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# EVALUATION GUIDE FOR THE INTERNATIONAL REACTOR PHYSICS EXPERIMENTS EVALUATION PROJECT (IRPhEP)

English - Or. English

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**EVALUATION GUIDE FOR THE**

**INTERNATIONAL REACTOR PHYSICS EXPERIMENTS**

**EVALUATION PROJECT (IRPhEP)**

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# Evaluation Guide for the International Reactor Physics Experiments Evaluation Project (IRPhEP)

## EXPERIMENT FORMAT

## EXPERIMENT TITLE

### IDENTIFICATION NUMBER:

Each experiment has a unique identifier that consists of two parts. Part 1 consists of the Reactor Name, Reactor Type, Facility Type and a Three Digit Numerical Identifier. Part 2 of the identifier begins on a separate line and includes the Measurement Type(s). Identifiers take the following form:

(Reactor Name)-(Reactor Type)-(Facility Type)-(Three-Digit Numerical Identifier)
(Measurement Type(s))

Identifier elements and their meanings are given below.

| REACTOR TYPE | | FACILITY TYPE | | MEASUREMENT TYPE | |
|---|---|---|---|---|---|
| Pressurized Water Reactor | PWR | Experimental Facility | EXP | Critical Configuration | CRIT |
| VVER Reactors | VVER | Power Reactor | POWER | Subcritical Configuration | SUB |
| Boiling Water Reactor | BWR | Research Reactor | RESR | Buckling & Extrapolation Length | BUCK |
| Liquid Metal Fast Reactor | LMFR | | | Spectral Characteristics | SPEC |
| Gas Cooled (Thermal) Reactor | GCR | | | Reactivity Effects | REAC |
| Gas Cooled (Fast) Reactor | GCFR | | | Reactivity Coefficients | COEF |
| Light Water Moderated Reactor | LWR | | | Kinetics Measurements | KIN |
| Heavy Water Moderated Reactor | HWR | | | Reaction-Rate Distributions | RRATE |
| Molten Salt Reactor | MSR | | | Power Distributions | POWDIS |
| RBMK Reactor | RBMK | | | Nuclide Composition | ISO |
| Fundamental | FUND | | | Other Miscellaneous Types of Measurements | MISC |

Examples of identifiers are:

ZPR-LMFR-EXP-001
CRIT-SPEC-REAC-COEF-KIN-RRATE

This identifier corresponds to the first evaluation of measurements made on the ZPR liquid metal fast reactor experimental facility. The critical configuration, spectral measurements, reactivity measurements and coefficients, kinetics parameters, and reaction rates were measured and the data are provided.

VENUS-PWR-EXP-001
CRIT-BUCK-RRATE

This identifier corresponds to the first evaluation of measurements made on the VENUS pressurized water reactor experimental facility. The critical configuration, buckling and extrapolation length, and reaction rate measurements were measured and the data are provided.

ZR6-VVER-EXP-001
CRIT-BUCK-SPEC-REAC-COEF-RRATE

This identifier corresponds to the first evaluation of measurements made on the ZR-6 VVER experimental facility. The critical configuration, buckling and extrapolation length, reaction rate, spectral measurements, reactivity measurements and coefficients, and reaction rates were measured and the data are provided.

**KEY WORDS:**

A list of words that describe key features of the experiment is provided.

## 1.0 DETAILED DESCRIPTION

This section should start with a brief description of the scope and objectives of the experiment carried out.

A detailed description of the experiments and all relevant data are provided in the appropriate subsections within this section. The detailed description includes the measurement methods used and the results obtained. Enough information should be given in this section so that the derivation of benchmark-model specifications in Section 3.0 is evident. In general, modeling (idealization, simplification) of the experiment is not discussed here. However, if the exact experimental configuration is unknown (was not reported) or was too complicated to describe in detail and an idealization was provided by the experimenters, then the idealized experiment may also be discussed here, as well as in Section 3.1. Any discussion of an idealized experiment includes an explanation of the assumptions used in going from the real experimental configuration to the idealization.

Sources of the data should be indicated. Sources of data include published reports, logbooks, photographs, memos or other records provided by experimenters, and discussions with experimenters. Any inconsistencies in the data are mentioned in this section. A justification as to why the data can still be used is provided in the Evaluation of Experimental Data section (Section 2.0). Uncertainties in the measurements that were assigned by the experimenters, either in published or unpublished (e.g. logbooks) sources, should be included. Details of the main features of an experiment given in Section 1.1 for the critical and / or subcritical configurations are often the same for all other types of measurements. It is not necessary to repeat this information in each subsequent section. However, additions and modifications to the geometry and additional materials that are introduced for each particular measurement type must be described in detail in the appropriate subsections.

### 1.1 Description of the Critical and / or Subcritical Configuration

This section contains a detailed description of the critical and / or subcritical configuration.

#### 1.1.1 Overview of Experiment

An overview of the experiment is given, which should include the name of the facility, the dates on which the experiments were performed, the organization that performed the experiments, and perhaps the names of the experimenters if available. The conclusions of the Evaluation of Experimental Data section, Section 2, should be briefly stated. (e.g., “Twenty experiments were evaluated, but only 12 were judged to be acceptable for use as reactor physics benchmark experiments.”)

#### 1.1.2 Description of Experimental Configuration

This section contains the description of the physical arrangement and dimensions of the experiment. The method of determining the critical condition and, if applicable, the excess reactivity are stated. Uncertainties in measurements, if known, are also given. Data are given in original published units; however, if original units are not SI, evaluators are encouraged to parenthetically provide SI units immediately following the original units.

Subcritical measurements may require more detailed information about the source and detectors than is typically required for critical assemblies.

### 1.1.3 Description of Material Data

This section contains a detailed description of the materials used in the experiment as well as significant materials in the surroundings. Uncertainties in material compositions, if known, are also given. When isotopic buildup and decay are important, relevant dates should be provided.

### 1.1.4 Temperature Information

The temperature at which the experiments were performed should be given and discussed in this section.

### 1.1.5 Additional Information Relevant to Critical and Subcritical Measurements

Additional information that is relevant to critical and subcritical measurements, such as reactivity measurements of components that are omitted or revised in the benchmark model, is presented in this section. Subcritical measurement must include a description of the measurement technology and a discussion on the interpretation of the measurements as well as the measured data.

## 1.2 Description of Buckling and Extrapolation Length Measurements

This section contains a detailed description of any buckling and/or extrapolation length measurements. Uncertainties in the measurements assigned by the experimentalists, either in published or unpublished (e.g., logbooks) sources, should be included. Subsections 1.2.1 through 1.2.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the buckling and extrapolation measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

## 1.3 Description of Spectral Characteristics Measurements

This section contains a detailed description of any measurements made to determine spectral characteristics such as neutron spectra or $^{238}U_c/^{235}U_f$ ratios. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.3.1 through 1.3.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the spectral characteristics measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

## 1.4 Description of Reactivity Effects Measurements

This section contains a detailed description of measurements such as control-rod worth, void effects, small sample worth, fuel substitution, and xenon effects. Values of parameters that were actually measured should be given in this section as well as specific data that were used to transform measured values into other parameters, such as group parameters of delayed neutrons. A clear distinction should be made between measured values, calculated values, and data that were used to process measured results. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.4.1 through 1.4.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the reactivity-effect measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

### 1.5 Description of Reactivity Coefficient Measurements

This section contains a detailed description of measurements such as the temperature coefficient of reactivity, $\partial\rho/\partial T$; the moderator-height coefficient of reactivity, $\partial\rho/\partial H$; and soluble boron worth, $\partial\rho/\partial C_B$. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.5.1 through 1.5.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the reactivity-coefficient measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

### 1.6 Description of Kinetics Measurements

This section contains a detailed description of measurements such as decay constants, $\beta_{eff}$, or prompt neutron lifetime. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g., logbooks) sources, should be included. Subsections 1.6.1 through 1.6.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the kinetics measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

### 1.7 Description of Reaction-Rate Distribution Measurements

This section contains a detailed description of reaction rate measurements such as flux maps, fission chamber scans, and wire activation fine-structure and macro-structure measurements. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.7.1 through 1.7.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the reaction-rate distribution measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

### 1.8 Description of Power Distribution Measurements

This section contains a detailed description of power distribution measurements. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.8.1 through 1.8.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the power distribution measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

### 1.9 Description of Isotopic Measurements

This section contains a detailed description of isotopic measurements of discharged fuel. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.9.1 through 1.9.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the isotopic measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

### 1.10 Description of Other Miscellaneous Types of Measurements

This section contains a detailed description of other miscellaneous types of measurements that do not fit directly into one of the other categories such as conversion or breeding ratio measurements. Uncertainties in the measurements that were assigned by the experimentalists, either in published or unpublished (e.g. logbooks) sources, should be included. Subsections 1.10.1 through 1.10.5 should contain an overview of the measurements, a description of the geometry of the experimental configurations, a description of the material data, temperature data, and additional information relevant to the measurements, respectively. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections.

## 2.0 EVALUATION OF EXPERIMENTAL DATA

Missing data or weaknesses and inconsistencies in published data are discussed in this section or the appropriate subsection. The effects of uncertainties in data on the measured parameters are discussed and, if practical, quantified. All codes and data used for calculations of the effects of uncertainties should be specified. Use of data with large uncertainties or data that require assumptions on the part of the evaluator is justified in this section. If all or part of the data is found to be unacceptable for use as benchmark data, this fact is noted, and the reasons summarized. Unacceptable data are not included in Sections 3.0, 4.0, and Appendix A.

### 2.1 Evaluation of Critical and / or Subcritical Configuration Data

This section contains an evaluation of the critical and / or subcritical configuration measurements described in Section 1.1

### 2.2 Evaluation of Buckling and Extrapolation Length Data

This section contains an evaluation of the buckling and extrapolation length measurements described in Section 1.2.

### 2.3 Evaluation of Spectral Characteristics Data

This section contains an evaluation of the spectral-characteristics measurements described in Section 1.3.

### 2.4 Evaluation of Reactivity Effects Data

This section contains an evaluation of the reactivity measurements described in Section 1.4.

### 2.5 Evaluation of Reactivity Coefficient Data

This section contains an evaluation of the reactivity coefficient measurements described in Section 1.5.

### 2.6 Evaluation of Kinetics Measurements Data

This section contains an evaluation of the kinetic measurements described in Section 1.6.

### 2.7 Evaluation of Reaction-Rate Distributions

This section contains an evaluation of the reaction-rate distribution measurements described in Section 1.7.

## 2.8 Evaluation of Power Distribution Data

This section contains an evaluation of the power distribution measurements described in Section 1.8.

## 2.9 Evaluation of Isotopic Measurements

This section contains an evaluation of the isotopic measurements described in Section 1.9.

## 2.10 Evaluation of Other Miscellaneous Types of Measurements

This section contains an evaluation of other miscellaneous types of measurements, as described in Section 1.10.

# 3.0 BENCHMARK SPECIFICATIONS

Benchmark specifications provide the data necessary to construct a calculational model that represents the important aspects of the experiment. Data that are determined to be acceptable as benchmark-model data are provided in Sections 3.1 through 3.10. In general, the benchmark-model specifications include a description of the calculational methodology (Section 3.X.1); dimensions (Section 3.X.2); material data (Section 3.X.3); temperature data (Section 3.X.4); and the experimental value of each parameter and the benchmark-model value of each parameter with the associated uncertainty (Section 3.X.5). Schematics of the benchmark models should always be included.

The benchmark specifications should retain as much detail as necessary to model all important aspects of the actual experiment. When it is necessary or desirable to simplify the representation of the experiment for the benchmark specifications, the benchmark specifications must include the transformations from the measured to the benchmark-model values and the uncertainties associated with these transformations.

## 3.1 Benchmark-Model Specifications for Critical and / or Subcritical Measurements

This section contains benchmark specifications for the critical or subcritical configuration described in Section 1.1. Specifications sufficient for both stochastic and deterministic calculations are provided.

### 3.1.1 Description of the Calculational Model and Methodology

A concise description of the benchmark model(s) is given in this section. Any simplifications and approximations made to geometric configurations or material compositions are described and justified and any resulting biases and uncertainties in $k_{eff}$ are quantified. All codes and data used for calculations of biases and uncertainties should be specified. If an idealized model developed by the experimenters is described here, discussion of the model includes an explanation of the assumptions used in going from the real experimental configuration to the benchmark-model configuration.

### 3.1.2 Dimensions

All required dimensions are included in this section. Dimensions are given with the number of significant figures necessary to preserve the measurement. Reported values should not be rounded and all additional digits that result from unit conversions should be retained.

### 3.1.3 Material Data

Atom densities for all materials are concisely listed in this section. Lists are broken into subheadings such as core, structural, and reflector materials. Unique or complicated formulas for deriving atom densities are provided. All constituents of the materials used in the experiment description are included, or a justification for leaving them out is provided. (Materials that are not included are, in most cases, replaced with void.) Atom densities are listed in scientific notation with five significant digits.

### 3.1.4 Temperature Data

Temperature data about the experiment and about the model are provided in this section.

### 3.1.5 Experimental and Benchmark-Model $k_{eff}$ and / or Subcritical Parameters

The experimental $k_{eff}$ and its reported uncertainty, if available, are given in this section. If the experimenters simply indicate that the system was critical, a $k_{eff}$ of 1.0 is assumed. If the experimental parameters are simplified or omitted in the benchmark-model specification (as described in Section 3.1.1), the effect on $k_{eff}$ of this transformation, carefully quantified either by experiment or by calculation, results in an adjustment to the experimental $k_{eff}$ to obtain the "benchmark-model $k_{eff}$". These simplifications must have a relatively small effect on the overall uncertainty in the adjusted benchmark-model $k_{eff}$. Generally, simplifications such as homogenizations or modification of shapes or materials that have a large effect on $k_{eff}$ are not made. The adjusted benchmark-model $k_{eff}$ and its uncertainty are also included.

Additional benchmark model parameters, such as spectral ratio, variance-to-mean, decay constant, or count-rate ratio values and their uncertainties, are included for subcritical measurements as well as the interpreted $k_{eff}$ values.

## 3.2 Benchmark-Model Specifications for Buckling and Extrapolation-Length Measurements

This section contains specifications for the benchmark-model of the buckling and extrapolation length measurements described in Section 1.2. Subsections 3.2.1 – 3.2.5, analogous to the subsections of Section 3.1, are also included.

## 3.3 Benchmark-Model Specifications for Spectral Characteristics Measurements

This section contains specifications for the benchmark-model of the spectral characteristics measurements described in Section 1.3. Subsections 3.3.1 – 3.3.5, analogous to the subsections of Section 3.1, are also included.

## 3.4 Benchmark-Model Specifications for Reactivity Effects Measurements

This section contains specifications for the benchmark-model of the reactivity-effects measurements described in Section 1.4. Subsections 3.4.1 – 3.4.5, analogous to the subsections of Section 3.1, are also included.

## 3.5 Benchmark-Model Specifications for Reactivity Coefficient Measurements

This section contains specifications for the benchmark-model of the reactivity coefficient measurements described in Section 1.5. Subsections 3.5.1 – 3.5.5, analogous to the subsections of Section 3.1, are also included.

## 3.6 Benchmark-Model Specifications for Kinetics Measurements

This section contains specifications for the benchmark-model of the kinetics measurements described in Section 1.6. Subsections 3.6.1 – 3.6.5, analogous to the subsections of Section 3.1, are also included.

### 3.7 Benchmark-Model Specifications for Reaction-Rate Distribution Measurements

This section contains specifications for the benchmark-model of the reaction rate distribution measurements described in Section 1.7. Subsections 3.7.1 – 3.7.5, analogous to the subsections of Section 3.1, are also included.

### 3.8 Benchmark-Model Specifications for Power Distribution Measurements

This section contains specifications for the benchmark-model of the power distribution measurements described in Section 1.8. Subsections 3.8.1 – 3.8.5, analogous to the subsections of Section 3.1, are also included.

### 3.9 Benchmark-Model Specifications for Isotopic Measurements

This section contains specifications for the benchmark-model of the isotopic measurements described in Section 1.9. Subsections 3.9.1 – 3.9.5, analogous to the subsections of Section 3.1, are also included.

### 3.10 Benchmark-Model Specifications for Other Miscellaneous Types of Measurements

This section contains specifications for the benchmark-model of any other miscellaneous types of measurements as, described in Section 1.10. Subsections 3.10.1 – 3.10.5, analogous to the subsections of Section 3.1, are also included.

## 4.0 RESULTS OF SAMPLE CALCULATIONS

Calculated results obtained with the benchmark-model specification data given in Section 3.0 are tabulated in this section. Details about the calculations, including code versions, cross sections, and typical input listings, are given in Appendix A (A.1 through A.10). Results should be reported both as obtained directly from calculations and in the form 100(C-E)/E, where C is the calculated result and E is the expected result from a calculation with the benchmark model as given in Section 3.X.5. Benchmark uncertainties should be repeated as percentages for comparison purposes.

### 4.1 Results of Calculations of the Critical or Subcritical Configurations

Calculated $k_{eff}$ values are presented in this section. Additional calculated parameters, such as spectral ratio, variance-to-mean, decay constant, or count-rate ratio values, are included for subcritical measurements as well as interpreted $k_{eff}$ values.

### 4.2 Results of Buckling and Extrapolation Length Calculations

Calculated buckling and extrapolation length values are presented in this section.

### 4.3 Results of Spectral-Characteristics Calculations

Calculated spectral characteristics are presented in this section.

### 4.4 Results of Reactivity-Effects Calculations

Calculated reactivity effects are presented in this section.

### 4.5 Results of Reactivity Coefficient Calculations

Calculated reactivity coefficient values are presented in this section.

### 4.6 Results of Kinetics Parameter Calculations

Calculated kinetics parameters are presented in this section.

### 4.7 Results of Reaction-Rate Distribution Calculations

Calculated reaction rate distributions are presented in this section.

### 4.8 Results of Power Distribution Calculations

Calculated power distributions are presented in this section.

### 4.9 Results of Isotopic Calculations

Calculated isotopic concentrations are presented in this section.

### 4.10 Results of Calculations for Other Miscellaneous Types of Measurements

Calculated results for other miscellaneous types of measurements, as described in Section 1.10, are presented in this section.

## 5.0 REFERENCES

All published documents referenced in the evaluation that contain relevant information about the experiments are listed. Internal documents such as logbooks, memos and internal reports should be included in footnotes. Handbooks and computer code documentation should also be included in footnotes. When a primary reference, internal or published, is available in electronic form, it may be included on the CD or DVD with a hyperlink from the point of reference.

## APPENDICES

Supplemental information that is useful, but not essential, to the derivation of the benchmark specification or the sample calculations is provided in appendices. Appendices are labeled using letters (e.g. Appendix A). Appendix A is reserved for a description of the codes, cross section data, and typical input listings used in the sample calculations whose results are given in Section 4. Other appendices may be added, as needed, after Appendix A.

### APPENDIX A: COMPUTER CODES, CROSS SECTIONS, AND TYPICAL INPUT LISTINGS

Appendix A provides a description of the codes, options, and cross section data used in the calculations of the results given in Section 4. The following information should be included in Appendix A for each measurement type, X. The format should be followed, but where certain information or data are determined to be "Not applicable", "Not available", or "Not Significant" it should be so stated.

**A.X.1 Name(s) of code system(s) used.**

**A.X.2 Bibliographic references for the codes used.**

**A.X.3 Origin of cross-section data –** Nuclear data libraries that were used in the evaluation such as ENDF/B-VI, JEF-2.2, JENDL-3.2 should be specified. Deviations from standard libraries, (e.g. mix of different libraries, details) should be described**.**

**A.X.4 Spectral calculations and data reduction methods used –** Describe calculational scheme, through a figure and explanatory words that provide essential details about assumptions made such as:

- Resonance shielding: specify method(s), energy range(s), the nuclides affected (actinides, clad, fission products, oxygen), and which unresolved resonance treatment is used;
- Describe how mutual shielding (overlapping of resonances) is handled, or not;
- Fission spectra: specify whether only a single spectrum was used or a weighted mix from all fissile nuclides, explaining the procedure for obtaining the weighted mix;
- Describe how the (n,2n) reaction was treated (Optional);
- Weighting spectrum for scattering matrices, e.g. corrections of the out-scatter and self-scatter terms considering the differences between the original weighting spectrum and the actual spectrum (Optional).

**A.X.5 Number of energy groups or if continuous-energy cross sections are used in the different phases of the calculation.**

**A.X.6 Component calculations –** The following information should be provided for each component calculation (pin cell, assembly, etc.) as well as full core calculations**:**

- Type of cell calculation (pin cell, assembly, etc.)
- Geometry
- Theory used (diffusion, transport)
- Method used (finite difference, finite element, nodal, $S_n$ (order), collision probability, Monte Carlo, J+/-, etc.)
- Calculation characteristics (meshes, elements/assembly, meshes/pin, number of histories, multi-group, continuous energy, etc.).

**A.X.7 Other assumptions and characteristics.**

**A.X.8 Typical Input Listings for each code system type –** Typical input listings used to obtain the results reported in Section 4.0 should be provided. Unique and/or important features of the input may also be discussed just prior to the input listings. Listing titles refer to the case number and number of the table in Section 4.0 that gives the calculated result.

## NUCLEAR CONSTANTS

Atomic densities are based on a consistent set of basic nuclear constants. Unless specifically stated otherwise, all nuclear constants are taken from "Nuclides and Isotopes," Fourteenth Edition, General Electric Nuclear Energy Operations, 1989. Where atomic densities are provided in an experimental report, and the values of Avogadro's Number and the atomic weights that were used by the experimenters to determine the atomic densities are known, reported atomic densities are adjusted to be consistent with the nuclear constants given in this section. Values from the consistent set that are used in the evaluations are given below. If these values are not used, the source of the data should be specified and values given.

Avogadro's Number $6.0221 \times 10^{23} \ \frac{\text{atoms}}{\text{gram} - \text{mole}}$

**TABLE 1. Atomic Weights.**

| Nuclide or Isotope | Atomic Weight |
|---|---|
| $^{1}$H | 1.0079 |
| $^{2}$H | 2.0141 |
| $^{6}$Li | 6.0151 |
| Li | 6.941 |
| Be | 9.0122 |
| B | 10.811 |
| $^{10}$B | 10.0129 |
| $^{11}$B | 11.0093 |
| C | 12.011 |
| N | 14.0067 |
| O | 15.9994 |
| F | 18.9984 |
| Na | 22.9898 |
| Mg | 24.305 |
| Al | 26.9815 |
| Si | 28.0855 |
| P | 30.9738 |
| S | 32.07 |
| Cl | 35.453 |
| K | 39.0983 |
| Ca | 40.078 |
| Ti | 47.88 |
| V | 50.9415 |
| Cr | 51.996 |
| Mn | 54.9380 |
| Fe | 55.847 |
| Ni | 58.69 |
| Cu | 63.546 |
| Zn | 65.39 |

**TABLE 1. Continued.**

| Nuclide or Isotope | Atomic Weight |
|---|---|
| Ga | 69.723 |
| Sr | 87.62 |
| Zr | 91.224 |
| Nb | 92.9064 |
| Mo | 95.94 |
| $^{99}$Tc | 98.9063[1] |
| Ru | 101.07 |
| Rh | 102.9055 |
| Ag | 107.8682 |
| $^{107}$Ag | 106.9051 |
| $^{109}$Ag | 108.9048 |
| Cd | 112.41 |
| In | 114.82 |
| Sn | 118.71 |
| $^{129}$I | 128.9050 [a] |
| Cs | 132.9054 |
| Ba | 137.327 |
| La | 138.9055 |
| Ce | 140.115 |
| Nd | 144.24 |
| Sm | 150.36 |
| $^{144}$Sm | 143.9120 |
| $^{147}$Sm | 146.9149 |
| $^{148}$Sm | 147.9148 |
| $^{149}$Sm | 148.9172 |
| $^{150}$Sm | 149.9173 |
| $^{152}$Sm | 151.9197 |
| $^{154}$Sm | 153.9222 |
| Eu | 151.96 |
| $^{151}$Eu | 150.9198 |
| $^{153}$Eu | 152.9212 |
| Gd | 157.25 |
| $^{152}$Gd | 151.9198 |
| $^{154}$Gd | 153.9209 |
| $^{155}$Gd | 154.9226 |
| $^{156}$Gd | 155.9221 |
| $^{157}$Gd | 156.9240 |
| $^{158}$Gd | 157.9241 |
| $^{160}$Gd | 159.9270 |
| Dy | 162.50 |
| Hf | 178.49 |
| Ta | 180.9479 |

[1] G. Audi, O. Bersillon, J. Blachot, A.H. Wapstra, Nuclear Physics A 624 (1997) p. 1-124. And Updates of March 2000 at Atomic Mass Data Center (A.M.D.C.).

**TABLE 1. Continued.**

| Nuclide or Isotope | Atomic Weight |
|---|---|
| W | 183.85 |
| $^{182}$W | 181.9482 |
| $^{183}$W | 182.9502 |
| $^{184}$W | 183.9509 |
| $^{186}$W | 185.9544 |
| Au | 196.9665 |
| Pb | 207.2 |
| $^{232}$Th | 232.0381 |
| $^{231}$Pa | 231.0359 |
| $^{233}$U | 233.0396 |
| $^{234}$U | 234.0409 |
| $^{235}$U | 235.0439 |
| $^{236}$U | 235.0456 |
| $^{238}$U | 238.0508 |
| $^{237}$Np | 237.0482 |
| $^{238}$Pu | 238.0496 |
| $^{239}$Pu | 239.0522 |
| $^{240}$Pu | 240.0538 |
| $^{241}$Pu | 241.0568[2] |
| $^{242}$Pu | 242.0587 |
| $^{241}$Am | 241.0568 |
| $^{242m}$Am | 242.0596[3] |
| $^{243}$Am | 243.0614 |
| $^{242}$Am | 242.0588 |
| $^{243}$Cm | 243.0614 |
| $^{244}$Cm | 244.0627 |
| $^{245}$Cm | 245.0655 |
| $^{246}$Cm | 246.0672 |
| $^{247}$Cm | 247.0704 |
| $^{248}$Cm | 248.0723 |
| $^{252}$Cf | 252.0816 |

[2] "Chart of the Nuclides," Thirteenth Edition, General Electric Company, 1984.

[3] G. Audi, O. Bersillon, J. Blachot, A.H. Wapstra, Nuclear Physics A 624 (1997) p. 1-124. And Updates of March 2000 at Atomic Mass Data Center (A.M.D.C.).

**COMMONLY USED SYMBOLS AND TERMS**

| | |
|---|---|
| A | mass number |
| $A_f$ | atom fraction |
| $A_w$ | atomic weight or mass (g/mole) |
| at.% | atom percent |
| $B^2$ | buckling ($cm^{-2}$) |
| $\beta_{eff}$ | effective fraction of fission neutrons that are delayed. |
| C | Dancoff correction factor |
| D | diameter |
| $\Delta$ | change in quantity [e.g., neutron multiplication factor, $\Delta k$; buckling, $\Delta B^2$; tank height, $\Delta H$; radius, $\Delta R$; etc.] |
| $\delta^{28}$ | ratio of $^{238}U$ fission to $^{235}U$ fission |
| $\delta^{25}$ | ratio of epithermal to thermal $^{235}U$ fission |
| H | height |
| k | neutron multiplication factor - The subscripts "eff" and "$\infty$" are used to denote the effective multiplication factor, $k_{eff}$, and the multiplication factor for an infinite system, $k_\infty$. |
| $\Lambda$ | prompt neutron lifetime |
| m | mass |
| M | molarity (moles/l) |
| M | neutron multiplication $M \cong \frac{1}{1 - k_{eff}}$ |
| $M_w$ | molecular weight or mass (g/mole) |
| $N_A$ | Avogadro's number [6.0221 x $10^{23}$ (atom, molecules, etc.) per mole] |
| $N_i$ | atomic density (atoms/barn-cm) - The subscript "i" is a general descriptor used to denote either the standard elemental symbol (e.g., $N_H$, $N_O$, $N_{Pu}$) or the isotopic mass number (e.g., $N_{235}$, $N_{238}$). For multi-elemental systems where isotopes of one element could be confused with those of another element, both the elemental symbol and the mass number are used (e.g., $N_{Pu238}$, $N_{U238}$). |

$N^a$ excess acid (moles/ℓ)

$\nu$ average number of neutrons per fission

R or r radius

$\rho$ reactivity: $\rho \equiv \frac{k_{eff}-1}{k_{eff}}$, sometimes denoted in units of \$ $\equiv \frac{\rho}{\beta_{eff}}$, where $\beta_{eff}$ is the effective fraction of fission neutrons that are delayed.

$\rho^{28}$ the ratio of epithermal to thermal captures in $^{238}U$

$\rho^{25}$ the ratio of epithermal to thermal captures in $^{235}U$

$\rho_i$ density (g/cm$^3$ or g/ℓ) - The subscript "i" is a general descriptor used to denote the nuclide or compound for which the density is given (e.g., $\rho_{UO_2NO_3}$, $\rho_{H_2O}$, $\rho_{Pu}$, $\rho_{HNO_3}$).

$s_i$ estimated standard deviation , equal to the positive square root of the statistically estimated variance $s^2_i$

$\sigma$ statistical uncertainty associated with Monte Carlo calculations or standard deviation (the correct value has a probability of 68% of being within $\pm \sigma$ of the quoted value, assuming a normal distribution)

$\sigma_i$ microscopic cross section for absorption (i=a), fission (i=f), scatter (i=s), capture (i=c), total (i=t)

$\Sigma$ macroscopic cross section or summation [e.g., $\Sigma_a$, $\Sigma_f$, $\Sigma_s$, $\Sigma_t$ are macroscopic absorption, fission, scattering, and total cross sections; $\sum_{i=1}^{m}$ is a summation over the range: i = 1 to i = m].

$u_i$ uncertainty of a measurement result by an estimated standard deviation, termed **standard uncertainty** and equal to the positive square root of the estimated variance $u_i^2$

V volume

$V_f$ volume fraction

$W_f$ weight fraction

wt.% weight percent

Note: When an index "i" is used in conjunction with another subscript, the two are separated by a comma (e.g., $W_{f,i}$).

**REFERENCES FOR UNCERTAINTY ESTIMATIONS:**


- ICSBEP Guide to the Expression of Uncertainties – Revision 1, "International Handbook of Evaluated Criticality Safety Benchmark Experiments", NEA/NSC/DOC(95)03/I-VIII, OECD-NEA, September, 2004.

- "American National Standard for Expressing Uncertainty - U.S. Guide to the Expression of Uncertainty in Measurement," National Conference of Standards Laboratories, ANSI/NCSL Z540-2-1997.

- Guide pour l'expression de l'incertitude de mesure - European Prestandard NF ENV 13005Août 1999.

- Zoltán Szatmáry: The Effects of Technological Uncertainties on the Neutron Flux, IRPhE Meeting, Budapest, May 2000.