattop | 1.00023 ± 0.00001 | 1.00354 ± 0.00005 |
| 27 | Masurca Zona 2 | 0.99550 ± 0.00002 | 1.00054 ± 0.00005 |
| 28 | Skidoo (Jezebel 23) | 1.00062 ± 0.00001 | 1.00114 ± 0.00005 |
| 29 | Popsy (49 Flattop) | 0.99993 ± 0.00001 | 1.00341 ± 0.00005 |
| 30 | FCA XIX-3 | 0.98545 ± 0.00001 | 0.99503 ± 0.00005 |
| 31 | P/C/SST (ZPR6-10) | 1.00390 ± 0.00002 | 1.00268 ± 0.00005 |
| 32 | Jezebel | 0.9997927== ± 0.00001 | 0.99923 ± 0.00005 |