KRITZ-1-MK CRITICAL MEASUREMENTS AT TEMPERATURES FROM 20 °C TO 250 °C

Dennis Mennerdahl[1]

[1]E Mennerdahl Systems
Starvägen 12, 18357 Täby, Sweden

dennis.mennerdahl@outlook.com

ABSTRACT

Benchmarks are needed to validate methods to account for temperature-dependence of nuclear data. An evaluation of 37 KRITZ-1-Mk critical water height measurements, together with associated iso-reactivity temperature effects and coefficients, is released with the 2019 Handbook of the International Reactor Physics Experiment Evaluation Project (IRPhEP). The KRITZ zero-power research reactor, operated between 1969 and 1975 in Studsvik (Sweden), was contained in a pressure vessel, allowing full size fuel assemblies or fuel rods in light water at temperatures up to 250 °C without boiling. Preliminary results were published in 1971 and 1972 for four series of altogether 37 measurements with Marviken (Boiling Heavy Water Reactor) UO_2 fuel rods, each containing a ^{235}U isotopic mass fraction of 1.35 %. Temperature was the predictor variable, while critical water height was the response variable. Each series was characterized by the fuel rod lattice design and by the soluble boron concentration in water. The KRITZ measurements were focused on temperature-dependence (differences). High measurement correlations reduced the Δk uncertainties, typically from 195 pcm to 40 pcm for a large temperature change. Thermal expansion of fuel and reactor components was not measured. Detailed and simple benchmarks include estimated thermal expansion as a simplification. Benchmark calculation results using JEFF-3.3 nuclear data reduce the large biases observed for older libraries but a remarkable positive temperature trend is observed for series 4. In 2019, Studsvik Nuclear released information on KRITZ-1-Mk and on other KRITZ-1 and KRITZ-2 critical measurements with Boiling Water Reactor fuel assemblies and fuel rod clusters.

KEYWORDS: critical benchmark measurements, low-enriched uranium, wide temperature range, reactivity effects, temperature coefficients

1. INTRODUCTION

Calculation of temperature effects and coefficients was a challenge in Sweden in the 1960's. A pressurized heavy water reactor (Ågesta) was designed, built and operated, producing electricity and district heating to a Stockholm suburb for ten years, starting in 1963. The boiling heavy water reactor (BHWR) Marviken was designed and completed but was never in operation. A major reason was a positive power coefficient. The UO_2 fuel was manufactured in Sweden. Some of the fuel, with the ^{235}U isotopic mass fraction 1.35 %, was used in the critical water height measurements discussed in this paper. Parallel to the BHWR development, boiling water reactors (BWRs) were also designed and built in Sweden (Oskarshamn 1 and Ringhals 1), for operation in the early 1970's.

To support the Swedish nuclear power reactor program, there were several research reactors of different types. The KRITZ reactor in Studsvik, used for the measurements discussed in this paper, was based on a pressure vessel large enough to allow multiple full-size fuel assemblies. Under pressure, the reactor temperature could be varied between room temperature and 250 °C, without water boiling. KRITZ was in operation between 1969 and 1975, resulting in about 1000 critical water height measurements. Other Studsvik research reactors included the FR0 zero power fast reactor and the R2 material testing reactor.

The author prefers the term “measurement” rather than “experiment” for the very specific procedure required to define a model (input, method and measurand) for determination of the value of the measurand. This explains the lack of reference to experiments in the paper (and in the evaluation). A benchmark model is a simplified model, typically without uncertainties. The input specification uncertainties of the measurement have been converted to benchmark result uncertainties. Measurement correlations (shared equipment, fissile materials, processes, procedures, etc.) are essential for observing trends (changes), for validation of calculation methods and for evaluation of nuclear data.

The unit for uncertainties is related to Δk in pcm. The bias (C/E-1), where C is the calculated value of k_{eff} and E is the expected benchmark value, is also expressed in pcm.

2. MEASUREMENTS IN THE KRITZ ZERO-POWER RESEARCH REACTOR

The measurements in the KRITZ facility involved determination of critical water heights of active fuel covered by water (HKA), activation of fuel and of copper wires, and flashing (reactivity coefficient during instant pressure relief, resulting in boiling water).

The measurement identifiers below are to some extent new. The year(s) of the measurements follow. All measurement groups except the first (KRITZ-1-OI) covered temperatures between 20 °C and 250 °C. Studsvik Nuclear information on the three last groups remains proprietary.

- KRITZ-1-OI. 1969-1970. BWR fuel assemblies for the Oskarshamn 1 (OI) BWR were the first to be made critical in KRITZ in October 1969. The measurements only covered temperatures up to 70 °C.
- KRITZ-1-Mk. 1971. During a long period, without access to BWR fuel, the fuel rods fabricated for the Marviken BHWR were made available for KRITZ measurements.
- KRITZ-1-RI. 1971-1972. BWR fuel assemblies for Ringhals 1 (RI) were made available.
- KRITZ-2-P1. 1972. Phase 1 included RI fuel assemblies where some of the UO_2 fuel rods had been exchanged for MOX (UO_2 and PuO_2) fuel rods, fabricated for the Experimental Boiling Water Reactor (EBWR) in the U.S.A.
- KRITZ-2-P2. 1972-1973. Phase 2 included RI UO_2 fuel rods and EBWR MOX fuel rods. Four of the UO_2 measurements and two of the MOX measurements were published by Studsvik Nuclear in 1990. They have been evaluated in the IRPhEP Handbook [2] as KRITZ-LWR-RESR-001, -002 and -003.
- KRITZ-3. 1973. PWR fuel assemblies from KWU, Germany.
- KRITZ-Pu-75. 1975. MOX fuel for the Garigliano BWR in Italy.
- KRITZ-4 (referred to as BA-75 by experimenters). 1975. BWR fuel assemblies with gadolinium rods.

This paper focuses on measurement of HKA as a function of temperature. Temperature effects and coefficients can be determined from criticality measurements, taking advantage of high correlations between measurements in a specific series. Such a series is characterized by just one independent input (predictor variable), the temperature, and with the critical water height HKA as the intended output (response variable, measurand). Temperature effects determined directly from critical water heights are useful for large temperature changes since the random effect uncertainties are too large for small changes.

For small temperature changes, the coefficients should be more useful. The same curves could be used to determine temperature effects for small temperature changes, reducing the uncertainties significantly.

Temperature-dependent input variables that needed measurement or estimation include water density, steam density, soluble boron concentration (no boron in steam) and thermal expansion of all materials in the reactor. The water level meter used to determine the HKA result was affected by thermal expansion.

3. KRITZ-LWR-RESR-004 – IRPHEP HANDBOOK EVALUATION OF KRITZ-1-MK

3.1. The International Reactor Physics Experiment Evaluation Project (IRPhEP).

The ICSBEP Handbook [1] contains evaluations of criticality measurements. The IRPhEP Handbook [2] was established to include reactor physics benchmark measurements, including criticality measurements. The ICSBEP Handbook links to the IRPhEP Handbook for reactor criticality benchmark measurements.

The 2019 edition of the IRPhEP Handbook contains an evaluation of the 37 KRITZ-1-Mk accepted benchmark measurements: KRITZ-LWR-RESR-004. The ICSBEP link is LEU-COMP-THERM-104.

3.2. KRITZ-1-Mk Measurements in 1971.

The BWR fuel assemblies intended to support KRITZ-1 measurements were complete fuel assemblies that had to be available for the startup of Oskarshamn 1 and Ringhals 1. The gap in KRITZ-1 availability of such fuel in 1971 was filled by Marviken BHWR fuel rods. They were available only for a few months.

A large number of KRITZ-1-Mk HKA measurements were made at temperatures ranging from 20 °C to 90 °C. The specifications are available but the results in the form of HKA values are not. Only curves showing temperature coefficients of the buckling or, in a few cases, the buckling as a function of temperature are available. This appears to be insufficient for benchmark measurement evaluation.

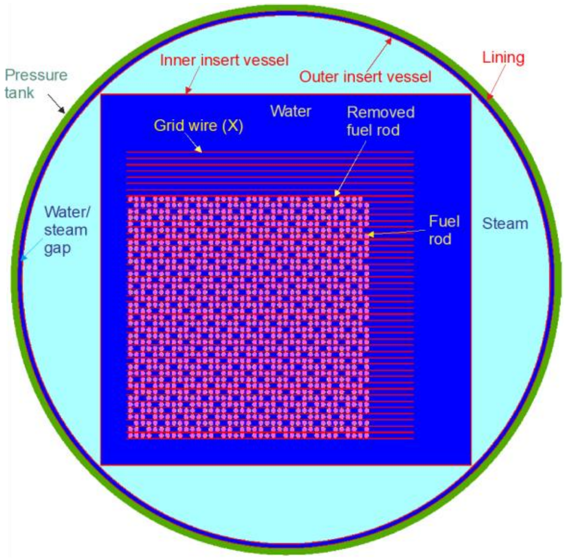
There were four series of KRITZ-1-Mk which included measurements at temperatures above 90 °C:

1. Nine measurements with 39 × 39 fuel rod clusters at temperatures ranging from 41 °C to 226 °C. The nominal soluble boron concentration at room temperature was 0.8 ppm.
2. Four measurements with 46 × 46 fuel rod clusters at temperatures ranging from 90 °C to 246 °C. The nominal soluble boron concentration at room temperature was 46.3 ppm.
3. Eleven measurements with 46 × 46 fuel rod clusters at temperatures ranging from 22 °C to 205 °C. The nominal soluble boron concentration at room temperature was 175 ppm.
4. Thirteen measurements with 39 × 39 fuel rod clusters, with 1/5 of the rods removed in a regular pattern, at temperatures ranging from 20 °C to 244 °C. The nominal soluble boron concentration at room temperature was 0.2 ppm.

3.3. Evaluation of KRITZ-1-Mk Benchmark Measurements for the 2019 IRPhEP Handbook.

The KRITZ-1-Mk data were found in published papers and reports, in safety documents submitted to the licensing authority and, near the completion (2019), through direct access to Studsvik Nuclear archives.

The IRPhEP evaluation contains 37 criticality benchmark cases, each with a detailed model and a simple model. The benchmark model specifications and results are included in the 2019 IRPhEP Handbook. As examples, a horizontal cut through a detailed model for one case is shown in Fig. 1(a) while a vertical cut through a simple model for a different case is shown in Fig 1(b).



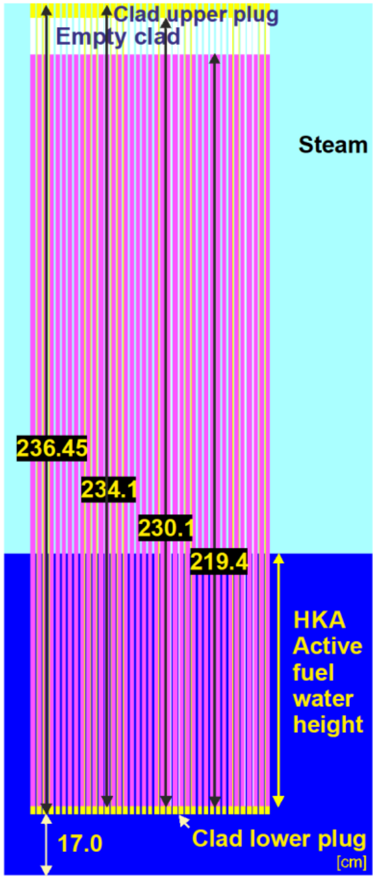


Figure 1(a). Detailed Model, Horizontal Cut. **Figure 1(b) Simplified Model, Vertical Cut**

Evaluation of measurement data resulted in bias corrections, uncertainty propagation and documentation of measurement correlations (sharing) of equipment, fissile materials, processes and procedures.

Measured HKA values with uncertainties were converted from results into input specifications. The input k_{eff} (unity) specifications were converted to results. Criticality was determined within 2 pcm (conclusion by experimenters). Each input correlation was converted to a k_{eff} correlation, preserving the cause.

The HKA change, as a function of temperature, was used to establish measured iso-reactivity (zero) temperature effects and coefficients. Polynomial fitting of measurement points had been applied by experimenters and such techniques were now used for the evaluated temperature coefficients. The uncertainty propagation could take advantage of the significant correlations between measurement specifications, leading to much lower uncertainties than if the measurements had been independent.

The detailed benchmark models include grids and other steel components, while the simple models have no steel. The subjective simplifications of the measurement models result in benchmark k_{eff} values different from unity. The estimated individual criticality benchmark uncertainties are in the range 125 pcm to 143 pcm. The benchmark temperature effects are determined directly from the criticality benchmark cases and thus lead to non-zero k_{eff} differences (unlike the zero-reactivity measurements). The temperature coefficients are based on slight HKA adjustments to correspond to iso-reactivity. For the detailed models, the iso-reactivity is zero. For the simple models, the iso-reactivity is set near the average k_{eff} (several hundred pcm) for each of the four KRITZ-1-Mk series of measurements.

The correlation effects were determined directly from the causational coefficients, all estimated to be +1, of the shared measurement data. Together with the already available sensitivity coefficients, best-estimate uncertainties of temperature effects could easily be determined. There was no need for, or benefit from, determination of k_{eff} uncertainty correlation coefficients (Pearson) between measurements or benchmarks. Such coefficients would hide well known measurement information within total statistical uncertainties.

A temperature effect, e.g. going from 225.6 °C to 41.2 °C in series 1 ($\rho_{1,8}$ in Table 3.14 in [2]), results in an uncertainty ($\sigma_{1,8}$ in Table 3.22 in [2]) of 40.2 pcm, accounting for measurement correlations. If the measurements had been assumed to be independent, the uncertainty would have been 195 pcm.

Additional information made available by Studsvik Nuclear, Sweden in 2019 justified some bias corrections to the results, without changing the benchmark models. In addition, the previously ignored fuel impurities need consideration. A bias in the order of -100 pcm, with some uncertainty, appears realistic. The impact on temperature effects and coefficients is very small due to the high correlations.

4. NUCLEAR COVARIANCE DATA, GENERALISED LINEAR LEAST SQUARE METHODS

Conversion of measurement input parameter biases and uncertainties to k_{eff} biases and uncertainties requires determination of associated sensitivity coefficients. Those were based on direct perturbations, large enough to give significant Monte Carlo changes, but small enough to preserve linearity.

The primary evaluation tool SCALE 6.2.3 [3], using ENDF/B-VII.1 continuous energy cross-sections, was used to determine C_k coefficients (based on similarity between nuclear data uncertainty contributions) for all the 37 criticality measurement, including no other measurements. All C_k values were above 0.95, with values of 1.00 for all measurements within the four evaluated series of KRITZ-1-Mk measurements. This confirms that the correlations between measurements were very strong.

The a priori k_{eff} uncertainty, due to nuclear data uncertainties, was found to be about 600 pcm. The measurement evaluation used SCALE 6.2.3 with ENDF/B-VII.1 continuous energy cross-sections and MCNP6.2 [4] with ENDF/B-VIII.0, as well as some older ENDF/B and JEFF cross-section libraries. The biases are large, with underprediction of k_{eff} at all temperatures.

The SCALE 6.2.3 calculation tool TSURFER, based on general linear least square methods (GLLSM), uses adjustments of nuclear data, within reasonable ranges, to provide best-estimate k_{eff} values and uncertainties. The results for the 37 measurements show that the large biases in the calculation results may be explained by the nuclear data uncertainties. The adjusted k_{eff} values vary between 0.99972 and 1.00154, with adjusted uncertainties between 31 pcm and 47 pcm. The totally dominating nuclear data adjustment is ^{238}U (n,γ). This method is not new but some caution is justified due to lack of validation and experience in using it. The TSURFER results support the IRPhEP evaluation.

5. CALCULATIONS OF KRITZ-1-MK BENCHMARKS

In the IRPhEP evaluation, the 37 KRITZ-1-Mk criticality benchmarks were calculated using different methods involving continuous energy cross-sections. Solutions included SCALE-6.2.3 with ENDF/B-VII.1 (author), a few SCALE-6.2.3 cases with draft ENDF/B-VIII.0 (ORNL, not for publication), MCNP6.2 with ENDF/B-VIII.0 (author), MONK11A Dev with JEFF-3.1.2 and ENDF/B-VII.1 (Wood), MORET 5.D.1 with ENDF/B-VIII.0 and JEFF-3.3 (IRSN). The results are expressed as (C/E-1) in pcm.

Older cross-section libraries (ENDF/B-VII.1 and JEFF-3.1.2), caused biases from -628 pcm to -256 pcm, with the smaller biases for the most thermalized series of measurements. No strong trend with temperature was observed and results for detailed and simple models appear to be consistent.

The most recent cross-section libraries, ENDF/B-VIII.0 and JEFF-3.3 resulted in smaller calculation biases, particularly for JEFF-3.3. The trend with temperature becomes stronger for series 4, in particular for JEFF-3.3. The JEFF-3.3 results were obtained for the simple benchmark model.

As a contribution to this paper, new calculations have been made for the detailed benchmark models, using MCNP6.2 with JEFF-3.3 cross-sections [5] at temperatures 293 K and 600 K (mixed cross-sections were applied, as described in the IRPhEP evaluation). The thermal scattering library includes data for 293 K, 323 K, 373 K, 423 K, 473 K and 523 K. Two MCNP6.2 calculations were made for each case, using interpolation to account for the actual temperature. The results are shown in Table I. The MCNP6.2 standard deviations were 6 pcm for all calculations (one hundred million active neutron histories).

The next to last column in Table I presents the ratio β/σ, i.e. the ratio of the calculation bias β (C/E-1) to the benchmark uncertainty σ. The absolute ratio $|\beta|/\sigma$ can be viewed as a coverage factor. The probability of a calculation bias being caused by the estimated measurement uncertainty is quickly reduced when the ratio β/σ becomes increasingly larger than two.

The Gauss function was used in the expression *0.5 – Gauss(*$|\beta|/\sigma$*)* to estimate whether the calculation bias is most likely caused by the calculation method (usually nuclear data), by the estimated measurement uncertainty or both. A small bias is not necessarily evidence of high calculation and measurement accuracy since the calculation and measurement errors may be cancelling each other. The square root of the inverse of this expression is used as a significance indicator *SI*:

$$SI = \left(0.5 - gauss\left(\frac{|\beta|}{\sigma}\right)\right)^{-\frac{1}{2}} \qquad (1)$$

Fig. 2 shows the results from Table I. The *SI* value was used to visually inspect trends and consistency between different benchmarks and between calculation methods. A bubble chart was selected to provide as much information as possible in one chart. The ordinate refers to the EALF (energy corresponding to the average lethargy of neutrons causing fission) values. The abscissa refers to temperature. The bubble size is based on the *SI* value for each calculated benchmark (shown for each bubble). Different bubble colors represent the four series of benchmark cases. The four bubbles to the left of the ordinate axis show the bubble sizes corresponding to coverage factors ($|\beta|/\sigma$) of 1, 2, 3 and 4.

Bubble-charts for other methods are presented in the IRPhEP evaluation. The maximum coverage factor was 4.44. The equation is slightly different to Eq. 1 so the *SI* value is not presented here.

The strong positive trend with temperature for series 4 is remarkable. Separate as well as combined substitutions of ^{238}U and ^{235}U JEFF-3.3 cross-sections with those from ENDF/B-VII.1 are informative. For 243.6 °C, there were separate Δk changes of -200 pcm and -100 pcm respectively and -350 pcm when combined. At 20.4 °C, the k_{eff} changes were -230 pcm, + 125 pcm and -110 pcm respectively. The reversed ^{235}U cross-section effect dominates the temperature trend. For series 1, the ^{235}U cross-section effect was negative both for the lowest and for the highest temperature.

6. KRITZ-1 AND -2 WITH BWR FUEL ASSEMBLIES AND ROD CLUSTERS AVAILABLE

Studsvik Nuclear informed in 2019 that information on KRITZ-1 measurements with BWR UO_2 fuel assemblies as well as on KRITZ-2 measurements with BWR UO_2 and UO_2/MOX fuel assemblies and fuel rod clusters are now available for IRPhEP evaluation. The information appears to be sufficient to evaluate quality benchmark measurements. Most of the directly measured results (e.g. water levels), documented by the experimenters on special forms, have not been preserved, but the logbooks are available.

Table I. KRITZ-1-Mk Detailed Model Benchmark Cases Using MCNP6.2 and JEFF-3.3

Benchmark (detailed model)				Benchmark results		MCNP6.2 with JEFF-3.3		β/σ	*SI* (Eq. 1)
Case	Series	Temp. (°C)	Boron[a] (ppm)	k_{eff}	Uncertainty σ (Δk, pcm)	k_{eff}	Bias β (pcm)		
1	1	41.2	0.8	1.00038	134	0.99738	-299	-2.27	9.3
2	1	90.0	0.8	1.00076	136	0.99754	-322	-2.40	11.1
3	1	120.4	0.8	1.00083	138	0.99783	-300	-2.20	8.5
4	1	142.4	0.8	1.00057	139	0.99799	-258	-1.88	5.8
5	1	183.1	0.8	1.00095	140	0.99831	-264	-1.90	5.9
6	1	195.6	0.8	1.00089	141	0.99824	-264	-1.90	5.9
7	1	207.2	0.8	1.00103	141	0.99847	-255	-1.82	5.4
8	1	216.6	0.8	1.00090	142	0.99852	-238	-1.70	4.7
9	1	225.6	0.8	1.00098	142	0.99841	-257	-1.82	5.4
10	2	90.4	46.3	1.00047	134	0.99767	-280	-2.12	7.7
11	2	206.0	46.3	1.00120	140	0.99832	-288	-2.09	7.4
12	2	227.3	46.3	1.00137	141	0.99863	-274	-1.96	6.3
13	2	245.8	46.3	1.00120	143	0.99825	-295	-2.09	7.4
14	3	22.4	175.0	1.00072	129	0.99761	-311	-2.43	11.4
15	3	34.3	175.0	1.00054	130	0.99755	-299	-2.34	10.1
16	3	50.3	175.0	1.00036	130	0.99762	-274	-2.12	7.7
17	3	64.0	175.0	1.00044	130	0.99777	-267	-2.07	7.2
18	3	79.4	175.0	1.00045	131	0.99776	-269	-2.07	7.2
19	3	89.4	175.0	1.00019	131	0.99791	-228	-1.75	5.0
20	3	162.1	175.0	1.00053	135	0.99836	-217	-1.62	4.4
21	3	171.7	175.0	1.00039	136	0.99838	-201	-1.49	3.8
22	3	186.7	175.0	1.00047	137	0.99835	-212	-1.56	4.1
23	3	201.3	175.0	1.00053	138	0.99812	-241	-1.76	5.0
24	3	205.3	175.0	1.00036	139	0.99815	-221	-1.60	4.3
25	4	20.4	0.2	1.00016	126	0.99715	-301	-2.42	11.4
26	4	50.2	0.2	1.00021	125	0.99733	-288	-2.32	9.9
27	4	87.0	0.2	1.00031	126	0.99804	-227	-1.83	5.4
28	4	152.7	0.2	1.00063	128	0.99903	-161	-1.27	3.1
29	4	162.4	0.2	1.00074	128	0.99898	-176	-1.38	3.5
30	4	171.1	0.2	1.00067	128	0.99893	-174	-1.37	3.4
31	4	179.6	0.2	1.00095	128	0.99903	-192	-1.51	3.9
32	4	185.8	0.2	1.00103	128	0.99897	-206	-1.62	4.4
33	4	204.6	0.2	1.00093	128	0.99926	-166	-1.31	3.2
34	4	211.3	0.2	1.00096	129	0.99945	-151	-1.18	2.9
35	4	214.7	0.2	1.00122	129	0.99968	-154	-1.20	3.0
36	4	226.0	0.2	1.00098	129	1.00001	-97	-0.75	2.1
37	4	243.6	0.2	1.00126	130	1.00043	-82	-0.64	2.0

[a] Nominal values. The boron concentration in water changes with temperature, as shown for each series.

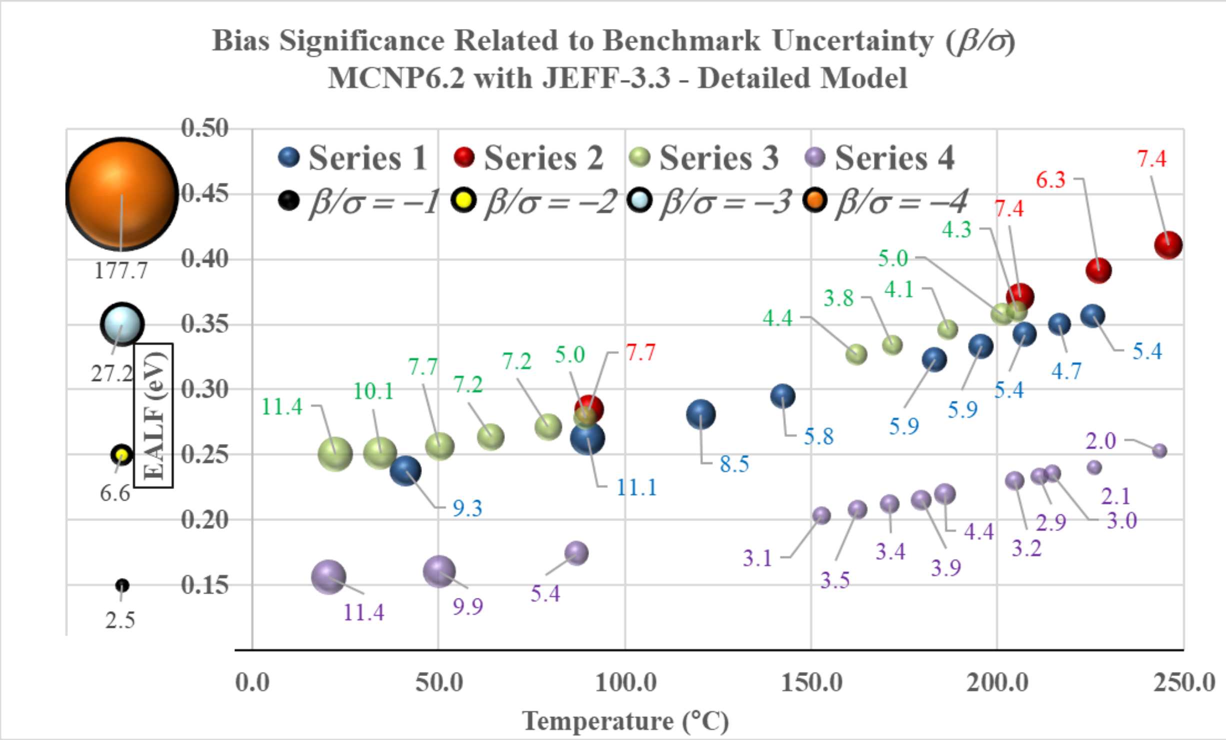


Figure 3. Bubble-Chart Showing KRITZ-1-Mk Significance Indicator Values from Table I.

7. CONCLUSIONS

The 37 criticality benchmark measurements, with uncertainties around 150 pcm (increased to account for fuel impurities), appear to provide critical water heights that are consistent with each other. Calculation results, using several methods and obtained by independent organizations, show consistent trends but they are different for different methods. New results with MCNP6.2 and JEFF-3.3 nuclear data show lower biases. The strong trend with temperature for series 4 benchmarks indicates remaining nuclear data biases. The evaluation accounts for correlations between different measurements. The temperature effects uncertainties are thus reduced from up to 200 pcm (assuming independent benchmarks) to 65 pcm and lower. Information from Studsvik Nuclear in 2019 has improved the KRITZ-1-Mk evaluation and will support future KRITZ-1 and KRITZ-2 evaluations involving BWR fuel assemblies and rods.

REFERENCES

1. International Criticality Safety Benchmark Evaluation Project (ICSBEP), “International Handbook of Evaluated Criticality Safety Benchmark Experiments”, ISSN: 2618-0421, NEA Nuclear Science Committee, September 2019 edition, released by NEA Data Bank as NEA-1486/17.
2. International Reactor Physics Experiment Evaluation Project (IRPhEP), “International Handbook of Evaluated Reactor Physics Benchmark Experiments”, ISSN: 2617-5614, NEA Nuclear Science Committee, July 2019 edition, released by NEA Data Bank as NEA-1765/14 in December 2019.
3. B. T. Rearden and M. A. Jessee, Eds., “SCALE Code System”, *ORNL/TM-2005/39*, Version 6.2.3, Oak Ridge National Laboratory, Oak Ridge, Tennessee (2018).
4. C.J. Werner, et al., "MCNP6.2 Release Notes", *Report LA-UR-18-20808*, Los Alamos National Laboratory, (2018).
5. Franco Michel-Sendis, JEFF-3.3 nuclear data files in ACE-format, NEA Data Bank, September 2019.