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

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English - Or. English

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

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Summary Information

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

General Format Guidelines

Final formatting, in terms of the document, including text, table and graphics, will be done by the publication staff. Evaluators are encouraged to follow the standard formatting guidelines outlined below, but should allow the publication staff to perform final formatting, to ensure consistency in evaluations contained within the Handbook. Publication templates will be used to ensure this consistency. Evaluations containing special/individual formatting functions, such as auto table/figure numbering, may interfere with the template styles and capabilities. Such special formatting functions should be avoided.

Note: Although final formatting will be done by the publication staff, evaluators should number tables and figures sequentially within sections (e.g., For Section 2 tables/figures, label as Table/Figure 2.1, 2.2, etc.). Authors of evaluations with unusually large numbers of figures and tables may, at their discretion, use additional levels of Table/Figure numbering (e.g., For Section 2 tables/figures, label as Table/Figure 2.1.1, 2.1.2, etc. or Table 2.1.1.1, 2.1.1.2, etc.); however numbering must be consistent throughout the evaluation and in no case should more than four levels be used.

General presentation guidelines that evaluators should follow are given below:

- *Paper size should be “A4”.*
- *Use 11-point, Times New Roman font for main text.*
- *Main text should be left-justified.*
- *Margins should be set as follows: top and bottom margins - .3 inches; left-hand margins – 1 inch; and right-hand margins - .8 inches.*

DOCUMENT FORMAT GUIDE**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))

| REACTOR TYPE | | FACILITY TYPE | | MEASUREMENT TYPE | |
|-------------------------------|-------|--------------------------------------|-------|---|--------|
| Pressurized Water Reactor | PWR | Experimental Facility ⁽¹⁾ | 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 | | | Isotopic Composition | ISO |
| Space Reactor | SPACE | | | Other Miscellaneous Types of Measurements | MISC |
| Fundamental ⁽²⁾ | FUND | | | | |

(1) Generally, experimental facilities are easily modified to represent a wide variety of core configurations and often criticality is achieved by a means other than control rod position (control rods are typically fully withdrawn). Facilities for which the primary focus is the production of integral-experiment data that support ex-core activities such as handling and storage of fissile material are also categorized as experimental facilities.

(2) Reactors or assemblies that are intended primarily to make fundamental physics measurements and do not support the design of a particular reactor type are categorized as Fundamental.

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
BUCK-RRATE-POWDIS

This identifier corresponds to the first evaluation of measurements made on the VENUS pressurized water reactor experimental facility. Buckling and extrapolation length, reaction rate, and power distributions 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. Keywords include the fissile material of the reactor as well as moderator and reflector materials (e.g., low-enriched uranium, light-water-moderated, graphite-reflected, unreflected).

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. It is recommended that only experimental data, 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, or evaluative statements in this section. 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, measured bounds), if known, should be noted.

Any inconsistencies in the data from different sources are mentioned. In addition to enough information that the derivation of benchmark-model specifications in Section 3 is evident, it is recommended that more experimental data, which might be useful for more detailed modelling or for justification of sufficiency of the model, be provided.

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.

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, following the recommendations exemplified in the details given for Sections 1.1.X, below.

In general, modelling (idealization, simplification) of the experiment is not discussed here. However, if the exact experimental configuration is unknown (e.g., perhaps it was not reported because 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. 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.

1.0 DETAILED DESCRIPTION

This section should start with a brief description of the scope and objectives of the experiment carried out. A short general description of the reactor or experimental facility is given, with a more detailed description optionally provided in an appendix. The types of evaluated experiments acceptable as benchmarks are summarized.

1.1 Description of the Critical and / or Subcritical Configuration

1.1.1 Overview of Experiment

The overview of the experiment should include the name of the facility, when 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 2.1, should be briefly stated. (e.g., “Twenty experiments were evaluated, but only 12 were judged to be acceptable for use as critical benchmark experiments.”)

1.1.2 Geometry of the Experiment Configuration and Measurement Procedure

This section contains the detailed description of the physical arrangement and dimensions of the experiment. The method of determining the critical condition and, if applicable, the measured reactivity are stated. 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.

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

1.1.3 Material Data

This section contains the detailed description of all materials used in the experiment as well as significant materials in the surroundings. Whether compositions are from physical or chemical analyses of the materials actually used in the experiments or are from material handbooks when only the type of material

was specified (e.g., stainless steel 304L) should be clear. Details of the methods of analysis and uncertainties, if known, are also given. When isotopic buildup and decay are important, relevant dates should be provided.

1.1.4 Temperature Data

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, is presented in this section. Subcritical measurement description must include 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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the buckling and extrapolation measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.2.1 through 1.2.5 are fixed and, with the exception of Section 1.2.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.2.5 is: **Additional Information Relevant to Buckling and Extrapolation Measurements.**

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 $^{238}\text{U}/^{235}\text{U}_f$ 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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the spectral characteristics measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.3.1 through 1.3.5 are fixed and, with the exception of Section 1.3.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.3.5 is: **Additional Information Relevant to Spectral Characteristics Measurements.**

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. 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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the reactivity-effect measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., group constants of delayed neutrons) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.4.1 through 1.4.5 are fixed and, with the exception of Section 1.4.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.4.5 is: **Additional Information Relevant to Reactivity Effects Measurements.**

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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the reactivity-coefficient measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.5.1 through 1.5.5 are fixed and, with the exception of Section 1.5.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.5.5 is: **Additional Information Relevant to Reactivity Coefficient Measurements.**

1.6 Description of Kinetics Measurements

This section contains a detailed description of measurements such as decay constants, β_{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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the kinetics measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.6.1 through 1.6.5 are fixed and, with the exception of Section 1.6.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.6.5 is: **Additional Information Relevant to Kinetics Measurements.**

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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the reaction-rate distribution measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.7.1 through 1.7.5 are fixed and, with the exception of Section 1.7.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.7.5 is: **Additional Information Relevant to Reaction-Rate Distribution Measurements.**

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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the power distribution measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.8.1 through 1.8.5 are fixed and, with the exception of Section 1.8.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.8.5 is: **Additional Information Relevant to Power Distribution Measurements.**

1.9 Description of Isotopic Measurements

This section contains a detailed description of isotopic measurements of discharged fuel from particular experimental configurations. 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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the isotopic measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.9.1 through 1.9.5 are fixed and, with the exception of Section 1.9.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.9.5 is: **Additional Information Relevant to Isotopic Measurements.**

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, respectively, an overview of the measurements, the configuration geometry and measurement procedure, material data, temperature data, and additional information relevant to the measurements. Detailed descriptions of the methods used to obtain the data should be included in the appropriate subsections. Values of the parameters that were directly measured should be given, as well as other data (e.g., constants) used in the data-reduction process. Clear distinction should be made between measured values, derived values, and data used to process measurements to obtain the experimental results. Subheadings for Sections 1.10.1 through 1.10.5 are fixed and, with the exception of Section 1.10.5, are the same as those heading listed in Section 1.1. The subheading for Section 1.10.5 is: **Additional Information Relevant to Other Miscellaneous Types of Measurements.**

Section 2 General Guidelines

Missing data or weaknesses and inconsistencies in published data are discussed and resolved in appropriate subsection of this section. The effects of uncertainties in parameter data on the measurement results are discussed and quantified. Codes and modelling methods used for calculations of the effects should be specified. Use of data with large uncertainties or data that require assumptions on the part of the evaluator is justified.

Besides effects of reported uncertainties, sensitivity of the measurement results 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 meaning of 'negligible' should be quantified.) Otherwise, a standard uncertainty (approximate standard deviation¹) 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 measuring device, and personal experience. The basis of the uncertainty estimate should be explained.

Differences between code input specifications whose 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.

At the end of Section 2, a summary table, showing effects of the standard uncertainties of experimental data on the parameter of interest, is presented. It is recommended to also include sensitivities of measurement results to the various parameters per unit measure or per 100% and with the sign (+ or -), to preserve in convenient form this outcome of the evaluation. The table concludes with the total evaluated uncertainty, which is defined as the individual uncertainty effects combined with the measurement uncertainty, of the experimentally measured value.

¹ See REFERENCES FOR UNCERTAINTY ESTIMATIONS at the end of this evaluation guide.

2.0 EVALUATION OF EXPERIMENTAL DATA

The general conclusion of acceptability of data evaluated in the following subsections is given here. If all or part of the data is found to be unacceptable for use as benchmark data, this fact is noted, and the reasons are summarized. [Unacceptable data are not included in Sections 3, 4, 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. It concludes with acceptance or rejection of the data for use as benchmark specifications.

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. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.3 Evaluation of Spectral Characteristics Data

This section contains an evaluation of the spectral-characteristics measurements described in Section 1.3. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.4 Evaluation of Reactivity Effects Data

This section contains an evaluation of the reactivity measurements described in Section 1.4. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.5 Evaluation of Reactivity Coefficient Data

This section contains an evaluation of the reactivity coefficient measurements described in Section 1.5. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.6 Evaluation of Kinetics Measurements Data

This section contains an evaluation of the kinetic measurements described in Section 1.6. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.7 Evaluation of Reaction-Rate Distributions

This section contains an evaluation of the reaction-rate distribution measurements described in Section 1.7. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.8 Evaluation of Power Distribution Data

This section contains an evaluation of the power distribution measurements described in Section 1.8. It concludes with acceptance or rejection of the data for use as benchmark specifications.

2.9 Evaluation of Isotopic Measurements

This section contains an evaluation of the isotopic measurements described in Section 1.9. It concludes with acceptance or rejection of the data for use as benchmark specifications.

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. It concludes with acceptance or rejection of the data for use as benchmark specifications.

Section 3 General Guidelines

Benchmark specifications provide the data necessary to construct calculational models that best represent the experiment. The benchmark-model 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 model, the benchmark specifications must include description of the transformations from the measured values to the benchmark-model values and the uncertainties associated with the transformations. The net effect of all transformation should be quantified by taking the difference between the untransformed model and a model in which all transformations are simultaneously applied, rather than the sum of the individual transformations; however the evaluator is encouraged to show the effect of the individual transformations.

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 simplifications (Section 3.X.1); geometry description and dimensions (Section 3.X.2); material data (Section 3.X.3); temperature data (Section 3.X.4); and the benchmark-model value of the parameter of interest and its evaluated uncertainty (Section 3.X.5).

Section 3.X.1 describes simplifications of the model compared to the experiment and estimates, by calculation or measurements, the effect of simplifications on the value of the parameter of interest. The effect is applied as an adjustment (i.e., correction, bias) to the expected value of the parameter to be calculated. (This expected value is called the 'benchmark-model value' of the parameter of interest.) Uncertainty of the value of the adjustment (an estimated standard deviation) is also given, to be combined with the total uncertainty from the end of Section 2.X to obtain the final evaluated uncertainty of the parameter of interest in Section 3.X.5.

Section 3.X.2 is the complete and concise description of the benchmark-model geometry. Schematics of the benchmark-model geometry should always be included in Section 3.X.2.

Values that define the benchmark model (Sections 3.X.2, 3.X.3, and 3.X.4) are, in general, derived from experimental data without rounding and are, thus, given with more digits than uncertainty of the experimental data implies. This is to maintain consistency between the benchmark model and the best

values obtainable from the evaluation of the experimental data. Uncertainties of values are given explicitly in other sections of the evaluation, namely in Sections 1, 2, 3.X.1, and 3.X.5.

3.0 BENCHMARK SPECIFICATIONS

A brief summary description of the benchmark model(s) may be given here.

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

The subsections in this section contain benchmark specifications for the critical or subcritical configurations described in Section 1.1. Specifications for both detailed and simplified models are recommended to be provided.

3.1.1 Description of the Benchmark Model Simplifications

Any simplifications and approximations made to geometric configurations or material compositions are described and justified and any resulting biases and additional uncertainties in k_{eff} are quantified. All codes and data used for calculations of biases and their uncertainties should be noted. If an idealized benchmark-model specification 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 and information needed to completely describe the geometry of the benchmark models are included in this section. Specifications are derived from reported values given in previous sections and should not be rounded, i.e., all additional digits that result from unit conversions should be retained. Sketches, including dimensions and labels, of the benchmark model(s) should always be included.

3.1.3 Material Data

Atom densities for all materials are derived from the reported values given in the previous sections and are concisely listed here. 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; i.e., their effect is truly negligible. Substitution of other material is discouraged because of the effect on the spectrum, thereby changing the basic nature of the configuration to an unknown extent.) Atom densities are listed in scientific notation with at least five significant digits.

3.1.4 Temperature Data

Temperature data about the experiment and for 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 it is available, are given in this section. If the experimenters simply indicated that the system was critical, a k_{eff} of 1.0 is assumed for the experiment.

If the experiment description is simplified (as described in Section 3.1.1) in the benchmark-model specifications, the effect on k_{eff} of this transformation, carefully quantified either from measurements or calculations, may result in an adjustment of the experimental k_{eff} to obtain k_{eff} of the benchmark model. The simplifications must have only a relatively small effect on the uncertainty in the adjusted benchmark-model k_{eff} . Generally, simplifications that have a large effect on k_{eff} or the neutron spectrum are not made.

Uncertainty of the adjustment of k_{eff} due to simplification of the model (from Section 3.1.1) is combined with the uncertainty of k_{eff} due to uncertainties in experimental data (from the end of Section 2.1) to obtain the final combined uncertainty of k_{eff} of the benchmark model.

The adjusted benchmark-model k_{eff} and its uncertainty are given. The benchmark-model k_{eff} is the expected value of k_{eff} from a calculation with the benchmark model, which is completely described in Sections 3.1.2, 3.1.3 and 3.1.4.

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 benchmark-model 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. Subheadings for Sections 3.2.1 through 3.2.5 are fixed and, with the exception of Section 3.2.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.2.5 is: **Experimental and Benchmark-Model Values for Buckling and Extrapolation Length.**

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. Subheadings for Sections 3.3.1 through 3.3.5 are fixed and, with the exception of Section 3.3.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.3.5 is: **Experimental and Benchmark-Model Values for Spectral Characteristics.**

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. Subheadings for Sections 3.4.1 through 3.4.5 are fixed and, with the exception of Section 3.4.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.4.5 is: **Experimental and Benchmark-Model Values for Reactivity Effects.**

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. Subheadings for Sections 3.4.1 through 3.4.5 are fixed and, with the exception of Section 3.4.5,

are the same as those heading listed in Section 3.1. The subheading for Section 3.4.5 is: **Experimental and Benchmark-Model Values for Reactivity Coefficients.**

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. Subheadings for Sections 3.6.1 through 3.6.5 are fixed and, with the exception of Section 3.6.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.6.5 is: **Experimental and Benchmark-Model Values for Kinetics Parameters.**

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. Subheadings for Sections 3.7.1 through 3.7.5 are fixed and, with the exception of Section 3.7.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.7.5 is: **Experimental and Benchmark-Model Values for Reaction-Rates.**

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. Subheadings for Sections 3.8.1 through 3.8.5 are fixed and, with the exception of Section 3.8.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.8.5 is: **Experimental and Benchmark-Model Values for Power Distributions.**

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. Subheadings for Sections 3.9.1 through 3.9.5 are fixed and, with the exception of Section 3.9.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.9.5 is: **Experimental and Benchmark-Model Values for Isotopic Compositions.**

3.10 Benchmark-Model Specifications for Other Miscellaneous Types of Measurements

This section contains specifications for the benchmark-models 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. Subheadings for Sections 3.10.1 through 3.10.5 are fixed and, with the exception of Section 3.10.5, are the same as those heading listed in Section 3.1. The subheading for Section 3.10.5 is: **Experimental and Benchmark-Model Values for Other Miscellaneous Measured Values.**

Section 4 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.

Methodologies used for the sample calculations and any other recommendations for the calculations are described.

4.0 RESULTS OF SAMPLE CALCULATIONS

Calculated results obtained with the benchmark-model specification data given in Section 3 are tabulated in this section, followed by detailed description of and recommendations for calculational methodology. At a minimum, results should be reported both as obtained directly from the 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. Benchmark-model uncertainties from Section 3.X.5 should be repeated here as percentages, for comparison purposes.

Other details about the calculations, including code versions, cross sections, and typical input listings, are given in Appendix A (A.1 through A.10).

4.1 Results of Calculations of the Critical or Subcritical Configurations

Calculated k_{eff} values and methodology 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 the interpreted benchmark-model k_{eff} values.

4.2 Results of Buckling and Extrapolation Length Calculations

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

4.3 Results of Spectral-Characteristics Calculations

Calculated spectral characteristics and methodology are presented in this section.

4.4 Results of Reactivity-Effects Calculations

Calculated reactivity effects and methodology are presented in this section.

4.5 Results of Reactivity Coefficient Calculations

Calculated reactivity coefficient values and methodology are presented in this section.

4.6 Results of Kinetics Parameter Calculations

Calculated kinetics parameters and methodology are presented in this section.

4.7 Results of Reaction-Rate Distribution Calculations

Calculated reaction-rate distributions and methodology are presented in this section.

4.8 Results of Power Distribution Calculations

Calculated power distributions and methodology are presented in this section.

4.9 Results of Isotopic Calculations

Calculated isotopic concentrations and methodology 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, and methodology are presented in this section.

5.0 REFERENCES

All published documents referenced in the evaluation that contain 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 labelled 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. Input listings for the calculations should be consistent with the benchmark-model description in Section 3. 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 Appropriate Measurement Type (i.e., A.1 Critical or Subcritical Configuration, A.2 Bucking & Extrapolation Length, etc.)

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, multigroup, continuous energy, etc.).

A.X.7 Other assumptions and characteristics. Any differences between the benchmark-model description (Section 3) and the model represented by the input listing should be noted.

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.

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

TABLE 1. Atomic Weights.

| <u>Nuclide or Isotope</u> | <u>Atomic Weight</u> |
|---------------------------|----------------------|
| 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.

| <u>Nuclide or Isotope</u> | <u>Atomic Weight</u> |
|---------------------------|-----------------------|
| Ga | 69.723 |
| Sr | 87.62 |
| Zr | 91.224 |
| Nb | 92.9064 |
| Mo | 95.94 |
| ⁹⁹ Tc | 98.9063 ² |
| 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 ¹ |
| 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 |

² 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.

| <u>Nuclide or Isotope</u> | <u>Atomic Weight</u> |
|---------------------------|-----------------------|
| 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 | 236.0456 |
| ²³⁸ U | 238.0508 |
| ²³⁷ Np | 237.0482 |
| ²³⁸ Pu | 238.0496 |
| ²³⁹ Pu | 239.0522 |
| ²⁴⁰ Pu | 240.0538 |
| ²⁴¹ Pu | 241.0568 ³ |
| ²⁴² Pu | 242.0587 |
| ²⁴¹ Am | 241.0568 |
| ^{242m} Am | 242.0596 ⁴ |
| 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 |

³ "Chart of the Nuclides," Thirteenth Edition, General Electric Company, 1984.

⁴ 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}) |
| β_{eff} | effective fraction of fission neutrons that are delayed. |
| C | Dancoff correction factor |
| D | diameter (OD is outer diameter; ID is inner diameter) |
| Δ | change in quantity [e.g., neutron multiplication factor, Δk ; buckling, ΔB^2 ; tank height, ΔH ; radius, ΔR ; etc.] |
| δ^{28} | ratio of ^{238}U fission to ^{235}U fission |
| δ^{25} | ratio of epithermal to thermal ^{235}U fission |
| H | height |
| k | neutron multiplication factor - The subscripts "eff" and " ∞ " or "inf" are used to denote the effective multiplication factor, k_{eff} , and the multiplication factor for an infinite system, k_{∞} or k_{inf} . |
| Λ | prompt neutron lifetime |
| m | mass |
| M | molarity (moles/l) |
| M | neutron multiplication $M \cong \frac{1}{1 - k_{\text{eff}}}$ |
| M_w | molecular weight or mass (g/mole) |
| N_A | Avogadro's number (atom, molecules, etc.) |
| 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) |
| ν | average number of neutrons per fission |
| R or r | radius |
| ρ | density or reactivity: $\rho \equiv \frac{k_{\text{eff}} - 1}{k_{\text{eff}}}$, sometimes denoted in units of $\beta \equiv \frac{\rho}{\beta_{\text{eff}}}$, where β_{eff} is the effective fraction of fission neutrons that are delayed. |
| ρ^{28} | the ratio of epithermal to thermal captures in ^{238}U |
| ρ^{25} | the ratio of epithermal to thermal captures in ^{235}U |
| ρ_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., $\rho_{\text{UO}_2\text{NO}_3}$, $\rho_{\text{H}_2\text{O}}$, ρ_{Pu} , ρ_{HNO_3} . |
| s_i | estimated standard deviation, equal to the positive square root of the statistically estimated variance s_i^2 |
| σ | statistical uncertainty associated with Monte Carlo calculations or standard deviation (the correct value has a probability of 68% of being within \pm of the quoted value, assuming a normal distribution) |
| σ_i | microscopic cross section for absorption ($i=a$), fission ($i=f$), scatter ($i=s$), capture ($i=c$), total ($i=t$) |
| Σ | macroscopic cross section or summation; e.g., Σ_a , Σ_f , Σ_s , Σ_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 5](#), “International Handbook of Evaluated Criticality Safety Benchmark Experiments”, [NEA/NSC/DOC\(95\)03/I-VIII](#), OECD-NEA, September 30, 2008.
- “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 13005 Août 1999.
- Zoltán Szatmáry: The Effects of Technological Uncertainties on the Neutron Flux, IRPhE Meeting, Budapest, May 2000.