Identification Number

DOCUMENT CONTENT AND FORMAT GUIDE

for the

International Criticality Safety Benchmark Evaluation Project (ICSBEP)
(Critical and Subcritical Measurements)

GENERAL FORMAT GUIDELINES

Final formatting, in terms of the document, including text, table and graphics, will be done by the Evaluator(s). Evaluators are strongly encouraged to follow the standard formatting guidelines outlined below; the publication staff will check the final formatting, to ensure consistency in evaluations contained within the Handbook. Publication staff can make minor corrections only; Evaluator(s) will be responsible for major corrections needed in the document. Documents that are not compliant will be returned to the evaluator(s) for editing and might miss inclusion in the current publication of the ICSBEP Handbook. Autonumbering of tables and figures, while not required, is highly recommended. Publication templates will be used to ensure this consistency. Both Word and LaTeX templates are available online and within the ICSBEP Handbook.

General publication guidelines that evaluators are strongly encouraged to follow are given below:

Paper Size:
- Either A4 or Letter.

Font and Size:
- Use 11-point, Times New Roman font for the main text.
- Headings are in Times New Roman (14-point for the Title, 11-point for primary section headers (e.g., 1.0, 2.0, etc.), and 11-point font for subheadings) or Arial (12-point for the Title, 10-point for primary section headers (e.g., 1.0, 2.0, etc.), and 10-point font for subheadings).
- Minimum size for text in tables and figures is 8-point font.

Text Justification:
- Left-justified.

Margins:
- The standard margin width is 1.0 in (2.54 cm) on left, top, and bottom, and 0.75 in (1.91 cm) on right. The required minimum margin width should be 0.5 in. (1.27 cm) on all four sides. This minimum margin width is an acknowledgement that sometimes figures or tables need to be outside of the standard margins.
- The Evaluator(s) should ensure that all tables and figures allow for the minimum margin width.

Footnotes:
- Page and table footnotes need to be consistent throughout the document.
- Use numerical footnotes for the main text (e.g., 1, 2, 3, etc.). This is an example footnote.[1]
- Tables use parenthetical alphabetical notation [e.g., (a), (b), (c), etc.] and should be placed just under the table and not at the bottom of the page. An example footnote for a table is provided in Table 1.

[1] This is an example footnote. It is typically utilized to denote the source of additional information from a reference that is not an official, or publicly available, reference for the evaluated experiment.

Table and Figure Numbering:

- Evaluator(s) can use desired table and figure numbering format as long as it is clear which table or figure is which (i.e. they are uniquely numbered). Examples of table numbering are provided below.

Tables:

- Table bordering and shading is not prescriptive. Example tables, with variations of table numbering, are provided below (see Tables 1, 1.1, 1-2, and 1.3). Tables, figures, and their headings should be centered.

Table 1: Example Table with Footnote[a]

Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**
Row 1	Data	Data	Data	Data
Row 2	Data	Data	Data	Data

[a] This is an example footnote for a table

Table 1.1. Example Table with Shading and Borders

Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**
Row 1	Data	Data	Data	Data
Row 2	Data	Data	Data	Data

Table 1-2. Example Table with Minimal Bordering.

Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**
Row 1	Data	Data	Data	Data
Row 2	Data	Data	Data	Data

Table 1.3. Another Example Table with Minimal Bordering.

Column 1	Column 2	Column 3	Column 4	Column 5
Row 1	Data	Data	Data	Data
Row 2	Data	Data	Data	Data

Headers and Footers:

- An example of the format for the header and footer of an evaluation is provided as the header and footer of this document.
- The header contains the NEA document number, NEA/NSC/DOC(95)03, followed by /#, where the value for the # depends on the volume of the ICSBEP Handbook where the critical/subcritical evaluation will reside:
    - Volume 1 = Plutonium (PU)
    - Volume 2 = Highly Enriched Uranium (HEU)
        - wt.% $^{235}U \geq 60$
    - Volume 3 = Intermediate Enriched Uranium (IEU)
        - $10 <$ wt.% $^{235}U < 60$
    - Volume 4 = Low Enriched Uranium (LEU)
        - wt.% $^{235}U \leq 10$
    - Volume 5 = Uranium-233 (U233)
    - Volume 6 = Mixed Plutonium-Uranium (MIX)
    - Volume 7 = Special Isotopes (SPEC)

- The header also reiterates the volume identifier by including “Volume #”.
- The header concludes with the identification number assigned to the evaluation.
- The footer includes the revision number and date. The first publication of an approved evaluation has a revision number of zero (0). The publication date is when the content is finalized with the ICSBEP.
- Page numbering is included in the footnote and is written as “Page X of Y”, where X is the current page number and Y is the total number of pages.
- Page 1 starts with Section 1.0 in an evaluation. The title page and any optional pages (acknowledgements, table of contents, etc) are numbered with lower case roman numerals (i, ii, iii, iv, etc).

Optional Contents:

- A table of contents can be included between the Title Page and First Page of the document.
    - It is recommended to not include a Table of Tables or Table of Figures.
- An acknowledgements page can be included between the Title Page and First Page of the document.
- An auspices statement, as required by the Evaluator(s)’ institution, can also be included.
- The recommended order for optional content is as follows: Title Page, Auspices Page, Acknowledgments Page, Table of Contents, First Page of Document (i.e. Section 1.0).

IDENTIFICATION NUMBER:

Each experiment has a unique identifier. The ICSBEP Chair distributes the Identification Number to prevent duplication of numbering; it is typically assigned when submitting the evaluation to the ICSBEP Technical Review Group (TRG). The elements of the identifier correspond to the categories and subcategories named in the organization section of this report. The identifier takes the following form:

(Fissile Material)-(Physical Form)-(Spectrum)-(Three-Digit Numerical Identifier)

Identifier elements and their meanings for each category and subcategory are given below.

Fissile Material		Physical Form		Spectrum	
Plutonium	PU	Metal	MET	Fast	FAST
Highly Enriched Uranium	HEU	Compound	COMP	Intermediate-Energy	INTER
Intermediate Enriched Uranium	IEU	Solution	SOL	Thermal	THERM
Low Enriched Uranium	LEU	Miscellaneous	MISC	Mixed	MIXED
Uranium-233	U233				
Mixed Plutonium - Uranium	MIX				
Special Isotope	SPEC				

Subcritical k_{eff} measurements are denoted by including the letters “SUB” at the beginning of the identifier.

Examples of identifiers are as follows: IEU-COMP-THERM-001 for thermal, intermediate enriched uranium system in which the fissile material is in the form of a compound; HEU-SOL-THERM-001 for highly enriched uranium solution; SUB-HEU-SOL-THERM-001 for subcritical measurements on highly enriched uranium solution systems.

KEYWORDS:

A list of words that describe key features of the experiment is provided. As a minimum, the keywords should include the fuel, moderator, reflector material, experimental assembly, etc. that represent the major materials and components of the experiment. Any additional keywords the Evaluator(s) feel necessary to include can also be provided. The keywords also include whether the evaluation was determined to be acceptable or unacceptable as a benchmark by the TRG. Various examples can be found in the ICSBEP Handbook. Here is an example of some of the key words provided for LEU-COMP-THERM-102:

Type of Keyword	Key Word Examples
Acceptability	acceptable
Fuel Type	uranium uranium dioxide
Moderator	water-moderated
Reflector	water-reflected
Experimental Assembly	array
Additional Key Words	square pitch undermoderated

A listing of existing keywords can be found in the Database of International Criticality Experiments (DICE) that is distributed with the ICSBEP Handbook. It is recommended that evaluators consult the list of keywords and use existing keywords when possible.

1.0 DETAILED DESCRIPTION

Section 1 General Guidelines

A detailed description of the experiments and all relevant experimental data are provided in the appropriate subsections within this section. The detailed description includes the measurement methods used and the results obtained for the parameters of interest, as well as methods used to obtain the experimental data. Experimental data are values of parameters that are needed to completely describe the experiment and that have been directly measured. Examples are dimensions obtained from tightly controlled specifications or with calibrated measuring devices, masses obtained from weighing, and temperatures from thermometer readings. These data should be reported in the units in which they were measured. It is recommended that only experimental data that are measured or taken directly from the references be included in Section 1. However, values derived from experimental data, such as density derived from masses and dimensions, or compositions normalized to 100 wt.%, may be included if clearly noted as derived with the method of derivation given.

In order to clarify the description of the experiment and to not prejudge the evaluation, there should be no mention of models, calculated results (e.g., results from neutron transport models),[2] or evaluative statements in this section (e.g., engineering judgement, assumption). Only the physical description of the actual experiment is given.

Uncertainties in the data that were assigned by the experimenters, either in published or unpublished (e.g., logbook) sources, should be given. How the uncertainties were determined and what they represent (e.g., standard deviation, specification tolerance, estimated bounds), if known, should be noted.

Any inconsistencies in the data from different sources are mentioned. There should be enough information that the derivation of benchmark-model specifications in Section 3 can be confirmed. It is recommended that any additional experimental data be provided, which might be useful for more detailed modeling or for justification of sufficiency of the model.

The source of each datum should be clear. Sources of data include published reports, logbooks, chemical-laboratory analyses, handbooks or standards of material compositions, photographs, memos or other records provided by experimenters, and discussions with experimenters.

In general, modeling (idealization, simplification) of the experiment is not discussed in Section 1. However, if the exact experimental configuration is unknown (e.g., perhaps it was not reported because the exact configuration was not relevant to the purpose for which the experiment was being used, or it was thought to be too complicated to describe in detail) and an idealization was provided by the experimenters, then the idealized experiment may be described here, but that must be stated. Evaluation (Sections 2 and 3.1) of an idealized experiment includes an explanation of the assumptions used in going from the real experimental configuration to the idealization.

1.1 <u>Overview of Experiment</u>

This section should include the following items as relevant to the evaluation:

- A summary description of the experiment (e.g., images of the experiment and components)
- Its original purpose (e.g., maximizing reactions of interest, application cases, etc.)
- Parameters that vary in a series of configurations (e.g., interstitial material thickness, interstitial material, addition of voids, reflector configurations, etc.)

[2] A summary of neutron energy groups, and the interpretation of subcritical results are exceptions. Calculations are required to interpret the experimental results.

- Methods used for determining reactivity of the benchmark configuration (e.g., fuel pin loading, reactor period, or moderator level)
- Whether the measured configuration was subcritical[3]/critical/supercritical.
- Significant relationships to other ICSBEP-evaluated experiments, (i.e., listing the ICSBEP identifiers for major components that are used in other evaluations)
- Name of the facility
- Date of the experiments
- The organization that performed the experiments
- Names of the operators and/or experimenters, if available
- Summary of neutron energy groups (i.e., % thermal, intermediate, and fast fissions). While generally Section 1 should not include model results, this is an acceptable use of neutron transport code in Section 1.

The conclusions of this section should be briefly stated. (e.g., "Twenty experiments were evaluated, but only 12 were judged to be acceptable critical benchmark experiments.")

1.2 Description of Experimental Configuration

This section contains the detailed description of the components and physical arrangement of the experiment, including the dimensions and relative positions of all components. The nomenclature used for the components should be established in this section and remain consistent throughout the benchmark. It is recommended to include engineering drawings and/or schematics that describe how the experiment is assembled. An explanation of how component measurements were obtained, if known (e.g., Vernier caliper), and associated uncertainties (i.e., calibration/tolerance information, model number, if known) should be included. It is good practice to include calibration documentation as an appendix, if available. The material of each component should be identified, if known. The density and mass may be reported here if measured (or derived from measurements) and not reported in Section 1.3. For ease of accurate transcription and checking, data and uncertainties are simply copied from the references, in their original units and to the precision that was recorded. However, if original units are not SI, evaluators are encouraged to parenthetically provide SI units immediately following the original units.

In some cases, it may be appropriate to include component information in an appendix or reference a publicly available document and only report an average in this section. This may be preferable when, for example, hundreds of a component type are being used and all have dimension and mass measurements that would require multiple pages of tables to fully describe the components. In those cases, averages, standard deviations, variances, etc. may be reported in Section 1.2. The use of sample or population standard deviation should be clear. When a measurement technique is inherently an average (e.g., coordinate measuring machine measurements or pycnometers) the details of the measurement technique should be stated.

Critical configurations should be reported in this section. The method of determining the critical condition, i.e., the parameter being benchmarked, should be described. Information associated with the types of measurements (e.g., period measurements, extrapolations to critical, etc.) should be included as well as the position of the measurement tools with respect to the configuration (e.g., location of the ion chamber (s)).

Subcritical measurements may require more detailed information about the source and detectors than is typically required for critical assemblies (e.g., detailed descriptions and dimensions of the detector(s) and the source).

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[3] There is a separate guide for subcritical experiments, but some subcritical experiments may be evaluated using this guide by extrapolating to a critical configuration or if the experiment is close to critical (i.e., multiplication >100). If this method is used, the evaluator needs to clearly state this in Section 1.1.

1.3 Description of Material Data

This section contains the detailed description of all materials used in the experiment as well as significant materials in the surroundings, primarily the composition of the materials used in the experiment. However, density and mass may be reported here if measured (or derived from measurements) and not already reported in Section 1.2. All material data should be reported in the units and significant figures of the measurement and may be converted to another unit of measure as appropriate. If original units are not SI, evaluators are encouraged to parenthetically provide SI units immediately following the original units. Sources (e.g., inspection reports) for material data also must be properly referenced. Material handbook data may be reported here or when relevant in Section 2. Details of the analysis method(s) and uncertainties, if known, are also given. If an analysis was incapable of detecting the presence of particular elements, this should be stated (e.g., ICP-MS cannot be used to measure volatile elements). When isotopic buildup and decay are important, dates of the experiment, of the chemical analysis, and of isotopic analysis or purification should also be provided.

1.4 Temperature Data

This section should discuss the temperature at which the experiments were performed as well as the tools used to measure the temperature and associated uncertainties, the location(s) of the temperature measurement tool(s), the measurement time with respect to the experiment (e.g., before or after the experiment), and calibration information on the temperature measurement tool(s).

1.5 Supplemental Experimental Measurements

This subsection contains additional experimental data that is not necessarily relevant to the derivation of the benchmark model, such as:

- Flux distributions
- Spectral indices
- β_{eff}
- Reactivity data (e.g., reactivity worth measurements that are not discussed as part of the uncertainty analysis)

Additional information that is not used in the evaluation may be included by reference to readily available documents or publications. If such documents are not available, the additional data may be included in this section or by reference to an appendix. If there is no such additional data, it is so stated.

This subsection also contains evaluations of subcritical measurements, including:

- a description of the measurement technology(e.g., source-driven noise analysis)
- a discussion on the interpretation of the measurements (i.e., relating the measure to k_{eff})
- the measured data.

For subcritical measurements, calculated results may appear in this section.

2.0 EVALUATION OF EXPERIMENTAL DATA

Section 2 General Guidelines

Evaluation of the experimental data is documented in this section and conclusions are stated and justified. Missing data or weaknesses and inconsistencies in published data are discussed and resolved in appropriate subsections of this section. Uncertainties of k_{eff} due to uncertainties of the experimental data are discussed and quantified. Use of data with large uncertainties or data that require questionable assumptions on the part of the evaluator is justified. Evaluators should focus on important uncertainties and small contributors can be evaluated with less effort. For example, for closely related experiments, previous benchmark results could be referenced instead of completing a new calculation, provided they are highly similar. Adjoint-based sensitivity methods[4] can radically reduce the number of calculations necessary for mass and composition uncertainty analysis. k_{eff} values should be reported to 5 decimal places to facilitate conversion to per cent mille (pcm, or 0.00001 $\Delta k/k$).

Every experiment has numerous associated uncertainties. Ideally, everything about the materials used in the assembly would be known, including the masses and compositions of constituents, and everything about the geometric arrangement of the components would also be known, including dimensions of individual parts and how they stacked together. While absolute truth, in this case the exact configuration, is unknowable, the attainable goals are an estimate of it (the benchmark model) and an estimate of how well the configuration and its neutronic state are known. In general, the aim of this section is to find the effect on k_{eff} due to the variation of each uncertain parameter that makes up the defined critical configuration. The following definitions are often used:

xi	the reference value (best estimate) of the ith parameter
Δx_i	a perturbation of the ith parameter
$\pm u_i$	the standard uncertainty (corresponding to 1σ) of the ith parameter
Δk_i	the reactivity effect on k_{eff} of changing x_i by $\Delta x_i = u_i$

Almost always, each u_i is small enough to have a first-order effect on k_{eff}. This means that for $\Delta x_i \leq u_i$, the change in k_{eff} produced by Δx_i is proportional to the magnitude of Δx_i.

The evaluator may choose a different parameter perturbation, δx_i, to compute the corresponding δk_i. The δx_i is chosen to be large enough to minimize ambiguity arising from roundoff, numerical convergence limits or statistical noise, depending on the method used to compute δk_i. At the same time, it is necessary that δx_i be kept small enough not to violate the linearity (first-order-effect) assumption, so that both u_i and δx_i are proportional to the corresponding changes in k_{eff} by the same factor. The evaluator should verify compliance by calculational tests if there is doubt. Then the desired reactivity effect is $\Delta k_i = u_i \delta_{ki}/\delta x_i$. The proportionality factor $\delta k_i/\delta x_i$ is the sensitivity of k_{eff} to x_i.

Another way of thinking about this is that the evaluator is applying the first-order propagation-of-error formula, $(u_{k_i})^2 = (\partial k_{eff} / \partial x_i)^2 (u_i)^2$. The ratio $\delta k_i/\delta x_i$ is then an estimate of $\partial k_{eff}/\partial x_i$, regardless of the size of δx_i. In other words, there is no need to limit the perturbation size to u_i and the evaluator should instead find a good estimate of the derivative. The evaluator should strive to use two-sided perturbations, which allows the evaluator to check the linearity of δk_i with respect to δx_i. Alternatively, an adjoint based sensitivity method can be used to compute the relative sensitivity $S_{k,x_i} \equiv (x_i / k_{eff})(\partial k_{eff} / \partial x_i)$.

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[4] Favorite, J., Zoltan, P., Kiedrowski, B., and Perfetti, C. "Adjoint-Based Sensitivity and Uncertainty Analysis for Density and Composition: A User's Guide." *Nuclear Science and Engineering.* Vol. 185. P. 384-405. March 2017.

Some perturbations are inherently one-sided (such as a one-sided dimensional tolerance on a part), and in that case, the uncertainties associated with them are also one-sided. Likewise, the effect of δx_i on δk_i may be nonlinear, and $+\delta x_i$ would need to be analyzed separately from $-\delta x_i$.

While uncertainties are generally assumed to be independent and evaluated independently, the evaluator should consider if any sources of uncertainty impact the reactivity sensitivity o another. In those cases, the dependent uncertainties should be assessed jointly.

The Δk_is are added in quadrature to obtain the overall uncertainty in k_{eff}. In practice, the subscript i is frequently omitted in the tables when it is clear which k_{eff} uncertainty is meant. Also, in practice, the Δ notation refers to any size perturbation; the δ notation is not necessary. The symbols δ and Δ should not be used to indicate an uncertainty; use σ or u instead.

If all or some of the configurations are found to be unacceptable for use as benchmark data, this fact is noted in this section, and the reasons are summarized. The evaluation process for the unacceptable configurations is terminated at this point (i.e., unacceptable data are not included in Sections 3 or 4 or Appendix A).

A decision made by the ICSBEP Working Group that a particular experiment is not acceptable for use as a "Criticality Safety Benchmark Experiment" is not intended to imply that the data, if properly interpreted and applied, cannot be used for validation efforts. In particular, experiments for which the combined uncertainty in the benchmark k_{eff} value exceeds 1% are often judged to be unacceptable. This is especially true when the data are not required to fill gaps in existing data. However, if the large uncertainty is properly taken into account, the data may be used in validation efforts.

Section 2.0 should describe the method or methods used to determine the impact of uncertainties on k_{eff} (such as experimental quantification or calculations). If a calculation was used, the code system and nuclear data libraries must be described, and additional uncertainty introduced due to the precision of the method must be taken into account. The definition of "negligible" is generally related to the precision of the method used to evaluate the k_{eff} uncertainty and should be quantified in this section. Section 2.0 should also present any definitions or equations used to describe how the uncertainty in k_{eff} was derived from the evaluation method.

Differences between code input specifications whose calculated results are subtracted to obtain effects, if not obvious, should be made clear. It is not necessary to use the exact benchmark model specifications for sensitivity calculations; however, any large discrepancies from the benchmark model should be noted. It is preferable to use as representative of a model as possible to the measured configuration for uncertainty quantification, as simplifications can impact sensitivity vectors.

Uncertainties evaluated are generally due to experimental k_{eff} measurement technique, mass, dimensions, compositions, spacing or geometrical arrangement of components, and temperature. These uncertainties should be evaluated in Sections 2.1-2.X. Uncertainties may be evaluated in any order. Additional guidance for each of these categories of uncertainties is provided under the section headings below. More detailed information about uncertainty quantification, with ICSBEP relevant examples, can be found in the ICSBEP Guide to the Expression of Uncertainties[5].

In some cases, uncertainties in experimental information (such as reported precision of measurement instruments or repeated measurements from which a standard deviation can be derived) are readily available from the experimental documentation and their effects on k_{eff} are quantified in this section. For cases where needed

[5] Dean, V.F., editor. *ICSBEP Guide to the Expression of Uncertainties for Critical Experiments*. Revision 5. September 30, 2008.

information is not reported (such as impurities in materials, gaps between components in the assemblies), reasonable justification of their likely values is required with assumptions clearly stated. Sensitivity of k_{eff} to variation in each parameter whose uncertainty was not reported is calculated or otherwise estimated and provided. If the sensitivity shows that the effect of a rough but reasonable estimate of the uncertainty is negligible, the effect may be evaluated simply as "negligible." The evaluator should base the uncertainty estimate on an understanding of the physical phenomena causing the parameter to vary about its nominal value. If the phenomena involved are not within the scope of the evaluator's expertise, it is prudent to consult experts and/or the pertinent literature. In some cases, a standard uncertainty (i.e., approximate standard deviation[6]) of the parameter is estimated based on whatever information is obtainable, such as typical uncertainty of the parameter at the experimental facility at the time of the experiments, information from the manufacturer of the component or of the measuring device, and personal experience. The basis of the uncertainty estimate should be explained. The evaluator should resist any tendency to either overestimate or underestimate uncertainty.

For each subsection, the evaluator should be clear how the uncertainty in k_{eff} was derived. It should be clear what reference value, x_i, and what standard uncertainty, $\pm u_i$, was used for each parameter, and how they were derived based on data in Section 1.0 or justified by additional data introduced in this section. The parameter perturbation $\pm\delta x_i$ that was used should be clearly stated. Additional scaling factors (such as those derived from assumed parameter distributions) or normalization factors (such as dividing by the square root of the number of simultaneously varied parts) used should also be clearly stated. If a computational sensitivity method (such as through a code that calculates sensitivity coefficients to k_{eff} relative to each isotope's nuclear data contributions) is used, calculated sensitivity coefficients and their uncertainties should be provided to allow independent verification of the effect on k_{eff}.

Since performing a rigorous uncertainty analysis requires a lot of work, there is motivation to perform the task efficiently. The most efficient strategy for the uncertainty analysis is a graded approach in which the effort expended in quantifying an uncertainty component is roughly proportional to the contribution of the component to the total uncertainty. Little effort is warranted if a simple estimate shows that the uncertainty in the parameter makes a small contribution to the total uncertainty in k_{eff}. Conversely, a large contributor warrants careful consideration. If a potentially large contributor is one for which there is a lack of readily available information (a "questionable" uncertainty), then it must be further investigated through, for example, extra measurements or analysis, checking in logbooks and other reference documents, or interviews.

In instances where a benchmark presents many closely related cases, it may be possible to extend the uncertainty analysis completed for one case to a collection of cases. A good practice is to check the validity of this extension, particularly focusing on the uncertainties that have the largest impact on the total benchmark uncertainty.

It is convenient for the reader if all results are presented in the sections in which they are discussed. It is required to show the sensitivities of k_{eff} to the various parameters per unit measure or per perturbation used and with the sign (+ or –), to preserve in convenient form this outcome of the evaluation. If adjoint sensitivities are used, sensitivities must be given; if direct perturbations are used, Δk_{eff}s must be given with the size of the perturbation used. Alternatively, all of this information can be given in the concluding subsection of Section 2.

2.1 Evaluation of the k_{eff} Measurement Uncertainty

Uncertainties in the measured k_{eff} due to the measurement technique should be quantified in this section. For example, some critical experiments are actually measured at a slightly supercritical state, with reactor period

[6] See the *ICSBEP Guide to the Expression of Uncertainties.* Uncertainties specified in evaluations published after 2001 correspond to one standard deviation, 1σ. Uncertainties published prior to that date often do not adhere to that convention.

being the measured quantity. Converting a reactor period to k_{eff} introduces some additional uncertainty such as the fitting technique for the measured period and the reliance on uncertain nuclear data (delayed neutron parameters). Some configurations might have been disassembled and reassembled multiple times, providing reproducibility measurements that provide additional uncertainty information on the measured configuration, although it is important to provide details about the specifics of the reproducibility measurements so it is clear they provide an adequate assessment of this uncertainty (all pieces positioned in exactly the same location, same orientation, etc.).

2.2 Dimensional Uncertainties

Uncertainties in the dimensions of parts used to assemble a critical configuration should be quantified in this section. In some instances, many similar parts might have been used to create an assembly and an average part was generated for the computational model. Uncertainties would come from the standard deviation of dimensional measurements and uncertainties due to the precision of the measurement technique. In cases without direct measurements, dimensional drawings and tolerances are used to determine the standard uncertainty of part dimensions. Some common dimensional uncertainties are the following:

- Fuel dimensions
  - radius or widths
  - height
- Cladding dimensions
  - radius or widths
  - thickness
- Critical water or solution height
- Tank dimensions
  - inner radius or widths
  - wall thickness
- Detector or other structure placement and dimensions
- Source geometry and placement
- Reflector dimensions
  - thickness
- Control/safety-rod or absorber
  - dimensions
- Relevant surroundings (including room walls)

2.3 Mass Uncertainties

Uncertainties in the masses of parts used to assemble a critical configuration should be quantified in this section. If the mass is unknown, an assumed or evaluated density uncertainty can be propagated instead of a mass uncertainty.. In some instances, many similar parts might have been used to create an assembly and an average part was generated for the computational model. Uncertainties would come from the standard deviation of mass measurements and uncertainties due to the precision of the measurement technique. In cases without direct measurements, expected densities and dimensional drawings and tolerances can be used to determine the standard uncertainty due to mass. As many systems are very sensitive to fissionable mass and expected densities can have large variation, it is very important to know the masses of the fissionable parts. Some configurations are also very sensitive to other materials in the configuration (such as absorbers in thermal systems or moderating materials in undermoderated systems), so having high-fidelity mass and/or density measurements is important to limit benchmark uncertainties.

2.4 Composition Uncertainties

Uncertainties in the compositions of parts used to assemble a critical configuration should be quantified in this section. Uncertainties examined are generally due to isotopics, alloy or chemical compositions, and impurities for the fuel, as well as alloy or chemical compositions and impurities for other assembly components. Fuel impurities can have a significant impact, either due to inclusion of a neutron absorber or simply from the reduction of fissioning mass. Uncertainties would come from the reported measurement uncertainty of the chemical or radiological analysis. In some cases, material characterization data does not exist for an assembly component and details have to be inferred based on the reported alloy, with generally larger uncertainties in the exact material compositions due to allowed alloy variations. Some common composition uncertainties are the following:

- Fuel
  - composition, including impurities
  - isotopics
- Cladding
  - composition, including impurities
- Structural components
  - composition, including impurities
- Reflector
  - composition, including impurities
- Absorber
  - composition, including impurities
- Moderator
  - composition, including impurities

2.5 Positional Uncertainties

Uncertainties in the positions of parts used to assemble a critical configuration should be quantified in this section. For lattice assemblies, fuel pitch and spacing of fissile units can be a driving uncertainty. Additional guidance on pitch uncertainty can be found in the ICSBEP Guide the Expression of Uncertainties.[7] For an assembly of stacked parts, small gaps will exist even in the most careful assembly of independent parts. Measurements of overall dimensions of an assembly are invaluable in quantifying these small gaps in the assembly. Other positioning uncertainties could come into play if fuel is being moved into position during an approach to critical and the final critical insertion position has an uncertainty. If measured data to inform positional uncertainties are not available, then a reasonable estimate of the uncertainty should be provided and evaluated.

2.6 Temperature Uncertainties

Uncertainties in the temperatures reported during a critical experiment should be quantified in this section. As nuclear cross sections are temperature dependent, generally the temperature of the experiment or ambient temperature is reported. The location and representativity of the temperature measurement to the experimental assembly should be assessed. Temperature uncertainties are generally due to the accuracy of the measurement device, and if not reported in the experimental reports, should be estimated by the evaluator. Special attention should be given to assemblies that generate heat due to radioactive decay of the components, such as plutonium

[7] Dean, V.F., editor. *ICSBEP Guide to the Expression of Uncertainties for Critical Experiments*. Revision 5. September 30, 2008.

systems. Systems near critical generally do not have appreciable heating due to fission. The effect of temperature uncertainties should be assessed in terms of its effect on material density (e.g. thermal expansion or contraction) and nuclear cross sections, if applicable.

2.X Any Additional Uncertainties

Any additional uncertainties in the experimental data should be quantified in this section.

2.XX Summary of Uncertainties

At the end of Section 2, a summary table showing effects on k_{eff} of the standard uncertainties is presented. It is recommended to also show sensitivities of k_{eff} to the various parameters per unit measure or per deviation used and with the sign (+ or -), to preserve in convenient form this outcome of the evaluation. This information is not required to be present in the summary table if all the required sensitivities, perturbations, Δk_{eff}s, etc. are given in the section in which they are evaluated. However, at a minimum the summary table should give the k_{eff} uncertainty derived in each section or subsection of Section 2. At the bottom, the table concludes with the total combined uncertainty in k_{eff}, which is defined as the individual uncertainty effects combined with the measurement uncertainty of the experimentally measured value of k_{eff}. Summary table uncertainties need to sum in quadrature to the total uncertainty presented. Tables 2 and 3 show excerpts from uncertainty tables with pertinent information included to provide examples of formatting. In the example Table 2, all the data associated with the uncertainties are given in the section in which they are discussed and only a summary is presented in this section. Table 3 shows an excerpted table (redacted for length) that includes all pertinent information about each uncertainty and the quadrature sum of all uncertainties at the bottom of the table.

Table 2: Example Uncertainty Table from HEU-MET-FAST-028, Rev. 3[8]

Parameter	k_{eff} Uncertainty	k_{eff} Uncertainty as pcm
Criticality Measurement	± 0.000068	± 6.8
HEU Core Mass	± 0.000649	± 64.9
Full Cap Mass	± 0.000008	± 0.8
Stationary Reflector Mass	± 0.000645	± 64.5
Safety Block A Mass	± 0.000345	± 34.5
Safety Block B Mass	± 0.000346	± 34.6
Control Rod E Mass	± 0.000012	± 1.2
Control Rod F Mass	± 0.000034	± 3.4
Control Rod G Mass	± 0.000006	± 0.6
NU Mass Adjustment Button Mass	± 0.000011	± 1.1
HEU Core Dimensions	± 0.000151	± 15.1
Full Cap Dimensions	± 0.000043	± 4.3
HEU Mass Adjustment Button Dimensions	± 0.000010	± 1.0
Glory Hole Filler Pieces Dimensions	± 0.000011	± 1.1
Stationary Reflector Dimensions	± 0.000050	± 5.0
Safety Block Dimensions	± 0.000019	± 1.9
Control Rod Dimensions	± 0.000008	± 0.8
Pedestal Adapter Dimensions	± 0.000036	± 3.6
Pedestal Base Dimensions	± 0.000018	± 1.8
Reflector Sleeve Dimensions	± 0.000009	± 0.9
NU Mass Adjustment Button Dimensions	± 0.000007	± 0.7
Reflector Adapter Ring Dimensions	± 0.000006	± 0.6
Lifting Fixture Plug Dimensions	± 0.000024	± 2.4
Brass Pedestal Base Dimensions	± 0.000023	± 2.3
Stationary Reflector Base Dimensions	± 0.000005	± 0.5
Safety Block Spacer Dimensions	± 0.000018	± 1.8
Steel Pedestal Base Dimensions	± 0.000031	± 3.1
Uranium Impurities	- 0.000035	- 3.5
HEU Core Composition	± 0.000731	± 73.1
Safety Block Movement	- 0.000188	- 18.8
Control Rod E Insertion	- 0.000038	- 3.8
Control Rod F Insertion	- 0.000070	- 7.0
Control Rod G Insertion	- 0.000028	- 2.8
Glory Hole Piece Alignment	± 0.000093	± 9.3
Pedestal Seating Position	± 0.000006	± 0.6
Vertical Reflector Position	± 0.000016	± 1.6
Total	+0.001287 / -0.001304	+ 128.7 / - 130.4

[8] Stolte, K. "Uranium-235 Sphere Reflected by Normal Uranium Using Flattop, HEU-MET-FAST-028, Rev. 3." in *International Handbook of Evaluated Criticality Safety Benchmark Experiments.* Paris: NEA 7645, OECD Nuclear Energy Agency, 2024

Table 3: Example Uncertainty Table Excerpt from PU-MET-THERM-004, Rev. 0.[9]
Parts of the table have been redacted for length.

Source of Uncertainty	Parameter Value used	Parameter Variation in Calculation	Calculated Effect $k_{eff+} - k_{eff-}$	Standard Uncertainty of Parameter [A or B]	N	Standard Uncertainty in k_{eff}
Mass Uncertainties						
Plutonium Core Mass	105.405 g	±0.20 g	0.00044	0.20 g [B]	1	0.00022
Plutonium Mass Distribution	16 Heavy/Light Plates	n/a	n/a	n/a [B]	1	0.00009
Stainless Steel Cladding Mass	24.764 g	±0.40 g	0.00034	0.40 g [B]	1	0.00017
Table Redacted for Length						
Measurement Uncertainties						
Calculational	Varies	± 1σ	n/a	n/a [B]	1	0.00001
Repeatability	n/a	n/a	n/a	n/a [B]	1	0.00011
					Quadrature Sum	**0.00154**

9 Percher, C. et al. "TEX Plutonium Thermal Assemblies: Plutonium Aluminum Metal Alloy Plates with Thick Polyethylene and Polymethyl Methacrylate (Lucite) Moderators, PU-MET-THERM-004, Rev. 0." in *International Handbook of Evaluated Criticality Safety Benchmark Experiments.* Paris: NEA 7645, OECD Nuclear Energy Agency, 2024.

3.0 BENCHMARK SPECIFICATIONS

Section 3 General Guidelines

The benchmark specifications provide the information necessary to construct calculational models that best represent the evaluated benchmark experiment without reference to other sections in the evaluation. Section 3 must be able to stand alone with all necessary information needed to derive the benchmark model and results duplicated from other sections as necessary. The benchmark model specifications should retain as much detail as necessary to preserve all important aspects of the actual benchmark experiment from Section 2. When it is necessary or desirable to simplify the representation of the experiment for the benchmark model, this section must include descriptions of the transformations from the evaluated benchmark experiment to the benchmark model and must provide the effect of the transformation on the benchmark model result. All benchmark model values provided in Section 3 must be given in appropriate SI units.

The benchmark specifications include a description of simplifications made to create the benchmark model (Section 3.1.1); the simplification effect on the benchmark result (Section 3.1.2); complete and concise description of the benchmark model geometry in a code-agnostic manner (Section 3.2); complete and concise description of the benchmark model materials (Section 3.3); the temperature(s) of the benchmark model (Section 3.4); and the benchmark result and its evaluated uncertainty (Section 3.5). An optional Section 3.6 is available for the discussion of correlations between measurements and other benchmark evaluations.

A benchmark model is typically prepared with a specific purpose, e.g. validation of calculation methods, codes, or nuclear data. More than one benchmark model can be prepared from a single benchmark experiment. A detailed benchmark model (though still simplified compared with the benchmark experiment) is suitable for some calculation methods. A simple benchmark model is suitable for other calculation methods and is typically obtained by simplification of the detailed benchmark model. The provided benchmark specifications may refer to a single benchmark but also applies to each of a larger number of benchmarks in the evaluation. For evaluations with multiple cases, the case numbers in Section 3 need to be consecutive, start with Case 1, and may not necessarily be identical to the numbering in Sections 1 and 2.

It is good practice for the completeness and consistency of the benchmark model to be verified by calculations based only on the model description provided in Section 3. One or more representative end-users of the benchmark, e.g. the external reviewer, is valuable for such verification. The results may be provided in Section 4 when completed using a different code/data library than the original evaluator.

3.1 Description of Model

This section begins by providing all codes and data used for calculations of simplification effects and their uncertainties. This also includes any necessary parameters used in setting up the calculation, e.g. total generations, particles per generation, spatial mesh sizes, angular quadrature, etc.

Section 3.1 (or sub-subsection) provides a description for simplifications applied to create the benchmark model including geometry, material compositions, or physical setting. Figures showing the simplifications can be provided for clarity as needed. Evaluator judgement should be used in determining the appropriate simplifications related to the computational code utilized. If correlations between experiments are utilized to inform the simplifications, those correlations should be discussed.

If the method of calculating atom densities uses values other than the recommended nuclear constants list (see Nuclear Constants appendix at the end of this guide), the constants are provided in an appendix to the benchmark evaluation and referenced in this section. Any simplification to a temperature, e.g. 20 °C, to allow direct use of nuclear data library values, needs to be discussed and its effect evaluated.

Section 3.1.2 quantifies any resulting simplification effects and associated uncertainties in k_{eff}. Their combined effects are propagated to the final benchmark $k_{eff,}$ and its associated uncertainty to be specified in Section 3.5. The quantification of the simplification effects should be done in such a way that the sign of the effect is preserved as the effect will be added to the experimental k_{eff} in Section 3.5. These simplifications are expected to have a small impact on both the $k_{eff,}$ and the expected neutron spectra of the benchmark model compared with the Section 2 benchmark experiment.

3.2 Dimensions

All required dimensions and information needed to exactly, completely, and consistently describe the geometry of the benchmark model(s) are included in this section without reference to any other sections of the benchmark. Labeled overview images of the benchmark model should be provided here. Specifications, provided in the appropriate SI units, are derived from reported values given in previous sections. The effects of rounding of values from unit conversions and measurement readings on the final benchmark result should be negligible. Dimensions may be provided in a figure, table, or both. Sketches, which do not have to be to scale, of the benchmark model(s) should always be included with, ideally, consistent coloration for part/material used throughout. Sketches can be created from code renderings, CAD programs, or other legible manners. The Reviewer Checklist should be consulted to ensure all dimensions are accounted for in the description. An example of a properly labeled figure is provided in Figure 1.

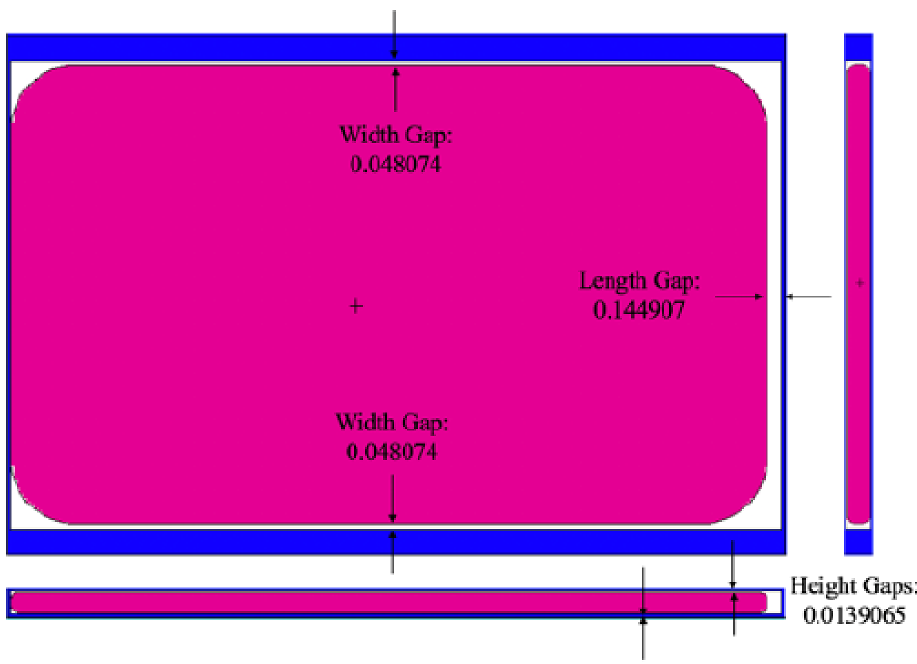

Figure 1. Labeled Figure of Plutonium Core Gaps in a PANN ZPPR Plate from PU-MET-MIXED-003, Rev. 0.[10]

[10] Percher, C. et al. "TEX Plutonium Assemblies with Tantalum: Plutonium Aluminum Metal Alloy Plates with Varying Thicknesses of Polyethylene Moderator, Interstitial Tantalum and a Thin Polyethylene Reflector, PU-MET-MIXED-003, Rev. 0." in *International Handbook of Evaluated Criticality Safety Benchmark Experiments.* Paris: NEA 7645, OECD Nuclear Energy Agency, 2024.

3.3 Material Data

Material densities, mass fractions of the constituents, and calculated atom densities for all materials specified for the benchmark model(s) are concisely listed here. It is preferred to report all mass fractions and atom densities broken down into their isotopic constituents (using the natural abundances listed in the Nuclear Constants appendix to this guide), and this isotopic specification is required for enriched materials and elements that might have natural variations (such as boron). If instead a natural element is specified the full isotopic composition is assumed to be standardized (as specified in the Nuclear Constants section of this guide). For other elements, e.g. enriched (^{235}U) uranium and enriched boron (^{10}B), the isotopic compositions need to be specified. Lists are broken into subheadings such as core, structural, and reflector materials. If the method of deriving atom densities uses values other than the nuclear constants listed in this guide, the constants are provided in an appendix and referenced here. Unique or complicated formulas for deriving atom densities are provided. Atom densities and mass fractions are listed in scientific notation with five significant digits as shown in the example in Table 4. If using mass fractions, the material density must also be specified.

Table 4. Example Composition Table for Stainless Steel 304 Taken from *PNNL-15870, Rev. 2*.[11]

Element/Isotope	Atom Density [1/(b·cm)]	Mass Fraction
C	3.2200E-04	8.0000E-04
Mn-55	1.7600E-03	2.0000E-02
P-31	7.0000E-05	4.5000E-04
S	4.5000E-05	3.0000E-04
Si	1.7220E-03	1.0000E-02
Cr	1.7671E-02	1.9000E-01
Ni	7.8270E-03	9.5000E-02
Fe	5.9182E-02	6.8345E-01
Total	8.8599E-02	1.0000E+00

3.4 Temperature Data

The temperature of the benchmark model is provided in this section. If using different temperatures for different components, that is specified here. If the measured temperature or temperature distribution from Section 2 was simplified to an arbitrary standard temperature (related to nuclear data libraries) of the benchmark model, the simplification is reported in Section 3.1.1. The simplification effect is evaluated in Section 3.1.2. Evaluator judgement should be used in determining a useful temperature or temperature distribution.

3.5 Experimental and Benchmark-Model k_{eff} and/or Subcritical Parameters

The evaluated benchmark experiment k_{eff}, here referred to as k_{E} and its uncertainty u (propagated from measurement parameter uncertainties) from Section 2 are reiterated in Section 3.5. Additional nomenclature to be used in Section 3.5:

- $\Delta k_{\mathrm{B\text{-}E}}$: k_{eff} of the evaluated simplification effect from Section 3.1, typical expressed as a change in k_{eff},
- k_{B}: k_{eff} of the evaluated, conceptual benchmark model described in Section 3.2, 3.3, and 3.4, which is calculated as $k_B=k_E + \Delta k_{B\text{-}E}$, and
- u_+ and u_-: standard uncertainty above and below the mean for non-normal uncertainty distributions.

[11] Detwiler, Rebecca S., et al. *Compendium of material composition data for radiation transport modeling*. No. PNNL-15870-Revision-2. Pacific Northwest National Lab (PNNL), Richland, WA (United States), 2021.

For experimentally derived uncertainties, a Δk_{eff} is provided. If Δk_{eff} is given as a reactivity, β_{eff} is also provided. An uncertainty is usually specified as having a normal distribution represented by a standard uncertainty, u. Asymmetric or other non-normal uncertainty distributions sometimes need to be preserved in the benchmark result. Such uncertainty distributions could sometimes be specified with different standard uncertainties in the positive and negative directions from the mean value. The different standard uncertainties below and above the mean value may be specified using the symbols u_- and u_+.

To obtain the final benchmark model uncertainty, the standard uncertainties from the benchmark experiment and the simplification effects are added in quadrature. An example table is provided in Table 5, with numerical data from HEU-MET-FAST-102, Rev. 0.

Table 5. Example Table of Benchmark Results Adapted from HEU-MET-FAST-102, Rev. 0.[12]

Case	Benchmark Experiment[(a)]			Simplification Effect[(b)]			Benchmark Model[©]		
	k_E	u_-	u_+	Δk_{B-E}	u_-	u_+	k_B	u_-	u_+
1	1.00456	0.00222	0.00094	-0.00116	0.00018	0.00018	1.00340	0.00223	0.00095
2	1.00427	0.00228	0.00088	-0.00109	0.00018	0.00018	1.00318	0.00228	0.00090
3	1.00315	0.00222	0.00095	-0.00118	0.00018	0.00018	1.00197	0.00222	0.00096
4	1.00236	0.00219	0.00097	-0.00118	0.00018	0.00018	1.00118	0.00220	0.00099

(a) Experiment k_{eff} and its asymmetric uncertainty distribution is carried forward from Section 2.
(b) Simplification effect is evaluated in Section 3.1.2.
(c) Benchmark k_{eff} is calculated from the two preceding columns ($k_B = k_E + \Delta k_{B-E}$).

Additional benchmark results of interest, such as spectral ratio, variance-to-mean, decay constant, or count-rate ratio values and their uncertainties, in general, should be included for subcritical benchmarks, as well as the interpreted benchmark k_{eff} values.

3.6 <u>Experimental and Simplification Correlations between Benchmarks</u>

Section 3.6 is an optional subsection that can be added at the discretion of the evaluator. The methodology used to assess these correlations needs to be fully described herein. Some discussion of methodology is provided in the Uncertainty Guide for ICSBEP. The correlations assessed may be between benchmarks in the same evaluation or between different evaluations.

A correlation between two measurement parameters or between two simplification procedures is specified by the correlation factor r, which can vary from -1 to 1. Only correlations that are expected to be significant for some end-users of the benchmarks should be documented in Section 3.6.

In addition to the correlation factor r, the uncertainties of each correlated parameter or procedure should be provided for each correlated benchmark. The k_{eff} sensitivity to a perturbation of the correlated parameter or procedure is needed for each correlated benchmark. Finally, an identification name for the correlated parameter or procedure is needed in each correlated benchmark.

[12] Amundson, K. et al. "ZEUS: Fast-Spectrum Critical Assemblies with a Pb-HEU Core Surrounded by a Copper Reflector, HEU-MET-FAST-102." in *International Handbook of Evaluated Criticality Safety Benchmark Experiments.* Paris: NEA 7645, OECD Nuclear Energy Agency, 2024.

4.0 RESULTS OF SAMPLE CALCULATIONS

For minor revisions, and if relevant, results from Section 4 may be carried along to the next revision. For a major revision, Section 4 should be revisited (recalculated). A subdirectory will be provided on the ICSBEP Handbook to preserve older legacy files, such as was done for Jezebel (PU-MET-FAST-001) and Flattop (HEU-MET-FAST-028).

It is highly recommended to include calculated results obtained by any reviewers (internal, external, or the TRG) who used a different code or nuclear data.

GENERAL GUIDELINES

Calculated results obtained with the benchmark-model specification data given in Section 3 are tabulated in this section. These are regarded as only “sample calculations” because codes often have several options available for representing the same benchmark-model configuration, and because details of input listings are not thoroughly reviewed. Choice of appropriate code input to represent the benchmark model described in Section 3 is the responsibility of the user of the evaluation. As such, any deviation(s) from the benchmark model description must be documented in this section along with the computed results.

Codes and cross section data sets used for the sample calculations are indicated in Section 4, but details about the calculations and input listings can be given in Appendix A. At least one input deck per case and per code used is requested to be included in the appendix. Results should be organized as shown in Table 6. Note that the format of the table bordering and shading is not mandatory, but the provision of eigenvalue data in the prescribed format is required. This is the only table in the entire document that has a minimum required organization structure. Results should include calculated and/or propagated uncertainties. Additional calculations, and discussion, provided in text, tables, and/or figures can be provided once the minimum expectation is met with k_{eff} values computed for each case number using identified codes and nuclear data libraries. If a table gets too large, it is acceptable to break it and repeat with additional information below each other. Do not repeat the benchmark k_{eff} value in this table.

Table 6. Sample Calculation Results.

Case Number	Code Name (Cross Section Name)	Code Name (Cross Section Name)	Code Name (Cross Section Name)
1	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$
2	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$
3	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$

Table 6 (continued). Sample Calculation Results.

Case Number	Code Name (Cross Section Name)	Code Name (Cross Section Name)	Code Name (Cross Section Name)
1	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$
2	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$
3	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$	$k_{eff} \pm 1\sigma$

The case numbers must be sequential. Other identifiers or identifying information such as experiment IDs, density or reflector material may also be included in the table but are not required as they might clutter the organization of this table and create confusion.

It is recommended to include calculated (C) versus experimental (E) values (such as C-E, C/E-1, or (C-E)/σ) either as a separate table or an additional column in the sample calculation results tables. Reactivity offset plots (such as can be seen in Section 4.0 of LEU-COMP-THERM-102) can also be beneficial in presenting and discussing the results.

Originally, results using specific codes and cross section data were required. Beginning with the 1997 edition of the handbook, selection of appropriate cross section data is left to the discretion of the evaluator. However, cross section data sets should be clearly identified and, for cases in which less well-known cross section data are used, a brief history discussing the development and intended use for the cross-section data set should be added to the appropriate section of Appendix A. Code versions are also discussed briefly in an introductory paragraph that precedes the input listings. At least one sample result should be presented using state-of-the-art nuclear data libraries and codes.

Exceptions to nuclides from the specified cross section data set shall be noted in footnotes to the table in which the results are presented. The person or persons who created the sample input listings or provided the calculation results, if not the evaluators, should also be acknowledged in a footnote to the results table.

Sample calculations for which exact representation of the benchmark model (Section 3) was not possible because of code limitations should be discussed in Section 4.

Calculated results that differ from the benchmark-model values (Section 3.5) by more than 1% or 3σ (whichever is smaller) should be noted and may be explained if the reasons are thought to be known.

The other benchmark model parameters given in Section 3.5 should be included for subcritical measurements as well as sample calculated eigenvalue results.

SPECTRAL CALCULATIONS

Evaluators can provide a file with detailed neutron spectra and absorption data. These data are not integrated directly into the evaluation format, but they can be accessed directly from the first page of each evaluation for which spectra data are available. (The word "spectra" appears to the right of the evaluation identifier near the top of page 1 and is electronically linked to the spectra data for that specific evaluation.) These data enable criticality safety practitioners to understand more clearly the range of applicability for the experimental configurations that are published in the handbook.

The required data for spectra files are:

1. the energy corresponding to the average neutron lethargy causing fission, *EALF (eV)*. The average neutron lethargy causing fission is defined for group calculations by

$$\overline{u} = \frac{\sum_m \sum_g (\overline{u}_g \times \Sigma_{\mathrm{fg}}^m \varphi_g^m)}{\sum_m \sum_g \Sigma_{\mathrm{fg}}^m \varphi_{\mathrm{fg}}^m},$$

where m is a physical zone inside the core; $\overline{u}_g$ is the midpoint of the g^{th} lethargy group, defined as lethargy of neutron with energy $\overline{E_g} = \sqrt{E_g E_{g-1}}$; Σ_{fg} is the group macroscopic fission cross section; and φ_g^m is the integral neutron flux in physical zone m and within lethargy group g.

Lethargy u of a neutron with energy E is defined as $\ln\left(\frac{E_0}{E}\right)$, where E_0 indicates maximum neutron energy, in this case, 10 MeV. Therefore, $\text{EALF} = \frac{E_0}{e^{\overline{u}}}$;

2. the average neutron energy causing fission, AFGE (eV), defined for group calculations by linear interpolation between energies of the upper and lower group boundaries

$$\text{AFGE} = \frac{\sum_m \sum_g (E_g \times \Sigma_{\text{fg}}^m \varphi_g^m)}{\sum_m \sum_g \Sigma_{\text{fg}}^m \varphi_{\text{fg}}^m},$$

where E_g is the midpoint of the g^{th} energy group, and other quantities are as previously defined (Energy-group boundaries are at the same energies as lethargy-group boundaries. A 299-energy-group structure is used.);

3. the neutron gas temperature (T_n) in the thermal energy range for group calculations, defined as

$$T_n = \frac{\pi}{4}\left(\frac{\sum_m \sum_g \varphi_g^m}{\sum_m \sum_g \sigma_g \, \varphi_{\text{fg}}^m}\right)^2 T_0 {\sigma_0}^2$$

where $\sigma_g = \sigma_0 \sqrt{\frac{E_0}{\overline{E}_g}}$; T_0 = 293.6 K; σ_0 is the cross section at E_0 = 0.0253 eV (v = 2 200 m/s, T = 293.6 K); and φ_g is the neutron flux in the groups collapsed into the thermal group (E < 0.625 eV). Thus,

$$T_n = 9114.3\left(\frac{\sum_m \sum_g \varphi_g^m}{\sum_m \sum_g \frac{\varphi_g^m}{\sqrt{\overline{E}_g}}}\right)^2, \text{ where } \overline{E}_g = \sqrt{E_g E_{g-1}};$$

4. the percentage of the neutron flux, fissions and captures that occur in the fast (Energy >100 keV), intermediate (0.625 eV ≤ Energy ≤ 100 keV) and thermal (Energy <0.625 eV) energy ranges (Please note that for heterogeneous cores, there is often a significant difference between the core-averaged flux and the flux within each separate region. For such heterogeneous cores, the flux within each region may be provided in addition to the core-averaged flux.);

5. the percentage of fissions and captures by isotope over the core region;

6. the average fission neutrons produced per neutron absorbed in the core, ($\nu\Sigma_f/\Sigma_a$);

7. a plot of the neutron spectrum for bounding cases in each evaluation;

8. the percentage of the neutron flux, fissions, and captures that occur in the thirty-group structure given in Table 7.

Table 7. 30-group energy structure

Group	Lower Energy (eV)	Upper Energy (eV)	Group	Lower energy (eV)	Upper energy (eV)
1	6.50E+06	2.00E+07	16	2.15E+02	4.64E+02
2	4.00E+06	6.50E+06	17	1.00E+02	2.15E+02
3	2.50E+06	4.00E+06	18	4.64E+01	1.00E+02
4	1.40E+06	2.50E+06	19	2.15E+01	4.64E+01
5	8.00E+05	1.40E+06	20	1.00E+01	2.15E+01
6	4.00E+05	8.00E+05	21	4.64E+00	1.00E+01
7	2.00E+05	4.00E+05	22	2.15E+00	4.64E+00
8	1.00E+05	2.00E+05	23	1.00E+00	2.15E+00
9	4.64E+04	1.00E+05	24	4.64E-01	1.00E+00
10	2.15E+04	4.64E+04	25	2.15E-01	4.64E-01
11	1.00E+04	2.15E+04	26	1.00E-01	2.15E-01
12	4.64E+03	1.00E+04	27	4.64E-02	1.00E-01
13	2.15E+03	4.64E+03	28	2.15E-02	4.64E-02
14	1.00E+03	2.15E+03	29	1.00E-02	2.15E-02
15	4.64E+02	1.00E+03	30	1.00E-05	1.00E-02

5.0 REFERENCES

All formally published and publicly available documents (e.g., laboratory reports, journal articles, etc.) referenced in the evaluation that contain relevant information about the experiments are listed. References to handbooks, logbooks, code manuals, textbooks, personal communications with experts, etc. are not included in this section but are given in footnotes where applicable in the document. Footnotes can also include unpublished and/or not publicly available laboratory reports. References used for calculations and methods in the evaluation are also considered footnotes.

If no formal references are available, include the following text in Section 5.0: “There are no official references for the experimental measurements.”

APPENDICES

Supplemental information that is useful, but is not essential, to the derivation of the benchmark specification is provided in appendices. Appendices are labeled using letters (e.g., Appendix A). Appendix A always provides typical input listings of the sample calculations.

APPENDIX A: TYPICAL INPUT LISTINGS

Brief comments about options chosen for calculations are included in an introductory paragraph. Any small differences from the benchmark-model specifications in Section 3 are noted. This paragraph states the version of the code (e.g., KENO-VI, MONK12A, MCNP6.3, MVP, OPEN-MC, Serpent, etc.) that was used for the calculations and additional information including:

S_N Codes

Quadrature order (i.e., N)

Scattering order for cross sections (P_1, P_2, P_3, etc.; corrected or not corrected for higher-order effects)

Convergence criteria for eigenvalue and flux

Representative mesh size (cm)

Monte Carlo Codes

Number of active generations

Number of skipped generations

Number of histories per generation or total number of histories

Unique and/or important features regarding 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.

Primary codes used in the analyses should be included here; additional codes and inputs should be summarized in a subsequent appendix. When multiple code systems are used, input listings are grouped by code system in the order established by that country (e.g., A.1 **KENO Input Listings**, A.2 **MCNP Input Listings**, A.3 **ONEDANT/TWODANT Input Listings, etc.**).

NUCLEAR CONSTANTS

Atomic densities are based on a set of basic nuclear constants and it is thus important to know which values were used in an evaluation to ensure consistent material definitions. Historically, until 2025, all nuclear constants used for ICSBEP were required to be taken from "Nuclides and Isotopes," Fourteenth Edition, General Electric Nuclear Energy Operations, 1989 (provided below in Table B.1). The atomic weights and Avogadro's number were required to be rounded to facilitate consistency among evaluations. Starting in 2026, evaluator(s) can use their preferred data source for these values but must provide the source of these data and also provide in an appendix the exact atomic weights and isotopic abundances used to compute atomic densities, as these change slightly over time and may be rounded differently. 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, these atomic densities should be reported in an appendix.

Some example resources for more recent sources of atomic and abundance data are provided below.

Internationally used atomic weights are provided by the Atomic Mass Evaluation (AME) database.

- The latest edition of the database is AME2020: https://doi.org/10.1088/1674-1137/abddaf
- The data is freely accessible online through:
    - International Atomic Energy Agency (IAEA): https://www-nds.iaea.org/amdc/
    - Argonne National Laboratory (ANL): https://www.anl.gov/phy/atomic-mass-data-resources

Internationally used isotopic abundances are provided by the International Union of Pure and Applied Chemistry (IUPAC) "Isotopic Compositions of the Elements" report.

- The latest edition of this report is 2013: https://doi.org/10.1515/pac-2015-0503
- The data is freely accessible online through the Commission on Isotopic Abundances and Atomic Weights (CIAAW): https://www.ciaaw.org/isotopicabundances.htm

$$\text{Avogadro's Number} = 6.0221 \times 10^{23} \text{ atoms/mol}$$

TABLE B.1. Atomic Weights and Isotopic Abundances from 14th Edition "Nuclides and Isotopes".

Nuclide or Isotope	Atomic Weight [(a)]	Isotopic Abundance (%)
H	1.0079	—
^{1}H	1.0078	99.985
^{2}H	2.0141	0.015
He	4.0026	—
^{3}He	3.0160	0.000138
^{4}He	4.0026	99.999862
Li	6.941	—
^{6}Li	6.0151	7.5
^{7}Li	7.0160	92.5
Be	9.0122	—

Nuclide or Isotope	Atomic Weight [(a)]	Isotopic Abundance (%)
^{9}Be	9.0122	100
B	10.811	—
^{10}B	10.0129	19.9
^{11}B	11.0093	80.1
C	12.011	—
^{12}C	12.0000	98.90
^{13}C	13.0034	1.10
N	14.0067	—
^{14}N	14.0031	99.63
^{15}N	15.0001	0.37
O	15.9994	—
^{16}O	15.9949	99.76
^{17}O	16.9991	0.04
^{18}O	17.9992	0.20
F	18.9984	—
^{19}F	18.9984	100
Ne	20.180	—
^{20}Ne	19.9924	90.48
^{21}Ne	20.9938	0.27
^{22}Ne	21.9914	9.25
Na	22.9898	—
^{23}Na	22.9898	100
Mg	24.3050	—
^{24}Mg	23.9850	78.99
^{25}Mg	24.9858	10.00
^{26}Mg	25.9826	11.01
Al	26.9815	—
^{27}Al	26.9815	100
Si	28.0855	—
^{28}Si	27.9769	92.23
^{29}Si	28.9765	4.67
^{30}Si	29.9738	3.10
P	30.9738	—
^{31}P	30.9738	100
S	32.07	—
^{32}S	31.9721	95.02
^{33}S	32.9715	0.75
^{34}S	33.9679	4.21
^{36}S	35.9671	0.02
Cl	35.453	—
^{35}Cl	34.9689	75.77
^{37}Cl	36.9659	24.23

Nuclide or Isotope	Atomic Weight [(a)]	Isotopic Abundance (%)
Ar	39.948	—
^{36}Ar	35.9675	0.337
^{38}Ar	37.9627	0.063
^{40}Ar	39.9624	99.60
K	39.0983	—
^{39}K	38.9637	93.2581
^{40}K	39.9640[13]	0.0117
^{41}K	40.9618	6.7302
Ca	40.078	—
^{40}Ca	39.9626	96.941
^{42}Ca	41.9586	0.647
^{43}Ca	42.9588	0.135
^{44}Ca	43.9555	2.086
^{46}Ca	45.9537	0.004
^{48}Ca	47.9525	0.187
Sc	44.9559	—
^{45}Sc	44.9559	100
Ti	47.88	—
^{46}Ti	45.9526	8.0
^{47}Ti	46.9518	7.3
^{48}Ti	47.9479	73.8
^{49}Ti	48.9479	5.5
^{50}Ti	49.9448	5.4
V	50.9415	—
^{50}V	49.9472	0.250
^{51}V	50.9440	99.750
Cr	51.996	—
^{50}Cr	49.9460	4.345
^{52}Cr	51.9405	83.79
^{53}Cr	52.9407	9.50
^{54}Cr	53.9389	2.365
Mn	54.9380	—
^{55}Mn	54.9380	100
Fe	55.847	—
^{54}Fe	53.9396	5.9
^{56}Fe	55.9349	91.72
^{57}Fe	56.9354	2.1
^{58}Fe	57.9333	0.28
Co	58.9332	—
^{59}Co	58.9332	100
Ni	58.69	—

[13] National Nuclear Data Center, http://www.nndc.bnl.gov/amdc/masstables/mass.mas03round, accessed 17 June 2013.

Nuclide or Isotope	Atomic Weight (a)	Isotopic Abundance (%)
^{58}Ni	57.9353	68.27
^{60}Ni	59.9308	26.10
^{61}Ni	60.9311	1.13
^{62}Ni	61.9283	3.59
^{64}Ni	63.9280	0.91
Cu	63.546	—
^{63}Cu	62.9296	69.17
^{65}Cu	64.9278	30.83
Zn	65.39	—
^{64}Zn	63.9291	48.6
^{66}Zn	65.9260	27.9
^{67}Zn	66.9271	4.1
^{68}Zn	67.9248	18.8
^{70}Zn	69.9253	0.6
Ga	69.723	—
^{69}Ga	68.9256	60.11
^{71}Ga	70.9247	39.89
Ge	72.61	—
^{70}Ge	69.9242	20.5
^{72}Ge	71.9221	27.4
^{73}Ge	72.9235	7.8
^{74}Ge	73.9212	36.5
^{76}Ge	75.9214	7.8
As	74.9216	—
^{75}As	74.9216	100
Se	78.96	—
^{74}Se	73.9225	0.9
^{76}Se	75.9192	9.1
^{77}Se	76.9199	7.6
^{78}Se	77.9173	23.6
^{80}Se	79.9165	49.9
^{82}Se	81.9167	8.9
Br	79.904	—
^{79}Br	78.9183	50.69
^{81}Br	80.9163	49.31
Kr	83.80	—
^{78}Kr	77.9204	0.35
^{80}Kr	79.9164	2.25
^{82}Kr	81.9135	11.6
^{83}Kr	82.9141	11.5
^{84}Kr	83.9115	57.0
^{86}Kr	85.9106	17.3

Nuclide or Isotope	Atomic Weight [a]	Isotopic Abundance (%)
Rb	85.4678	—
^{85}Rb	84.9118	72.16
^{87}Rb	86.9092	27.84
Sr	87.62	—
^{84}Sr	83.9134	0.56
^{86}Sr	85.9093	9.86
^{87}Sr	86.9089	7.00
^{88}Sr	87.9056	82.58
Y	88.9059	—
^{89}Y	88.9059	100
Zr	91.224	—
^{90}Zr	89.9047	51.45
^{91}Zr	90.9056	11.22
^{92}Zr	91.9050	17.15
^{94}Zr	93.9063	17.38
^{96}Zr	95.9083	2.80
Nb	92.9064	—
^{93}Nb	92.9064	100
Mo	95.94	—
^{92}Mo	91.9068	14.84
^{94}Mo	93.9051	9.25
^{95}Mo	94.9058	15.92
^{96}Mo	95.9047	16.68
^{97}Mo	96.9060	9.55
^{98}Mo	97.9054	24.13
^{100}Mo	99.9075	9.63
Ru	101.07	—
^{96}Ru	95.9076	5.54
^{98}Ru	97.9053	1.86
^{99}Ru	98.9059	12.7
^{100}Ru	99.9042	12.6
^{101}Ru	100.9056	17.1
^{102}Ru	101.9043	31.6
^{104}Ru	103.9054	18.6
Rh	102.9055	—
^{103}Rh	102.9055	100
Pd	106.42	—
^{102}Pd	101.9056	1.02
^{104}Pd	103.9040	11.14
^{105}Pd	104.9051	22.33
^{106}Pd	105.9035	27.33
^{108}Pd	107.9039	26.46

Nuclide or Isotope	Atomic Weight [a]	Isotopic Abundance (%)
^{110}Pd	109.9052	11.72
Ag	107.8682	—
^{107}Ag	106.9051	51.839
^{109}Ag	108.9048	48.161
Cd	112.41	—
^{106}Cd	105.9065	1.25
^{108}Cd	107.9042	0.89
^{110}Cd	109.9030	12.49
^{111}Cd	110.9042	12.8
^{112}Cd	111.9028	24.13
^{113}Cd	112.9044	12.22
^{114}Cd	113.9034	28.73
^{116}Cd	115.9048	7.49
In	114.82	—
^{113}In	112.9041	4.3
^{115}In	114.9039	95.7
Sn	118.71	—
^{112}Sn	111.9048	0.97
^{114}Sn	113.9028	0.65
^{115}Sn	114.9033	0.36
^{116}Sn	115.9017	14.53
^{117}Sn	116.9030	7.68
^{118}Sn	117.9016	24.22
^{119}Sn	118.9033	8.58
^{120}Sn	119.9022	32.59
^{122}Sn	121.9034	4.63
^{124}Sn	123.9053	5.79
Sb	121.75	—
^{121}Sb	120.9038	57.4
^{123}Sb	122.9042	42.6
Te	127.60	—
^{120}Te	119.9040	0.095
^{122}Te	121.9031	2.59
^{123}Te	122.9043	0.905
^{124}Te	123.9028	4.79
^{125}Te	124.9044	7.12
^{126}Te	125.9033	18.93
^{128}Te	127.9045	31.70
^{130}Te	129.9062	33.87
I	126.9045	—
^{127}I	126.9045	100
Xe	131.29	—

Nuclide or Isotope	Atomic Weight [a]	Isotopic Abundance (%)
^{124}Xe	123.9059	0.10
^{126}Xe	125.9043	0.09
^{128}Xe	127.9035	1.91
^{129}Xe	128.9048	26.4
^{130}Xe	129.9035	4.1
^{131}Xe	130.9051	21.2
^{132}Xe	131.9041	26.9
^{134}Xe	133.9054	10.4
^{136}Xe	135.9072	8.9
Cs	132.9054	—
^{133}Cs	132.9054	100
Ba	137.327	—
^{130}Ba	129.9063	0.106
^{132}Ba	131.9050	0.101
^{134}Ba	133.9045	2.42
^{135}Ba	134.9057	6.593
^{136}Ba	135.9046	7.85
^{137}Ba	136.9058	11.23
^{138}Ba	137.9052	71.70
La	138.9055	—
^{138}La	137.9071	0.090
^{139}La	138.9063	99.910
Ce	140.115	—
^{136}Ce	135.9071	0.19
^{138}Ce	137.9060	0.25
^{140}Ce	139.9054	88.43
^{142}Ce	141.9092	11.13
Pr	140.9076	—
^{141}Pr	140.9076	100
Nd	144.24	—
^{142}Nd	141.9077	27.13
^{143}Nd	142.9098	12.18
^{144}Nd	143.9101	23.80
^{145}Nd	144.9126	8.30
^{146}Nd	145.9131	17.19
^{148}Nd	147.9169	5.76
^{150}Nd	149.9209	5.64
Sm	150.36	—
^{144}Sm	143.9120	3.1
^{147}Sm	146.9149	15.0
^{148}Sm	147.9148	11.3
^{149}Sm	148.9172	13.8

Nuclide or Isotope	Atomic Weight [a]	Isotopic Abundance (%)
^{150}Sm	149.9173	7.4
^{152}Sm	151.9197	26.7
^{154}Sm	153.9222	22.7
Eu	151.96	—
^{151}Eu	150.9198	47.8
^{153}Eu	152.9212	52.2
Gd	157.25	—
^{152}Gd	151.9198	0.20
^{154}Gd	153.9209	2.18
^{155}Gd	154.9226	14.80
^{156}Gd	155.9221	20.47
^{157}Gd	156.9240	15.65
^{158}Gd	157.9241	24.84
^{160}Gd	159.9270	21.86
Tb	158.9253	—
^{159}Tb	158.9253	100
Dy	162.50	—
^{156}Dy	155.9243	0.06
^{158}Dy	157.9244	0.10
^{160}Dy	159.9252	2.34
^{161}Dy	160.9269	18.9
^{162}Dy	161.9268	25.5
^{163}Dy	162.9287	24.9
^{164}Dy	163.9292	28.2
Ho	164.9303	—
^{165}Ho	164.9303	100
Er	167.26	—
^{162}Er	161.9288	0.14
^{164}Er	163.9292	1.61
^{166}Er	165.9303	33.6
^{167}Er	166.9320	22.95
^{168}Er	167.9324	26.8
^{170}Er	169.9355	14.9
Tm	168.9342	—
^{169}Tm	168.9342	100
Yb	173.04	—
^{168}Yb	167.9339	0.13
^{170}Yb	169.9348	3.05
^{171}Yb	170.9363	14.3
^{172}Yb	171.9364	21.9
^{173}Yb	172.9382	16.12
^{174}Yb	173.9389	31.8

Nuclide or Isotope	Atomic Weight [a]	Isotopic Abundance (%)
^{176}Yb	175.9426	12.7
Lu	174.967	—
^{175}Lu	174.9408	97.41
^{176}Lu	175.9427	2.59
Hf	178.49	—
^{174}Hf	173.9400	0.162
^{176}Hf	175.9414	5.206
^{177}Hf	176.9432	18.606
^{178}Hf	177.9437	27.297
^{179}Hf	178.9458	13.629
^{180}Hf	179.9465	35.100
Ta	180.9479	—
^{180}Ta	179.9475	0.012
^{181}Ta	180.9480	99.988
W	183.85	—
^{180}W	179.9467	0.12
^{182}W	181.9482	26.3
^{183}W	182.9502	14.28
^{184}W	183.9509	30.7
^{186}W	185.9544	28.6
Re	186.207	—
^{185}Re	184.9530	37.40
^{187}Re	186.9557	62.60
Os	190.2	—
^{184}Os	183.9525	0.02
^{186}Os	185.9538	1.58
^{187}Os	186.9557	1.6
^{188}Os	187.9558	13.3
^{189}Os	188.9581	16.1
^{190}Os	189.9584	26.4
^{192}Os	191.9615	41.0
Ir	192.22	—
^{191}Ir	190.9606	37.3
^{193}Ir	192.9629	62.7
Pt	195.08	—
^{190}Pt	189.9599	0.01
^{192}Pt	191.9610	0.79
^{194}Pt	193.9627	32.9
^{195}Pt	194.9648	33.8
^{196}Pt	195.9649	25.3
^{198}Pt	197.9679	7.2
Au	196.9665	—

Nuclide or Isotope	Atomic Weight [(a)]	Isotopic Abundance (%)
^{197}Au	196.9665	100
Hg	200.59	—
^{196}Hg	195.9658	0.15
^{198}Hg	197.9667	10.0
^{199}Hg	198.9683	16.9
^{200}Hg	199.9683	23.1
^{201}Hg	200.9703	13.2
^{202}Hg	201.9706	29.8
^{204}Hg	203.9735	6.85
Tl	204.3833	—
^{203}Tl	202.9723	29.52
^{205}Tl	204.9744	70.48
Pb	207.2	—
^{204}Pb	203.9730	1.4
^{206}Pb	205.9744	24.1
^{207}Pb	206.9759	22.1
^{208}Pb	207.9766	52.4
Bi	208.9804	—
^{209}Bi	208.9804	100
Th	232.0381	—
^{232}Th	232.0381	100
U	238.0289	—
^{232}U	232.0371	—
^{233}U	233.0396	—
^{234}U	234.0409	0.0055
^{235}U	235.0439	0.720
^{236}U	236.0456	—
^{238}U	238.0508	99.2745
^{237}Np	237.0482	—
^{238}Pu	238.0496	—
^{239}Pu	239.0522	—
^{240}Pu	240.0538	—
^{241}Pu	241.0568[14]	—
^{242}Pu	242.0587	—
^{241}Am	241.0568	—
^{243}Am	243.0614	—
^{242}Cm	242.0588	—
^{243}Cm	243.0614	—
^{244}Cm	244.0627	—

14 "Chart of the Nuclides," Thirteenth Edition, General Electric Company, 1984.

Nuclide or Isotope	Atomic Weight [(a)]	Isotopic Abundance (%)
^{245}Cm	245.0655	—
^{246}Cm	246.0672	—
^{247}Cm	247.0704	—
^{248}Cm	248.0723	—
^{252}Cf	252.0816	—

(a) Rounded values

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})

C Dancoff correction factor

D or Ø diameter (OD outer diameter; ID inner diameter)

Δ change in quantity (e.g., neutron multiplication factor, Δk; buckling, ΔB^2; tank height, ΔH; radius, ΔR; etc.)

H height

Ih inhour – The reactivity that will make the stable reactor period equal to 1 hour (3600 seconds).

k neutron multiplication factor - The subscripts "eff" and "∞" are used to denote the effective multiplication factor, k_{eff}, and the multiplication factor for an infinite system, k_∞, respectively.

m mass

M molarity (moles/ℓ)

M neutron multiplication $M \cong \frac{1}{1 - k_{eff}}$

M_w molecular weight or mass (g/mole)

mil $\frac{1}{1000}$ inch

mNile (mN) 1 pcm = 0.00001 $\Delta k/k$

N_A Avogadro's number [6.0221×10^{23} (atoms, molecules, etc.) per mole; 0.60221 (atoms, molecules, etc.)/(barn-cm-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)

R or r radius (OR outer radius; IR inner radius)

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

ρ_i density (g/cm³ 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., ρ_{U02N03}, ρ_{H20}, ρ_{Pu}, ρ_{HN03}).

pcm A unit used to measure reactivity from criticality. One pcm is equal to one-thousandth of a percent (0.00001 $\Delta k/k$)

σ or u uncertainty representing one standard deviation. σ_i or u_i is the standard deviation of parameter i; $\sigma_{k,i}$ or $u_{k,i}$ is the standard deviation of k_{eff} due to the standard deviation in parameter i.

σ_{MC} statistical uncertainty associated with Monte Carlo calculations

σ_p Hansen-Roach 16-energy-group cross section resonance correction; background potential-scatter cross section per absorber atom

σ_s scattering cross section

Σ macroscopic cross section (e.g., Σ_a, Σ_f, Σ_s, Σ_t are macroscopic absorption, fission, scattering, and total cross sections;).

V volume

V_f volume fraction

w_f weight fraction

wt.% weight percent

$\chi(E)$ fission spectrum

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